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Water Footprint Assessment of Carbon in Pulp Gold Processing in Turkey

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Abstract: This paper presents water the footprint assessment (WFA) of carbon in pulp (CIP) gold processing. The main objectives of the study are determining grey and blue water footprints and identifying the hotspots of the process. Results revealed that the total blue water footprint, including the extraction and processing of the gold, was found to be 452.40 m^3/kg Au, and the grey WF to be 2300.69 m^3/kg Au. According to the results, the lost return flow on the direct blue WF side has the largest contribution, with a value of 260.61 m^3/kg Au, and the only source of the lost return flow is the tailing pond. On the indirect side, it is seen that the oxygen consumption used for the leaching process has the highest value, with 37.38 m^3/kg. Among the nine contaminants in the mine tailings, the critical component responsible for the grey water footprint is by far arsenic, with a value of 1777 m^3/kg Au. The results will be used to make recommendations for reducing water consumption in mining operations, for a better design for the environment. The study is a pioneering study, being the first implementation of water footprint assessment in a gold mine in Turkey.

Keywords: sustainability; water footprint; water footprint assessment; gold processing; sustainable water use; Turkey; water resource management

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1. Introduction

Water resource management is one of the greatest global challenges of the 21st century [1]. In Global Risk Reports (2019), while water crisis risk was not even listed in the top 10 risks in terms of impact in the world in 2009, after that year it has always been among the top 5, although its location has been constantly changing. Water crisis risk ranks 4th in 2019. Its supply and accessibility are vital for all sectors, including the mining industry, as it is one of the key water consumers [2].

The mining industry, relying on water as an industrial input during operations, needs to adopt better water management strategies to sustain its viability and growth. Gold mining also results in water consumption and may cause severe water pollution [3,4]. In mining operations, water is used for mineral processing, material handling of ore and waste in the form of slurry, dust control, drilling, cooling systems, cleaning machinery and equipment, remediation of mine sites, and to support the workforce (for drinking water and sanitation). Moreover, water drainage, when water table is exceeded, further contributes to the reduction of the available water sources.

Research studies revealed that about 70 percent of the mining activities under the largest global mining companies are in water-stressed countries. Water issues have emerged in 58 percent of the mining cases filed by IFC's Compliance Offer Ombudsman (CAO), an independent referral mechanism that responds to the complaints of the proposed communities [5].

When this is issue examined specifically in the mining sector in Turkey, it is a fact that Turkey shares the same fate as the world. Studies show that with the impact of population growth and climate change, water availability is expected to decrease from 1500 m^3/person/year to 1000 m^3/person/year by 2050. Turkey is among the countries that will experience water scarcity in the coming years [6,7]. From the mining point of view, the Turkish Statistical Institute (TUIK) has produced data on mining, water, wastewater, and waste Statistics, considering the OECD/EUROSTAT's definition, scope, classifications, and international regulations, every 2 years since 2010. According to the report published by the TUIK, mining operations drew a total of 55 million m^3 of water from wells, the sea, pit lakes, rivers, lakes, and other sources in 2010 [8]. This number was found to be 116 million m^3 in 2012 [9], 220 million m^3 in 2014 [10], 241 million m^3 in 2016 [11], and 219 million m^3 in 2018 [12]. The problems caused by water scarcity in the mining sector will continue to grow steadily, since the amount of high-grade ore is decreasing. Therefore, the industry will begin to produce lower-grade ores that require an increasing amount of water [13]. Considering the increasing water demand due to the growth in production and the upcoming water scarcity crisis, it is inevitable that mines should quantify and assess their water footprints through adapting effective water management strategies.

Over the last two decades, the pressure of the water management challenge has led to the improvement of approaches to measuring the water consumption and water pollution of regions, products, and processes. One of the new approaches is the water footprint (WF) concept. The WF concept is an indicator of freshwater appropriation, with the aim to quantify and map the direct and indirect volumetric water use and show the relevance of involving consumers and producers along the supply chains in water resources management [14]. The Water Footprint Assessment (WFA) developed a means of quantifying and locating the WF of a process, a product, a consumer, a consumer group, a geographically determined area, a nation, a business, a municipality or another government agency, a catchment, or a river basin, to evaluate the environmental, social, and economic sustainability of the calculated WF and to produce a solution to lower the calculated WF and achieve a more sustainable process [15].

