WATER FOOTPRINT ASSESSMENT OF MINING AND PROCESSING OF GOLD

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ABSTRACT

WATER FOOTPRINT ASSESSMENT OF MINING AND PROCESSING OF GOLD

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Water management in mining industry has strategic importance due to the increasing water scarcity. Water Footprint Assessment (WFA) is a systematic way that provides an assessment of sustainable water management from multiple perspectives. The main objective of this study is to analyse the water footprint of mining and processing of gold and identifying hotspots of carbon in pulp (CIP) gold processing using WFA and life cycle assessment (LCA). In this study, after determining the goal and scope, data was collected for these definitions, the process facility was designed, and the hotspots were determined after calculations were made with LCA and WFA methodologies. At the last stage, response formulations were shared. The results obtained from this research revealed that the lost return flow has the largest contribution on the blue water footprint (WF), with a value of 260.61 m^3/kg Au, and the only source of the lost return flow is found to be the tailing pond. Among the indirect water footprint values, Oxygen which is used in leaching operation to increase the rate of gold dissolution has the highest value with 37.38 m^3/kg. In addition, the critical component responsible from the grey WF is found to be the use of Arsenic, with a value of 1,777 m^3/kg Au. Blue WF was found as 357.32 m^3/kg according to LCA methodology and diesel made the highest contribution to the indirect blue WF with 12.5 m^3/kg Au. Climate change human health is the most affected category in this study. The results obtained from this study could be used to make recommendations for reducing the amount of water consumed, and therefore, the negative impacts on the environment. The result of the study is expected to contribute to mineral industry by providing a systematic approach towards better water management and thus more sustainable mining.

Keywords: Water Footprint Assessment, Life Cycle Assessment, Sustainable Water Management, Gold Mining, Water Consumption in Gold Processing

ÖZ

ALTIN MADENCİLİĞİNİN VE ZENGİNLEŞTİRİLMESİNİN SU AYAKİZİ DEĞERLENDİRMESİ

Güney, Emre
Yüksek Lisans, Maden Mühendisliği
Tez Yöneticisi: Prof. Dr. Nuray Demirel

Şubat 2022, 87 sayfa

Madencilik sektöründe su yönetimi, artan su kıtlığı nedeniyle stratejik öneme sahiptir. Su Ayak İzi Değerlendirmesi (SAD), sürdürülebilir su yönetiminin birden fazla perspektiften değerlendirilmesini sağlayan sistematik bir yoldur. Bu çalışmanın temel amacı, altının ocaktan çıkarılmasının ve işlenmesinin su ayak izini (SA) analiz etmek ve SAD ve yaşam döngüsü değerlendirmesi (YDD) kullanarak pülpte karbon altın işlemesinde kritik noktaları tespit etmektir. Bu çalışmada amaç ve kapsam belirlendikten sonra bu tanımlara yönelik olarak veriler toplanmış, proses tesisi tasarlanmış ve LCA ve WFA metodolojileri ile hesaplamalar yapıldıktan sonra kritik noktalar belirlenmiştir. Son aşamada ise SA değerini azaltmak için alınması gereken önlemler paylaşılmıştır. Elde edilen sonuçlara göre, mavi su kaynaklarının tüketimi olan doğrudan mavi SA tarafında kayıp dönüş akışı 260.61 m^3/kg Au ile en büyük değere sahiptir ve kayıp dönüş akışının tek kaynağı atık havuzudur. Dolaylı SA değerleri arasında Oksijen 37,38 m^3/kg Au ile en yüksek değere sahiptir. Ayrıca, gri SA’ dan sorumlu kritik bileşenin 1.777 m^3/kg Au değer ile Arsenik kullanımı olduğu tespit edilmiştir. YDD metodolojisine göre mavi SA 357,32 m^3/kg olarak bulunmuş ve dolaylı mavi SA’ ya en yüksek katkıyı 12,5 m^3/kg Au ile dizel sağlamıştır. İklim

Değişikliği İnsan Sağlığı bu çalışmada en çok etkilenen kategoridir. Bu çalışmadan elde edilen sonuçlar, tüketilen su miktarının ve dolayısıyla çevre üzerindeki olumsuz etkilerin azaltılmasına yönelik önerilerde bulunmak için kullanılabilir. Çalışmanın sonucunun, daha iyi su yönetimine ve dolayısıyla daha sürdürülebilir madenciliğe yönelik sistematik bir yaklaşım sağlayarak maden endüstrisine katkı sağlaması beklenmektedir.

Anahtar Kelimeler: Altın Madenciliği, Sürdürülebilir Su Yönetimi, Su Ayak İzi Değerlendirmesi, Yaşam Döngüsü Analizi, Altın İşlemesinde Su Tüketimi

To Generations to Come

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TABLE OF CONTENTS

CHAPTERS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

CHAPTER 1

INTRODUCTION

1.1 Background Information

Management of water resources is one of the most current worldwide issues of the twenty-first century. Access to water is vital for all sectors and mainly for agriculture, industry, and domestic use. However, water scarcity is now one of the growing global challenges threatening the future of humankind. There are various causes for water shortage such as, overuse of water, pollution of water resources, increased levels of urbanization, increasing rate of population, unsustainable land use, a lack of investment in infrastructure for water resources, and effects of climate change. Water demand is expected to climb by 55 percent by 2050 according to OECD (2012) and PBL Netherlands Environmental Assessment Agency (2012) due to a 400 percent increase in manufacturing water demand and population expansion (Figure 1.1). According to the report, groundwater depletion is the greatest threat to both agricultural and urban water supplies, and by 2050, 1.4 billion people would lack basic sanitation. Furthermore, according to the 2018 edition of the United Nations World Water Development Report, by 2050, more than half of the world's population (57 percent) will live in locations where water scarcity occurs at least once a year (*World Water Development Report*, 2018). The Global Risk Reports is another report that supports this conclusion (2019). While the water crisis risk was not even mentioned among the top ten global risks in terms of impact in 2009, it has always been within the top 5 since then, despite its position moving constantly since then, according to this report.Water crisis risk ranks 4th in 2019. It is understood from this report that water crises has become a critical risk after a long negligence and that it cannot be ignored anymore (World Economic Forum, 2019).

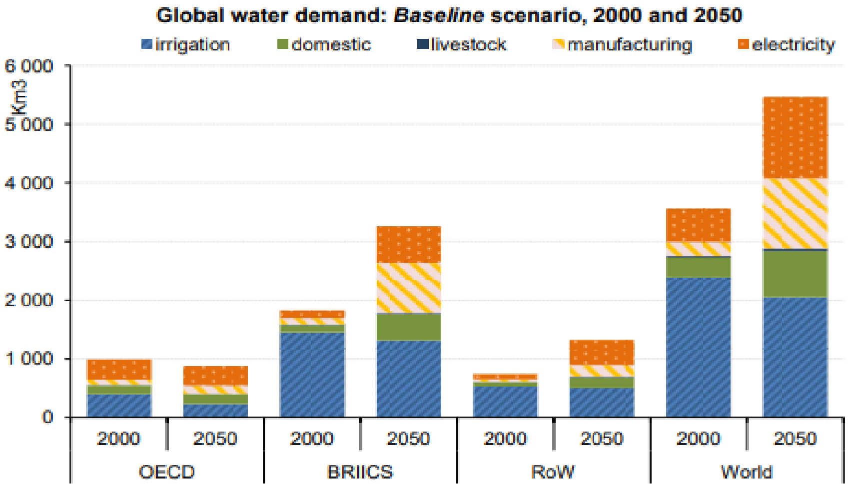


Figure 1.1. Number of People Living in Water Stressed Areas in OECD, BRIC and Rest of World *(OECD Environmental Outlook to 2050, 2012)*

In addition to decreasing the amount of water per person and gradually decreasing water resources in the world, pollution of water resources and poor sanitation have also become a major problem in the world. One of the consequences of this problem is that approximately 844 million people cannot access clean and affordable water in their homes in half an hour. In addition, approximately 300,000 children under the age of five die each year due to diarrhea disease, which develops in connection with dirty water and poor sanitation (Cullinan, 2019).

Since the water situation has become a global concern, water-related goals are included in the 2030 Agenda for Sustainable Development and the Sustainable Development Goals. Water availability, with regard to both quantity and quality, is accounted as a key global issue by the United Nations. Several of the United Nations' Sustainable Development Goals (SDGs) are linked to water. Goal six is titled 'Clean Water and Sanitation, and it includes objectives such as providing access to safe drinking water, improving water quality, enhancing water use efficiency, creating capacity, and incorporating local people in water management. Also, with the publication of the "Our Common Feature" report, also known as Brundtland Report, which has entered the world agenda, has led to some radical changes in all sectors including the mining industry.

The mining industry, which relies on water as an industrial input during mining operations, must make these drastic changes in order to remain viable. In mining operations, water is used to suppress dust, process ore, support the workforce (for drinking water and sanitation), in addition to drilling, remediation of the mine site, and to compensate for water lost due to evaporation and seepage (Bleiwas, 2012). Hence, secure and stable water supply is critical for mining operations.

Besides its vital essence, water may also cause a great problem between mining companies and local communities. In addition, the decreasing water resources proposes a risk for the mining sector financially. At the same time, the measures taken by the states by enacting new laws on this issue create new rules to obey for mining companies. According to a research, water-stressed countries account for almost 70% of the mining activity of the world's top mining companies. Water problems have been raised in 58% of the cases of mining submitted by the International Finance Corporation’s (IFC) Compliance Offer Ombudsman (CAO) (Hamilton, 2019).

Figure 1.2 presents freshwater consumption of the copper mining industry data obtained from The Ministry of Mining of Chile covering 2009 and 2014. A forecast was made using this data. This forecast shows that in the following years, the amount of water to be used for copper mining activities in Chile which is the largest copper producer in the world is gradually increasing.

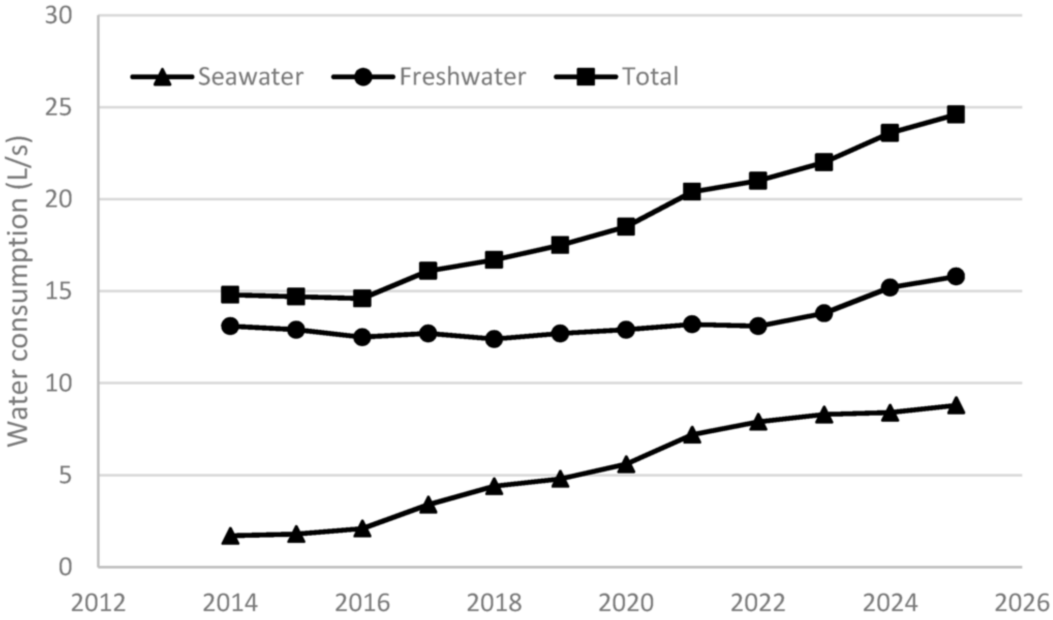


Figure 1.2. Water Consumption Forecasts for Chile's Copper Mining Industry (Aitken et al., 2016)

When the water scarcity issue is examined specifically for Turkey, the situation seems bleak as it is worldwide. The annual per capita water availability in Turkey was 4,000 m^3 in the 1960s. in Turkey was 4,000 m^3 in the 1960s. However, this value decreased by almost half in the 2000s when the population reached 67.8 million. With the predictions of this decrease in available water quantity will continue at the same rate, the population will reach 100 million in 2030s and the amount of usable water will decrease to 1,000 m^3 per person. According to the estimates, Turkey will fall into the class of countries suffering from water scarcity from water stress class in 25 years (Ergin, 2008). It is clear that Turkey's mining sector shares the same situation as the rest of the globe. Since 2010, the Turkish Statistical Institute (TUIK) has published data on mining, water, wastewater, and waste statistics based on OECD/EUROSTAT definitions, scope, and classifications, as well as international rules, biennially. Reports showed that mining operations drew 55 million m^3 of water from wells, the sea, pit lakes, rivers, lakes, and other sources in 2010 (TUIK, 2010). This number is 116 million m^3 in 2012, 220 million m^3 in 2014, 241 million m^3 in 2016, and 219 million m^3 in 2018 (Figure 1.3) (TUIK, 2012; 2014; 2016; 2018).

Mining industry accounted for 1.4% of total water consumption in Turkey and thermal power plants have a share of 49% in 2016 (TUIK, 2016). Besides, it is a sad fact that the total of 14 million m^3 of wastewater was treated by mining enterprises in 2018. Of the 14 million m^3 wastewater treated in wastewater treatment plants, 54.2% was discharged and 45.8% was reused in-house (TUIK, 2018).

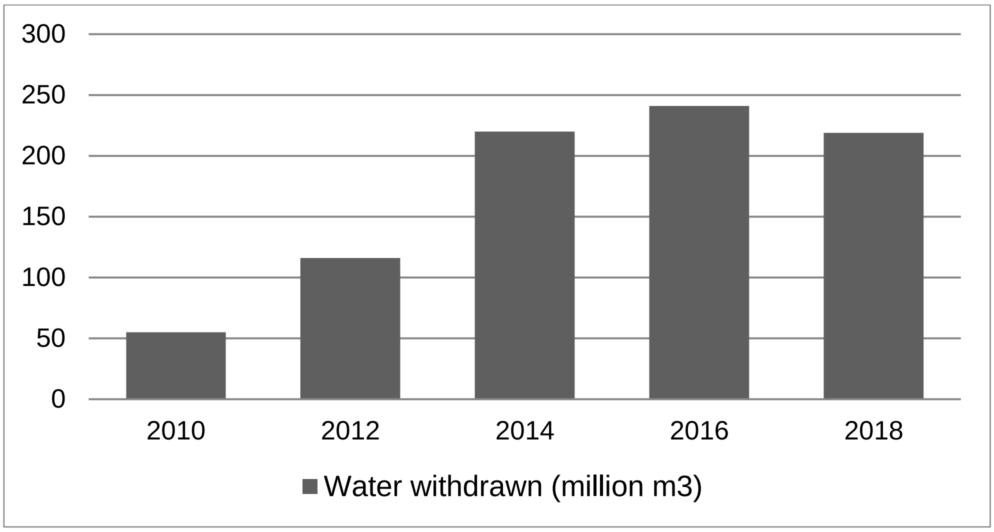


Figure 1.3. The Amount of Water Consumed in Turkish Mines (TUIK, 2018)

Mining activities in Turkey have an important place in water consumption. For example, it can be clearly seen that the amount of water consumed by the mining operations has increased by approximately 4.5 times within six years, and this number will increase because production is increasing. As a result, the supply of high-grade ore is diminishing and the mining sector will start to process lower-grade ores that demand more water. Therefore, incorporating a sustainable water management method into mining production has become unavoidable.

The strain of the water management dilemma has prompted improvements in techniques to assessing water consumption and pollution. The water footprint (WF) idea is one of the innovative techniques. Prof. Dr. Arjen Hoekstra and his colleagues introduced the WF concept as a freshwater appropriation indicator with the goal of quantifying and mapping indirect water use and direct water use. Another major result of the concept is illustrating the significance of incorporating consumers and producers in water resource management. The Water Footprint Assessment (WFA) developed later for WF concept to quantify and locate the WF of processes, products or services in a specified area.

In the following years, a group of researchers working on this subject combined the WF methodology with the Life Cycle Assessment (LCA) methodology to investigate the environmental impact of this absence, and they created a new LCA standard, ISO 14046. This new method, like WFA, is a method created to solve the problem of water scarcity.

1.2 Statement of the Problem

To date, there are studies using the WFA methodology for mining sector, especially for some mines in Chile and South Africa. In some studies, only blue WF calculation was made, while in others, blue WF and grey WF account were combined. However, these studies are only studies in which the WF calculation is made and it does not go further. In Turkey there is no study to calculate WF of a mine or processing plant or any other parts of the mining operation.

Water scarcity will continue to exacerbate the challenges in the mining industry. There are two reasons for this. The first reason is the decrease in water resources caused by global warming and population increase. The second reason is that due to the increasing population, minerals are produced more and as minerals continue to be produced, reserves close to the earth are gradually running out. This means that mining activities are carried out deeper and in the new fields which are located in remote regions. Therefore, more water will be consumed at every stage of mining underground and surface resources will be more polluted.

