Water footprint for a South African platinum mine

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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 in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

E Haggard.

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(Signature of candidate)

_______22______ day of ______________June________________ (year) ______2015______

ABSTRACT

The volume of water consumed by a platinum mine located in South Africa was quantified in two ways: (1) using WaterMiner software to complete the Water Accounting Framework (WAF), and (2) using the Water Footprint Network (WFN) method. The WAF was developed by the Minerals Council of Australia and the Sustainable Minerals Institute at the University of Queensland, and the WFN method was developed by Hoekstra *et al*. (2011). The process steps included in the study were, two concentrator plants, a smelter plant and a tailings dam. The mining step and the external water footprint associated with electricity and chemicals were not included. Flow rate, production rate and rainfall data were obtained from the mining company and average monthly historic evaporation rates was obtained from a South African Department of Water Affairs report (DWAF, 1985). Unknown flow rates around flotation plants, cyclones and thickeners were calculated by closing the mass balance and using densities and percent solids for flows out of this equipment. The measured flow rates, calculated flow rates, rainfall and evaporation data were entered into WaterMiner and the results used to complete the WAF. The measured flow rates, calculated flow rates, rainfall and evaporation data were used to calculate the water footprint for the operation.

When using the WAF, it was found that 12 686 ML/year of water was consumed, while the WFN method showed that 10 649 ML/year of blue water was consumed. The difference in the values calculated was due to the water inputs included in each method. The WAF included water entrained in ore and water obtained from third parties whereas the blue water footprint only included water consumed from surface or ground water sources. The yearly average total water footprint per kilogram of platinum group metal was 806 m^3/kg PGM. Of this, 228 m^3/kg PGM was blue water and 578 m^3/kg PGM was grey water. Concentrator plant 1 had the largest blue water footprint (124 m^3/kg PGM) and the tailings dam the smallest (4 m^3/kg PGM). The largest loss of water was through tailings dam evaporation.

Methods that could be implemented by the mining company to reduce the volume of water consumed on site may include covering the tailings dam to reduce evaporation or to add a pre-concentration step to concentrator plant 2. The blue water footprint can be reduced to 204 m^3/kg PGM (10% reduction) if the tailings dam is covered and evaporation is reduced.

The blue water footprint can be reduced to 216 m^3/kg PGM (5% reduction) if a pre-concentration step is included in concentrator plant 2.

DEDICATION

To my parents
Johannes Bernardus Haggard and Annalene Haggard
for their love and support.

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NOMENCLATURE

C	Concentration (g/ML)
EFR	Environmental flow requirement
f	Correction factor to convert measurements from pan evaporation to evaporation losses (dimensionless)
L	Pollution load (g/month)
m	Moisture content (dimensionless)
P	Ore processed (Mt/month)
Pan	Pan evaporation rate (mm/month)
Price	Price (R/kg)
R	Rainfall (mm/month)
SA	Surface area (ha)
t	Time
V	Volume (ML/month)
WA	Water availability (ML/month)
WF	Water footprint (ML/month)
WS	Water scarcity (dimensionless)
x	Catchment area (ha)

GREEK CHARACTERS

β	Rainfall to runoff factor (dimensionless)

SUBSCRIPTS

ent	Entrained
evap	Evaporated
incorp	Incorporation
lost	Lost return flow
rainfall	Rainfall
runoff	Runoff
max	Maximum

nat	Natural
proc	Process step
prod	Product
blue	Blue water
green	Green water
grey	Grey water

ACRONYMS

BIC	Bushveld Igneous Complex
CDP	Carbon Disclosure Project
COM	Chamber of Mines
CWiMI	Centre for Water in the Minerals Industry (at the University of Queensland)
DWAF	South African Department of Water Affairs
DMR	South African Department of Mineral Resources
GRI	Global Reporting Initiative
LCA	Life Cycle Assessment
M	Mine
MC	Mine and Concentrator
MCA	Minerals Council of Australia
MCS	Mine, Concentrator and Smelter
MCL	Mine, Concentrator and Leaching
MCSR	Mine, Concentrator, Smelter and Refinery
MCSL	Mine, Concentrator, Smelter and Leaching
MCSRL	Mine, Concentrator, Smelter, Refinery and Leaching
ML	Mine and Leaching
OP	Open Pit Mine
O/U	Open Pit and Underground Mine
PGM(s)	Platinum Group Metal(s)
SD	Standard Deviation
SMI	Sustainable Minerals Institute (University of Queensland)
Stats SA	Statistics South Africa
TDS	Total Dissolved Solids

UG	Underground Mine
UG2	Upper Group 2
UQ	University of Queensland
VWC	Virtual Water Content
WAF	Water Accounting Framework
WFN	Water Footprint Network
WWF	World Wildlife Fund

CHEMICALS

Ag	Silver
Au	Gold
Cu	Copper
FeS	Iron Sulphide
FeO	Iron (II) Oxide
Ir	Iridium
Mo	Molybdenum
Ni	Nickel
Os	Osmium
Pb	Lead
Pd	Palladium
Pt	Platinum
Rh	Rhodium
Ru	Ruthenium
SO_2	Sulphur Dioxide
U	Uranium
Zn	Zinc

Chapter 1 INTRODUCTION

1.1 Background

In South Africa during 2012, there were 1 579 mine sites (DMR, 2013a) extracting a wide variety of minerals (gold, platinum, coal, diamonds, copper, chrome, iron ore, manganese, and more). In 2012, the minerals industry generated 8.3% of South Africa's gross domestic product (GDP) (COM, 2013) and created 518 240 jobs (DMR, 2013a). The minerals industry also directly funded local community improvement projects (R 2.4 billion) and education (R 330.5 million spent on scholarships and bursaries and R 4.9 billion on learnership programs) (COM, 2013). This shows how important the minerals industry is in South Africa.

Mining products (coal, iron, nickel, copper, aluminium *etc.*) are a necessity for today's living standard (energy, cars, circuitry, computer, television *etc.*), but the effect of mining on the environment, especially water resources, can be severe. High quality water resources in South Africa (WWF, 2013) and in the rest of the world are declining. This is cause for concern, because water is a valuable natural resource, which is required in virtually all industrial and agricultural processes. Good quality water is also required for human consumption and for the sustenance of healthy ecosystems.

South Africa receives on average 500 mm of rainfall in a year. Taken across the surface area of the land, this equals to 611 billion m^3 per year, of which only 13.2 billion m^3 (2.1%) is useable (Stats SA, 2006). The global average renewable water resource is 8 210 m^3 per person per year, while in South Africa it is only 1 048 m^3/person/year (CDP, 2010). A country is considered to be water stressed if the renewable water resource is below 1 700 m^3/person/year, and water scarce if the renewable water resource is below 1 000 m^3/person/year (CDP, 2010). Therefore, South Africa is classified as a water stressed country, bordering on a water scarce country. This is cause for concern and measures should be taken to prevent further decrease of the renewable water resource.

In South Africa, the mining industry consumes 236 million m^3, this is 5% of the total water consumed in South Africa (Table 1). Compared to other industries in South Africa, the mining industry does not consume a great volume of water, but because of an increase in demand for mining products, as well as a decrease in ore grade, water usage is increasing (Mudd, 2008).

Table 1: Volume of water distributed to industries in South Africa during 2010 (Stats SA, 2012).

Type of consumer	**Volume (million m^3)**	**Percentage (%)**
Redistributors*	2 310	46
Agricultural users (farmers)	1 969	39
Households	308	6
Mining	236	5
Industry	119	2
Commercial users	93	2
Total water distributed	**5 035**	

* Water redistributors are water service providers (municipalities and water boards) that buy water from other water service providers to meet their own needs for distribution between consumers.

Mining activities can increase the concentration of metals, dissolved solids and salts present in surface and ground water resources, causing the water to become unusable by humans and ecosystems. Contamination of water resources means that there is less water available for human consumption and ecosystems, and that a large amount of capital has to be spent to increase the quality of contaminated water.

The National Business Initiative included a Water Disclosure Project as part of the Carbon Disclosure Project (CDP). Eight South African companies participated in the project, of which three were in the mining sector. According to the results of the project, 88% of South African companies taking part in the initiative have been negatively impacted by water shortages in the previous five years, compared to the global average of 39% (CDP, 2010). By reducing the volume of water required by the company's processes, recycling water or other measures, the dependence on fresh water resources can be reduced, and the negative effects of water shortages could be reduced.

The water requirements of the mining industry can also be reduced with the correct implementation and/or improvement of current mine water management strategies. Any reduction in mine water requirements will reduce the demand, and hence, pressure on current water resources. In order to reduce the water usage, an operation must first understand how water is used within the process: where does it originate, how much does it use, what are the return flows and their qualities? This can be achieved through calculating the volume of water consumed by the process.

Different methods are used to determine the volume of water required by an organisation, in a process or to manufacture a product. Two methods used to quantify water use are the Water Accounting Framework (WAF) and the Water Footprint Network (WFN) method. This information can be benchmarked with other (similar or dissimilar processes) to compare a specific operation's water use in order to understand if the operation is utilising the water resource efficiently. This could also be used to identify the specific areas in the production process where water is used inefficiently and strategies can be developed to reduce water usage for these areas.

During times of drought, water has to be divided between agricultural, domestic and industrial water use. When governments decide how to divide the water they have to take into consideration the water requirements of the different sectors and what the different sectors mean to the economy of the country or catchment. The industrial sector creates jobs and manufactures products that can be exported. The agricultural sector provides jobs, food and food products that can also be exported. Domestic water is used for human consumption and survival. When comparing water use from a purely financial point of view, a water financial value, which is the value of the products sold per cubic meter of water used during production (R/m^3), can be calculated for each product.

1.2 Study objectives

This study focused on calculating and reducing the impact of a South African platinum mine on local fresh water resources, by reducing the volume of fresh water consumed at the processing operation. Objectives set out for the investigation were:

- To calculate the volume of water consumed by the process – using both the WAF and the WFN methods;
- To assess the effect of the mining operation on the local water environment;
- To compare the volume of water used in similar mineral processing facilities;

- To recommend steps that could be taken to reduce the volume of fresh water required by the processing operation; and
- To compare the financial value of the volume of water consumed during platinum production to the volume of water consumed when producing agricultural products.

1.3 Research methodology

Using the WAF and the WFN methods, the water required by two concentrator plants, a smelter plant and a tailings dam for a platinum processing plant located in the North West province in South Africa was calculated. The monthly water account was calculated for a 12-month period from June 2012 until May 2013. The mining company supplied flow rate, rainfall and production data for the study, while average monthly historical evaporation data was obtained from a report of the South African Department of Water Affairs (DWAF, 1985). For the unknown flow rates, design criteria (densities and percentage solids) of flotation plants, cyclones and thickeners were used. Other unknown flow rates were calculated by closing the water balance. The volume of water used for the different process steps was calculated to identify which process steps consume the most water, and thus requires the most attention to reduce the water usage. The effect of the processing operation was then evaluated using water scarcity and environmental impact assessments as set out in the WFN method. Suggestions were made on how to reduce the volume of water consumed and new water use figures were calculated.

The WAF was developed for use in the Australian minerals industry; the method was chosen to evaluate the applicability of the framework in the South African minerals industry, due to similar climatic conditions and mines.

The WFN method was developed for, and has mostly been applied in, the agricultural sector. In the private sector the WFN method has been used to quantify the volume of water consumed in a process, company *etc*., compare water usage to similar projects, determine the risk posed by water shortages in supply chain and to plan for future expansions and sourcing supplies to ensure effect on the environment is as small as possible (Hastings & Pegram, 2012). At the time of writing, only three published case studies (Peña & Huijbregts, 2013, Osman *et al*., 2013 and Ranchod *et al*., 2013) could be found were the WFN method was applied in the mining industry. The WFN method was chosen to help expand the database for the WFN in the mining industry.

1.4 Structure of thesis

This thesis is broken into seven chapters. A short description of each is presented below:

Chapter 1: Introduction

Chapter 1 provides a description of South Africa's water resources and the effect of mining in South Africa. A brief description of the method followed during the investigation is also provided.

Chapter 2: Literature review

Chapter 2 contains the literature review where the two calculation methods, the WAF method and the WFN, are explained. Further, the origins of the methods are discussed and examples are provided.

Chapter 3: Method

This chapter describes the method used and assumptions made while calculating the volume of water consumed by the mining operation.

Chapter 4: Results

Chapter 4 contains the results of the water account, the effect of the mine on the environment and possible improvements to reduce the volume of water consumed by the mine.

Chapter 5: Discussion

The results are compared with similar mining operations. The applicability of the WAF and WFN method in South African mining is also discussed.

Chapter 6: Conclusion

The conclusion chapter summarises the main findings of this study.

Chapter 7: Recommendations

Recommendations for possible improvements on the mine are summarised and recommendations for further studies are made.

Chapter 2 LITERATURE REVIEW

2.1 Platinum background

2.1.1 Introduction

The Bushveld igneous complex (BIC), located in South Africa (Figure 1), is the largest platinum reserve in the world (Cramer, 2001). The BIC contains the Merensky reef, Upper group 2 (UG2) reef and the Plat reef (Cramer, 2001). These were first discovered in 1923 by Mr Adolf Erasmus at Naboomspruit (Hochreiter *et al.*, 1985) and in 1924, by Dr Hans Merensky on the farm, Maandagshoek, this deposit was later named the Merensky reef (Hochreiter *et al.*, 1985). Other countries producing platinum include Zimbabwe, America and Canada (Glaister & Mudd, 2010).

Platinum is not found alone but together with other metals and minerals. The precious metals found with platinum are known as the platinum-group metals (PGMs). The PGMs are: platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir), and osmium (Os) (Crundwell *et al.*, 2011). South Africa has 41 platinum mines and 96% of the world's PGMs reserve (DMR, 2013b). Together with coal, PGMs generate the most revenue of all commodities in South Africa (DMR, 2013b). In 2012, 30.4 ton (R 8 285 million) PGMs were sold locally and 210.9 ton (R 60 918 million) were exported (DMR, 2013b). In 2012 the platinum industry employed 197 847 people and spend R 34 409 million on salaries (DMR, 2013b). Table 2 shows the percentage of platinum use during 2012.

Table 2: Platinum use during 2012 (DMR, 2013b).

Use	**Percentage of total platinum use in 2012**
Auto catalyst	40.3
Jewellery	34.5
Investment (coins)	5.7
Other*	19.5

*Glass manufacturing, petroleum, medical, biomedical, *etc*.

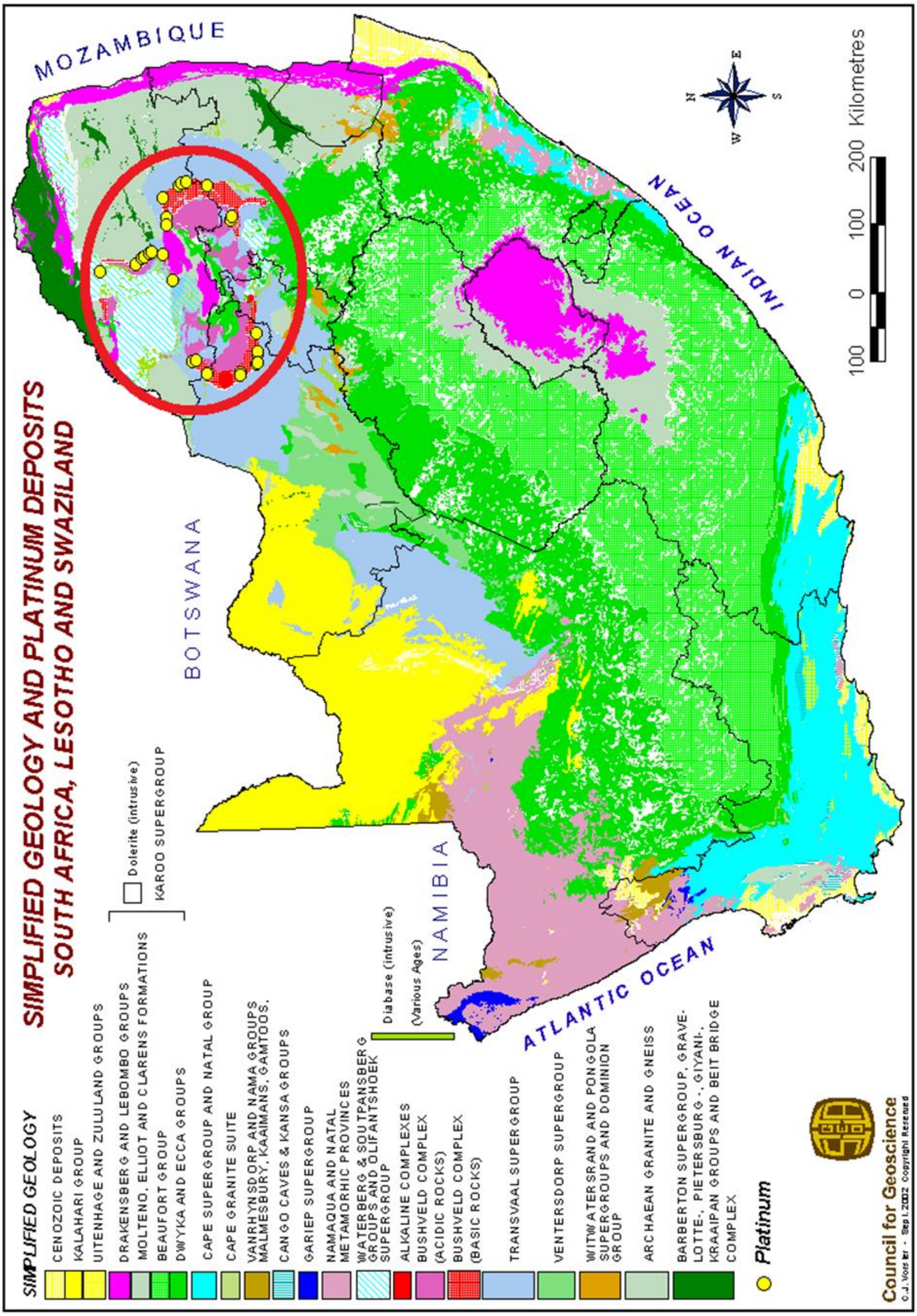

Figure 1: Map of South Africa showing location of the Bushveld ingeous complex (Council for Geosience, 2012)

2.2 Platinum processing

2.2.1 Introduction

Platinum ore is mined using underground or open cut techniques (Glaister & Mudd, 2010). The platinum ore is transported from the mine to the processing plant by conveyor, road or rail. The mined ore usually contains about 3-4 g PGM/t of ore (Crundwell *et al.*, 2011). The processing steps to extract platinum are concentrating, smelting and converting, base metal recovery and precious metal recovery. Each processes step increases the concentration of the PGMs. The concentrator, smelter and converter steps are discussed in more detail in this chapter, with a flow diagram shown in Figure 2. Due to differences in the UG2 and Merensky ore types, the ores are processed using the same steps but under different operating conditions.

2.2.2 Concentrator plant

During concentration, ore received from the mine is screened, crushed, milled and treated in a flotation cell. Crushing and milling is required to expose the metal sulphides and make it easier to remove from the waste rock during flotation. Water is added to the ore during milling to create a slurry and make transport of the ore easier. For Merensky ores, a ball mill or semi-autogenous mill can be used (Cramer, 2001). Hydro-cyclones are included between milling and flotation to separate the ore particles based on size, shape and density (Becker, 2008). The larger particles are recycled back to the mill feed and the smaller particles are transferred to flotation.

UG2 ore is high in chromite (Jones, 1999) and the smelter feed requires less than 3% chromite (Crundwell *et al.*, 2011) to prevent problems in the smelter. Chromite is dense and hydrophilic (Wessledijk, 1999 and Crundwel *et al.*, 2011) and is found in the overflow of flotation, due to entrainment (Crundwell *et al.*, 2011). The grinds in the primary autogenous mill and float step are kept coarse to prevent entrainment of the dense chromite particles (Crundwell *et al.*, 2011 and Cramer, 2001). The sulphide minerals form approximately 1% of the Merenksky ore and 0.4% of the UG2 ore (Crundwell *et al.*, 2011). The primary flotation concentrate contains the metals associated with sulphides (Leroy *et al.*, 2011). To ensure that the chromite content remains below required value, UG2 concentrator plants have more cleaning stages than Merensky concentrator plants to remove the extra chromite before the smelting process (Cramer, 2001). Merensky and UG2 flotation concentrates are processed in the same smelter and converter (Jones, 1999). The secondary UG2 mill can be a ball (Cramer, 2001) or tumbling mill (Becker, 2008) followed with a secondary flotation step (Cramer, 2001). The secondary flotation recovers PGMs found in silicates (Leroy *et al.*, 2011). Because the sulphide metal grains is smaller in UG2 than in Merensky ore, the UG2 final grinds have to be milled finer than Merensky final grinds (Cramer, 2001).

During flotation, reagents are added to the slurry to enhance or change the natural surface properties of the product and the waste material to allow separation (Wesseldijk *et al.*, 1999). The product (PGMs) is removed in the overflow of the flotation and further processed in the smelter plant, and the waste material is removed in the underflow of the flotation cell. Cyclones and thickeners are used to remove water from the underflow of the flotation. The water recovered from thickeners and cyclones can be reused within the process while the waste streams are sent to the tailings dam. The flotation concentrate contains 100-200 g PGM/t of ore (Crundwell *et al.*, 2011). For the UG2 and Merensky float operations, the same chemicals are used but at different quantities (Cramer, 2001) due to the difference in waste and product characteristics.

The reagents added during flotation include:

- **Collectors:** to increase the hydrophobicity of sulphide minerals to allow the minerals to form part of the overflow (Wesseldijk *et al.*, 1999). Collectors used include xanthates (sodium isobutyl, sodium-normal propyl and sodium ethyl) and dithiophosphates (ethyl, butyl and isobutyl) (Cramer, 2001).
- **Activators:** to increase the absorption of the collectors onto the sulphide minerals and increase the floatability of sulphide (Wesseldijk *et al.*, 1999). The activator chemicals that are typically used include copper sulphate (Cramer, 2001).
- **Depressants:** to prevent waste materials from entering the overflow. Chemicals used as depressants include guar reagents or carboxymethyl cellulose (Cramer, 2001).
- **Frothers:** to form stable bubbles. Frothers that are typically used include polyglycol ethers (Wiese *et al*., 2007).

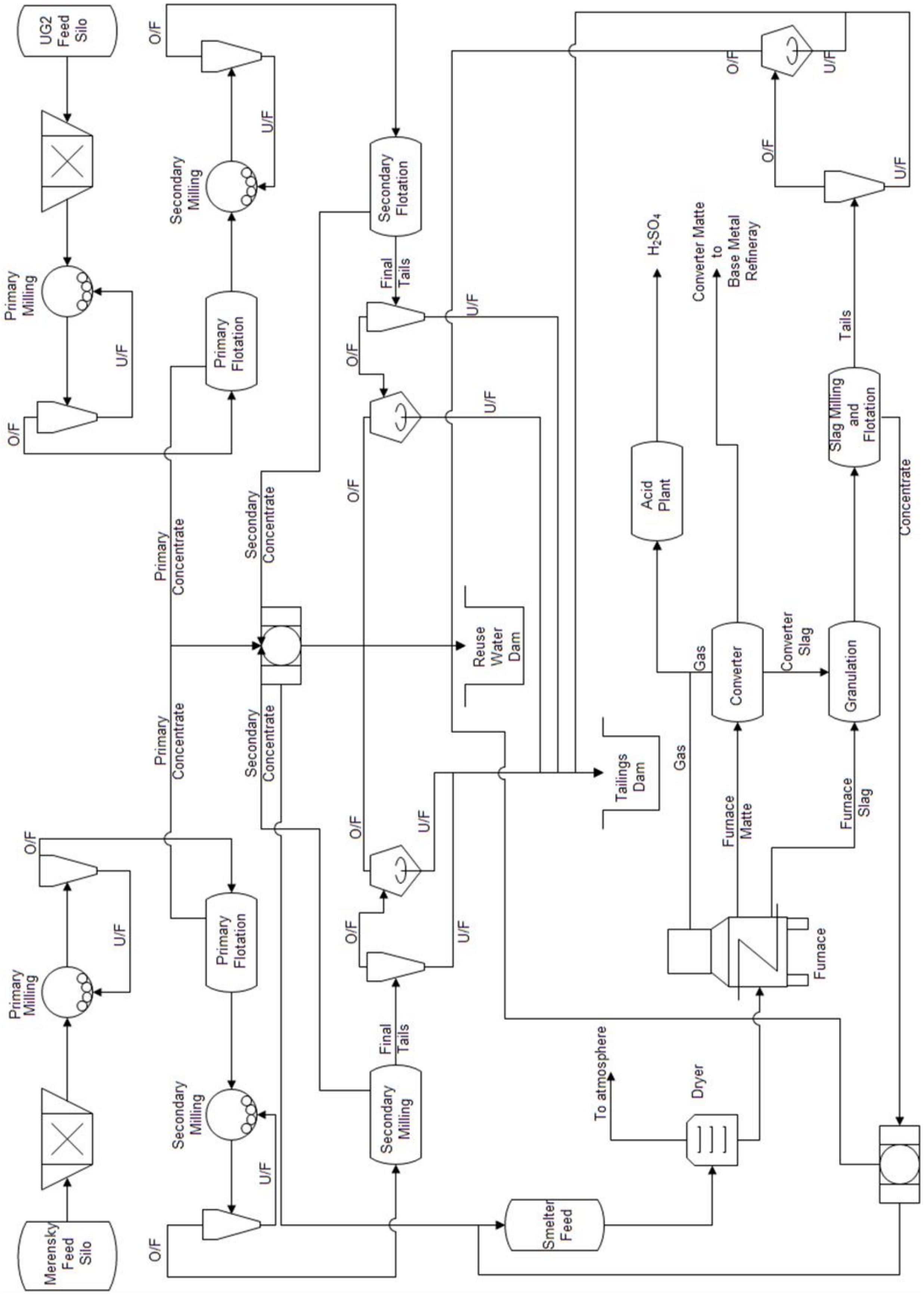

Figure 2: General process flow diagram for platinum concentrator and smelter (adapted from Crundwell *et al*., 2011, Cramer, 2001 and Hochreiter *et al.*, 1985).