Despite the developments in the WF, the global interest in the mining has remained limited. These studies are concentrated in South America and South Africa, and there has been no previous study on this subject in Turkey. Moreover, most of the studies are on copper and platinum mining, and there is no study in the literature in a process facility operating with the Carbon in pulp (CIP) processing method in detail. Considering the limited understanding of the variability and size of water resource use between regions where mining is actively carried out, this study is expected to contribute significantly to the literature in one more region and one more processing method.

One of the studies on this topic measured the consumption of only blue WF for the extraction of copper from both copper sulphide ore and copper oxide ore in the Atacama Desert, Chile [16]. Green and grey water footprints were not included in the study. The results obtained belong to the copper cathode produced from copper sulphide, with the largest blue WF value of 96 m^3/t. For the copper cathode produced from copper oxide ore, the value was 40 m^3/t. At the end of the study, it was emphasized that the water consumption of the processing plants could be reduced by 50–70% by using sea water in the facilities, reducing evaporation and using more water from the waste dam. The study voiced uncertainties regarding the water footprint and the weak controls of operations over the amount of water evaporated or lost.

Another study was conducted by Haggard et al. (2013) in a platinum mine in South Africa [17]. In this study, two different water footprint calculation tools were used, and the results were compared. The first tool used is the WFA, and the second tool is the Water Miner software. In the study conducted for the tailing roof of two concentrate plants, the total of WF was found to be 11,811 ML/a, and the biggest contribution was the inflow water footprint. The results obtained with the Water Miner tool also show that the volume of water imported is equal to 5719 ML/a, while the water exported amounts to 5253 ML/a.

The study by Harding et al. (2014) was conducted in South Africa, and only the blue WF value of a platinum mine was calculated [18]. In this study, grey and green water footprints were not calculated. According to the results of the study, the total blue water footprint, including direct and indirect consumption, was calculated to be $2229 \times 103\ m^3/\text{ton}$ of refined platinum. Uncertainties about the weak controls of operations over the amount of water evaporated or lost were articulated in the study. It was also stated that the information detailing the water flows within the mineral processing plant is limited.

Pardavé and Delvasto (2017) conducted a water footprint assessment study in Colombia [19]. The aim of the study was to calculate the water footprint and to evaluate the water usage of the Reina de Oro gold plant in Vetan, Colombia (Santander), which is a small-scale mine using mercury. In this study, blue and grey water footprints were examined separately. However, these calculations were made by taking instant data from the field instead of formulas of the water footprint concept.

Another study was conducted by Osman et al. (2013) in South Africa for a base metal refinery (BMR) [20]. In this study, the data were taken directly from the field via flow meters. With the data collected in the study, a water balance diagram was obtained by using the Water Accounting Framework. In the study, blue, grey, and green WF values were calculated. The values obtained were, respectively, 33.4 m^3/tonne of base metal product for blue WF, 10.5 m^3/tonne of base metal product for green WF, and 0 m^3/tonne of base metal product for grey water, since BMR did not have waste water discharge.

In the study by Islam and Murakam (2020), a blue, green, and grey WF study was conducted for an open pit copper mine in Laos. According to the results obtained from the study, blue, green, and grey WF was found as 988.83 m^3/tonne, 52.04 m^3/tonne, and 69.78 m^3/tonne of copper concentrate, respectively. In this study, the results also show that the grey water footprint was reduced five times as a result of the treatment plant established. In the study, it is stated that the biggest source of blue WF is the electricity obtained from the hydroelectric power plant. The Mn concentration was found to be the first among the chemicals contributing to the grey water footprint. With this study, it has been revealed that the grey water footprint can be reduced with treatment in mining [21].

Another study in which the direct and indirect WF calculation model was developed for the iron and steel industry, by Gu et al. (2015), focused on an iron factory in Eastern China. The study found that the blue WF amounted to 2.24×10^7 m^3 for 2011, while the grey WF amounted to 6.5×10^8 m^3. In general, the grey water footprint was found to be high, and it was stated that this was a great risk. In addition, the contribution of the iron and steel industry sector to China's total footprint was calculated as 0.4% in the study [22].

