The quantification of water usage in a South African platinum refinery using various water accounting methods

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DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

Signature: Phruti

Date: October 2018

ABSTRACT

South Africa is the darling of the platinum world with majority of the global platinum reserves being located in its backyard. Despite boasting extensive platinum mining activity, South Africa contrastingly has limited water resources. Additional pressure is placed on existing water resources due to climate change, poor water infrastructure and greater urbanisation. Hence water management in the mining sector, particularly the platinum mining sector is of great significance.

Platinum precious metal refineries are often neglected in terms of water related studies as they are comparatively smaller than other components involved in platinum production, such as platinum mines, hence the significance of this study as a means to increase awareness about platinum PMRs.

Accurate accounting of water usage in mining operations is necessary if water is to be effectively managed and minimised. Two water accounting methods were employed to evaluate water usage in a South African platinum precious metal refinery, namely the Water Accounting Framework and Water Footprint Network method. Flowrates and rainfall data were provided by the refinery, whilst evaporation data was obtained from the South African Department of Water and Sanitation. This information along with the appropriate assumptions was used to generate a comprehensive water account for the refinery.

The Water Accounting Framework found the volume of the total water inputs into the refinery to be 48.51 ML/year and the total volume of water outputs from the refinery is about 0.99 of the volume of the total inputs. The Water Footprint Network method found the total water footprint to be 49086.07 m^3 /year or 49.09 ML /year, comparable to the results of the Water Accounting Framework. The total water footprint was equivalent to the blue water footprint. The total product water footprint of the refinery being valued at 1.20 m^3/kg PGM was found to be greater than that of base metal refineries.

After viable recommendations were taken into consideration the total product water footprint was reduced by 25%.

DEDICATION

To my sister

Shiksha Dheda

for believing in me when I could not believe in myself.

You are present in every page.

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NOMENCLATURE

Amm SC	Ammonia Scrubbing Circuit
CT	Cooling Tower
Cond	Condensate
Demin	Demineralised Water
Ignit SC	Ignition Scrubbing Circuit
f	Correction factor to convert measurements from pan evaporation to evaporation losses (dimensionless)
L	Pollution load (kg/year)
m	Moisture content (dimensionless)
Nox SC	Nitric Oxide Scrubbing Circuit
Pan	Pan evaporation rate (mm/year)
PP	Processing Plant
R	Rainfall (mm/year)
SA	Surface area (ha)
SC	Scrubbing Circuit
t	Time
V	Volume (ML/year)
Vac	Vacuum

GREEK CHARACTERS

γ	Disturbed or undisturbed catchment area (ha)
β	Volumetric rainfall to runoff factor (dimensionless)

SUBSCRIPTS

ent	Entrained
evap	Evaporated
incorp	Incorporated
lost	Lost return flow
max	Maximum
proc	Process step
prod	Product
rainfall	Rainfall/ Precipitation
runoff	Rainfall runoff

ACRONYMS

BMR	Base Metals Refinery
GDP	Gross Domestic Product
LCA	Life Cycle Assessment
MCA	Minerals Council of Australia
PGM	Platinum Group Metals
PMR	Precious Metals Refinery
SMI	Sustainable Minerals Institute
WAF	Water Accounting Framework
WFN	Water Footprint Network
WWG	Water Working Group
ZAR	South African Rand

CHEMICALS

Ir	Iridium
Os	Osmium
Pd	Palladium
Pt	Platinum
Rh	Rhodium
Ru	Ruthenium

Chapter 1 INTRODUCTION

1.1 Background

The importance of water

Water is an integral part of life. Water is necessary for drinking, basic hygiene and food production all of which are vital for survival. Water is the basis of all ecosystems and thus indispensable for sustaining the biodiversity of the environment, which strongly impacts wellbeing. Water is also crucial to the financial sector. It is not only essential for food production but is also critical for the production of manufactured goods and services and it plays a vital role in the trading of manufactured goods and services (Koehler, 2008).

Currently, there is a worldwide freshwater shortage. The increasing shortage of freshwater sources bodes ill for wellbeing of all. The far reaching effects of climate change are becoming prominent. Climate change has been linked to changing rainfall patterns, long droughts and elevated evaporation, the culmination of which is increased water scarcity. As the modern world expands, rapid urbanisation and increased infrastructure are becoming a social norm, generating increased industrial activity. The growth of activity in the industrial sector, leads to competition for the use of available water resources with other sectors, such as the agricultural sector and the mining sector. Roughly, 70% of the global freshwater resources are invested in the agricultural sector, responsible for food production. The escalation in the shortage of freshwater resources places strain on the agricultural industry and hence on food production. The strain on food production places food security at risk in terms of food quantity and quality and gives rise to various concerns, specifically health issues, such as malnutrition. The need to sustain the water requirements of the agricultural sector invariably leads to the exploitation of other existing water resources, such as ground and surface water sources, further increasing water scarcity. Continued rapid population growth only intensifies the strain placed on existing water sources (Koehler, 2008).

In short, freshwater sources are depleting faster than they can be replenished and drastic measures need to be taken to decrease the consumption of water sources, the first step of which should be accurate accounting of water usage in all sectors.

South Africa: The paradox of water scarcity and mineral abundance

South Africa (SA) is not immune to the water crisis facing the rest of the world. Instead SA is becoming increasingly more susceptible to the effects of increased water scarcity owing to the pressures placed on existing freshwater sources by a rapidly growing economy. Constituents such as poor water management practices, lack of appropriate water infrastructure, increased urbanisation, rapid population growth and the adverse effects of the ever-problematic climate change only serve to further intensify the water scarcity situation facing the nation. The country's innate climate does not assist in the dire water situation, with SA experiencing a low average annual rainfall (much below the global average annual rainfall) due to its location within a water stressed, semi-arid region (Ranchod, *et al*., 2015).

A paradoxical condition has developed in South Africa, where the country's limited water resources are strongly contrasted by its abundance in mineral resources. The mining sector is thus a point of much contention, as a sector which is economically lucrative but environmentally taxing. Surprisingly, about only three percent of South Africa's water resources are invested in the mining sector (Haggard, *et al*., 2015) , despite SA being the fifth largest global mineral producer (Ranchod, *et al*., 2015). In terms of platinum, 95% of the known world platinum reserves are found in South Africa and South Africa together with Russia produce 85% of the world primary PGM supply, 58% of which is produced solely by South Africa (IPA: International Platinum Group Metals Association, 2013).

As a major global mineral producer, the South African mining industry cannot be disregarded, without jeopardising the economic condition of the country (Ranchod, *et al*., 2015).Yet, even a small percentage of water invested in the mining sector, which boasts such extensive mining activity, accumulates to a huge amount of water being consumed. The mining industry gives rise to numerous negative and adverse environmental effects which make the hugely profitable mining industry, a cause for apprehension instead of celebration. The immediate and obvious environmental consequence of mining activity is the exploitation of existing water resources, not only through the depletion of available water sources but also through the decline if the quality of existing water sources (Haggard, *et al*., 2015).

Not only does the depletion of existing water sources pose an environmental threat, but it also raises concerns about human health. Escalation in water scarcity is also a cause for alarm in terms of the continued functioning of the mining industry and hence the financial growth of South Africa (Haggard, *et al*., 2015). Water is vital to all operations involved in the mining process and hence severe water scarcity will cause a halt in mining activity. Hence the reduction of water consumption is necessary for the safeguarding of existing water sources. It is essential that water consumption in current mining operations is decreased and thus it is imperative to effectively monitor and manage water usage in mining operations as a starting point for reduced water consumption (MCA , 2012).

The significance of effective water management

Improved water management in mining activities is fundamental for the reduction of water consumption in the mining industry. Sustainable water use will not only ensure continued mining activity, buy will also decrease water usage expenses and enable mining corporations to easily remain within legal environmental boundaries; hence allowing them to sustain a competitive edge over rival corporations (Morrison, *et al*., 2010).

It is imperative to understand how water is consumed in mining operations before water usage in these operations can be managed. Water consumption in mining operations is complicated and at times very subtle and as such it is challenging to understand the extent of its utilisation in mining activities. The collection and dissemination of valuable water related information is complex and tedious. Various water accounting methods have been developed to provide guidelines for estimating water usage. Two such common methods are the Water Accounting Framework (WAF) and the Water Footprint Network (WFN) method (Morrison, *et al.*, 2010).

This study will apply the WAF and WFN methods to a South African platinum precious metals refinery (PMR). The water usage in the PMR will be calculated and evaluated according to the guidelines and procedures set out by these methods. The results achieved from each method will then be compared to each other. These results will also be compared to results found by other similar studies.

In summary, the South African mining sector is of economic importance to the country. The platinum mining sector is of particular importance as South Africa has the most platinum reserves globally and is the largest international platinum supplier and consequently the platinum mining activity in the country is extensive. Thus this study has chosen to focus on platinum mining. There are many stages to the platinum mining process, however very little attention has been given to the platinum refinery stage in terms of the water thus far, hence a platinum precious metals refinery was chosen for study and the application of the two water accounting methods; to increase knowledge and insight into this otherwise overlooked area of platinum mining. The PMR was also selected for study as it was one of the only sites at the time this study was done that was willing to share valuable data for academic purposes and thus became the PMR became the primary focus of the study.

Cumulatively, this study aims to understand and estimate water usage in the platinum PMR and to compare the results found, in a bid to identify areas of high water consumption and hence possible water usage reduction in the PMR using the two chosen water accounting methods. After which the strengths and weaknesses of each of the employed methods as well as the circumstances and/or situations which warrant the appropriate use of each method will be established.

The WFN method has been extensively applied in the agricultural sector and hence is not readily applied in the mining sector. This study will evaluate the application of WFN in the mining sector and compared the results found by this method to the results found by the WAF and a handful of similar studies.

The WAF is employed in the mining sector. It was developed in Australia for the evaluation of water usage in the Australian mining sector. It is generally used as method for water usage evaluation in the South African mining sector as South Africa is climatically similar to Australia.

The WAF and the WFN method were selected for application in this study instead of other water accounting methods as both these methods were the most suited to the level of data supplied by the PMR. The data supplied by the PMR was not sufficient for the application of other water accounting methods, such as the LCA water based assessment. Also the PMR had already conducted other water related studies on their site and wished to have insight into their water usage from another perspective, using water accounting methods which they has not previously utilised, such as the WAF and WFN method.

1.2 Research Objectives

The focus of this research was to compare two water accounting methods and their application to the data provided by a South African platinum PMR.

The objectives of this research are to:

- Apply the water accounting methods namely, the Water Accounting Framework (WAF) and the Water Footprint Network (WFN) method to an existing South African platinum PMR in order to quantify the usage of water in the PMR and to determine the areas of high water consumption in the platinum PMR;
- Compare the two water accounting methods in terms of their advantages and disadvantages in their application to the given data;
- Compare the results obtained from the water accounting methods, with regards to platinum PMR operation and to determine whether these results are in accordance to the trends observed in literature; and

- Explore steps that could be taken to reduce water consumption in the considered platinum PMR.
- To increase knowledge of water usage in a rather overlooked mining stage, such as the platinum refinery process.

1.3 Research Methodology

The WAF and the WFN methods were employed to evaluate the usage of water in the South African platinum PMR. The monthly water account was calculated for the PMR over a 12 month period. The PMR supplied certain volumetric water flowrates and ratios, as well as rainfall data and the production rate over the specified time period, which was used to start the water mass balance. Unknown water flowrates were found by closing the water balance and making reasonable assumptions.

The volume of water consumed in each process of the PMR was calculated. This allowed for the systematic identification of high consumption areas in the PMR. The effect that the PMR had on surrounding water resources was evaluated in accordance to the guidelines of the water accounting methods. Recommendations on how to reduce water consumption in the PMR were made. The most viable was theoretically applied and the new results were found.

1.4 Structure of Thesis

This thesis is divided into the following sections.

Chapter 1 INTRODUCTION

Chapter 1 provides background to the research by describing the importance of water, the water crisis facing South Africa and the contrasting extensive mining activity in South Africa and how water usage evaluation is imperative in the mining activities is imperative for the reduction of water consumption in the mining sector.

Chapter 2 LITERATURE REVIEW

Chapter 2 contains the literature review, which is the backbone of the thesis. The two water accounting methods, the Water Accounting Framework (WAF), along with the Water Footprint Network (WFN) method are discussed in detail. The platinum mining industry in South Africa is also discussed.

Chapter 3 METHOD

Chapter 3 focuses of the procedures used and the assumptions made to evaluate water usage in the platinum PMR and to find all the necessary results.

Chapter 4 RESULTS

Chapter 4 contains the results found from the platinum PMR after the application of the two water accounting methods.

Chapter 5 DISCUSSION OF RESULTS

Chapter 5 focuses on the comparison of the results found by the two different water accounting methods. These results were also compared to results found by similar studies. The strengths and weakness of the water accounting methods were discussed.

Chapter 6 RECOMMENDATIONS

Chapter 6 contains the recommendations on how to reduce water consumption in the platinum PMR, new results were calculated from the recommendations.

Chapter 7 CONCLUSION

Chapter 7 contains the main findings and highlights of this study

"Water, like religion and ideology, has the power to move millions of people. Since the very birth of human civilization, people have moved to settle close to it. People move when there is too little of it. People move when there is too much of it. People journey down it. People write, sing and dance about it. People fight over it. And all people, everywhere and every day, need it." ***Mikhail Gorbachev***

Chapter 2 LITERATURE REVIEW

This section contains background information on the platinum industry and the water accounting methods.

2.1 Platinum Background

As mentioned earlier, South Africa dominates the global production of the platinum group of metals (PGMs) due to the large PGM reserves found in the Bushveld Complex. Minor contributors are Russia, Canada, Zimbabwe and United States of America (Mudd & Glaister, 2009). 58% of world PGM production takes place in South Africa, while Russia accounts for 26% of world PGM production. The deposits in South Africa and Zimbabwe are rich in platinum while the deposits in Russia and North America have high palladium content (IPA: International Platinum Group Metals Association, 2013).

In 1924, platinum nuggets were found in South Africa for the first time. This led to the discovery of two platinum deposits by geologist Hans Merensky. Each of the deposits was approximately 100 kilometres in length, these deposits would later become known as the Bushveld Igneous Complex. Soon afterwards, in 1925, the eastern limb of the Bushveld Complex was identified. The advent of World War 2 brought about new applications for metals and as a result platinum mine production in South Africa began to grow consistently. The primary new use for platinum was in the petroleum industry. In the petroleum industry platinum catalysts were introduced to increase the octane rating of petroleum and for the manufacture of significant primary feedstocks for the budding plastics industry. This was followed by the 1960s where platinum was in demand for jewellery purposes due to its colour, value, purity and prestige; a testament to the 1960s as a period of euphoric prosperity and halcyon atmosphere (Chamber of Mines of South Africa, 2018).

The South African platinum sector was dominated by Gencor, JCI and Lonrho in the last half of the 20th century. The mines housed under these groups contributed up to 80% of the world's PGM supply. Later with the introduction of black economic empowerment and a new approach to mineral rights colloquially termed as the 'use-it-or-lose-it', which was envisaged in the Mineral and Petroleum Resources

Development Act (MPRDA) caused a shift in the platinum sector. This shift along with a growing intense interest of both foreign investors and operators in South African platinum reserves led to the growth and rise of a number of smaller platinum companies. This occurred along with an increase not only in PGM demand but also in PGM prices, in what can be called the golden platinum days from 2002 to 2008. The period after 2008 was marked by a global economic depression which brought an end to the golden age in the platinum sector. The worldwide economic depression caused many small platinum companies and operators to shut down (Chamber of Mines of South Africa, 2018). Only large platinum companies and operators have survived this economic depression and continue to do so. This emphasises the need for the effective management of resources in South African platinum corporations, especially water, not only for environmental sustainability but for the continued economic viability of existing platinum corporations.

As previously stated, the platinum group of metals are uniquely concentrated in one region of the world. The Bushveld Complex is a huge igneous complex which extends roughly 370 km east-east and about 240 km north-south and is located in the North West province of South Africa (Mudd & Glaister, 2009). The Bushveld Complex was formed about 2 billion years ago and is the world's largest layered intrusion. Not only is the Bushveld Complex home to more than half the global platinum group metals, it also houses other associated minerals such as vanadium, chromium and refractory minerals (University of the Witwatersrand , 2017). The Bushveld Complex hosts about 80% of PGM-bearing ore (Chamber of Mines of South Africa, 2018).

The Bushveld complex outcrop arises in three main areas, a linear northern lobe and two bracket shaped lobes on the east and west side (Mudd & Glaister, 2009). The Bushveld Complex is overlain by Karoo sediments and is underlain by rocks from the Transvaal Supergroup; it made up of the Lebowa Granites, the Rooiberg Felsic and the Rustenburg Layered Suite. The Rustenburg Layered Suite is divided into many different zones and is mainly contains mafic rocks. Around the edge of the intrusion of the Rustenburg Layered Suite, the marginal zone appears. From the base of the complex upwards, the Lower Zone, the Critical Zone, the Main Zone and finally the Upper Zone appear in that specific sequence. Between the Main Zone and the Critical

Zone, the Merensky Reef occurs. The Merensky Reef is rich in Platinum Group Metals. In the Upper Zone, magnetite is present which is rich in vanadium and chromitite seams are also present in the Critical Zone (University of the Witwatersrand , 2017). Hans Merensky's work has resulted in the naming of the Merensky Reef (Chamber of Mines of South Africa, 2018).

The concentration of PGMs in South Africa is an indicator of the extensive mining activity that occurs in the area to meet global platinum needs. This high level of mining activity surrounding this specific group of metals make the study and discussion around these metals and their processing significant, particularly in terms of water usage and environmental impacts.

There are six platinum group metals (PGMs) which have similar chemical and physical properties: platinum (Pt), ruthenium (Ru), iridium (Ir), rhodium (Rh), osmium (Os) and palladium (Pd). These six metals are divided into two groups based on their densities. The heavier group comprises if platinum, iridium and osmium and the light group consists of palladium, rhodium and ruthenium (Mudd & Glaister, 2009). Platinum and palladium are the most significant of the PGMs due to their economic value and high quantities (IPA: International Platinum Group Metals Association, 2013). PGMs have a high oxidation resistance; they do not corrode easily and are found to be relatively scarce in the earth's crust, a similarity which it shares which gold (Au) and silver (Ag). These characteristics allow PGMs to be classified as precious and noble metals (Mudd & Glaister, 2009).

PGMs have distinctive chemical and physical properties which make them appropriate for use in a variety of applications. The primary use for platinum is in catalytic converters for vehicle exhaust control, which accounts for about 50% of its application (Mudd & Glaister, 2009). Auto catalysts accounted for about 34% of the gross world demand for platinum, palladium and rhodium combined (Chamber of Mines of South Africa, 2018). About 30% of platinum is used in jewellery (Mudd & Glaister, 2009), due to the quality, durability and aesthetic appeal of its silvery white colour. About 50% of the global platinum jewellery offtake is accounted by China (Chamber of Mines of South Africa, 2018). Other secondary uses of platinum include electronic components, chemical process facilities, glass, hydrogen fuel cells, specialty medical uses, petroleum process catalysts and financial investments (Mudd & Glaister, 2009) .

The extraction and manufacture of PGMs create large revenues and hence are financial beneficial to the countries, particularly South Africa, where they are mined and processed (IPA: International Platinum Group Metals Association, 2013). Fortunately PGMs are highly recyclable and thus PGMs are considered to be 'used' rather than to be consumed (Chamber of Mines of South Africa, 2018), hence increasing the economic value of PGMs.

2.2 Platinum Processing

In this section the procedures and operations involved in processing platinum from PGM bearing ores are briefly discussed and background information about the South African platinum PMR under consideration is given.

2.2.1 Platinum Mining and Processing

The basic outline for any PGM mining project is as follows, extraction from the ground (mine), grinding, gravity based separation, flotation concentrator, smelter and lastly the refinery. PGM ores can be mined through two methods, either the conventional underground mine or the less common open cut mine. Only a small amount of the Bushveld Complex ore is extracted from open cut mines. However, many PGM producers are looking to incorporate open cut mines into their operations as open cut mining seems to be less energy intensive than underground mines. The higher energy requirements for underground mines are probably related to the depth of the mine. The disadvantage of the less energy consuming open cut mine, is the vast volumes of waste rock produced during mining (Mudd & Glaister, 2009). Finding the most suitable mining method for PGM-bearing ores will depend upon location and resource availability.

The platinum recovery process can be divided into six main stages, carried out in sequence as follows: concentration, smelting, converting, magnetic separation, base metals removal and lastly the refining of the precious metals (Ranchod, *et al*., 2015), refer to Figure 1 for an illustration of the above mentioned stages. The PGM-bearing ores usually have a low PGM content of between 2 and 6 grams PGM per tonne ore (IPA: International Platinum Group Metals Association, 2013) and thus this necessitates the release of this slight PGM content from the comparatively larger ore. The first stage is the concentration stage in which the ore in crushed and milled to liberate the PGM mineral particles (Ranchod, *et al*., 2015). This is followed by grinding and then gravity based or dense media separation. After the gravity based separation, the flotation process takes place to a produce a PGM-rich concentrate (Mudd & Glaister, 2009). If the liberated PGM particles from the concentration stage were very fine and are hence more difficult to recover through the flotation cells than coarser particles than multiple milling and flotation stages would be required (Ranchod, *et al*., 2015).

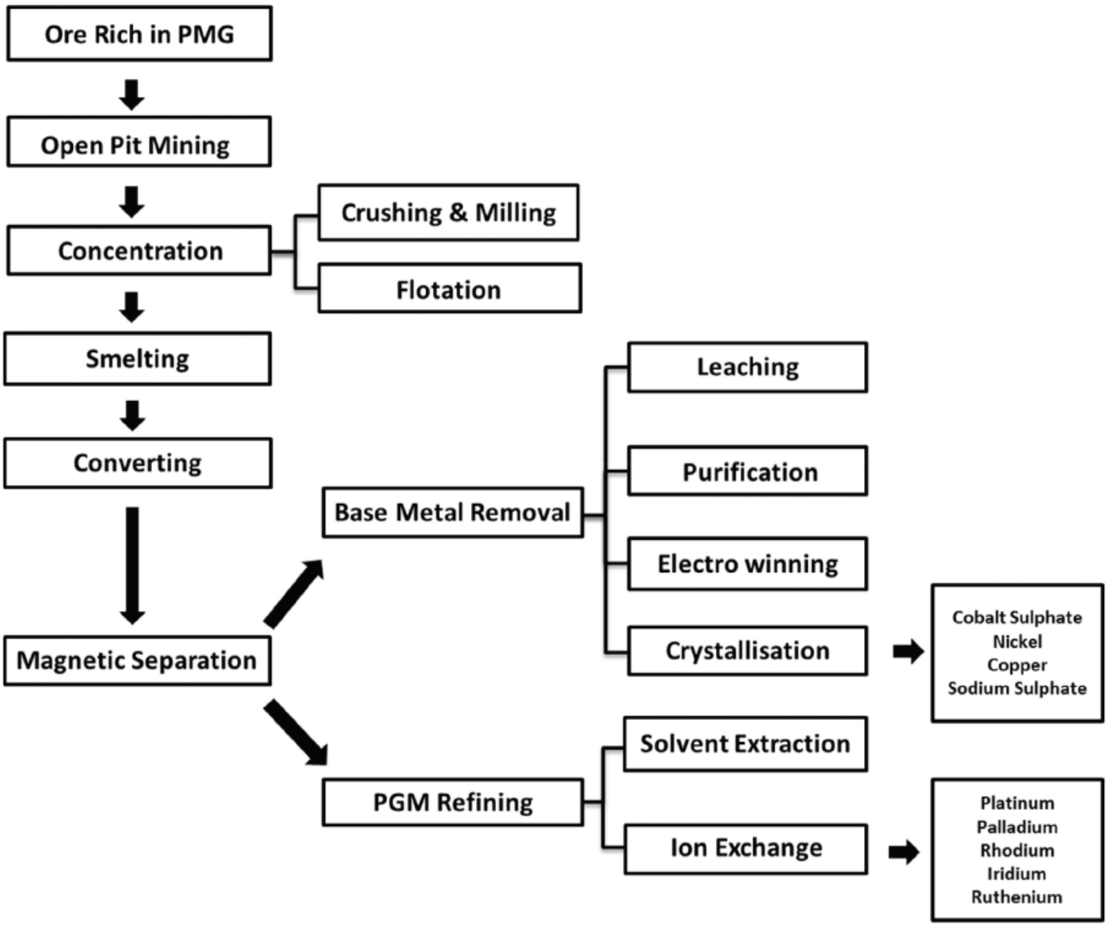


Figure 1 Generalised operational flow chart of a platinum mine (Ranchod, *et al*., 2015)

The PGM-rich concentrate is sent to the smelter. In the smelter the concentrate is melted in the electric furnace. Upon being melted the concentrate separates into two layers. The lower layer is matte, which is a mixture of a metal with its sulphides. The matte is sent to the next stage, which is the conversion stage. The upper layer is an oxide/silicate slag which is simply tapped off from the smelter. The oxide/silicate slag is either discarded or returned to the concentration stage where it can repeat the process until this point (Ranchod, *et al*., 2015).

During the conversion stage the excess sulphur and iron in the matte are oxidised in a refractory lined vessel. An iron-rich slag is formed through the addition of fluxing agents during the conversion stage. This iron-rich slag is later removed and returned to the furnaces. The resulting converter matte (main product of conversion stage) is then slow cooled to concentrate the PGM into a metallic fraction. The metallic PGM fraction can then be magnetically separated from the converter matte. This resultant concentrate then undergoes refining processes. The non-magnetic solids are rich in base metals and hence are transferred to the base metals refinery for additional processing. The processing of base metals at the refinery generally includes leaching, purification, electro-winning and crystallisation (Ranchod, *et al*., 2015).

Refining processes for the resultant concentrate commonly either involve solvent extraction or ion exchange (Ranchod, *et al*., 2015). The resultant concentrate is broken down in a smelter to yield metallic and copper anodes (Gouldsmith & Wilson, 1963) and hence to produce a PGM-rich Nickel- Copper (Ni-Cu) matte (Mudd & Glaister, 2009). This is followed by the electro-refining operation. During the electro-refining operation, pure copper and nickel are produced from the electrolytic dissolution of the nickel and copper anodes. Thereafter chemical operations take place. During the chemical operations the concentrate is treated with acids to separate the individual platinum group metals from each other (Gouldsmith & Wilson, 1963), followed by final refining. Hence the three main processes of extraction of the platinum group metals from the metallic PGM concentrate are the smelter, electro-refining and chemical operations refer to Figure 2 for an illustration of the steps mentioned above in a basic platinum refining process.

The process of mining, concentration and refining of PGMs from PGM-bearing ore to the final platinum product is complex, expensive and energy intensive. It generally takes about six months and roughly between ten and forty tonnes of PGM-bearing ore to produce one ounce of platinum (IPA: International Platinum Group Metals Association, 2013). The general ore grade of PGM-bearing ores are similar to gold in terms of grams per tonne ore but the processing of PGMs is more analogous to that of base metals processing in terms of percentage in matte and concentrate as well as in processing as the gold-silver mills use a cyanide based hydrometallurgical approach (Mudd & Glaister, 2009).

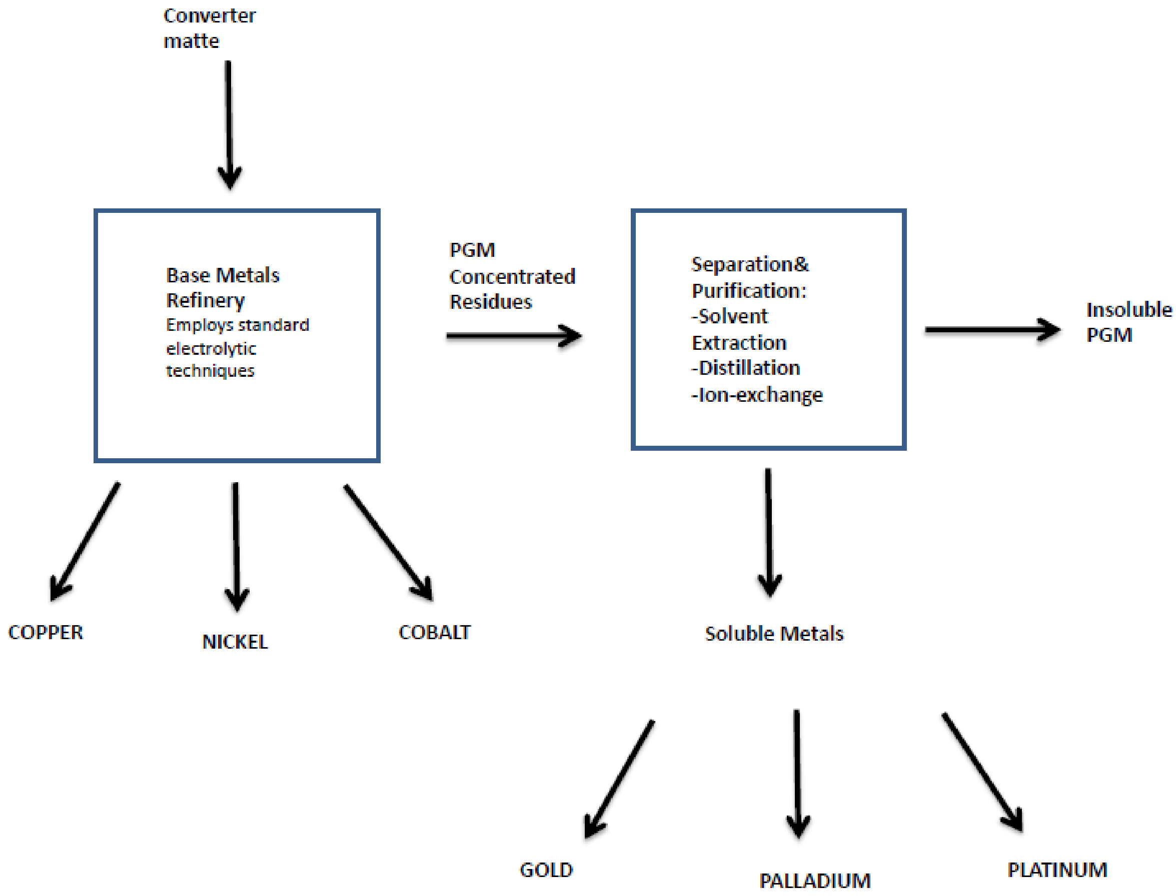


Figure 2 Basic platinum refining process

2.2.2 The South African Platinum Precious Metals Refinery

The platinum precious metals refinery (PMR) is roughly situated in the central north eastern region of South Africa. The exact location and name of the PMR will not be mentioned for the purpose of confidentiality. The platinum PMR receives bulk precious metal concentrates from the base metal refinery (BMR) belonging to the same corporation as the PMR. The PMR currently refines platinum, palladium, gold, rhodium, ruthenium and iridium from the precious metal concentrates to a high grade. The high grade refined products are sold to consumers for various trade purposes.