2.2.3 Smelter plant

The steps involved in smelting and converting are drying, smelting and converting.

Drying

Prior to drying, water is removed from the flotation concentrate by using a thickener or filter and then either flash or spray dried (Cramer, 2001 and Jones, 1999). If spray drying is used in the smelter, the filtration step can be left out. The desired water content entering the smelter is less than 5% (Lidell *et al.*, 1986) as a higher water content can cause hydrogen explosions in electric furnaces. A dry concentrate also requires less energy in the furnace for smelting (Jones, 1999). During drying, water is returned to water stores and lost to the atmosphere.

Smelting

The dried concentrate is typically smelted in electric furnaces where it is separated into two liquid phases of different densities (Crundwell *et al.*, 2011). Burnt lime or limestone is added to increase the separation by reducing the melting point of the slag (Lidell *et al.*, 1986 and Cramer, 2001). The two liquid phases that form are the:

- Slag phase, containing the waste material; and
- Matte, containing the valuable metals, including the PGM, iron, nickel, copper and cobalt (Jones, 1999 and Liddel *et al.*, 1985).

The slag can be granulated and processed in a flotation plant to recover further PGMs or can be thrown away (Crundwell *et al.*, 2011 and Cramer, 2001), while the smelter matte (containing approximately 1000-2500 g PGM/t of ore) is further processed in the converter (Crundwell *et al.*, 2011).

Converter

The smelter matte is separated into a converter matte and converter slag. The iron sulphide (FeS) and sulphur contained in the smelter matte is oxidised to iron (II) oxide (FeO) and sulphur dioxide (SO_2) by blowing air over the smelter matte (Crundwell *et al.*, 2011, Nell, 2004 and Jones, 1999). The oxidised iron is found in the converter slag and the sulphur leaves the converter as a gas. The SO_2 is treated in a sulphuric acid plant (Cramer, 2001). The converter matte is low in iron, and sulphur but rich in PGM, nickel, copper and cobalt (Crundwell *et al.*, 2011 and Jones, 1999). Pierce Smith and Ausmelt converters are typically used for this process (Crundwell *et al.*, 2011). The converter slag can be sent back to the smelter to remove any PGM still contained in the slag (Lidell *et al.*, 1986 and Nell, 2004) or granulated, milled and floated (Jones, 1999 and Cramer, 2001). The converter matte is further treated in a base metal refinery.

2.3 Water accounting framework

The Water Accounting Framework (WAF) is a data publication method used within the Australian minerals industry. The method allows companies to publish water use figures in a consistent format to allow easy water use comparisons within the industry.

2.3.1 Development

Development of the WAF began in 2005 by the Minerals Council of Australia (MCA) and the Sustainable Minerals Institute (SMI) of the University of Queensland (UQ) (SMI & MCA, 2012). The WAF was developed to be consistent with the Global Reporting Initiative (GRI) and Australian Water Accounting Standard (SMI & MCA, 2012).

The GRI was established in 1997 to allow companies to report their economic, environmental and social performance in a consistent manner and allow them to be compared on a global scale (GRI, 2011). The protocol has 7 sections (GRI, 2011):

- The control, use and management of land;
- The contribution to national economic and social development;
- Community and stakeholder engagement;
- Labour relations;
- Environmental management;
- Relationships with artisanal and small-scale mining; and
- An integrated approach to minerals use.

The environmental section of the GRI describes the effect that the company's operation has on the local ecosystems, land, air and water. Water use is specified in 5 performance indicators (GRI, 2011):

- EN8: Total water withdrawal by source;
- EN9: Water sources significantly affected by withdrawal of water;
- EN10: Percentage and total volume of water recycled and reused;
- EN21: Total water discharge by quality and destination; and
- EN25: Describe water areas affected by water released by the company.

Three of the GRI water performance indicators are used by the WAF to create a report consisting of four statements. The EN8 and EN21 indicators are used to create an Input-Output statement which is a list of inputs and outputs, with flows, destination or source and quality (SMI & MCA, 2012). The EN10 indicator is used to create a statement of operational efficiencies. This statement provides the reuse and recycling efficiency; this can be used to estimate the dependence of the operation on water resources (SMI & MCA, 2012). In addition to the GRI indicator the WAF also has the accuracy statement and a contextual information statement. The accuracy statement states the percentage of flows measured, estimated or simulated and the level of confidence (SMI & MCA, 2012). The contextual information statement describes the area surrounding the mining operation and how the mining operation interacts with the surroundings (SMI & MCA, 2012).

2.3.2 WaterMiner

Development

The WaterMiner tool was developed by the Centre for Water in the Minerals Industry (CWIMI) at the University of Queensland. It is available via the internet and can be used to model water use of mineral processing sites. The results obtained can be used to complete the WAF. The results obtained can be used to improve water management on site. The user provides the program with flow rates between imports, exports, tasks, water stores and treatment plants. Tasks are activities on site where water is used, for example, dust suppression, tailings storage facility and ore processing (SMI & MCA, 2012). The

WaterMiner programme assumes steady state. The tool calculates the volume of water imported, exported, recycled and re-used (CWIMI, 2013). WaterMiner also provides a list of replacement flows, which suggests alternative sources and destinations for current flows. The list is used to identify all possible water sources available for an object and all possible water resources to where the water can be transferred (Tobin, 2011). A table of additional replacement flows are also given. This lists water flows that can be used in addition to the water flows already on site (Tobin, 2011).

Example

Tobin (2011) used WaterMiner to assess the water use of three Australian and one New Zealand gold mine: Newmont Jundee, Kalgoorlie Consolidated Gold Mine, Newmont Tanami and Newmont Waihi Gold (New Zealand). By implementing some of the recommended replacement flows, the mines would be able to save between 8 and 31% of freshwater used. Only Newmont Jundee is discussed in detail here. For a discussion of the other three sites, see Tobin (2011).

Newmont Jundee is a gold mine located approximately 1 150 km northeast of Perth and 50 km northeast of the Wiluna Township in the north eastern goldfields of Western Australia. A water management plan did not exist for the site. For the operation, the two tasks with the lowest reuse and recycling efficiency were found to be water used in the mine village and the tailings storage facility. When deciding which suggested water flows to implement, the following was taken into account: cyanide contamination, distances between water objects, and aquifer recharge. To increase recycling percentage at the Mine Village the following water flows suggested by WaterMiner were recommended:

- Water flow from Village Waste Water Treatment Plant to Jundee Process Water Dam (0.66 ML/year)
- Water flow from Village Waste Water Treatment Plant to Turkeys Nest (0.57 ML/year)

To increase reuse/recycling rates at the tailing storage facility the following water flows were suggested by WaterMiner in addition to current flows:

- Water flow from Tailing Storage Facility to Jundee Process Water Dam (168 ML/year)
- Water flow from Tailing Storage Facility to Seepage Recovery Bores (5 ML/year)

By creating a water management plan and implementing the flows mentioned above, the site could potentially reduce its water use by 175 ML/year (8.01%).

2.4 Water footprint method

2.4.1 Introduction

The water footprint of a product is the volume of fresh water consumed or polluted to produce the product. The volume of water consumed is quantified in the blue and green water footprints. Blue water is the volume of surface and ground water consumed and green water is the volume of rain water consumed. The grey water footprint is an indication of the volume of pollution caused by the product.

2.4.2 Development

The water footprint concept is based on the concepts of virtual water and ecological footprint (Hoekstra & Hung, 2002). The ecological footprint is the amount of land required to produce a product. The virtual water of a product is the total volume of water consumed during the entire production chain of the product. This includes direct and indirect water used during the production chain. This water is seen as being exported with the product in a virtual form. Virtual water does not mean that the amount of water is transported with the product, it is just an indication of the volume of water consumed in the country or area where the product was produced (Hoekstra & Hung, 2002). Countries can make informed decisions on which products to import and export based on the virtual water content (VWC) of products. Water scarce countries can import products with a high virtual water content and produce products with a small virtual water content (Hoekstra & Hung, 2002). The virtual water concept was introduced as a method to reduce the stress on global water resources. In this first study (Hoekstra & Hung, 2002), the water footprint for every country was calculated based on the amount of crops consumed with in the country and the volume of virtual water traded during international crop trade was calculated.

The water footprint of a country is defined as the water required to produce the products consumed within the country (some of which are imported) and not the products produced within the country (some of which are then exported). To quantify the water footprint of a country based on consumption and not production the water footprint is defined as (Hoekstra & Hung, 2002):

- the volume of domestic water used to produce the locally produced products consumed within the country; and
- the volume of virtual water associated with the production of products in other countries that is consumed in the country under study.

Initially, Hoekstra & Hung (2002) defined blue water use as water used from ground or surface water resources and green water used as the volume of rain water used during the production of crops. For this first estimate, water consumption referred to the volume of water consumed during evapotranspiration by the plants. This definition of water use was not considered ideal because crops do not always receive the required volume of water for evapotranspiration; at times the crops receive less water. It was also noted that water is also lost during supply to crops and water that is lost should also be included as water consumption. For this first estimation, domestic water use only included blue water (surface and ground water), and for virtual water imported, blue and green (rain water) water were included. Hoekstra & Hung (2002) defined water self-sufficiency of a country as the volume of domestic water used to produce products consumed within the country and water dependency as the volume of water used from other countries to produce the products consumed within the country.

Chapagain & Hoekstra (2003a, 2003b) calculated the VWC of live animals and animal products. This data was combined with the crop data from Hoekstra & Hung (2002) to determine the virtual water flows between nations. To determine the VWC of animal products, Chapagain & Hoekstra (2003a, 2003b) made a distinction between primary and secondary products. Primary products (meat, milk, leather *etc*.) being produced from the live animal and secondary products (cheese, butter *etc*.) produced from primary products. Product fraction was defined as the weight fraction of a product to the live animal in the case of primary products and for secondary products the product fraction is the weight fraction of the secondary product to the primary product. A value fraction was defined as the fraction of the financial value of a product to the financial value of all the products produced from the live animal or primary product. To calculate the VWC of a primary product it is necessary to know the VWC of the live animal and the processing water required to produce the primary product from the live animal. The sum of the VWC of a live animal and the process water is distributed over different primary products based on their value fraction. This volume of water is then divided by the product fraction of the primary product to get the virtual water content of the particular primary product. This study used the same definition for blue and green water and water self-sufficiency and water dependency as Hoekstra & Hung (2002). For the livestock study, water consumed included water used for drinking, servicing and the virtual water of the feed, for the crop consumed as feed the only water use was for evapotranspiration. The water footprint for livestock and livestock products is further discussed in section 2.4.3.

Chapagain & Hoekstra (2004) calculated the water footprints of nations by looking at water used for crop growth and producing crop products, animal growth and producing animal products and domestic and industrial water withdrawal. The internal water footprint of a country was defined as the volume of the country's water used to produce products consumed within the country and external water footprint of a country was defined as the volume of water used from another country to produce the products consumed within the country under study. This study used the top down approach when calculating a country's water footprint, where the volume of water used from the country is summed with the water used in other countries to produce the products consumed in the country under study. Another approach is the bottom up approach where the product consumed is multiplied with the VWC of the product at the site of production. The internal water footprint of a country is the sum of the water used for agriculture, industrial and domestic water, minus the virtual water exported with domestically produced products. Domestic and industrial water use is the volume of water withdrawn from the country's water resources. Agriculture water is the use of rain water that is stored in the soil (green water) and ground and surface water withdrawn that is used for irrigation (blue water). For the external water footprint, the imported products that were re-exported are not included. The authors mentioned that a decision has to be made whether irrigation losses should be included or excluded from the water footprints. In this study the water lost during transport or irrigation was excluded. It was suggested that the water should be excluded because it is returned to the water resource but should be included because it is not always returned to the same resource from which it was withdrawn, is lost through evaporation and could be polluted and thus not be available for reuse by another water user.

Chapagain *et al.* (2005, 2006) accounted for the effect of pollution by calculating the volume of water required to dilute the polluted streams returned to a water resource, to such an extent that the quality of the water remains below an agreed water quality standard. The study did not consider that some of the waste streams might be treated before being released into a water resource. It was suggested that the water required during treatment should also be included in the water footprint. The natural background concentration of the pollutants in the water resource was not taken into account when calculating the dilution volume required. This pollution volume was termed the grey water footprint by Hoekstra & Chapagain (2007). Chapagain *et al.* (2005, 2006) used the largest dilution volume required by a pollutant in a waste stream as the dilution volume required for the entire waste stream.

The water footprint method has mainly been applied for agricultural products. Mekonnen & Hoekstra (2011) calculated the global water footprint; including agriculture, industrial and domestic water use. The study found that 92% of the global water footprint is caused by agricultural activities. The large agricultural water footprint is likely the reason for the large amount of case studies in the agricultural sector. The study done by Mekonnen & Hoekstra (2011) is further discussed in section 2.4.3.

2.4.3 Examples for water footprint network

Table 3 summarises the main findings of the Water Footprint (WF) studies consulted. The only industrial case studies for companies and products include Tata in India, copper in Chile, nickel and copper in South Africa and platinum in South Africa.

Table 3: Water footprint network examples.

Reference	**Product**	**Location**	**Main findings**
Hoekstra & Hung, 2002	Crops	Global	Water footprint: 7 404 billion m^3/year (78% green, 12% blue and 10 % grey)
Chapagain & Hoekstra, 2003b	Livestock	Global	Water footprint: 2 422 Gm^3/year (87.2% green, 6.2% blue and 6.6% grey)
Chico *et al.*, 2013	Jeans	Spain	Cotton: 3 233 m^3/item Lyocell fibre: 454 m^3/item
Mekonnen & Hoekstra, 2011	Crops, Livestock and industrial	Global	Global water footprint: 9 087 Gm^3/year (74% green, 11% blue and 15% grey)
Unger *et al.*, 2013	Tata: Chemicals, Steel, Motors, Power	India	Blue: 29.9 million m^3/year Grey: 15.2 million m^3/year Green: 122 500 m^3/year
Peña & Huijbregts, 2013	Copper	Chile	Blue water footprint: Copper sulphide ore: 96 m^3/t copper Copper oxide ore: 40 m^3/t copper
Osman *et al.*, 2013	Base metal refinery, Nickel and Copper	South Africa	43.9 m^3/t of base metal
Ranchod *et al.*, 2014	Platinum	South Africa	Blue water footprint: 2 229x10^3 m^3/ton of refined platinum

Crop global water footprint

Hoekstra & Hung (2002) were the first to apply the water footprint concept to crops. Mekonnen & Hoekstra (2010a) improved on this study by calculating the blue, green and grey water footprint, adding products derived from crops and using more accurate data in the calculations. For the grey water footprint the concentration of the contaminants in the water resource was also taken into consideration. They calculated the global water footprint for crop production to be 7 404 billion m^3/year (78% green water, 12% blue water, 10% grey water). The total water footprint related to crop growth and crop products for South Africa is 44 565 Mm^3/year (Mekonnen & Hoekstra, 2010a). The blue water footprint is 6 412 Mm^3/year, green water footprint is 35 027 Mm^3/year and grey water footprint is 3 125 Mm^3/year (Mekonnen & Hoekstra, 2010a). The average rainfall in South Africa is 611 billion m^3/year (Stats SA, 2006). The global volume of water used to produce agricultural products is 1 112% more than the average rainfall in South Africa. The South African crop water footprint is 7.3% of the average rainfall in South Africa.

The crops with the largest total water footprint are wheat (1 827 m^3/t), rice (1 673 m^3/t) and maize (1 222 m^3/t). The countries with the largest crop water footprint are India (1 047 Gm^3/year), China (967 Gm^3/year), United States (826 Gm^3/year), Brazil (329 Gm^3/year), Russia (327 Gm^3/year) and Indonesia (318 Gm^3/year). The counties in arid regions had the highest blue water footprint. Irrigated crops had a lower global average consumptive water footprint (blue and green) per ton of crop than rain fed crops. The global average water footprint per ton of crop is: sugar (200 m^3/t), vegetables (300 m^3/t), roots and tubers (400 m^3/t), fruits (1 000 m^3/t), spices (7 000 m^3/t) and nuts (9 000 m^3/t).

Livestock global water footprint

Virtual water flows for livestock and livestock products was first calculated by Chapagain & Hoekstra (2003b). This study was improved by Mekonnen & Hoekstra (2010b) by calculating the blue, green and grey water footprints and using more accurate data and adding the water footprints for products produced from animals. For the grey water footprint the concentration of the contaminant in the water resource was also taken into account. The improved study used virtual water for crops calculated by Mekonnen & Hoekstra (2010a).

The global water footprint for animal production is 2 422 Gm^3/year (87.2% green, 6.2% blue, 6.6% grey). Water used for growing crops contributed to 98% of the water footprint. Drinking water accounted for 1.1%, services water accounted for 0.8% and water used for feed mixing accounted for 0.03% of the water footprint. The global average water footprint per ton of meat from beef cattle is the largest, at 15 400 m^3/t. For meat from other animals the water footprints are: sheep, 10 400 m^3/t, pig, 6 000 m^3/t, goat, 5 500 m^3/t and chicken, 4 300 m^3/t. The average global water footprint for animal products are chicken eggs, 3 300 m^3/t and cow milk, 1 000 m^3/t. When the water footprint of animal products per ton is compared to the water footprint of crop products per ton it is observed that the animal products have a larger water footprint than crop products (Mekonnen & Hoekstra, 2010b). The water footprint of animals include the water footprint of their feed; the more feed consumed the greater the water footprint of the feed the larger the water footprint of the animal. All animal products except butter have a larger water footprint per gram of fat than oil crops. When looking at the water footprint per nutritional value it seems that a diet based on crop products is preferred over a diet based on animal products.

Also calculated was the water footprint for different production systems: grazing, mixed and industrial. Grazing means animals eat the grass and crop waste that is available on the farm or in the area (Mekonnen & Hoekstra, 2010b). Industrial production systems are those where the animals eat concentrated feed (Mekonnen & Hoekstra, 2010b). Products obtained from an industrial production system normally have a smaller water footprint per product unit than products produced from a grazing production system, except for dairy products. Industrial feed systems have a larger blue and grey water footprint per ton of product, with the exception of chicken products. From the above, grazing systems are preferred over industrial feed production.

The water footprint is also influenced by the climatic conditions of the country from where the feed was obtained and the method in which the crops was grown (Mekonnen & Hoekstra, 2010b). The water footprints calculated for crop and animal products can be used by food companies when deciding where to obtain their supplies and by consumers for deciding which product or brand to use. Table 4 is a summary of the water footprint for crops and livestock.

Table 4: Summary of agricultural (crop and livestock) water footprints (Mekonnen & Hoekstra, 2010a, 2010b).

Product	**Water footprint**
Wheat	1 827 m^3/t
Rice	1 673 m^3/t
Maize	1 222 m^3/t
Sugar	200 m^3/t
Vegetables	300 m^3/t
Roots and tubers	400 m^3/t
Fruits	1 000 m^3/t
Spices	7 000 m^3/t
Nuts	9 000 m^3/t
Meat from beet cattle	15 400 m^3/t
Meat from sheep	10 400 m^3/t
Meat from pig	6 000 m^3/t
Meat from goat	5 500 m^3/t
Meat from chicken	4 300 m^3/t
Chicken eggs	3 300 m^3/t
Cow milk	1 000 m^3/t

Water footprint for a pair of jeans

Chico *et al*. (2013) calculated the water footprint of a pair of jeans manufactured from cotton or Lyocell fibre. The water footprint of a product can be used to determine which production method required the most water and during which production step the most water was consumed. A blue, green and grey water footprint was calculated for each production step, including all agricultural and industrial aspects. The agricultural water footprint included water used for wood and cotton growth (Chico *et al.*, 2013). The industrial water footprint included the processing of wood and cotton: ginning, fibre production, spinning, weaving, cutting and finishing (Chico *et al.*, 2013). For a pair of jeans produced from cotton the process steps are: cotton growth, ginning, spinning and weaving. For a pair of jeans produced from Lyocell fibre the process steps are: wood growth, fibre production and spinning and weaving. The results show that a pair of jeans produced from cotton has the larger water footprint (3 233 m^3/item on average). The cotton growth phase consumed the most water and the largest water footprint in the growth phase for cotton was blue water footprint. Trousers from Lyocell fibre consumed 1 454 m^3/item on average. The largest water footprint for Lyocell fibre was during wood growth. The wood growth phase has only a green water footprint. For Lyocell fibre the largest grey water footprint was during fibre production and for cotton during cotton growth. Wood from central Europe, had a water footprint of 1 012 m^3/t during wood growth, compared to South Africa which was 682 m^3/t. The different values for raw materials, together with transport values, could be used in decision-making around where to obtain raw materials.

Chico *et al.* (2013) also included a blue water sustainability assessment for the cotton growth stage. This was done by calculating an adjusted blue water stress index for the river basin. Usually the water stress index is defined as the ratio of the water footprint to the water available for use in the basin, where the water available is the river flow under natural conditions minus the volume of water required by the environment. Chico *et al.* (2013) also included a stress index for a dam, where the water available in the dam is the actual water of volume available minus the domestic water used minus the water required by the environment in the dam. From June to September the crop blue water footprint was larger than the blue water available in the catchment.

Total global virtual flow

A global water footprint can be calculated by adding the global water footprint for crops, crop products, livestock and livestock products and global industrial and domestic water consumption data. Global water footprints have been calculated by:

- Chapagain & Hoekstra (2004): Water footprints and virtual flows for countries;
- Hoekstra & Chapagain (2007): Morocco and the Netherlands global water footprint; and
- Mekonnen & Hoekstra (2011): Calculated a water footprint for all the countries and thus humanity.

Mekonnen & Hoekstra (2011) assumed that for the grey water footprint, if untreated water was returned to a water resource, that the grey water footprint for the returned water, was equal to the volume of water released. The global production water footprint calculated by Mekonnen & Hoekstra (2011), for 1996-2005 was 9 087 Gm^3/year (74% green, 11% blue, 15% grey). The average rainfall in South Africa is 611 billion m^3/year (Stats SA, 2006). South Africa’s total water footprint was 58.9 Mm^3/year (Mekonnen & Hoekstra, 2011). The volume of water used to produce agricultural products is 1 387% more than the average rainfall in South Africa.

Agricultural production had the largest water footprint and made up 92% of the global water footprint. The volume of water saved by a country due to importing products instead of producing the products within the country can also be calculated. Mexico and Spain save the largest volume of blue water by importing products. The water footprint for an average consumer is 1 385 m^3/year (92% agricultural, 5% industrial, 4% domestic). China has the largest water footprint of consumption, at 1 368 Gm^3/year. To make an informed decision on consumption of products it is important to know where the products are produced because the water use is influenced by local climate.

Industrial corporate water footprint

The case study evaluated was for 12 facilities of four Tata companies located within India. The four companies were: Tata Steel, Tata Chemicals, Tata Motors and Tata Power. According to Unger *et al*. (2013) the study that they conducted was the first industrial water footprint assessment. Water footprints were calculated for each process step in the production chain, and for each month, to determine which process step makes the largest contribution to water consumption and pollution. They also identified which time of year most water was used and compared this to the volume of water available for use in the catchment. The water footprint assessment procedures for all four companies were the same, hence only Tata Steel is discussed in more detail. For a discussion on the other three companies consult Unger *et al.* (2013).