The application of this methodology in different mines has been a guide for this study. Where and how the methodology will be applied in the mining sector, the points to be considered for direct and indirect WF calculation, and the units that will be caused by the grey water footprint are examples for this study. However, it should be noted that there is no study that directly examines gold mining and the CIP method alone. At the same time, the WFA methodology has not been applied to the mining industry in Turkey before.

The main purpose of this research study is to determine the direct blue WF, indirect WF, and grey WF values for both the extraction and processing facility sides of a mine using Carbon in Pulp (CIP) with the WFA methodology and to identify the hotspots. The results may be used to formulate a response to the water consumed in mining activities and, therefore, to the negative impact on the environment, and as a means of ensuring a sustainable production. This study was carried out on a mine in Turkey. In this sense, this study will be the first in this field, considering that there is no previous no study on a gold mine in Turkey. At the same time, there is no detailed study of the water footprint of CIP management. In this study, all operations of the process plant are examined separately for both direct and indirect blue WF.

2. Materials and Methods

2.1. Data

For the implementation of the water footprint assessment of gold processing, the mines operating in Turkey that process gold ore using the CIP method were taken as reference. Technical reports, sustainability studies, and a literature review for these mines were examined in detail. Water balance calculation was made in the facility created by blending these water footprints, and was obtained separately for each of the upstream and downstream processes. All the data collected and processed for gold processing were justified through publicly available data and references. The process flow sheet belonging to the CIP process is illustrated in Figure 1.

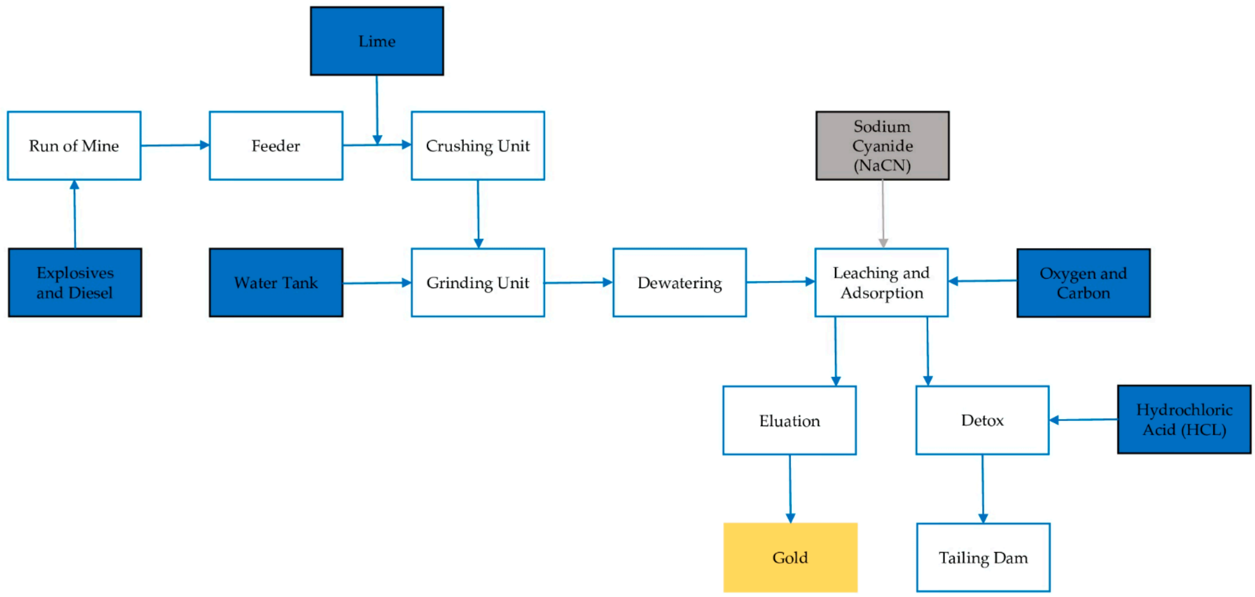

Figure 1. Flow diagram of gold processing.