For this reason, one of the main problems in the mining operations in the world in the coming years is that the mine operations will fall into an economic, social and environmentally difficult situation due to the combination of the increasing depletion of water reserves and increasing water demand of the mining operations. While the whole world is moving towards a sustainable production approach, today, any form of production that is not sustainable is no longer supported. It is inevitable for mines to keep up with this understanding, especially when their effects are known both socially and environmentally.

Therefore, effective water management in mining, development of mine water resource utilization has to be developed and its impact on the environment, economy, and community has to be reduced. To achieve this in this study, factors or hot spots to reduce WF of mining and processing of gold and its environmental impact to the water resources are examined. WFA and LCA approaches are employed to achieve objective of this study. The research questions based on this study are as follows:

- RQ1: What is the value of the grey and blue WF of the mining and processing of gold?
- RQ2: Among the 7 pollutants that contribute direct blue WF, 8 contributors that contribute indirect blue WF, and nine pollutants that cause grey WF, which contributor has the highest value in its category and which core activity in the mine is this contributor take part in?
- RQ3: How does the WF of mining and processing of gold impact the environment?

1.3 Objectives and Scope of the Study

The major goal of this research is to use WFA and LCA to determine the WF of a carbon in pulp (CIP) Gold Mine and find hotspots. The findings will be used to develop response formulations for lowering the amount of water utilized in mining operations and consequently their negative environmental impact.

The components of the main objective are:

- To gather essential data for blue and grey water consumption for the whole life cycle,

- To determine blue and grey WF for each operation and location using WF Accounting,
- To perform LCA considering certain impact categories,
- To determine hotspots that to reduce the volume of fresh water and environmental impact required by the operations and location, and
- To show the mining sector for the impending water crisis danger and in that sense this danger can be minimized with a sustainable approach emphasizing environmental impacts of mining in the world and especially in Turkey.

1.4 Research Methodology

There are four stages to this research. The aim of the WFA process and the scope of the process in the mine are introduced in the first stage, according to goal and scope definition. Then, in accordance with scope definition, the WF of the mine was calculated separately as blue and grey. The blue WF is a measure of how much water is used from both subsurface and surface sources (blue WF resources). The amount of water used to return tainted water to its natural state in terms of concentration and meet the existing water quality standard is referred to as the grey WF. All structures within the mine where WF can be calculated have been subjected to these computations. If a tank is included in the scope, the grey and blue WFs of that tank were calculated independently. Afterwards, evaluations were made in the third stage of WFA with the calculated WF data and the environmental impact of the calculated WF was evaluated. Finally, response formulations to decrease the mine's WF and environmental impact are determined by assessing the WF and sustainability evaluation produced in step four.

In the second stage, the WF of the mine was calculated also using LCA approach (ISO 14046), which is a 4-stage process. In the first stage, as in WFA, goal and scope definition were determined. Then, in the second stage, inventory analysis, data were collected. In the third stage, SimaPro 7.3.2 (Pre, 2011) was used to calculate the WF using this data. With the resulting WF calculation, interpretation, which is the fourth stage according to the selected impact categories, was made and it was determined which effect categories of the calculated WF had, and recommendations were made to take necessary measures (Figure 1.4).

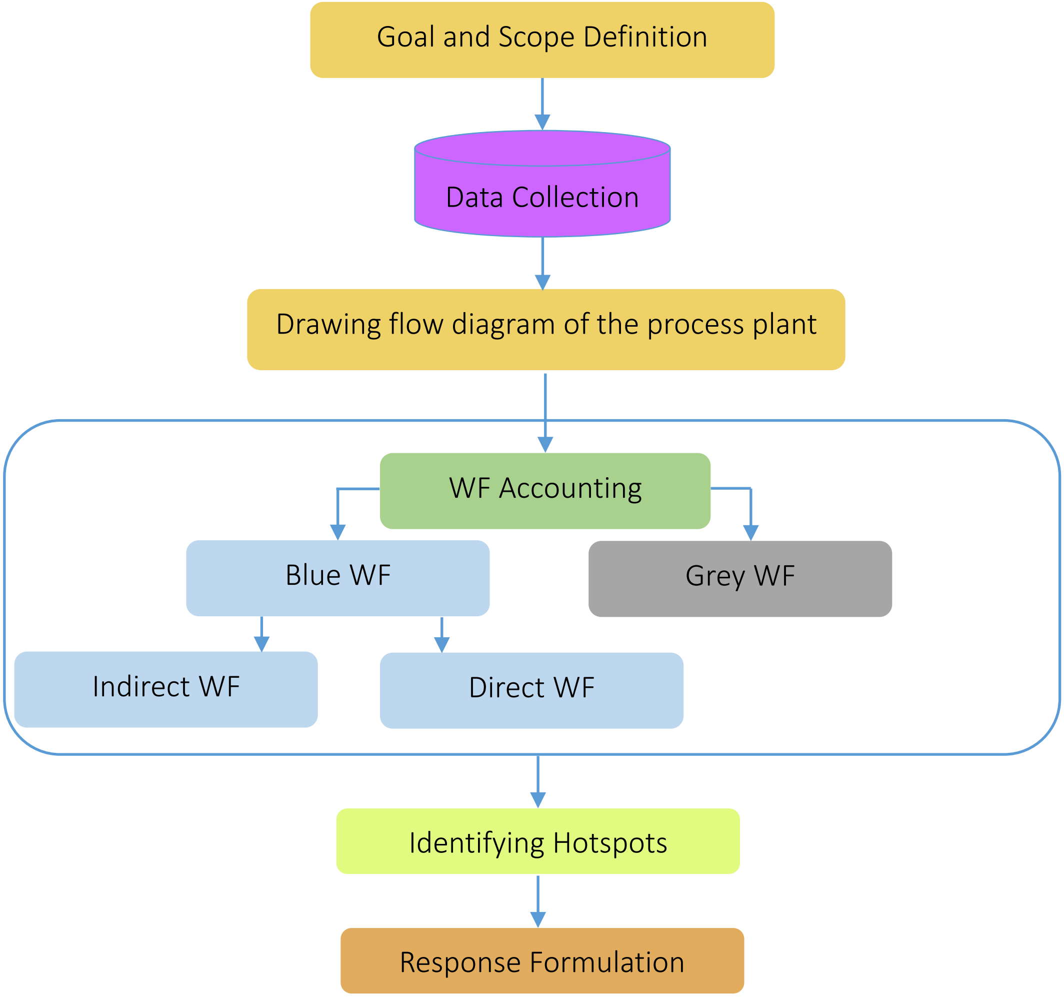


Figure 1.4. Flow diagram of the study

1.5 Expected Scientific and Industrial Contribution

This research could aid in improving Turkey's existing mining industry from the standpoint of sustainable development. In that sense, the largest scientific and industrial contributions of this work is to highlight how water consumption in the mining operations would be more sustainable. No previous research on this topic has been conducted in Turkey. Counter to the improvements in the WF, there has been little interest around the world in mining. Researches in this field are primarily concentrated in South Africa and South America. Furthermore, the majority of the research are focused on platinum and copper. There is no comprehensive analysis of a process facility using the CIP processing technology in the literature. Because the subject of WF is a very new subject for the mining industry, there is a scarcity of information on the state of water resource utilization in mining locations. Another place and approach where WF are used in the mining sector will be included in the literature as an example with this study.

In the global point of view WFA studies in mining have been performed but with this study, to our knowledge, WF of a mine and investigating its environmental effect using the ISO 14046 standard is examined for the first time. Therefore, this study will be a guide for further studies in this field. Also, from the industrial point of view, with this study mining companies could clearly understand the WF concept and its importance. Therefore, they can integrate this very important concept to their environmental management policies and management plans. This study may help to define the total water consumption of the operations and deal with excessive water consumption. Also, it may also contribute to the legal aspects of water consumption in mines and can be integrated into the environmental impact assessment report in particular.

CHAPTER 2

LITERATURE REVIEW

The decline of water resources in the world in recent years and the idea of sustainable development becoming more widespread have led researchers to investigate how these resources can be managed. One of the studies that emerged as a result of these studies is the WFA methodology discovered by the water resources community. Another is the IS0 14046 Water Footprint Standard, which is the result of work done by the LCA community. Although these two studies have common aspects, they actually touch on different points.

In this section, scientific and academic studies in this research domain are investigated and criticized by a comprehensive literature review covering related databases, peer-reviewed articles, books, open-source publications.

This chapter is structured into 9 parts. In the first chapter, a detailed explanation of the development of the WFA methodology, which has been briefly mentioned before, from its first emergence to the present, is given. In the second chapter, the LCA methodology is explained in detail in particular ISO 14046. In the next chapter, the differences and similarities between these two methodologies are explained by evaluating the articles published between the two groups. In the fourth, fifth, and sixth chapters, the examples in which the two methodologies have been studied before are criticized. In order to show the examples and diversity of both methodologies in different sectors, examples from the agriculture and livestock sector in the fourth chapter, examples from the energy sector in the fifth chapter, and examples from the steel sector in the sixth chapter are shared. In the seventh chapter, the articles of the WFA methodology, which were studied specifically for Turkey, were included and these articles were criticized. In the chapter eight articles on which methodologies are applied to the mining sector are shared. In last chapter novelty of the study is shared.

2.1 Water Footprint Assessment

WF concept introduced in September 2002 in the Value of Water Research Report Series No. 11 (Hoekstra and Hung, 2002). This concept is essentially built on ecological footprint and virtual water definitions. The ecological footprint is the amount of land required for production. After that, in December 2002, this notion was presented at a meeting on the topic of the virtual water commerce, which was held in Delft, the Netherlands. (Hoekstra, 2003). Virtual water is a concept discovered by John Anthony Allan in the early 90's and this concept forms the basis of the WFA. By definition, virtual water means the amount of water used to manufacture a product. Allan makes this definition in his article, which he argues that during the production of the water deficit in the Middle Eastern countries, agricultural products that consume too much water can be closed by importing them from countries that do not have a water problem (Allan, 1997).

Then, it was thought that there may be a connection about the effect of the amount of water consumed on the environment with the studies that started over virtual water. With a connection between these two facts, it is started to focus on which product consumes more water and has more impact on the environment and how water consumption can be reduced. This has been a factor in the creation of the WF concept by (Hoekstra and Hung, 2002). The total virtual water content of all goods and services consumed by a person is measured in WF.

The first study of the concept of WF was carried out to estimate the amount of water required to produce agricultural products in different countries, to measure the volume of virtual water trade that took place between 1995 and 1999, as well as to reveal the virtual water trade balance of nations by considering the national water needs and water presence (Hoekstra and Hung, 2002). At the same time, definitions of blue and green water are completed in this study. The utilization of ground and surface water is referred to as blue water, whereas precipitation is referred to as green water. Between 1995 and 1999, the global amount of virtual water commerce between states was estimated to be 695 Gm^3/year on average. (Hoekstra and Hung, 2002).

After the introduction of this concept, WFA has emerged as a result of studies concentrated on water use and scarcity in the world especially depending on consumption and trade. The first manual for WFA was given to users in the form of a report in 2009 (Hoekstra et al., 2009). It was later published in 2011 under the name The WFA Manual: Setting the Global Standard (Aldaya et al., 2012). Definition of WF can be found in the above mentioned in this manual. It defined the WF as follows:

> *"The water footprint is an indicator of freshwater use that looks not only at direct water use of a consumer or producer, but also at the indirect water use. The water footprint of a product is the volume of freshwater used to produce the product, measured over the full supply chain" (Aldaya et al., 2012).*

The direct WF of a consumer or manufacturer is related to the water directly used by the consumer or the manufacturer. This connection is between the use of fresh water and pollution. The indirect WF represents the consumption of water that may be connected with the production of consumer goods and services, or with the inputs used by producers. WF has three components. These are blue WF, green water WF, and grey WF.

The concept of WF, which was introduced with WFA, was later started to be worked on by the LCA group and the ISO 14046 standard was created as a result of the studies. The stages of this study are discussed in the following section.

2.2 Life Cycle Assessment

After the publication of the concept of WFA, it has created great interest in the world. Especially since 2009, the LCA group has attracted attention because of the importance of the WF concept in evaluating and comparing the environmental performance of the products (Hoekstra, 2016).

With the WULCA which is a Life Cycle Initiative group and was established in August 2007 under the auspices of the UNEP/Society for Environmental Toxicology and Chemistry (SETAC), research has started on the use and depletion of water resources in LCA, including academics and industry members from different countries around the world. The primary goal of these research is to develop a general platform for industry, practitioners, and academia to analyze, compare and reveal how freshwater products and processes perform in terms of environmental performance. After the studies, the WULCA group published the AWARE (Available Water Remaining) method in 2015 as a joint decision framework (Boulay et al., 2018). The increasing interest in sustainable production in the world has played a major role in increasing the interest in this concept. The studies scientifically put forward by the studies carried out by this group are as follows: A study that provides a framework for water use impact assessment in LCA (Bayart et al., 2010), a study on the review of existing methods for water use in LCA (Kounina et al., 2013), articles obtained from the comparison and application of midpoint end endpoint methods.

In addition to these studies, WULCA has an important role in the start of the ISO 14046, which is the draft standard for WF. In the process of establishing this standard, five WULCA members were directly involved as national representatives. This methodology is based on ISO 14040 (ISO, 2006) and ISO 14044 (ISO, 2006a) and developed in 2014 in order to perform the WFA of any product, process or organization and to investigate the potential environmental effects of the WF in the light of the selected problems (ISO, 2014). These problems are mainly eutrophication, acidification, and toxicity to humans and ecosystems.

2.3 Similarities and Differences of the Water Footprint Assessment and Life Cycle Assessment

The methods used between these two groups that serve the same purpose have been criticized. For this purpose, there have been letters between the groups that started in 2009. The first criticism was made for the work done by (Gerbens-Leenes et al., 2009). It was emphasized that the WF calculated in this critique should be calculated with regional indices and another argument is that green WF has to be ignored because effects would be negligible. As a reason, it has been suggested that the water scarcity in each region is different (Pfister and Hellweg, 2009). The answer given in response to the comments was that volumetric calculations are an important source of information for WF calculations and this information will be lost when converted into aggregated indices. It has been stated that making these indices without physical interpretation will not make sense for water resource management

Later, in correspondence between the two groups, the letter from Ridoutt and Huang, (2012); reply from Hoekstra and Mekonnen, (2012), it was suggested by the LCA group that in order to reduce the impact, the environmental impact of WF calculations should be started from places where water scarcity is higher. On the other hand, the WFA group stated that this may be a priority, but it is also a way to start using resources more effectively in areas with abundant water. In addition, it was emphasized that search for solutions should be global within the scope of global sustainability thought.

Then, in a study conducted by the two groups together (Boulay et al., 2013) the differences and similarities between the two methods were explained, and the similarities and complementarities of the steps belonging to the methods were shared. However, difficulties in implementing these complementarities are described separately in an answer in the study of (Pfister and Ridoutt, 2014).

To integrate WF into the product lifecycle, LCA scholars have proposed to assign weight to the original volumetric WF by water scarcity in the catchment area where the WF is located, thereby obtaining a water scarcity-weighted WF that reflects the potential local situation. These suggestions were interpreted by Hoekstra in five main issues (Hoekstra, 2016). Later, the response to this study is (Pfister *et al.*, 2017).

The results of all these studies show the following; LCA and WFA are methods that have been created by different working groups indirectly under the same purpose. This aim is to protect water resources against the problems caused by human activities. Both methodologies consist of four stages, but the different stages are specific to the methodologies and differ in themselves. Both approaches use quantitative approaches in essence.

On the basis of the LCA methodology, potential impacts arising as a result of human activities are presented specifically for environmental problems. In order to evaluate this methodology in terms of water consumption, especially human health, ecosystems impact, and resources depletion categories are evaluated. These categories also include certain potential impacts from contaminants that affect and spread water (Kounina et al., 2013).

On the other hand, the WFA methodology is based on water consumption indicators. Unlike LCA, this method has been developed to support a better water management. In addition, unlike LCA, the water consumption computation in this model is done individually for green, grey, and blue water.

2.4 Water Footprint Assessment Applications in Agriculture and Livestock Sector

It is not a coincidence that the agriculture and livestock sector are among the sectors where the WFA methodology was first applied. According to (*Water for Sustainable Food and Agriculture*, 2017) report prepared by Food and Agriculture Organization of the United Nations (FAO), approximately 70 % of global fresh water consumption among sectors is used in agriculture. A large amount of the water used is spent on food and products for the livestock industry (Opio et al., 2011).

With the advent of the WF concept, work in this area has continued to increase, gaining speed. Following the work done in 2002 by Hoekstra and Hung is, another study is completed by (Chapagain and Hoekstra, 2003). The purpose of this study is to compute the content of virtual water of some livestock and products for this sector and to construct a methodology to measure the commercial water-related virtual water flows of these food groups. What is intended to be done later is to combine this study with the study of Hoekstra and Hung, 2002, where virtual water flows are estimated by the trade of agricultural products. This study covers between 1995 and 1999.