The Tata Steel operation that was studied is the Jamshedpur facility located in the Subarnarekha river basin. The process steps used at the facility were sinter making, iron making, coke oven, steel making, hot strip mill, cold rolling mill and power houses. The direct blue water footprint was 24.9 million m^3/year. The iron and steel making process steps made the largest contribution accounting for 38% of the blue water footprint. To calculate the direct grey water footprint five pollutants and two oxygen demand parameters were assessed. The total direct grey water footprint was 15.2 million m^3/year, the critical pollutant was total suspended solids and was mainly caused by the steel making process step. The facility did not have a green water footprint for the production system but did have a green water footprint for horticulture. The green water footprint was 122 500 m^3/year. An indirect blue water footprint was calculated for three raw materials: iron ore, coal and limestone. The indirect blue water footprint was 5 million m^3/year. The blue water footprint for the product was calculated by combining the direct and indirect blue water footprint and dividing by the tonnes of steel produced. The total blue water footprint print was 4.21 m^3/t of steel. For the sustainability assessment the water source for the facility was identified. The river from which the facility receives most of the freshwater used on site also supplies the local community and other industrial facilities. Of the water withdrawn from the river 30% was used by Tata Steel, 42% was supplied to the local community and 28% was used by other companies. To determine if the dam could experience water scarcity, the run-off and water availability and the water withdrawal was compared. The dam did not experience any water shortages. During the response strategy step, a cost curve was drawn to determine which of the suggested water reduction methods would be most cost effective. Possible strategies were:

- Short term: Recirculating more water;
  Treating more water for subsequent reuse; and

Metering all intake and discharge points to capture and track water data.

- Long term: Converting waste water to clarified water;
  Converting a once-through system into a recirculating system;
  Installing “coke dry quenching” for a new coke oven;
  Installing INBA slag granulation system that reduces water associated with slag quenching; and
  Installing a common effluent treatment plant.

If all the strategies above were implemented, 27 million m^3/year could be saved on the total water withdrawn. Other water saving measured that were planned for implementation were installing rain water harvesting at homes, schools and the mines in the supply chain, increasing the capacity of a nearby reservoir and installing a dry crushing facility for an iron ore mine in the supply chain.

One of the Tata chemicals plants, TCL-Mithapur, had a very small blue water footprint because 97% of the plant’s water requirements were met by using seawater. The wastewater was also discharged into the sea. Seawater is not a freshwater resource thus the use of sea water is not included as blue water and discharges into the sea do not cause a grey water footprint. The study done on Tata Power Ltd showed that including the indirect water footprint is very important. The type of fuel used influenced the blue water footprint a great deal. Oil: blue water footprint: 1.06 m^3/GJ, Coal: blue water footprint: 0.16 m^3/GJ and gas 0.11 m^3/GJ. Neither one of the power plants had a grey water footprint. TPL-Trombay discharged its waste streams into the sea and TPL-Jojobera had a treatment plant before wastewater was released.

The water footprint only accounted for the global consumption of fresh water resources. Based on the definition of a water footprint, not including seawater is correct. As the world population increases and more food and products are being produced, more water will be required and alternative water resources will be necessary. The ocean is an alternative water resource. If large amounts of polluted water are released, at a constant rate, it will affect local seawater life. If we do not start accounting for the consumption and pollution of the local ocean life now, when we start to use the ocean water in industrial production, then at some point in the future the ocean will be affected.

From a water efficiency point of view, not accounting for ocean water could cause companies consuming and polluting vast amount of sea water to report a very low water use value, which will not reflect the true water use of the operation. This could cause companies to become stagnant when it comes to research and development of new water efficient production methods.

Industrial product water footprint

Peña & Huijbregts (2013) calculated the blue water footprint of an industrial product, to produce a tonne of grade A copper cathode from copper sulphide and copper oxide ore. The copper sulphide ore is processed using a pyrometallurgical process and the copper oxide is processed using a hydrometallurgical process. The mine and processing plants are located in the Atacama Desert in Chile. The process included all steps from extraction to delivery of the copper cathode to a sea port. The indirect water footprint included water associated with energy generation and materials that were consumed at more than 1% by weight of the copper produced. For the oxide process the blue water footprint was only allocated to copper. During the processing of copper from copper sulphide ore molybdenum, sulphuric acid and anodic slime are produced as by-products. The blue water footprint for each process step was allocated to the different products produced during the process step, using value fractions. Copper cathode produced from copper sulphide ore had the largest blue water footprint at, 96 m^3/t of copper cathode. Concentration contributed 59% of the total water footprint. Most of the water was lost through seepage, accumulation at tailings dam and evaporation. The indirect water footprint was 18 m^3/t of copper cathode. The water due to electricity accounted for 54% of the indirect blue water footprint. Copper cathode produced from copper oxide ore had a blue water footprint of 40 m^3/t of copper cathode. The heap leaching process step attributed 44% of the total blue water footprint. Evaporation was responsible for most of the water loss. The indirect water footprint was 11 m^3/t of copper cathode and electricity again made the largest contribution to the indirect water footprint. The water consumption of the processing plants could be reduced by 50 – 70% if seawater was used, evaporation reduced and more water reused from thickeners and tailings dam.

In a different study Osman, *et al*. (2013) calculated the volume of water used to produce an industrial product by a base metal refinery using the WAF and the WFN. The base metal refinery is located in South Africa. Nickel and copper formed 98% of the base metal product. Cobalt and sodium sulphate is also produced. The water footprint was calculated per ton of nickel, copper and cobalt produced. Before the water footprint was calculated flow meters and pipes were verified. The total water footprint calculated was 43.9 m^3/t of base metal. With blue (33.4 m^3/t of base metal), larger than green (10.5 m^3/t of base metal). No grey water footprint was calculated because no water was released back into a water resource. The total water footprint is 43.9 m^3/tonne of base metal produced. By using the WFN Osman *et al.* (2013) was able to determine that potable water (832 363 m^3) and rain water (261 970 m^3) are the major inflows into the refinery. Most of the water was consumed by the utilities section (401 800 m^3) and was used as process water (179 720 m^3). Evaporation (937 058 m^3) and accumulation in dams (119 830 m^3) were the largest outputs for the refinery.

Ranchod *et al.* (2014) calculated the blue water footprint for a platinum mine located in South Africa. Included in the mining operation were the concentration, smelting, converting, magnetic separation, base metals removal and precious metal refining process steps. The total blue water footprint for the platinum mine was 2 229x10^3 m^3/ton of refined platinum. Most of the blue water was consumed due to evaporation (67% of blue water consumed). Evaporation from the mineral processing plants accounted for 36.8% blue water consumption and evaporation from the tailings storage facility for 19.4% blue water evaporation. Blue water that is returned to a different catchment accounted for 28% and water incorporated into the product accounted for 5%. The total blue water footprint for the mineral processing plants were the largest 47.3%. Ranchod *et al.* (2014) recommend to using floating covers to reduce evaporation.

2.5 Other water accounting frameworks

2.5.1 Life cycle assessment

The life cycle assessment (LCA) method determines the environmental impact of a product from cradle to grave (Mudd, 2008). This includes environmental impacts created during the gathering of raw materials, manufacturing, distribution, usage, recycle, maintenance and disposal (Mudd, 2008). The environmental impact of different manufacture processes to produce the same product can be assessed and used when deciding which process to use. There are four steps involved in LCA investigation:

- Goal Definition and Scoping: Define system boundaries, Identify the product or service, assumptions and limitation.
- Inventory Analysis: Create list of inflows of water, energy and raw materials, and the release of products or waste products to air, land and water. Add flows of the resources from input through production and finally to the environment.
- Impact Assessment: Determine the impact of the product or service on the environment.
- Interpretation: The results are evaluated to determine the level of accuracy of the results.

2.5.2 Goldsim

Goldsim (Goldsim, 2014) is a computer programme used for environmental, engineering and business modelling. Modelling is done by showing elements and functions in a visual format. Elements are inputs like rainfall and can also be water stores. Functions (equations) are added to the elements to calculate outputs. The program can model simple functions like plus and minus but also differential equations used for accumulation in a dam. The program has a list of functions, but the functions can be changed as required. The program can provide a graph that shows the change in volume and can also simulate non-steady state. The functions can be grouped together to represent a process step for instance a concentrator, smelter or tailings dam. The program can also be used to optimise the use of resources and for sensitivity analysis.

2.6 Water content of metals

No published examples of the WAF, applied in the mining industry, were found. However, the studies below are all based on the water use information found on mining companies' web sites, reported following the GRI method. Table 5 summarises the main findings in the studies consulted. From Table 5 it can be observed that the average water consumption for platinum mining in South Africa and Zimbabwe is smaller than the average global water consumption for gold mining and larger than the average Australian water consumption for gold mining.

Table 5: Main findings of water consumption on mines.

Reference	**Mineral**	**Location**	**Water consumption**
Glaister & Mudd, 2010	Platinum	South Africa and Zimbabwe	391.5 m^3/kg PGM
Mudd, 2007a	Gold	Global	1.42 kL/t ore and 691 kL/kg Au
Mudd, 2007b	Gold	Australia	0.88 kL/t ore and 325 kL/kg Au
Northey *et al.*, 2013	Copper	Global	74 kL/t Cu

Water use for platinum mining in South Africa and Zimbabwe

Glaister & Mudd (2010) calculated the water and energy use and greenhouse gas emissions for platinum mines in South Africa and Zimbabwe. The data used for the calculation was from annual reports found on the companies' websites. The water use for individual mines is reported in Table 6 as m^3/kg PGM and m^3/t ore.

It was found that for the case studies water use efficiency was very little influenced by ore grade. Water use efficiency remained almost constant over time, even though the ore grade has been declining over time and UG2 processing has increased. This was not observed for Lebowa and Northam. Lebowa mine showed a decrease in water use over time and Northam mine an increase for water use over time. The reason for this observation was not stated. According to the study, water use ranges from 192–1 612 m^3/kg PGM and 0.509–12.6 m^3/t ore. The paper also mentioned that water used in milling on average is 1.32 m^3/t ore. Not all companies report the volume of water that was reused or recycled, only the total volume of water consumed, and therefore the paper did not report a water reuse or recycling efficiency.

Table 6: Water use for PGM mines (Glaister & Mudd, 2010).

Individual project/Mine[*]	**Number of years**	**Mt ore/year**	**g PGM/t ore**	**Water consumption**[**] **(m^3/kg PGM)**	**Water consumption**[**] **(m^3/t ore)**
Bafokeng–Rasimone (MC)	7	2.518	4.36	235	0.828
Lebowa (M)	7	1.509	4.54	385	1.397
Potgietersrus (MC)	7	4.830	3.62	277	0.695
Amandelbult (MC)	7	6.602	5.46	209	0.928
Rustenburg (MC)	7	11.457	4.26	229	0.828
Union (MC)	7	5.717	3.79	237	0.660
Twickenham (MC)	2	0.142	4.77	409	1.626
Mototolo JV (MC)	2	1.314	3.46	192	0.509
Mimosa (MC)	3	1.406	3.67	579	1.640
Manila (MC)	3	1.043	3.88	582	2.155
Crocodile River (MC)	1	0.844	4.66	1 086	2.328
Northam (MCS)	4	1.993	5.57	1 612	12.600
Zimplats (MCS)	3	2.059	3.49	606	1.760
Average				**391.5**	

[*] M – water intensity for mine only; MC – water intensity for mine and concentrator; MCS – water intensity of mine, concentrator and smelter

Global average water use in gold mining

Mudd (2007a) calculated average global water use values for gold by using water use data from annual company reports for 23 companies located in Australia, North America, Africa and Asia Pacific. Most of the annual reports used, stated total water consumed and did not distinguish between freshwater and recycled water consumed. Table 7 shows the results of this study. As can be observed in Table 7 the water consumption values ranges from 224 to 1 783 kL/kg Au and 0.72 to 2.82 kL/t ore. From 1997 until 2000, and during 2004 and 2006, the water use values per kilogram of gold produced were high compared to the other years. The standard deviations for 1997 to 2001, and during 2003 and 2004, were also very high compared to other years. The paper does not comment on these observations.

Table 7: Global average water intensity of gold mining (1991 - 2006) (Mudd, 2007a).

Year	**Water consumption (kL/kg Au)**			**Water consumption (kL/t ore)**		
	Ave.*	**SD****	**No. of mines**	**Ave.**	**SD**	**No. of mines**
1991	390		3	1.14		3
1992	335		3	0.96		3
1993	346		3	1.02		3
1994	323		3	1.16		3
1995	260		3	1.17		3
1996	224	118	4	0.97	0.24	4
1997	1 579	2 482	18	2.82	6.27	18
1998	1 443	1 846	29	2.56	8.73	29
1999	1 368	1 734	26	2.67	7.42	26
2000	1 281	1 733	27	2.67	6.09	27
2001	378	1 266	29	0.77	0.95	28
2002	374	993	27	0.74	1.08	26
2003	426	1 261	24	0.74	2.10	24
2004	725	1 711	34	1.51	7.27	34
2005	398	309	56	0.72	1.51	56
2006	1 783	776	22	2.87	4.50	22
Average	**691**			**1.42**		

* Average
** Standard deviation

Figure 3 and Figure 4 shows the change in water use with ore grade and amount of ore milled. As can be observed water consumption differs considerably with ore grade. With low ore grade water consumption increases. This is in contrast to the observation made by Glaister & Mudd (2010), that ore grade does not significantly influence the water use of platinum mines. Other reasons that can explain the scatter observed in Figure 3 and Figure 4 is local climate, type and degree of processing, number of mines and configuration of mines.

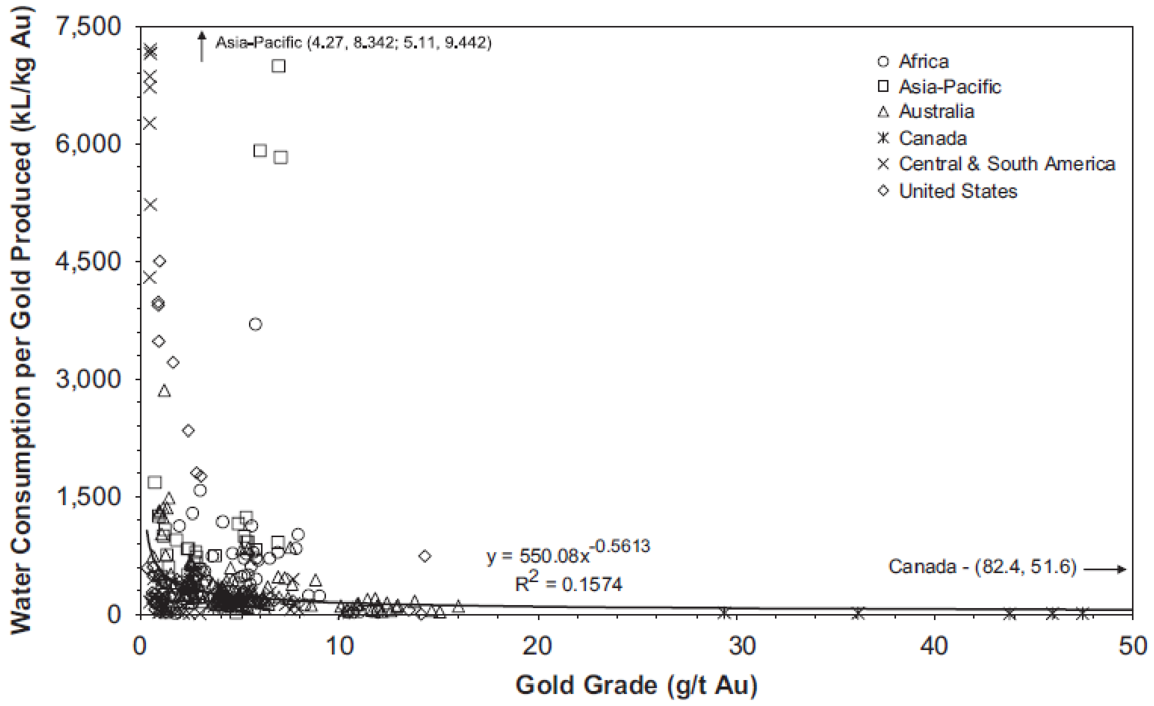

Figure 3: Effect of ore grade on water use on gold mines globally (Mudd, 2007a).

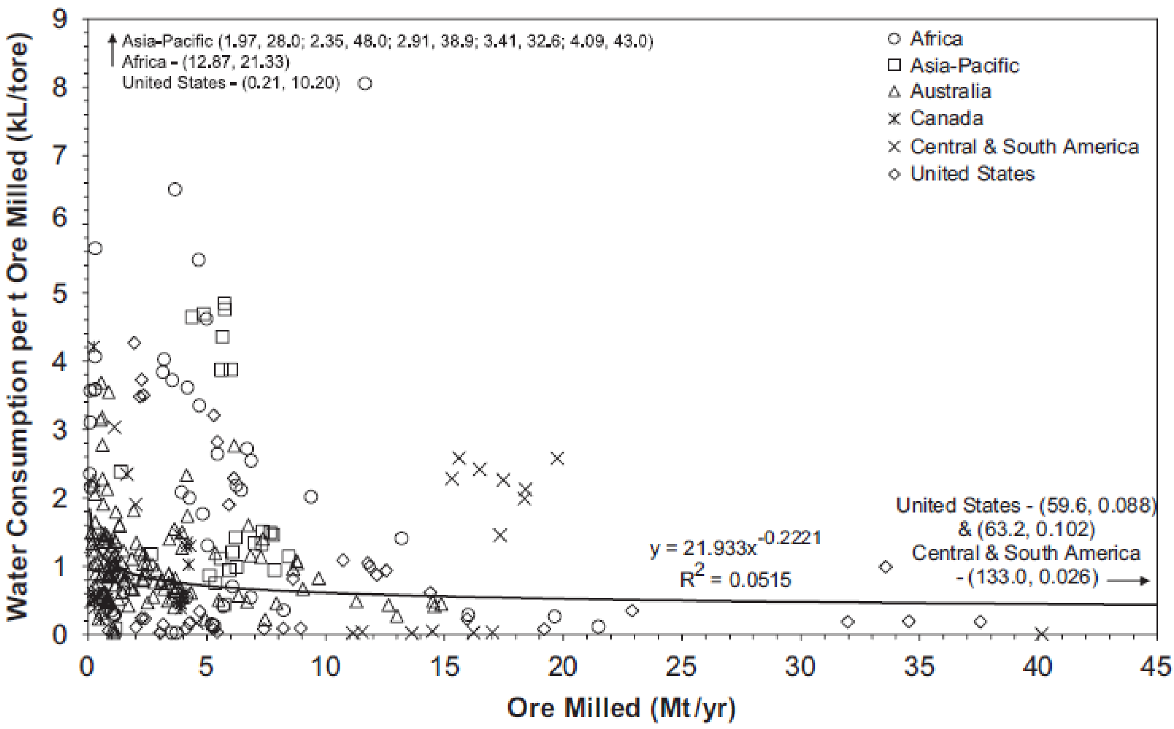

Figure 4: Effect of ton of ore milled on water use on gold mines globally (Mudd, 2007a).

Water use in gold mining in Australia

Mudd (2007b) analysed public available water use data for Australian gold mining companies. The reports analysed did not report data in a consistent manner (Mudd, 2007b).

As can be observed from Table 8 the average water intensity per year ranges from 224 to 666 kL/kg Au and 0.67 to 1.72 kL/t ore. Also reported by Mudd (2007b) is that as ore grade and throughput decreases the volume of water consumed increases for gold mining in Australia. The same observation was made by Mudd (2007a) regarding global water use values for gold mining, but Glaister & Mudd (2010) stated that water use values for platinum is independent of ore grade.

Table 8: Average water intensity of Australian gold mining (1991-2005) (Mudd, 2007b).

	Water consumption (kL/kg Au)		**Water consumption (kL/t ore)**		**No. of mines**
	Ave.[*]	**SD**[**]	**Ave.**	**SD**	
1991	390		1.14		3
1992	335		0.96		3
1993	346		1.02		3
1994	323		1.16		3
1995	260		1.17		3
1996	224	118	0.97	0.24	4
1997	666	1 002	1.72	1.29	7
1998	427	341	0.82	0.76	17
1999	436	394	1.04	0.70	15
2000	375	400	0.95	1.25	17
2001	233	379	0.67	0.81	18
2002	249	201	0.91	0.90	13
2003	302	164	0.81	0.57	8
2004	278	142	0.78	0.45	13
2005	238	73	0.69	0.49	11
Average	**325**		**0.88**		

[*] Average
[**] Deviation

Global water use for copper

Northey *et al.* (2013) analysed publicly available water use data from eleven countries. Table 9 shows the results obtained from the study. When comparing the results the deposit type, mine type and processing methods were considered.

Northey *et al.* (2013) observed that the local climate has the largest effect on the amount of water used. More water is used in dry areas. The reason for this observation was reported as being caused by a high evaporation rate which decreased the volume of water that can be recovered from tailings dams and open water stores, which then has to be replenished with imported water (Northey *et al.*, 2013). Ore grade has less of an effect on water intensity than the region from which the mineral is mined (Northey *et al.*, 2013). This is in contrast to observations made by Mudd (2007a, 2007b) regarding gold. The size of the mine has a limited effect on the water use. In Table 9 it can be observed that Escondida mine produces the most copper but the water use is below the average water use and Phyasalmi produces the least amount of copper but the water use is above the average.

Table 9: Average water intensities for copper (Northey *et al.*, 2013).

Operation	Metals extracted	Mine type*	Process**	Water Consumption kL/t Cu***	Production t Cu/year
Australia					
Cadia-Ridgeway	Au-Cu	O/U	MC	49.0(7)	64 228
Ernest Henry	Cu-Au	OP	MC	42.3(7)	95 130
Golden Grove	Ag-Pb-Zn-Cu	UG	MC	33.0(3)	19 446
Mount Isa	Cu	UG	MCS	19.5(7)	222 261
Northparkes	Cu-Au	O/U	MC	74.0(8)	40 679
Olympic Dam	Cu-Au-Ag-U	UG	MCSRL	46.6(14)	136 827
Prominent Hill	Cu-Au-Ag	OP	MC	39.8(2)	104 241
Rosebery	Ag-Pb-Zn-Cu-Au	UG	MC	1046.9(1)	1 985 000
Telfer	Au-Cu	O/U	MC	161.1(6)	30 510
Argentina					
Alumbrera	Cu-Au	OP	MCL	91.3(6)	174 078
Canada					
Highland Valley	Cu-Mo	UG	MC	135.4(2)	164 827
Kidd Creek	Cu-Zn	OP	MCSR	76.7(2)	87 009
Chile					
Andina	Cu-Mo	O/U	MC	99.4(7)	226 932
Codelco Norte	Cu-Mo	OP	MCSL	53.3(8)	888 618
Collahuasi	Cu-Mo-Au-Ag	OP	MCL	31.9(2)	479 263
El Soldado	Cu	O/U	MCL	48.2(7)	62 626
El Teniente	Cu-Mo	UG	MCS	139.7(7)	409 692
Escondida	Cu-Au-Ag	OP	MCL	52.5(6)	1 242 644
Lomas Bayas	Cu	OP	MH	75.5(3)	65 937
Los Bronces	Cu-Mo	OP	MCL	80.7(7)	228 300
Mantos Blancos	Cu	OP	MCL	226.5(7)	89 957
Mantoverde	Cu	OP	ML	46.6(7)	61 093
Salvador	Cu-Mo	O/U	MCSL	321.3(8)	74 379
Quebrada Blanca	Cu-Zn	OP	ML	21.9(1)	85 000
Finland					
Pyhasalmi	Zn-Cu	UG	MC	211.0(7)	16 650
Laos					
Sepon	Cu-Au	OP	ML	34.0(5)	53 370
South Africa					
Palabora	Cu	UG	MCSR	94.4(11)	77 656
Turkey					
Cayeli	Cu-Zn	UG	MC	87.3(7)	30 229
Peru					
Tintaya	Cu-Au	OP	MCL	42.5(5)	103 179
PNG					
Ok Tedi	Cu-Au-Ag	OP	MC	38.8(7)	176 460
USA					
Kennecott Utah	Cu-Au-Ag-Mo	OP	MCSR	9.8(7)	242 122

*OP is an open pit mine, UG refers to an underground mine and O/U to an open pit and underground mine.