The grade of the ore is 4.36 g/ton. In order to find the water consumption in the designed facility, the solids by mass ratio (pulp ratio) used in the processes, the surface areas of the tanks, the thickener, and the tailing pond were also determined on the basis of realistic data [23–28]. Water is supplied from water wells to the processing plant. The domestic wastewater discharge amounts to 30 m^3/day [29]. The value provided by Northey and Haque (2013), 0.15 m^3/ton, was used for the pit dewatering value in the mine [30].

As illustrated in Figure 1, the facility consists of a 3-stage crusher unit to reduce size. Water is sprayed on the relevant points in order to suppress the dust. In order to calculate this amount of water, it was considered that there was a water spray for each crusher in the unit as a representative, and the water consumption value for these sprays was determined as 10 lpm [31]. The output of the crushing circuit is fed to the grinding circuit via the fine ore bin. Here, lime is added to the grinding circuit at the same time to adjust the required pH value. The grinding circuit consists of a rod mill with 75% solids by mass and a ball mill with 72% solids by mass [28,32]. Water is added to the grinding unit from the process water tank. At the end of the circuit, the grinded material is fed to the hydrocyclone from the slurry box. The upper flow of the hydrocyclone is reported to the thickener. The thickener's overflow gravitates to the process water tank, while the thickener's underflow has 50% solids pumped to the leach circuit [33]. The pulp fed from the leaching tanks to the adsorption unit is then sent to the eluation circuit to separate the gold from the activated carbons. The pulp, which is free from activated carbons, is sent to the chemical treatment (Detox) circuit. After this process, it is transferred to the tailing pond.

As a result of the research conducted for this study, pan evaporation data were obtained from the EIA Application File of the Ovacık Gold Mine Third Waste Storage Facility Project to calculate the blue WF. The data from this report are taken from the Turkish State Meteorological Service's Bergama Station. Evaporation data were formed by taking the average of the data collected between 1960 and 2012 [26]. When calculating the blue WF, if rainwater is also collected and used for consumption, it is necessary to distinguish this value from the green WF. Here, according to the methodology, if rainwater was not collected, it would come in a run-off state. However, since this water was collected and used for consumption, it was taken from the run-off. Therefore, this water can also be counted as the blue WF according to the situation specified in the methodology [14]. As in the case of evaporation, the amount of rain per square meter has been taken from the Ovacık Gold Mine Third Waste Storage Facility Project EIA Implementation File. The monthly evaporation amount (mm) and precipitation amount (mm) are shared in Figure 2.

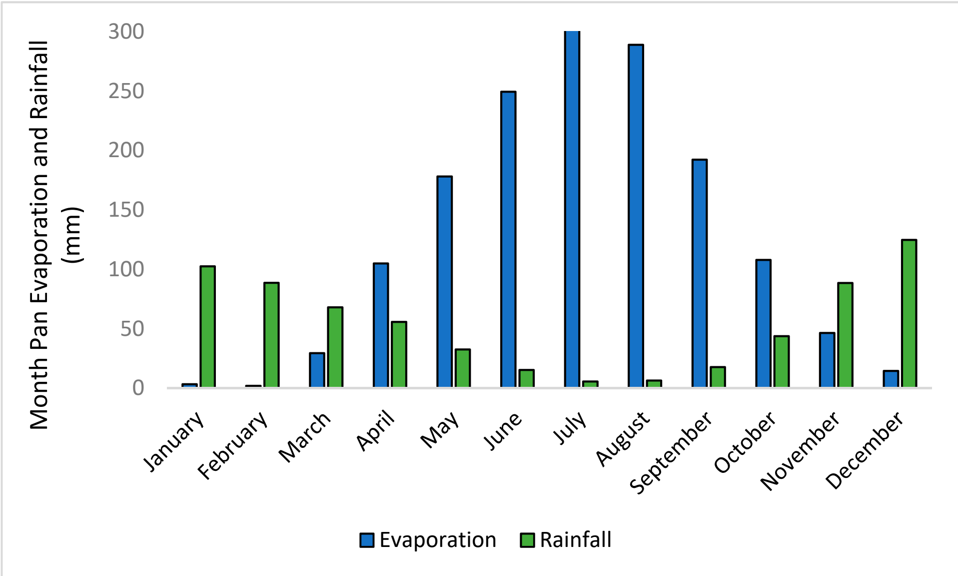

Figure 2. Monthly evaporation amount (mm) and precipitation amount (mm) [26].