2.3 Water Accounting Methods

For the evaluation of water usage in numerous operations, particularly complex and intricate mining operations, water accounting methods have proven to be the most effective and efficient tools. The two previously mentioned water accounting methods, the Water Accounting Framework (WAF) and the Water Footprint Network (WFN) method are both founded on the concept of a mass balance over the entire operation. The volume of the water entering the process is equal to the volume of the water exiting the process is the basic principle on which a typical water mass balance is based. The change in water volume over time needs to be considered and hence the change in the volume of water over time is the sum of the water streams entering and exiting the process. The following equation illustrates this:

$$Mass\ IN_{water} - Mass\ Out_{water} = \Delta(Stored_{water} - Losses_{water}) \tag{1}$$

2.4 Water Accounting Framework (WAF)

The Water Accounting Framework (WAF) is colloquially referred to as the WaterMiner Tool. The aim of the WAF is to monitor, measure, analyse, record and report on valuable on-site water related information (ChemTech, 2012). The WAF was developed in Australia to evaluate the water usage in the Australian mining sector (MCA , 2012). The similar climatic conditions between South Africa and

Australia are the major factor in the application of the WAF not only in this study but in the other similar analysis of water usage in the mining industry.

The cumulative purpose of the WAF is to provide an easily accessible and efficient platform where onsite water usage and management of various mining operations can be compiled and compared. The information stored on this platform is readily accessible to anyone on an online central database to compare onsite water behaviour of similar and sometimes to different processes. The results of the WAF are easily understood as the results are presented in the format of a water balance, highlighting important information such as the total volume of water inputs and the total volume of water outputs (MCA , 2012).

2.4.1 Background and development of the Water Accounting Framework (WAF)

In 2005, the development of the Water Accounting Framework (WAF) commenced as part of a massive strategic program to gain greater understanding of water usage and water usage requirements amongst all stakeholders involved in the water reform process in the minerals industry. This strategic program was led by the Minerals Council of Australia (MCA) (MCA , 2012).

Members of the MCA are committed to sustainable development which also includes the responsible usage of natural resources. While the MCA is representative of about 85% of the minerals production in Australia, the MCA only impacts 0.02% of the Australian landscape and makes use of approximately only 3.6% operations; despite this the MCA's mineral operations contribute to 42% of goods and services exports, 8% of the national GDP and amounted to $ 21 billion of tax and royalties between 2008-2009 and about $23.4 billion in tax and royalties between 2009-2010. In order for mining companies to become members of the MCA, mining companies have to become signatories to *Enduring Value- The Minerals Industry Framework for Sustainable Development*. Operational guidance on the implementation of the principles of sustainable development is provided in the *Enduring Value* agreement. These principles were set out by the International Council on Mining and Metals'10 (MCA , 2012).

The strategic development of the WAF was overseen by the MCA's Sustainable Development (SD) Committee along with the Water Working Group (WWG). The MCA Secretariat was responsible for the 'hands-on' development of the WAF. The first step in development of the WAF was the collaboration of the WWG with the Sustainable Minerals Institute (SMI) for the creation of a 'suite of metrics' which would allow for consistent reporting of water usage within the minerals industry. In order to achieve this existing monitoring and reporting activities on the water usage within the minerals industry had to be reviewed, whilst simultaneously identifying the easiest approach for the adoption of a new consistent water usage reporting framework, which would allow for the adoption of this approach throughout the industry. This involved the investigation of other voluntary mining corporate reporting initiatives, delving into the reporting obligations in the annual environmental reports of mining processes and understanding an operations water balance. In the mist of all these developments, the National Water Initiative water policy reform program in Australia was making investments into the creation of water accounting frameworks. This conveniently coincided at the point when the Bureau of Meteorology had just received new powers from the Water Act of 2007, allowing it to collect and assimilate water related information from any entity which possessed it (MCA , 2012).

The preliminary framework of the WAF was delivered by the SMI to the MCA's SD Committee and WWG in 2008 for consideration. The MCA commissioned a third-party review of the framework in the latter half of 2008. The third-party review involved targeted engagement with all stakeholders including the minerals industry and the governmental and non-governmental representatives. This targeted engagement involved a joint mineral industry-government workshop in Perth and an open workshop at the SD08 (Sustainable Development) conference. By 2009, through a joint initiative by the SMI, MCA, NSW Minerals Council and the National Water Accounting Development Committee, a pilot project which encompassed the framework was launched in Central NSW, named the Minerals Industry Water Accounting Pilot Project. The pilot project was completed in October 2009. The completion of the pilot project was followed by further engagement of the MCA with the mineral industry and other stakeholders. Using the findings of the pilot study and the feedback from the implementation of the pilot framework, the pilot framework was amended to the form of the current Water Accounting Framework (MCA , 2012).

Many minerals operations and corporations have already had in place other individual private frameworks for monitoring, measuring and reporting water usage. There were various problems with these private frameworks which necessitated the need for the development of the WAF, the major problem being the lack of consistency. There was no consistency between the mining corporations within the minerals industry and hence comparison was difficult. There was also no consistency between operations within each mining corporation and entire offsite impacts would be ignored. There results or the finding of the private frameworks were very complex and difficult to communicate to a find range of parties. Interestingly, in most cases involving private water frameworks in corporations, all the necessary data was recorded and simply needed to be repackaged to promote consistency. Hence there was a need to a consistent and accessible water framework in the mining sector (MCA , 2012).

The difference between water accounting and water reporting should be noted. Water accounting involves the consolidation of water balance information as shown throughout the framework description. Water reporting differs from water accounting in that it simply presents the water balance information in the formats that are most appropriate to the needs of the users, it does not involve the consolidation of this information. The WAF attempts to provide a single platform for water information and interpretation (MCA , 2012).

2.4.2 Outline of the Water Accounting Framework (WAF)

The WAF has four main constituents which take the form of four main reports. The four main reports are referred to as (MCA , 2012):

1. The Input-Output Statement
2. The Statement of Operational Efficiencies
3. The Accuracy Statement
4. The Contextual Statement

The input- output statement shows all the total volume of the water inputs, water outputs and diversions between the site boundary and the surrounding environment. An input is a volume of water received by the site and intended for use by the operational facilities of the site. An output is defined as the volume of water removed from site, after use by operational facilities, mainly through tasks or having been treated or stored by the site. A diversion is water that flows from input to output without being utilised by the operational facilities of the site, 'diverted from the processes' (MCA , 2012).

The last column of the Input-Output statement comments on how each of the volumetric water flowrates were found (measured, estimated etc.) and the level of precision of each value (high, low etc.). The input-output statement offers a detailed summary of the main water flowrates between the site boundary and the environment in terms of volumetric water flowrates over a 12 month period in units of ML/year (MCA , 2012).

The statement of operational efficiencies illustrates the internal onsite water flows, such as the flow of water from onsite water storage facilities to onsite water tasks and treatment points (Osman, *et al.*, 2013).

The statement of operation efficiencies attempts to calculate the reuse and recycle efficiency of the operation, through the use of the operational model which estimates onsite water usage by calculating the proportion of reused and recycled water into tasks from the total flow of water into tasks (MCA , 2012).

The accuracy statement is used in conjunction with the input-output statement by providing a measure of how reliable or precise the values in the report are. It provides the percentage of the volumetric water flowrates that were measured, estimated or simulated at the percentage of the confidence level at which they were found (high, medium or low confidence level). The contextual statements places the entire study in context by providing information of the location and placement of the operation, such as the surrounding water resources in the region (MCA , 2012).

2.5 Water Footprint Network (WFN) method

The Water Footprint Network (WFN) method evaluates the volume of water consumed both directly and indirectly in a process. The total water footprint of the process is the summation of three small constituent water footprints, namely the blue, green and grey water footprints, which are defined below. The main purpose of the WFN method is to quantify direct and indirect water consumption by a process. The secondary aim of the WFN method is after identifying areas of high water consumption is to find means to reduce water consumption in the identified areas (Hoekstra, *et al*., 2011).

2.5.1 Background and development of the Water Footprint Network (WFN) method

Traditionally water consumption and pollution have been associated with particular activities such as cooling, processing, irrigation and bathing to mention a few. Total water consumption would then be a sum of these independent water consuming activities. Recently however, water management in terms of water consumption and pollution across the entire supply chain and not only with regard to particular activities has been considered as a more realistic approach to water usage. Lately the characteristics as well as the organisation of a supply chain are being deliberated as having a strong influence on the level of water consumption and pollution associated with the final product (Hoekstra, *et al*., 2011).

The increase in international trade of water intensive products have caused freshwater to be considered a global resource, in the sense that the consumption of freshwater in the final product can span over countries. Examples of water intensive products that are traded in the global market are crop, natural fibres and livestock. For example a raw product can be grown or formed in one country and then be exported to another country where it will be processed and refined after which the processed product will later be exported to yet another country for final consumption. There are many production steps in place from the formation of the raw product to the consumption of the final or end product; each of these distinct production steps will have a different impact on water resources. Hence water usage throughout the entire process has become spatially disconnected from the consumers. The impact that the consumption of the final product had on the global freshwater resources can be found by looking at the complete production chain from formation to processing to consumption and considering the consumption of water for each step in the respective countries in which those production steps occurred (Hoekstra, *et al*., 2011).

Traditionally final consumers, food industries, retailers and traders of water intensive goods have been excluded from the scope of water consumption in the archaic concept of water usage in the production process. They have now been included not only in their roles as direct water users but also in their capacity as indirect water consumers. For example the final consumer of a product could be a direct water user in the domestic sector as a household owner and can now also be considered an indirect water user through the consumption of a final or end product and the ancillary water usage associated with that consumption. Hoekstra and Chapagain believe that also taking these hidden or ancillary water usage amounts into consideration along with major water usage amounts in production can give an enhanced understanding of global freshwater usage and aid in quantifying the effects of water consumption and trade on water resources (Hoekstra, *et al*., 2011).

In 2002, the 'water footprint' was introduced by Hoekstra, which considered water usage along the entire supply chain for a particular product or service. The water footprint not only takes direct water usage of a producer or a consumer into consideration but also indirect water usage along the supply chain. When compared to the traditional and limited measure of water withdrawal for production, the water footprint concept can be regarded as a comprehensive marker of freshwater resource appropriation. The water footprint is multidimensional marker which marks both water consumption and water pollution. Water consumption is shown by water volumes according to source and water pollution is shown by polluted water volumes according to the type of pollutant. All components of the water footprint have to be specified temporally and geographically. The water footprint is a volumetric measure of water consumption and water pollution (Hoekstra, *et al*., 2011).

The water footprint is divided into the blue, green and grey water footprints are defined as follows by (Hoekstra, *et al*., 2011):

The blue water footprint is the volume of ground or surface water that is consumed in a process through evaporation, through incorporation of water into the product and lost return flow. Consumption refers to the loss of water from the available ground-surface water body in a catchment area. Lost return flow refers to water which is consumed and not returned to the same catchment or is returned at another time. The blue water footprint can be calculated as shown (Hoekstra, *et al.*, 2011):

$$Blue\ Water\ Footprint\ \left[\frac{volume}{time}\right] = Blue\ Water\ Evaporated + Blue\ Water\ Incorporation + Lost\ Return\ Flow \quad (2)$$

The green water footprint is the volume of rainwater consumed in a process which could have been temporarily stored in the soil or in the topsoil and could have been used for evapotranspiration by plants. In short, the green water footprint involves the consumption of green water resources, which is rainwater insofar as the rainwater does not become rainfall runoff, in which case the rainwater as rainfall runoff will no longer be considered as a green water resource. The green water footprint can be calculated ad illustrated below (Hoekstra, *et al.*, 2011):

$$Green\ Water\ Footprint\left[\frac{volume}{time}\right] = Green\ Water\ Evaporation + GreenWater\ Incoporation \quad (3)$$

The grey water footprint refers to the volume of clean freshwater that is required to dilute the wastewater stream before it id released into a natural water body, to ensure that the wastewater stream does not disturb the ambient water quality of the natural water body and to also ensure that the legal environmental requirements of the natural water body are not breached. The grey water footprint can be calculated as follows (Hoekstra, *et al.*, 2011):

$$Grey\ Water\ Footprint\left[\frac{volume}{time}\right] = \frac{L}{C_{max}-C_{natural}} \quad (4)$$

Where:
L is the pollutant load (mass/time);
C_{max} is the ambient water quality standard of the pollutant (mass/volume); and
$C_{natural}$ is the natural concentration in the receiving natural water body (mass/volume).

The total water footprint for a process, product or service is evaluated as follows (Hoekstra, *et al.*, 2011):

$$Total\ Water\ Footprint \left[\frac{volume}{time}\right] = Blue\ Water\ Footprint + Green\ Water\ Footprint + Grey\ Water\ Footprint \quad (5)$$

The traditional measure of ‘water withdrawal’ and the water footprint as an indicator or marker of water use differ with regards to three aspects. The water footprint is not restricted to only blue water use (surface and ground water) but also included the use of green and grey water resources, unlike the traditional measure which only includes blue water sources. The water footprint is not restricted to direct water use but also includes indirect water use, unlike the traditional measure which only includes direct water use and excludes indirect water use. The water footprint does not account for blue water usage insofar as this water is returned to where it was taken from (refer to the definition of lost return flow above), which differs from the traditional measure which includes this usage of blue water sources. From above it can be concluded that the water footprint offers an improved and broader perspective than the traditional measure on how a producer or consumer relates to water usage and freshwater systems. The water footprint accounts from spatially and temporally explicit information with regards to the utilisation of water for various human purposes. Water footprint accounts can not only form a good basis for the assessment of environmental, social and economic effects on the local surroundings but they can also enhance the discussion on sustainable and reasonable water usage and water allocation (Hoekstra, *et al.*, 2011).

2.5.2 Outline of the Water Footprint Network (WFN) method

There are four main steps involved in the WFN method. These steps have to be followed in sequence (Hoekstra, *et al.*, 2011):

1. Setting Goals and Scope
2. Performing an account of the Water Footprint
3. Completing the Sustainability Assessment

4. A Response Formulation

The setting goals and scope step is the starting point of the WFN method. Decisions made in this step have an impact on the overall water footprint account. Assumptions on which the entire water footprint will be based are made in this step as well as decisions on what to include and exclude from in the study of the process. In the performing an account of the water footprint step, the water balance over the process is carried out. The water balance is carried out in accordance to the assumptions made in the setting goals and scope step. From the water balance, water is separated into type, resource and quality. After which water consumption is categorised into blue, green and grey water as outlined by the WFN method definitions (Hoekstra, *et al*., 2011).

The final water footprint assessed and evaluated to see if water usage in the process is sustainable or not, when completing the sustainability assessment. The effect of the entire process of the surrounding community and environment is assessed. The response formulation is the reaction and response to the calculated water footprint. Suggestions of how to reduce water consumption by the process and to lessen the strain placed on scarce freshwater resources and to lessen pollution. The viability of each recommendation is considered and the most viable recommendations are chosen, thereafter suitable people and a reasonable time frame is finalised to carry out them out (Hoekstra, *et al*., 2011).

2.6 Other water accounting methods: Life Cycle Assessment (LCA)

The Life Cycle Assessment (LCA) assesses the total environmental impact of any process over the full life cycle of the process. If only the results of a portion or a specific part of the process are required than the LCA will only present the results for that part and not for the entire process (Morrison, *et al*., 2010). All LCA studies are performed within a framework, which is a set of standards that are defined by the International Organisation for Standardisation (ISO). The framework ensures that the results obtained from the LCA study are consistent and are of a high quality. LCA studies are performed within the framework defined by ISO 14040 (Harding, 2011).

Four major stages are part of the LCA:

- Goal and Scope Definition
- Inventory Analysis
- Impact Assessment
- Interpretation

The iterative nature of LCA imply that these four steps do not have be followed in sequence and after the interpretation step has been completed, it is valid to return to any of the previous steps (ChemTech, 2012).

During the goal and scope definition stage the purpose of the LCA and what is to be investigated by the LCA is decided (Berger & Finkbeiner, 2010). The functional unit for the investigation is defined in this stage; it is usually dependent on the level of detail required in the LCA study (Harding, 2011).

The mass and energy balance of the complete process is contained in the inventory analysis. A range of values are included in this balance from economic values such as goods and services to environmental values such as resources and emissions. As the mass and energy balances values are converted to values which are relative to the functional unit (which was defined in the first stage). These values are usually mass values and are placed in the inventory table (Harding, 2011).

The mass values in the inventory table are then converted to representative values in the impact assessment, which are fewer and so easier to manage. This stage includes three components: classification, characterisation and valuation. In the classification component, the inventory table values are classified according to an environmental problem. Each material value in the inventory table can contribute to one than one environmental problem. In the characterisation component, each classified value is given a weighing factor which presented as various chemicals. In the final valuation component, the weighing factor of each material is multiplied by the amount of material in each step of the process; this converts the characterisation values to single values to get the final LCA values (Harding, 2011).

The interpretation stage involves the questioning and understanding of the results. The interpretation stage does not necessarily have to be carried out right at the end once the other three stages have been completed, instead it can be carried out after each individual stage to assess the quality of the results after each stage. This allows for the continuous improvement of results throughout the entire process and also gives the LCA its iterative nature (Berger & Finkbeiner, 2010).

The LCA method was initially created to cater for most environmental sectors but not for water usage quantification. The LCA method has been modified to include the water sector and hence water usage evaluation and water related impacts are continuously under review as part of the LCA method. The ISO 14046 was established, which accounts for water quality, the location of water at each stage, the location where water use will end and the impact of water in that region (ISO, 2014). WULCA (Water Use in LCA) was created in 2007, which focuses on water use and water footprinting from a life cycle perspective (WULCA, 2014).

The LCA method will not be applied to the PMR in this study as a similar method has been employed in the evaluation of the PMR independently prior to this study.

2.7 Similar Studies of Water Accounting Methods

Similar studies surrounding the application of water accounting methods in mines and refineries where undertaken by other researchers. Their research and findings are discussed in the three case studies below.

2.7.1 Assessing the blue water footprint of an open cast mining operation in South Africa

Ranchod, *et al* published this study in 2014 and 2015 (Ranchod, *et al.*, 2014) and (Ranchod, *et al.*, 2015).

The platinum mine under investigation in this study was located in the northern region of South Africa. Conventional open cast method were used for the extraction of minerals at this site and this site accounted for the highest production rate of refined platinum, valued at 8.87 tons/year by the consortium in 2011. The process steps involved in this study included comminution, flotation, and smelting, converting, base metals removal and refinery process (Ranchod, *et al*., 2014).

The WFN method was employed to produce a comprehensive water footprint of a platinum mining operation, which quantified the direct and indirect water consumption across the supply chain. To find the volume of water consumed to produce one ounce of refined platinum was one of the aims of the study. The study was carried out over a 12 month period, from January 2011 to December 2011 (Ranchod, *et al*., 2015). This study only focuses on the blue water footprint and does not address both the green and grey water footprint as it argues that blue water resources generally have higher opportunity costs and are scarcer (Ranchod, *et al*., 2014).

The total blue water footprint, including both direct and indirect water consumption was found to be 63.2 m^3/oz. of refined platinum or 2 229 000 m^3/ton of refined platinum. The mineral processing plants and the tailings storage facilities consume the highest percentage of blue water in the process, consuming 47% and 43% respectively (Ranchod, *et al*., 2015). The high value of the blue water footprint for the mineral processing plant is due task losses from the comminution, flotation, and smelting, converting, base metals removal and refining stages of platinum recovery. The main contributor from the above mentioned stages is the converting stage. During the conversion stage, the converter matte is slow cooled and this process leads to extensive water evaporation (Ranchod, *et al*., 2014).

The tailings storage facilities onsite contributes to the blue water footprint through evaporative consumption as well as entrainment losses during the tailings discharge. Evaporative consumption amounted to 19.4% while entrainment losses amounted 23.7%, which cumulatively make up the 43% that the tailings storage facilities contributes to the blue water footprint (Ranchod, *et al*., 2014).

Blue water was mainly sourced from harvested rainfall and consumed as new water. Harvested rainfall was 38% of the blue water that was used; wastewater was 35% of the blue water that was consumed (indicating the attempt to be more sustainable) and 27% of the water came from ground water (Ranchod, *et al*., 2015).

It was found that evaporative abstractions from the mineral processing plants, the tailings storage facility and the water stores were the largest contributors to the blue water footprint, attributing 67% of the blue water footprint. Blue water losses which were comprised of ore and tailings entrainment losses, surface water discharges, non-primary activities and human consumption in the mine, offices and contactors camp, accounted for 28% of the blue water footprint and was the second largest contributor. Product incorporated blue water amounted to 5% of the total blue water footprint (Ranchod, *et al*., 2014).

As most of the water was consumed due to evaporative losses from the tailings storage facility and the mineral processing plants, the most viable suggestion would be to mitigate the evaporative effects of wind and sun. This study recommended the use of floating covers to mitigate evaporative losses. Floating covers operate by not only serving as a physical barrier to the passage of water vapour but by also reflecting a proportion of the incoming solar radiation (Ranchod, *et al*., 2014).

2.7.2 Water management at a base metals refinery

Publications from this study by Osman, *et al*., were made in 2013 and 2016 (Osman, *et al*., 2013) and (Osman, 2016).

Both the WAF and the WFN methods were applied to evaluate water usage in a base metals refinery (BMR). The study was carried out over a 12 month period. The base metals refinery was located in the North West Province of South Africa (Osman, 2016).

From the WFN method, the total water footprint was found to be 43.9 m^3/ton base metals produced (Osman, *et al*., 2013). The blue water footprint accounted for 76% of the total water footprint at 832 363 m^3/year and the green water footprint accounted for 24% of the total water footprint at 261 970 m^3/year. There was no grey water footprint for this study as the site under investigation did not discharge polluted water (Osman, 2016).

From the WAF method, the input-output statement was generated. The total inputs were valued at 1094 333 m^3. The major water inputs into the BMR were the potable water and the rainfall. Most of the incoming portable water was used by the utilities section and as process water. The total outputs were valued at 1120 830 m^3. Major water outputs from the BMR were evaporation and accumulation in dams. The difference between the inputs and outputs for the annual balance is 44 m^3/day. There was a 2% difference between the inputs and outputs, possibly due to the estimation of certain values (Osman, *et al*., 2013).

The accuracy statement showed that from the flowrates of the water entering the site, 24% was at a medium confidence level and 76% was at a high confidence level. From the flowrates of the water flowing out of the site, the accuracy statement showed that 91% was at a medium confidence level and 9% was at a high confidence. The operational model is part of the WAF method, allowed the study to identify wasteful water flows and provided an indication of the complexity of onsite water flows (Osman, 2016).

The biggest water consumers in the base metal refinery were the utilities section and the boilers. The total potable water requirement for the refinery amounted to 2 280 m^3/year which accounted for 0.16% of the daily water usage for the Bojanala Platinum District and the Rustenburg Local Municipality (Osman, 2016)

When the water footprint values were compared to the water usage at other refineries and processing plants in literature, they were found to be less (Osman, 2016); indicating that this particular base metals refinery was operating more efficiently than other base metal refineries.

It was recommended that the dam water be used as top-up to the rainwater tanks and that the water taken for the fire suppression services should be reduced as another measure to reduce the total water footprint (Osman, *et al*., 2013).

It was also suggested by the study that the total water footprint could be reduced by increasing the return of the steam condensate to the boilers and the gland seal steam to the hotwells, hence reducing the freshwater required by the process. Another recommendation was that a water treatment process should be added to the base metals refinery for the treatment and subsequent reuse of process condensate (Osman, 2016).

2.7.3 Water footprint of a South African platinum mine

Haggard, *et al*., published this study in 2015 (Haggard, et al., 2015) and (Haggard, 2015).

Both the WAF (using the WaterMiner software) and the WFN methods were employed for the evaluation of water usage at a South African platinum mine over a 12 month period. The rivers in the surrounding areas experience at least three months of severe water scarcity each year (Haggard, 2015).

The process steps including in the evaluation of water usage in the platinum mine were a smelter plant, two concentrator plants and a tailings dam; the mining step was excluded. Data such as the rainfall data, the flowrates and the product rate were obtained from the mining company under study. Monthly historic evaporation rates were received from a report by South African Department of Water Affairs. A mass balance was carried out over the chosen process steps, unknown flowrates around the cyclones, thickeners and flotation plants were calculated by closing the mass balance and using the percent solids and densities for flows out of these units of equipment (Haggard, 2015).

The total water footprint was found to be 806 m^3/kg PGM using the WFN method. The blue water footprint accounted for 28% of the total water footprint and grey water footprint accounted for 72% of the total water footprint. This study has no green water footprint. There were 4 main contributors to the blue water footprint: concentrator 1, concentrator 2, smelter and tailings dam. The tailings dam (4 m^3/kg PGM) made the smallest contribution to the blue water footprint as it consisted only of rainwater entering the dam. The smelter was the third highest contributor, amounting to 11 m^3/kg PGM of the blue water footprint. The two concentrators were the highest contributors to the blue water footprint. Concentrator 1 had a largest blue water footprint at 124 m^3/kg PGM. For PGM mines located in South Africa, the average water use was found to be 391.5 m^3/kg PGM (Haggard, 2015); thus the mine under evaluation in this study consumes more water per kilogram PGM produced that the average South African platinum mine.

Rainfall and evaporation data, calculated flowrates and measured flowrates were entered into WaterMiner and the results were used to complete the WAF. The WAF method found that 12 686 ML/year was consumed. The WFN method had found that 10 649 ML/year was consumed (blue water only) (Haggard, 2015). The reuse and recycle efficiencies of the concentrators were found using operational efficiencies of the WAF method. The concentrators use almost the same amount of water for the process. However, concentrator 1 reuses more water than concentrator 2, but does not use any recycled water at all. Concentrator 2 has a lower water reuse percentage than concentrator 1 but recycles 2% of the water used (Haggard, *et al*., 2015).

The tailings dam experienced the largest loss of water through evaporation and thus had the highest water footprint. As this water loss was due to evaporation, it was suggested that the dam be covered with floating modules to reduce evaporation and it was predicted that this would reduce the total water footprint by 2.5% (Haggard, *et al*., 2015) and that blue water footprint could be reduced to 204 m^3/kg, amounting to a 10% reduction of the blue water footprint (Haggard, 2015).

It was recommended that a pre-concentration step be added to concentrator plant 2 to reduce the amount of water required in the flotation and milling processes as this would reduce the blue water footprint to 216 m^3/kg, which amounts to a 5% reduction of the blue water footprint.

All three of the above case studies will be discussed further, particularly in relation to this current study, in CHAPTER 5 Discussion.

2. 8 Water intensity

Resource intensity is a measure of the resources necessary for the production of a unit of good or service. These resources can be many and varied, such as energy consumption, greenhouse gas emissions and water use. It is usually expressed as a ratio of amount of resource used to product made (Antunes, 2012).

Energy intensity is defined as the amount of energy consumed per unit of product or service generated. It is used as a measure of the energy efficiency of product and service such as appliances, vehicles, buildings and transportation systems. Energy intensity can also be used as an indicator in energy policy and climate change discussions as a measure of national energy efficiency. The measure of national energy is calculated as the amount of energy consumed per unit of GDP (Gross Domestic Product) generated in the economy (Antunes, 2012).

Water intensity can be defined as the amount of water consumed per unit of product or service produced. It can be considered to be a ratio between the water intake and a defined unit of production (IPIECA, 2014). Many a time, water is removed from natural water bodies for industrial purposes and if it is not returned to the same water body in its original quantity and quality than it could lead to the depletion of lakes and rivers. Sometimes water might not be an obvious resource for the production of a certain product/service and might only be consumed in certain processes in the production chain, such as for heating, cooling or washing, in such cases the calculation of the water intensity for particular processes is more significance than just knowing the amount of water than went into the entire production process. In areas where water security is under threat, it is important to monitor water intensity as an indication of the water efficiency of a process and ultimately as a measure of the water sustainability of the process (OECD, 2018).

However, the concept of resource intensity is not without controversy. The use of the resource intensity as guiding principles and measuring sticks for the creating of sustainability strategies has been heavily criticised. Different materials or mediums have different impacts on the environment. The reductions in the amount of the material or medium used in order to lower the resource intensity of that particular material/medium can at times lead to higher environmental burdens. This occurs if the reduction of the amount of material/medium used was the result of replacing that material/medium by materials that might be more environmentally harmful, especially in its role as the replacement material (Antunes, 2012).

2.9 The cost of water

If the cost of potable water from reliable and easily accessible corporation was valued at ZAR 5.17 per kilolitre of water (Mawson, 2006) in 2006, then using the rate of inflation, the value of water from the corporation would be valued at ZAR 10.80 per kilolitre of water (Crause, 2018). This approximate tariff will applied to calculating the theoretical cost of water by the PMR.

2.10 Summary of Literature Review

South Africa leads the international production of the platinum group of metals (PGMs) due to the large PGM reserves found in the Bushveld Complex. 58% of world PGM production takes place in SA. The concentration of PGMs in SA is an indicator of the extensive mining activity that occurs to meet global platinum needs. This high level of mining activity make the study and discussion around these metals and their processing significant, particularly with regards to water usage and water related environmental impacts.

A worldwide economic depression caused many small platinum companies to shut down, only a few large platinum companies managed to survive and continue to do so. Thus the need for the effective management of resources, especially water in South African platinum corporations, is of paramount importance not only for environmental sustainability but for the continued economic viability of these existing platinum corporations. The extraction and manufacture of PGMs generates large revenues and is hence financially beneficial to SA. Fortunately PGMs are highly recyclable and thus PGMs are considered to be ‘used’ rather than to be consumed, increasing their economic value.