M means mining is done onsite, C – concentration, S – smelting, R – refining and L – leaching, solvent extraction and electrowinning. * The number in brackets is the number of years for which data was available.

Comparing water use between metals

Publically available data from 36 companies was used to calculate the water use of a metal (Mudd, 2008). Mudd only used data if it was known that the volume of water consumed included both fresh water and recycled water. This was to ensure consistency between data. In above case studies it was not always clear if recycled water was included. Table 10 shows the data obtained during the investigation.

Table 10: Summary of results for water consumption across different mineral commodities (Mudd, 2008).

Mineral/metal	**Total number of years of data**	**Water consumption (*e.g.* kL/t ore)**		**Water consumption (*e.g.* kL/t metal)**	
		Ave.[**]	**SD**[***]	**Ave.**	**SD**
Bauxite (kL/t bauxite)	17	1.09	0.44	-	-
Black coal (kL/t coal)	18	0.30	0.26	-	-
Copper (kL/t ore; kL/t Cu)	48	1.27	1.03	172	154
Copper–gold (kL/t ore; kL/t Cu)	42	1.22	0.49	116	114
Diamonds (kL/t ore; kL/carat)	11	1.32	0.32	0.477	0.170
Gold (kL/t ore; kL/kg Au)	311	1.96	5.03	716	1 417
Zinc ± lead ± silver ± copper ± gold (kL/t ore; kL/t Zn ± Pb ± Cu)[*]	28	2.67	2.81	29.2	28.1
Nickel (sulfide) (kL/t ore; kL/t Ni)	33	1.01	0.26	107	87
Platinum group (kL/t ore; kL/kg PGM)	30	0.94	0.66	260	162
Uranium (kL/t ore; kL/t U_3O_8)	24	1.36	2.47	505	387

[*] The metals are mined on the same mine
[**] Average
[***] Standard deviation

Mudd (2008) found that throughput had little influence on the water used for base metals less and that lower grade ore required more water per kg metal. Gold and platinum were the only metals and minerals for which a larger project scale lead to greater water use efficiency. Gold mining used the largest volume of water per tonne of metal and platinum the second largest (Mudd, 2008). The volume of water required for a mining operation can be influenced by: mine type, ore mineralogy, mill configuration and design, water quality, project age, climate, long distance slurry pipelines, and whether a smelter and refinery is used (Mudd, 2008).

Chapter 3 METHOD

This chapter describes the Water Accounting Framework (WAF) and the Water Footprint Network (WFN) methods used to calculate the volume of water consumed by a platinum mine located in South Africa. Also discussed are assumptions made while calculating the volume of water.

In addition to Figure 2, the mine operation also has an outflow (waste stream) to a third party. The third party removes a mineral that is not extracted by this operation. The waste stream from the third party is then further processed within this operation. The UG2 concentrator plant has also changed because the ore grade has changed and more UG2 was processed. The plant still contains the same elements but the flow of the process streams between these elements has changed. The UG2 concentrator plant configuration is unique and due to confidentiality agreement the exact configuration can not be discussed.

3.1 Water accounting framework

3.1.1 Calculation method

In this section the steps used to calculate the volume of water consumed by using the WaterMiner program and the steps to complete the WAF is discussed (SMI & MCA, 2011):

Input output statement

The input output statement is a report that states the volume flow rate, quality and destination or source of each input and output. A list of all the water inflows into the site was made. Information assigned to each stream was source, volume and quality. The inflows for this site were surface and ground water, water entrained in ore, rainfall, runoff and third party water. WaterMiner assumes steady state, therefor the flow rates entered into WaterMiner were monthly averages. Water quality can be classified into 3 categories.

- Category 1 is water that can be used for human consumption;
- Category 2 can be used for most purposes; and
- Category 3 is unusable water.

For this investigation the suggested categories as shown in the decision tree (Figure 5) were used.

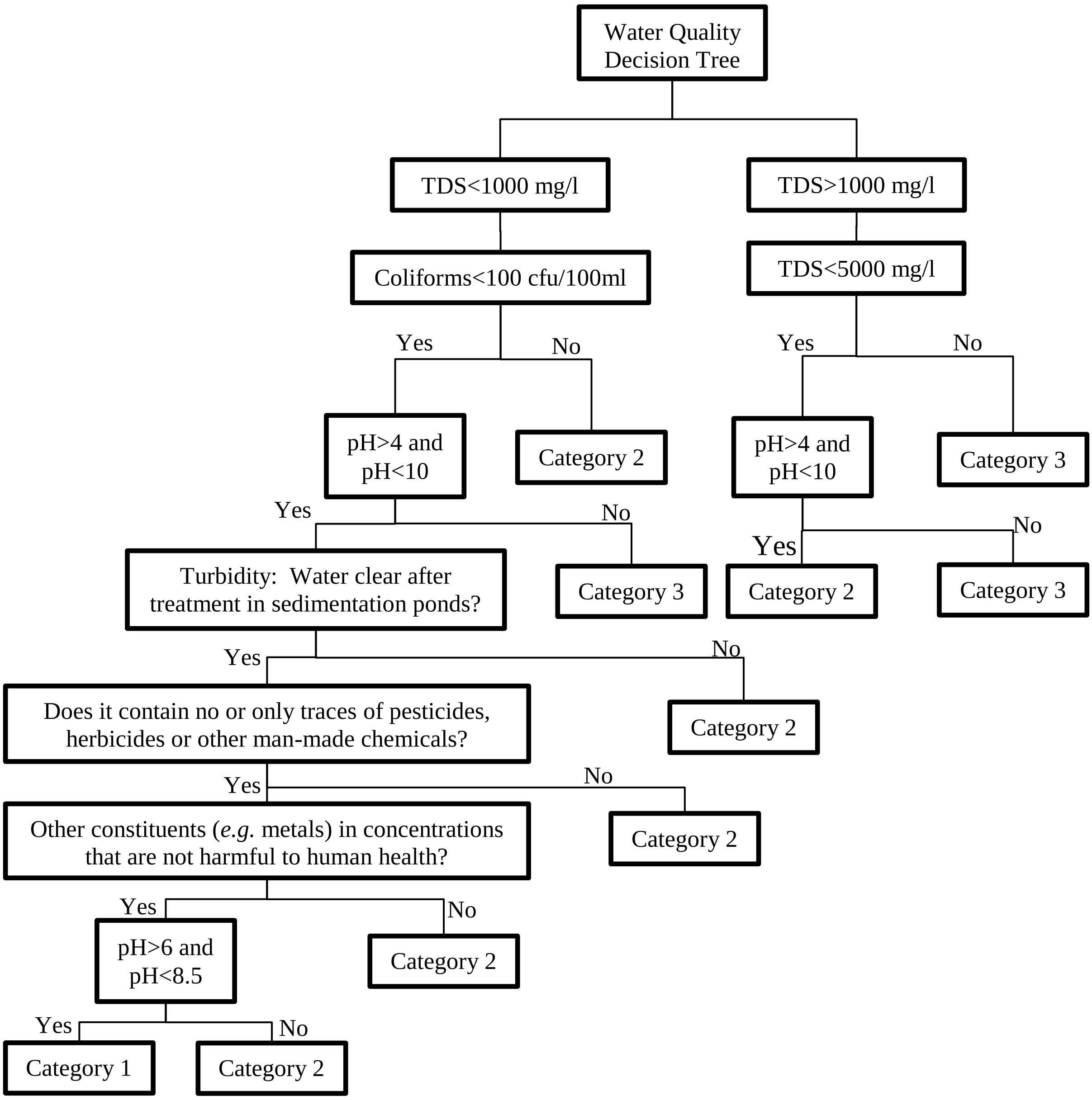

Figure 5: Decision tree to assign quality categories to water streams and water stores.

The volume of water sourced from surface, ground and third party sources was measured on a daily basis. The volume of water entrained in the ore was calculated using Equation1:

$$\mathrm{V_{ent}} = 1000(\mathrm{P})(\mathrm{m}) \tag{1}$$

Where:

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

The water quality of water entrained in ore was assigned category 3 quality. The mining company suggested a moisture content of 5% for the ore. For concentrator plant 1 the ore flow rate was measured and for concentrator plant 2 the maximum production rate was used. Due to confidentiality reasons the type of concentrators cannot be named.

The volume of rainfall captured by the facility was assigned category 1 quality and can be calculated with the following equation:

$$\mathrm{V_{rainfall}} = 0.01(\mathrm{R})(\mathrm{SA}) \tag{2}$$

Where:

$V_{rainfall}$ = volume of rainfall (ML/month);
R = rainfall for the reporting period (mm/month); and
SA = total amount of surface area that captures rain (ha).

The rainfall was measured by the mining company and reported on a monthly basis. The company also provided the surface areas of the water stores. Google Maps was used to confirm the surface areas and determine the surface areas for stores where surface areas were not provided. The monthly rainfall and surface area of open water stores were entered into the WaterMiner program and the program calculated the volume of rainfall that entered the open surface areas.

The volume of runoff can be calculated with the following equation:

$$V_{\mathrm{runoff}} = 0.01(\mathrm{R})(\mathrm{x})(\beta) \tag{3}$$

Where:

V_{runoff} = volume of runoff (ML/month);
x = disturbed or undisturbed catchment area (ha); and
β = volumetric rainfall to runoff factor (dimensionless), undisturbed = 0.05, disturbed = 0.15.

The undisturbed catchment is a catchment where runoff does not come into contact with any by-products and in a disturbed catchment the runoff come into contact with by-products. Two water stores that received runoff were identified. Both of these stores were located in and undisturbed catchment and was assigned 0.05 as the rainfall to runoff factor. The catchment area and the rainfall to runoff factor were entered into WaterMiner and the program calculated the volume of water that entered the water stores as runoff. The water quality assigned to the undisturbed runoff was quality 1 and for disturbed catchment it was quality 2.

A list of all the out flows out of the site was made. Destination, quality and volume, was assigned to each out flow. The quality assigned to each flow rate was done as set out in Figure 5. Outflows for this site include: third party streams, water entrained in waste or product, seepage and evaporation. It was assumed that the only seepage occurred at the tailings dam with a constant seepage rate provided by the company. For one water store, water overflows to the immediate environment and is lost through seepage and evaporation. It was determined that this does not happen a lot, and only in small amounts, so was ignored.

Class A pan evaporation data was obtained from a report of the South African Department of Water Affairs (DWAF, 1985). Pan evaporation data is the rate of evaporation of water from an evaporation pan. A correction factor is used to convert pan evaporation into evaporation from open storage. The correction factor is required because the depth of the evaporation pan and the open storage has an influence on the rate of evaporation. Both SMI & MCA (2011) and DWAF (1985) recommended using a correction factor of 0.75. For the tailings dam an average evaporation rate was assumed that was provided by the company. The volume of water evaporated from the operation was assigned category 1 quality and can be calculated using the following equation:

$$V_{evap} = 0.01(SA_{evap})(Pan_{evap})(f) \tag{4}$$

Where:

V_{evap} = volume of water evaporated (ML/month);

SA_{evap} = average surface area (ha) from which the water evaporates;

Pan_{evap} = pan evaporation rate (mm/month); and

f = correction factor to convert measurements of pan evaporation into evaporation losses = 0.75 (dimensionless).

The pan evaporation rate and the correction factor were entered into WaterMiner and the volume of water lost through evaporation was calculated by the WaterMiner program.

When water flows from an input to an output without being used or stored in the process, it is classified as a diversion. The mine site has one diversion.

Operational efficiency statement

The operational efficiency statement is a report that states the reuse and recycling efficiency. Water that has been used in a task onsite and is used again without being treated is reused water. Water that has been used in a task onsite and is used again after being treated is recycled water.

A list of all the tasks, treatment plants and water stores on site were made. The unknown flows around these elements were calculated by using design criteria (densities and percentage solids) of flotation plants, cyclones and thickeners, and by completing the water balance. The WaterMiner program used the flow rate data to calculate a reuse and recycle efficiency for each task.

Accuracy statement

The accuracy statement states the percentage of flows measured, estimated or simulated and the level of confidence of the data used. When entering the flow rates into WaterMiner it was stated whether the flow rates were measured, estimated or simulated and if the level of confidence in the flows was high, medium or low. This information was used by WaterMiner to generate an accuracy statement was generated using WaterMiner.

3.2 Water footprint network

The Water Footprint Network Assessment Tool is a method used for determining the volume of direct and indirect water consumed and polluted by an organisation, in a process or to manufacture a product (Hoekstra *et al.*, 2011). Water footprints can be expressed as volume per unit product, volume per nutritional unit, volume per mass product or volume per time. For industrial products the water footprint can also be expressed as volume per US$ (Hoekstra *et al.*, 2011). The water footprint calculated can be used to assess the organisation's effect on the local environment, society and economy. Suggestions can then be made on how to reduce the effect of the water footprint. The method described below is as set out in The Water Footprint Assessment Manual (Hoekstra *et al*., 2011).

The Water Footprint Assessment Manual suggests the following four steps for the assessment (Figure 6):

1 Setting goals and scope;
2 Water footprint accounting;
3 Water footprint sustainability assessment; and
4 Water footprint response formulation

These four steps are discussed in more detail below.

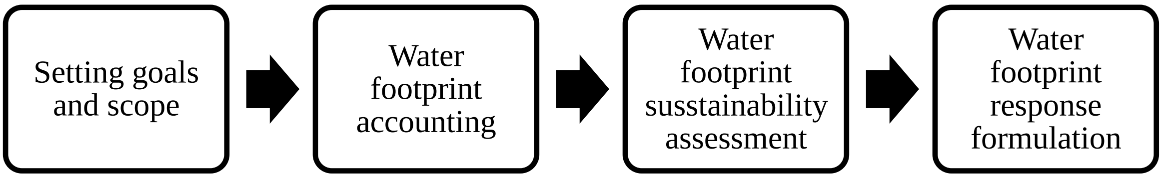

Figure 6: Water footprint assessment steps (Hoekstra *et al.*, 2011).

3.2.1 Setting goals and scope

The first step involves determining why the assessment is being done. Before the water footprint can be calculated the goals and scope for the investigation have to be determined. The following possibilities have to be considered to decide what should be excluded and included in the investigation:

- The purpose of the water assessment

  Possible reasons for starting an investigation can be to determine the dependency of a country on foreign water, to identify hotspots within a country, catchment or process step in the production or supply chain of a product *etc*.,
- Decide if all four steps of the water footprint assessment will be included,

  It is possible that a business might only want to know the size of the water footprint but is not interested in the effect on the local environment or reducing the water footprint,
- Types of water footprint to be calculated

  A water footprint can be calculated for a process step, a product, consumer, group of consumers, within a catchment, within a country, for humanity, for a business, or a business sector;
- Decide which type of water to consider for the water footprint accounting,

  Blue and/or green and/or grey; and
  Direct and/or indirect water.
- Choose a time period for the investigation; and
- Where the analysis should be truncated

  Decisions regarding the inclusion of labour and transport have to made.

The reason for the investigation presented in this thesis was to quantify the water used to produce one gram of PGM contained in the converter matte which is sent to an off-site base metal refinery for further processing. Additionally, the study aimed to compare the water consumed during the production of PGM to water consumption values of similar products. If the process step that uses the most water can be identified, the company will know where to spend most of its resources to reduce the water required by the operation.

For this investigation the blue, green and grey water footprints were quantified. The indirect water required by the process included water used to produce the reagents used during flotation and electricity used in the plant and offices, however this value was not included. The water footprint was calculated on a monthly basis from June 2012 to May 2013. Water sample analysis provided by the mining company were at irregular intervals and data for every month were not available, so for the grey water footprint a yearly average was used. Water used in change houses, offices, hostels, workshops, laboratories and to clean the plant was also included. Water used directly in the process was calculated for two concentrator plants, a smelter plant and tailings dam. Sewage generated on site is treated on-site, the water used in the treatment process was not included.

3.2.2 Water footprint accounting

In this step, data is collected and the water footprint is calculated. To calculate the water footprint of a product, the water footprint for each of the process steps to produce the product has to be calculated and summated. The total water footprint of a process step is the sum of the blue, green and grey water footprints for that process step.

Blue water footprint

The blue water footprint is defined as the volume of water consumed from scarce water resources, where scarce water resources are surface and ground water, but not sea water. Consumption refers to water that was withdrawn by the operation and was not returned to the original water resource. The blue water footprint for a process step can be calculated from equation 5:

$$\mathrm{WF_{proc,blue}} = \mathrm{V_{blue,evap}} + \mathrm{V_{blue.incorp}} + \mathrm{V_{blue.lost}} \tag{5}$$

Where:

$\mathrm{WF_{proc,blue}}$ = blue water footprint for a process step(ML/month);

$\mathrm{V_{blue,evap}}$ = volume of blue water that evaporates from the site (ML/month);

$\mathrm{V_{blue,incorp}}$ = volume of blue water that is entrained in the product (ML/month); and

$\mathrm{V_{blue,lost}}$ = water that is returned to a different catchment than from where it was withdrawn (ML/month).

If water is transferred from catchment A to catchment B, then the users of catchment B are using catchment A water and they have a footprint in catchment A (Hoekstra *et al.*, 2011). The mining operation in this study is located in the Crocodile West catchment: the operation uses rainwater and groundwater from that catchment. The operation also receives surface water through municipal supply that withdraws water from Middle Vaal catchment. Thus the mining operation has blue water footprints in two catchments.

If measures are taken to prevent rain water from entering the soil such as concrete surface or increase runoff to a dam, the rain water forms part of the blue water footprint (Hoekstra *et al.*, 2011). If measures are taken to increase the volume of water in the top parts of the soil, to increase the volume of water available for evapotranspiration the rain water forms part of the green water footprint (Hoekstra *et al.*, 2011).

For this site, there was no need to increase the volume of water contained in the ground because no garden or plant life is cared for by the company. Rain water entered the site as runoff into catchment dams or directly into open water surfaces. The runoff water and volume of rainwater that falls into an open water store was assumed to be part of the blue water footprint.

Green water footprint

The green water footprint is the volume of rainwater incorporated into the product and the volume of water lost through evapotranspiration. The green water footprint can be calculated with Equation 6:

$$\mathrm{WF}_{\mathrm{proc,green}} = \mathrm{V}_{\mathrm{green,evap}} + \mathrm{V}_{\mathrm{green,incorp}} \quad (6)$$

Where:

$WF_{proc,green}$ = green water footprint for a process step(ML/month);
$V_{green,evap}$ = volume of green water that evaporates from the site (ML/month); and
$V_{green,incorp}$ = volume of green water that is entrained in the product (ML/month).

Therefore there is no green water footprint for this operation.

Grey water footprint

A grey water footprint is calculated for a waste stream that is released into a water resource. For this study it was assumed that only seepage from the tailings dam is released into a water resource. It was assumed that the seepage reaches a ground water resource.

The grey water footprint is not a volume of water withdrawn by the operation, but the volume of water consumed in a water resource if polluted water is released. The grey water footprint is an indication of the level of pollution caused by the waste stream that is released by the organisation into a water resource. It is assumed that the volume of fresh water consumed in the water resource, for dilution (grey water footprint) cannot be consumed by users downstream.

The grey water footprint is defined as the volume of water required, from the water resource into which the waste stream is released, to dilute the contaminants to ensure that the water resource quality remains below an agreed value (C_{max}). The agreed value is the maximum concentration that a contaminant can reach in the water resource. The grey water footprint can be calculated with Equation 7:

$$\mathrm{WF_{proc,grey}} = \frac{\mathrm{L}}{\mathrm{C_{max}} - \mathrm{C_{nat}}} \tag{7}$$

Where:

$WF_{proc,grey}$ = grey water of a process step (ML/month);

L = pollutant load (g/month);

C_{max} = maximum allowable concentration of pollutant in the water resource (g/ML); and

C_{nat} = natural concentration in the receiving water resource (g/ML).

The grey water footprint of the operation step is the largest grey water footprint calculated for the different contaminants. The contaminant responsible for the grey water footprint is known as the critical pollutant.

For the load (L in Equation 7), the water quality in the tailings dam, instead of the quality as the water enters the groundwater resource was used. This assumption was made because the depth of the groundwater unknown. It is expected that the contaminants in the seepage could be absorbed as the seepage flows toward the ground water. The minerals in the ground could also dissolve into the seepage and raise the concentration. The water quality of the tailings dam was provided by the company.

For C_{max} the drinking water quality of South Africa (DWAF, 2005) was used because ground water's maximum allowable concentrations are often the same as drinking water standards (Hoekstra *et al.*, 2011). The values are included in Appendix A.

C_{nat} is the concentration of a particular contaminant in the water resource if the resource was not affected by human activities. For substances that do not occur naturally but is introduced into the water body by human activities, it can be assumed that the value for C_{nat} for that particular substance is zero. For C_{nat} the measurable water quality of the ground water (DWAF, 2013) was used instead of the natural concentration.

3.2.3 Water footprint response formulation

In the final step of the water footprint assessment, recommendations are made on how to reduce the water footprint impact on the local environment. A new water management plan is created by identifying responses as well as a time frame and responsible person and/or organisation to reduce the water footprint and make it more sustainable.

3.3 Financial value of water used for product production

Product food prices were obtained from the Woolworths website (Woolworths, 2014). Water footprint data for products produced in South Africa were obtained from Mekonnen & Hoekstra (2011). The water footprint data includes the blue, green and grey water footprint.

3.4 Calculation assumptions

This section contains a summary of all assumptions made while calculating the volume of water consumed by the platinum mine site.

- It was assumed that the mine closes down for seven days during December and three days for Easter. Daily measured water inflow rates were available from June 2012 to May 2013. In addition to the December and Easter shutdowns it was also assumed that if all water sources had a 0 m^3/day value it was assumed that the plant did not operate on those days. This assumption was made because the plant was shut down over weekends if the stock pile was low.
- Evaporation data was not measured but based on average monthly historical values for the region (DWAF, 1985).
- For concentrator plant 2 a maximum ore flow rate, based on design, was assumed and kept constant. In some instances the ore processing rate could be lower than used during the calculations.
- It was assumed that the ore contained 5% water.
- Water entrained in the ore from the mine and shaft water removed during the mining process was not included as blue water. These water resources formed part of the blue water footprint of the mining operation, which was not included in this investigation.

- For flotation, cyclones and thickeners the flow rate was calculated by assuming constant density and solids concentration values for the out flows.
- The flow rates for the smelter plant were calculated from average monthly water flow rates and not daily or monthly measured values.
- There was no green water footprint for this investigation because there was no water used for gardening, and rain water consumed on site came from runoff or direct falling of rain water into open water stores.
- It was assumed that the only water that leaves the plant is through seepage at the tailings dam.
- For the grey water footprint the water quality in the tailings dam instead of the quality as the water enters the groundwater resource was used. The drinking water quality of South Africa (DWAF, 2005) was used as the maximum allowed concentration for the catchment. The measured water quality of the ground water (DWAF, 2013) was used instead of the natural concentration.

Chapter 4 RESULTS

In this section the Water Accounting Framework (WAF) and Water Footprint Network (WFN) results for the platinum processing plant in South Africa are presented. Results obtained for two concentrator plants and a tailings dam were presented at the Water in Mining Conference in Queensland, Australia, on the 28th of November 2013. The conference paper, showing concise results as presented below, was peer reviewed and is attached in Appendix B. The smelter plant results were included in a paper accepted to WaterSA based on a presentation to WISA 2014 in Nelspruit. This paper will be published in a special edition of the conference proceedings of WISA 2014.

4.1 Evaporation and rainfall data

To create a water balance, rainfall and evaporation data were entered into WaterMiner. The rainfall data were measured on a monthly basis and were provided by the mining company for June 2012 until May 2013. The average monthly historical evaporation rates were obtained from DWAF (1985). The rainfall and evaporation rates are shown in Appendix C.

In South Africa the four seasons are as follows: spring from September to November, summer from December to February, autumn from March to May, and winter from June to August. The mine is located in an area that receives rain during the spring and summer months. The highest rainfall was measured during October 2012 at 147 mm/month. The lowest rainfall was measured during February 2013 at 52 mm/month. According to Figure 7 during June 2012, July 2012, August 2012, April 2013, and May 2013 there were no rainfall. This is the autumn and winter months in South Africa.