In this study, virtual water content of livestock was first calculated. While doing this calculation, the amount of water used to produce and process the feed given to the animal, the amount of water that the animal consumed during its lifetime and water to clean its housing and the like amounts were collected. The amount of virtual water content found later was used to find virtual water content of livestock products. Later virtual water content of livestock products such as milk, cheese, butter, leather, etc. The products obtained from the animal were examined in two groups as primary and secondary. The primary products include products obtained directly from the animal (e.g., milk), while secondary products are included in the products obtained by processing the primary products obtained from the animal (e.g., cheese). The same virtual water content calculation method was used by both groups. In this method, firstly "product fractions" were obtained for the products, and then, together with these ratios, the “value fraction” value was obtained by using total value obtained per ton of live animal. Then, it is multiplied by virtual water content of the animal value fraction and the value obtained is divided into product fraction. Apart from using the same method in secondary products, virtual water content of the process applied to obtain the product is also taken into account. Data on international product commerce and virtual water content of each commodity were used to compute virtual water flows between countries.

According to the results obtained at the end of the study, international virtual water flows are estimated to be 1,031 Gm^3 per year (695 Gm^3/year from the product trade and 336 Gm^3/year from the livestock and livestock products trade) (Hoekstra and Chapagain, 2003).

Another issue that WFA methodology discussed worldwide in the following years was cotton consumption (Chapagain et al., 2006). This study is also the study in which the foundations of the grey WF concept are laid. The aim of the study on this subject is to find the WF of the cotton consumed worldwide with the import and export of raw cotton or cotton products. This amount is calculated by multiplying virtual water flows between countries by the total virtual water content of commodity trade flows and also to determine the regional and characteristic features of the effect of this consumption. These effects were analyzed in 3 stages in agriculture stage, which is the first of the stages that should pass from the production of cotton to the final product. These are precipitation amount for planting cotton growth, withdrawing soil or surface water for irrigation, and water pollution due to leakage of manure and pesticides. In the processing stage, where cotton passes to obtain the final product after production, 2 main effects were examined. These are the surface or underground water resources used to process cotton and the process water contamination with the chemicals used after the cotton process.

During these two processes, the impact on water quality was measured by comparing the amount of chemicals polluting the water with the amount of water required to assimilate these chemicals. Therefore, the most important part of this study in terms of WF is that it measures the effect of water consumed on water quality (water pollution) and covers the concept in an even wider frame.

According to the results obtained as a result of the study, 256 Gm^3 of water is required annually for the consumption of cotton products in the world.

According to the results in the Table 2.1 approximately blue WF contributes 42%, green WF contributes 39% and 19% belongs to dilution water. In addition, 44% of the water used to grow and process cotton globally is for export, not to serve the domestic market. Therefore, roughly half of the water-related problems associated with growing cotton in the world and processing it to obtain the final product depend on foreign trade for cotton products. Cotton consumption accounts for approximately 84 percent of the WF in the EU25 region, and has a significant impact, particularly in India and Uzbekistan. The result is that many countries depend on water resources in other countries.

Table 2.1. Contribution of the blue, green, and grey WF (Chapagain et al., 2006)

Type of Travel	Blue WF	Green WF	Dilution WF	Total WF	Contribution to the Total WF
Internal WF	59.6	54.8	28.5	143	56
External WF	48	44.7	20.7	113	44
Total WF	108	99	49	256	
Contribution to the total WF (%)	42	39	19		

The WF of global food production was carried out by Mekonnen and Gerbens-Leenes in 2020. According to the result obtained, the total global blue and green WF varies between 5.938 and 8.508 km^3/year. This study also makes a prediction for the year 2090. As a result of climate change and land usage, the WF is predicted to grow by up to 22 %. The biggest reason for this will be meat consumption due to population growth. Another result is that 57% of the world's blue WF violates environmental flow requirements. Also, wheat, rice, cotton, sugarcane, fodder and corn are dominated by an unsustainable footprint. On a national basis, India, China, USA, Pakistan, and Iran contribute the most.

As a result, quick action to promote water sustainability and protect ecosystems is required. Increasing water efficiency, defining benchmarks, capping the WF per river system, shifting diets to low water demand consumables, and decreasing food waste are just a few of the strategies.

2.5 Water Footprint Assessment Applications in Energy Sector

WF concept is a concept that can be applied in every sector where water consumption exists. The energy sector is one of them. Especially in renewable energy, hydropower and bio-energy are among the important energy sources that the WF concept can be applied because hydropower is a resource directly using water power and on the other hand, it can be applied to bio-energy because plants that need water for growth is required for bio-energy production. In the bio-energy and other primary energy carriers Gerbens-Leenes *et al.* (2009).

Conducted a study to evaluate the WF (m^3/GJ) of biomass per unit energy and to compare it with the WF of fossil energy carriers and other renewable energies such as wind, solar, and hydroelectric.

As a result of the study, the total (average) WF values (m^3/GJ) obtained for all energy carriers other than biomass are given in Table 2.2.

Table 2.2. Total (Average) WF of Energy Sources (Gerbens-Leenes *et al.*, 2009)

Operation	Total (Average) WF (m^3/GJ)
Coal	0.164
Uranium	0.086
Crude Oil	24.58
Natural Gas	0.109
Hydropower	22.300
Solar Active Space Heat	0.265
Wind Energy	0

As seen from Table 2.2, crude oil is the biggest difference among the nonrenewable energy carriers with the highest WF value. In renewable energy sources, hydropower has the highest WF with great difference. In addition, it is seen that the total WF of renewable energies, excluding hydroelectricity and non-biomass, is the smallest, and the largest non-renewable.

According to the results of the study, Table 2.3 shows the WF results expressed in cubic meters of water per cubic meter average of fifteen products such as cotton, cassava, maize, soybeans, wheat grown for biomass in four different countries which are US, Netherlands, Zimbabwe, Brazil.

Table 2.3. WF Results Average of Fifteen products in Four Different Countries (Gerbens-Leenes *et al.*, 2009)

Average Biomass in	Average WF (m^3/GJ)
Netherlands	0.164
Zimbabwe	0.086
United States	24.58
Average of 4 countries	0.109

The results show that there are large differences between countries on this issue. The reason for this is the different production methods in the countries, the characteristics of the products and the different climatic conditions. At the same time, if the use of biomass energy increases in the following years, the water consumed will increase at the same rate. The fact that biomass energy’s WF is 70 to 400 times higher than the non-renewable energy sources shows that in the coming period, more water will be needed besides getting rid of the greenhouse gas effect.

Another study on this subject was carried out to calculate the WF of energy resources in China (Ding *et al.*, 2018). In the study, crude oil, natural gas, and coal are in the first group and wind, nuclear, thermal, solar, and hydropower are in the second group as energy sources. The results show that the WF calculated for the first group is 0.14 m^3/GJ, 0.29 m^3/GJ, and 0.11 m^3/GJ for coal, crude oil, and natural gas, respectively. For the second group, these values are 0.14 m^3/GJ, 0.19 m^3/GJ, 1.19 m^3/GJ, 5.3 m^3/GJ, and 6.75 m^3/GJ, respectively. Looking at the results, it is seen that the lowest value belongs to natural gas and the highest value belongs to hydropower. This result is not surprising as hydropower uses water as its energy source. Another result obtained from the study is that for all energy resources belonging to the first group in terms of life cycle, it was seen that most of the water was spent in the extraction phase. In the second group, upstream stages are higher in percentage than extraction. Due to the lack of some national statistics, the data used in the study was also derived from sector reports. It is obvious that more accurate results will be obtained with the increase of studies on this subject.

In the study carried out by Chini and Peer in 2021, a database study was conducted that deals with the virtual water consumption for the trade of 11 different energy sources. It is stated that this study is the first in its field according to the article. In the study, the virtual water trade between the countries between the years 2010 and 2018 was taken as a basis. The calculations are based on data from the UN Commodity Trade database provided via an API for the R scripting language. Data and codes are also shared open source, thus making the database open to development.

2.6 Water Footprint Assessment Applications in Steel Industry

Steel plays a vital role in many sectors, especially in construction and automotive, with its low cost and high tensile strength. In addition, a lot of energy and water is required for steel production (He and Wang, 2017). The wastewater generated during steel production contains many chemicals and these chemicals pose an environmental threat. Studies have been carried out to make WF assessments for this sector. In order to provide an example for these studies, some are shared discussed.

In the study by Gu *et al.* (2015), blue WF and grey WF calculations were made by using the WF method instead of traditional calculation methods such as FWC or WC for the iron and steel industry. An iron factory in East China was taken as a reference for the study. In the study, risk analysis and uncertainty analysis were also carried out. As a conclusion, the blue WF of the factory was 2.24×10^7 m^3 and the grey WF was 6.5×10^8 m^3. In addition, the analyzes show that the WF due to electricity consumption is higher. As for the grey WF, it is seen that the chemicals in the discharged water still do not meet the Seawater Quality Standard, even if the businesses comply with the laws that must be followed. For these reasons, businesses need to increase their water treatment efficiency. Since the study sets an example for an enterprise in the steel industry, it sheds light on the water consumption of this sector and the places that need attention. In addition, the lack of data for the WF calculation of raw materials such as coal used in the enterprise is an indication that the study should be developed in this sense. In addition, the dependence of energy resources on regional and temporal issues also causes great variability in the calculations.

A life cycle analysis was undertaken for China in another study, with grey and blue WF calculated using ISO 14046 standard. (Ma et al., 2018). Data are obtained from an iron and steel plant in Shandong Province. The main aim of the study is to make a WF-based LCA to develop the steel industry's environmental performance. In this study, it was found that 1 ton of crude steel production at the national level in China causes 12.60 m^3 grey WF and 7.09 m^3 blue WF. The findings also revealed that the grey WF from aquatic eutrophication, carcinogens and non-carcinogenic substances was higher than the blue WF. As a result, indirect resources should be optimized in order to control the grey WF. In order to reduce the environmental impact, it has been determined that the critical substances are COD, Cr (VI), phosphate, BOD5, Hg, As, nitrogen oxides, particles, and sulfur dioxide. Although the converter technology was examined in this study, other technologies also need to be investigated further. Also, in the national WF assessment, a dynamic database is required to calculate WF values in different regions.

2.7 Water Footprint Assessment Applications in Turkey

Similar to the trend in the world, Turkey's agriculture and animal husbandry sector has an important place among the sectors that are subject to this study. These two sectors use the world's fresh water reserves the most. In addition, studies include WF assessment of a basin and municipal water consumption studies.

A report prepared by World Wildlife Fund (WWF) with the corporation Turkey Forestry and Water Affairs Ministry was prepared to investigate Turkey's production WF, consumption WF, export and import WF, WF of special export and import products for Turkey in detail. In addition, at the end of the report, there are recommendations for decision-makers, business and individuals to lower the WF of the country and to develop water management. Turkey's agricultural production WF reveals that the primary factor; about 89% of the total WF and 83% of the WF of agriculture are due to crop production.

One of the studies conducted on WF in Turkey is made in order to calculate the amount of water consumed to grow animals (Ocak *et al.*, 2013). However, the water used for the drinking and cleaning of animals while growing up is not considered. The results indicate that animal feed produced in the country is not enough for livestock sector. In this sense Turkey is dependent on the exports. Gradually decreasing pasture lands also decreased livestock animal production and caused WF to increase. For a more sustainable production approach and to prevent the increase of the water stress index, the water resources in the country should be increased and more importantly, the management of these resources should be considered as crucial. In addition, another measure, feeds with less WF should be produced, state policies should be implemented in this regard. While great importance for Turkey of the study is not specified in the agreement WF rises exactly why.

Boyacıoğlu (2018) who is also one of the researchers that took part in the supporting guidelines study for the grey WF. Franke *et al.*, (2013) conducted to examine the blue WF of Turkey's 81 provinces. This study aimed to present a common research method on WF calculation for use in municipalities. In addition, defining the water consumption profile and evaluating the spatial and temporal distributions of the provinces were among the objectives of the study. Municipal WF has been examined with three main components which are domestic WF, industrial/commercial WF and public WF. According to the results, on average, the municipal WF value was calculated as 140 L/ca.day and in some cities this value was calculated to be up to 300 L/ca.day. It has been determined that the cities with a domestic WF of approximately 100 L/day and less are mostly located in the north-west and south-east of the country. In addition, low values for industrial/commercial WF with an average of 10 L/ca.day belong to the cities in the southeast region.

The work done by Muratoğlu (2019) for Upper Tigris River Basin has great importance for Southwest Asia and the Middle East. All type of the WF values were investigated individually for agricultural production, animal husbandry, domestic and industrial. In addition, per capita WFs and virtual water contents of agricultural products produced in Upper Tigris River Basin were compared with neighboring countries. With this study, Upper Tigris River Basin was examined for the first time in this context. Results showed that the annual WF was found to be 1,748 m^3/cap/year and 79% of this was based on agricultural production. Among 41 agricultural products, wheat is responsible for 45% of the water consumption of all products. Although the basin has entered the low scarcity class as a result of the study, the water used in the basin is expected to be a guideline for water management strategies.

A detailed study in the field of agriculture was made on the evaluation of wheat WF and virtual water trade (Muratoğlu, 2020). The main aim of this study was wheat production in Turkey and to analyze the consumption and allow national blue and green WF of virtual water transfers. It is the first study conducted in the field in Turkey. The study covers data between 2008 and 2019. In addition, the study was compared with the study by Mekonnen and Hoekstra (2010a). Due to the lack of data, grey WF was not included in the study. Turkey's wheat production WF's according to the results of the study was found as 39.3 Gm^3/year WF's total consumption of 48.1 Gm^3/year, respectively. International VW value has been calculated as 1.76 Gm^3/year.

Yet Turkey is not among the countries suffering from water shortages. However, water scarcity has begun to manifest itself regionally, and there is a possibility that it will take its place among countries that have suffered water shortage in recent years due to poor water management and increasing population and increasing water use

(FAO, 2016). Therefore, it should be noted that, the number of studies about the WF should be increased quickly.

2.8 Water Footprint Assessment Applications in Mining Sector

Literature studies conducted with this concept have been mostly on agricultural sector. The reason for this is that approximately 70 percent of water consumption in the world is consumed by this sector. However, in recent years there are examples where this concept has been applied to the mining sector. As it is a newly recognized concept in the world, its application to the mining sector is still few, but it is hoped that this number will increase.

In the Atacama Desert, Peña and Huijbregts (2014) conducted a WFA study to determine the blue WF for copper extraction of 1 tonne from copper sulfide and copper oxide ore. In the study, as indirect water consumption, it was considered how much water was used to produce the electricity used to produce the copper concentrate. However, when calculating direct and indirect WF, data is collected from different mines and normalized for calculations. This had led to uncertainties. In addition, green and grey WF are not included in the study.

The procedures for obtaining copper from sulfide ore and oxide ore are dissimilar. As a result, the sulfide ore refining process's blue WF (96 m^3 per metric ton) was calculated to be 2.4 times greater than the oxide ore refining process's (40 m^3 per metric ton).

Haggard *et al.*, (2013) did another work in a platinum mine located in South Africa. Two distinct WF calculation tools were employed in this investigation, and the comparison is made between the results. The WFA is the first tool employed. Grey and blue WF were estimated individually in the study, however green WFs were not. The Water Miner software is the second instrument. In this study, the flow diagram of the platinum process plant is given and the calculations are carried out on this diagram. According to the results of the study, the results found with the two tools are very close to each other. The total WF for the tailing dam of two concentrate facilities was determined to be 11,811 ML/a, with the inflow WF contributing the most. The Water Miner tool also revealed that the volume of water consumed is 5,719 ML/a, whereas the volume of water exported is 5,253 ML/a, according to the data. Recommendations were given about how to reduce the WF resulting from the study.

Harding (2014) conducted WFA study platinum mine in South Africa with purpose calculating the blue WF of the mine. In this study, only blue WF was calculated. The reason for this is stated that the sources of blue water are less in the country and the opportunity cost is generally higher. The overall blue WF, both indirect and direct blue WF, was assessed to be 2,229 m^3/ton of refined platinum, according to the study's findings.

Livia and Angarita (2017) conducted WFA study in Colombia. The study's goal was to compute the WF and assess the water use of the Reina de Oro gold facility in Colombia. Grey and blue WF were studied independently in this study. However, instead of using WF concept formulas, these calculations were conducted using real-time data from the field. The results show a statistically representative value. However, according to the results of the analysis, it shows that the mining of Reina De Oro Mine in Vetas municipality can be considered as environment friendly.

Osman *et al.* (2017) did another study in South Africa. The data for this investigation was collected directly from the mine area using flow meters. Then, with the help of these data, a water balance scheme was created specifically for the facility. Input of the site utilizing the Water Accounting Framework as part of the study's continuation. Green, grey, and blue WF values were determined in the study. As the tailing pond did not have discharge of waste water, the value obtained was 0 m^3/tonne of base metal product for grey water. Blue WF value is found as 33.4 m^3/tonne of base metal product, and green WF was calculated as 10.5 m^3/tonne of base metal product. This study is the most realistic study among the studies carried out because the data is taken directly from the field. However, environmental damage of consumed water is not included in the study.