PGMs to be classified as precious and noble metals as they have a high oxidation resistance; they do not corrode easily and are found to be relatively scarce in the earth’s crust. There are six platinum PGMs which have similar chemical and physical properties: platinum (Pt), ruthenium (Ru), iridium (Ir), rhodium (Rh), osmium (Os) and palladium (Pd). Auto catalysts accounted for the greatest gross world demand for platinum, palladium and rhodium combined. Due to the quality, durability and aesthetic appeal of its silvery white colour, platinum is also used for jewellery. Other secondary uses of platinum include electronic components, chemical process facilities, glass, hydrogen fuel cells, specialty medical uses, petroleum process catalysts and financial investments.

The platinum recovery process can be divided into six main stages, carried out in sequence as follows: concentration, smelting, converting, magnetic separation, base metals removal and lastly the refining of the precious metals. The main product of the conversion stage, the converter matte is slow cooled to concentrate the PGM into a metallic fraction. The metallic PGM fraction is magnetically separated from the converter matte and then goes through the refining processes. The non-magnetic solids are rich in base metals and are transferred to the base metals refinery for additional processing. The processing of PGMs is analogous to that of base metals processing in terms of percentage in matte and concentrate and in method of processing.

The exact location and name of the PMR will not be mentioned for the purpose of confidentiality. The platinum PMR receives bulk precious metal concentrates from the base metal refinery (BMR) belonging to the same corporation. The PMR currently refines platinum, palladium, gold, rhodium, ruthenium and iridium from the precious metal concentrates to a high grade. The high grade refined products are sold to consumers for various trade purposes.

The aim of the Water Accounting Framework (WAF) is to provide an efficient platform where onsite water usage can be compiled and compared in a consistent manner. The stored information is readily accessible to anyone on the online central database. The results of the WAF are presented in the format of a water balance and hence are easily understood. The WAF has four main reports: the input-output statement, the statement of operational efficiencies, the accuracy statement and the contextual statement.

The Water Footprint Network (WFN) method evaluates the volume of water consumed both directly and indirectly in a process. The total water footprint of the process is the summation of three smaller footprints, namely the blue, green and grey water footprints. There are four main steps involved in the WFN method: setting goals and scope; performing an account of the water footprint; completing the sustainability assessment and a response formulation. These steps have to be followed in sequence.

The Life Cycle Assessment (LCA) assesses the total environmental impact of any process over the full life cycle of the process. All LCA studies are performed within a framework, which ensures that the results obtained from the LCA study are consistent and are of a high quality. Four major stages are part of the LCA and include goal and scope definition; inventory analysis; impact assessment and interpretation. The LCA method has been modified to include water usage evaluation. WULCA (Water Use in LCA) was created to focus on water use from a life cycle perspective.

Three case studies focusing on water accounting and the application of water accounting tools were reviewed. The first case study assessed the blue water footprint of an open cast mining operation in South Africa. The study found that the mineral processing plants and the tailings storage facilities consume the highest percentage of blue water in the operation. The tailings storage facilities onsite contributed to the blue water footprint through evaporative consumption and entrainment losses during the tailings discharge.

The second case study focused on water management at a base metals refinery in the North West Province of South Africa. The study employed the use of both the WAF and WFN methods. The blue water footprint accounted for 76% of the total water footprint, while the green water footprint accounted for 24%. There was no grey water footprint for this study as the site under investigation did not discharge polluted water.

The third case study focused on the water footprint of a South African platinum mine. The blue water footprint accounted for 28% of the total water footprint, while the grey water footprint accounted for 72%. This study has no green water footprint.

Resource intensity is a measure of the resources necessary for the production of a unit of good. Water intensity can be defined as the amount of water consumed per unit of product produced. It can be considered to be a ratio between the water intake and a defined unit of production.

After taking inflation into consideration, this study considers that the cost of water from the corporation would be valued at ZAR 10.80 per kilolitre of water. This approximate tariff will applied to calculating the theoretical cost of water used by the PMR.

“Water, the Hub of Life. Water is its mater and matrix, mother and medium. Water is the most extraordinary substance! Practically all its properties are anomalous, which enabled life to use it as building material for its machinery. Life is water dancing to the tune of solids.” ***Albert Szent-Gyorgyi***

Chapter 3 METHOD

This chapter describes the application of the Water Accounting Framework (WAF) and the Water Footprint Network (WFN) method to quantify the volume of water consumed by a South African Platinum Precious Metals Refinery (PMR). This chapter also discusses the water balance on the PMR and the assumptions used to complete it.

3.1 Water Balance

The water balance was calculated in Microsoft Excel. The water balance over the PMR was completed using the data provided by the site and data from a consulting firm which did a water related study of the PMR previously, their work was used for further insight into the PMR, along with reasonable assumptions and material balances over specific units in the PMR, which allowed for the calculation of unknown values. The water balance effectively showed the amount of water entering and exiting the PMR. Monthly water balances were summed and averaged to provide a yearly water balance. From here onwards, all processes and units used in the PMR operations will be referred to by coded names due to confidentiality purposes.

3.1.1 Water Balance Calculation Assumptions

This section contains the assumptions made to complete the water balance over the PMR and hence calculate the volume of water entering and exiting the PMR.

Simplistic, yet informative diagrams of the PMR operations and processes are provided below. Complete detailed diagrams as well as process flow diagrams of the operations that occur in the PMR cannot be made available in this text in accordance with the confidentiality arrangement with the PMR and its parent mining corporation.

The overview of the PMR platinum refinery process and the overall system boundary around which the water balance was carried out is illustrated below in Figure 3, showing both the direct and indirect water inputs and outputs of the PMR operation.

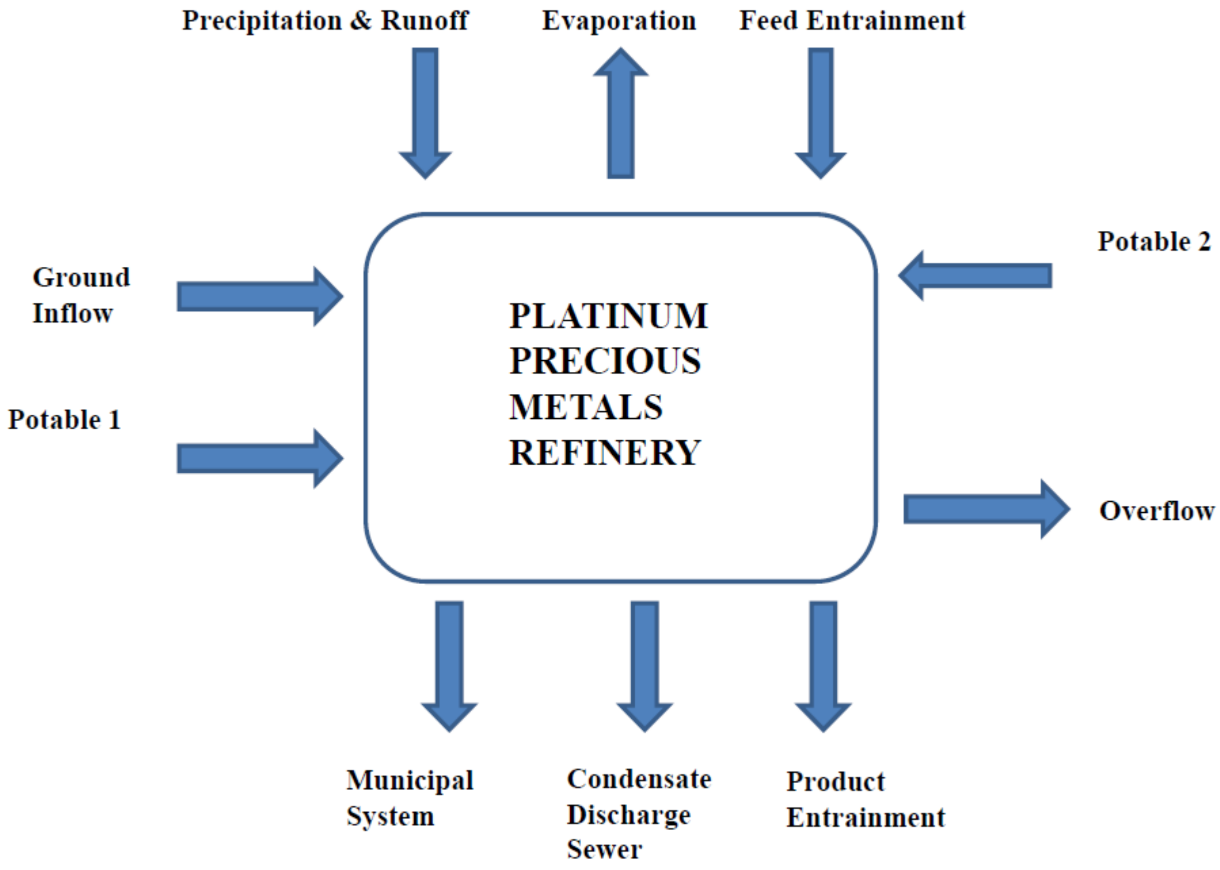


Figure 3 Overview of the PMR process showing the major water inputs and outputs

Figure 3 illustrates a general overview of the PMR process showing the major water inputs as well as the major water outputs from the PMR. Water enters the PMR through potable water tanks, Potable 1 and Potable 2; through rainfall (precipitation) collected directly and from collected runoff water; water also enters the site through moisture that is contained in the feed and there is also water inflow through a minor fissure in the bunds, referred to as ground water. Water leaves the PMR through evaporation; through discharge into the municipal system and the condensate discharge sewer and also through water that is entrained in the product and through an overflow from a water storage tank.

The system boundary for this study encompasses the entire PMR and all its internal workings. The main inputs and outputs of the overall system boundary on which the overall water balance was based are shown in Figure 3. Inputs into overall system boundary and hence the overall water balance are water entering from Potable 1 and

Potable 2, rainfall (precipitation) and rainfall runoff, water entrained in the feed, water inflow from a minor fissure in the bunds. Output from the overall system and hence the overall water balance include water lost through evaporation, through discharge into the municipal system and the condensate discharge sewer, water entrained in the product and water that overflows from the water storage tank and is lost to the system.

The operations of the PMR are illustrated in more detail below in Figure 4. In Figure 4, more insight is given in terms of the distribution of water from the potable tanks as well as how the water exactly enters and exits the PMR through the mixed water storage tanks.

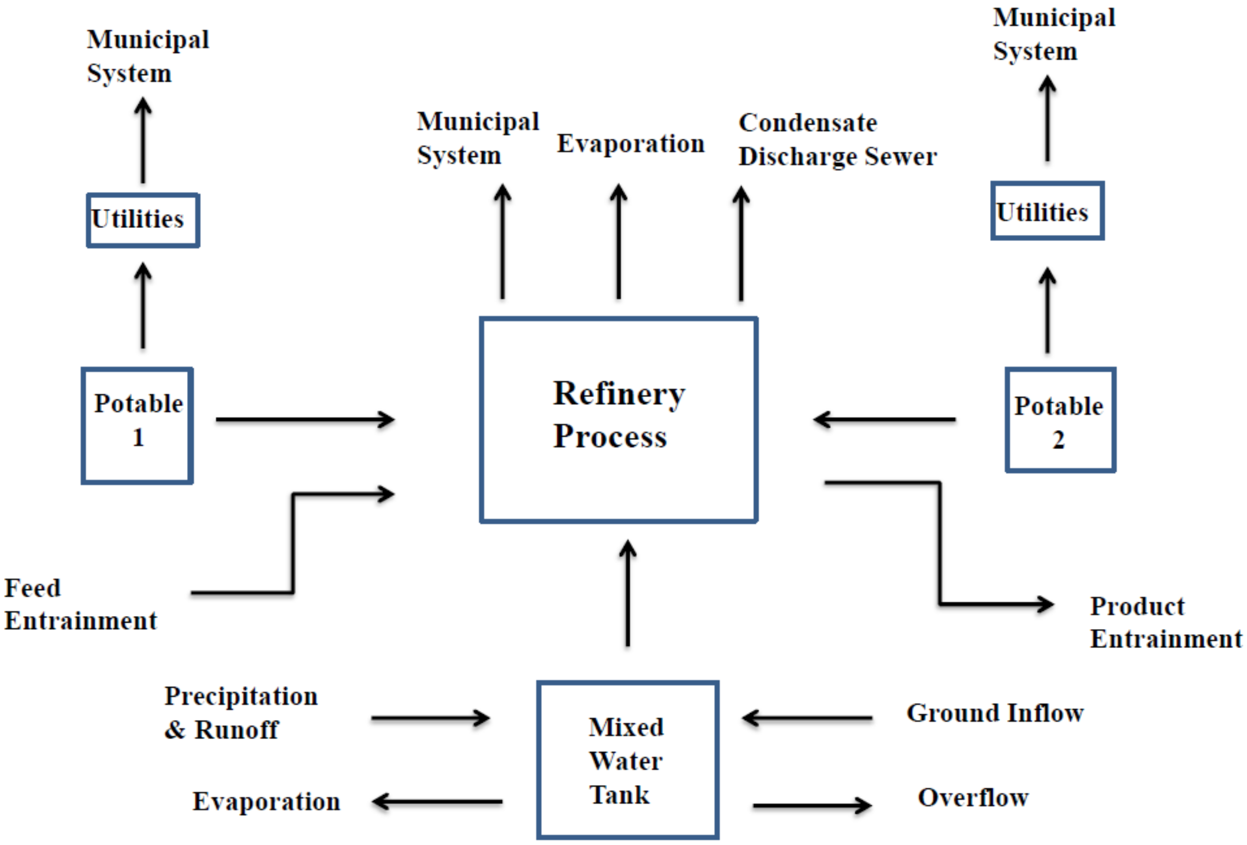


Figure 4 A detailed overview of the PMR process and the water inflows and outflows

As stated previously, Figure 4 provides greater insight to Figure 3. From Figure 4, it can be seen that Potable 1 supplies water to the main refinery process and to some utilities, the same can be noted about Potable 2. Used water from the utilities is discharged to the municipal system.

Water from the main refinery process is discharged to the municipal system and the condensate discharge sewer; water also leaves the main refinery process through evaporation and water that is entrained in the product also leaves the refinery process. Water enters the main refinery process through Potable 1 and 2, through moisture in the feed to the refinery process and through water from the mixed water storage tank.

Water stored in the mixed water tank comes from collected rainfall (precipitation) and rainfall runoff and from the minor fissure water inflow from the bunds. Water leaves the mixed water tank when there is too much water in the tank which results in an overflow from the tank and when water evaporates from the surface of the mixed water tank and when the stored water in the mixed water tank is used to supply water to the main refinery process.

A fairly detailed diagram of the PMR is available in Chapter 4, section 4.3.2 as the Operational Model in Figure 14. This is not a full thorough diagram of PMR which will not be explicitly illustrated in this dissertation in accordance with the confidentiality framework, but it provides enough detail for assessment and evaluation of water usage in this study.

Assumptions made to complete the water balance over the PMR and hence calculate the volume of water entering and exiting the PMR are noted below.

1. Assumptions about the operational variables:
   - The PMR operates for about 277 days per year.
   - 96% PMR availability due to negligible downtime which results from unscheduled maintenance.
2. The moisture content of the feed was assumed to be 0.5%. And the moisture content of the product was assumed to be 0.1%.
3. Metered data is available for potable water. From the metered data 97.8% is for Potable 1 and the rest goes to Potable 2. It is important to note that the only difference between Potable 1 and Potable 2 is Potable 1 supplies potable water to the main PMR operation, whereas Potable 2 supplies water only to the office area and to utilities that are on site but are not involved in the main

PMR operations, with the exception of one unit that Potable 2 supplies water to that is part of the main operation. A basic diagram is provided below to illustrate this in **Figure 5** for further understanding.

4. There are several users of water that share one meter reading, especially those connected directly to the potable water. Using the percentage distribution assumptions provided by the consulting firm, it was possible to find the distribution of the water by the users sharing one meter reading.
5. Boiler consumes potable water and distributes the steam as outlined (refer to the Operational Model in Figure 14 for illustration):
   - 25% to Processing Plant 2
   - 23% to Processing Plant 6
   - 16% to Effluent Management (alkaline)
   - 15% to Processing Plant 3
   - 15% to Processing Plant 5
   - 4% to General Utilities Facility
   - 1% to Change House
6. Assumed that the Demin distributes the potable water it receives as follows, 60% to Processing Plant 3, 23% to Processing Plant 4 and 17% to Processing Plant 5 (refer to the Operational Model in Figure 14 for illustration).
7. Processing Plant 2 Condensate and Processing Plant 7 Condensate returns assume 98% condensate discharges to the sewer with the remaining 2% pumped to the effluent management (acid), refer to the Operational Model in Figure 14 for illustration.
8. 90% of the steam supplied to the Processing Plant 4, Processing Plant 3, Processing Plant 6 and Processing Plant 5 is discharged to the Processing Plant 7 Condensate Tanks (refer to the Operational Model in Figure 14 for illustration).
9. It is assumed that the effluent amounts into the Effluent Management (acid and alkaline) are equal to the amounts exiting the tanks.
10. As the bunds are sealed it was assumed that there were zero seepage losses. There is minor fissure water inflow from bunds. The consulting firm approximates this water inflow is $2m^3$/month in winter and $4m^3$/month in summer.

11. A small amount of water was lost/ discharged to the environment due to an overflow of water from the storm water tank area.
12. The PGM product contains both PMR Final Product and the other products.
13. Evaporation data for the region was provided by South African Department of Water and Sanitation
14. Rainfall data was provided by the site.
15. It was assumed that there was no green water footprint for the this study as the rainfall runoff and/or collected rainfall was consumed on site and was not used to increase the amount of water in the topsoil i.e. it was not used for gardening.
16. As the PMR does not treat any waste water on site and transports the effluent to the Effluent Treatment Corporation, the PMR effectively has not grey water footprint as the PMR does not discharge any waste water into a natural water body
17. The data used and the amounts calculated were only for a 12 month period from Month 1 to Month 12. The months and year of this study will not be explicitly stated due to confidentiality concerns.

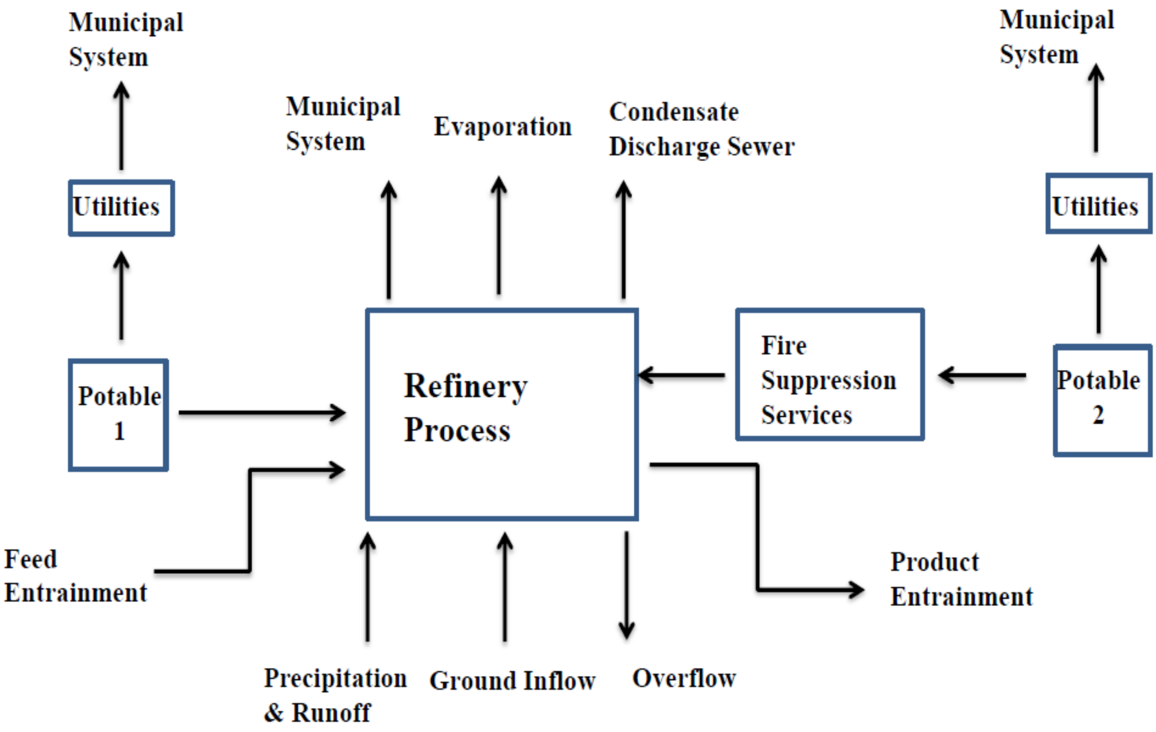


Figure 5 Diagram showing the flow of water into and out of PMR with emphasis on the water flow from the potable tanks

Figure 5 elaborates on the diagrams shown in Figure 3 and Figure 4. Figure 5 shows that whilst Portable 1 supplies water to the main refinery process, Portable 2 only supplies water to one unit linked to the main refinery process, the fire suppression services. The remaining water from Potable 2 is used to supply water to the utilities.

3.1.2 Outline of method

The first phase involved the collection of data from the PMR site and the consulting firm. The second phase was the water balance. Using the given information, a water balance over the entire PMR was started in Microsoft Excel. Firstly, assumptions about the entire PMR operation were made using techniques defined in both the WAF and WFN, particularly the WFN. The first step of the WFN, setting goals and scope, extensively deals with what to include and exclude from the mass balance, by considering a variety of factors such as the purpose of this study, the time period and system boundary of the investigation and the type of water to be included in the study, such as direct or indirect water or both. These assumptions and decisions are discussed in detail further on in this chapter in section 3.3.1.

The PMR supplied certain volumetric water flowrates and ratios, as well as rainfall data and the production rate over the specified time period, which was used to start the water mass balance. The next step was to calculate the amount of water used by the entities that directly consume water from Potable 1 and Potable 2. There were several users of water for one meter reading. In most cases this was just a matter of a sensible water distribution assumption to each user of the meter reading, based on the size and function of the entity. After which water flow to some of the other units could be calculated.

The next step in the water balance was completing the balance over the main units in the PMR.

In areas where there was a dearth of information, unknown water flowrates were found by closing the water balance and making reasonable assumptions. This completed the water balance over the units in the operation. The monthly water account was calculated for the PMR over a 12 month period.

However, the complete water balance of the total amount of water entering and leaving the PMR and not necessarily just the water directly entering or leaving the site had to be calculated, for example the amount of water that entered the site through rainfall etc. This could not be done only using the previous data provided and an excel spreadsheet, but the procedures outlined in the WAF had to be applied to calculate those indirect values.

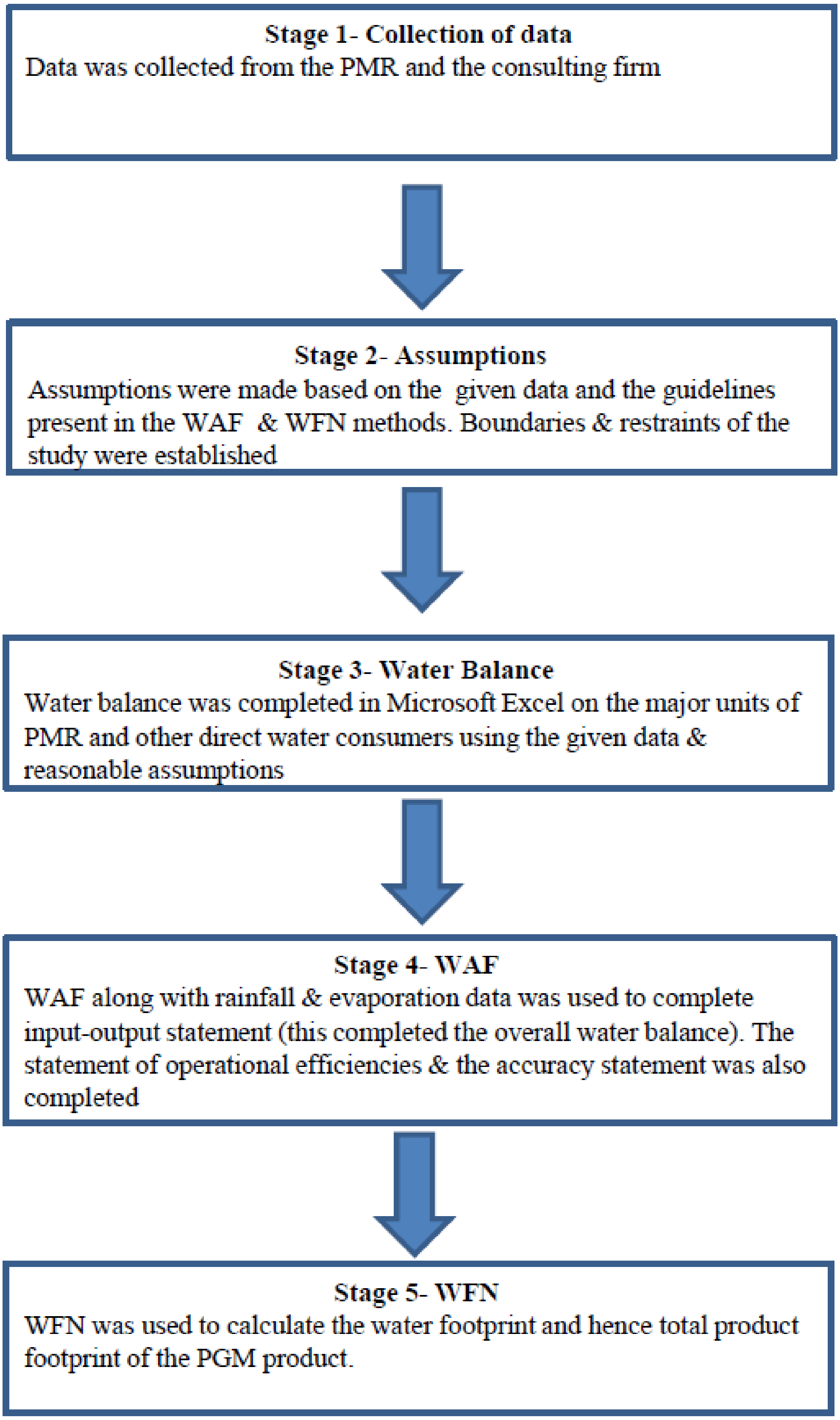
The rainfall data provided by the site and the evaporation data provided by the South African Department of Water and Sanitation as well as the calculation methods outlined in the WAF (this will be discussed in greater detail below), along with reasonable assumptions, were used to calculate the volume of rainfall and rainfall/ precipitation runoff captured by the site. The volume of water lost through evaporation was also calculated using calculation methods provided by the WAF as was the volume of water entrained in the feed. The calculation of these values was also necessary for the completion of the input-output statement which is part of the WAF. The procedures are expansively outlined in section 3.2.1 of this chapter.

Thereafter these direct and indirect amounts were used to complete the total water balance over the entire PMR.

After the completion of the water balance, the amounts calculated had to evaluated using the water accounting methods. Internal water flows were evaluated using the statement of operational efficiencies (WAF), shown in section 3.2.2 and gave an idea of the proficiency of water usage in the PMR. Water was categorised according to quality using descriptions outlined in section 3.2.1 as part of the input-output statement (WAF). The accuracy of the calculated values was evaluated using the accuracy statement (WAF) in section 3.2.3, which provided an indication of the precision of all the results and in which areas the calculated values were not as precise as in other areas. This showed which in which areas calculations, assumptions and data had to be improved to increase the accuracy of the overall results.

Water usage was classified according to definitions provided the WFN as described in section 3.3.2 as part of dividing water into the blue, green and grey water footprint groups. All of this provided (definitions of the WFN method and the input-output statement) detailed understanding and insight into water usage in the PMR, not only in terms of quantity but also in terms of quality, source, destination and usage. Areas of high water consumption were easily identifiable now and additional information in terms of water usage quality, source and destination was used to find means increasing the amount of water reused, decreasing the amount of freshwater used and finding alternate means of saving water onsite. This all formed part of the response formulation (WFN) in section 3.3.4

The above process can be illustrated by Figure 6:



Stage 1- Collection of data

Data was collected from the PMR and the consulting firm

Stage 2- Assumptions

Assumptions were made based on the given data and the guidelines present in the WAF & WFN methods. Boundaries & restraints of the study were established

Stage 3- Water Balance

Water balance was completed in Microsoft Excel on the major units of PMR and other direct water consumers using the given data & reasonable assumptions

Stage 4- WAF

WAF along with rainfall & evaporation data was used to complete input-output statement (this completed the overall water balance). The statement of operational efficiencies & the accuracy statement was also completed

Stage 5- WFN

WFN was used to calculate the water footprint and hence total product footprint of the PGM product.

Figure 6 Sequence of work that was followed for completion of this investigation

3.2 Water accounting framework

It is important to note that during the course of this study, during the last stages of research, the later part of 2017, the use of the of the software that supports the WaterMiner Program became obsolete and hence it could no longer be used to generate results for the study. Measures were then taken to replicate the processes and calculations modelled by the WaterMiner Program, using the Water Accounting Framework manual to manually calculate and replicate what would have been automatically generated by the program. A discussion on the calculation steps used by the WaterMiner Program (which are a crucial part of the WAF) follows below.

3.2.1 Input-Output Statement

The input-output statement is a report which shows the flow of water between the site boundary and the surrounding environment. Each input, output and diversion was assigned a volumetric flowrate, a water quality category and source or destination (SMI & MCA, 2012). The WaterMiner Program operates at steady state (SMI & MCA, 2012) and hence the yearly average volumetric flowrates were used to calculate the values in the report.

Water inflows to the PMR

The data from the water balance was used to complete the input-output statement, whilst calculation methods outlined in the WAF were used to calculate indirect water flowrates into and out of the PMR. A list of all the water inflows into the PMR was made. The inflows into the PMR include municipal water (potable water), water entrained in the feed to the PMR and water entering as precipitation and rainfall runoff as well as a small amount of water as fissure water inflow. Each inflow was allocated certain information which included the volume, the source and quality of each inflow.

Water quality can be divided into three categories according to (SMI & MCA, 2012):

Category 1: Water almost meets drinking water standards and is possibly if not probably safe for human consumption. It can be used in for all purposes.

Category 2: Water is only suitable for some purposes. Treatment is required to make water suitable for drinking purposes.

Category 3: Water is unsuitable for most purposes, mainly due to high pH or high salinity. Water in category 3 would have to undergo significant treatment to be suitable for category 2 and especially category 1.

Each of the water inflows into the PMR was assigned a quality as outlined by the three categories mentioned above.