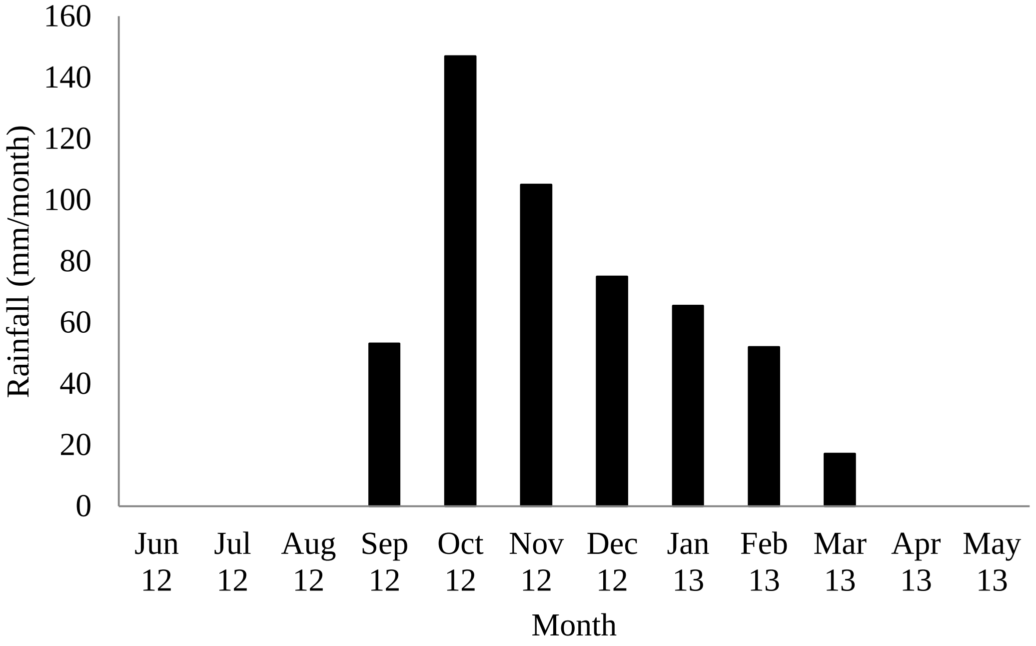

Figure 7: Measured monthly rainfall data from June 2012 until May 2013.

As can be observed from Figure 8 during the spring and summer months the highest evaporation rates were measured. The highest evaporation rate was measured during October 2012 at 253 mm/month. During autumn and winter the evaporation rates are lower. The lowest evaporation rate was measured during June 2012 at 97 mm/month.

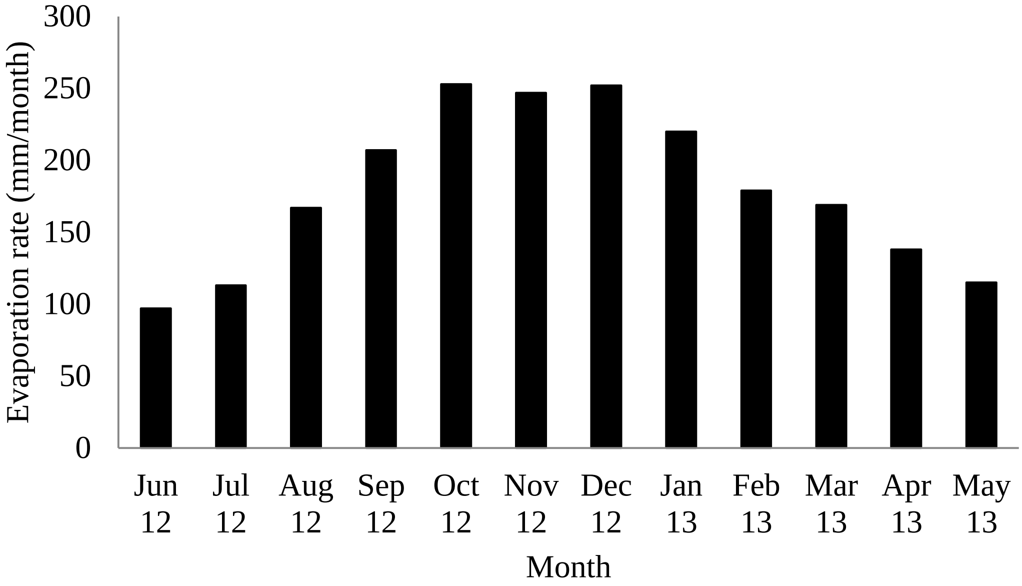

Figure 8: Historically average monthly evaporation rate (DWAF, 1985).

Figure 9 shows the monthly difference between rainfall and evaporation rate at the mine site. From this it can be observed that for every month of the year, the evaporation rate is greater than the rainfall rate. The highest net evaporation rate was observed during December 2012 at 177 mm/month.

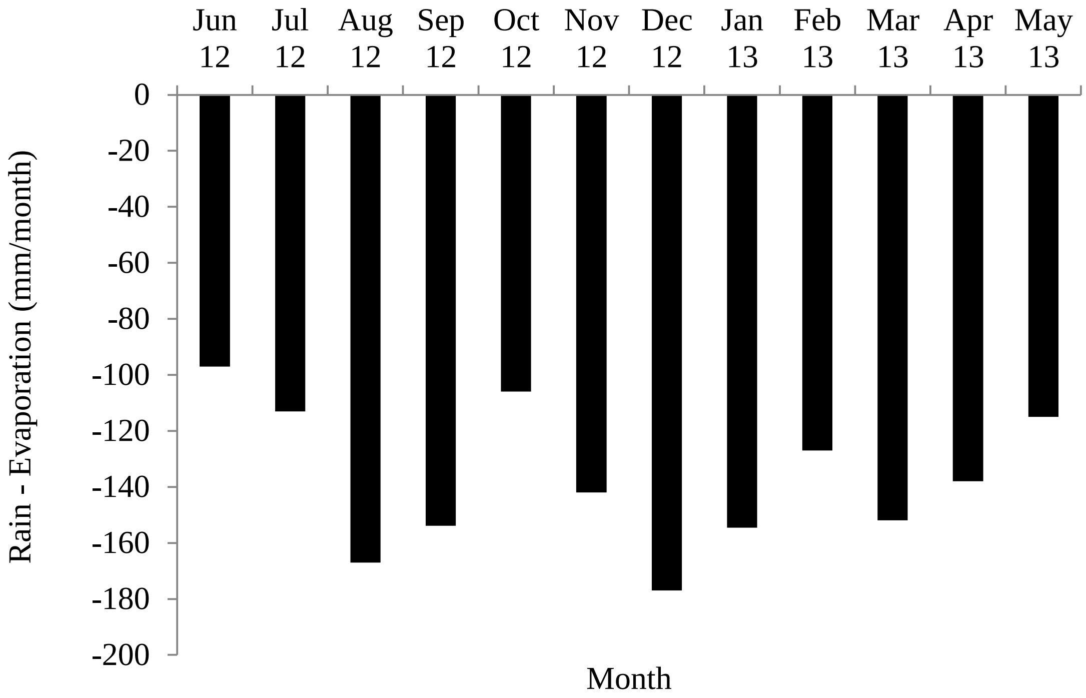

Figure 9: Difference between rainfall and evaporation rate on a monthly basis for June 2012 to May 2013 at the mine site.

For the volume of water lost through evaporation from the tailings dam an average evaporation rate was assumed as provided by the company. The volume of water lost through evaporation is more than the volume of water gained through rainfall for every month as can be observed from Figure 10. The highest volume of water lost through evaporation occurred during December 2012 at 161 057 ML/month and the highest volume of water gained through rainfall occurred during October 2012 at 111 882 ML/month.

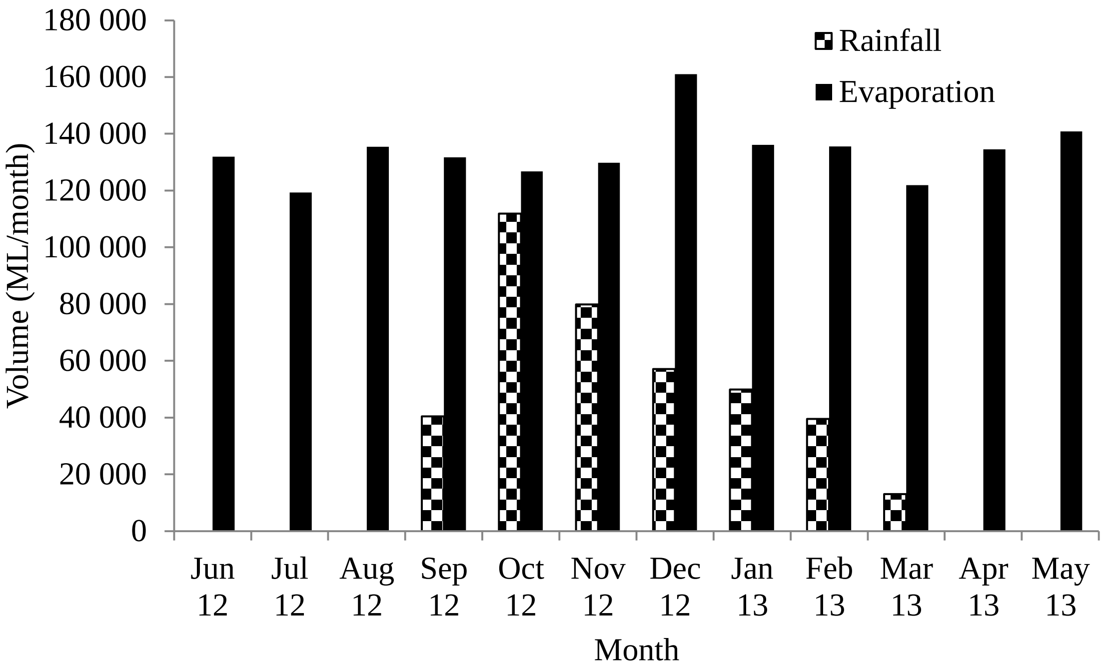

Figure 10: Monthly volume of rainfall and evaporation gained and lost from open water surfaces onsite.

4.2 Water accounting framework

Flow rate data was obtained from the mining company and unknown flow rates were calculated by using design criteria (densities and percentage solids) of flotation plants, cyclones and thickeners, and by completing the water balance. The monthly rainfall rate and seepage from the tailings dam provided by the company and monthly evaporation rate (DWAF, 1985) was entered into WaterMiner. WaterMiner then calculated the volume of water lost through evaporation and seepage and the volume of water gained through run off and rainfall.

4.2.1 Input output statement

The input output statement is a report that states the volume flow rate, quality and destination or source of each input and output. The process flow diagram shown in Figure 11 was created by entering flow rate data into the WaterMiner program. The diagram shows the flow rates in ML/year between water stores, tasks, inputs and outputs.

In Figure 11 the green squares indicates the inflows into the mine site. The silt trap was a sedimentation pond where runoff is collected. Water source 1 and 2 was water supplied from dams located in the Upper Vaal and Crocodile West catchments through the municipalities. Water source 3 was ground water removed from bore fields onsite. Water source 4 was water removed from a dam onsite (Crocodile West catchment). Third party 2 was water contained in a waste product obtained from a third party that is further processed onsite.

The red squares indicate outflows from the mine site. The blue squares were water stores onsite. The grey squares were tasks, these included the concentrator plants, smelter plant and the sewerage treatment plant.

Table 11 shows the import and export volumes of water to and from the platinum mine, the quality and the source and destination of the imports and exports. A quality category was assigned to sources and destinations using the decision tree in Figure 5. The information presented in Table 11 was obtained using the WaterMiner program. The volume of water imported was 12 686 ML/year and the volume of water exported was 12 599 ML/year. The difference in the imports and exports volumes was 87 ML/year, this is 0.69% of the imports volume and the site thus operated at a slight surplus. The volume of water diverted and thus not used on site was 45 ML/year.

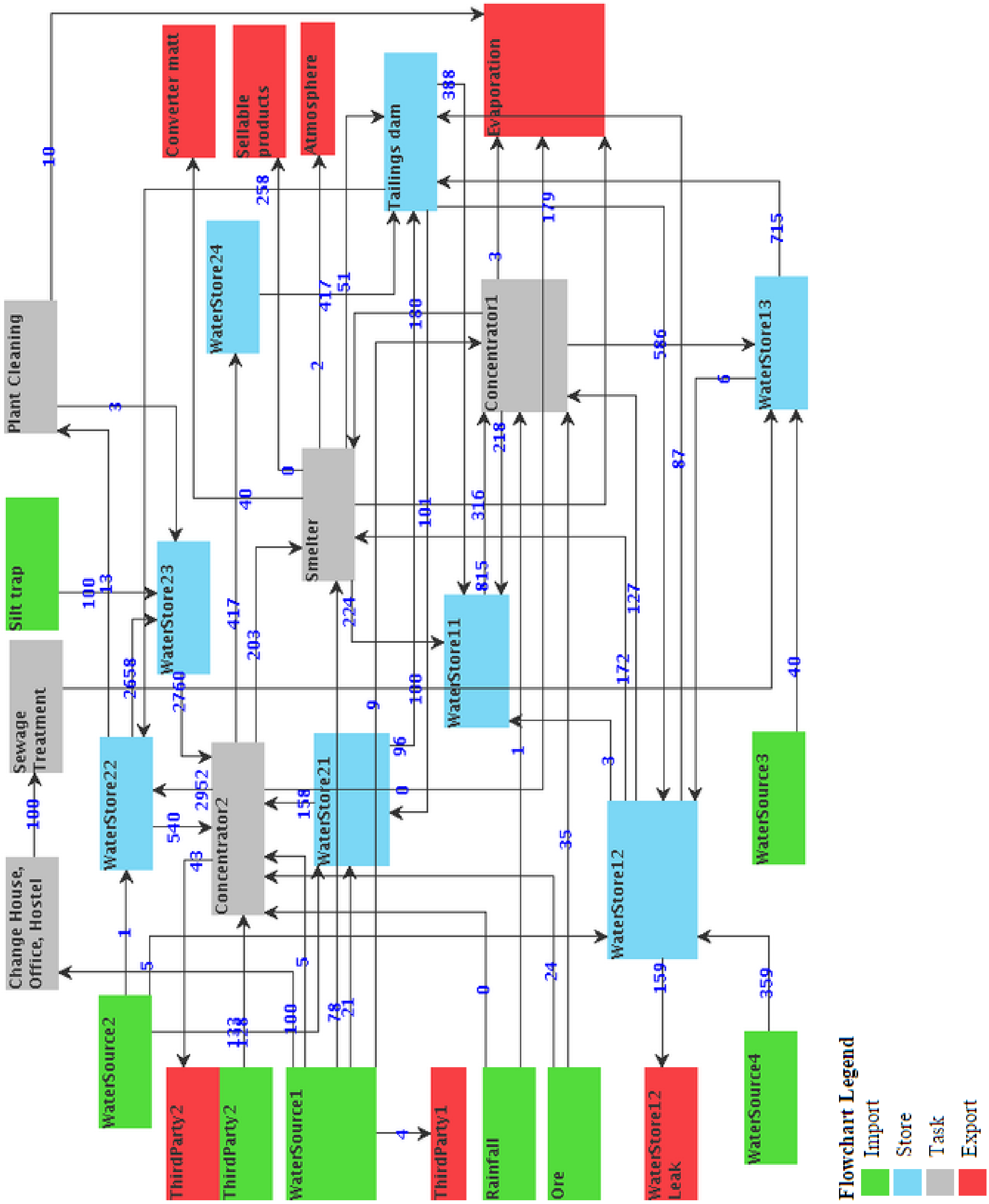

Figure 11: Water flow diagram created with WaterMiner for a platinum mine in South Africa.

Table 11: Water account for a platinum mine in South Africa for one year, June 2012 until May 2013 (ML/year).

Input-Output	**Source/ Destination**	**Inputs/Outputs**	**Water Quality**			**Sub-Element Total (ML)**
			Category 1 (ML)	**Category 2 (ML)**	**Category 3 (ML)**	
Inputs	Surface Water	*Precipitation and Runoff*	115	1 207		1 322
		Rivers and Streams	8 622			8 622
		External Surface Water Storages				0
	Ground Water	*Aquifer Interception*				0
		Bore Fields	483			483
		Entrainment			2 259	2 259
	Sea Water	*Estuary*				0
		Sea/Ocean				0
	Third Party Water	*Contract/Municipal*				0
		Waste Water				
	TOTAL INPUTS		**9 220**	**1 207**	**2 259**	**12 686**
Outputs	Surface Water	*Discharge*				0
		Environmental Flows				0
	Ground Water	*Seepage*	7 361			7 361
		Reinjection				0
	Sea Water	*Discharge to Estuary*				0
		Discharge to Sea/Ocean				0
	Supply to Third Party		45			45
	Other	*Evaporation*	4 185			4 185
		Entrainment			1 008	1 008
		Other				0
	TOTAL OUTPUTS		**11 591**		**1 008**	**12 599**
DIVERSIONS						
Inputs	Surface Water	*Precipitation and Runoff*				0
		Rivers & Streams	45			45
	Ground Water	*Aquifer Interception*				0
	TOTAL DIVERSION INPUTS		**45**	**0**	**0**	**45**
Outputs	Surface Water	*Discharge*				0
	Ground Water	*Reinjection*				0
	Supply to Third Party		45			45
	Other	*Other*				0
	TOTAL DIVERSION OUTPUTS		**45**	**0**	**0**	**45**

The volume of water received from surface sources through municipal supply (68% of the total imported volume) was the largest component. The water imported as entrainment was water entrained in ore and water entrained in a waste product from a third party that is further processed on site. The entrained water accounted for 18% of the water imported. Most of the water exported was through seepage from the tailings dam and a leak from a water store (7 361 ML/year, 58% of volume exported). Water lost as evaporation was 4 185 ML/year (33% of volume exported). Water evaporates from the smelter, tailings dam and open water stores. The water lost as entrainment (1 008 ML/year) was the volume of water that leaves the system with the product and a waste slurry to a third party. No water was returned to surface water.

In Figure 12 it can be observed that the total input volume is higher than the output volume during October 2012, December 2012, April 2013 and May 2013. The highest input volume is observed during December 2012 and the lowest input volume during July 2012. The highest output volume is observed during February 2013 and the lowest output volume during April 2013.

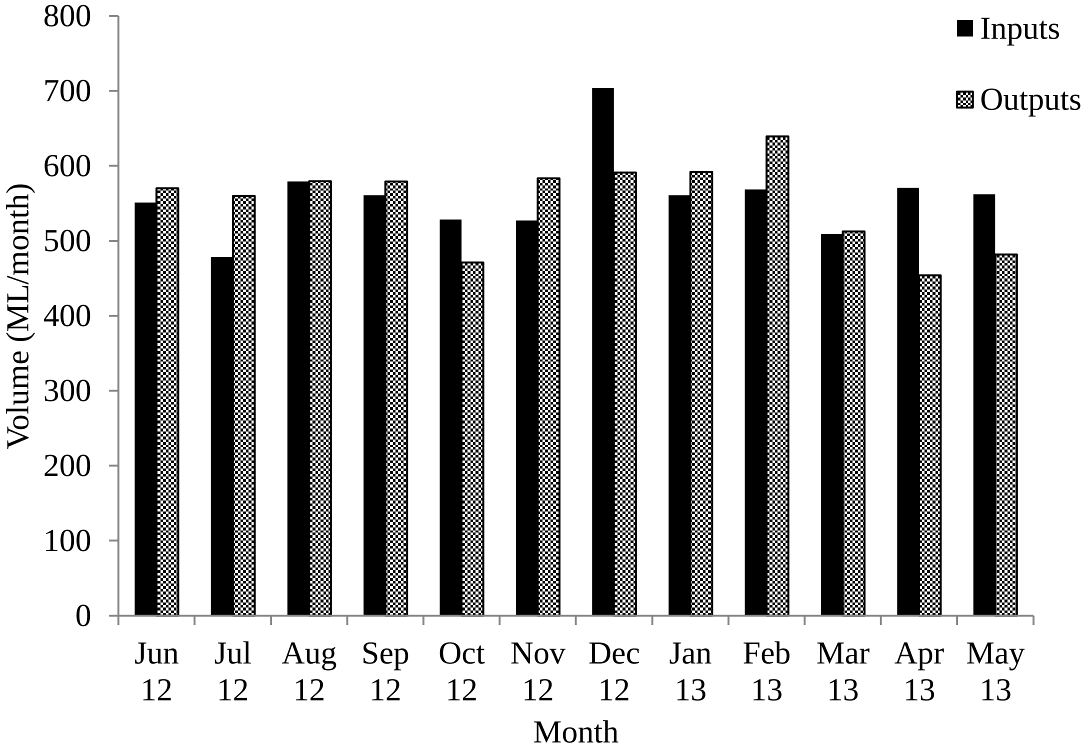

Figure 12: Volume of inputs and outputs for a platinum mine in South Africa from June 2012 until May 2013.

4.2.2 Operational efficiency statement

The operational efficiency statement is a report that states the reuse and recycling efficiency. Water that has been used in a task onsite and was used again without being treated was reused water. Water that has been used in a task onsite and was used again after being treated is recycled water. A low water use efficiency indicates that more water is imported from outside than reused or recycled internally. The operation was thus more depended on outside water resources. If the area was experiencing drought and water restriction was implemented an operation with a low reuse and recycling efficiency will be influenced more by the water restriction than an operation with higher reuse and recycling efficiency.

According to Table 12 all the tasks had high reuse efficiencies and none used recycled water. The change house, office and hostel had the lowest reuse efficiency and the smelter plant had the second lowest reuse efficiency at 70%, while the sewage treatment plant has the highest reuse efficiency at 100%. Concentrator plant 2 had a lower reuse efficiency than concentrator plant 1. Concentrator plant 2 also had a lower intake flow volume than concentrator plant 1. Concentrator plant 2 processes less ore than concentrator plant 1, which can contribute to the lower water requirement.

Table 12: Water reuse and recycle efficiency as calculated by WaterMiner for a platinum mine (ML/year).

Task	**Water flow into tasks**				
	Intake	**Raw**	**Worked**	**Reuse (%)**	**Recycle (%)**
Sewerage treatment plant	1 203	0	1 203	100	0
Plant cleaning	158	0	158	100	0
Concentrator plant 1	43 662	2 733	40 929	94	0
Concentrator plant 2	11 916	1 590	10 326	87	0
Smelter	7 648	2 327	5 322	70	0
Change house, office, hostel	1 203	1 203	0	0	0
Total	**65 791**	**7 853**	**57 939**	**88**	**0**

4.2.3 Accuracy statement

The accuracy statement states the percentage of flows measured, estimated or simulated and the level of confidence of the data used. This can be used to indicate which data was the least reliable. Measures can be taken to increase the confidence of these flows and thus increase the confidence of the results.

Table 13 shows the accuracy statement created using WaterMiner. This was done by assigning a high, medium or low level of confidence to estimated, measured or simulated streams. WaterMiner then calculated the percentage of flows that had a high medium or low level of confidence, based on the volume of the streams and the number of streams.

The total volume of water imported from municipalities was measured and a high level of confidence was assigned to the flow stream. The distribution of the measured flow rates between stores, tasks, inflows and outflows were estimated. Flow rates that were estimated using design criteria (densities and percent solids), estimated using monthly averages and estimated by closing the mass balance were assigned a medium level of confidence. Appendix C shows which streams were measured, estimated or simulated and the level of confidence assigned.

By stream volume 97% of the streams, and by number of streams 93% of streams were estimated. By stream volume 97% of the streams, and by number of streams 89% of the streams had a medium level of confidence. The level of confidence of the data can be improved if more flow meters are installed onsite. This will make the calculations more accurate and increase the level of confidence in the results. None of the streams were simulated or had a low level of confidence.

Table 13: Accuracy statement, for water flows, created using WaterMiner.

Flow Types	**By stream volume**				**By number of streams**			
	Percent of all flows	**Confidence Percent**			**Percent of all flows**	**Confidence Percent**		
		High	**Medium**	**Low**		**High**	**Medium**	**Low**
Measured	3	3	0	0	7	7	0	0
Estimated	97	0	97	0	93	4	89	0
Simulated	0	0	0	0	0	0	0	0
Unassigned	0	0	0	0	0	0	0	0
Total		**3**	**97**	**0**		**11**	**89**	**0**

4.3 Water footprint network method

In this section the blue and grey water footprints calculated for the platinum mine are shown. Because no water is used to maintain agricultural activities, and most of the surface of the operation is unpaved, by definition, the site has no green water footprint.

4.3.1 Total water footprint

The distribution of the total water footprint between the process steps and types of water footprints are shown in Figure 13. The grey water footprint is larger (578 m^3/kg PGM, 71.8%) than the blue water footprint (228 m^3/kg PGM, 28.2%). The tailings dam is the only contributor to the grey water footprint. Concentrator plant 1 had the largest blue water footprint, 124 m^3/kg PGM (15.4%). Concentrator plant 2 had the second largest blue water footprint, 76 m^3/kg PGM (9.5%). The smelter plant and hostel had the third largest blue water footprint, 11 m^3/kg PGM (1.4%). The smallest blue water footprint calculated was for the tailings dam, 4 m^3/kg PGM (0.5%).