A green, grey, and blue WF research was undertaken for an open pit copper mine in Laos by (Islam and Murakami, 2020). Blue, green, and grey WF were determined to be 988.83 m^3/tonne, 52.04 m^3/tonne, and 69.78 m^3/tonne of copper concentrate, respectively, according to the study's findings. In addition, the most significant source of blue WF is energy generated by hydroelectric power plants. Among the pollutants that contribute to the grey WF, Mn was determined to be the highest. Result of this study demonstrate that the treatment plant decreased the grey WF by five times.

2.9 Novelty of the Study

The study was guided by the implementation of this method in various mines. This study's examples include where and how the approach will be applied in the mining industry, the points to examine for direct and indirect WF assessments, and the processes can be caused by the grey WF. It should be emphasized; however, no study has specifically looked at gold mining and the CIP process in the world. In addition, the WFA methodology has not been applied to the mining industry in Turkey before. Furthermore, no studies have been conducted both using LCA and WFA methodologies in the same study. All process plant operations are analyzed individually for both direct blue WF and indirect blue WF in this study. This thesis will be the first in the field as a result of these factors.

CHAPTER 3

METHODOLOGY AND DATA

In this chapter, first of all, the two different methodologies used for the study and the four stages that make up these methodologies are explained in detail. Both of these methodologies serve the same purpose in essence. The aim of both is to protect water resources with a sustainable approach. But they do this in different ways. Both methodologies include four stages. LCA methodology consists of target and scope, inventory accounting, impact assessment, and interpretation stages. WFA, on the other hand, is a four-step approach that includes setting goals and scope, WF accounting, sustainability assessment, and intervention formulation. These steps are explained in detail in the first and the second sections of this chapter for both methodologies, respectively.

In the third, fourth, and the fifth parts of the chapter, the data required to calculate the blue and grey WF are presented. First of all, all the values required for the design of the CIP gold process plant where the study is carried out: the amount of feed, the amount of water required in the processes, the equipment to be used, the diameters of the open surfaces, the connections between upstream and downstream processes are explained. Research has been done for all values used. Plants in Turkey and feasibility reports of the production facilities located in the CIP method and the data obtained after the literature has been designed accordingly.

A literature search was conducted for monthly average open surface evaporation data and monthly total precipitation average data required to calculate the blue WF. In the researches, reports of mining companies were reviewed and at the same time, the data provided by the Turkish State Meteorological Service was investigated. Then, based on these values, all publicly available data sources were analyzed and computations were done.

Grey water pollutant required for the footprint calculation load, the maximum acceptable concentration of pollutant and natural concentration in a receiving water body values again for Turkey's CIP with the aim of running and find the waste values mines being established NI-43-101 report, written additional reports, and sustainability reports were reviewed.

3.1 Water Footprint Assessment

In general, WFA is an effective analytical tool for people to understand how their actions, the services they receive and the products they produce, and much more have an impact on fresh water resources. This effect may be the depletion or pollution of water resources. At the same time, WFA also shows which processes are caused by these effects or which product is the most common. In this way, WFA is also a helpful tool in finding the solutions required to reduce these effects.

In WFA, there are three different types of WFs. The blue WF is a measure of how much water is used from both subsurface and surface sources (blue WF resources). The amount of water consumed from rainwater is shown in the green WF (green WF source). However, the thing to be careful about here is that this resource should not be mixed (become run-off) with surface or groundwater in any way. The amount of water used to return tainted water to its natural state in terms of concentration and meet the existing water quality standard is referred to as the grey WF.

Following ongoing studies, 4 stages of WFA have been developed. These are setting goal and scope, WF accounting, WF sustainability assessment, and WF response formulation.

In the following sections, the steps of WFA shown in Figure 3.1 are explained in detail.

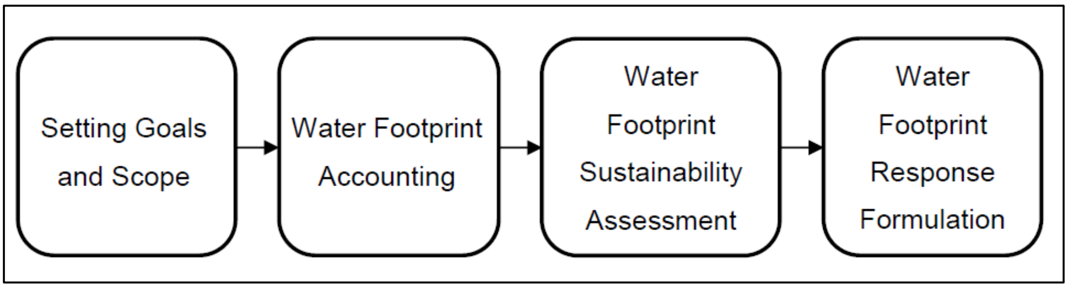


Figure 3.1. Stages of the WFA

3.1.1 Setting Goals and Scope

Setting the aims and scope of the WF research is the first step in a WF assessment. WFA can be carried out for a variety of reasons. It could be done, for example, to assist a specific company in attaining sustainable water management within its direct operations and supply chain. WF Assessment could be customized to match the study's objectives and scope. The WFA's purpose outlines what you'll perform in the next steps: accounting, sustainability analysis, and response formulation. The entire WFA study is shaped towards the originally determined goal. In this section, it is stated which study will focus more on the remaining steps.

The study's spatial and temporal scale is determined by the scope of the assessment. For example, whether the focus will be worldwide or within a specific basin, whether it will cover one year or more than one year, and whether it will cover part or all of the value chain are all addressed in this section. In the scope part, the items included and not included in the study are specified for the purpose of the study. This part is still effective on other steps. For example, with the scope to be determined, it can create a boundary for the WF Accounting section where WF will be calculated later. For example, if it is desired to conduct a study depending only on the amount of contaminated water, it will be sufficient to add only the grey WF to the study. For the sustainability assessment part depending on the purpose of the study, the researcher can make an assessment specific to blue, green or grey WFs, and only environmental sustainability can continue to work, for example. All these scopes should be determined for the purpose of the study.

3.1.2 Water Footprint Accounting

The basic goal of WF Accounting is to determine a process', product's, manufacturer's, consumer's, or geographic area's WF over time. This calculation is conducted to meet the goals and objectives set forth in the goal and scope definitions. Calculations are made using water data. The data to be used in these calculations can be obtained from the field or international data banks such as WaterStat. Calculations at this stage may include green water, grey water, and blue water.

The usage of blue water resources (surface and groundwater) in a product's production stage is called to as the blue WF. The loss of water from a catchment area's available ground-surface water body is referred to as consumption. Water evaporation, returning to another catchment area water source like sea, absorbed into a product, or does not return in the same period, resulting in losses.

The formula used to calculate the blue WF in a process step is as follows (Hoekstra et al., 2011):

$WF_{proc,blue}$ = Blue Water Evap. + Blue Water Incorp. + Lost Return Flow Eqn. (3.1)

In Equation 3.1:

Blue Water Evaporation [volume/time]: Volume of blue water evaporated in the process step

Blue Water Incorporated [volume/time]: Volume of blue water entrained in the product in a process step

Lost Return Flow [volume/time]: The fraction of the return flow (water) that cannot be utilized in the same reservoir and within the same withdrawal time is referred to as loss return flow. This could be due to the extracted water being returned to another basin (or released into the sea) or being returned within a different time frame.

The term "green WF" was defined by to describe the consumption of green water resources such as rainwater that does not run off or reach surface or groundwater water resources. The formula for calculating a process step's green WF is as follows:

$WF_{proc,green}$ = Green Water Evap. + Green Water Incorp. Eqn. (3.2)

In Equation 3.2:

Green Water Evaporation [volume/time]: Volume of green water evaporated in the process step

Green Water Incorporation [volume/time]: Volume of green water entrained in the product in a process step

The volume of freshwater needed to assimilate the amount of contaminants given natural background levels of concentration and current ambient water quality requirements is known as the grey WF. (Hoekstra *et al.,* 2013). The grey WF was first defined by Hoekstra and Chapagain (2008). In this definition, the grey WF was defined as the pollutant amount divided by the maximum acceptable concentration in the receiving water body. It was later found that a better result would be obtained by dividing the pollutant load between the acceptable maximum and the natural background concentration to calculate the grey WF (Hoekstra *et al,* 2009a). The formula used to calculate the grey WF in a process step is as follows:

$WF_{proc,grey} = L / (C_{max} - C_{nat})$ Eqn. (3.3)

In Equation 3.3:

L [mass/time]: Pollutant load

C_{max} [mass/volume]: Maximum acceptable concentration of pollutant in the receiving freshwater body.

C_{nat} [mass/volume]: Natural concentration in a receiving water body.

C_{max} values indicates ambient water quality standards for the receiving freshwater body, in other words, standards with respect to maximum allowable concentrations (Hoekstra *et al.*, 2011).

C_{nat} value is the concentration that will occur if there was no human effect on the water body. C_{nat} value can be accepted as 0 for man-made chemicals that are not naturally found in water. If the natural concentrations are not known exactly but are considered to have a small effect when estimated, this value can also be accepted as 0.

3.1.3 Water Footprint Sustainability Assessment

The Water Footprint Sustainability Assessment (WFA) is used to determine if water use is environmentally sustainable, resource efficient, and equitably distributed. When the blue WF exceeds the available water, for example, environmental flows are disrupted, and freshwater ecosystems degrade over time, which is not a sustainable occurrence. If the WF exceeds a resource efficiency benchmark for that activity, for example, this suggests that WF reduction is possible through a change in practices or technology. In addition to ensuring that the WF is environmentally sustainable and resource efficient, it must also be distributed equitably among all people, and this fact allows it to assess the computed WF's social sustainability.

3.1.4 Water Footprint Response Formulation

As a result of the study, by using the information obtained from the accounting and sustainability assessment steps of the WFA, actions to be taken to reduce the WF of the product or process or country or region being studied, and also priorities to develop and implement the necessary intervention strategies to increase the sustainability of the water consumption is determined at this stage.

3.2 Life Cycle Assessment

Another approach for WFA is LCA (ISO 14046) which provides the understanding of the potential environmental impact of water consumption as well as potential impact on economy and communities. In the following section this approach is examined in detail.

ISO 14046 methodology includes four phases. These are goal and scope, WF inventory analysis, WF impact assessment and interpretation (Figure 3.2).

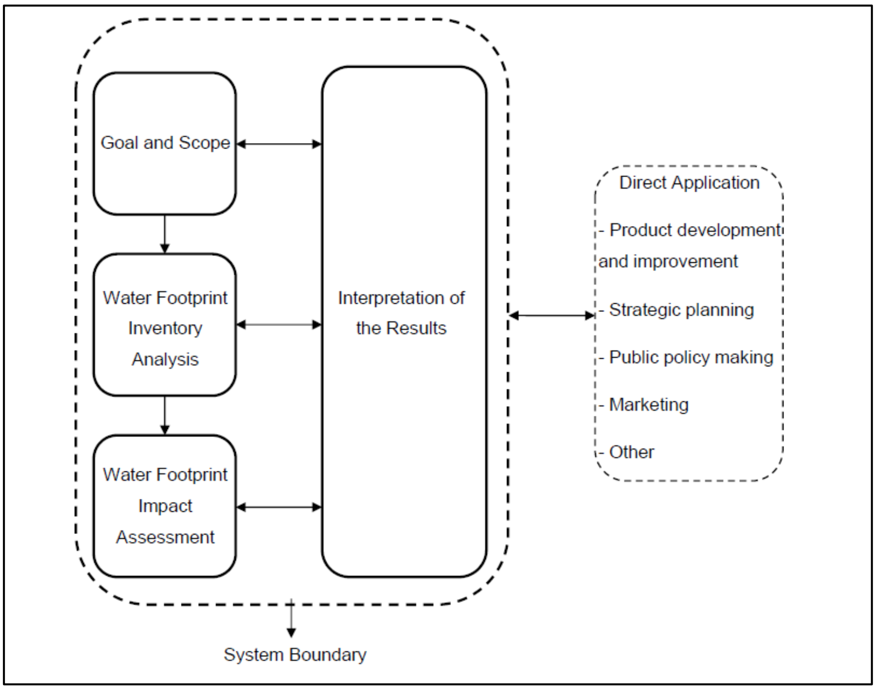


Figure 3.2. Phases of the LCA (Rebitzer *et al.*, 2004)

3.2.1 Goal and Scope

According to Rebitzer *et al.* (2004) an LCA study first begins with the introduction of purpose and scope. The purpose and scope include a description of the limits of the system or product to be examined and a functional unit. The functional unit is an important factor that allows two different systems or products to be compared and analyzed to learn about their environmental impact. The main purpose of the functional unit is to provide the same unit for two different products so that the comparison is made on the same basis. For example, if two different packaging techniques are to be compared in terms of WF, the WF caused by these packaging techniques when producing a 1 m^3 package can be compared. When defining the system boundaries, details such as where you started, where to go, flow chart, data collection and processing, calculations, data quality are important.

3.2.2 Water Footprint Inventory Analysis

At this stage of the LCA study, all data related to the study begins to be collected. The data to be collected in the inventory analysis include all environmental inputs and outputs, such as raw materials and energy use, pollutant emissions and waste streams associated with a product or servicewater and soil impact water quality locations of water use, types of water resources used, water evaporation, water quality data, timing of water use and length of water storage, emissions to air, stream flow, water withdrawal, groundwater flow, seasonal changes in water flows (Forin *et al.*, 2020). As one of the critical points at this stage, as the work progresses and starts to be completed, target and scope may be need to adjust again after data collection.

3.2.3 Water Footprint Impact Assessment

Environmental impacts are classified in life cycle impact assessment, the product or process under study has potential environmental impacts as a result of data collected and calculated. These effects are transformed into environmental themes, such as global warming or human health. With ISO 14046, both midpoint and endpoint impact assessment methods can be selected according to the audience addressed or the data it contains. Midpoint methods in ISO 14046 are methods focused on impacts of water use on water scarcity. There are differences in how midpoint methods are expressed in themselves. For example, some methods use maximum and minimum

(0-1) for the water scarcity value Boulay *et al.,* (2018) while other methods do not (Hoekstra *et al*, 2011; Frischknecht *et al.*, 2006). End point methods are methods that focus on damage in areas of protection in order to maintain good life quality (water use impacts on human health, ecosystem quality, and resources). These methods also differ according to the number of damages in areas of protection they examine. While Motoshita et al., 2010 and Boulay *et al.*, 2011 only looks Human Health, Pfister *et al.,* 2010 and Pfister *et al.,* 2009 looks for 3 areas of protection (Kounina *et al.,* 2013).

The method used in the study is the Recipe version 1.06 (Recipe, 2011). Water depletion was chosen as the midpoint category. Freshwater ecotoxicity, freshwater eutrophication, climate change human health, marine ecotoxicity and climate change ecosystem were selected as the endpoint category (Recipe, 2011).

3.2.4 Interpretation of the Results

The interpretation is the section where the evaluation of the system or product caused by the evaluation of the inventory analysis and impact assessment results, the important environmental impacts caused by the system, their integrity, sensitivity and consistency are obtained. Also, suggestions for the results of the study are given in this section. In addition, with ISO 14046, it is the part where the processes that have an important contribution to the formation of WF, water sources (basically affected environmental mechanisms) where this effect is seen most are revealed. In addition, an interpretation can be made to these processes geographically and temporally. In this sense, the weakest link of the system is learned. In the light of this information, measures to be taken, measures and arrangements to reduce the WF of processes, changes in the design of the product or re-evaluation of production or process in accordance with state regulations are defined.

3.3 Evaporation and Rainfall Data for Blue WF Calculation

Blue WF is an indicator of consumptive water use. As seen in the formula of the blue WF (Eqn. 3.1), the amount of water evaporated in the production processes is also included in the consumptive water use category. The data required to calculate the amount of water evaporating from open spaces is the area of the surface where water evaporates with the data of average monthly pan evaporation (mm).

If rainwater is additionally gathered and used for consumption, this figure must be distinguished from the green WF when computing the blue WF. If rainfall was not collected, it would be in a run-off state, according to the WFA. This water, however, was removed from the run-off since it was collected and consumed. As a result, according to the methodology's scenario, these amount of water can also be included as a blue WF.

In the following section, data and sources used to calculate evaporation and rainwater are provided.

3.3.1 Evaporation Data

Pan evaporation data was obtained from the EIA Application File of the Ovacık Gold Mine Third Waste Storage Facility Project as a result of the research undertaken for this study. The Bergama Station of the Turkish State Meteorological Service provided the data for this report. The average of data acquired between 1960 and 2012 was used to create evaporation data, which is shown in Figure 3.3 (SRK Consulting and Engineering Inc, 2014).