The **volume of water entrained in the feed** was calculated using the following equation (SMI & MCA, 2012):

$$V_{ent} = 1000 \times P \times m \tag{6}$$

Where:

- V_{ent} = volume of entrained water (ML/year);
- P = amount of feed processed (Mt/year); and
- m = moisture content of the ore (dimensionless)

The PMR suggested a moisture content of 0.5% for the feed to be processed in the PMR and a moisture content of 0.1% for the total product processed from the PMR. The PMR feed undergoes extensive drying processes before entering the PMR and is further dried in a number of the PMR operations; hence the moisture content levels are quite low in comparison when compared to the amount of water entrained in the ore during primary mining processes.

The actual amount and composition of the feed cannot be revealed for confidentiality purposes.

The water entrained in the feed and the product was assigned the water category of 3.

The **volume of rainfall** captured by the PMR was calculated using the following equation (SMI & MCA, 2012):

$$V_{rainfall} = 0.01(R)(SA) \tag{7}$$

Where:

- $V_{rainfall}$ = volume of rainfall captured by the facility (ML/year);
- R= rainfall for the reporting period (mm/year);
- SA= surface area that captures the rain (ha)

The rainfall over the 12 month period was provided by the PMR. The rainfall was measured by the PMR and reported on a monthly basis mm/month. The monthly rainfall was summed to give the total rainfall for the year, 628.8 mm/year, for the purpose of this calculation. The rainfall data can be found in Appendix A.

The surface area that captures the rainfall was estimated from information provided by the site in hectares, however in accordance with confidentiality outlines these values will not be stated explicitly.

The volume of rainfall captured by the PMR was assigned category 1 water quality.

The **volume of rainfall runoff** was calculated using the equation below (SMI & MCA, 2012):

$$V_{runoff} = 0.01(R)(\gamma)(\beta) \tag{8}$$

Where:

- V_{runoff} = volume of rain runoff (ML/year);
- R = rainfall for the reporting period (mm/year);
- γ = disturbed or undisturbed catchment area (ha);
- β = volumetric rainfall to runoff factor (dimensionless)

β is the dimensionless volumetric rainfall to runoff factor, which either has a value of 0.05 or 0.15. These values are related to the γ, catchment area. If it is a disturbed catchment area then the value of β is 0.15 and if it is an undisturbed catchment area then the value of β is 0.05. In a disturbed catchment area, the runoff comes into contact with by-products and in an undisturbed catchment area; the runoff does not come into contact with any by-products (SMI & MCA, 2012). This study chose a value of 0.15 for the disturbed catchment area of the PMR.

The rainfall data provided by the PMR (Appendix A) was used again in this calculation.

The size of the disturbed catchment area of the PMR in hectares was estimated from information provided by the PMR; however the value of the catchment area cannot be stated explicitly in this text due to confidentiality concerns.

Water outflows from the PMR

A list of all the water outflows from the PMR was made. Water outflows from the PMR included water discharged through the municipal system (water exiting through the condensate discharge sewer is included here), water that is part of effluent, water overflow from the storm water area and water lost from the PMR through evaporation.

Water lost through evaporation from actual units and processes involved in the PMR operations were included in the water balance calculated in Microsoft Excel. However the volume of water lost through evaporation from open water surfaces present on the site had to be calculated using the methods outlined in the WAF (this will be shown below). This calculated value was then added to the value of evaporation from the PMR process units to give the total volumetric value of water lost from the site due to evaporation.

The **volume of water evaporated** from the site was calculated using the following equation (SMI & MCA, 2012):

$$V_{evap} = 0.01(SA_{evap})(Pan_{evap})(f) \tag{9}$$

Where:

- V_{evap} = volume of water evaporated (ML/year);
- SA_{evap} = average surface area from which the water evaporates (ha)
- Pan_{evap} = pan evaporation rate (mm/year)
- f = correction factor to convert pan evaporation measurements into evaporation losses (0.75)

The pan evaporation rate is the rate of the evaporation of water from an evaporation pan. It is generally used alongside a correction factor. The purpose of the correction factor is to convert the pan evaporation rate to the evaporation rate of water from open storage. This is necessary as the depth of the evaporation pan and the open storage differ and this difference has an impact of the final rate of evaporation. The pan evaporation rate is usually a value or a range of values that can be found from literature. This method is generally employed in the absence of evaporation rate data during the given time period.

However the evaporation rate over the given time period, specific to the location of the PMR was provided by the South African Department of Water and Sanitation on a monthly basis in mm/month. The given monthly evaporation rate was summed to give a total evaporation rate of 1662.07 mm/year for the purpose of this calculation. The provided evaporation data can be found in Appendix A.

As the evaporation rate was known there was no need to use the pan evaporation rate and the correction factor and thus the equation was modified as shown below:

$$V_{evap} = 0.01(SA_{evap})(Evap) \tag{10}$$

Where:

- V_{evap} = volume of water evaporated (ML/year);
- SA_{evap}= average surface area from which the water evaporates (ha)
- Evap = evaporation rate (mm/year)

The surface area from which the water evaporates in hectares from the site was calculated using information given by the PMR; however this value cannot be openly disclosed in this text in accordance with confidentiality concerns.

The volume of water evaporated from open water storage was assigned a quality category of 1. The same quality category was assigned to the water that evaporated from the unit processes in the PMR.

Diversions

The PMR has one diversion only. By definition a diversion is the flow of water from an input to an output, without the water being used or stored in the process (SMI & MCA, 2012). This diversion was mentioned in the last section of the input-output statement. Potable 2 supplies water only to the office area and to utilities that are onsite but are not involved in the main PMR operations, with the exception of a fire suppression services which is the only unit that Potable 2 supplies water to that is part of the main operation. The flow of water from the Potable 2 to the office area and the secondary utilities (excluding the water that goes to the fire suppression services), is considered to be a diversion as this water is not consumed in the main PMR operations.

3.2.2 The Statement of Operational Efficiencies

The statement of operational efficiencies forms part of the WAF and shows the efficiency of onsite internal water flows by highlighting the flow of water from water stores to tasks and treatment points and calculating the proportion of reused and recycled water. Reused water is water that has been used in an onsite task and is used again without being treated. Recycled water is water that has been used in an onsite task and is used again but is only used again after it has been treated (SMI & MCA, 2012).

All the water stores, tasks and treatment plants in the PMR were noted. The tasks were numerous and varied. There were only a couple of water stores and there were no treatment plants onsite the PMR at the time of the period of assessment. The total inflow into the tasks was found by summing the all the water flows into the tasks. The sum of worked water inflows into tasks was found by adding the water that was used in an onsite task and then used in another task without prior treatment. The Reuse Efficiency was then calculated by dividing the sum of worked water inflow into tasks by the total water inflow into tasks (SMI & MCA, 2012).

The WaterMiner Program would have calculated the reuse efficiency using the flowrate data. However as this was not possible the reuse efficiency was manually calculated. The equation used to calculate the reuse efficiency can be found below and was outlined in the WAF (SMI & MCA, 2012):

$$Reuse\ Efficiency = \left(\frac{Sum\ of\ Worked\ Water\ Flows\ to\ Tasks}{Sum\ of\ all\ Flows\ to\ Tasks}\right) \times 100 \qquad (11)$$

Where:

- Reuse Efficiency = Proportion of worked water into tasks without prior treatment in relation to the total water into tasks (%);
- Sum of Worked Water Flows to Tasks = The total amount of reused water that flows to tasks without any prior treatment (ML/year); and
- Sum of all Flows to Tasks = The total amount of water that flows to tasks (both freshwater and reused water) (ML/year)

The Recycle Efficiency is calculated in a similar manner, by dividing the sum of treated worked water to tasks by the total water inflow to tasks. As it was assumed that no water was treated onsite the recycle efficiency was zero. Equations to calculate the recycle efficiency manually are also outlined by the WAF. As there was no need to employ any of calculations for the evaluation of the recycle efficiency in this study, this dissertation did not delve into further detail into this matter.

3.2.3 Accuracy Statement

The accuracy statement is a report which presents a list of volumetric water flows (from the input-output statement), showing which flows are measured, estimated or simulated and the level of confidence associated with each flow (high, medium or low). The final accuracy statement shows the percentage of flows that were measured, estimated or simulated along with the level of confidence associated with the data used. The accuracy statement is usually presented alongside the input-output statement to a measure of the precision of the input-output statement (SMI & MCA, 2012).

Essentially, when water flows are entered into the WaterMiner Program, it had to be entered along with the flow type (measured etc.) as well as the confidence of the flow data used and hence the WaterMiner would generate the accuracy statement. However, as this was done manually an interim step had to be included before the final accuracy statement could be produced.

The interim step involved the evaluation of the different types of water flows mentioned in the input-output statement. From the input-output statement, the water flowrates that were measured were summed, followed by the summation of the water flowrates that were estimated and then by the summation of the water flowrates that were simulated. It must be noted that there were no simulated water flowrates. Each of the different types of flows (measured or estimated) was allocated a confidence level.

The total volumetric flowrate of all the water flows was found by the summation by the total measured flowrates and the total estimated flowrates. The proportion of the measured flowrates over the sum of the total flowrates was found. This gives an indication of the percentage of flows that were measured in the WAF. This process was repeated for the estimated flowrates at the three different confidence levels. The results were recorded in the final accuracy statement, which showed the percentage of flows measured and estimated at three confidence levels for the PMR.

3.3 Water Footprint Network

The Water Footprint Network Assessment Tool is a method that calculates the volume of water that is consumed both directly and indirectly in a process or to manufacture a product or service. The complete water footprint is an aggregation of three lesser water footprints, namely the blue, green and grey water footprints (Hoekstra, *et al*., 2011).

The main focus of this method is to quantify both the direct and indirect water usage to produce a product, after which it aims to reduce water consumption by identifying areas of excessive consumption. The Water Footprint Assessment Manual outlines the following four steps for assessment (Hoekstra, *et al*., 2011):

1. Setting goals and scope
2. Water Footprint Accounting
3. Water Footprint sustainability assessment; and

4. Response Formulation

3.3.1 Setting goals and scope

The first step involved deciding what to include and exclude in the water footprint assessment of the production of refined platinum from the PMR and ultimately deciphered why the assessment was being done. Decisions made in this step were explicit and had a big impact on the overall water footprint assessment. In this step, assumptions were made on which the entire water footprint account was based. The following things were taken into consideration (Hoekstra, *et al.*, 2011):

Purpose of the water footprint assessment

The purpose of the investigation presented in this dissertation was to quantify the volume of water (both direct and indirect water) consumed by the PMR to produce one kilogram of PGM product. This investigation also attempted to identify areas in the PMR operation which consumed the greatest amount of water and to suggest ways in which the overall water consumption of the PMR could be reduced. Additionally, this investigation aimed to compare the results achieved by the two different water accounting methods used to each other and to the results achieved by other researchers of similar processes.

Time period of the investigation

The period of investigation spanned over a 12 month period. The months and the sequence in which they occurred as well as the year cannot be explicitly mentioned here due to confidentiality issues. The water footprint was calculated on a monthly basis and a yearly average was used to present overall results.

System boundary of the investigation

This involved determining until which point in the PMR operation would the WFN method analysis be carried out (Hoekstra, *et al.*, 2011): This study included all the processes and activities utilising water in the PMR, including water used in offices, support services, medical purposes, canteens, change houses, the auxiliary facilities and many other uses that were not directly linked to the main processes necessary for the refinement of the platinum feed. A succinct explanation of the overall system boundary can be found in Figure 3. Any processes related to the water utilised by the PMR that occurred off site was not considered in this investigation.

Type of water footprint to be conducted

Here it was determined whether the water footprint assessment would be for a product or a service for a consumer or a country or process etc. (Hoekstra, *et al*., 2011): It was determined that the water footprint assessment would carried out for the PGM Product that contained both the PMR final product and other products. And hence results were given in volume of water per mass (kilogram) PGM product.

Type of water considered in the water footprint

In this step, it was determined whether to consider blue, green or grey water; direct and/or indirect water; internal and/or external water (Hoekstra, *et al*., 2011): This research considered both direct (water inflow from potable water etc.) and indirect (water entrained in feed etc.) water consumption. The rainfall and/ or rainfall runoff captured by the PMR was not used to increase water in the topsoil i.e. not used for gardening, thus this study did not consider a green water footprint. During this specific 12 month period, there were no water treatment plants on site and all waste water was treated off-site, hence this research did not consider a grey water footprint. Thus, due to the assumptions made by this research the PMR only had a blue water footprint.

3.3.2 Water Footprint Accounting

This stage involved the calculation of the water footprint from the collected data given by the PMR, the data calculated from the water balance completed in Microsoft Excel and the results found from the calculations in the WAF method. The water footprint of each of the process steps involved in the production of the product, such as the refined platinum product, has to be calculated and summated to find the total water footprint of the refined platinum product. The total water footprint would be the sum of the blue, green and grey water footprints; however this study only considered a blue water footprint for the PMR. The three different water footprints, particularly the blue water footprint, are discussed below.

Blue Water Footprint

The blue water footprint refers to the volume of ground or surface water that is consumed to produce a product (refined platinum product), consumed through evaporation, consumed through incorporation into the product and through lost return flow (Hoekstra, *et al*., 2011). Refer to Equation 2, section 2.5 in CHAPTER 2: Literature Review.

Municipal potable water was the main source of water into the PMR and by definition was classified as blue water. Other sources of blue water are water incorporated into the product, the water captured by rainfall/ rainfall runoff and the water lost through evaporation.

The classification of captured rainfall and/or rainfall runoff was rather complex, this study followed the definitions outlined in the (Hoekstra, *et al*., 2011).

If measures are taken to use rain water to increase the volume of water in the topsoil and hence to increase the amount of water available for evapotranspiration by plants, the captured rainfall and/or rainfall runoff can be classified as green water and will add to the green water footprint (Hoekstra, *et al*., 2011).

The PMR did not support any significant plant life nor did the PMR participate actively in gardening and hence there was no need to increase the volume of water in the top parts of the soil. Rain water entered the PMR directly through open water surfaces and as runoff into catchment areas. Hence the volume of rain water into open water stores and the runoff were considered to be part of the blue water footprint and not the green water footprint.

This study extensively explored the blue water footprint in all its component parts, such as the volume of water that was incorporated into the product, the volume of water that was lost through evaporation and the volume of water that forms part of lost return flow. Lost return flow refers to water which was consumed by the process and was not returned to the same catchment or was returned at another time.

Grey Water Footprint

The grey water footprint refers to the volume of clean freshwater that is required to dilute waste water before it is released back into a natural water body, thus ensuring that the waste water does not hamper the ambient quality of the water body and/or that the legal environmental requirements of the water body are met (Hoekstra, *et al*., 2011). Refer to Equation 4, section 2.5 in CHAPTER 2: Literature Review.

No waste water was treated onsite in the PMR within the chosen time frame of this research. The PMR also did not discharge any waste water into a natural water body. The effluent was removed from site and was treated elsewhere. Hence there was no grey water footprint for the PMR in this research.

Green Water Footprint

The green water footprint is the volume of rainwater consumed in the production of a product, which could have been stored in the soil or in the top soil temporarily and is used for evapotranspiration by plants (Hoekstra, *et al*., 2011). It is the volume of water lost through evapotranspiration and the amount of rainwater incorporated into the product (Hoekstra, *et al*., 2011). Refer to Equation 3, section 2.5 in CHAPTER 2: Literature Review.

The green water footprint was excluded for the PMR in this research as the PMR does not support any significant plant life as previously discussed.

The Water Footprint of a Product

The water footprint of a product is the volume of freshwater used directly or indirectly to produce a product. It can be evaluated by taking water consumption at all points in the production chain into consideration. There are two methods available to calculate the water footprint of a product, the chain-summation approach and the step-wise accumulative approach. The chain summation approach was applied in this study. The chain summation approach can only be applied when the production system only produces one output or product. The step-wise accumulative approach is used when the production system produces more than one product or output (Hoekstra, *et al*., 2011). In this study, only the final refined platinum product- the PGM product was considered and all other by-products from the process were excluded from this study. Thus taking all assumptions into consideration, the process under consideration in this study only produces one product and so the chain summation approach was applied.

The water footprint of the refined platinum- the PGM product was calculated from the chain-summation approach by applying the following definition: The water footprint of a product is equal to the summation of relevant process water footprints divided by the production quantity of the product (Hoekstra, *et al*., 2011), this can be illustrated by the following equation (Hoekstra, *et al*., 2011):

$$WF_{prod,[p]} = \left(\frac{\sum_{s}^{k=1} WF_{proc,[s]}}{P_p}\right) \tag{12}$$

Where:

- WF $_{\text{prod, [p]}}$ = water footprint (volume/mass) of product or output p;
- WF $_{\text{proc, [p]}}$ = water footprint of process steps (volume/time);
- P $_{[p]}$ = production rate of the product (mass/time).

The blue water footprint was calculated using the definitions and equations mentioned above and in the literature review. Firstly, the blue water footprint was calculated in parts. The volume of water lost through evaporation per year was calculated. After which the volume of water incorporated into the product per year was evaluated. Followed by the calculation of the volume of water that forms part of the lost return flow per year, essentially this was the volume of water that left the PMR through the Municipal System, through effluent discharge (this was treated and discharged by another corporation offsite) and discharge to the environment (small quantity of water that overflows from the storm water storage area). Per year refers to the chosen time frame of the study which spanned 12 months.

The total blue water footprint was the summation of all the component parts of the blue water footprint mentioned above per year. As both the green and grey water footprints were excluded from this study, due to reasons previously mentioned, the blue water footprint is the only relevant water footprint for the PMR and hence the total water footprint for the PMR is equivalent to the total blue water footprint of the PMR.

The water footprint of the PGM product was calculated using the chain summation approach illustrated by Equation 12. The total water footprint of the PMR production process in terms of volume (m^3) of water consumed per year was divided by the production rate of the PMR in terms of mass (kg) of PGM product produced by the PMR per year to find the total product water footprint in terms of volume (m^3) of water consumed by the PMR to produce a kilogram of PGM product.

3.3.3 Sustainability Assessment

The sustainability assessment evaluates the impact of the overall operation (in this case the PMR) on the local environment and society. The water consumption of the operation is compared to the water availability in the local area (Hoekstra, *et al*., 2011). This is beyond the scope of this study and the requirements of the PMR and thus will not be included in the water footprint account of the PMR.

3.3.4 Response Formulation

The final step of the WFN method revolved around the response to the calculated water footprint. This involved the evaluation of the level of water consumption in the PMR and recommendations being made on how to reduce water consumption in the operation (Hoekstra, *et al*., 2011).

The viability of each of the recommendations were considered and were theoretically applied to the existing water footprint to evaluate if water consumption would in fact be reduced and by how much, not only in terms of water usage but in terms of cost as well. This was done to make the water footprint method analysis more attractive to the PMR operators.

In practice to carry out viable recommendations, generally many variables have to be considered such as a realistic time frame, qualified people to ensure the success of these recommendations and reliable methods to carry out the agreed upon recommendations (Hoekstra, *et al*., 2011). This study only considered the theoretical and financial viability of each of the recommendations.

"Water is the most critical resource issue of our lifetime and our children's lifetime. The health of our waters is the principal measure of how we live on the land." ***Luna Leopold***

Chapter 4 RESULTS

This sections focuses on the results derived from the Water Accounting Framework (WAF) and the Water Footprint Network (WFN) method. Significant results from the water balance as well as the rainfall and evaporation data will also be discussed.

4.1 Water Balance

The water balance was performed using the in is equal to out principle. Some of the inputs and outputs of the water balance were calculated using rainfall and evaporation data, using procedures outlined in the WAF and WFN, which will be discussed below.

Table 1 The total water gains into and water losses out of the PMR

	Volume of Water m^3
Total Gains	49368
Total Losses	49086
Storage	282
% Difference between gains and losses	0.01

From Table 1, it can be seen that the water inflows (49368 m^3) are roughly equal to the water outflows (49086 m^3), during the 12 month period; the difference between the two values, 282 m^3, remained in storage. The water gains are equivalent to the water losses, with the total water losses being 99% of the total water gains and the percentage difference between the two values is only 1%. Thus the basic mass balance principle has been satisfied.

4.1.1 Water source distribution and major water consumers

Table 2 The distribution of potable water between potable 1 and potable 2 of the PMR

Potable Water	**% Distribution**
Potable 1	97.76
Potable 2	2.24
Total	**100.00**

The direct water inflow to the PMR is through potable water. The total potable water is divided into Potable 1 and Potable 2. Approximately 98% of the water goes to Potable 1 and the other 2% goes to Potable 2, as shown in Table 2.

As previously noted Potable 1 supplies potable water to the main PMR operation and a couple of utilities. Potable 2 supplies water only to the office area and to utilities that are on site but are not involved in the main PMR operations, with the exception of a fire suppression services. Hence it is reasonable that Potable 1 has majority of the water.

Potable 2

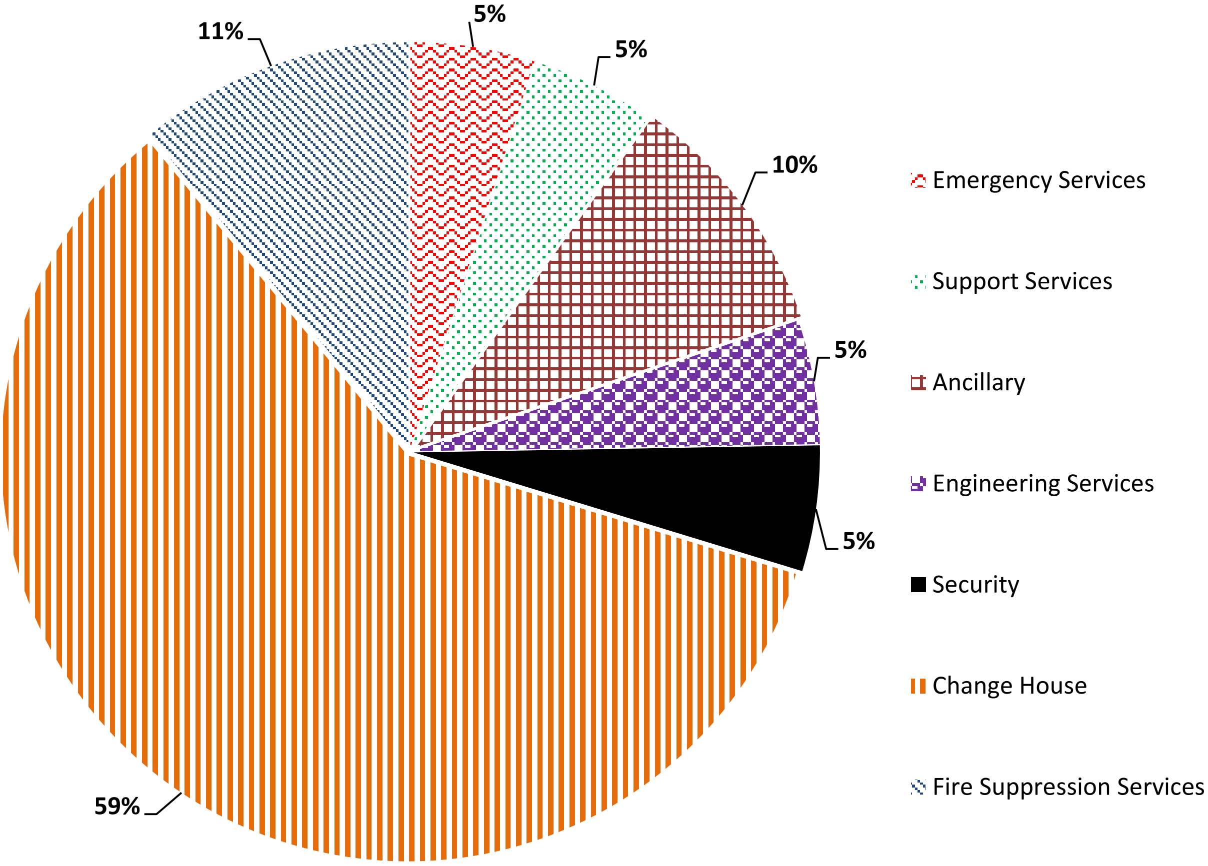


Figure 7 The distribution of water from Potable 2 of the PMR

From Figure 7 it can be seen that the change house is the largest consumer of water from Potable 2 and the fire suppression services is the second largest consumer of Potable 2, followed by the ancillary. Hence these are the areas that need to be targeted first if water consumption from Potable 2 has to be reduced. The emergency services, support services, security and the engineering services (engineering services here provides storage for engineering equipment) use approximately the same amount of water.

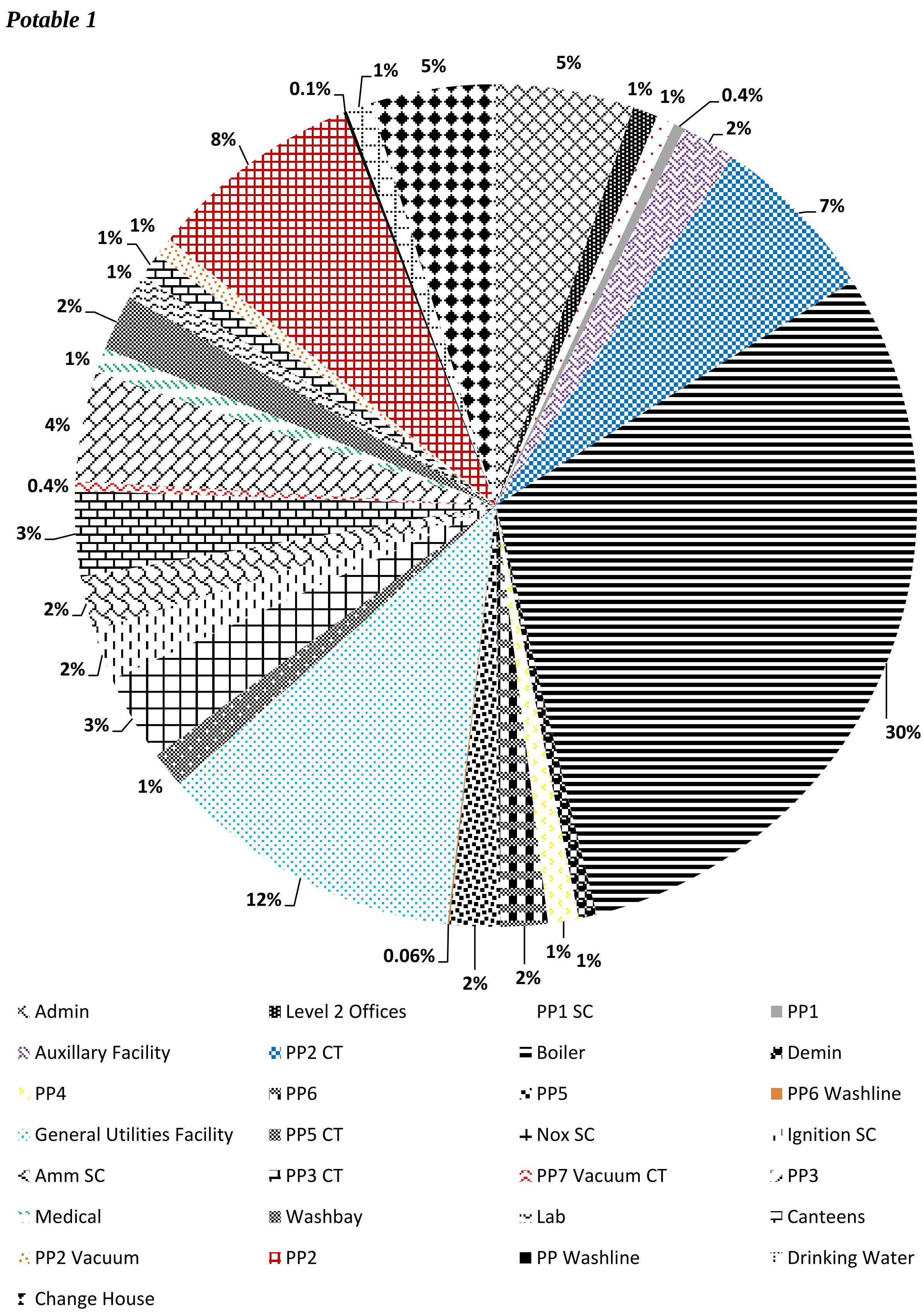


Figure 8 The distribution of water from Potable 1 from the PMR

From Figure 8 it can be seen that the main consumer of Potable 1 water is the Boiler, using approximately 30% of the water, followed by the General Utilities Facility which consumes 12% and then the Processing Plant 2 and the Processing Plant 2 Cooling Tower, which consume 8% and 7% respectively. The other units use 5% or less of the water. Some of the units consume such a small amount of water that it aggregates to just slightly above 0% per unit, such as the Processing Plant 1, Processing Plant 6 Washline, Processing Plant 7 vacuum cooling tower and the Processing Plant Washline. These exact values are given in Table 3:

Table 3 Percentage distribution of small consumers from Potable 1

Units	**% Distribution from A**
Processing Plant 1	0.4
Processing Plant Washline	0.1
Processing Plant 6 Washline	0.06
Processing Plant 7 vacuum cooling tower	0.4

4.1.2 Water inputs into the PMR and water outputs from the PMR

Table 4 The distribution of water into the PMR

Water Inflows	**% Distribution**
Potable 1	85.26
Potable 2	1.96
Inflow	0.07
Rainfall & Runoff	12.71
Feed Entrainment	0.001
Total	100.00

Table 4 shows that the Potable 1 is the main water inflow into PMR, amounting to 85% of the total water. Potable 2 accounted to only 2% of the total water. The second biggest contributor of water into the system is the rainfall and rainfall runoff water which was 13% of the total water. The inflow (from the minor fissure in the bunds) and the feed entrainment into the system are so little that it is reflected as roughly zero in the above table. The water inflow is 0.073% and the feed entrainment is 0.001%.

Table 5 The distribution of water outflows from the PMR

Water Outflows	**% Distribution**
Municipal System	15.45
Overflow	0.41
Condensate Discharge Sewer	35.43
Effluent Treatment Corporation	44.84
Total Evaporation Loss	3.87
Product Entrainment	0.0001
Total	100.00

Table 5 shows that most of the water leaves as wastewater through the Effluent Treatment Corporation, approximately 45% and the second highest amount of water is lost to the Condensate Discharge Sewer, roughly 35%. 16% of the water goes out through the Municipal System and 4% is lost through evaporation. Water loss through water overflow from the storm water tanks and through water entrained in the product is roughly 0%, although the amounts are actually 0.41% and 0.0001%, respectively.