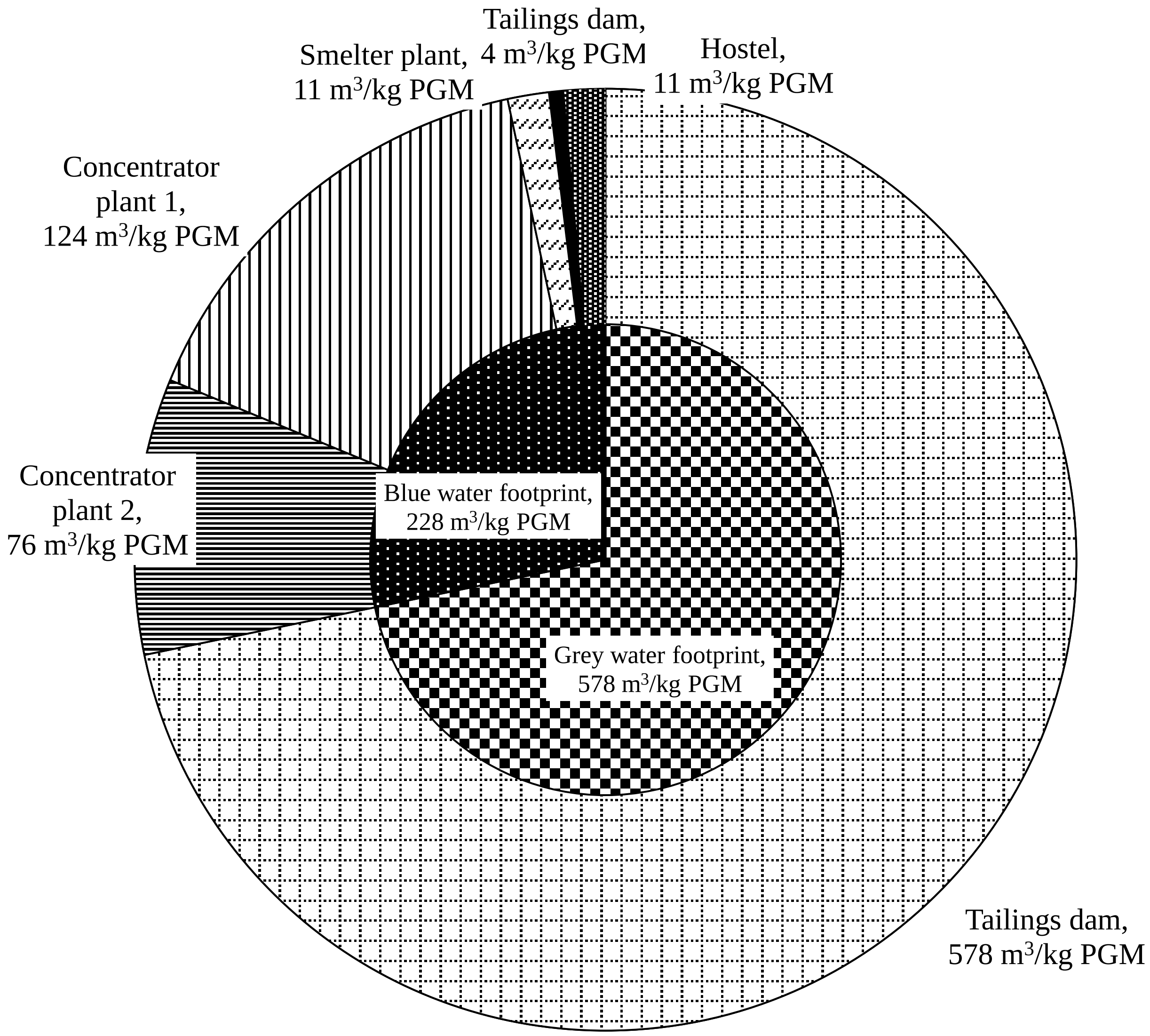

Figure 13: Distribution of the total water footprint between the process steps on an annual basis for June 2012 to May 2013.

4.3.2 Blue water footprint

A blue water footprint is the volume of surface and ground water consumed during the production process. For this investigation the monthly blue water footprint to produce a kg of PGM was calculated. The blue water consumed in two concentrator plants, a smelter plant and the tailings dam was included.

Concentrator plant 1

Figure 14 shows the monthly blue water footprint for concentrator plant 1. From Figure 14 it is observed that the largest blue water footprint occurs during January (174 m^3/kg PGM) and the smallest during October (99 m^3/kg PGM). Less ore was milled during January than in October. If less ore was milled it is expected that less water should be consumed. The opposite was observed for concentrator plant 1. October has the second lowest evaporation rate as is observed from Figure 9. Less water is lost through evaporation during October and less blue water is required to replenish the water lost. For concentrator plant 1, blue water is consumed when blue water imported evaporates from open water surfaces, was transported in the flotation concentrate to the smelter plant and with the waste to the tailings dam. Blue water that enters the system includes water received from rivers through municipal supply and rainfall. The blue water footprint for concentrator plant 1 for one year was 124 m^3/ kg PGM or 0.7 m^3/t ore.

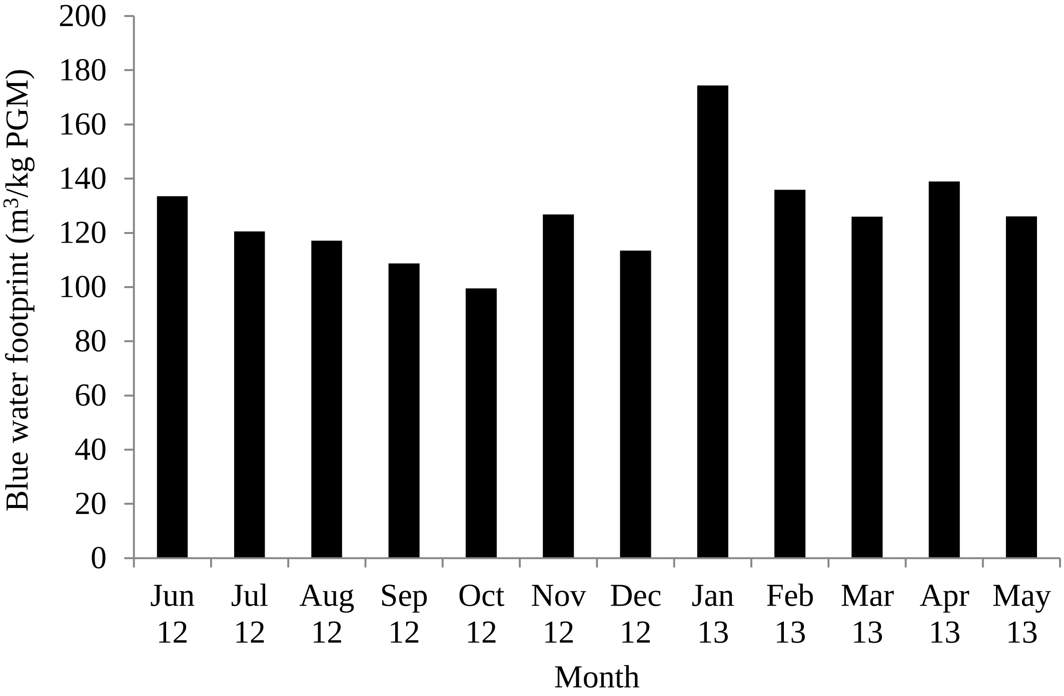

Figure 14: Monthly blue water footprint for concentrator plant 1.

Concentrator plant 2

Figure 15 shows the blue water footprint for concentrator plant 2. The source of blue water and the types of consumption of blue water is the same as for concentrator plant 1. The largest blue water footprint is experienced during January (121 m^3/kg PGM) and December (109 m^3/kg PGM) and the smallest blue water footprint during July (54 m^3/kg PGM). Less ore was milled during January than in July. If less ore was milled it is expected that less water should be consumed. The opposite is observed for concentrator plant 2. From Figure 9, January has the third largest difference between rainfall and evaporation, December the largest and July the third smallest. Because of high evaporation rates during January and December water is lost from open water stores and more blue water is required to replenish the water lost. During July the net evaporation rate is lower and less blue water is required. The blue water footprint for concentrator plant 2 for one year is 76.34 m^3/kg PGM or 0.54 m^3/t ore. Concentrator plant 1 thus has a larger blue water footprint than the concentrator plant 2.

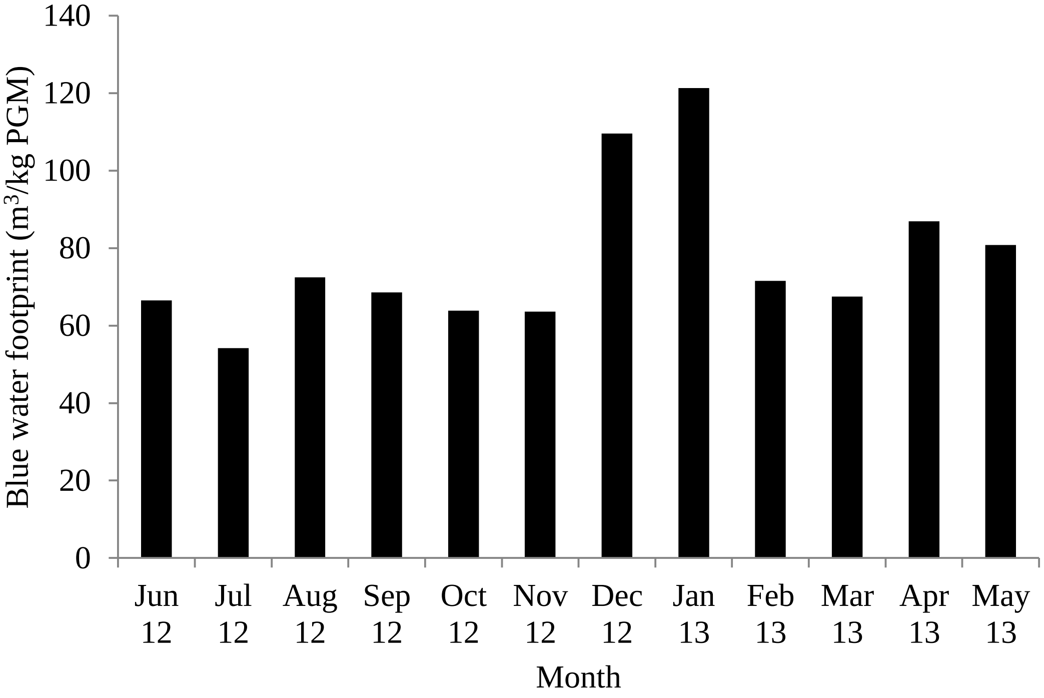

Figure 15: Monthly blue water footprint for concentrator plant 2.

Smelter plant

Figure 16 shows the blue water footprint for the smelter plant. The smelter plant has a small blue water footprint compared to the concentrator plants. Most of the water lost through evaporation in the smelter plant is water contained in the concentrate received from the concentrator plants. This blue water is accounted for in the concentrator plant's water footprint and not again in the smelter plant's water footprint. Blue water is consumed in the smelter plant as evaporation and entrainment in the product. The highest blue water footprint for the smelter plant occurs during January (13.6 m^3/kg PGM) and the smallest blue water footprint during July (8.8 m^3/kg PGM). The blue water footprint for the smelter plant for one year is 11 m^3/kg PGM or 0.07 m^3/t ore.

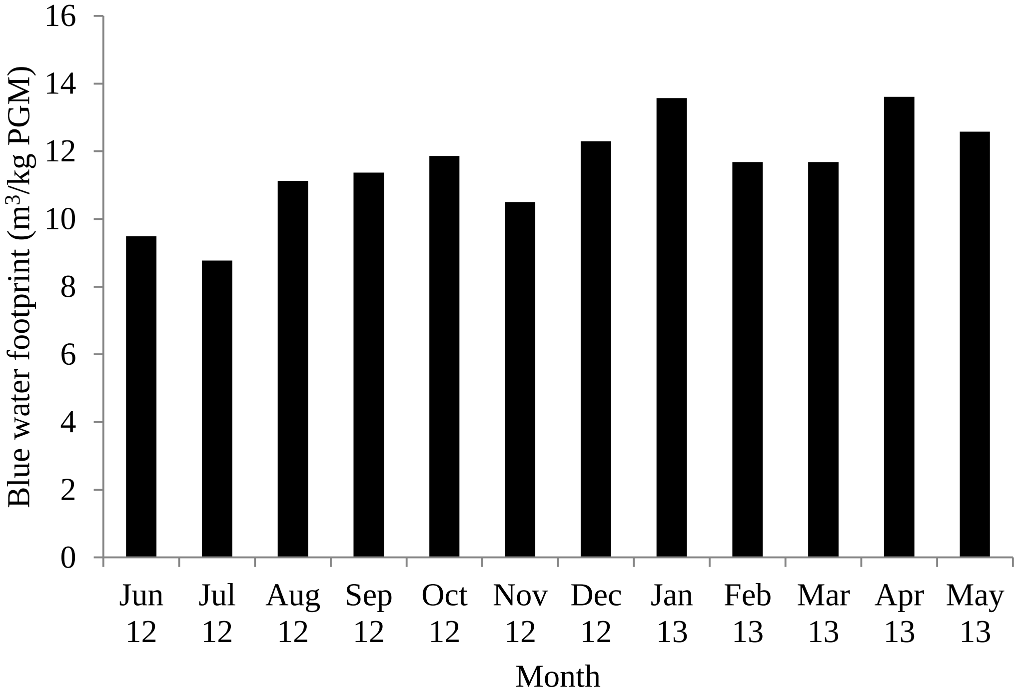

Figure 16: Monthly blue water footprint for the smelter plant.

Tailings dam

Figure 17 shows the blue water footprint for the tailings dam. The tailings dam receives waste water from the concentrator plants and smelter plant, rain water and runoff. Blue water that enters the tailings dam is the volume of rain water (including rain water runoff). Blue water is consumed in the tailings dam if it is reused in the process and lost from the tailings dam through evaporation or seepage. Waste water received from other process steps is not included in the water footprint of the tailings dams, because the blue water contained in these streams has been accounted for in previous process steps. During October (14 m^3/kg PGM) the highest blue water footprint occurs. The blue water consumed in the tailings dam does not have to be replaced by more blue water. For this reason an increase in evaporation will not increase the blue water footprint, because the water lost is replaced by water in waste streams from the concentrator plants and smelter plant. During June, July, August, April and

May no blue water footprint occurs, because during these months there was no rainfall. If no rain enters the tailings dam then no blue water can be consumed in the tailing dam. The blue water footprint for the tailings dam for one year is 4 m^3/kg PGM or 0.026 m^3/t ore.

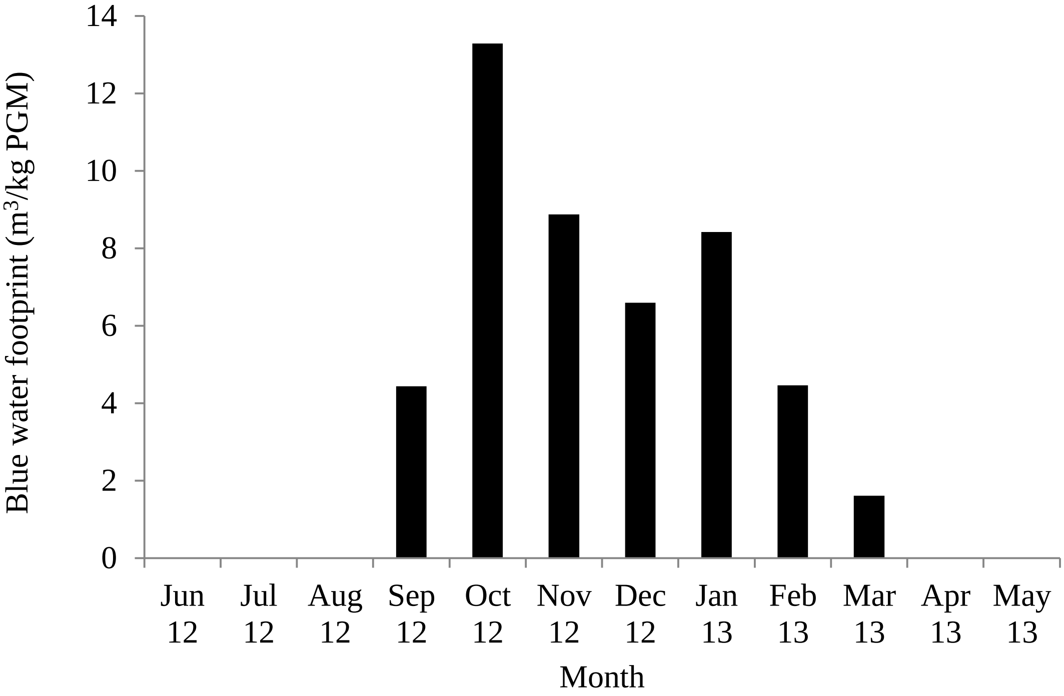

Figure 17: Monthly blue water footprint for the tailings dam.

Platinum processing plant

Figure 18 shows the total blue water footprint for the entire plant. The largest blue water footprint occurs during January (334 m^3/kg PGM) the smallest blue water footprint is found during July (191 m^3/kg PGM). Concentrator plant 1 and 2 also has a larger water footprint during January. From Figure 9 it can be observed that January has the third largest difference between rainfall and evaporation, therefore more water is lost during January. The lost water is replenished from blue water sources and thus cause and increase in the blue water footprint. The total blue water footprint for one year is 228 m^3/kg PGM, 1.4 m^3/t ore or 10 649 ML/year.

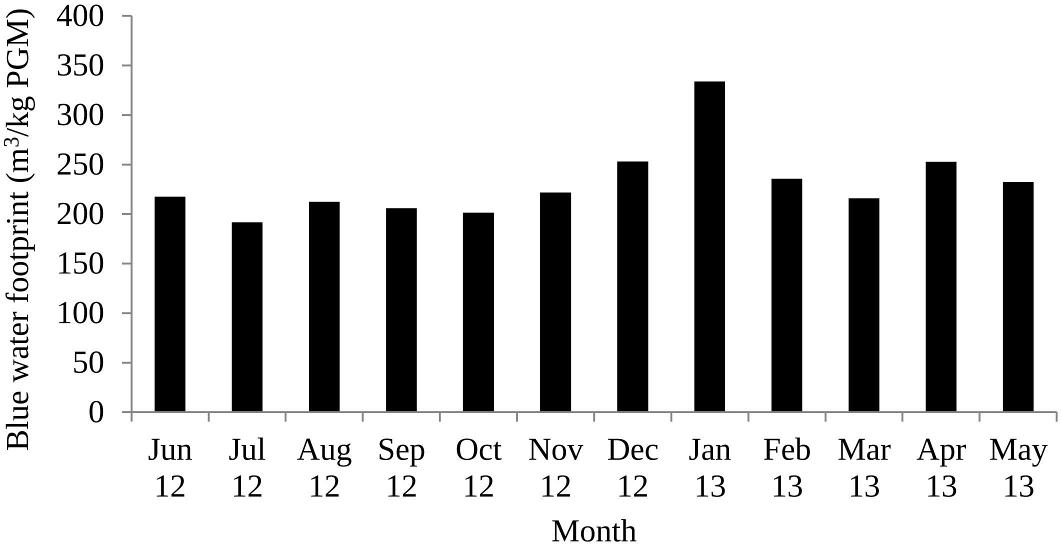

Figure 18: Total monthly blue water footprint for a platinum processing plant.

Figure 19 shows that concentrator plant 1 makes the largest contribution to the total blue water footprint every month. In December the contribution made by concentrator plant 1 and 2 was almost equal. The tailings dam and smelter plant have very small water footprints compared to the concentrator plants.

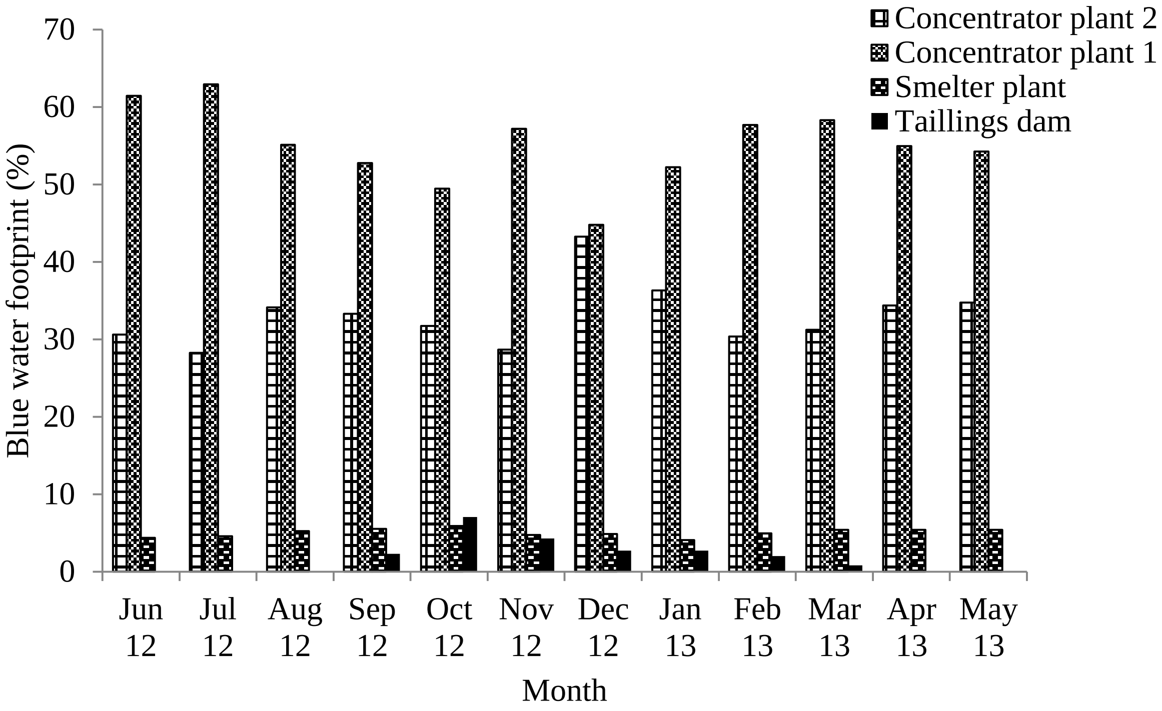

Figure 19: Distribution of the total blue water footprint between the process steps on a monthly basis from June 2012 to May 2013.

4.3.3 Grey water footprint

For both the concentrator plants there is no grey water footprint because water leaves the concentrator plants as evaporation or as process water to the smelter and tailings dam (both defined as blue water). Further, no water is released from the concentrators directly into a water resource.

The tailings dam has the only grey water footprint, 578 m^3/kg PGM, caused by seepage from the tailings dam into an underground aquifer. The total water footprint for the platinum mine is 806 m^3/kg PGM.

Figure 20 shows seven chemical contaminants that could cause a grey water footprint. The critical component that is responsible for the grey water footprint is magnesium. If the magnesium concentration is lowered by at least 55% to cause a grey water footprint of less than 261m^3/kg PGM then calcium will be the new critical contaminant. Magnesium and calcium possibly enters the system with the ore as waste or with ground water.

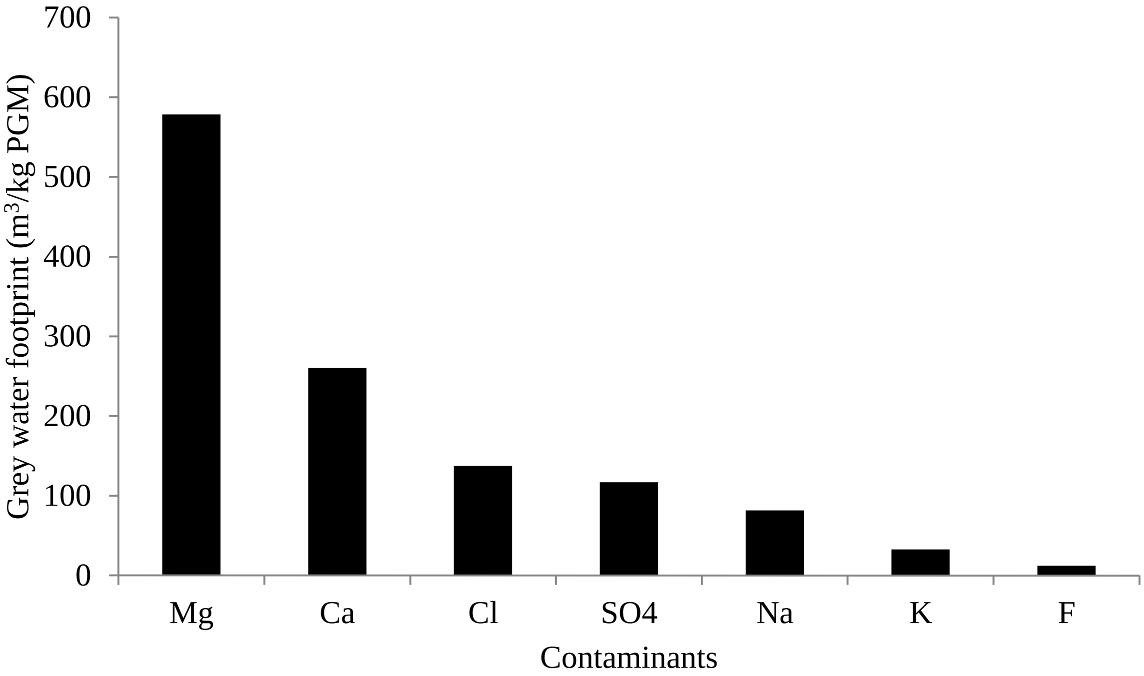

Figure 20: Grey water footprint in the tailings dam seepage based on by different contaminants present.