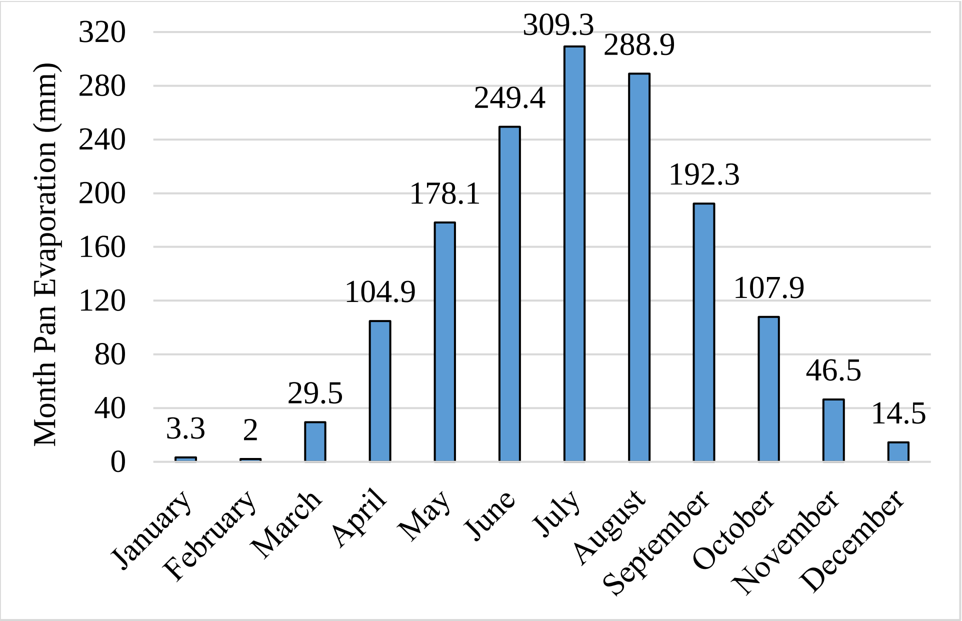


Figure 3.3. Monthly evaporation amount (mm) (SRK Consulting and Engineering Inc, 2014).

According to the data given in Figure 3.3, it is seen that the evaporation amount is high in the summer months compared to the other seasons. Among the summer months, July has the highest value with 309.3 mm. The least evaporation occurs in the winter months. In the winter months, February is the month when evaporation is the least with 2 mm.

3.3.2 Rainfall Data

Whether the rainwater falling on the tanks and tailing pond is green or blue water was decided by examining the WFA manual. According to the suggestion given in this manual, the harvested rainwater can be considered as a blue WF since it will decrease from the flow when used for consumption purposes (Hoekstra *et al.*, 2011). As a result, precipitation that falls on surfaces is also seen as having a blue WF. The amount of rain per square meter was collected from the Ovacık Gold Mine Third Waste Storage Facility Project EIA Implementation File, like evaporation. (SRK Consulting and Engineering Inc, 2014).

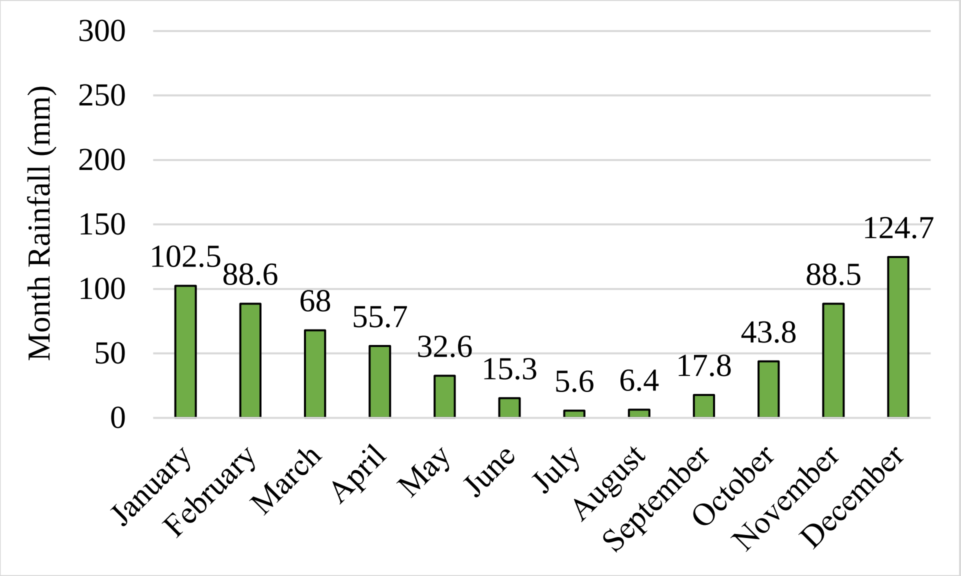


Figure 3.4. Monthly precipitation amount (mm) (SRK Consulting and Engineering Inc, 2014).

According to the data given in the Figure 3.4 it is seen that the amount of precipitation is higher in the winter months compared to other seasons. December has the highest value with 124.7 mm between the winter months. The least rainfall occurs in the summer months. The least rainfall is July with 5.6 mm in the summer.

3.4 Water Chemistry Values for Grey WF Calculation

The pollutant load was obtained from the weekly tailings pond metal analysis of the Ovacık Gold Mine for nine pollutants (Köksal *et al.*, 2003). For all of the contaminants in this dataset, the weekly average was found by averaging the 83 week-data after eliminating outliers. According to the results obtained, nine pollutants are cadmium, copper, chromium, arsenic, lead, iron, nickel, mercury and zinc. The obtained data were used to calculate the grey WF value. In the Table 3.1 the value indicated by L (mass/time) is the pollutant load, the value indicated by C_{max} (mass/volume) is the maximum acceptable concentration of pollutant in the receiving freshwater body, and the value indicated by C_{nat} (mass/volume) is the natural concentration in a receiving water body. The C_{max} value was determined considering the Water Pollution Control Regulation Table 7.1 and the Former IFC General Environmental Guidelines (published in 1998) as another value used in the calculations. Lowest Water Quality Classification (II) values belonging to Turkish Water Pollution Control Regulation, including the water body from which the water is discharged, are used for the natural concentration (C_{nat}) in the receiving water body. All of these values are given in Table 3.1.

Table 3.1. Values of Contaminants Causing Grey WF (Golder Associates, 2017; Köksal *et al.*, 2003)

Contaminants	C_{max} (mg/L)	C_{nat} (mg/L)	L (mg/month)
Arsenic (As)	0.1	0.02	0.1
Cadmium (Cd)	0.1	0.002	0.01
Chromium (Cr)	0.5	0.02	0.01
Copper (Cu)	0.5	0.02	0.44
Iron (Fe)	3.0	0.3	0.047
Lead (Pb)	0.1	0.01	0.05
Mercury (Hg)	0.01	0.0001	0.0012
Nickel (Ni)	0.5	0.02	0.05
Zinc (Zn)	2.0	0.2	0.0069

3.5 Indirect WF Sources

Groundwater combined with minerals is also factored into the equations. In addition, the amount of diesel fuel, electricity and chemicals used in the operations inside the mine are also included in the indirect WF class. A literature review was conducted for the calculations made for these values and other sources. As a result of the researches, the WF value for a unit of indirect WF sources used in the mine is shown in Table 3.2. On the other hand, Table 3.3 contains the data required to calculate how much is consumed from each source. For example, the amount of electricity required to produce 1 ton of gold is 15.5 GWh according to Table 3.3, and the total WF value of 1 kWh electricity production is 0.0021 m^3 according to Table 3.2.

Table 3.2. Unit WF Values of the Materials Used in the Mine (*EcoQuery - Search*, n.d.; Perry *et al.,* 1999**;** Köksal *et al.,* 2003; Northey *et al.,* 2014)

Source	WF per unit	Unit
Sodium Cyanide	0.196	m^3/kg
Lime	0.02	m^3/kg
Hydrochloric Acid	0.026	m^3/kg
Electricity	0.0021	m^3/kWh
Explosives	0.034	m^3/kg
Activated Carbon	0.012	m^3/kg
Oxygen	0.0042	m^3/kg
Diesel	0.0013	m^3/kg

Table 3.3. Unit Amount Values of the Materials Used in the Mine (*EcoQuery - Search*, n.d.; H. Gu *et al.,* 2018; Northey *et al.,* 2014)

Source	Amount	Unit
Sodium Cyanide	0.5	kg/t
Lime	0.5	kg/h
Hydrochloric Acid	32	t/per ton gold
Electricity	15.5	GWh/per ton gold
Explosives	658	t/per ton gold
Activated Carbon	9.3	t/per ton gold
Oxygen	8.9	kt/per ton gold
Diesel	2.1	kt/per ton gold

These data, which were obtained after a wide literature review, were used in the calculations required for both WFA and LCA in the following chapter. The values obtained as a result of the calculations form the basis of the evaluations to be made within the scope of the study.

CHAPTER 4

WATER FOOTPRINT ASSESSMENT OF THE CARBON IN-PULP GOLD PROCESSING

Water is used extensively in gold processing (Bahrami *et al.,* 2007). The use of water for gold processing depends on many reasons. The first is a low-energy and low-cost way of transporting pulp between processes used in the facility, mixing and sourcing reactants from tanks used to separate gold. Also, water is an essential chemical component in chemical processes (Norgate and Lovel, 2006)**.**

Various methods are used in gold beneficiation facilities. All of these methods will be explained in detail in the following chapter. In all of these methods, the use of water is one of the fundamentals of the method. For example, leaching method which is the today's highly popular, treatment steps involve the crushing, screening, grinding, dewatering, leaching and adsorption, elution and gold recovery (electrowinning). The water, which is used to suppress the dust in the crushing stage, which is the first stage of this system, is then used in each step. In fact, water is so important for this process that one of the inputs of the reaction that occurs during the leaching process is water. Also, in electro-recovery, aqueous reactive solutions are required to concentrate and purify gold contained in the pregnant solution (Prosser *et al.*, 2011). Therefore, it is impossible to carry out these operations without water.

4.1 Gold Processing

Gold is an element with the symbol Au and atomic number 79. It was the first metal utilized by humans, along with copper, since both metals are malleable and ductile, and can be easily handled with a crude tool. (Marsden and House, 2006; Wai Wong *et al.*, 2009).

Thanks to its properties, gold is used in many areas. These features are high workability, ductility, resistance to many chemical reactions and high electrical conductivity. Its durability under corrosive conditions led to its widespread use in coins and jewelry throughout the ages (Kizuka, 2008; Nicol *et al.*, 2006).

According to the statistics of 2020, 46.64% of the gold produced in the world was used in investment, 36.83% in jewelry, 8.58% in central banks and the remaining 7.95% in the technology sector (Garside, 2021).

Various methods are used to separate gold from its ore after it is produced as ore from underground mines or open pits. The main methods used are cyanidation, flotation, amalgamation, and gravity concentration. These methods are briefly described below:

Gravity concentration: In this method, separation is performed using the high density (19.3 g/cm^3) feature of gold. Assuming that the density of a typical ore containing gold is 2.6 g/cm^3, the basis of this method is to separate heavy particles (gold) from light particles (rock) by gravitational force. While the equipment used in this method collects the heavy gold bottom, it cleans the other light parts by washing them from the surface. The method is generally used for placer type of mines (Wong *et al.*, 2009).

Amalgamation: This enrichment method was used for gold reserves with large particle size. The method is illegal in most countries as mercury is a toxic material and is no longer used. In the process, metallic gold is first wetted using mercury. After this process, mercury and gold solution called amalgam is formed. Amalgam is then passed over copper plates. When the plates are fully loaded with amalgam, the plate is removed and the amalgam is scraped. To evaporate the mercury, the hardened amalgam is heated in a retort oven and the gold material remains (Adams, 2005).

Flotation: Flotation is a technique based on the adhesion of a single mineral or particles of a mineral group to air bubbles with the help of collectors, frothers, modifiers. The flotation method is based on the hydrophobicity of the surface of valuable minerals. In this method, the surface of gangue minerals is hydrophilic. When three phases, liquid, gas, and solid, come into contact, an equilibrium is established between the interface tensions of solid-air, solid-liquid, and liquid-air (Gupta and Yan, 2006b).

This technique is often used for ore containing small amounts of gold in combination with base metals. In this method, the process is not actually done for gold. Gold is obtained as a byproduct during the processing of base metals. Flotation is frequently used with cyanide leaching. Depending on the mineralogy and flowchart economics, cyanidation of flotation concentrates or buoyancy effluents is performed (Wong *et al.*, 2009)**.**

Cyanidation: Among these methods, the most common method used today is cyanidation. In this technique, dilute sodium cyanide (NaCN) or potassium cyanide (KCN) solutions are used as lixiviates (leaching agents) to separate gold from ore, and these solutions dissolve gold from ground ore (Marsden and House, 2006). This technique, which takes place in the presence of oxygen and lime, was discovered by Elsner in 1846 and the reactions of the technique are given below:

Elsner’s equation (Parga *et al.*, 2013) :

$$\mathrm{2Au + 4KCN + O2 + 2H2O = 2KAu\ (CN)2 + 2KOH + H2O2}$$

$$\mathrm{2Au + 4KCN + H2O2 = 2KAu\ (CN)2 + 2KOH}$$

$$\mathrm{4Au + 8CN^{-} + O2 + 2H2O \rightarrow 4Au\ (CN)2^{-} + 4OH^{-}}$$

There are three different application types in this method. These are heap leach, agitation leach, and vat leach. While the heap leach method is a cheaper method for the enrichment of low-grade gold ores, tank leaching is used for ores with high grade. In the process following the leaching methods, the recovery of dissolved gold is done by adsorption using activated carbons.

In heap leaching, the main advantage is that capital and operating costs are lower rather than the others, and another advantage is that it does not require any solid-liquid separation. In contrast to these advantages, to use heap leaching, ore deposit must be relatively larger, and also the disadvantages of this method are low solution efficiency and longer retention time of leaching. In heap leaching, retention time is between 30 and 60 days, and solution efficiency is 40-60 % for coarse size ore and 60-80 %for finer size ore (Yüce, 1997).

Besides, according to (Marsden and House, 2006) vat leaching is generally carried out in large structures made from concrete or wood. Also, steel tanks or can be used by heap leaching in a configuration of valley-fill, where the heap can be flooded. However, the method is rarely used due to high capital and operating cost with vat construction.

Agitation leaching is based on mixing the ore with cyanide in cylindrical tank under -0.3 mm particle size. In this method, oxygen can be added to the system to increase the reaction. The leaching time varies between 16-48 hours, and 24 hours in average, in further, the solution efficiency can reach above 80%. In agitation leaching, the material to be leached is typically between 45 and 150 µm, and depending on the particle size and specific gravity of solids, leaching is normally done at slurry concentrations of 35 to 50 percent solids. (Marsden and House, 2006).

The cyanidation method was preferred to process the gold ore in the process facility designed for this study. The primary reason for this preference is that it is the most common and effective method used to process gold ore today. In this way, the study will be a useful model for many gold processing facilities in the world.

After the cyanidation process, the carbon adsorption method was used as the gold recovery from solution method in the facility. Here, as in cyanidation, there are different methods. The names of these methods are carbon in column (CIC), carbon in pulp (CIP) and carbon in leach (CIL). Although activated carbons are used to separate gold from pregnant solution in all three methods, the processes work differently within themselves.

In CIC, pregnant solution needs to be clarified, hence it is more applicable in use of heap leaching. The process is carried out by passing the pregnant solution through the carbon column. In the CIP method, recovery occurs after the leaching gradual part of the plant in separate tanks. On the other hand, in the CIL process, cyanidation and adsorption take place simultaneously. Representative diagram of a CIP or CIL is given in the Figure 4.1.

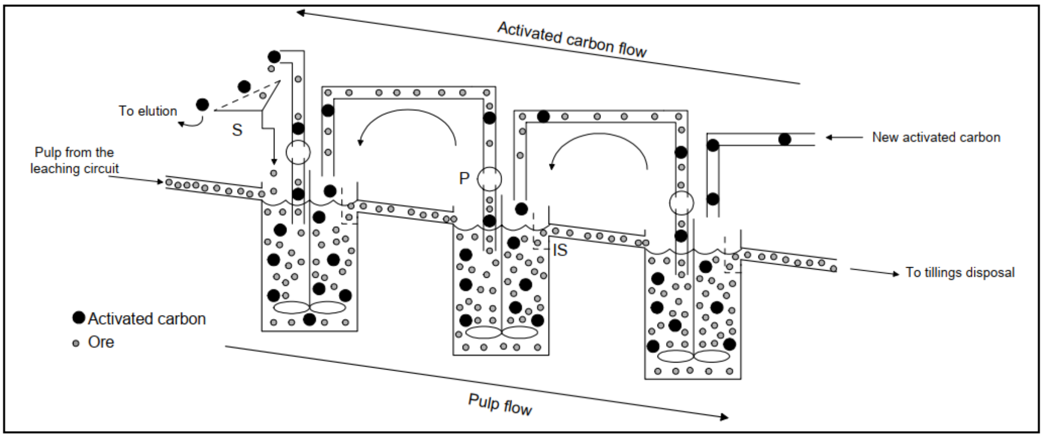


Figure 4.1. Representative diagram of a CIP or CIL (De Andrade Lima, 2007)

In Figure 4.1 IS, S, and P refers to interstate screens, the screen at the exit of the first tank, and the carbon transfer pumps respectively. As seen in this diagram, as a common point of these processes is that activated carbon is transported from one tank to another in counter current with the ore pulp until the carbon loaded in the first tank is recovered. Thanks to the counter current, activated carbon parts continuously adsorb the gold in the cyanide solution. Therefore, the gold concentration of the carbons in the first tank is higher. Then, the gold-filled carbon is collected from the tanks with sieves and sent to the elution circuit for separation.

Among these methods, the CIP method was preferred for the recovery process from the designed facility. The general CIP gold processing plant flow diagram is shown in Figure 4.2.