The water lost through the Effluent Treatment Corporation is distributed to Effluent Management. Approximately 66% of the water in the Effluent Treatment Corporation is acidic, 30% of the water is alkaline and only 4% of the water has ammonia in it, which is reasonable as only one process in the PMR uses ammonia.

All the water from rainfall and the rainfall runoff goes to the storm water tanks where this water is stored. Some of this water is sent to the Effluent Management (acidic) and Effluent Management (alkaline), which were mentioned above, to dilute the contents before it is released to the Effluent Treatment Corporation. Approximately 67% went to the Effluent Management (acidic) and 33% went to Effluent Management (alkaline).

From the water that is lost through the condensate discharge sewer, 65% of the water that is lost from the Processing Plant 7 Condensate and 34% comes from the Processing Plant 2 Condensate and a meagre 1% comes from the Change House.

4.1.3 Rainfall and evaporation data

Rainfall and evaporation data was used to complete the mass balance over the PMR, using system equations outlined in the Water Accounting Framework (WAF). The monthly rainfall data over the site was provided by the PMR and the evaporation data for the given time period of the area was provided by the South African Department of Water and Sanitation.

Comparison between rainfall and evaporation

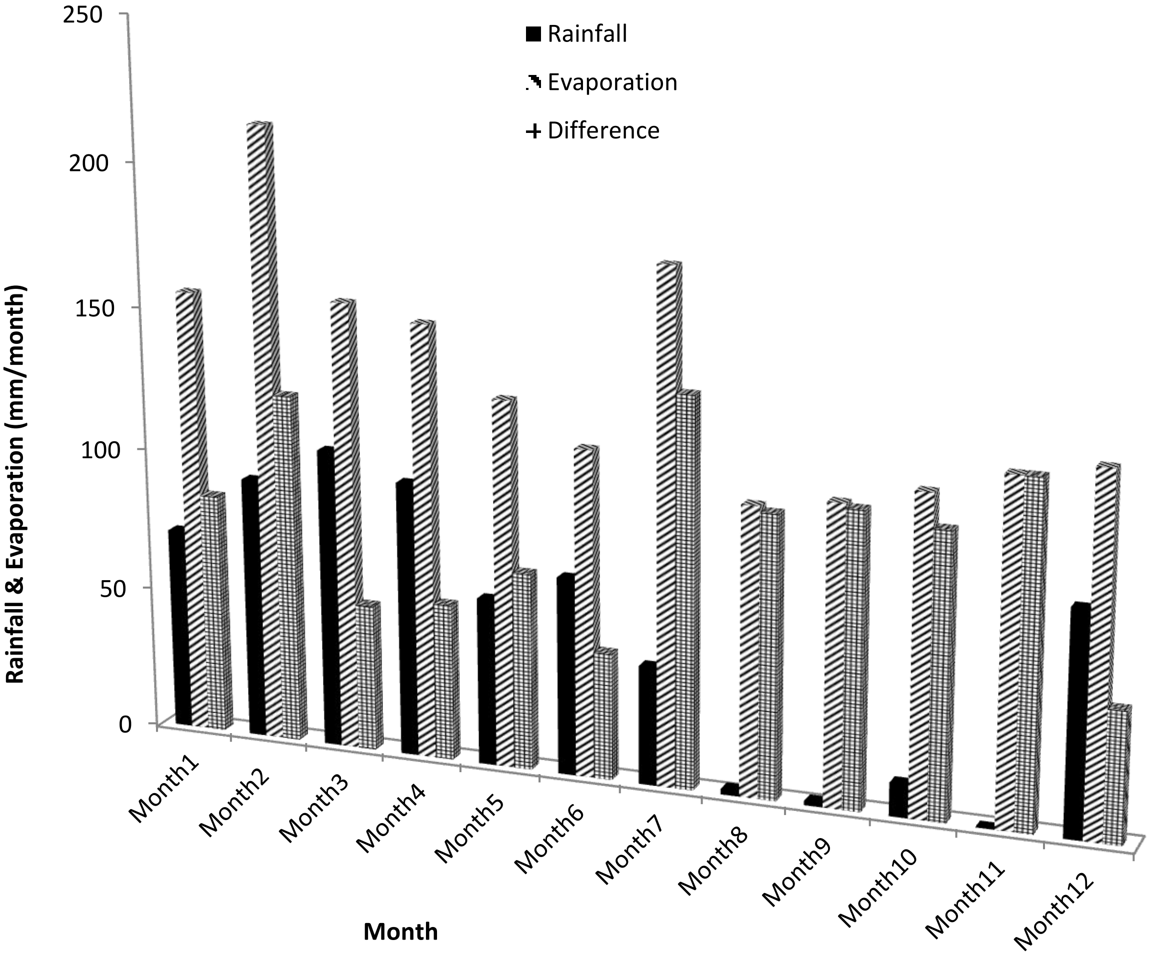


Figure 9 Measured monthly rainfall and evaporation data along with the monthly difference between rainfall and evaporation rates

There was no rainfall in Month 11 and minimal rainfall in Month 8 and Month 9. The highest rainfall was observed in Month 3 at 105 mm/month and the lowest rainfall was observed in Month 9 at a meagre 1.5 mm/month and Month 8 at 2 mm/month. The PMR is located in an area which experiences summer and spring rainfall. Spring in South Africa occurs from Months 12 to 2 and summer from Months 3 to 5. The highest rainfall was observed in spring and summer months, with less rainfall in the autumn months from Months 6 to 8 and almost no rain in some of the winter months from Months 9 to 11 as shown in Figure 9.

The highest evaporation rate was observed at 214.8 mm/month in Month 2, one of the hottest months of the year. The lowest evaporation rate was observed at 101.08 mm/month in Month 8. The higher evaporation rates were observed in the summer and spring months when it is hotter with lower evaporation rates being prevalent in the colder winter and autumn months. The high evaporation rate in Month 7 at 178.1 mm/month during an autumn month is the only outlier.

The difference between the evaporation and rainfall data is also illustrated in Figure 9. The difference was calculated by subtracting the rainfall rate from the evaporation rate. From the graph it can be observed that monthly evaporation rates are higher than the monthly rainfall rates and hence the difference between them will also result in a positive value as the evaporation rate will always be bigger than the rainfall rate. The highest net evaporation rate is 119.83 mm/month in Month 11 when there was no rainfall.

The rainfall and evaporation data used to generate these graphs are available in Appendix A for further reference. From the graph it can be seen that that data correlates with general weather patterns prescribed for that area.

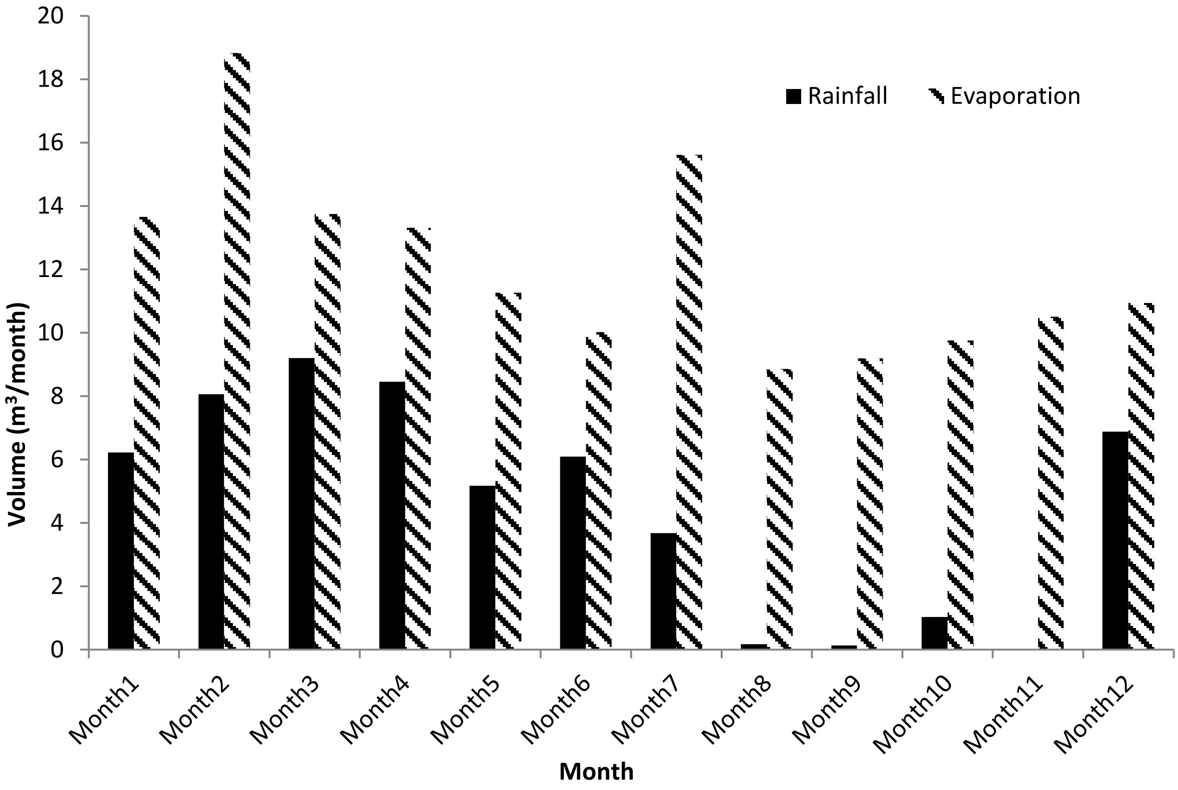


Figure 10 The volume of monthly evaporation and rainfall from only the open surfaces on site

The above graph in Figure 10 illustrates the volume of water that enters the site as rainfall that has been captured by open water surfaces alongside the volume of water that exits the site as evaporation from open water surfaces. Figure 10 shows that the volume of water lost through evaporation from open water surfaces is the higher than the volume of water gained through direct rainfall into open water surfaces. The highest volume of water lost through evaporation was observed at 18.83 m^3/month during Month 2 and the highest volume of water gain through direct rainfall was observed at 9.21 m^3/month during Month 3. It is important to note that these evaporation values only concern evaporation from onsite open water surfaces and excludes the evaporation from the process units in the PMR. The rainfall values here only include the rainfall captured directly into the open onsite surfaces and exclude the rainfall runoff that flows are later directed into the onsite water stores.

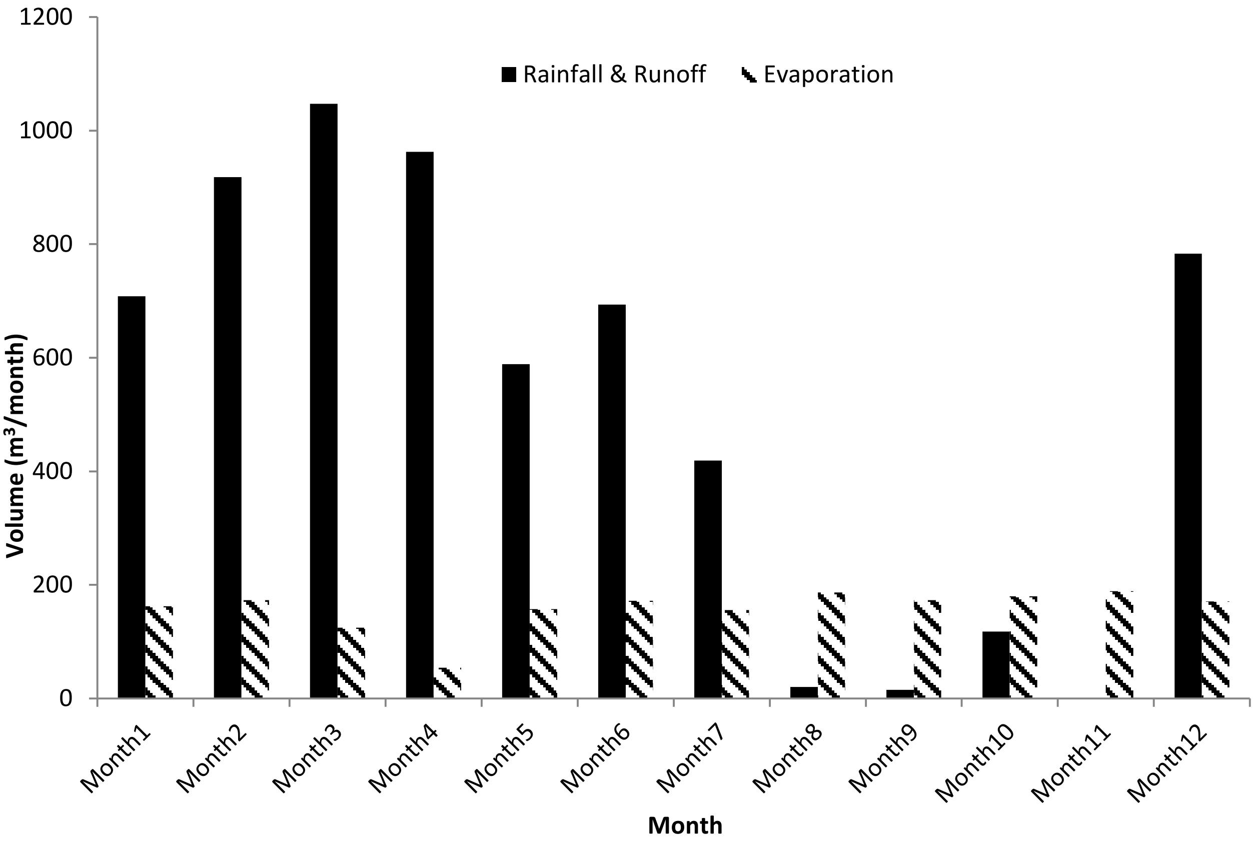


Figure 11 The monthly volume of rainfall and evaporation from the entire site

Figure 11 differs drastically from Figure 10 and the two should not be confused. The graph in Figure 11 shows the volume of water that enters the site not only as rainfall into open water surfaces but also the volume of water that is captured by the site as rainfall runoff (this is not captured directly as the runoff is forwarded to the water storage tanks); whereas the graph in Figure 10 only shows that volume of water that has been captured directly from rainfall. The graph in Figure 11 shows that volume of water that has been lost through evaporation from the entire site, not only the open water surfaces. The illustrated values include the volume of water that has been lost through evaporation from the PMR process units as well as from open water surfaces; whereas the graph in Figure 10 only shows the volume of water that was lost through evaporation from open water surfaces.

The results illustrated by Figure 11 are the exact opposite of those in Figure 10. Figure 11 shows that the volume of water gained through rainfall and runoff is much greater than the volume of water lost through evaporation from the entire site;

whereas Figure 10 shows that the volume of water gained through direct rainfall capture is less than the volume of water lost through evaporation from open water surfaces.

This proves that the combined volume of water received through direct rainfall into onsite open surfaces added to the rainfall runoff from the entire site is much greater than the volume of water lost through evaporation (evaporation from both onsite open surfaces and process units in the PMR).

4.2 High and low water consumption periods

The following series of graphs illustrate water consumption and PGM production each month during the chosen time period.

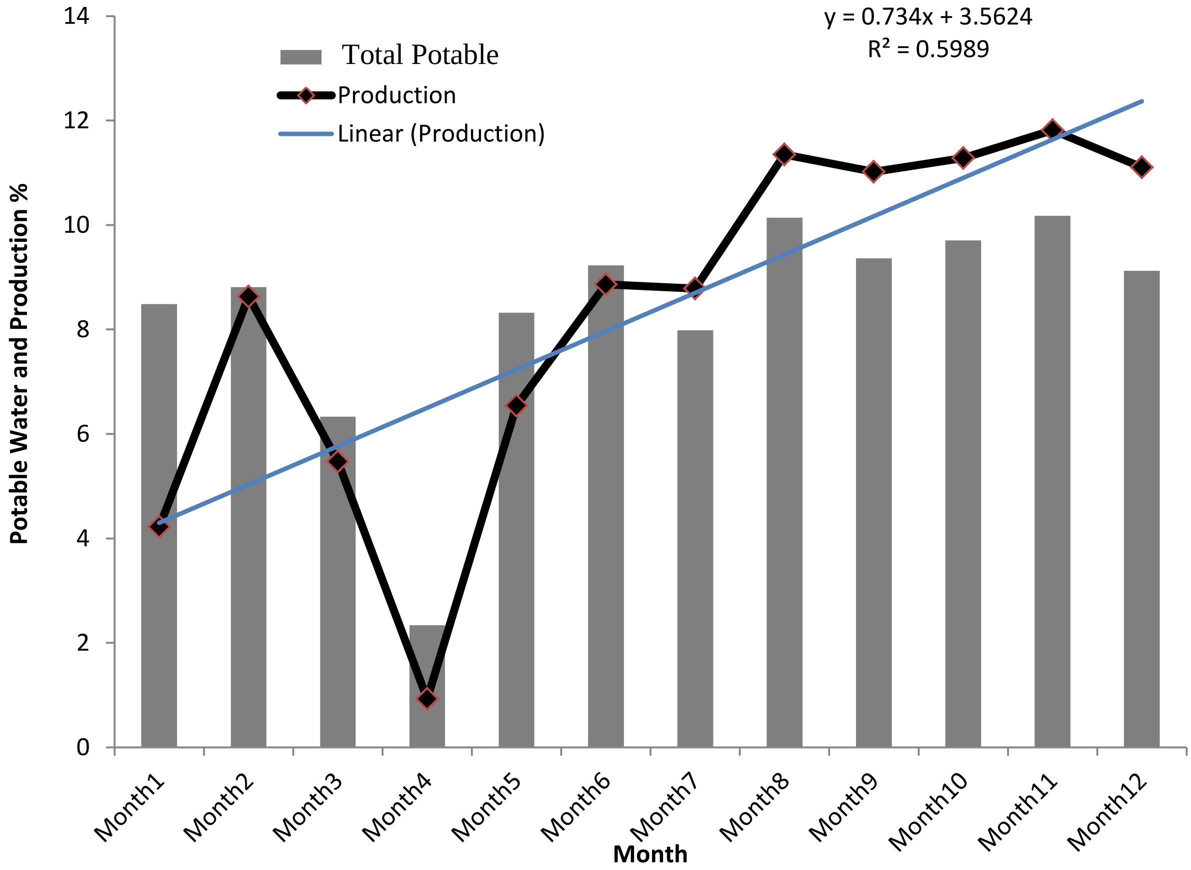


Figure 12 The monthly consumption of potable water with the monthly PGM production throughout the year from Month 1 to Month 12

Figure 12 shows the monthly freshwater intake to the PMR from the potable water along with the monthly PGM production in percentage. Percentages were used instead of explicit volume and mass values for confidentiality concerns. The freshwater intake was given as a percentage per month of the annual freshwater intake. The PGM production was given as a percentage per month of the total annual PGM production. The most striking point in the graph is the low fresh water consumption in Month 4 at 2.3%; this was due an operational disruption, which brought the PMR operations to a complete halt and hence the decrease in water consumption. The low production in Month 4 at 0.92% in Figure 12 supports the low fresh water consumption where operations had to be stopped. The same can be observed about the low production level in Month 3 at 5.5%. The fresh water consumption in Month 3 at 6.3% was fairly low as well; this was due to operational issues, which would later lead to an operation disruption in the coming month. The production level in Month 1 was also fairly low at 4.2% as production during the beginning on the financial year is usually low, despite a relatively regular level of water consumption at 8.5%. Production levels picked up the following month in Month 2 at 8.6% whereas the water consumption level did not increase as much at 8.8% in Month 2.

In Month 5, the freshwater consumption had increased to a reasonable level due to the resolving of the operational disruption at 8.3%; along with PGM production at 6.5%. Freshwater consumption levels throughout the rest of the year seemed to be at a reasonable level except in Month 12, where the fresh water intake is slightly lower at 9.1% than previous months due to an investigation into reducing freshwater usage by increasing the amount of water reused in the PMR. The reasonable production level in Month 12 at 11.1% proves that despite the lower fresh water intake, production was not majorly affected. It can be seen from Figure 12 that in general as potable water consumption increases so does PGM production. A coefficient of correlation valued at 0.60 was found.

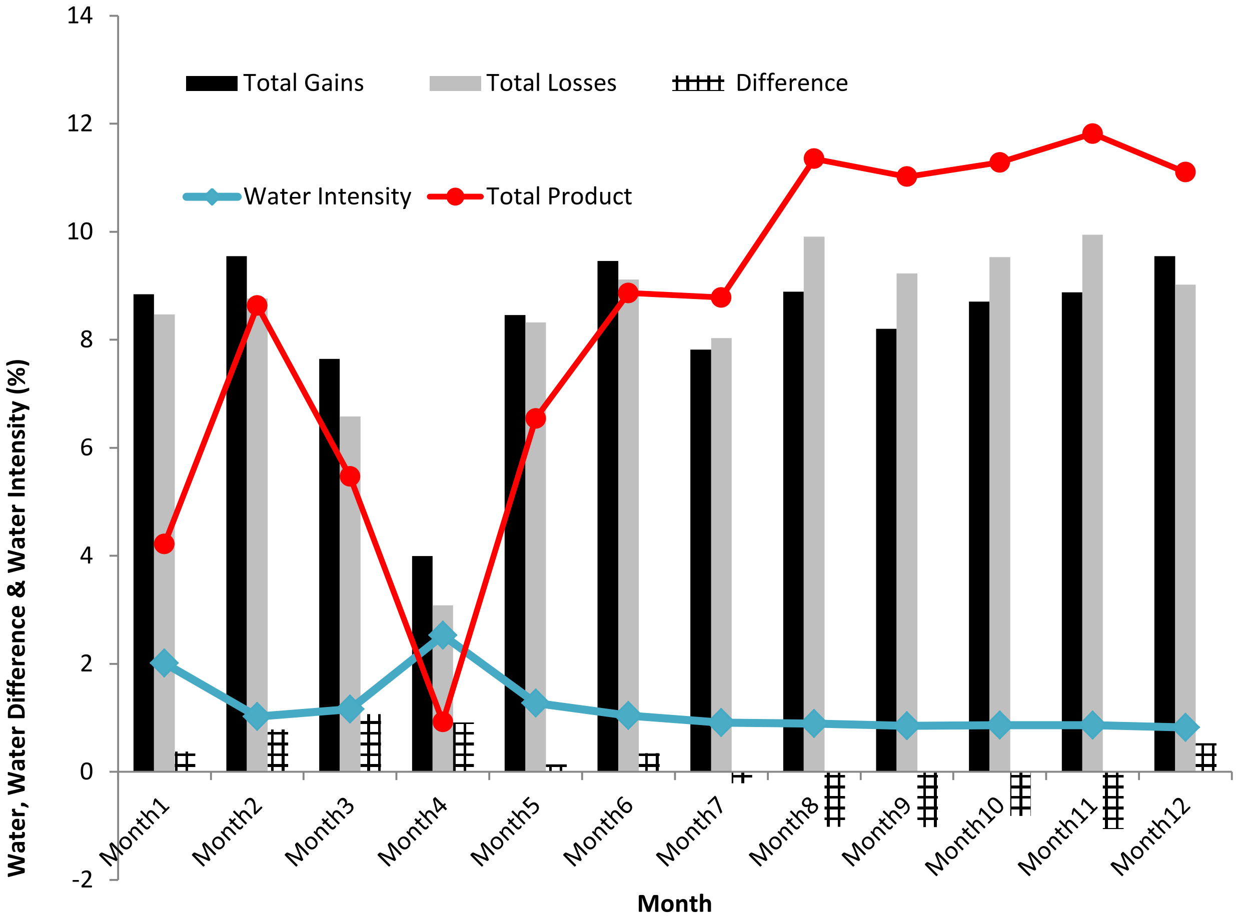


Figure 13 The monthly total water gains into the PMR and water losses from the PMR along with the monthly PGM production and the water intensity of the PMR throughout the year from Month 1 to Month 12

The total water gains into the PMR are reflected in the above graph in Figure 13 and not merely the potable water but the total water gains also include indirect water inputs in the system, such as precipitation and runoff, minor fissure water inflow and feed entrainment. The total water losses include all the water outflows from the PMR, such as the water lost through evaporation, overflow, Municipal System and condensate discharge sewer. The water inflows to the PMR and outflows from the PMR per month are roughly equal, with the water gains sometimes being slightly higher than the water losses and vice versa during different months. The water gains into the PMR per month are a percentage of the total annual water gains into the PMR and water losses out of the PMR per month are a percentage of the total annual water losses into the PMR. Percentages were used instead of explicit volumes for confidentiality purposes.

The difference between the total gains and total losses are reflected in the Figure 13 as well. When the total water losses are greater than the total water gains, it is reflected as a negative bar graph below the x-axis. The difference between the total water gains and water losses are also represented in percentage for confidentiality purposes. The total water losses are greater than the total water gains in the months from Month 8 to Month 11, as shown above. The trend of the reduced water usage in Month 3 and Month 4 shown in Figure 12 are reflected in the graph in Figure 13. The highest inflow volume is observed in Month 12 at 9.6% and the lowest water inflow was observed Month 4 at 3.9%. The highest outflow volume is observed in Month 11 at 9.9% and the lowest outflow volume is observed in Month 4 at 3.0%.

The water intensity per month is also reflected above in Figure 13. Water intensity is a measure of the usage of water in terms of volume per mass of product produce. However, in this graph, water intensity per month has been expressed as a percentage of the total annual water intensity of the PMR. Percentages were used instead of explicit values for confidentiality purposes. The largest water intensity is observed in Month 4 at 2.5%, when production at the PMR is at the lowest at 0.92% and the amount of water in the system is almost more than double the amount being produced at 3.9%. The second highest water intensity is observed during Month 1at 2.01%, with production at 4.2% and the amount of water in the system at 8.8%. The lowest water intensity is observed at Month 12 at 0.82%, where the production is at 11.1% and the water in the system is at 9.5%. Water intensity remains consistent from Month 7 to Month 12. The trend observed that as more water is consumed and fewer products are produced, the water intensity will increase as was shown by the high water intensity values in Month 1 and Month 4. In Month 12, the difference between the water consumed and the product produced was the lowest at about two percent and hence the water intensity during that Month 12 was the lowest. Hence if the amount of water consumed increases, whilst the amount of product produced remains constant or decreases, the water intensity of the system will increase.

4.3 Water Accounting Framework

The WaterMiner Programme, the software that supports Water Accounting Framework (WAF) was rendered obsolete during the course of this research dissertation. Measures were taken to replicate the processes and equations that are used by the programme as well as the reports and diagrams and generated by the software. The WAF methods were used to complete the mass balance over the PMR, especially in terms of evaluating the volume of water associated with the rainfall, rainfall runoff and evaporation, using the rainfall data and moisture content provided by the PMR and the evaporation data evaporation data provided by the South African Department of Water and Sanitation. The three main reports were generated from the application of the WAF, namely the Input-Output Statement, Statement of Operational Efficiencies and the Accuracy Statement.

4.3.1 Input-Output Statement

The input-output statement is essentially a list of all the inputs, outputs and the diversions between the PMR site boundary and the surrounding environment. Each input, output or diversion water flow was represented by a volumetric flow rate, a source or destination and water quality category. The input-output statement is usually accompanied with the accuracy statement to give an indication of the quality of the results presented in the input-output statement. The accuracy statement will be discussed in more detail below.

The volume of the total inputs into the PMR is valued at 48.51 ML/year from Table 6 (input-output statement). Potable water (municipal water) accounted for 42.20 ML/year, which was 87% of the total input volume. The rainfall and rainfall runoff amounted to 6.31 ML/year, 13% of input volume into the PMR and the feed entrainment was valued at 0.001% of the total input volume. Potable water was the biggest contributor of water into the PMR.

The volume of the total outputs was valued at 48.23 ML/year. About 24.12 ML/year, amounting to 50% of the water exited the PMR through the Municipal System (this included water that goes directly to the Municipal System and the water that goes to the condensate discharge sewer which was ultimately directed to the Municipal System). The Effluent Treatment Corporation amounted to 22.01 ML/year and formed 46% of the total output volume. Approximately 4% of the total output volume was lost through evaporation, valued at 1.90 ML/year. Roughly 0.20 ML/year of rain water was discharged to the environment (0.42% of the output volume) when the storm water tank overflowed and a meagre 0.0001% of the total output volume was lost through product waste entrainment.

The total input volume was higher than the total output volume. The difference between the inputs and outputs are 0.28 ML/year, which was 0.58% of the volume of the total inputs into the system. Hence that was not much difference between the inputs into the system and the outputs from the system and the positive balance indicated that the PMR operated at a surplus as there was more water coming into the PMR than going out of the PMR.

Entrainment in the feed (input into the PMR) and entrainment in the product (output from the PMR), was negligible valued at 0.00030 ML/year and 0.000041 ML/year respectively. Although these values were negligible as they were much less when compared to the other values in the input-output statement, it was important to include them to show entrainment as an indirect means of importing or exporting water into a system. These values especially are much smaller than the values that would have been calculated for mine sites as the quantity of ore processed in a mine site is much larger and has greater moisture content than the feed processed in the PMR. The low moisture content in the feed and product processed from the PMR as it had been dried multiple times until the moisture content was 0.5% in the feed and 0.1% in the product.

The volume of water diverted and thus not used in any of significant and consequential processes onsite in the PMR amounted to 0.86 ML/year as shown in Table 7. The input-output statement has been divided between two tables (Table 6 and Table 7) due to the length of the table. Table 6 includes the water inputs and outputs into the PMR and Table 7 involves the water diversion from the PMR.