4.3.4 Response formulation

In this section possible options to reduce the water footprint of the platinum mine are discussed.

Evaporation reduction

Evaporation accounts for 60.79% of water consumed onsite. More water evaporates from open surfaces than water entering as rain water as is shown in Figure 10. Evaporation can be reduced by making the evaporation surface smaller and by covering any open surfaces to prevent evaporation leaving the system and rain water entering the system (Gunson *et al.*, 2012). Floating modules can be placed on the tailings dam. These modules can prevent up to 80% evaporation depending on the shape and amount of modules used (Marris *et al.*, 2011). Most water from the tailings dam can be reused within the concentrators and smelter plants and thus reduces the blue water footprint for these plants. The blue water footprint can be reduced to 204 m^3/kg PGM (10% reduction) and 1.27 m^3/t (9% reduction).

Pre-concentration

A pre-concentration step can be added between the crushing and milling processes for concentrator plant 2. This would allow waste water to be separated before the milling and flotation processes, because less material has to be processed there would be a decrease in energy and water demand. Since less waste material is processed the tailings storage facility would be smaller and less water could be lost in the tailings dam. Separation is possible due to the density difference between platinum reef and the silicate waste material. Ferrosilicon is mixed with ore and send to a cyclone. Possible pre-concentration processes include X-ray transmission (XRT), X-ray fluorescence (XRF) (Smith *et al.*, 2013) and dense medium separation (DMS). The recommended method of pre-concentration is DMS (Smith *et al.,* 2013). If pre-concentration step is added, up to 15% of fresh water can be saved (Smith *et al.,* 2013). If the pre-concentration step is added, the blue water footprint for concentrator plant 2 could be reduced to 64.89 m^3/kg PGM and 0.46 m^3/t, with the total blue water footprint reduced to 216 m^3/kg PGM (5% reduction) and 1.34 m^3/t (4% reduction).

4.4 Financial value of water used during product production

The financial value for the volume of water consumed during production of PGM and agricultural products were calculated. This information could be used by governments in times of drought to decide on how to distribute the water from a particular catchment. From Table 14 it can be observed that grapes (250.31 R/m^3) have the greatest financial value per m^3 for agricultural products. The agricultural product with the lowest financial value per m^3 is sunflower seed oil. All of the food products shown in Table 14 have a smaller financial value than PGM (686 R/m^3).

PGM production consumes the largest volume of water at 806 161 m^3/ton. This value seems high but as shown in section 1 mining only consumes 5% of South Africa's water resources (Stats SA, 2012). All the agricultural products consume less water than PGM production, with clove production the largest for agricultural products at 56 429 m^3/ton and tomato production the smallest at 117 m^3/ton.

Table 14: Water financial values for PGM and food products in South Africa.

	m^3/ton	**R/ton**	**R/m^3**
PGM	806 161.00	553 007 693.00	686.00
Grapes	426.00	106 633.33	250.31
Tomatoes	117.00	16 990.00	145.21
Potatoes	224.00	21 414.29	95.60
Pepper	7 458.00	621 111.11	83.28
Nuts	3 998.00	266 583.33	66.68
Lemons	511.00	32 929.41	64.44
Dates	2 961.00	112 475.00	37.99
Sunflower seed	3 016.00	103 800.00	34.42
Apples	482.00	15 993.33	33.18
Coconut oil	7 724.00	231 995.66	30.04
Grapefruit	378.00	11 326.67	29.96
Onions	496.00	13 990.00	28.21
Bananas	751.00	17 491.67	23.29
Poultry meat	5 390.00	103 376.47	19.18
Barley	1 188.00	21 900.00	18.43
Coffee	20 152.00	349 750.00	17.36
Mutton	9 173.00	155 000.00	16.90
Tea	6 532.00	107 800.00	16.50
Peas	1 966.00	31 900.00	16.23
Cloves	56 429.00	898 333.33	15.92
Pig meat	6 307.00	98 780.00	15.66
Sweet potatoes	2 457.00	37 980.00	15.46
Beans	3 133.00	39 900.00	12.74
Olive oil	13 408.00	164 599.34	12.28
Milk	1 112.00	12 572.67	11.31
Sesame seed oil	32 554.00	361 832.06	11.11
Oranges	443.00	4 857.14	10.96
Eggs	3 902.00	33 515.33	8.59
Oats	2 961.00	23 850.00	8.05
Beef	17 325.00	135 000.00	7.79
Sugar	1 275.00	9 180.00	7.20
Rice	3 294.00	16 950.00	5.15
Maize	1 698.00	8 380.00	4.94
Sunflower seed oil	6 084.00	14 121.68	2.32

Chapter 5 DISCUSSION

5.1 Variation in water accounting framework and water footprint network methods

For this study the volume of water consumed on a platinum mine were calculated using two methods: Water Accounting Framework (WAF) and the Water Footprint Network (WFN) method. Included in the study were two concentrator plants, a smelter plant and the tailings dam. Table 15 is a summary of the differences between the WAF and WFN methods observed during the study.

According to the WAF results, 12 686 ML/year of water was imported into the mine site from June 2012 until May 2013. The total water footprint of the mine (WFN method) was 10 649 ML/year. The difference in the water consumption values is because the methods define inputs differently. The imports of the WAF include blue (ground, surface water) and green (rain water) water sources but also sea water and third party waste water, that are not included in the WFN method. Therefor the volume of water consumed according to the WAF should always be equal to or greater than the blue and green water footprints.

WAF is a method to report water use information in a consistent manner, while the WFN determines the volume of the global water resource that is consumed. A rough comparison between the values from the methods can be made to determine if the order of magnitude is correct and if the water use efficiency is within acceptable limits. If a stricter comparison is required the values obtained from the methods should not be compared.

Table 15: Summarised comparison of WAF and WFN methods (SMI & MCA, 2012 and Hoekstra *et al*., 2011).

	WAF	**WFN**
Aim	Publish and compare water use in mining in consistent manner.	Quantify volume of global fresh water being consumed.
Water sources/inputs	Includes wastewater, ocean, third party. Only includes direct water consumed.	Consumption and pollution of scarce water resources (Ground, surface and rain water) Include direct and indirect water consumed.
Application	Mining	All sectors

Including a grey water footprint in the WFN method is useful because it alerts operations to be aware of the pollution caused by their operations and not just the volume of water used by the operation. This could also lead to more companies weighing the effect of releasing polluted water into environment versus treating the water and reusing it within the system, or allowing another operation to use the wastewater if a lower quality water can be used in the second operation. The WAF does not have a volume indicator for pollution that is similar to the grey water footprint of the WFN. The WAF has 3 quality categories that is assigned to the sources the imports and the destinations of the exports.

5.2 Water intensity of metals

As shown in Table 16 Glaister & Mudd (2010) calculated the water intensity values for platinum mines in South Africa and Zimbabwe. The maximum water use calculated was 1 612 m^3/kg PGM or 12.6 m^3/t ore, while the minimum water use was shown to be 192 m^3/kg PGM or 0.509 m^3/t ore. The average water use for all sites investigated was reported as 391.5 m^3/kg PGM (Table 16). Mudd (2008) calculated the world average water consumption values for platinum as 0.94 m^3/t ore or 260 m^3/kg PGM (Table 10).

The blue water footprint calculated for this study, which included two concentrator plants and a smelter plant was 228 m^3/kg PGM or 1.4 m^3/t ore. These values fall within the range reported by Glaister & Mudd (2010) and below the world average 260 m^3/kg PGM value but above the 0.94 m^3/t ore value reported by Mudd (2008). The reason for this difference is because of different ore grade, processing techniques, rainfall and evaporation. This indicates the mine studied in this investigation uses water in an efficient way compared to other operations producing the same metal. The water consumption values for the mine are not the lowest compared to other producers of PGM, thus indicating that water could be used more efficiently on site. The blue water footprint calculated in this study is smaller than the blue water footprint calculated for platinum by Ranchod *et al.* (2014) (2 229x10^3 m^3/ton of refined platinum). This is because Ranchod *et al.* (2014) also included magnetic separation, base metals removal and precious metal refining process steps.

Mudd (2008) stated that gold uses the largest volume of water per tonne metal and platinum the second largest. Compared to the results of Mudd (2008) (Table 10), the water use calculated for platinum in the current study is smaller than for gold and larger than the other metals (bauxite, black coal, copper, diamonds, zinc, lead, silver, nickel and uranium) investigated by Mudd (2008). According to Mudd (2008) platinum is the second lowest user of water/t ore. When comparing the current study results to that of Mudd (2008), the platinum mine is the third greatest user of water/t ore. Only gold and a combination of zinc, lead, silver, copper and gold use more water.

Table 16: Comparison of water use of other mines to water use of the platinum mine investigated.

Reference	**Mineral**	**Location**	**Water consumption**
Glaister & Mudd, 2010	Platinum	South Africa and Zimbabwe	391.5 m^3/kg PGM
Mudd, 2007a	Gold	Global	1.42 kL/t ore and 691 kL/kg Au
Mudd, 2007b	Gold	Australia	0.88 kL/t ore and 325 kL/kg Au
Northey *et al.*, 2013	Copper	Global	74 kL/t Cu
Ranchod *et al.*, 2014	Platinum	South Africa	Blue water footprint: 2 229x$10^3$$m^3$/ton of refined platinum
Current study	Platinum	South Africa	Blue water footprint: 228 m^3/kg PGM, 1.4 m^3/t ore

5.3 Financial value of water used during product production

The financial value for the volume of water consumed during production of PGM and agricultural products were calculated, to determine which is more important during a drought. The financial value of water consumed during PGM production is higher than for agricultural products, therefor, from a strictly financial point of view South Africa will receive more capital per volume of water consumed if PGM is produced instead of agricultural products.

If water becomes a scarcity, continuing mining of PGM is the best option from a financial point of view because PGM has a higher water financial value than agricultural products. If the water is used for mining instead of agricultural product production, the food prices will increase because less food will be produced in the country. Food will have to be imported which will increase the price. By mining and selling PGMs, money could be brought into the country and people working in PGM related fields would be able to afford the more expensive food.

If the water is used for agricultural product production instead of PGM mining, food prices would be less affected. The agricultural sector will still be supplied with the same volume of water and can produce the same amount of food. There will not be a decrease in food production and therefor the prices should not increase. The PGM production will receive less water and experience a decrease in production, the PGM companies will have a smaller profit and workers could possibly lose their jobs.

Chapter 6 CONCLUSIONS

The mine is located in a country where all the rivers have at least three months of severe water scarcity during a year. This indicates that it is necessary for the mine and other operations located within South Africa to be aware of the volume of water consumed and make efforts to reduce the volume of water consumed.

The Water Accounting Framework (WAF) and Water Footprint Network (WFN) methods can both be used to calculate water use values on a mine site. The blue and green water footprints of the WFN are also imports in the WAF. The WAF includes sea and waste water that are not included in the footprints calculated with the WFN. Therefore, results obtained with the two methods would not give the same water use values, but could be used if a rough comparison between sites is required.

According to the WAF results, 12 686 ML/year of water was imported into the mine site from June 2012 until May 2013. The total water footprint of the mine (WFN method) was 806 m^3/kg PGM (10 649 ML/year). When these results were compared to other operations producing PGM (192 m^3/kg PGM to 1 086 m^3/kg PGM), the mine used in this study operates with in the range of other Platinum Group Metal (PGM) mines located in South Africa. The average water use for PGM mines located with in South Africa is 391.5 m^3/kg PGM. The mine in this investigation consumes more water per kg of PGM produce than the average for PGM mines in South Africa.

Several methods can be used to reduce the water used on the mine site. These include covering the tailings dam and adding a pre-concentration step to concentrator plant 2. If the tailings dam is covered, evaporation will be reduced by 80% or an equivalent of 10% (204 m^3/kg PGM) of the total blue water footprint. If a pre-concentration step is added to concentrator plant 2, the total blue water footprint could be reduced by 5% to 216 m^3/kg PGM.

Economically, the water is more important in PGM extraction than it is in producing agricultural products. If PGM products were produced instead of agricultural products, the country would receive more capital.

Chapter 7 RECOMMENDATIONS

Based on the results of this study the following recommendations can be made:

- Cover the tailings dam to prevent evaporation.
  By covering the dam, the total water footprint can be reduced from 228 m^3/kg PGM to 204 m^3/kg PGM, a saving of 9%.

- Add a pre-concentration step to concentrator plant 2.
  The blue water footprint of concentrator plant 2 could be reduced from 76.3 m^3/kg to 216 m^3/kg PGM, a saving of 4% if a pre-concentration step is added.

It is recommended that if similar studies were to be done in the future, all flow rates should be calculated instead of, as in this study, calculating unknown flow rates. This will ensure that the results are more accurate.

PGM production has more financial value for the volume of water consumed than agricultural production. Based on financial considerations alone it would be recommended that PGMs should be produced instead of agricultural products during drought.

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APPENDICES

APPENDIX A: GREY WATER FOOTPRINT QUALITY DATA

A grey water footprint was calculated for tailings dam seepage into ground water. To calculate the grey water footprint the natural contaminant concentration (C_{nat}) and the maximum allowable concentration (C_{max}) in the ground water has to be known. For the natural contaminant concentration in the ground water it was assumed that the natural concentration is equal to the actual measured concentration of the contaminants in the ground water. For the maximum allowable contaminant concentration the drinking water quality (DWAF, 2005) was used.

Table 9 below shows the natural concentration and the maximum concentration used to calculate the grey water footprint caused by seepage from the tailings dam.

Table 9: Water quality data used to calculate the grey water footprint.

Contaminant	**Ground Water (C_{nat}) (DWAF, 2013)**	**Drinking water quality (C_{max}) (DWAF, 2005)**
Ca (mg/l)	77.855	< 150
Cl^- (mg/l)	10.3645	< 200
Electrical conductivity (mS/m)	63.85	< 150
F^- (mg/l)	0.3235	< 1.0
K (mg/l)	3.083	< 50
Mg (mg/l)	34.31	< 70
Na (mg/l)	15.611	< 200
NH_4 as N (mg/l)	0.025	< 1.0
$NO_3 + NO_2$ as N (mg/l)	4.2635	< 10
pH	8.538	5 – 9.5
SO_4 (mg/l)	3.5225	< 400

APPENDIX B: PAPER: WATER FOOTPRINT FOR A SOUTH AFRICAN PLATINUM MINE

Water in Mining 2013

Paper Number: 65

Water Footprint for a South African Platinum Mine

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Abstract

Mining is a water intensive sector, contributing to declining water resource quality around the world. Improvements to current mine water management practices can help reduce the amount of water utilised by the mining sector and the impact on water resources. Creating a water account can help companies understand water use in their operations and identify areas where water reduction is possible. Water accounting methods include the Water Footprint Network method and the WaterMiner tool.

The Water Footprint Network method is used to determine the amount of direct and indirect water used by an organisation in a process or to manufacture a product. The total water footprint is divided into the blue-, green-, and grey water footprints. Blue water is the amount of water abstracted from surface and ground water resources. Green water is the amount of rain water utilised. Grey water is the amount of freshwater required to assimilate the waste stream to the natural resource and still conform to ambient water quality standards.

The WaterMiner tool is a program available via the internet, which can be used to model water use of mineral processing sites. The program reports the amount of raw, worked and treated water used by the process and recommends flows that can be added to reduce the amount of fresh water required by the process.

To gain information on mine water management practices in South Africa, a water account for a platinum mine was developed using the Water Footprint Network method and WaterMiner tool. Based on the results, suggestions to reduce the amount of fresh water utilised are made.

Introduction

Unpolluted water resources in South Africa and in the rest of the world are declining. The proper use and management of water resources is therefore a necessity for ensuring a sustainable water supply for anthropogenic and non-anthropogenic use.

The mining industry consumes 3% of the total water withdrawn in South Africa (Statistics South Africa, 2000) and yet is one of the industries responsible for significant deterioration of water quality in South Africa. These water requirements can be reduced with correct implementation and/or improvement of current mine water management strategies. Any reduction in mine water requirements will reduce the demand and hence pressure on current water resources and hence the impact on water quality. A reduction in water use is not only necessary to ensure clean water for human use and the environment, but will also help to ensure that future mine water requirements are met without placing additional burdens on available resources.

In order to reduce water usage, an operation must first understand how water is used within the process: where does it originate, how much does it use, what are the return flows and their qualities. This information could also be benchmarked with other (similar or dissimilar processes) to compare a specific plant's water use in order to understand if the operation is utilising the resources efficiently.

This can be done by calculating a water balance for the process. Two methods that can be used are the Water Footprint Network method and the WaterMiner tool.

Background

Water Footprint Network Method

Water footprinting is an accounting method used to determine the amount of direct and indirect water consumed and polluted by an organisation; either in a process or to manufacture a product (Hoekstra *et al.*, 2011). Information obtained from a water footprint can be used to improve the water management plan and thus reduce the water requirement of the mining operation.

The water footprint of a country was first defined by Hoekstra and Hung (2002) as the sum of the net virtual water of crops imported into a country and the volume of water used inside the country to produce the products consumed by the people in the country. Virtual water contained in a product is defined as the amount of water required to produce the product. Chapagain and Hoekstra (2004) calculated the water footprint of nations by calculating the volume of water used for crops, livestock, industrial process and domestic use. Before the water footprint concept was introduced the amount of water used by a country was defined as the amount of water used to produce products, within the country The water footprint defines the amount of water used by a country as the amount of water used to produce the products consumed within the country. The water used for livestock included the water used to produce their feed, the volume of water used for drinking and service water. The water footprint for crops included the volume of water used for irrigation. This study included both surface and ground water (blue water) and precipitation (green water). Internal water footprints of a nation were defined as the volume of water used within a country to produce the products and services consumed by the people inside the country. External water footprint was defined as the volume of water used outside the country to produce the products and services imported and consumed inside the country. To calculate the water footprints of countries the water footprints of products has to be known. Chapagain *et al.* (2006) provides an example of calculating the water footprint for cotton. In this study the effect of pollution, caused by the process, on the local environment is taken into account. It was defined as the volume of water required, to dilute the water returned to surface and ground water resources, to such an extent that the concentration of the contaminants in the water resource remains below an agreed value.

According to the latest water footprint assessment manual (Hoekstra *et al.*, 2011) the water footprint for any given stage of a process is the sum of the blue, green and grey water footprints. The water footprint of a product is the sum of the water footprints for each processing stage used during production of a product.
The latest definitions of blue, green and grey water footprints for a process are (Hoekstra *et al.*, 2011):

Blue water

The blue water footprint of a process is the volume of ground and surface water that is consumed in the process. Consumption is defined as water that is not returned to the same water resource or returned during the same time (lost return flow), lost through evaporation or integrated into the product and is shown by equation 1. Evaporation includes water that evaporates from any stores, during transport, process and collection and disposal.

$$\mathrm{WF_{proc,blue}} = \mathrm{Blue\ Water_{Evaporation}} + \mathrm{Blue\ Water_{Incorporation}} + \mathrm{Lost\ Return\ flow}$$

[volume/time] Equation 1

Green water

The green water footprint of a process is the volume of rain water integrated into the product or lost through evaporation from open water surfaces and is calculated by equation 2.

$$\mathrm{WF_{proc,green}} = \mathrm{Green\ Water_{Evaporation}} + \mathrm{Green\ Water_{Incorporation}} \quad \text{[volume/time]}$$

Equation 2

Grey water

The grey water footprint for a process is the volume of clean water required to dilute pollutants in the waste water, to such an extent that it does not disturb the ambient water quality of the catchment into which it is released. The volume of clean water required is calculated with equation 3:

$$\mathrm{WF}_{\mathrm{proc,grey}} = \frac{\mathrm{L}}{\mathrm{C}_{\mathrm{max}} - \mathrm{C}_{\mathrm{nat}}} \quad \text{[volume/time]} \qquad \text{Equation 3}$$

L – pollutant load (mass/time)
C_{max} – ambient water quality of the pollutant (mass/volume)
C_{nat} – natural concentration in the catchment (mass/volume)

The grey water footprint is calculated for every contaminant present in the waste stream. The total grey water footprint is the water footprint for the contaminant with the largest grey water footprint. The grey water footprint is included because it is assumed that the volume of water used to dilute the contaminants to the natural concentration of the water resource, is not available for use by downstream users. The grey water footprint is not a volume of water used by the operation but an indication of pollution.

The Hoekstra *et al*. (2011) water footprint calculation method has had limited use in the mining and minerals industries.

The WaterMiner tool

WaterMiner was developed by the Centre for Water in the Minerals Industry (CWiMI) at the University of Queensland. It is available via the internet and can be used to model water use. The results obtained can be used to improve water management on site. The user provides the program with flow rates between imports, exports, tasks, water stores and treatment plants. The tool calculates the volume of water imported, exported, recycled and re-used (Centre for Water in the Minerals Industry, 2013). The program can be used to identify where water can be re-used and recycled, as well as make recommendations for stream reduction (Tobin, 2011).

Tobin (2011) used WaterMiner to assess the water use of four Australian gold mines, Newmont Jundee, Kalgoorlie Consolidated Gold Mine, Newmont Tanami and Newmont Waihi Gold. As part of the results reuse and recycling efficiencies are provided, this can be used to identify the tasks where the most improvements can be made. WaterMiner also provides a list of replacement flows, which suggests alternative sources and destinations for current flows. The list is used to identify all possible water sources available for an object and all possible water resources the water can be transferred to (Tobin, 2011). A table of additional replacement flows are also given. This lists water flows that can be used in addition to the water flows already on site (Tobin, 2011). By implementing some of the recommended replacement flows Tobin (2011) was able to save between 8 and 31% of freshwater used by the mining operations.

For the Newmont Jundee operation, the two tasks with the lowest reuse and recycling efficiency was water used in the mine village and tailings storage facility. By implementing four of the recommended replacement flows the amount of water used by the mining operation can be reduced by 174.99 ML/yr or 8.01%.

The Kalgoorlie Consolidated Gold Mine had one task with a low water reuse and recycling efficiency (40%), the Fimston Gold Plant. Through implementing two recommended replacement flows the freshwater usage can be reduced by 1479.04 ML/yr or 31.27%,

For the Newmont Tanami operation, the ore crushing had a reuse and recycling efficiency of 35% and the milling platform had a reuse and recycling efficiency of 53%. By implementing three of the recommended replacement flows the freshwater usage can be reduced by 329.84 ML/yr or 17.2%.

The Newmont Waihi Gold operation had a reuse and recycling efficiency for the tailings storage facility of 0% and for road water/belt wash the reuse and recycling efficiency was 10%. By implementing two recommended replacement flows the fresh water usage can be reduced by 1031.23 ML/yr or 14.67%.

Process and water flow description

The major process steps in the platinum recovery process are: mining, concentrating, smelting, base metal recovery and precious metal refining. This investigation focuses on the water use of the two concentrator plants and the tailings dam. Different types of platinum ores have different gangue materials and different grain sizes of precious metals and sulphides, and thus are processed in different concentrators, under different conditions

(Liddell, McRae and Dunne, 1985). For the site investigated, the concentrator process included crushing, milling and flotation which are each discussed below. The aim of concentration is to separate the waste material from the platinum group metals. Figure 1 shows a simplified water flow sheet for the concentrators and tailings dam.

Crushing and milling

The ore is processed in crushing and milling to reduce the coarse ore to fine particles, liberating the sulphide containing platinum group metals, iron, nickel and copper from the waste ore. This allows for easy separation during flotation (Crundwell *et al.*, 2011). Water is added during milling to form a slurry; allowing for easy transportation of small particles and to adjust the density of the slurry for flotation.