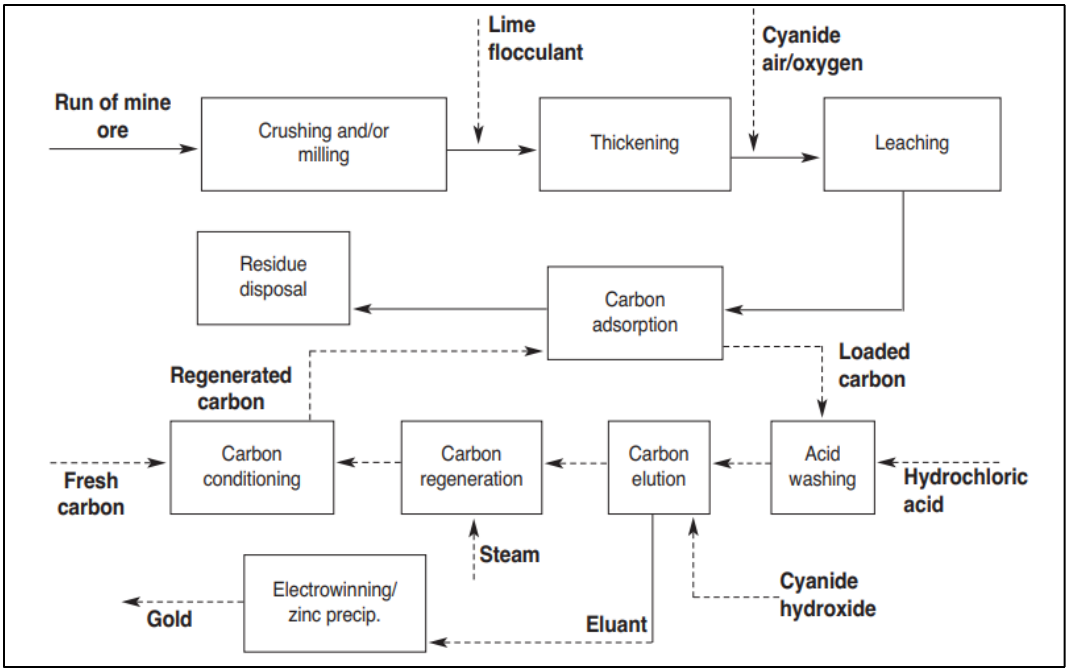


Figure 4.2. Flow Diagram of a Typical CIP Plant (Stange, 1999)

4.2 Conceptual Design of the Processing Plant

The facility designed for operation is designed on a typical CIP facility model shown in Figure 4.3. In order to design the designed facility as close to a real facility, research has been carried out on mines that continue to produce in Turkey and use the CIP method and in this way the values are as close to reality as possible.

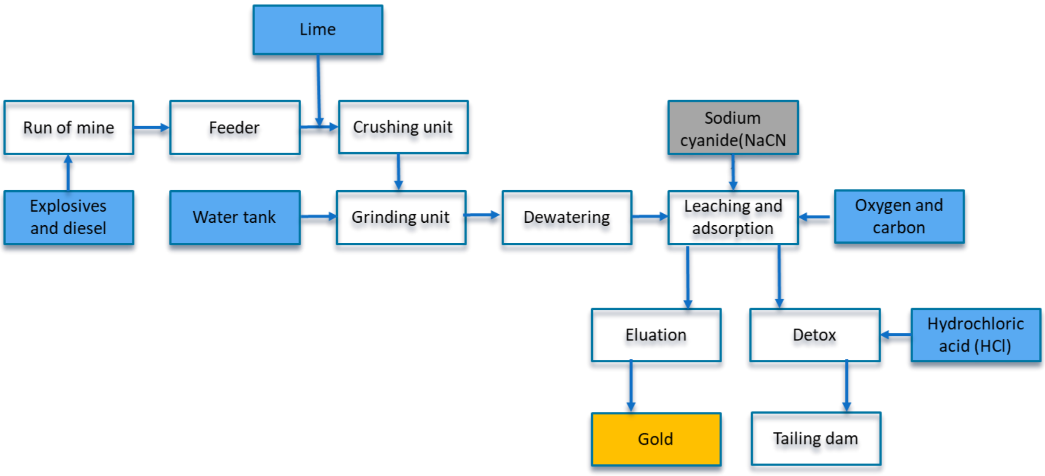


Figure 4.3. Flow Diagram of the Facility

The hourly feed amount of the facility designed for the study was determined as 250 tons and the grade of ore processed at the facility is 4.36 g/ton (Onal, 2013). The processing plant is fed with water from wells and 30 m^3/day of domestic wastewater is discharged. (Golder Associates, 2017). The value provided by Northey and Haque (2013), 0.15 m^3/ton of water, was used for the pit dewatering value in the mine.

The run of mine (ROM), fed by an apron feeder to the plant, is first fed into a 3-stage crusher circuit to reduce particle size. The ore, which is reduced to a certain particle size in the crusher circuit, is then sent to a fine ore bin with a belt conveyor.

Water is sprayed to the relevant points in order to suppress the dust that may occur while the ROM from the mine is being discharged into the bunker and to suppress the dust that may arise while the material is fed from the silo to the first crusher (Sarikaya and Orhan, 2018). In order to calculate this amount of water, it was considered that there was a water spray for every crusher in the crushing unit, and the water consumption value for these sprays was assumed as 10 lpm (“Guidance for Controlling Silica Dust from Stone Crushing with Water Spray Technology,” 2008).

One of the materials used in the CIP process is lime. Lime is added to the ore, which has passed the crushing stage, while it is sent to the grinding stage. The amount of lime used in the designed facility is 0.5 kg/h. The purpose of using lime in the plant is to raise the pH value, because the high pH prevents the formation of hydrogen cyanide gas in the tanks (Perry *et al.*, 1999).

There is 1 rod mill and 1 ball mill in the grinding circuit. The ore sent from the fine ore bin is fed to the rod mill along with the lime. Wet grinding process is applied in the grinding circuit. For this reason, water is also supplied from the water tank in the facility to the rod mill. As a result, the pulp in the rod mill is set to 75% solids by mass. The pulp rate of the ball mill in the grinding circuit is set to 72% solids by mass (Gupta and Yan, 2006a; Sarikaya and Orhan, 2018). After the ball mill and rod mill discharge are collected in the slurry box, it is pumped to hydrocyclones. The pulp in the slurry box has a solid by mass ratio of 50% (Stange, 1999). Therefore, water is sent here from the water tank in the facility. Hydrocyclone unit works with ball mill closed loop. The overflow of the hydrocyclone is fed to the thickener.

To recover the mineral in the ore, the water body must be separated or reduced. The plant has a gravity sedimentation thickener for the separation of solids from liquids. This reduces also the size of the leaching plant that reduces the amount of leaching reagents required.

As a result of the settlement of the pulp sent to the thickener, the solid by weight ratio becomes 50%. The pulp which has solid by weight ratio reaches this level, is sent to the leaching 1 tank with the help of a pump under the thickener. The water collected on the surface of the thickener is pumped to the process tank for reuse.

The leaching consists of two mechanically stirred tanks and adsorption circuit consists 8 mechanically stirred adsorption tanks (*Extraction and Beneficiation of Ores and Minerals*, 1994; Sarikaya and Orhan, 2018). 0.5 kg/t NaCN is added to the leach tank 1 (Köksal *et al.*, 2003). In addition, to raise the leakage rate and improve carbon loadings, oxygen is introduced to both leach tanks (Marsden and House, 2006). Chemical reaction starts at the leach 1 and leach 2 tank. The carbon is transported from the last tank to the first adsorption tank countercurrent, into the slurry stream.

When the carbon is loaded with enough gold it is removed from the circuit and sent to elution where the adsorption process is reversed and the gold is stripped off the carbon back into solution. This process is reversed proses of adsorption that gold is peeled from the carbon and returned to solution. After completion of the elution, electrowinning is commenced with electrolyte being circulated from the electrolyte tank to the electrowinning parallel cells. In electro-wining, carbon eluates are sent to cathodes to produce loaded cathodes and cathodes cell sludges. A cathodic reduction reaction in aqueous solution can be driven by applying a voltage across a pair of electrodes immersed in the solution.

The waste water resulting from the filtration of carbons filled with gold is subjected to chemical treatment to be sent to the waste pond. The purpose of these processes is to reduce the concentration of heavy metals and other chemicals harmful to nature in the waste. At the facility, for destruction of cyanide Inco SO2/AIR process is carried out. This cycle is called detoxification and it has two stages. In the first stage of the process, the concentration of cyanide is lowered, while in the second stage arsenic and antimony are precipitated. In the first step, the agitated solution containing sodium metabisulfite ($Na_2S_2O_5$) and air at pH between 8 and 9 reacts with metal cyanide complexes and CN-. The second tank is used to precipitate metal hydroxides. The cyanide strongly complexes with iron is precipitated as an insoluble ferrocyanide salt by the process (Köksal *et al.,* 2003). The tailings produced from the CIP plant will be deposited in the tailing pond with a surface area of 16 ha (Akçıl, 2002). The volume of water reused or recycled from the tailing pond is 0 for the designed facility. It should be noted that recycling all of the water to be discharged after the necessary treatment processes or reusing it for another purpose will zero the grey WF. It will also reduce the blue water footprint by recycling water (Aldaya et al., 2012).

The water balance of the process facility of the mine is given in the Figure 4.4.

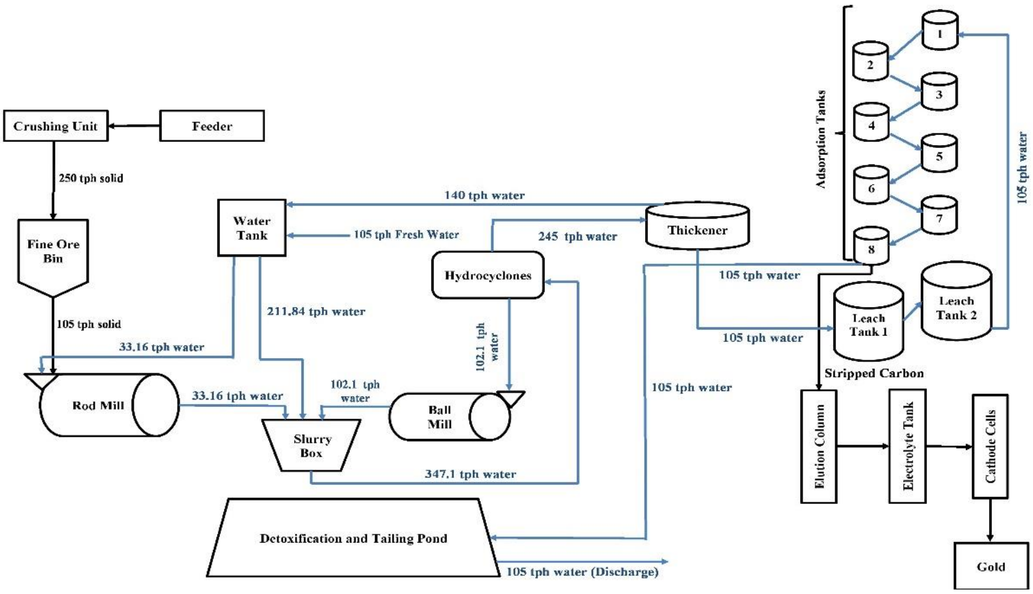


Figure 4.4. Water Balance of the Processing Plant

While making water balance, the design criteria (densities and solids percentage) used for rod mill and ball mill, cyclones, thickener and leaching and adsorption processes were used. In this way, unknown flow rates could also be calculated. According to the result obtained, the amount of water discharged from the facility was obtained as 105 tph.

4.3 Goal and Scope of the Study

The primary purpose of this study is to calculate the blue WF value and the grey WF value of the mining and processing of gold, which was designed as a concept and the CIP method was used, with the data obtained and measuring environmental effects. By dividing the blue WF value into two, both the direct and indirect blue WF value will be calculated. The green WF was excluded from the study. The exclusion of the green WF is based on certain reasons. The first reason is that there is no area to increase the water holding capacity of the soil in the facility designed as a concept.

At the same time, as stated in the WFA manual, the usage area of green WF is mostly for forest and agricultural processes. Inputs that will cause indirect WF in the study include fuel used primarily to process gold in the mine, electricity, and chemicals used for CIP operation. In addition, the amount of water used by the field workers to meet their daily needs is also within the indirect WF values. The aim of the study after this stage is to determine the hot spots as a result of the evaluation of the blue WF and grey WF values obtained for each process and contributors. Identified hotspots are critical areas where measures must be taken to contribute to water management and sustainable production.

Within the scope of the study, a period of one year was determined as the duration. The purpose of this is to obtain a more accurate result by using evaporation and rain data for both summer and winter seasons. The study was carried out to measure the amount of water required to produce 1 kg of gold.

4.4 Water Footprint Accounting

In this thesis, the grey WF and blue WF of the facility were calculated. Blue WF is an indicator of consumptive water use. Blue WF occurring in three states within the definition of it. These situations are evaporated water (Blue Water Evap.), water included in the product (Blue Water Incorp.), as seen in section 3.1.2, and portion of the return flow (water) that cannot be reused in the same basin and within is the amount of the same withdrawal period (Lost Return Flow).

The formula used to calculate the amount of evaporation from the open areas in the facility is given in Equation 4.1 (Minerals Council of Australia, 2014). This formula is used to measure the amount of water evaporated in the Water Accounting Framework (WAF) established by The Australian Minerals Council.

V_{Evap} (ML) indicates the total loss in evaporation, S_{Evap} is used to indicate the surface area as (ha) which the amount of water that evaporates over the calculated time period. Pan_{Evap} represents the value of the evaporation amount (mm) for the time period for which the calculation will be performed. Another value in the formula, f, is the correction factor. This value is generally accepted as 0.75 when evaporation rates are measured with a Class A pan.

$$V_{Evap} = 0.01 \times S_{Evap} \times Pan_{Evap} \times f \qquad \text{Eqn. (4.1)}$$

As an example of this calculation, the amount of water evaporated from the tailing pond in June is given below:

$$V_{Evap,\ Tailing\ Pond\ (June)} = 0.01 \times 16\ \text{ha} \times 249.4\ \text{mm} \times 0.75 = 29.928\ \text{ML}$$

In order to calculate the WF of the rain water, which is accepted as the blue WF, the open surfaces on which the rain falls are taken into account. Examples of these areas are the tanks in the facility. The amount of rain accumulated in the tanks was considered as rain harvest.

The blue WF value of rain water was calculated using Equation (4.2) (Minerals Council of Australia, 2014). Volume of rainfall is represented with $V_{Rainfal}$ (ML). R represents the value of the precipitation amount (mm) for the time period for which the calculation will be performed and open surface area is represented by $SA_{R,M}$ (ha) (Minerals Council of Australia, 2014).

$$V_{Rainfall} = 0.01 \times R \times SA_{R,M} \qquad \text{Eqn. (4.2)}$$

As an example of this calculation, the amount of rainfall collected in the tailing pond June is given below:

$$V_{Rainfall,\ Tailing\ Pond\ (June)} = 0.01 \times 15.3\ \text{mm} \times 16\ \text{ha} = 2.448\ \text{ML}$$

The entrained water, V_{ent} (ML), which is blue water embedded in the ore. V_{ent} was calculated using Equation (4.3). P value in the equation is the processed ore amount during the specific time period (Mt). Moisture content is represented by m value which is a fraction (Minerals Council of Australia, 2014).

$$V_{ent} = 1000 \times P \times m \qquad \text{Eqn. (4.3)}$$

The amount of embedded water in the ore for a month due to moisture content is given below:

$V_{\text{ent, Moisture}}$ = 1000 × (250 ton/hour × 10 hour/day × 27.5 day/month × 0.000001) × 0.05 = 3.437 ML

To broaden the scope of the study, several indirect water sources have been included by calculating the overall WF value of the supply chain and to obtain a more realistic result. These values are all on the side of the blue WF value.

Indirect WF (WF_{Ind}) calculation is done by using equation 4.4. In the study, since the functional unit is 1 kg of gold, the WF value of all values that indirectly contribute to WF was calculated based on the amounts required to produce 1 kg of gold. R_i value is used for each contributor that it is the total amount used in entire year from the contributor to produce gold and P is the annual gold production amount. Value of the amount of water consumed per unit of contributor is represented by (W_i).

Equation used to calculate indirect WF is following:

$$WF_{Ind}=\sum_{i=1}^{n}\frac{R_iW_i}{P} \qquad \text{Eqn. (4.4)}$$

As an example of this calculation, calculation of the indirect blue WF of lime is given below:

$$WF_{\text{Ind, Lime}}=\frac{(24\text{ hour/day} \times 330\text{ day/year} \times 0.5\text{ kg/hour}) \times 0.02\text{ m}^3\text{/kg}}{3{,}191\text{ kgAu/year}}$$

$= 0.02\text{ m}^3\text{/kg Au}$

The concentrations of minerals and heavy metals harmful to the environment in the waste separated from carbon are pumped to the tailing dam after the necessary chemical processes are made in the Detox unit. A certain amount of water accumulated in the tailing dam is discharged to nature. This discharged wastewater is the cause of grey WF. To calculate this grey WF value caused by the facility, the formula included in the WFA Manual and presented in Equation (3.3) was used.