Table 6 Water account for a South African PMR throughout the year

INPUT-OUTPUT STATEMENT Reporting Period: Month 1 - Month 12							
			Water Quality				
Input-Output	**Element**	**Sub-Element**	**Category 1 (ML)**	**Category 2 (ML)**	**Category 3 (ML)**	**Sub-Element Total (ML)**	**How were flows obtained & Confidence Level**
Inputs	**Surface Water**	**Precipitation & Runoff**	**6.31**	0	0	**6.31**	**Estimated; Medium**
		Rivers & Creeks	0	0	0	0	
		External Surface Water Storages	0	0	0	0	
	Ground Water	Aquifer Interception	0	0	0	0	
		Bore Fields	0	0	0	0	
		Feed Entrainment	0	0	**0.00030**	**0.00030**	**Measured; High**
	Sea Water	Estuary	0	0	0	0	
		Sea/Ocean	0	0	0	0	
	Third Party Water	**Municipal/Contract**	**42.20**	0	0	**42.20**	**Measured; High**
		Waste Water	0	0	0	0	
	Total Inputs		**48.51**	**0**	**0.00030**	**48.51**	

Outputs	**Surface Water**	**Discharge**	0	**0.20**	0	**0.20**	**Estimated; Medium**
		Environmental Flows	0	0	0	0	
	Ground Water	Seepage	0	0	0	0	
		Reinjection	0	0	0	0	
	Sea Water	Discharge to Estuary	0	0	0	0	
		Discharge to Sea	0	0	0	0	
	Supply to Third Party	**Effluent Discharge**	0	0	**22.01**	**22.01**	**Estimated; Medium**
		Municipal System	0	0	**24.12**	**24.12**	**Estimated; Medium**
	Other	**Evaporation**	**1.90**	0	0	**1.90**	**Estimated; Medium**
		Product Entrainment	0	0	**0.000041**	**0.000041**	**Measured; High**
		Task Loss	0	0	0	0	
	Total Outputs		**1.90**	**0.20**	**46.13**	**48.23**	

Table 7 Water account for a South African PMR throughout the year continued

INPUT-OUTPUT STATEMENT Reporting Period: Month 1 - Month 12 CONTINUED							
Input-Output	**Element**	**Sub-Element**	**Water Quality**			**Sub-Element Total (ML)**	**How were flows obtained & Confidence Level**
			Category 1 (ML)	**Category 2 (ML)**	**Category 3 (ML)**		
DIVERSIONS							
Inputs	**Surface Water**	Precipitation and Runoff	0	0	0	0	
	Ground Water	Aquifer Interception	0	0	0	0	
	Third Party Water	**Municipal/Contract**	**0.86**	0	0	**0.86**	**Measured; High**
	Total Diversion Inputs		**0.86**	**0**	**0**	**0.86**	
Outputs	**Surface Water**	Discharge	0	0	0	0	
	Ground Water	Reinjection	0	0	0	0	
	Other	Evaporation	0	0	0	0	
	Supply to Third Party	**Municipal System**	0	0	**0.86**	**0.86**	**Estimated; Medium**
	Total Diversion Outputs		**0**	**0**	**0.86**	**0.86**	

4.3.2 Statement of Operational Efficiencies

The statement of operational efficiencies showed the internal onsite water flows and highlighted the flow of water from water stores to tasks. The statement of operational efficiencies provided the reuse and recycle efficiency of the system (in this case the PMR), by calculating the quantity of reused and recycled water into tasks in proportion to the total water flow into tasks. Reused water is water that has been used in an onsite task and is used again without being treated. Recycled water is water that has been used in an onsite task and is used again but only after it has been treated.

There were no treatment plants onsite and thus none of the water was treated and then used again after treatment onsite, hence the recycle efficiency of the site was zero. However water was reused in tasks after they had been used in other tasks and water had been received by tasks from mixed water stores.

An operational model was constructed to assist in the calculation of the reuse efficiency. The operational model was constructed using the guidelines provided in the WAF (this diagram would have been automatically generated by the WaterMiner Programme if it was in operation) (SMI & MCA, 2012):

- Inputs into the site are green in colour;
- Outputs from the site are red in colour;
- Diversions are yellow in colour;
- Water stores onsite are blue in colour;
- Tasks are grey in colour; and
- Treatment plants are purple in colour (of which there were none)

The operational model with water volumetric flowrates in cubic metres can be found in Figure 14. It follows the above colour code.

Table 8 Water reuse efficiency for the platinum PMR

Statement of Operational Efficiencies	
Total Volume of Water to Tasks (ML/year)	95.22
Total Volume of Reused Water to Tasks (ML/year)	47.30
Reuse Efficiency (%)	**49.67**
Total Volume of Recycled Water (ML/year)	0
Recycling Efficiency (%)	0

From the Table 8 the overall reuse efficiency of the PMR was found to be 49.67%, approximately 50%. This indicated that at least half of the water that was fed to tasks onsite the PMR was reused water and thus freshwater was not used for each task, implying that the PMR was not as dependent on external sources of water as other systems which have lower reuse efficiencies. Sites and/or systems with low reuse efficiencies reuse a smaller amount of water in onsite tasks and thus have to depend heavily on external sources of water and hence would be adversely affected by any change in the external environment such as a drought, water transportation changes and increases in the cost of water.

Figure 14 is on the following page.

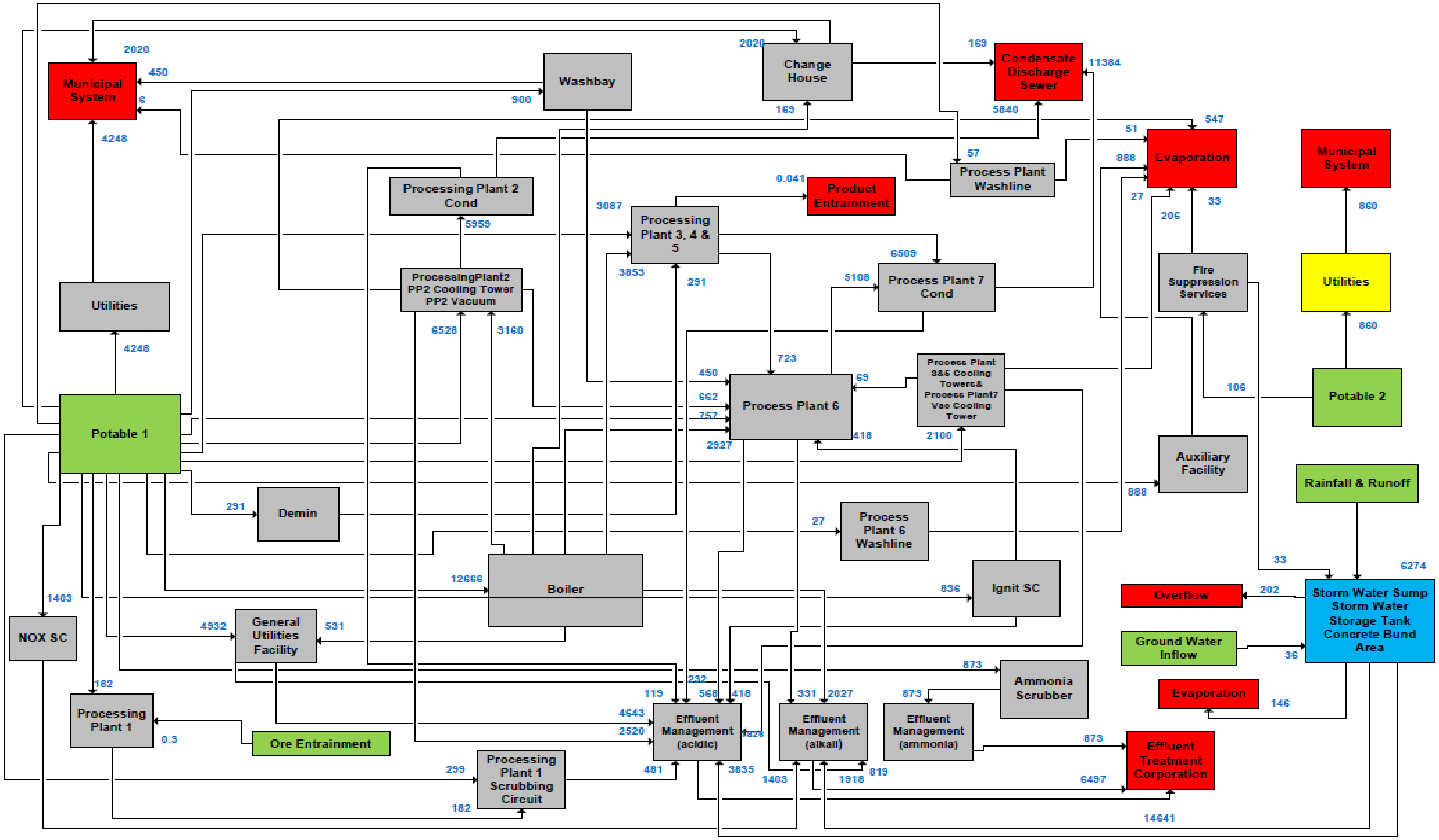


Figure 14 The operational model of the PMR

4.3.3 Accuracy Statement

The accuracy statement is a list of volumetric water flowrates from the input-output statement that shows which of the flowrates were measured, estimated or simulated and the level of confidence (high, medium or low) of the data associated with each flowrate. The accuracy statement is usually presented alongside the input-output statement as a measure of the reliability of the results in the input-output statement. It will highlight which results are the most reliable and which are the least reliable, based on the confidence level associated with each result. After which it will be known which values need to be made more precise in order to improve the overall accuracy of the results and then measures can be taken to do so.

Table 9 The accuracy statement for PMR water flows

ACCURACY STATEMENT				
Flow Types	**Confidence Level**			
ML	**High**	**Medium**	**Low**	**Total**
Measured	43.06	0	0	43.06
Estimated	0	55.40	0	55.40
Simulated	0	0	0	0
Total	43.06	55.40	0	**98.45**
Flow Types	**Flow %**	**Confidence %**		
		High	**Medium**	**Low**
Measured	43.73	43.73	0	0
Estimated	56.27	0	56.27	0
Simulated	0	0	0	0
Total	**100.00**	43.73	56.27	0

Table 9 shows the accuracy statement created from the input-output statement of the PMR. The above table would have been generated by the WaterMiner Programme if it was in operation, however it was created manually using guidelines available in WAF manual. This was done by outlining which of the volumetric flowrates in the input-output statement were measured, estimated and simulated and then noting the associated confidence level with which each of the flowrates were found, such as a high, medium or low confidence level. Refer to the input-output statement, in Table 6 and Table 7 where the above was included in the last column of the tables.

By stream volume 55.40 ML had been estimated and 43.06 ML had been measured, none of the streams were simulated as shown in Table 9. All of the estimated stream volumes are of medium confidence and all of the measured stream volumes are of a high confidence level. The total stream volume was 98.45 ML.

The bottom part of the table which deals with the volumetric stream results in confidence level percentage is a clearer and simpler indication of the confidence level associated with the results. Valued at 43.73%, approximately 44% of the flowrates were measured and all of the measured flowrates had a high confidence level associated with them, none of the measured flowrates were at a medium or low confidence level. Valued at 56.27%, roughly 56% of the flowrates were estimated. All of the estimated flowrates were at a medium confidence level. None of the estimated flowrates were at a high or low confidence level.

Overall, about 44% of the flowrates were at a high confidence level (these were all measured flowrates); about 56% of the streams were at a medium confidence level. None of the streams were at a low confidence level. This indicated that the input-output statement was fairly accurate as about 44% of the streams (which is almost half of the streams) are at a high confidence level and are measured and the other half is estimated at a medium confidence level. No of the results in the input-output statement are at a low confidence nor have any of the results been simulated, adding to the accuracy of the report.

The confidence of the data can be improved by enhancing the flow meter network onsite, the most obvious way to do so, would be to simply increase the number of relevant flow meters, so that fewer stream flows would have to be estimated and the results would be more accurate.

4.4 Water Footprint Network Method

The Water Footprint Network (WFN) method calculates the direct and indirect volume of water consumed to manufacture a product. The complete water footprint is the sum of the blue, green and grey water footprints.

As no significant plant life was supported by the PMR and thus no measures were in place to increase the volume of water in the topsoil. Hence the volume of rainwater that entered open water stores and the rainfall runoff were both considered to be part of the blue water footprint. The PMR has no green water footprint. The PMR also does not discharge any waste water into any natural water body. The waste water was removed from site and was treated elsewhere. Hence the PMR has no grey water footprint. The PMR only has a blue water footprint.

4.4.1 Total Water Footprint

The chain summation formula was used to calculate the water footprint of the platinum PMR product per year. The total water footprint was calculated to be 49086m^3 water per year (12 month period) within the chosen time frame.

The blue water footprint was the sum of the blue water evaporated, the blue water lost and the blue water incorporated into the product. As previously stated, blue water lost refers to lost return flow which is consumed by the process that is not returned to the same catchment or is returned at another time.

As the PMR only has a blue water footprint, the total water footprint for the PMR is equivalent to the blue water footprint. The values are shown in the table below:

Table 10 The components of the blue water footprint for the PMR

Blue Component Water Footprint	**Flow m^3/year**	**% Distribution**
Blue Water Evaporated	1897.29	3.87
Blue Water Lost	47188.75	96.13
Blue Water Incorporated in Product	0.041	0.0001
Total Water Footprint	**49086.08**	**100.00**

From Table 10 it can be seen that a meagre 0.0001% of the water entering the system has been incorporated into the final product. This result was reasonable considering that the feed entering the system only has a moisture content of 0.5%, as the material was refined and dried through the process, the final product only has a moisture content of 0.1%.

Although a fair amount of water was lost through evaporation, it amounted to 3.87%, about 4% of the total water in the process. Water was lost through evaporation from process units and through evaporation from open water store surfaces. The figure below shows the distribution of the water lost through evaporation.

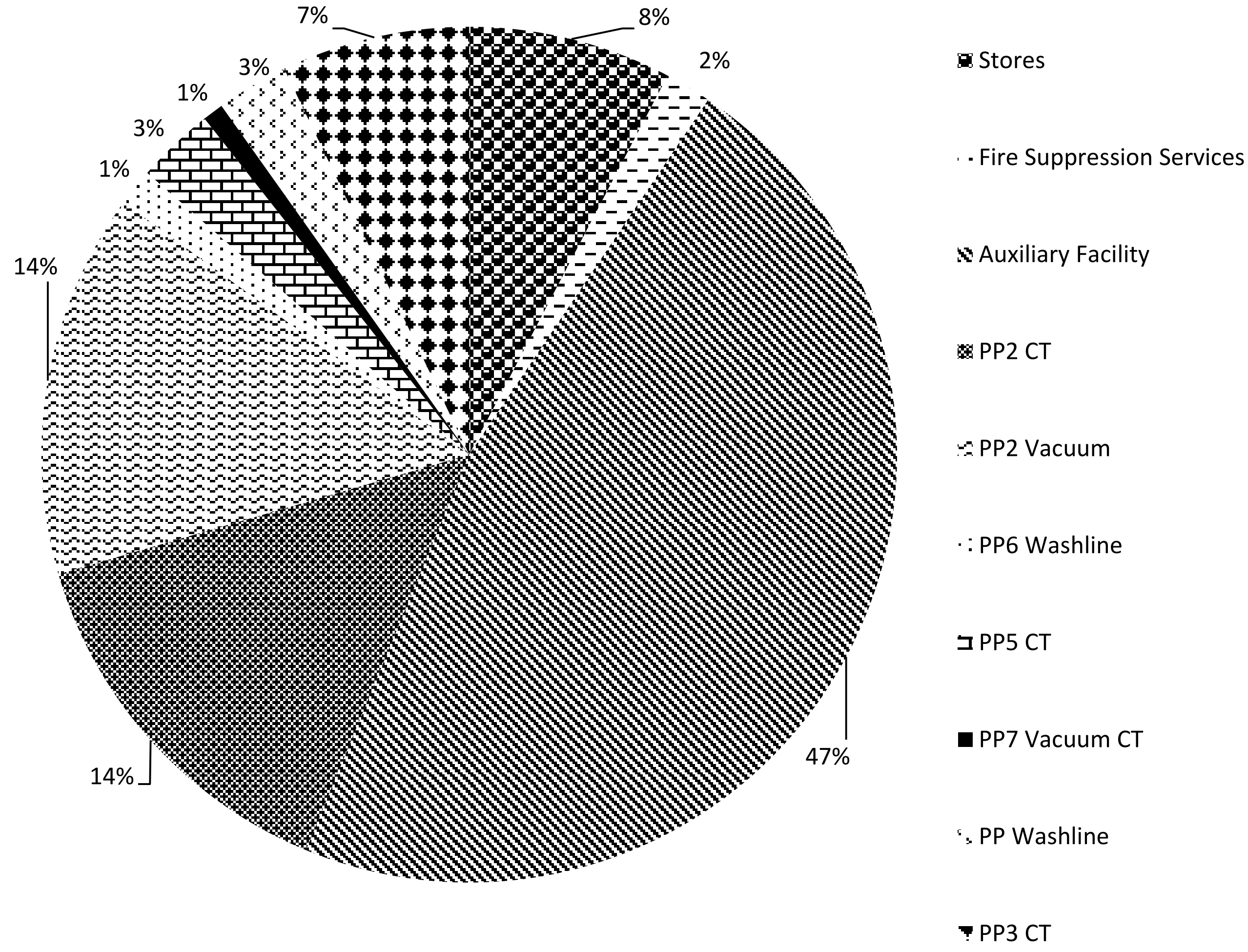


Figure 15 The distribution of evaporation loss from the PMR

From Figure 15, it can be seen that most of the water lost through evaporation was from the auxiliary services, about 47%. The second highest evaporation lost was equally from the Processing Plant 2 Cooling Tower and the Processing Plant 2 Vacuum, at 14%. The water stores contributed 8% to the evaporation loss, while the Processing Plant 3 Cooling Tower accounted for 7% of evaporation loss. Processing Plant 5 Cooling Tower and Processing Plant Washline contributed 3% each to the evaporation loss, with 2% from the fire suppression services and a meagre 1% each from the Processing Plant 6 Washline and Processing Plant 7 Vacuum Cooling Tower.

4.4.2 Product Blue Water Footprint

The final product water footprint was calculated by dividing the components of the total blue water footprint, shown in Table 10, by the production rate and their summation gave the final product water footprint.

Table 11 The components of the product water footprint for the PMR

Product Component Water Footprint	**Water Footprint m^3/kg PGM**
Product Water Evaporated	0.05
Product Water Lost	1.15
Product Water Incorporated	0.000001
Total Product Water Footprint	**1.20**

The components of the product water footprint are shown in Table 11. The final product water footprint was calculated to be approximately 1.20 m^3/kg PGM product or 49.04 ML/year (49086.08 m^3/year).

Majority of the water in the blue water footprint is lost returned water, which was valued at about 96% of the blue water footprint. The blue water lost was distributed as follows:

Table 12 The distribution of blue water lost from the PMR

Water Loss Channel	**% Distribution**
Effluent Discharge	46.65
Municipal System	52.93
Overflow	0.43
Total	100.00

From Table 12 approximately 53% of the lost blue water went to Municipal System and about 47% went to the effluent discharge. Only 0.43% of the water was lost through a small overflow from the storm water area. From the water going to the Municipal System, some of the water was wastewater that goes directly from the process to the Municipal System and the rest was water that first goes to the condensate discharge sewer and eventually goes to the Municipal System.

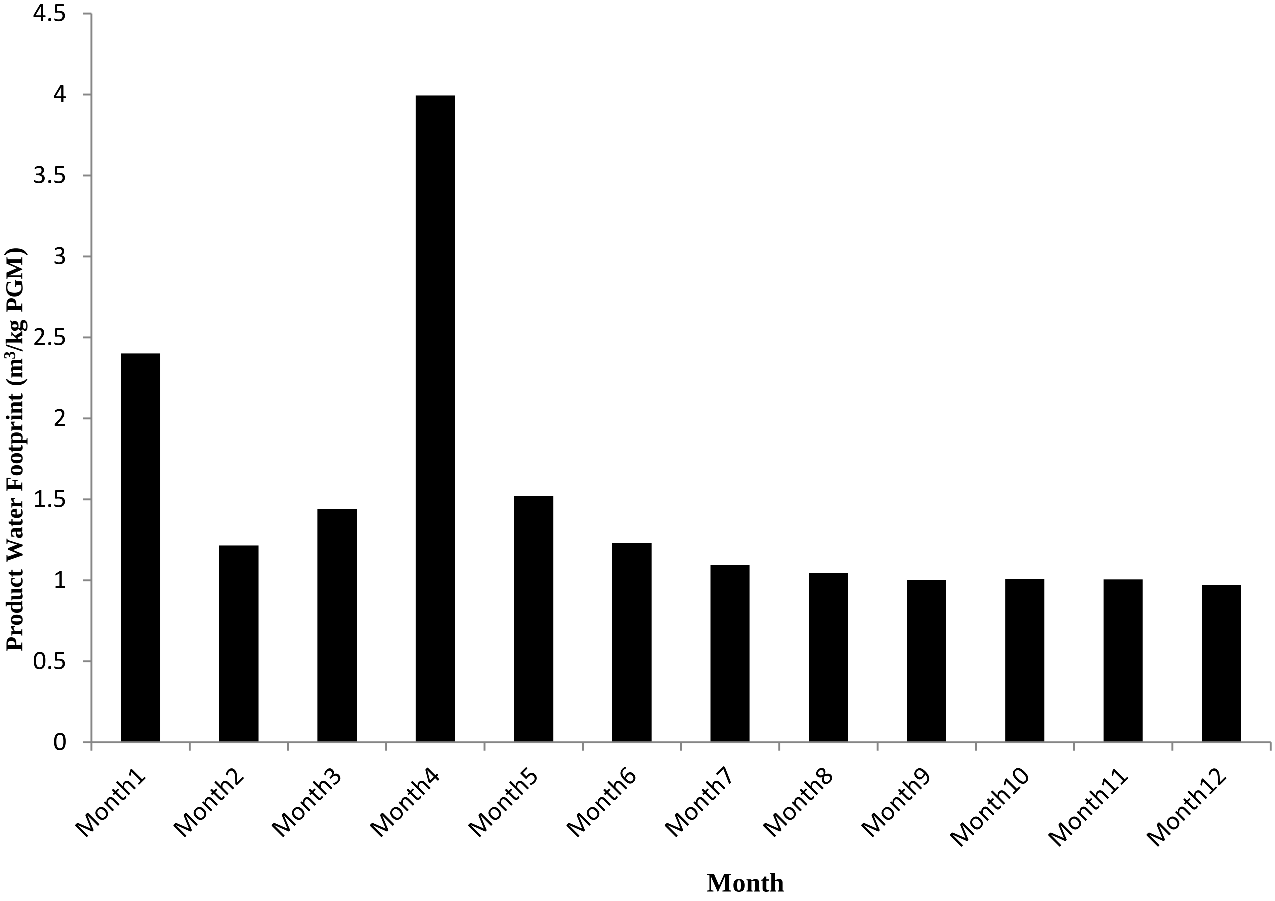


Figure 16 The monthly product water footprint from the PMR over a 12 month period

From Figure 16 the highest product water footprint was observed in Month 4 at 3.99 m^3/kg PGM as a result of a low production rate in Month 4 due to an operational disruption. The second highest product water footprint is valued at 2.40 m^3/kg PGM in Month 1, mainly due to a slightly low production rate which is generally the trend at the beginning of the financial year. The lowest product water footprint was observed in Month 9 at 1.00 m^3/kg PGM, which coincided with the lowest rainfall month in the 12 month period. Throughout the year the product water footprint steadily decreased as the production rate steadily increased, until they both stabilised from Month 6 onwards. The product water footprint was slightly lower in Month 12 than in the months before due to an experimental attempt to lower the freshwater intake.

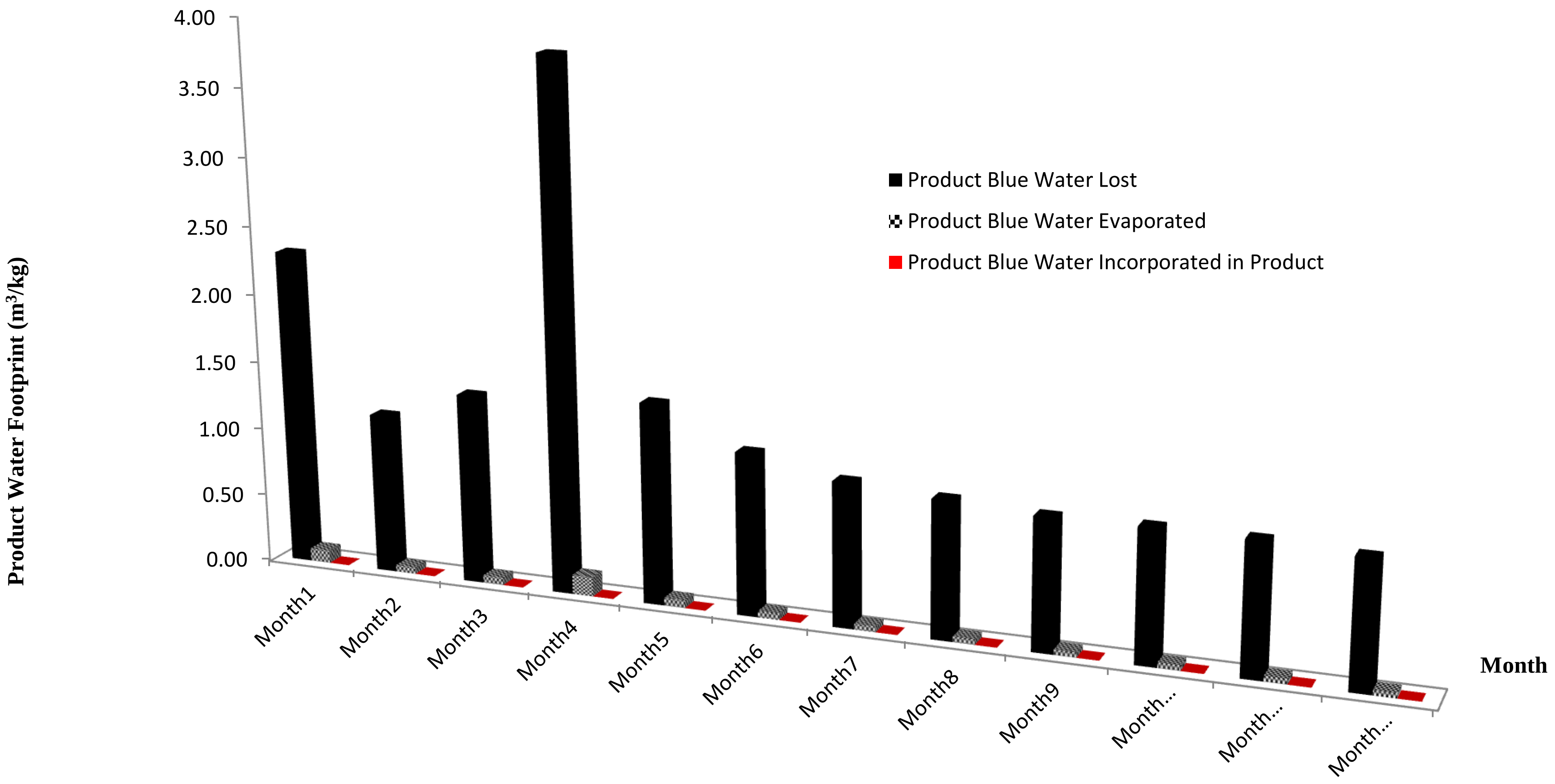


Figure 17 The distribution of the monthly product water footprint into components from the PMR

Figure **17** shows the distribution of the monthly product water footprint. The blue water lost was the biggest contributor to the product water footprint, followed by the water lost through evaporation and lastly by the water incorporated into the product, which is a negligible contributor to the product water footprint. The graph in the figure above follows the same trend as Figure 16, where the highest product water footprint was observed in Month 4 and the lowest product water footprints was observed in Month 9. The reasons for these observations were the same as stated for Figure 16.

4.4.3 Response Formulation

The response formulation focuses on possible options to reduce the water consumption of the PMR. The most viable suggestions are chosen for implementation.

The following is a list of areas to target to reduce water consumption in the PMR:

1) Biggest consumers of potable water from Potable 1 and Potable 2
2) Highest areas of water loss
3) Possible areas for water reuse and recycle in the PMR

4.5 Summary of Main Results

Table 1 showed the total gains being slightly higher than the total losses. The water gains are valued at 49368 m^3 and the losses at 49086 m^3. This is also shown by the input-output statement in Table 6 where the total volume of the inputs is valued at 48.51 ML/year and the total volume of the outputs is valued at 48.23ML/year. From the input-output statement difference between the inputs and outputs are 0.28 ML/year, which was 0.58% of the volume of the total inputs into the PMR. With only a slight difference between the gains and losses, the mass balance requirement was fulfilled.

The Potable 2 accounted for only 2.24 % of the total freshwater entering the system as shown in Table 2. The main consumer of water from Potable 2 was the change house, amounting to about 59% as shown in Figure 7. The second highest consumers were the fire suppression services followed by the ancillary, which respectively used 11% and 10% of the Potable 2 as shown in Figure 7. The main consumer of water from Potable 1 was the boiler, which used 30% of the water, as shown in Figure 8. This was more than all the water from Potable 2. The boiler was not only the main consumer from Potable 1, but from the entire PMR. Other major water consumers of Potable 1 showcased in Figure 8 are the General Utilities Facility which consumed 12% and then the Processing Plant 2 and the Processing Plant 2 Cooling Tower, which consume 8% and 7% respectively, which are relatively low compared to the boiler freshwater consumption.

Table 5 shows the major water outflows from the PMR, 15.45% of the water exited the PMR through the Municipal System, 35.43% through the condensate discharge sewer (which ultimately goes to the Municipal System) and 44.84% to the Effluent Treatment Corporation. The water sent to the Effluent Treatment Corporation had a high chemical content; where 66% of the water came from the Effluent Management (acid) and 30% of the water came from the Effluent Management (alkaline). As only three process units discharged water to the condensate discharge sewer, namely the Processing Plant 7 condensate, the Processing Plant 2 Condensate and the change house, the water to the condensate discharge sewer was less contaminated than the water that goes directly to the Municipal System.

Table 5 shows that 3.87% of the water outflows from PMR was due to water lost through evaporation. This was not a big amount of water when compared to the total water outflows, however it could be reduced. Figure 15 shows the distribution of the water lost through evaporation. Majority of water lost through evaporation was from the auxiliary facility, it amounts to 47% of the water lost through evaporation. The other units from which water was lost through evaporation was the Processing Plant 2 Cooling Tower and the Processing Plant 2 Vacuum, which cumulatively accounted for 24% of the water lost through evaporation. The fire suppression services accounts for 2% of the water lost through evaporation. About 8% of the water lost through evaporation was from the water stores.

Figure 11 proved that the combined volume of water received through direct rainfall into onsite open water surfaces added to the rainfall runoff collected from the entire site was much greater than the volume of water lost through evaporation (evaporation from both onsite open surfaces and process units in the PMR).

It can be seen from Figure 12 that in general as potable water consumption increases so does PGM production.

The largest water intensity was observed in Month 4. During this month, the lowest amount of water was consumed by the PMR, largely due to the operational disruption as shown by the graph in Figure 13 and it was the month with the lowest production rate as shown by the graph in Figure 12. It was observed that as the amount of water consumed increases, whilst the amount of product produced remains constant or decreases, the water intensity of the system will increase.