Flotation and tailings dam

Flotation separates the valuable metals from the waste material (Crundwell *et al.*, 2011). The driving force for the separation is the difference in surface hydrophobicity. Various reagents are added during flotation which can include guar and carboxymethyl cellulose; used as depressants to prevent naturally floating materials from entering the froth (Wiese *et al.*, 2007). Xanthates and dithiophosphates are added as collectors to enhance the hydrophobicity of the valuable mineral (Cramer, 2001). Copper sulphate is added as an activator to allow strong mineral-collector attachments to form (Cramer, 2001). Air is pumped through the solution to carry the platinum compounds to the surface. The top product or concentrate is rich in platinum group metals and is sent to smelting. The bottom product (waste) or tailings is sent through a cyclone and thickener to remove water before being sent to the tailings dam. Water can be recovered from the cyclone, thickener and tailings dam and reused in the process. The tailings dam is where most of the water is lost due to evaporation, seepage and entrainment in the tailings.

Method

The method described by Hoekstra *et al.* (2011) was used to calculate the direct water footprint for the two concentrator plants as well as the tailings dam of a platinum processing plant located in South Africa. The water footprint results were then compared to the results obtained by using the WaterMiner tool.

Included in the investigation are the water stores and tasks (offices, change houses, reagent mixing) associated with the operation. For the concentrator plants and tailings dam a blue, green and grey water footprint was calculated to determine the total water footprint of the processes. Green water was included because of the large exposed surface area of the tailings dam.

Inlet flow rates, flow rate data to some of the stores as well as tasks for the calendar year 2012 were provided by the mining company. Any unknown flow rates were calculated based on equipment design criteria, or by closing the water balance. Water from change houses and offices are treated and reused in the process. The water footprint for this treatment plant was not included in the study.

Rainfall data was provided by the company and average monthly evaporation data for 1986 for a station approximately 60 km away were used. This data was used to calculate the volume of rain water that enters the process streams by falling into any open water stores and the volume of water lost through evaporation.

For this plant, water leaves the system boundary as seepage, evaporation or flow to the smelter. Water used in the process is obtained from municipalities, surface water sources and water reused from the tailings dam, sewage treatment plant and smelter. No blue water is returned to water resources from which it was received. The grey water footprint was calculated by using the concentration of contaminants in tailings dam instead of the concentration when it enters the aquifer. The maximum allowable concentration in the ground water was taken as the drinking water quality (DWAF, 2005) and the natural concentration was obtained from the Department of Water Affairs and Forestry (DWAF, 2013). Water quality data was provided by the company.

The data obtained was used to create flow diagrams for the concentrators and tailings dam. A list of imports, stores, tasks, treatment plants and export were created. This data was then used to run the WaterMiner simulation.

Results

For the two concentrator plants and the tailings dam, the total water footprint was calculated 11 811 ML/yr. These results are presented in Figure 2 to Figure 5.

As is seen from Figure 2 the grey water made the largest contribution to the total water footprint accounting for 50% (5 929 ML/yr), of the total water footprint. The blue water footprint was second largest (47%, 5 537 ML/yr) and the green water footprint (3%, 344 ML/yr) the smallest. According to Figure 3 the tailings dam makes up 53% (6 253 ML/yr) of the total water footprint. The reason is the large amount of water gained through precipitation and the pollution created by the seepage. Concentrator plant 2 has a larger water footprint (3 594 ML/yr) than concentrator plant 1 (1 965 ML/yr) because it processes more ore and use more water per gram platinum group metals produced. For concentrator 2 plant the water footprint is 125 L/gpgm and for concentrator plant 1 it is 94 L/gpgm.

For both the concentrator plants there is no grey water footprint because water leaves the concentrator plants as evaporation or as process water to the smelter. The tailings dam has the only grey water footprint (5 929 ML/yr), caused by seepage from the tailings dam into an underground aquifer.

The tailings dam has no blue water footprint (Figure 4), because all the water entering the tailings dam is waste streams from the concentrator plants. The blue water footprints for concentrator plant 1 and 2 are 3 578 ML/yr and 1 960 ML/yr. The tailings dam has the largest open surface area and thus also the largest green water footprint (324 ML/yr) (Figure 5). Concentrator plant 2 has second largest green water footprint (16 ML/yr) and concentrator plant 1 the smallest green water footprint (5 ML/yr).

The amount of water lost to evaporation is 1 142 ML/yr. The amount of water lost through seepage was 281 ML/yr.

Table 1 shows the volume of water imported and exported from the site, as calculated using the WaterMiner tool. The volume of water imported is 5 719 ML/yr and the volume of water exported is 5 253 ML/yr. The error is 8.15%.

WaterMiner reports the amount of raw, worked and treated water used within a task. It also reports the percentage of water reused and recycled. From Table 2 it can be seen that concentrator plant 2 has the lowest reuse percentage (69%) and concentrator plant 1 the highest (85%). Concentrator plant 1 does not recycle any water and concentrator plant 2 only recycles 2%. The intake water reported in Table 2 includes the volume of water reused and recycled. From the intake water it can be observed that concentrator plant 1 (11 051 ML/yr) and concentrator plant 2 (10 221 ML/yr) almost uses the same volume of water for their operations.

WaterMiner also provides a list of flows that can replace current water flows (alternative water sources and destinations), and a list of additional water transfers. None of the recommended flows can be applied because the program recommends recycling the tails before it goes to the tailings dam. These flows are slurries and solids have to be removed before it can be recycled.

Discussion

The WaterMiner tool was created for application in the minerals industry whereas the Water footprint has mostly been used in the agricultural sector. The WaterMiner calculates the volume of raw, worked, and treated water and provides a reuse and recycle percentage. The Water footprint calculates the blue, green and grey volume of water consumed by the process and only considers the amount of fresh or rain water consumed. The Water footprint considers the pollution effect on the environment with the grey water footprint.

In this study water footprints were calculated for the concentrator plants and tailings dam of a platinum processing plant. The tailings dam was included in the water footprint because it was expected that the tailings dam would have a large water footprint due to the amount of precipitation and seepage. The mining industry was chosen because of the large amount of water used by the industry and the poor quality at which the water is returned to the environment.

The volume of the blue water footprint is almost the same as the WaterMiner imports. The WaterMiner imports include the water in the ore, which is not seen as being part of the blue water footprint. Since concentrator plant 2 has the largest water footprint (3 594 ML/yr) and the lowest recycling percentage (69%) it can be concluded that concentrator plant 2 has the greatest potential for water reduction.

According to a study by Vietti, Boshoff and Cope (2010) increasing the solids concentration to 70% would help save water in the tailings dam. Increasing the solid concentration beyond 70% would not result in significant water saving. If less water is sent to the tailings dam from the thickeners, more water can be reused in the process. Further less water will be lost due to evaporation and seepage in the tailings dam.

Evaporation in the tailings dams is increased by smaller particle size and a larger tailings dam surface area (Mwale, Musonge and Fraser, 2005). The smaller particles lower permeation and allow more water to collect on the surface of the dam, making it available for evaporation. Larger particles will increase permeation and allow more water to exit as seepage. An optimum particle size for metal recovery and water recovery has to be decided on for the crushing and milling stages (Mwale, Musonge and Fraser, 2005).

Another option is to cover any open surfaces to prevent evaporation leaving the system and rain water entering the system (Gunson *et al.*, 2012). More water evaporates from open surfaces than water entering as rain water. Water lost through evaporation will be reduced and less blue water is required to replenish the water stores. If no rain water enters the system there is no green water footprint. The tailings dam has a large open water surface and it is recommended that floating modules be used to cover the tailings dam (Marris, Woodfield and James, 2011). This will not completely prevent evaporation and rain water will still be able to enter, but the green water footprint for the tailings dam will be reduced. Due to the decrease in evaporation, more water is available for recycle and the blue water footprint can be reduced. If the water surfaces is covered the blue water footprint is reduced to 4 883 ML/yr and the green water footprint to 69 ML/yr, this will allow the total water footprint to be reduced to 10 881 ML/yr.

A pre-concentration step can be added between the crushing and milling processes for concentrator plant 1. This allows waste water to be separated before the milling and floatation processes, because less material has to be process there is a decrease in energy and water demand. A small amount of platinum is lost during pre-concentration. A recommended method for pre-concentration is dense medium separation (DMS) (Smith *et al.*, 2013). Other pre-concentration processes include X-ray transmission (XRT) and X-ray fluorescence (XRF) (Smith *et al.*, 2013). The DMS has a small plant footprint. Separation is possible due to the density difference between platinum reef and silicate waste material. Ferrosilicon is mixed with ore and send to a cyclone. If pre-concentration is added, up to 15% of fresh water can be saved. Since less waste material is processed the tailings storage facility would be smaller and less water lost in the tailings dam. If the pre-concentration step is added, the blue water footprint for concentrator plant 1 can be reduced to 1 666 ML/yr and the total water footprint to 11 517 ML/yr.

Figure 6 and Figure 7 show the new water footprint if the open water surfaces are covered and a pre-concentration step installed for concentrator plant 1. The total water footprint would be reduced to 11 173 ML/yr. From Figure 6 it is observed that the water footprint of concentrator plant 2 would be reduced to 3 529 ML/yr, concentrator plant 1 would be reduced to 1 650 ML/yr and the tailings dam to 5 994 ML/yr. From figure 7 it is observed that the green water footprint would be reduced to 69 ML/yr and the blue water footprint to 5 175 ML/yr. The grey water footprint remains at 5 929 ML/yr.

Other options include maintenance to prevent water lost through leaks in pipes or equipment. Educating the workers on water saving measures and replacing current showers and toilets with water saving options could save further water. Running simulations to optimise the water use of equipment used in the process.

Conclusion

This study has calculated the water footprint for two concentrator plants and the tailings dam of a platinum processing plant in South Africa. The aim of the study was to identify areas in the processes where water use can be reduced. The water footprint was found to be 11 811 ML/yr.

It was found that the tailings dam has the largest total and green water footprint due to seepage and evaporation. The blue water footprint made up 47% of the total water footprint.

Methods recommended to reduce the amount of water required by the mineral processing process includes covering any open water surface to reduce evaporation and installing a pre-concentration step to reduce the amount of water required by the milling and flotation processes. By increasing the solids concentration of the waste sent to the tailings dam less water is available to be lost through seepage or evaporation.

By calculating the water footprint of mining operations the companies are made aware of the amount of water they use. Areas where the most water is lost can be identified; steps can be taken to prevent the loss of water and reduce the amount of water used.

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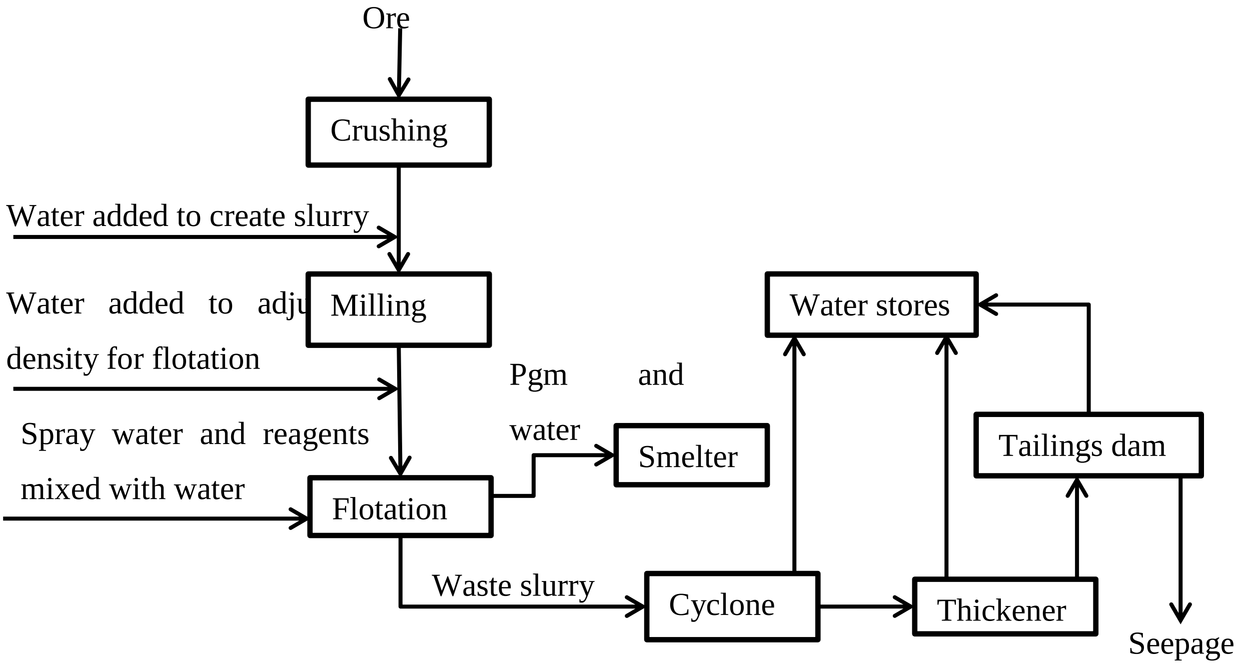

Figure 21. Simplified water flow sheet for the concentrator plant and tailings dam of a platinum processing plant.

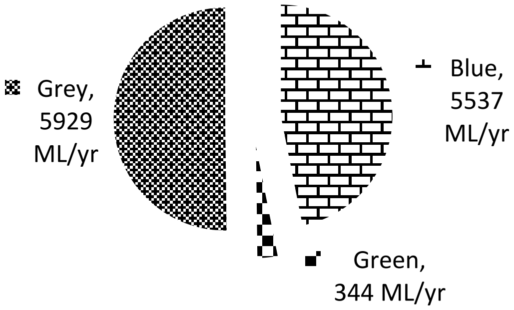

Figure 2: Distribution of the blue, green and grey water of the total water footprint.

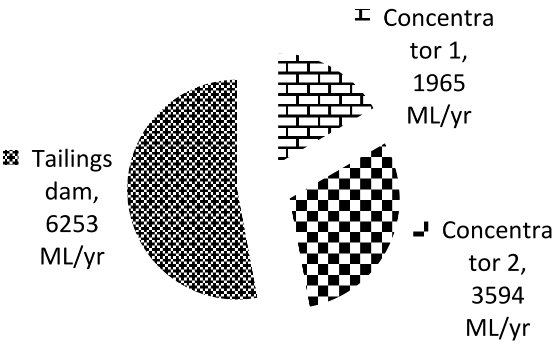

Figure 3: Distribution of the water footprint between the concentrator plants and tailings dam.

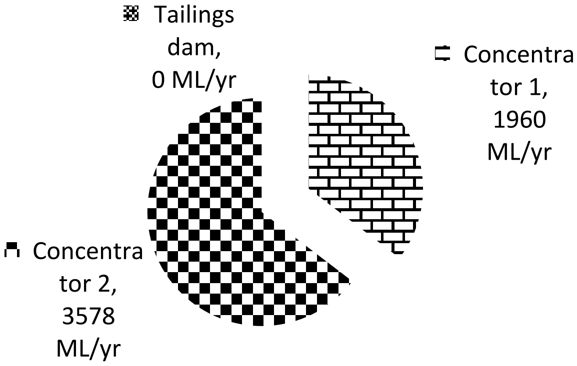

Figure 4: Distribution of the blue water footprint between the concentrator plants and tailings dam.

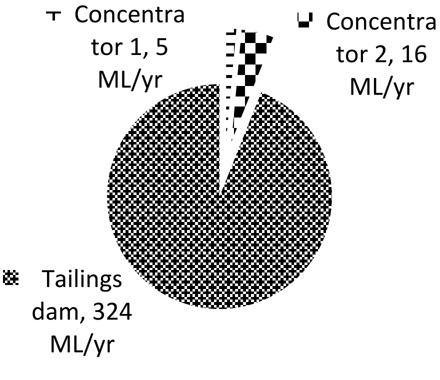

Figure 5: Distribution of the green water footprint between the concentrator plants and tailings dam.

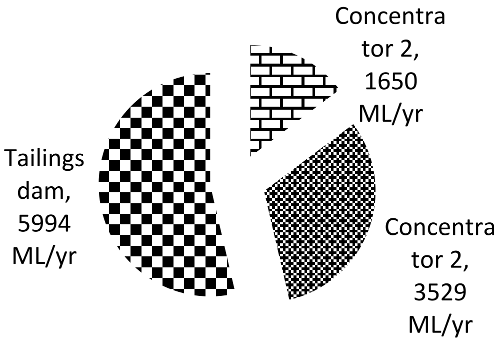

Figure 6: New distribution of water footprint for the concentrator plants and tailings dam.

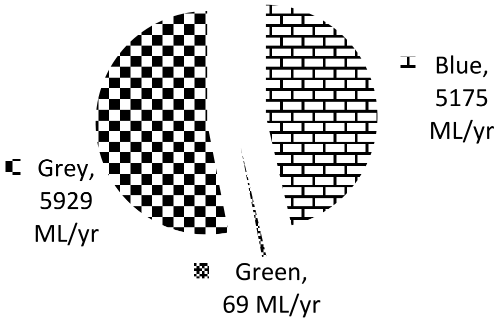

Figure 7. New water footprint, showing the distribution of the blue, green and grey water footprints.

Tables

Table 1: Results of the water balance using WaterMiner.

Imports and exports (ML/yr)	
Imports	5719
Exports	5223
Difference (Imports – Exports)	466

Table 2: Amount of water reused and recycled within the concentrator plants.

Task	Intake (ML/yr)	Raw (ML/yr)	Worked (ML/yr)	Treated (ML/yr)	Reuse %	Recycled %
Concentrator plant 1	11051	1650	9401	0	85	0
Concentrator plant 2	10221	2952	7062	206	69	2

APPENDIX C: WATERMINER FLOW DATA

In this appendix the data used to calculate the volume of water consumed using the WaterMiner to complete Water Accounting Framework (WAF) is discussed. If flow rate were measured a high level of confidence were assigned to the flow stream. Flow rates that were estimated using design criteria (densities and percent solids), estimated using monthly averages and estimated by closing the mass balance were assigned a medium level of confidence. Rainfall was measured by the company and evaporation was based on historical average data (DWAF, 1985). The level of confidence in the rainfall and evaporation data was high. Table 17 shows which flows were measured, estimated or simulated and the level of confidence in each flow rate. The flow rate cannot be shown due to a confidentiality agreement.

Table 17: Data entered into WaterMiner for quality and to complete accuracy statement.

From	To	Measured/Estimated /Simulated	Level of confidence
WaterSource1	Change House, Office, Hostel	Estimated	Medium
WaterSource1	Concentrator1	Estimated	Medium
WaterSource1	ThirdParty1	Estimated	Medium
WaterSource1	Smelter	Estimated	Medium
WaterSource1	Concentrator2	Estimated	Medium
WaterSource1	WaterStore21	Estimated	Medium
WaterSource2	WaterStore21	Estimated	Medium
WaterSource2	WaterStore22	Estimated	Medium
WaterSource2	WaterStore12	Measured	High
Rainfall	Concentrator1	Measured	High
Rainfall	Concentrator2	Measured	High
Ore	Concentrator1	Estimated	Medium
Ore	Concentrator2	Estimated	Medium
Silt trap	WaterStore23	Estimated	Medium
WaterSource3	WaterStore13	Measured	High
ThirdParty2	Concentrator2	Estimated	Medium
WaterSource4	WaterStore12	Measured	High
Tailings Dam	WaterStore21	Estimated	Medium
WaterStore21	Tailings dam	Estimated	Medium
WaterStore21	Concentrator2	Estimated	Medium
Tailings Dam	WaterStore22	Estimated	Medium
Concentrator2	WaterStore22	Estimated	Medium
WaterStore22	WaterStore23	Estimated	Medium
WaterStore22	Plant Cleaning	Estimated	Medium
WaterStore22	Concentrator2	Estimated	Medium
Plant Cleaning	WaterStore23	Estimated	Medium

Silt trap	WaterStore23	Estimated	Medium
WaterStore23	Concentrator2	Estimated	Medium
Concentrator2	WaterStore24	Estimated	Medium
WaterStore24	Tailings Dam	Estimated	Medium
WaterStore12	WaterStore11	Estimated	Medium
Concentrator1	WaterStore11	Estimated	Medium
Tailings dam	WaterStore11	Estimated	Medium
Smelter	WaterStore11	Estimated	Medium
WaterStore11	Concentrator	Estimated	Medium
WaterStore13	WaterStore12	Estimated	Medium
Tailings Dam	WaterStore12	Estimated	Medium
WaterStore12	WaterStore12Leak	Estimated	Medium
WaterStore12	Tailings Dam	Estimated	Medium
WaterStore12	Smelter	Estimated	Medium
WaterStore12	Concentrator1	Estimated	Medium
Sewage Treatment	WaterStore13	Measured	High
Concentrator1	WaterStore13	Estimated	Medium
WaterStore13	Tailings dam	Estimated	Medium
Smelter	Tailings Dam	Estimated	Medium
Concentrator2	Evaporation	Estimated	Medium
Concentrator2	Smelter	Estimated	Medium
Concentrator2	ThirdParty2	Estimated	Medium
Change House, Office Hostel	Sewage Treatment	Estimated	Medium
Concentrator1	Smelter	Estimated	Medium
Smelter	ConverterMatt	Estimated	Medium
Smelter	Atmosphere	Estimated	Medium
Smelter	Evaporation	Estimated	High
Smelter	Sellable Products	Estimated	Medium
Concentrator1	Evaporation	Estimated	High
Plant Cleaning	Evaporation	Estimated	High

For water imports into the system the volume, source and quality of the import had to be known. In Table 18 WaterSource1 and WaterSource2 is water from dams supplied by municipalities. Ore is the water entrained in the ore. Silt trap is runoff from an undisturbed catchment into a sedimentation pond. WaterSource 3 is ground water pumped from bore fields onsite. Third party is water entrained in a waste product obtained from a nearby plant that is further processed on site. WaterSouurce 4 is runoff from an undisturbed catchment into a dam.

Table 18: Water imports entered into WaterMiner.

Imports	Water Source	Water Source Type	Water Source Quality
WaterSource1	Surface	Lakes and Rivers	1
WaterSource2	Surface	Lakes and Rivers	1
Rainfall	Surface	Precipitation	1
Ore	Ground	Entrainment	3
Silt trap	Surface	Runoff	1
WaterSource3	Ground	Borefield	1
ThirdParty2	Third Party	Third Party Entity	3
WaterSource4	Surface	Runoff	1

All the exports entered into WaterMiner required a flow rate, destination and destination quality. In Table 19 Sellable products is water entrained in by products produced during the production process. Third Party 1 is water supplied to a plant located nearby. Third Party 2 is water entrained in a waste product that is further processed by a plant located nearby. Converter Matt is water entrained in the converter matt that is treated further off site. Atmosphere is water entrained in gas waste stream from the off gas treatment plant. WaterStore12Leak is the volume of water lost through seepage due a leak in WaterStore12.

Table 19: Water exports entered into WaterMiner.

Exports	Destination	Destination Type	Destination Quality
Evaporation	Evaporation	Evaporation	1
Sellable products	Entrainment	Entrainment	3
ThirdParty1	Third Party	Third Party Entity	1
ThirdParty2	Entrainment	Entrainment	3
Converter Matt	Entrainment	Entrainment	3
Atmosphere	Evaporation	Evaporation	1
WaterStore12Leak	Ground	Seepage	1

The rainfall data entered into WaterMiner was measured by the mining company on a monthly basis. According to Table 20 during June 2012, July 2012, August 2012, April 2013, and May 2013 there were no rainfall. This is the autumn and winter months in South Africa. The mine is located in an area that receives summer rain. The highest rainfall was recorded during summer months, October 2012 and November 2012.

Table 20: Monthly measured rainfall data for June 2012 to May 2013.

Month	Rainfall (mm/month)
June 2012	0
July 2012	0
August 2012	0
September 2012	53
October 2012	147
November 2012	105
December 2012	75
January 2013	66
February 2013	52
March 2013	17
April 2013	0
May 2013	0

In South Africa the spring and summer months are from September to February. As can be observed from Table 21, these are the months with the highest evaporation rate. During autumn and winter the evaporation rate is lower.

Table 21: Historical average evaporation rate for June 2012 until May 2013 (DWAF, 1985).

Month	Average evaporation rate (mm/month)
June 2012	97
July 2012	113
August 2012	167
September 2012	207
October 2012	253
November 2012	247
December 2012	252
January 2013	220
February 2013	179
March 2013	169
April 2013	138
May 2013	115