As an example of this calculation, calculation of the grey WF of arsenic is given below:

$$WF_{\text{proc,grey, arsenic}} = \frac{0.5\text{ mg/L} \times 105\text{ m}^3\text{/hour} \times 720\text{ hour/mnth}}{0.1\text{mg/L} - (2\text{E-}02)\text{mg/L}} \times \frac{1}{(9.67\text{ kg/day} \times 27.5\text{ day/month})}$$

$= 1{,}777\ \text{m}^3\text{/kg Au}$

4.5 Water Footprint Impact Assessment

The Recipe Midpoint-H method for midpoint and Recipe Endpoint-H for endpoint in SimaPro 7.3.2 (Pre, 2011) was used to find the amount of water used for the production of 1 kg of gold, which is a functional unit, and impact assessment using the LCA method respectively. There are two main reasons for using these methods. The first one is that the WF method developed by Pfister *et al.* (2011) for LCA and accepted as the End-Point in this field is based on the same end-point categories as the Recipe method. At the same time, the only method that measures water consumption among the methods is the Recipe method.

In order to make the calculations, first of all, a new unit process was created by taking the gold unit processes available in SimaPro 7.3.2 (Pre, 2011) as an example. The unit process model obtained after the study is shared in Figure 4.5.

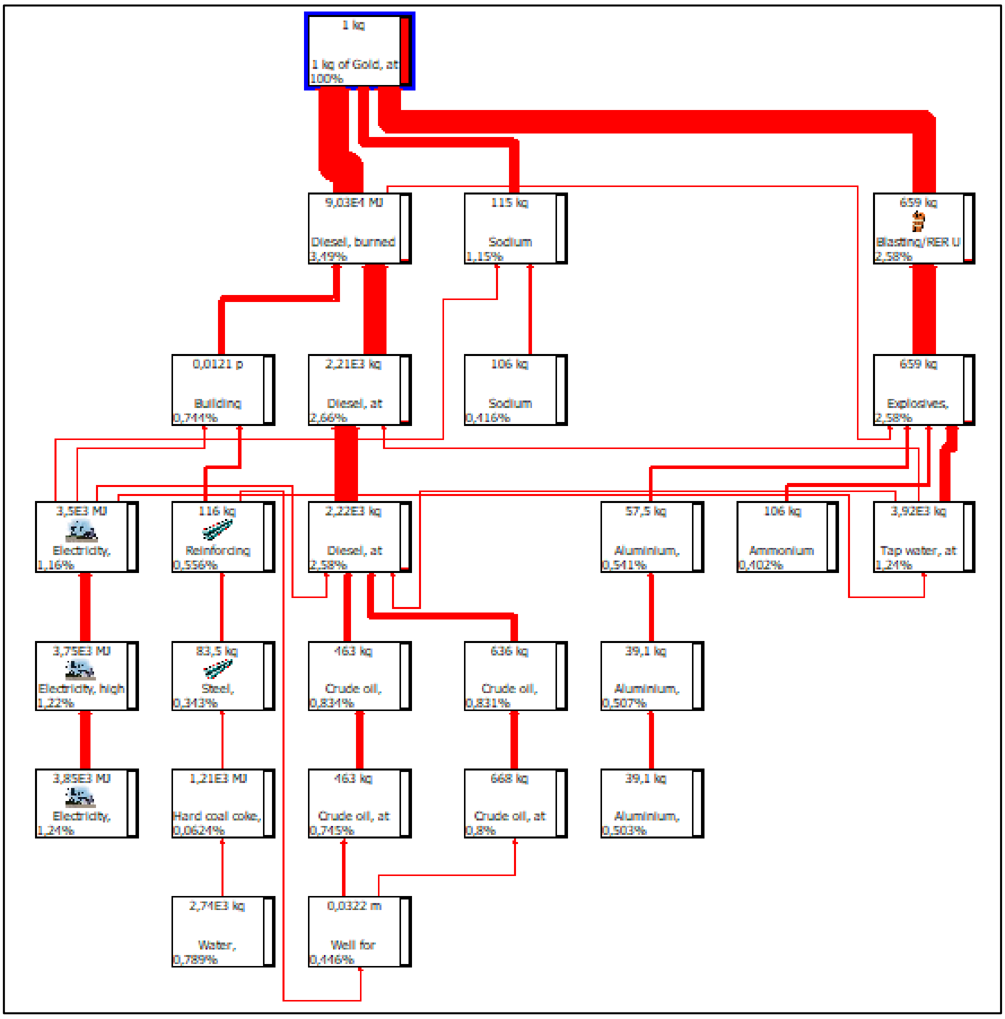


Figure 4.5. The Unit Process Model

Direct blue WF, indirect blue WF (for known inputs from nature and from technosphere) and grey WF (for emission to water and known outputs to the technosphere) data in WFA methodology used in the created process. Based on these data, the values required to produce one kg of gold were calculated.

There is not yet a system for calculating grey WF using LCA. Therefore, numerical results were evaluated only for blue WF. However, the inputs used for grey WF are taken into account when evaluating the impact factors because these inputs are emission to water values.

Evaluation of the results obtained after the calculations in a broad perspective was made in the following chapter. As a result of the evaluations, hotspots were determined. At the same time, the study was compared with previous studies for water consumption in the field of gold mining.

CHAPTER 5

RESULT AND DISCUSSIONS

In this chapter, the WFA and LCA results calculated for the concept mine created were shared. In the Chapter 5.1, the WFA results were analyzed under two parts as grey WF and blue WF. Blue WF is also divided into two as indirect and direct blue WF. In Chapter 5.2, the results obtained using SimaPro 7.3.2 (Pre, 2011) are explained in detail. In this chapter, water consumption (water depletion) and water-focused environmental effects were examined under the categories of freshwater ecotoxicity, freshwater eutrophication, climate change human health, human ecotoxicity, and climate change ecosystem. Finally, the uncertainty analysis results obtained using Monta Carlo Simulation are explained under this chapter. In the chapter 5.3 comparison of the studies with studies previously done is examined in detail.

5.1 Water Footprint Assessment

The results obtained as a result of WF Accounting are interpreted in this section. All of the results obtained were made for the facility to produce 1 kg of gold and the unit is m^3/kg Au. Evaluation of the results was made from general to specific. The results obtained after the general evaluation made in this section are further examined under the Chapter 5.1.1 and Chapter 5.1.2

Looking at the results, it is seen that 16% of the total WF of the facility belongs to the blue WF with a value of 452.40 m^3/kg Au, while the remaining 84% belongs to the grey WF with a value of 2,300.69 m^3/kg Au. It has been discovered that the grey WF is bigger than the blue WF in investigations in the mining sector where grey and blue WF calculations are done at the same time. (Gu *et al.*, 2015; Haggard *et al.*, 2013; Ma *et al.,* 2018; Osman *et al.,* 2017). The same result was obtained in this study.

The values of all contributors from which both grey WF and blue WF originate in the facility are summarized in Table 5.1.

Table 5.1. Grey WF and Blue WF Originate in the Facility

WF Category	Sub-Category	Contributor	Value (m^3/kg Au)
Blue WF	Direct WF	Pit Dewatering	39.09
		Lost Return Flow	260.61
		Human Use	3.28
		Moisture Content	12.93
		Dust Suppression	3.72
		Rainfall	3.38
		Evaporation	7.95
	Indirect WF	Sodium Cyanide	25.49
		Lime	0.02
		HCL	0.81
		Explosives	22.24
		Electricity	32.55
		Oxygen	37.38
		Carbon	0.11
		Diesel	2.73
Total Blue WF			452.40
Grey WF		Tailing Pond	2,300.69

As seen in Table 5.1, seven contributors directly create the WF value. On the other hand, the sum of the indirect blue WF value consists of eight contributors. When all contributors are evaluated together, it is seen that the highest blue WF is due to the lost return flow and blue WF of lime has the smallest value. Among the indirect WF values, oxygen has the highest value. The point that draws attention here is that the second lowest value among WF per unit values belongs to oxygen, but it has the highest indirect WF value. This is because the oxygen consumption in the processing plant is much higher than other indirect contributors. The grey WF value is a value related to contaminants. Therefore, the grey WF is calculated only for the tailing pond.

5.1.1 Detailed Evaluation of Blue WF

In this section, a thorough examination of the blue WF is made. First of all, blue WF values were evaluated monthly. Secondly, the blue WF values were discussed separately according to the processes in the mine, and the processes with the highest and lowest blue WF values were examined. The distribution of the blue WF by months is given in Figure 5.1

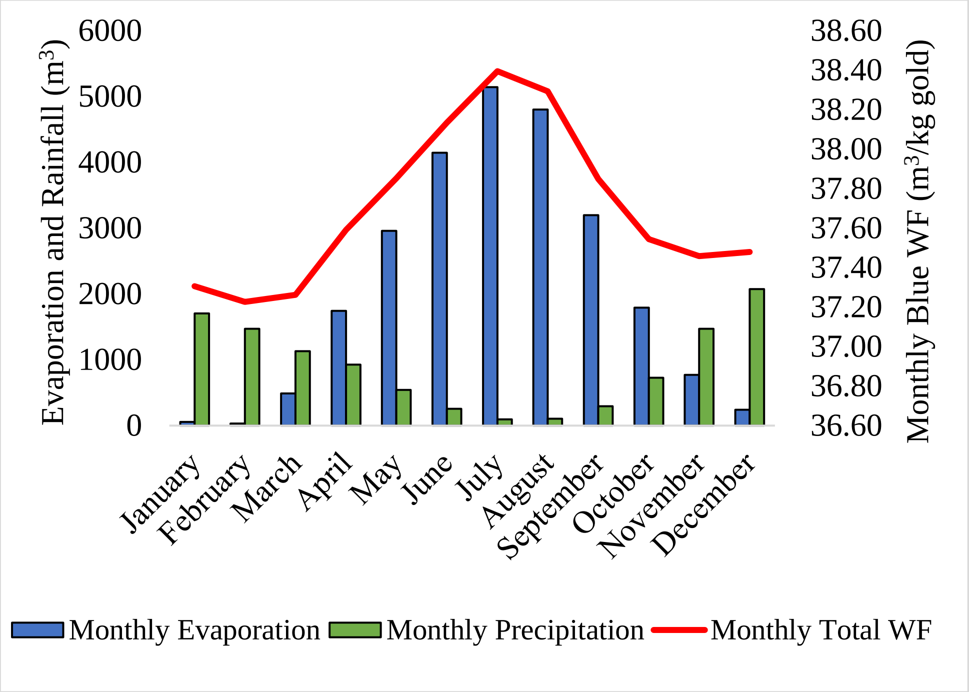


Figure 5.1. Distribution of the Blue WF by Months

On a monthly basis, blue WF value of the mine reaches its highest value in July with 38.40 m^3/kg Au value. The lowest value belongs to February with 37.23 m^3/kg Au. Another result emerging from the graph is that the blue WF value is directly proportional to the evaporation value and inversely proportional to the rainfall value. Therefore, the blue WF is higher in July and lower in February. At the same time, there is little variation in the blue WF values between February and July, despite the large difference seen when comparing evaporation and precipitation values. It is understood from here that other contributors contribute more to the blue WF value.

In Figure 5.2 the blue WF values between the processes are shared. All blue WF values related to ore extraction are gathered under one name as Mining.

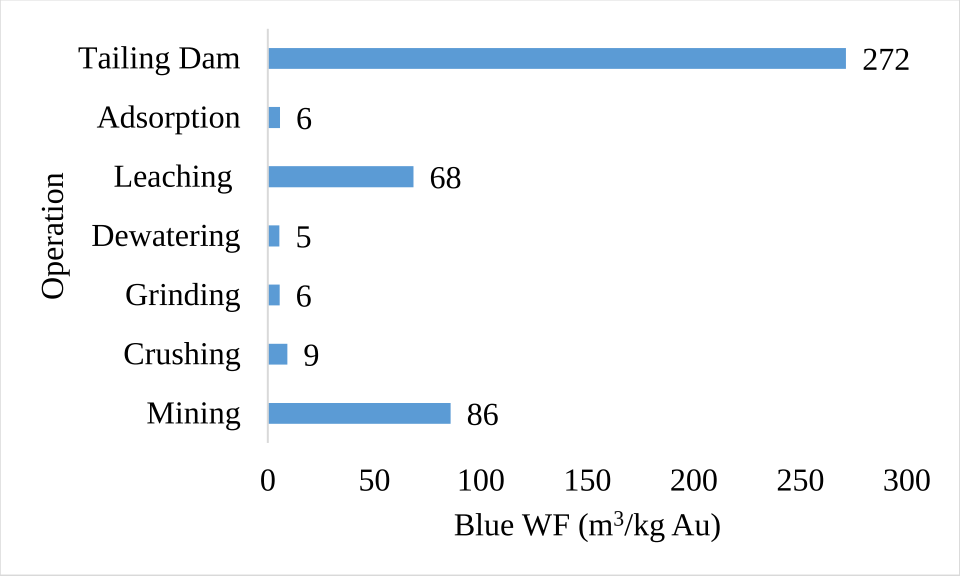


Figure 5.2. Blue WF Values Between the Processes

The blue WF formed in the process facility was analyzed by dividing it into the main operations at the facility. When the results are investigated, the highest value comes from tailing pond. In addition to the lost return value (the highest blue WF value), the blue WF value formed in the tailing pond is due to precipitation and rainfall. Mining and leaching processes have much higher values than other processes. Here, it can be seen once again that oxygen and electricity consumption and pit dewatering values are the biggest contributors after lost return flow value.

5.1.2 Distribution of Grey WF Among Pollutants

The grey WF is the amount of fresh water needed to separate pollution concentrations to ambient background concentrations while meeting current water quality requirements. In this study, the only place where pollutants (heavy metals) are found is the tailing pond. Some of the waste water collected in the tailing pond is discharged into the river around the mine. Before this process, the water used in the process and containing pollutants is subjected to a detox process and sent to the tailing pond in accordance with the regulations. However, the water released to the nature from here causes a grey WF. Grey WF caused by these pollutants separately is given in Figure 5.3.

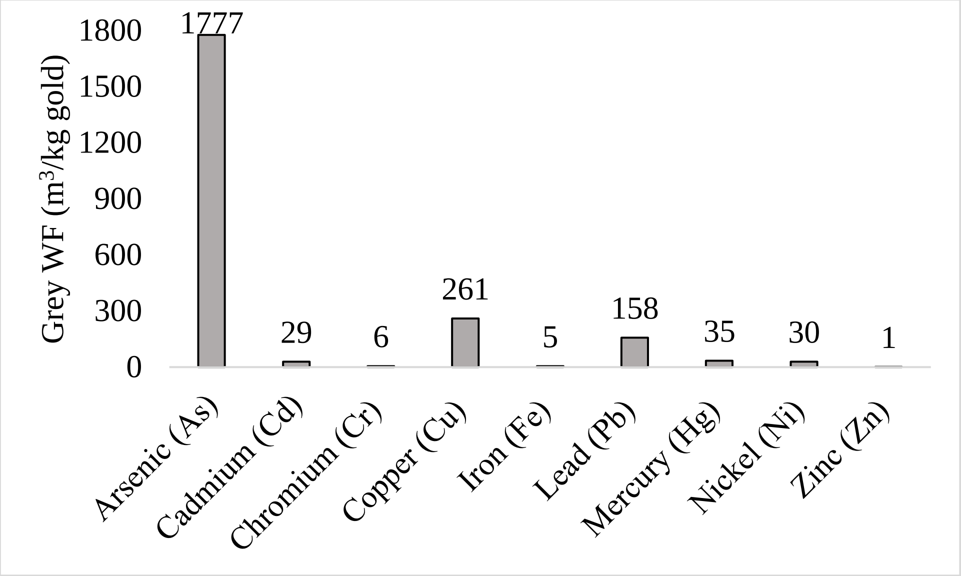


Figure 5.3. Grey WF Values of Pollutants

As seen in the table, the highest value among the pollutants belongs to arsenic. When an evaluation is made as a percentage, it is seen that the share of arsenic in the total grey WF is 77.23%. Among the pollutants, Zinc has the lowest value with 1%. Specifically, since arsenic is very high compared to other pollutants, it demonstrates the importance of focusing on the grey WF of arsenic in order to reduce the value on the grey WF side.

5.2 Life Cycle Assessment

In this chapter, the environmental impact of the facility as midpoint and endpoint has been examined with LCA methodology. The calculations were made with the Recipe version 1.06 (Recipe, 2011) using the SimaPro 7.3.2 (Pre, 2011). There is only one impact category selected for Midpoint, which is Water Depletion. The result found was compared with the blue WF value obtained with the result of the WFA methodology. The categories selected for the endpoint are freshwater ecotoxicity, freshwater eutrophication, climate change human health, marine ecotoxicity and climate change ecosystem. The results obtained were evaluated with both characterization and normalization values. At the same time, the uncertainty analysis of the study is also provided under this chapter.