Chapter 5 DISCUSSION

This section involves observations and discussion around the results found in Chapter 4. An extensive review and comparison of water accounting methods, namely the Water Accounting Framework (WAF) and the Water Footprint Network (WFN) method was carried out and complied as a part of this research, after which it was selected, presented and published at the SAIMM Hydrometallurgy Conference in August 2016. The paper which discusses some of the general WAF and WFN method observations discussed below can be found in Appendix B. This section will also address the research objectives stated in CHAPTER 1: Introduction (section 1.2 Research Objectives).

5.1 Notable Observations

If alternative options are considered to supply water to the utilities supported by Potable 2, than water that has been used cannot be utilised by the change house due to health concerns, however if the used water was treated and brought to a level for human consumption than it could be used again; this might not be a viable option as treating water to a drinkable standard especially for a small operation might prove to be very costly. The same concerns could be raised about the support services, the emergency services and the security. The fire suppression services and the ancillary could however safely be operated with used water (or water that might only need minimal treatment as it does not have to be treated for human consumption).

The boiler was not only the main consumer of water from Potable 1, but from the entire PMR. Hence it can be deduced that the freshwater consumed by the boiler needs to be reduced in order to reduce the overall water consumption of the PMR.

The water sent to the Effluent Treatment Corporation had a high chemical content as discussed earlier and hence could not be used anywhere else in the PMR, nor does the PMR have any facilities to treat water of such a high chemical content. Not much else can be done with this water except to let it get treated safely elsewhere.

The used water that goes directly to the Municipal System does not have a chemical content as high as the water that is sent off to be treated at Effluent Treatment Corporation, yet it cannot be used without some prior treatment. It has been previously inferred that the water to the condensate discharge sewer was less contaminated than the water that goes directly to the Municipal System. This water ultimately gets sent out along with the other wastewater to the Municipal System despite not being as polluted, which is probably not the best use of water that is fairly uncontaminated.

About 3.87% of the water outflows from PMR were due to water lost through evaporation. This was not a big amount of water when compared to the total water outflows, however it could be reduced. Majority of water lost through evaporation was from the auxiliary facility. About 8% of the water lost through evaporation was from the water stores.

The combined volume of water received through direct rainfall into onsite open water surfaces added to the rainfall runoff collected from the entire site was much greater than the volume of water lost through evaporation (evaporation from both onsite open surfaces and process units in the PMR). This was unlike most sites, where the volume of water lost through evaporation was much higher than the volume of water gained through rainfall. In this site, the volume of water gained through rainfall and more specifically rainfall runoff is one of the largest contributors of the water into the system. As the PMR is a refinery it is relatively small when compared to other mining activity sites, such as mines, which make up the majority of operations to which these two chosen water accounting methods have been applied. Mine sites have open tailings dam and big open water storage facilities from which huge volumes of water can be evaporated. This is not the case with refineries from where less evaporation occurs due to smaller water surfaces.

It can be seen from Figure 12 that in general as potable water consumption increases so does PGM production; however there are some exceptions, such as in Month 1, hence only a relatively reasonable coefficient of correlation at 0.60 was found.

The total water gains into the system are greater than the total water losses from the system and sometimes the vice versa occurs. The total water losses are greater than the total water gains in the months from Month 8 to Month 11, as shown in Figure 13.

These months (Month 8 to Month 11) are the months during which there was little to no rainfall as was shown in the graph illustrated in Figure 9, indicating that a big proportion of the water gains come from the water collected through rainfall and runoff.

Water intensity is a measure of the usage of water in terms of volume per mass of product produce. The largest water intensity was observed in Month 4. During this month, the lowest amount of water was consumed by the PMR, largely due to the operational disruption as shown by the graph in Figure 13 and it was the month with the lowest production rate as shown by the graph in Figure 12.

From here it was observed that as the amount of water consumed increases, whilst the amount of product produced remains constant or decreases, the water intensity of the system will increase.

The water from the discharge condensate sewer could be used by the boiler instead of being released into the Municipal System. This water will eventually be heated up in the boiler, removing the few impurities present in water before the water is released to the other.

Hence the water that originally goes to the condensate discharge sewer can be reused for the boiler. If the required water is routed back to the boiler, then 30% less freshwater from Potable 1 will be required by the boiler. It should be noted that the boiler is the biggest water consumer in the PMR.

This will decrease the total blue water footprint from 49086.04 m^3/year to 36420.33 m^3/year, which amounts to a 25.8% decrease in the blue water footprint. The total product water footprint will decrease from 1.20 m^3/kg to 0.89 m^3/kg, which amounts to a 25.8% decrease in total product water footprint.

The amount of water required from Potable 1 will then be decreased. This will have financial implications. The original cost for Potable 1 would be ZAR 433554.30. The new cost of Potable 1, if the above change is made will be ZAR 303097.17. Hence ZAR 130457.12 is saved.

5.2 Comparison of the Water Accounting Framework and the Water Footprint Network method

In this research the Water Accounting Framework (WAF) and the Water Footprint Network (WFN) method were used to calculate the total water gains and losses from the PMR.

The input-output statement of the WAF reports the volume of total water inputs to be 48.51 ML/year and the volume of the total outputs to be 48.23 ML/year as shown in Table 6. The total blue water footprint as calculated by the WFN method is 49.09 ML/year (49086.08 m^3/year) as shown by Table 10. The difference between the total input volume from the WAF and the total water footprint is 0.58 ML/year, which is approximately 1.2% of the WFN total water footprint value.

The slight difference in the values is due to the definitions which provide the scope, boundaries and structure of the methods. The input-output statement separates volume of water into inputs, outputs and diversions. Hence the volume of water accounted for by the inputs, outputs and diversions will each individually be less than the total water footprint volume which cumulatively accounts for all the water in system. The diversion from the input-output statement shown by Table 7 is valued at 0.86 ML/year, when added to the output value of 49.23 ML/year; it comes to a value of 49.09 ML/year which is the value of the total water footprint.

The difference in the structure of the two methods is due to the different purposes of each method. The WAF aims to provide a platform where water usage in various mining operations can be compared in a consistent manner (SMI & MCA, 2012). The WFN method aims to evaluate and quantify the volume of freshwater being consumed globally (Hoekstra, *et al*., 2011). As such the application of the WAF is majorly limited to the mining industry, whereas the WFN method can be applied to any sector (Hoekstra, *et al*., 2011); although it has been mainly applied to the agriculture sector. Hence the WAF only considers water that enters the PMR directly and the WFN considers water that enters the PMR both directly and indirectly.

The similar results achieved by the WAF and the WFN method prove that the WFN method can be as effective as the WAF, a water accounting tool primarily used for mining, with regards to evaluating water usage despite being a water accounting tool primarily used for agriculture. Hence in accordance with the results of this study, provided that appropriate data is available, the WFN method can be comfortably used as a water accounting tool to evaluate water usage in mining operations and refineries.

The WFN method presents results in the form of a total water footprint volume. This singular value is usually a sum of the three different water footprints, the blue, green and grey water footprints (this study however only has a blue water footprint); the different components supply information about different aspects of water usage in the process, hence helping to contextualise water usage in the process (Hoekstra, *et al.*, 2011). Contextualising water usage in terms that are more explicit than just inputs and outputs is one of the advantages that the WFN method has over the WAF. This provides a good general overview of the process and draws attention to specific areas of water usage (Morrison, *et al.*, 2010). Although this study only considers a blue water footprint, the components that make up the final result, such as the blue water lost, blue water evaporated and the blue water incorporated into the product, gives an indication of how water was utilised in the process and where the water went as illustrated in Table 10.

Another big advantage of the WFN method over the WAF is the grey water footprint which gives an indication of the pollution (Hoekstra, *et al.*, 2011) caused by an operation and not just the volume of wastewater discharge by the operation. In this regard, the WFN method attempts to address water related environmental impacts while the WAF does not address this matter, except in the context of the three water quality categories associated with the sources of the inputs and the destinations of the outputs (SMI & MCA, 2012). This is however not as useful as the grey water footprint in the WFN method which provides a volume indicator of the pollution produced by the system.

However, the grey water footprint, although valuable has its shortcomings. The grey water footprint only considers the primary pollutant and none of the other pollutants in the wastewater stream and uses the primary pollutant to calculate the theoretical volume of water required to dilute the wastewater stream to meet regulatory standards. Consideration of only the main pollutant and not any of the other pollutants in the wastewater stream might not be a fair indication of the pollution level in the wastewater stream. Also the summation of the component water footprints to give a total water footprint is not reasonable as the blue and green water footprints are measured values and the grey water footprint is a theoretical value (Morrison, *et al.*, 2010) .

This study was unable to calculate a grey water footprint as the effluent produced by the PMR was not discharged by the PMR, instead it was collected and sent to Effluent Treatment Corporation to be treated and safely discharged of and hence the level of pollution that is generated by the process could not be calculated due to the limitations of the grey water footprint definition which does not make allowance for wastewater which is collected onsite but not discharged by the site. Also water quality data in terms of pollutants was not made available by the PMR for the purpose of confidentiality. This highlights the shortage of transparent data available to South African academics for research purposes from mine sites and mining operations, particularly with regards to water and the limitations that it adds to research and the conclusions that can be drawn from research analysis.

An advantage of the WAF is the use of the accuracy statement and the statement of operational efficiencies along with the input-output statement. These reports provide invaluable background information to the input-output statement. The accuracy statement, shown in Table 9, gives an indication of how precise and reliable the values in the input-output statement are and hence whether the report can be trusted to relay the reality of the process and where further work needs to be done to increase the reliability of the report. This is not possible with the WFN method which does not make allowance for the reliability of the results presented by the method. The statement of operational efficiencies, shown in Table 8 gives an indication of how much of the water onsite is reused and recycled within the process through the reuse and recycles efficiencies along with the operational model. These values and diagrams provide significant insight into onsite water usage and efficiency which is neglected by the WFN method.

The WFN method provides comprehensive measurements of both water usage and water discharge and gives an indication of water discharge related risks (Hoekstra, *et al*., 2011). The WAF method provides information on water usage and specifically comprehensive results with regards to onsite water usage and efficiency (SMI & MCA, 2012). The WAF method gives an indication of the reliability of the results presented in the reports. The WAF however gives little indication of water related environmental impacts (Morrison, *et al*., 2010). The WFN method and the WAF are both focused on the usage of water and efficiency and have very little to offer in terms water related impacts.

There is another point, albeit a non-technical on which the WAF and WFN methods can be compared, that is the acceptance and ease of communication of each method. The extent to which each method has been established in the environmental community will affect the level of acceptance that it receives from the environmental community.

The WFN method is a fairly well known method that has been relatively well established in the water management community; despite this it has only been recently introduced to the private sector. The use of the WFN method in the mining sector is quite recent as the WFN method was previously mainly employed in the agricultural sector (Morrison, *et al*., 2010). An advantage of the WFN method is that the results of the method are conducive to discussion with corporations and business management as the results can be easily understood by non-technical audiences (Morrison, *et al*., 2010); this only increases the acceptance of the method in the environmental sector as it facilitates discussion with the business sector. A major advantage of the WFN method with regards to business corporations is the ability of the method to be corporations a general overview of an entire operation, to provide corporations with the view of the ‘bigger picture’, by contextualising water usage through different water footprint components and thus highlighting specific areas in an operation, hence aiding in strategic planning (Morrison, *et al*., 2010).

The WAF is used equally in both the public and private sectors. The use of WAF has mainly been rather focussed on the mining sector (SMI & MCA, 2012). No prior expertise is required for the application of this method; the results produced from this method can be easily understood by non-technical audiences as well. One of the biggest advantages of the WAF is that the method provides a platform which is also accessible to financial corporations to efficiently and consistently compare and compile mining related water data (Morrison, *et al*., 2010). The results from the WAF method can be globally received and understood as the WAF was created to align with other well-known water frameworks, such as the Australian Water Accounting Standard (AWAS) and the Global Reporting Initiative (GRI) (SMI & MCA, 2012).

It should be noted here, although it has been previously stated in this text, that the software supported by the WAF, the WaterMiner Programme was rendered obsolete during the course of this research. Presumably the resources necessary for the upkeep and maintenance of the WaterMiner Programme was lacking and hence it was brought to a close. This could be considered as circumstantial or simply a shortcoming of the method. Further investigation and more information on the motives behind the closure need to be found before any concrete conclusion can be made. However, it is possible to apply the WAF manually without the software, using the guidelines provided by the Water Accounting Framework manual as shown by this study.

The WAF and the WFN methods have been compared in terms of technical and non-technical aspects above and it can be concluded that each method has various strengths and weaknesses and the use of one will be more appropriate than the other under a certain set of circumstances.

The use of other water accounting tools, such as the LCA water based assessment tool/method were excluded from this study due to the level of data provided by the PMR. The LCA water based assessment, which was discussed in the Chapter 2, Literature Review, required a huge amount of data intimate to the operation; data of this nature was not made available by the corporation for research in accordance with the purpose of confidentiality. Also the PMR had independently conducted a water study similar to the LCA water based assessment and was not interested in providing data to receive feedback from a similar method.

5.3 Water intensity of metals

Water intensity is the measure of the amount of water needed for the production of a unit of good. In this case water intensity is a measure of the volume of water needed for the production of a kilogram of PGM. Water intensity is therefore a measure of the efficiency of water use for the production of PGM. The water intensity of a process is essentially the water footprint of a process.

The following table shows the water intensity for various mines and metal refineries.

Table 13 Water intensity of mines and refineries

Water Consumption	**Mineral**	**Location**	**Process (mine/refinery)**	**Reference**
0.096 m^3/kg base metal (96m^3/ton)	Copper	Chile	Copper Sulphide Refinery	(Peña & Huijbregts, 2013)
0.04 m^3/kg base metal (40 m^3/ton)	Copper	Chile	Copper Oxide Refinery	(Peña & Huijbregts, 2013)
0.044 m^3/kg base metal (43.9m^3/ton)	Copper, Nickel & Cobalt (simultaneous refinement)	South Africa	Base Metal Refinery (Sulphide ore)	(Osman, *et al*., 2013)
1.2 m^3/kg PGM (1200 m^3/t PGM; Blue Water Footprint)	Platinum	South Africa	Platinum PMR (Refinery)	Current Study
391.5 m^3/kg PGM	Platinum	South Africa and Zimbabwe	Platinum Mine	(Mudd & Glaister, 2009)
260 m^3/kg PGM	Platinum	Global Average	Platinum Mine	(Mudd, 2008)
228 m^3/kg PGM (Blue Water Footprint)	Platinum	South Africa	Platinum Mine	(Haggard, *et al*., 2015)
2229.30 m^3/kg of refined platinum (Blue Water Footprint)	Platinum	South Africa	Platinum Mine	(Ranchod, *et al*., 2015)

Several comprehensive studies have been carried out on platinum mines (not platinum refineries) in terms of water intensity, using water accounting methods that are similar to the ones that have been employed by this research. The blue water footprint of 228 m^3/kg PGM (Haggard, *et al*., 2015) is relatively close to and falls within range of the global average of 260 m^3/kg PGM (Mudd, 2008) and that of 391.5 m^3/kg PGM (Mudd & Glaister, 2009) from the South African and Zimbabwean platinum mines. However, the value of 2229.30 m^3/kg of refined platinum (Ranchod, *et al*., 2015) is much larger than that of the global average as this study not only included the platinum mining processes but also the platinum refining process. Unfortunately, the study did not indicate how much of the water footprint was accounted to the mining processes and how much of the footprint was accounted to the refinery process.

In comparison to the water intensities of platinum mines, the water intensity of the platinum PMR is considerably smaller, with the global average being 260 m^3/kg PGM and the platinum PMR at a value of 1.2 m^3/kg PGM. This means that the water intensity of the platinum PMR is 0.5% that of the water intensity of the average platinum mine. This is reasonable as the size of a platinum mine is much larger than that of a platinum refinery. Also mining operations generally involve the capturing of the valuable metal from the ore and all the other subsequent processes are aimed that liberating the metal into its purest form. These processes are not only energy intensive but also water intensive. The platinum refinery (PMR) reviewed by this study, only deals with the refinement of platinum after it has been processed by the base metals refinery, hence the PMR here deals with the final stages of platinum refinement and thus would not require as much water as a mining operation.

The huge difference between the water intensity values of the platinum PMR compared to that of average platinum mine might be one of the reasons why water studies on platinum refineries are rare as they do not consume as much as water platinum mines do and hence are overlooked. However, studies on platinum refineries are essential as the water usage optimisation of every stage in the platinum production process are necessary if water consumption is to be reduced and if any operation, regardless of its size is functioning at its optimal than the resources and money saved will ultimately increase the sustainability of the entire process. As most refineries, including platinum refineries are found inland away from major water bodies or rivers, the cost of purchasing and transporting water is major and hence a platinum refinery where water usage has been minimised usually through the reuse of water onsite would drastically lowered the water associated costs.

This study has a water intensity of 1.2 m^3/kg PGM for the South African platinum PMR, while the other refineries, such as the one in Chile have lower water intensities. The Chilean copper sulphide refinery has a water intensity of 0.096 m^3/kg base metal and the Chilean copper oxide refinery has a water intensity of 0.04 m^3/kg base metal. The South African base metals refinery has a water intensity of 0.044 m^3/kg base metal from a sulphide ore. The water intensity for the South African base metals refinery for copper from a sulphide ore is relatively close to the water intensities achieved by the Chilean copper refineries. The similarities between the water intensities of the base metal refineries are proof of the validity of the results found by each case study.

In this study it was necessary to compare the current platinum PMR refinery to base metal refineries as there is a shortage of water accounting studies done on platinum refineries. In fact, not a single similar comprehensive study carried out on a platinum refinery in terms of water intensity was found for comparison at the time this study was carried out and hence this study had to make do with results from base metal refineries. It should be noted that the processing of PGMs is analogous to that of base metals processing as stated in the literature review and hence the water intensities of base metals refineries were chosen for comparison to the water intensity of the platinum PMR.

In comparison, the base metal refineries in South Africa and Chile have lower water intensities than platinum PMR refinery. This could be due to different processing techniques. Products from the base metal refinery include copper, nickel, cobalt and PGM concentrated residues as shown in Figure 2; these products are from the final stage of the base metal refinery process. The PGM concentrated residue from base metal refineries are fed to platinum refineries for further processing. In the final stages of platinum refinement process, both insoluble PGMs and soluble metals are present. The insoluble PGMs are either sent back to the beginning of the platinum refining process to be reprocessed or they are discarded. The soluble metals have to be further processed to produce gold, palladium and platinum. This step does occur in base metal refineries and could be a possible reason for the lower water intensity of the base metal refineries as compared to the platinum PMR, which produces platinum, palladium, gold, rhodium, ruthenium and iridium.

Other possible reasons have the difference in water intensities between the platinum PMR and the base metal refineries could be differences in the time period of the study as well as differences in rainfall and evaporation conditions.

5.4 Comparison of similar studies of water accounting methods

Three other studies have employed the use of the water accounting methods namely, WAF and WFN method) applied in this study:

1. Assessing the blue water footprint of an open cast mining operation in South Africa (Ranchod, *et al*., 2015) (Ranchod, *et al*., 2014)
2. Water footprint of a South African platinum mine (Haggard, *et al*., 2015) (Haggard, 2015)
3. Water management at a base metals refinery (Osman, *et al*., 2013) (Osman, 2016)

Table 14 Comparison of similar studies of water accounting method

Process	**Water Intensity**	**Input-Output Statement**	**Operational Efficiency**	**Accuracy Statement**	**WFN**	**Reference**
Mine (2 concentrator plants, a smelter plant & tailings dam)	228 m^3/kg	Input: 12686 ML/year Output: 12599 Ml/year	Reuse Efficiency: 88%; Recycle Efficiency: 0%	Estimated: 97% of streams at medium confidence Measured: 3% of streams measured at high confidence	Total WF: 806 m^3/kg PGM; Blue WF:28% of Total WF; Grey WF: 72% of Total WF	(Haggard, 2015); (Haggard, *et al.*, 2015)
Refinery (entire refinery)	0.044 m^3/kg base metal	Input: 1094.33 ML/year Output: 1120.83 ML/year	Not available	Estimated: 27% of streams at medium confidence Measured: 73% of streams at high confidence	0.044 m^3/kg base metal; Blue WF: 76% of Total WF; Green WF: 24% of Total WF	(Osman, 2016); (Osman, *et al.*, 2013)
Mine & magnetic separation & base metals refinery & precious metals refinery	2229.30 m^3/kg	Not available	Not available	Not available	Blue WF is Total WF	(Ranchod, *et al.*, 2015)

Case one and case two are relevant as both cases deal with platinum and this study is focussed on platinum PMR. Case three is of relevance as it involves water accounting methods applied to a base metals refinery, which in the absence of platinum refinery studies in terms of water accounting methods, is the closest point for comparison.

The major findings of the three studies were compiled in Table 14. In case one: *Assessing the blue water footprint of an open cast mining operation in South Africa*, the highest water footprint was found due to the study including comminution, flotation, smelting, converting, base metal removal and the refinery stages (Ranchod, *et al*., 2014). It is reasonable for this all-encompassing platinum mine water accounting study to have such a big water footprint. The other platinum mine study in which water accounting methods were applied was case two: *Water footprint of a South African platinum mine*, here the water footprint was considerably smaller, as the study only covered two concentrator plants, a smelter plant and tailings dam, the mining step was excluded from this study (Haggard, 2015). Only application of the WFN method is available for case one. Case two and case three, *Water management at a base metals refinery*, applied both the WAF and the WFN methods to focus areas under study.

In case one the total water footprint was equivalent to the blue water footprint as it was in this study. The total blue water footprint components were as follows: blue water evaporated accounted for 67% of the total blue water footprint; blue water lost accounted for 28% and blue water incorporated into the product accounted for 5%. In accordance to Table 10, the highest contributor to the blue water footprint in this study was the blue water lost at 96.13%, followed by the blue water evaporated and a meagre amount involved in blue water incorporated into the product. This difference is due to multiple platinum recovery stages included in the case one, where the major evaporative abstractions were from the mineral processing plants, the tailings storage facility and the water stores that made up 67% of the blue water footprint (Ranchod, *et al*., 2015). Such vast evaporative abstractions were not possible in this study as the PMR does not include a tailings storage facility and the water stores on site were relatively small.

Case two had grey water footprint and a smaller blue water footprint. There was no green water footprint. The tailings dam was found to be highest contributor to the total water footprint, due to evaporation and seepage. The greatest loss of water was through evaporation from the tailings dam (Haggard, *et al*., 2015). This follows the same trend as case one, but again differs from this study and for the same reasons: the PMR does not have a tailings dam and only has small water stores; hence evaporation for open water surfaces is minimal.

This emphasises the huge difference that exists between the rest of the platinum mining operations and the platinum refinery process; the platinum mining operations will require a huge tailings storage facility and the platinum refinery will only have comparatively smaller water stores on site and as such further investigation into platinum refineries should be done to find the differences between the operations of the refineries as compared to the rest of the platinum mining stages. This stresses the importance of this study.

Case three did not have a grey water footprint, but had bigger blue water footprint with a smaller green water footprint. Case three stated that the mixture of blue and green water sources made it impossible to find separate evaporation values for the individual footprints and hence both the water footprints were calculated based on consumption (Osman, *et al*., 2013). The main contributor to the blue water footprint was the consumption of portable water and the main contributor to the green water footprint was rainfall in case three (Osman, *et al*., 2013). This differs from the current study which did not include a green water footprint as previously mentioned in the method (Chapter 3 Method), due to the definitions outlined by the Water Footprint Assessment Manual (Chapter 2 Literature Review), where if the captured rainfall and rainfall runoff were not used to increase moisture/water in the topsoil, i.e. if the water was not used for gardening, but employed elsewhere in the production process, the water would be considered as part of the blue water footprint and not the green water footprint (Hoekstra, *et al*., 2011). This definition was supported by case one.

In terms of the input-output statement, case two had larger volumetric water inputs and outputs than case three; presumably this is due mining operations requiring more water than refinery operations. The volumetric water inputs and outputs for this study, presented in Table 6 are noticeably smaller than those of the refinery in case three.

The water input is valued at 1094.33 ML/year in case three and 48.51 ML/year in this study; the water output for this study is valued at 48.23 ML/year for this study and 1120.83 ML/year for case three.

The major water inputs into case three were the potable water and the rainfall (Osman, *et al*., 2013). The major water inputs for this study were potable water as Potable 1 (85.26%) and precipitation and rainfall runoff (12.71%) as shown in Table 4. From these similarities, it can be gauged that potable water is a major source of water for refineries as is captured rainfall, this is probably the case with most refineries as many refineries are located fairly inland away for dams and natural water bodies, hence the reliance on potable and captured water.

Major water outputs from case three were evaporation and accumulation in dams (Osman, *et al*., 2013). This is similar to the case one where evaporative losses where a major cause of water loss. However, it differs to the current study as shown in Table 5, where the main water outflows were the effluent discharge (44.84%) and the discharge to the Municipal System, which included the condensate discharge sewer (50.88%). Evaporative losses only account for 3.87% of the water outflow. This could point to a difference in the general operating of a base metals refinery and a platinum refinery, where a general base metals refinery might have more evaporative losses due to have greater water storage facilities; however this statement cannot be validated until further studies have been done on platinum refineries; after all this difference could mainly be a difference that exists between these two particular case studies.

The reuse and recycle efficiencies were found using the operational model. Case two found the reuse efficiency to be 88% and the recycle efficiency to be 0% as there were no treatment plants onsite (Haggard, 2015). This is somewhat similar to operational efficiencies shown in Table 8, where the recycle efficiency was 0% due to the absence of an onsite water treatment plant; the reuse efficiency was found to be 49.67%, about 50%. From here it would see that mine in case two uses water more efficiently that the platinum PMR in this study; however it must be noted that study focus of case two only considered a couple of process steps and units and the mining step was excluded, whereas this study considered the entire platinum PMR.

5.5 Comparison of the general water mass balance to water accounting methods

The general water mass balance which functions on the basis of the volume of water entering the system should be equal to the volume of water exiting the system was the starting point of this study. This mass balance was then used in both the WAF and WFN methods. The traditional water mass balance is often considered a sufficient evaluation of water usage in a process and hence water usage evaluation of a process by other water accounting methods which are also based on water mass balances might be considered unnecessary.

This however might only hold true in certain circumstances as both the WAF and WFN methods were used equally along with the mass balance to complete this study. The WAF method was used to complete the water mass balance in terms of indirect water inputs and outputs of the system, such as through the calculation of the volume of water gained by the PMR through precipitation and rainfall runoff and the volume of water lost by the PMR through evaporation. These values were calculated using methods outlined in the WAF. There are other methods available to calculate these amounts such as the volume of captured rainfall etc.; however the ease of calculation provided by the WAF was helpful.

Both the WAF and WFN method helped to provide additional information about water usage in the PMR that went beyond the water quantities provided by the mass balance.

By providing water quality categories to each of the sources of the inputs and the destinations of the outputs, the WAF was able to give an indication of the quality of the water associated with each water quantity in the input-output statement. Through the accuracy statement, the WAF gave an indication of the reliability of the results presented by the report and the areas which could be improved upon to increase the precision of results and hence the reliability of the report. This is information that cannot be gained from the general mass balance even if each of the inputs and outputs of the system is known. The statement of operational efficiencies provides knowledge of onsite water usage and efficiency through the onsite reuse and recycles efficiencies. Although, the volume of internal water flows can be calculated from the mass balance, the WAF was needed to calculate reuse and recycle efficiency.

The WFN method provides an indication of different areas of water usage in the process through the three component water footprints. Each water footprint focuses on a water usage for a specific purpose, based on where the water comes from, how the water enters the site and how it is utilised by the site and how water exits the site. It is this classification of water that allows for the contextualisation of water usage in the process which is not easily obtainable from the mass balance. This study only had a blue water footprint, however due to the WFN method; the blue water footprint could be broken up into components, assisting in contextualising of water usage in the PMR.

Hence a general mass balance, although a good starting point for evaluating water usage in a process should be used alongside water accounting methods to gain greater understanding of water usage, quality and efficiency in the process.

Chapter 6 RECOMMENDATIONS

The water (or at least a portion of the water) from the discharge condensate sewer could be used by the boiler instead of being released into the Municipal System. This water will eventually be heated up in the boiler during which the small amount of impurities present in water will be removed before the water is released to the other units from the boiler.

The main recommendation is to reuse the water that goes to the condensate discharge sewer for the boiler. If the required water is routed back to the boiler, then 30% less freshwater from Potable 1 will be required by the boiler. It should be noted that Potable 1 was the main water inflow into PMR, amounting to 85.26% of the total water into the PMR and that the boiler is the biggest water consumer in the PMR.

This recommendation will decrease the total blue water footprint to 36420.33 m^3/year and the total product water footprint will decrease to 0.89 m^3/kg, which amounts to a 25.8% to 26% decrease in the blue water footprint and the total product water footprint.

The amount of water required from Potable 1 will be decreased by the recommendation mentioned above. This will have financial implications. The cost of the new lesser amount of water from Potable 1, if the recommendation is considered will be ZAR 303097.17. Hence ZAR 130457.12 is saved.

Once the water from the condensate discharge is routed back to the boiler, there still remains 27% of the water from the condensate discharge sewer. This water can be reused somewhere else in the PMR. However, the decision on whether or not to treat the water should be made accordingly depending on the purpose for its reuse in the PMR in order to avoid any water quality issues. As previously stated Potable 2 only accounted for about 2% of the water entering the PMR. Hence the remaining water from the condensate discharge can be used to supply water to some of the utilities supported by Potable 2. This used water can be readily employed by the fire suppression services and the ancillary supported by Potable 2. However, utilities such as the change house, support services, emergency services and security cannot consume used water directly from the condensate discharge sewer due to health concerns unless the water has been treated. The water here would have to be treated and brought to a level for human consumption before it can be used again. The cost of treating water for utilities that require an insignificant amount of water relative to the water consumed by the entire PMR should be weighed in terms of viability; cost is always a factor and the cost of water treatment should be weighed against the cost of water disposal here.

Precipitation and rainfall runoff water was the second biggest contributor of water into the system and was 12.71% of the total water as shown in Table 4; this water goes to the storm water storage tanks. About 67% of the water from the storm water storage tank goes to the Effluent Management (acid) and 33% goes to the Effluent Management (alkaline). The storm water storage tank has more water than is required by the chemical tanks. The remaining water in the storm water tanks can be used elsewhere in the PMR.