5.2.1 Blue WF Evaluation (Midpoint)

According to the results obtained, the water depletion which is a midpoint indicator simply expressing the total amount of water used Goedkoop *et al.* (2013) was found as 357.32 m^3/kg Au in total. The distribution of the total water depletion among the inputs is shared in the Table 5.2.

Table 5.2. Distribution of the Total Water Depletion Among the Inputs

WF Category	Sub-Category	Contributor	Value (m^3/kg Au)
Blue WF	Direct WF	Water Consumed	331
	Indirect WF	Sodium Cyanide	4.13
		Lime	0.0003
		HCL	0.399
		Explosives	9.22
		Electricity	0.062
		Carbon	0.009
		Diesel	12.5
Total Blue WF			357.32

There is no water consumption related to the amount of oxygen in the results. The reason for this is that oxygen is not available on the inputs from technosphere side of the database.

A comparison between contributors in direct blue WF values cannot be made because contributors for these values are not available in the Ecoinvent database.

Therefore, the values obtained from the inputs are written together. On the indirect blue WF side, the water consumed due to diesel consumption has the greatest value with 12.5 m^3/kg Au.

5.2.2 Environmental Impact Evaluation (Endpoint)

There are 17 impact categories in the Recipe version 1.06 database (Recipe, 2011). The freshwater ecotoxicity, freshwater eutrophication, climate change human health, marine ecotoxicity and climate change ecosystem categories selected from these categories were chosen to show the effects of 1 kg of gold production at the CIP facility. The categories are especially water-focused and have been chosen in order to see the global effects. The characterization results obtained are given in Table 5.3 and Figure 5.4.

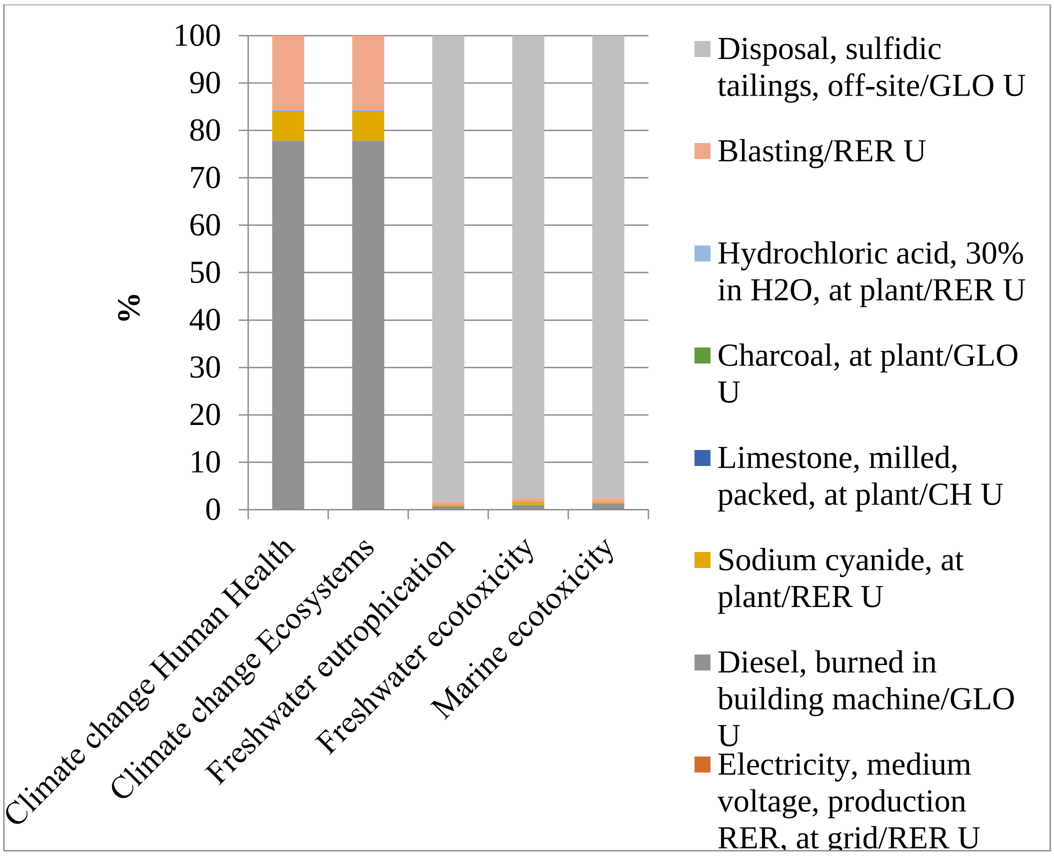


Figure 5.4. Process Contributions in Impact Categories

Table 5.3. Characterization Results of the Impact Categories

Impact Category	Unit	Value
Climate Change Human Health	DALY	0.0148
Climate Change Ecosystem	species.yr	8.39 E-5
Freshwater Eutrophication	species.yr	2.56E-06
Freshwater Ecotoxicity	species.yr	3.04E-07
Marine Ecotoxicity	species.yr	8.59E-10

Considering the distribution in categories, it is seen that the waste discharged from the mine's tailings dam makes the most contribution to the environment for those other than based on climate change. The reason for this is nine pollutants found in the waste and mentioned before. These pollutants also create the grey WF value. In this case, it is clearly seen that the impact of these pollutants in terms of environmental impact is great.

When climate change-based impact analysis is made, it is seen that the impact of diesel, which is used as fuel by the machines working in the mine, on the environment is much higher than the others.

Normalization results of the study is given in the Table 5.4 and Figure 5.5.

Table 5.4. Normalization Results of the Impact Categories

Impact Category	Value
Climate Change Human Health	0.734
Climate Change Ecosystem	0.48
Freshwater Eutrophication	1.47E-02
Freshwater Ecotoxicity	1.74E-03
Marine Ecotoxicity	4.92E-06

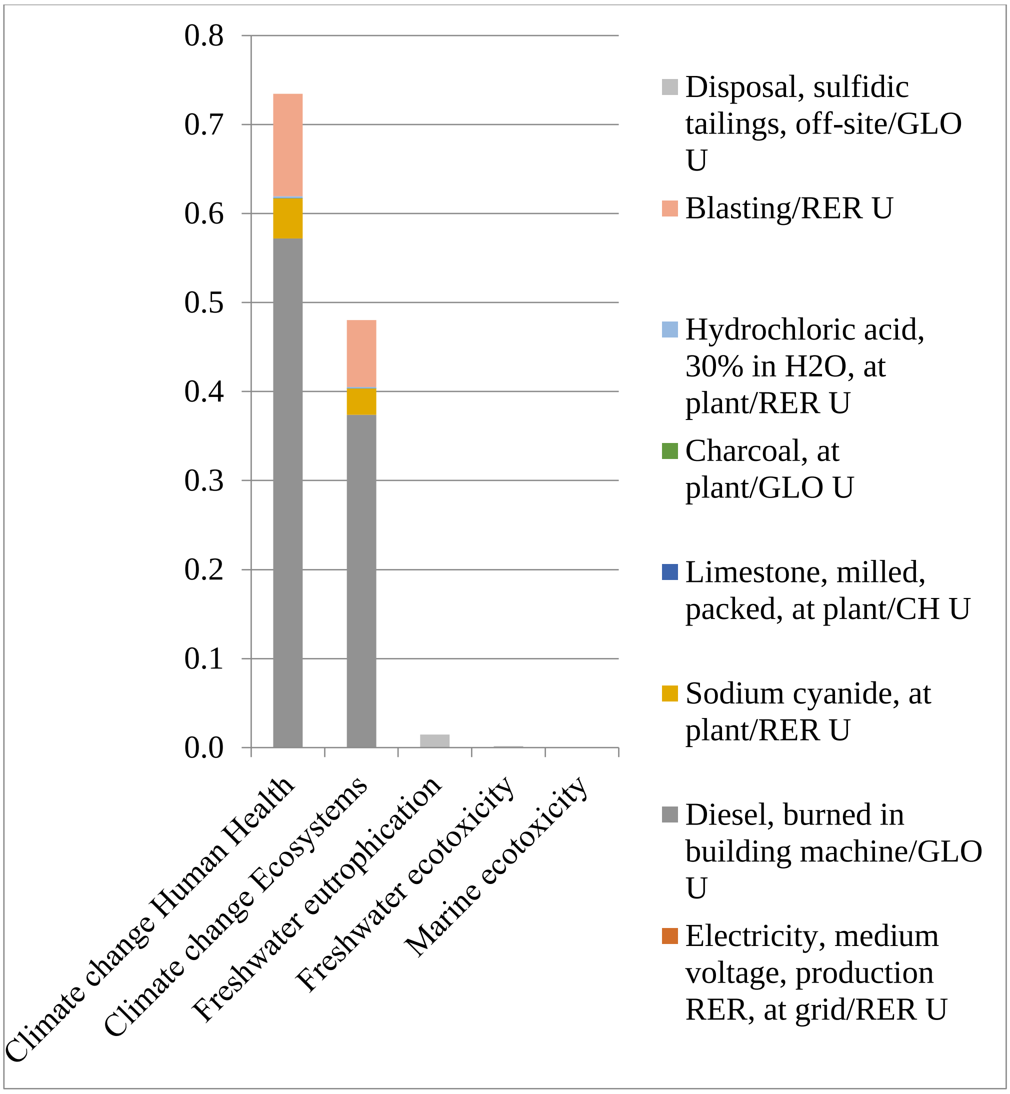
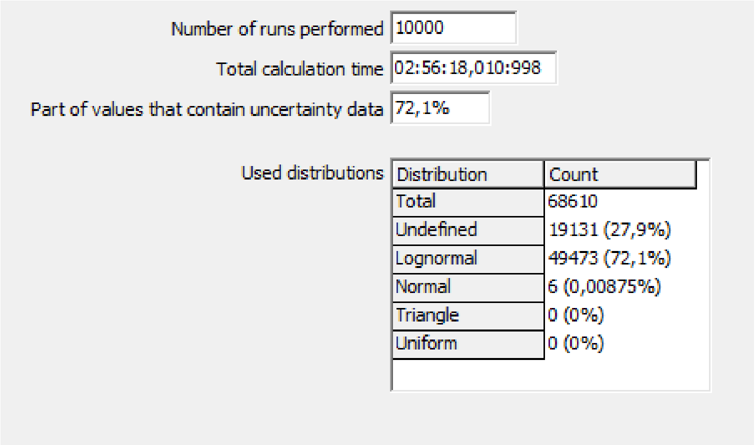


Figure 5.5. Normalization Results of the Impact Categories

According to the data obtained as a result of the normalization calculations, among the impact categories that are in common ground, Climate Change Human Health is most affected environmentally. Climate Change Ecosystem took the second place. The values of the remaining three impact categories are close to 0.

5.2.3 Uncertainty Analysis for the LCA Model

Uncertainty analysis was done with Monte Carlo Simulation in SimaPro. Details of the analysis are given in Figure 5.6. The data was then taken from the Ecoinvent database, which was integrated into SimaPro 7.3.2 (Pre, 2011), and updated to match the calculated data. The values obtained for the determined impact categories are given in Table 5.5.



Number of runs performed: 10000
Total calculation time: 02:56:18,010:998
Part of values that contain uncertainty data: 72,1%

Used distributions

Distribution	Count
Total	68610
Undefined	19131 (27,9%)
Lognormal	49473 (72,1%)
Normal	6 (0,00875%)
Triangle	0 (0%)
Uniform	0 (0%)

Figure 5.6. Details of the Uncertainty Analysis

Table 5.5. Uncertainty Analysis of Impact Categories

Impact Category	Mean	Median	SD	CV	SEOM*
Climate Change HH	0.0148	0.0147	0.00164	11.10%	0.00111
Climate Change E	8.38E-05	8.32E-05	9.26E-06	11.10%	0.00111
Freshwater Eco	3.02E-07	2.68E-07	1.50E-07	49.60%	0.00496
Freshwater Eut.	3.02E-07	2.68E-07	2.03E-06	80.10%	0.00801

*: Standard Error of Mean

For uncertainty analysis, a total of 10,000 steps was made and the simulation was completed in 2 hours 56 minutes. A total of 68,610 processes were utilized in the LCA comparison of the conceptual study. 72.1 percent of the utilized data is defined with a lognormal distribution. The reason of the dominance of lognormal distribution is that steel and other metal related data is commonly defined by lognormal distribution.

5.3 Comparison with the Previous Studies

The study's findings were compared with the results of two previous studies on water use in gold mining. The first comparative study (Mudd, 2007) looked at the resources used in gold mining from 1992 to 2006, depending on sustainability reports. The second study includes water use statistics from 75 different mines for various years (Mudd *et al.*, 2017). Among the 75 reported mines, only gold producing mines were selected for comparison. The number of these mines is 19. Table 5.6 shows the maximum, mean, and minimum results for the two studies.

Table 5.6. Water Consumption Values of the Studies

Study	Unit	Maximum	Average	Minimum
Mudd (2007)	m^3/kg Au	1783	691	224
	m^3/t ore	2.87	1.42	0.74
Mudd *et al.* (2017)	m^3/t ore	5.24	2.09	0.04
Thesis Study	m^3/kg Au		452.4	
	m^3/t ore		1.73	

As a result of the comparison blue WF value which is 452.40 m^3/kg Au is between the maximum and minimum values obtained in the two previous studies. The blue WF is below the average value obtained from the study by Mudd (2007). Consumed amount of water as per ton was calculated as 1.73 m^3/t ore. This value is between the maximum and minimum values obtained in the study by Mudd (2007) and is higher than the average value. The reason for this difference is ore grade, processing techniques, precipitation and evaporation differences. The result obtained by Mudd et al. (2017), the value of 1.73 m^3/t ore is also in the range of maximum and minimum values and is smaller than the average value.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

This study consists of two stages and two different methodologies were used. Although these methodologies basically serve the same purpose, WFA does this for water management, while LCA does it for environmental impact.

The results show that both WFA and LCA methodologies can be used as supportive decision-making tools in managing the water crisis in the mining industry and will grow in the future. In the study, hotspots both in water management and in reducing the environmental impact for a sustainable production were determined. The steps that will be taken will be far more effective as a result of this.

6.1 Conclusion of the Water Footprint Assessment and Life Cycle Assessment

Main conclusions derived from WFA are:

1. Grey WF and blue WF values were calculated with the WFA methodology of the mining and processing of gold, which was designed as a concept and these values were found to be 452.40 m^3/kg Au and 2,300.69 m^3/kg Au, respectively. As a conclusion grey WF of the study is higher than blue WF of the mine.
2. Both direct and direct blue WF values were computed using the necessary formulas and hotspots determination were done as a result of the calculations. This assessment was also done as process-based. As a conclusion, the tailings dam is found as the highest source of direct blue WF by a large margin due to lost return flow.

3. For indirect blue WF, the leaching process was found to have the greatest value depending on the consumption of oxygen and cyanide.
4. When the grey WF values are examined, Arsenic is the biggest pollutant among the nine pollutants.

The main conclusions derived from LCA are:

1. Calculations using LCA methodology for the blue WF resulted in 357.32 m^3/kg. Therefore, total blue WF values calculated using WFA and LCA methodologies are close to each other.
2. As a result of detailed examination, it is seen that diesel makes the most contribution on the indirect side, but no detailed study has been done for direct blue WF since SimaPro 7.3.2 contributors for these values are not available in the Ecoinvent database.
3. Among the impact categories, Climate Change Human Health is the mainly affected category due to mining operations in this study.
4. When a detailed examination is made, it has been seen that the calculated values are completely different than WFA for indirect and direct blue WF. There are certain reasons for the difference between these values. Methods, equations and logic of calculating the amount of water consumed by these two methods and the database used are completely different. At the same time, no value was found in the Ecoinvent database for oxygen consumption.

6.2 Recommendations

The following are the primary recommendations for further study in the same field:

1. One of the main problems in this study was the lack of data for both WFA and LCA. One of the things that can be done to give more precise results of the study is to collect the data directly from the mine site.
2. As the mining sector, the creation of Turkey's own database in the field of water consumption will provide a great advantage for future studies. The

reason for this is that the WFA methodology shows great variation according to the spatial and sectoral data. As a result, more precise results can be obtained with data from Turkey.

3. Response formulation for blue WF can serve as the basis for long-term water management. The tailings dam is the location with the greatest blue WF value. As a result, starting blue water management from here will be more effective. More water recycled from the tailings dam for use in operations reduces the discharge value, resulting in less water being collected from the wells. Recycling and reusing water can be effective in reducing the blue WF of a process only if it effectively reduces water consumption. Also, a final filtration process to be added to the facility will reduce the amount of water supplied to the tailings dam. At the same time, solutions should be taken to prevent evaporation in summer (Gunson *et al.,* 2012). On the Indirect blue WF side, there should be remedial solutions for electricity and oxygen consumption.
4. For Grey WF, among the nine pollutants, first of all, the arsenic concentration should be reduced by using new methods before it is given to a natural system. These measures can be taken with the use of new technologies for arsenic removal in mining industry. Among the 14 arsenic removal methods determined by mine wastes, the application of the appropriate one and evaluating the methods together with their advantages and disadvantages can be a solution (Langsch *et al.*, 2012).
5. Complete recycling and reuse of water is effective in reducing the grey water footprint of water users. Even when the water is completely recycled or reused for the same or other purpose, there is no waste to the environment, the gray water footprint will be zero.

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