Amendments need to be made to the current WFN method with regards to the grey water footprint as to make allowance for the effluent that is generated by the processes carried out in the PMR, but has been discounted as part of the grey water footprint as the effluent despite being created by the PMR was not treated or discharged by the PMR. The restrictions present in the current definition of the grey water footprint limited the ability of this study to provide a realistic depiction of the PMR in terms of waste water generation.

This study was limited to the minimisation of water usage in platinum PMR and further investigation into water related impacts was not considered. Hence a follow up study to this research, should be to investigate the effects that the PMR has on surrounding water sources in the area, this would form part of a sustainability evaluation, specifically in terms of water for the PMR.

If this study is repeated or if similar studies are carried out on the same platinum PMR, than more measured flowrate data should be made available i.e. the number of relevant flowmeters at the PMR should be increased and the precise size of some of the units should be made known so that some of the values in the mass balance and hence the input-output statement would not need to be estimated. The accuracy statement in Table 9 shows that more than half the streams were estimated at a medium confidence, 56%; improvement of measured data more analysis will increase the overall accuracy of the results of the study.

During the course of this study, no other water intensity and minimisation study carried out on a platinum refinery in terms of the chosen water accounting methods were found and hence comparison was not possible. More water usage and water management studies should be carried out at platinum refineries, especially in terms of water accounting methods, preferably the WAF and WFN methods to allow for accessible and consistent comparison of water management across platinum refineries and hence increased water minimisation across the board. These studies should be carried out across the globe where applicable; however emphasis should be placed on carrying out these studies in South Africa where majority of the world platinum is located.

A study which focussed on resource intensities particularly with regard to platinum mines in South Africa, found that the extent of water consumption for the production of PGMs falls within range of the water consumption required for the production of various metals. It argued that many metal ores have to undergo similar processes of grinding and flotation in order to produce concentrates and thus it is expected that the water consumption for PGM production and for that of other metals would be the same.

The study also found that while energy costs of PGM production have increased considerably over time, the water costs of PGM production have only increased marginally over time. This implies that the amount of energy required to produce PGMs has been amplified over the years, whilst the quantity of water consumed to produce PGMs has remained relatively unchanged. The study deliberates that the increase in energy costs are probably linked to the increasing depth of platinum mines. Hence the study concludes total energy consumption will largely be a function of platinum production more than any other resource (Mudd & Glaister, 2009). Also water intensity for platinum and other metal production seem to be similar; hence energy intensity is the factor that might distinguish platinum production from all other metal production. This implies that energy intensity is of greater importance than water intensity when considering platinum production. Thus the final recommendation of this research paper would be that more focus should be place on energy related research than on water related research with regards to the platinum production process.

“We forget that the water cycle and the life cycle are one.” ***Jacques Cousteau***

Chapter 7 CONCLUSION

South Africa's abundance in platinum resources increases the significance of sustainable water usage in all platinum related operations, including platinum precious metal refineries (PMR). As platinum refineries do not consume as much water as other operations involved in platinum recovery, such as platinum mining, it has been relatively ignored in the water minimisation process. However, platinum refineries do consume a fair amount of water and hence appropriate and ecological usage of this water is necessary.

Two water accounting methods, namely the Water Accounting Framework (WAF) and the Water Footprint Network (WFN) method, along with a general water mass balance were used to evaluate water usage and to identify high water consumption areas in the South African platinum PMR.

The WAF generated three important reports which provided insight on the water consumption in the PMR. The input-output statement found the total water inputs into the PMR to be 48.51 ML/year and the total volume of water outputs from the PMR to be 48.23 ML/year. The statement of operational efficiencies found the internal water reuse efficiency to be about 50% and the accuracy statement showed that 44% of the water flowrates used in the study were measured at a high confidence level and the other 56% were estimated at a medium confidence level.

The WFN method found the total water footprint was equivalent to the blue water and was valued at 49086.07 m^3/year or 49.09 ML water/year and was comparable with WAF results. The total product water footprint was 1.20 m^3/kg PGM. The product water footprint for the platinum PMR was considerably smaller when compared to the water footprint of platinum mining operations. The total product water footprint for the platinum PMR was greater than that of the product footprints for base metal refineries. During the duration of this study, no other water intensity study using similar water accounting methods on a platinum refinery was found and hence comparison to another platinum refinery was not possible. Both the WAF and WFN methods were compared in terms of technical and non-technical aspects and both had different advantages and disadvantages. The appropriate use of one method over the other would be circumstantial and depend heavily on the purpose of the user. Although both methods provide invaluable in evaluating processes in terms of water usage, both methods have little to offer in terms of water related impacts.

Taking viable recommendations taken into consideration, mainly the reuse of wastewater in other parts of the PMR, theoretically allowed for a 25% reduction of the total product water footprint.

"No water, no life. No blue, no green." ***Sylvia Earle***

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APPENDIX A: Rainfall and evaporation data

Table showing rainfall data provided by the PMR from Month 1 to Month 12

12 Month Period	**Rainfall (mm)**
Month 1	71
Month 2	92
Month 3	105
Month 4	96.5
Month 5	59
Month 6	69.5
Month 7	42
Month 8	2
Month 9	1.5
Month 10	11.8
Month 11	0
Month 12	78.5
Total	**628.8**

Table showing evaporation data provided by the South African Department of Water and Sanitation from Month 1 to Month 12

12 Month Period	**Evaporation (mm)**
Month 1	155.83
Month 2	214.8
Month 3	156.77
Month 4	151.83
Month 5	128.47
Month 6	114.37
Month 7	178.1
Month 8	101.08
Month 9	104.83
Month 10	111.33
Month 11	119.83
Month 12	124.83
Total	**1662.07**

APPENDIX B: Conference Paper

A Review of Methods for the Quantification of Water Use in South African Mines

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South Africa's abundance of mineral resources has led to extensive mining activity across the country. However, the country's water resources are limited, with water shortages intensifying due to increased urbanization, poor water infrastructure and climate change. As such, water management becomes important in the mining sector. Improved water management is not only necessary for the sustainable use of water; it also allows mining corporations to cut costs, enabling them to maintain a competitive edge against rival corporations and also to remain within legal environmental boundaries. Improved water management is possible only if water usage can be accurately accounted for.

The collection and dissemination of useful water-related information is difficult and complex; particularly in the mining industry. Various water accounting methods have been developed to provide guidelines for estimating water usage. Some of the most common methods include the Water Footprint method, the Water Accounting Framework and Life Cycle Assessment. In this paper, these methods are compared in terms of their weaknesses and their strengths, particularly in the mining industry, to establish which circumstances and/or situations will warrant the appropriate use of each method.

Water Footprint measures the total volume of fresh water consumed, both directly and indirectly, to produce a product. The complete footprint is sum of three component footprints. Life Cycle Assessment is the quantification of environmental impacts that occur due to the production of the product. Water Accounting Framework is a data publication method that provides a general standard format for corporations to release their water use data.

INTRODUCTION

Hydrometallurgy Conference 2016: Sustainable Hydrometallurgical Extraction of Metals
Cape Town, 1–3 August 2016
Southern African Institute of Mining and Metallurgy

Water is an indispensable part of our daily lives. We require water for drinking, basic hygiene and food production. Water is integral to the functioning of ecosystems, and necessary for the continued biodiversity of our environment on which our survival is based. Water also plays a key role in the financial sector, not only forming the basis for food production, but also the production of manufactured goods and services, and also takes part in the trading of these products (Koehler, 2008).

Globally, the world is experiencing increasing fresh water shortages, threatening the wellbeing of all. Approximately 70% of the fresh water resources around the world are used for agricultural activities, responsible for food production. The increase in fresh water shortages places a strain on food production, thus putting food security at risk and presenting health issues, such as malnutrition. The need to find fresh water for agricultural purposes leads to the exploitation of other existing water resources, such as surface and groundwater resources. The depletion of these resources further intensifies water scarcity. Increasing urbanization and infrastructure requirements are a permanent reality of the modern world, leading to a general rise in industrial activity and to competition for available water resources used in other sectors, such as the agricultural and mining sectors. Additionally, the effects of climate change are becoming prominent. Climate change increases water scarcity by changing rainfall patterns and causing long droughts and elevated evaporation. All-round population growth continues to increase rapidly, placing further strain on existing water resources (Koehler, 2008).

The Water Crisis in South Africa

South Africa is not exempt from the water crisis facing the rest of the world. With a rapidly growing economy, South Africa is becoming even more susceptible to the consequences of water scarcity, a situation that is further intensified by rapid population growth, increased urbanization, lack of water infrastructure, poor water management techniques and climate change. The natural climate of the country also adversely affects the already dire water situation. South Africa is located within a semi-arid, water-stressed region and has a low average annual rainfall that is much below the global average annual rainfall (Ranchod, *et al.*, 2015).

South Africa is facing an abundance of mineral resources on one hand and limited water resources on the other. This makes mining both a lucrative and taxing economic sector. Although only 3% of South Africa's water resources are invested in the mining sector (Haggard, *et al.*, 2015), the country is said to be the fifth largest mineral producer in the world (Ranchod, *et al.*, 2015). South Africa, being one of the largest mineral producers in the world, even the small percentage of water invested the mining sector represents a huge consumption of water.

The mining industry cannot simply be disregarded, because it is considered as one of the most lucrative sectors in the country, without jeopardizing the livelihood of the entire nation (Ranchod, *et al.*, 2015). Despite being such a profitable sector, the effect of the mining industry on existing fresh water resources is adverse. Mining not only decreases the available water resources, but also causes a decline in the quality of the remaining water resources (Haggard, *et al.*, 2015).

The deterioration of existing water resources is not only a threat to human health and the environment, but also poses a threat to the continuation of the mining industry and hence to the progress of the economy (Haggard, *et al.*, 2015). Water is crucial for the functioning of any mine, playing a key role in both small and large processes. Severe water shortages will bring the mining sector to a standstill and adversely affect the economy. It is thus imperative to reduce the amount of water used in mining processes. Improved water management is essential to reduce the amount of water consumed in mines (MCA , 2012).

The Importance of Effective Water Management

A decrease in water consumption will enable mining corporations to remain within legal environmental boundaries, and the decrease in expenditure will allow corporations to maintain a competitive edge against rivals mining corporations (Morrison, *et al.*, 2010).

In order to manage the water used by mining processes, it is imperative to first understand how water is consumed in various mining operations. The use of water in mining operations is complex, multi-layered, and very subtle and hence it is not a simple task understand its utilization. The collection and dissemination of meaningful water-related information is challenging and complex in any process, more so in mining operations, which include numerous intricate steps. Fortunately, various water accounting methods have been recently developed to assist in this rather tedious task. These methods provide guidelines needed for estimating the amount of water used in a process and/or to produce a product or service. Some of the most common and widely used methods include the Water Footprint (WF) method, the Water Accounting Framework (WAF) and Life Cycle Assessment (LCA) (Morrison, *et al.*, 2010).

This paper provides a comparison between the three abovementioned water accounting methods in terms of their weaknesses and their strengths, focusing on their application in the mining industry, although these methods can be applied to any process that uses water. The comparison is used to establish which circumstances and/or situations warrant the appropriate use of each method. The methods are firstly compared in terms of definition, scope and structure and output; and are then compared in terms of interpretation and response to water usage and impact of the operation or process. Lastly, these methods are compared in their ability to convey results to corporate and business management.

WATER ACCOUNTING METHODS

Water accounting methods have proven to be effective and efficient in the estimation of the usage of water in numerous operations processes, especially in complex mining operations.

The three water accounting methods previously mentioned are all based on the concept of a water balance over the entire operation or process. A basic water balance operates on the principle that all the water entering the process is equivalent to all the water exiting. However, the change in the mass of water over time also needs to be considered. The change in the mass of water with time is equivalent to the sum of all the streams of water entering and exiting the operation. The above can be illustrated by the following equation:

$$\text{Mass In}_{\text{water}} - \text{Mass Out}_{\text{water}} = \Delta(\text{Stored}_{\text{water}} - \text{Losses}_{\text{water}}) \qquad [1]$$

Water Footprint Method

The WF method calculates the volume of fresh water used both directly and indirectly in an operation. The complete water footprint of an operation is the sum of three separately calculated components; namely, the blue, green and grey water footprints, which are defined below. The WF method has two main aims. The first is to quantify both the direct and indirect water usage across an operation. After the areas of excess water consumption have been identified, the second aim is to reduce the consumption of water in the identified areas (Hoekstra, *et al.*, 2011). The three components of the WF are defined as follows.

The **blue water footprint** refers to the volume of ground or surface water that is consumed during a process or the production of a product or a service, from evaporation through incorporation of water into the product and to when consumed water is not returned to the source or during the same time period (Hoekstra, *et al.*, 2011):

$$\text{Blue Water Footprint }\left[\frac{\text{volume}}{\text{time}}\right] = \text{Blue Water Evaporation} + \text{Blue Water Incorporation} + \text{Lost Return Flow} \qquad [2]$$

Lost return flow refers to water that is consumed and not returned to the same area or returned at another time.

The **green water footprint** refers to the amount of rainwater consumed in a process or in the production of a product or service, which could have been stored in the soil or in the topsoil temporarily and used for evapotranspiration by plants (Hoekstra, *et al.*, 2011):

$$\text{Green Water Footprint }\left[\frac{\text{volume}}{\text{time}}\right] = \text{Green Water Evaporation } + \text{Green Water Incorporation} \qquad [3]$$

The **grey water footprint** of a process refers to the volume of clean water that is required to dilute the wastewater stream before it is released back into the natural water body, ensuring that the wastewater stream does not degrade the ambient quality of the water body and/or that the legal requirements of the water body are met (Hoekstra, *et al.*, 2011):

$$\text{Grey Water Footprint }\left[\frac{\text{volume}}{\text{time}}\right] = \frac{\text{L}}{\text{C}_{\text{max}} - \text{C}_{\text{natural}}} \qquad [4]$$

where L is the pollutant load (mass/time); C_{max} is the ambient water quality standard for the pollutant (mass/volume); $C_{natural}$ is the natural concentration in the receiving natural water body (mass/volume).

Hence, the total water footprint for a process, product or service is calculated as follows:

$$\text{Total Water Footprint }\left[\frac{\text{volume}}{\text{time}}\right] = \text{Blue Water Footprint} + \text{Green Water Footprint} + \text{Grey Water Footprint} \qquad [5]$$

The WF method involves four main steps, which have to be followed in sequence (Hoekstra, *et al.*, 2011):

1. Setting goals and scope;
2. Performing an account of the water footprint;
3. Completing a sustainability assessment ;
4. A response formulation.

The decisions made during the 'Setting goals and scope' step of the WF have the greatest overall impact on the water footprint account. Decisions on what to include and exclude in the water footprint, and hence the assumptions on which the entire water footprint is based, are made in this step. During the 'Performing an account of the water footprint' step, the actual water balance is carried out in accordance with the assumptions made in the previous step. Water consumption is classified into blue, green and grey, as outlined in the definitions above. Water is separated into type, quality and resource. When 'Completing the sustainability assessment', the final water footprint is assessed and evaluated to determine if water usage in the operation or process is sustainable or not. In short, the effect of the entire operation on the local environment and community is evaluated. The 'Response formulation' includes the reaction and response to the calculated water footprint. Recommendations are made on how to reduce the amount of water consumed by the process so that the effects of the operation on local water resources and pollution are lessened. The viability of each suggestion is considered. This step also involves the finalization of reliable methods, a reasonable time frame and suitable people to carry out these suggestions (Hoekstra, *et al*., 2011).

Water Accounting Framework Model (Water Miner Tool)

The Water Miner Tool is a colloquial term used to refer to the WAF. Essentially, the WAF is used to measure, monitor, analyse, record and report information related to on-site water usage of the operation (ChemTech, 2012). The WAF provides a platform by which the on-site water management of various operations can be compiled and compared in an efficient manner. The final result of the WAF is easily available because the results are shown in the form of a water balance. This water balance clearly highlights the most important information pertaining to the process or operation, including water inputs and water outputs, water shortage, water losses and water accumulation. This information is readily accessible on an online central database for all to compare their on-site water behaviour to similar and/or different processes or operations (MCA , 2012).

The WAF also consists of four main components, which take the form of four main reports (MCA , 2012):

1. The input-output statement or model;
2. The statement of operational efficiencies;
3. The accuracy statement;
4. The contextual statement.

The input–output statement includes all the water inputs, outputs and water diversions between the site boundary and the local environment. It provides a detailed summary of the flow of water between the site boundary and the environment. The statement of operational efficiencies showcases the internal on-site water flows, which is basically the flow of water from the on-site water storage facilities to the water utilization and treatment points (Osman, *et al*., 2013).

The accuracy statement attempts to illustrate the precision of the WAF by providing a list illustrating which of the water flows in the WAF results are measured, calculated or estimated. This report is generally used in conjunction with the input–output statement to gauge the overall accuracy of the WAF results. The contextual statement, as the name suggests, places the entire process or operation in context by providing information of the placement and location of the operation or process, such as the local water resources in the surrounding regions (catchments, etc.) (MCA , 2012).

Life Cycle Assessment

The LCA evaluates the full environmental impact of any operation over the entire life cycle of the operation. However, it is not necessary for the results of the LCA to be reported for the entire system. The results for just a portion or a specific part of a system can be given if that is required (Morrison, *et al.*, 2010). To ensure that the results obtained from the LCA calculations are of good quality and are consistent, the LCA is performed within a framework. This framework involves a set of standards that are defined by ISO (International Organization for Standardization) 14040 (Harding, 2011).

There are four main stages involved in the LCA. The LCA is iterative in nature because these four steps do not have to be followed in sequence. It is valid to return to a previous stage once the interpretation stage is completed (ChemTech, 2012):

1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Interpretation.

The purpose of the LCA is decided upon in the goal and scope definition; essentially, what is to be investigated by the LCA and the goals and range of the LCA are finalized (Berger & Finkbeiner, 2010). Depending on the detail required by the LCA study, a functional unit for the investigation is defined (Harding, 2011).

The inventory analysis involves the mass and energy balance for the entire operation. The balance includes the entire life cycle of the operation, from the raw materials in the beginning to the disposal or final use of these materials. It also includes all the emissions (water, air or solids) that occur as the operation progresses. A variety of values are included in this balance, from economic values, such as goods and services, to environmental values, like emissions and resources. An inventory table is then constructed, which comprises the conversion of all the mass and energy balance values to values that are relative to the functional unit defined earlier. These new values are generally mass values. The impact assessment is a complex step involving the conversion of the mass inventory table numbers to representative values. The representative values are easier to manage because they are fewer. The step includes three smaller steps: classification, characterization or normalization and valuation. The values in the inventory table are categorized according to an environmental problem during the classification step. A single material value in the inventory table can contribute to more than one environmental problem. Each value is then classified into a category and given a weighing factor; these are presented as various chemicals and are dependent on the impact that each value has in that category. This is done in the characterization or normalization part of the step. In the final part, the valuation part, the characterization values are converted to a single value to obtain the final LCA values. These values are found when the amount of material in each step is multiplied by a weighting factor for each material (Harding, 2011).

Interpretation and questioning of the results occurs in the interpretation stage. The interpretation stage can actually be carried out after each of the previous stages, to check the quality of the results at each stage. This process gives the LCA its iterative nature and also allows for continuous improvement of results throughout the entire LCA process (Berger & Finkbeiner, 2010).

The above illustrates the basic outline of the LCA method. LCA was initially not designed to cater specifically for water usage quantification, but for other environmental sectors, and hence the measurements of water usage and water-related impacts are constantly undergoing development. A new standard was established, ISO 14046, which takes into account the quality of the water, the location of the water at each stage and the location where water use will end as well as the impact of water in that region (ISO, 2014). The development of water quantification methods within the LCA method, specifically at the inventory and impact assessment levels, was driven by the UNEP/SETAC (United Nations Environmental Programme/Society of Environmental Toxicology and Chemistry) Life Cycle Initiative (Berger & Finkbeiner, 2010). The UNEP/SETAC Life Cycle Initiative led to the creation of WULCA (Water Use in LCA) in 2007. WULCA is an international working group focused on water use assessment and water footprinting from a life cycle perspective. The main objective of WULCA is to provide users of methods adopted by WULCA with the ability to measure assess and compare the environmental performance of operations with regard to fresh water use within a comprehensive framework (WULCA, 2014).

One of the methods recommended by WULCA for water consumption impact assessment in LCA is AWARE (Available WAter REmaining), which is an extension of another method called AMD (Availability Minus Demand). AMD refers to the water available after demand water by humans and aquatic ecosystems has been met, and is calculated relative to the area/region under consideration. AWARE calculates the relative available water remaining per area (in a watershed) once the water demands of humans and aquatic ecosystems have been accounted for, and hence assesses the potential for water shortfalls for humans or ecosystems. The method is founded on the assumption that the smaller the quantity of water that remains available per area, the greater the likelihood that another user will be deprived of water. A basic outline of the steps followed in the AWARE method is (WULCA, 2014):

1. AMD is calculated relative to the area ($m^3/m^2 \cdot$ month);
2. AMD is normalized using the world average AMD, which is valued at 0.0136 $m^3/m^2 \cdot$ month;
3. The AMD result is inverted (1/AMD);
4. This factor (1/AMD) is multiplied by water consumption (inventory) to arrive at the water scarcity footprint (indicator for water scarcity footprint).

COMPARISON OF WATER ACCOUNTING METHODS

All three of the water accounting methods, the WF, WAF and the LCA, were compared in terms of their strengths and weaknesses to establish under which circumstances the use of each method is most appropriate.

Scope, Boundaries and Structure of Water Accounting Methods

The definitions of the three different methods, provided previously, are indicative of the scope and boundaries of each method. From the definitions, it can be seen that the WF method and the WAF are both water-specific, as all the calculations and results of both methods are focused on the usage of water. The WF method provides comprehensive measurements of water usage and/or water discharge. The WAF provides fairly accurate estimates of on-site water usage and efficiency. These two methods focus on water usage and efficiency and have very little to offer in terms water-related impacts.

LCA differs from the other methods in the sense that environmental evaluation in this method includes water, but is not limited to water, because the LCA evaluates many environmental resource uses and emissions. As previously stated, the LCA was not initially created to cater for water; however, big strides have been made recently in quantification of water usage and water-related impacts according to ISO 14046, which not only lays out guidelines for water assessments in the LCA, but also for conducting a stand-alone water footprint assessment, which does not have to be part of the LCA (ISO, 2014). Hence, the LCA provides a fairly decent measure of water usage as well as an assessment of its impacts.

The different structure of each method gives rise to various outputs and hence diverse means of conveying results. Due to the structure of the WF method, results are given in actual volumes in terms of the three smaller water footprint components, namely the blue, green and grey water footprints, which are later summed to give the volume of the total water footprint. The results of the WAF are expressed in terms of a water balance, namely the input–output statement, with the other three reports providing a detailed background for the results. The results are presented in a more complicated manner when using the LCA method, where results are expressed in weighted impacts across different impact categories. Also, with the advent of the AWARE method, the results are represented in terms of an indicator, which ranges from 0.1 to 100, with the value of unity corresponding to the world average value (WULCA, 2014). Hence, each method has a unique way of conveying results.

Strengths and Weaknesses of Water Accounting Methods

The scope, boundaries and structure (and hence outputs) of each method give rise to different strengths and weaknesses, which are discussed below.

Technical advantages and disadvantages of the WF method

The WF method provides a total water footprint, which can easily be divided into the three component water footprints. Each component provides information about different areas of water usage in the operation or process (Haggard, *et al.*, 2015) and hence helps corporations to understand and contextualize their water use. As such, the WF method provides a good general overview of water usage for the entire operation. The WF method thus enables corporations to perceive their operation in 'the bigger scheme of things' and hence makes strategic planning easier, in terms of prioritizing certain actions and setting long-term goals and objectives (Morrison, *et al.*, 2010).

Generally, the WF method reports the final result as a single total water footprint of the operation or process. The blue, green and grey components are aggregated into one number (Ranchod, *et al.*, 2015). Many corporations find this result rather misleading and pointless because this single value is somewhat meaningless in providing understanding of the various effects of the entire operation (Morrison, *et al.*, 2010). Another point of contention with the WF method is the grey water footprint. The grey water footprint focuses only on the primary pollutant and calculates the theoretical volume of water needed to dilute the waste water stream so that it falls within regulatory standards. Many corporations feel that the grey water footprint should not be included with the other two footprints as the grey water footprint is a theoretical value and the other two are measured values, and the grey water footprint may not be a fair representation of the level of pollution in the waste water stream (Morrison, *et al.*, 2010).

Technical advantages and disadvantages of the WAF method

The WAF provides results in a very concise and precise manner and is hence useful in delivering the most basic evaluation of on-site water usage (Osman, *et al.*, 2013). This method can be considered invaluable if used as a first tier for evaluation of water usage in an operation. An additional advantage lies in the application of the method. The WAF is inexpensive and fast to use and no special expertise is required for application, hence adoption of the method will not add to the corporation's costs, nor will the corporation need to recruit new people (Morrison, *et al.*, 2010).

The WAF, although the simplest method to use, has some downfalls in terms of the nature of results that it conveys (Morrison, *et al.*, 2010). The WAF does not address water quality, only water quantity, nor does it convey risks related to water discharge. It provides no information directly on water-related impacts (SMI & MCA, 2012).

Technical advantages and disadvantages of the LCA method

The LCA method provides an evaluation of many environmental resources simultaneously and hence this method is irreplaceable for providing cross-media environmental assessments. The LCA is also the only one of the three methods that provides information not only about the quantity of water used, but also gives insight into water quality impacts based on sound scientific methods (Morrison, *et al.*, 2010). The WF approach to assessing water quality is mainly in terms of the grey water footprint, which deals with the dilution volume (Haggard, *et al.*, 2015). The traditional LCA method, however, assesses the quality of the water by directly measuring the mass or volume of the contaminants, and also accounts for one than one pollutant during assessment. Hence, the LCA is more reliable in regard to assessing the quality of the water used.

There have been promising developments with regard to the addition of new water assessments in the LCA method. The AWARE method, mentioned above, gives a good indication of the water scarcity and potential of water shortfalls in an area (WULCA, 2014). Although a valuable method, more detailed inventories and impact pathways need to be included to make this method more thorough, as different watercourses fulfil different functions. Another disadvantage is the high resolution of inventory data that is required for the application of this method, which is not possible to achieve at all times (Berger & Finkbeiner, 2010). This method is also fairly new and hence information on the method is not readily accessible nor easily understood.

Acceptance and ease of communication of each method

The level of establishment of each method in the environmental sector varies. This level of establishment will affect the degree of acceptance that each method receives from the environmental community. The WF method is well known and is relatively well established in the water management community at large; however, it has only recently been introduced to the private sector (Morrison, *et al.*, 2010). A desirable factor in the use of the WF method is that the results are easily understood by non-technical audiences, making the method conducive to discussion with business managers and hence increasing the acceptance of the method (Morrison, *et al*., 2010).

The WAF was conceptualized around 2005 and became fairly widespread around 2007. It is used in both the private and public sectors (SMI & MCA, 2012). This method does not require any expertise for application and the results can be understood by non-technical audiences. This method also provides a platform where corporations can efficiently and consistently compile and compare their water data (Morrison, *et al*., 2010). The WAF was also created to align with other well-known frameworks, such as the Global Reporting Initiative (GRI) and the Australian Water Accounting Standard (AWAS); hence results from the WAF method can be globally accepted and understood (SMI & MCA, 2012).

The LCA method is a very well established and accepted method for environmental assessments of entire operations. However, in recent years the use of water in LCA has been emphasized, with various new methodologies coming to the forefront. The mostly widely accepted and used are those adopted by WULCA. The LCA method, including the new water-focused methods in the LCA, uses mature scientifically-based methods for assessing the quantity and quality of water usage, as compared with the other two methods. However, the rigorous scientific nature of the LCA results makes them difficult to communicate to non-technical audiences, such as corporate management (Morrison, *et al*., 2010) .

APPLICATION OF WATER ACCOUNTING METHODS IN SOUTH AFRICAN MINES

The type of water accounting method employed by South African mines differs from mine to mine and usually caters for the water-specific needs of each mine. Sometimes, a mine can use more than one water accounting method for comparison of results and to gain a more extensive view of water usage on the mine (Morrison, *et al*., 2010). However, it is rare that a mine will publicly disclose the water accounting methods used or the results obtained (Incite, 2014). From the Carbon Disclosure Project (CDP) South African Water Report 2014, an initiative to drive the sustainable use of water in various economic sectors, including the mining sector was undertaken along with CDP's leading business partner, the National Business Initiative (NBI). The CDP reported that only 11 of the 15 mines that were invited to participate in the water programme agreed to participate, and that the level of participation between the mines differed. Although the participants used at least one of the water accounting methods referred to in this paper, the methods that were specifically employed by each participant were not disclosed (Incite, 2014).

CONCLUSION

The above discussion shows that all three water accounting methods have various strengths and weaknesses and that the use of one method will be more appropriate than the others under a certain set of circumstances. The WF method specializes in water usage assessments, although it does not have much to offer in terms of water impact evaluation. Hence, the WF method is most appropriate in situations where the focus is placed on water management, in terms of fresh water use and allocation, rather than the evaluation of water-related impacts. The WF also provides corporations with a general overview of the entire operation and results are easy to communicate to non-technical audiences; hence the WF is also suited for use when dealing with corporate management, especially for strategic planning purposes. The WAF is inexpensive, fast, and does not require any special expertise for application. It provides a platform where corporations can compile and compare their on-site water data in manner that is consistent, rigorous, and explicit. The WAF is most applicable for use when attempting to gauge the efficiency of on-site water usage. The WAF constitutes a good first tier for the understanding of on-site operations and for the screening of any major water risks. This method is most applicable for use by a corporation that desires a rough estimate of water usage in an operation, in a fast and economical manner, possibly in the primary stages of water usage evaluation; after which it is suggested that other methods can be employed to obtain a more in-depth analysis. The LCA provides information on both water usage and water-related impacts, with new water assessment techniques coming to the fore to evaluate the potential for water shortfall per area. Due to the high resolution of inventory data required by the LCA, the results are the most precise of all the methods, although acquiring these data can hinder the application of the method. LCA assessments have a strong scientific basis and are hence difficult to convey to non-technical audiences. Thus, the LCA method is most pertinent for use in cross-media environmental assessments and when assessing the impacts of various environmental resources.

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