In addition, the groundwater mixed with the ore is also used in the calculations. In addition, a data analysis based on the literature was made to calculate the value of the embedded virtual blue WF calculated for the amount of diesel used in the production stages in the mine, the amount of electricity used in the mine, the chemicals used, and other sources. The results are shown in Table 1.

Table 1. Unit WF values of the materials used in the mine.

Source	WF per Unit	Unit	Reference
Sodium Cyanide	0.1956	m^3/kg	[30]
Lime	0.02	m^3/kg	[30]
Hydrochloric Acid	0.0254	m^3/kg	[30]
Explosives	0.0338	m^3/kg	[30]
Electricity	0.021	m^3/kWh	[30,34]
Oxygen	0.0042	m^3/kg	[30]
Activated Carbon	0.012	m^3/kg	[35]
Diesel	0.0013	m^3/kg	[30]

To calculate the grey WF, the pollutant load is obtained from a weekly tailing pond metal analysis of Ovacık Gold Mine for 9 contaminants: arsenic, cadmium, chromium, copper, iron, lead, mercury, nickel, selenium, and uranium (Table 2) [24,29]. In the table, 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.

For all of the contaminants in this dataset, the weekly average was found by averaging the 83 week-data after eliminating outliers. The maximum acceptable concentration value was determined according to the Water Pollution Control Regulation (Table 7.1) and the former IFC General Environmental Guidelines (published on 1998) [29]. A natural concentration in the receiving water body is achieved with the Water Quality Classification

(II) values, including the stream in which the water is discharged [29]. The next section presents the methodology followed in this study.

Table 2. Values of contaminants causing grey WF [24,29].

Contaminant	C_{max} (mg/L)	C_{nat} (mg/L)	L (mg/L)
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	0.00121
Nickel (Ni)	0.5	0.02	0.05
Zinc (Zn)	2.0	0.2	0.00687

2.2. Method

In the WFA, the water footprint of a process, product, manufacturer, consumer, or a certain geographical area in a certain time interval is calculated. This calculation is made for the limits and purposes specified in the goal and scope definition [14]. In this study, the WFA methodology was used to calculate the WF of the gold mine. Water footprint assessment consists of four different stages: goal and scope setting, water footprint accounting, water footprint sustainability assessment, and water footprint response formulation. The research methodology followed in this study is presented in Figure 3. In the first stage, the purpose of the WFA process and the goal and scope of the process in the mine are determined. In the "Goal and Scope setting" stage, the reasons for doing the study are presented in general terms, and information is given about the limitations of the study. Reference is made to what is included in the calculations and what is excluded for the boundaries of the study. These limits are shaped according to the purpose of the study [14].

The main goal of this study is to estimate the direct and indirect WF of a mine where gold is obtained using the CIP method in the processing plant, using the WFA methodology. With this information, hotspots will be detected and the responses that can be taken to reduce WF will be determined.

The scope of this study is to calculate the blue and grey WF of the studied mine both for the extraction and processing of the gold ore. In the study, direct and indirect WF were examined. In the indirect WF, the WF of the electricity, fuel, and chemicals used to produce the gold are included. In addition, the water used by the employees in the field to meet their daily needs was also added. While the calculations were made, a twelve-month period, from January to December, was selected for a representative case study, and the amount of water used to produce 1 kg of gold was determined as the functional unit.

Then, a comprehensive literature review was conducted for the data collection and the information required for computations and process plant design in accordance with the goal and scope definition. After the facility was designed, the blue and grey water footprints were calculated separately, and hotspots through the process were identified. These calculations have been applied to all the structures within the mine where the water footprint can be calculated. Finally, by evaluating the water footprint suggestions were made to reduce the water footprint and the environmental impact of the mine.

There are three types of WF in WFA. Blue WF is an indicator that shows how much water is consumed from underground and surface resources (blue WF resources). Green WF shows how much water is consumed from rain water (green WF source). However, the critical point to be considered here is that this resource should not be mixed (become run-off) with surface or groundwater in any way. The grey WF is the amount of water spent to bring the contaminated water to its natural concentration and to the existing water quality standard [14]. In the next section, water footprint accounting is explained comprehensively, including the relevant formulations to be utilized.

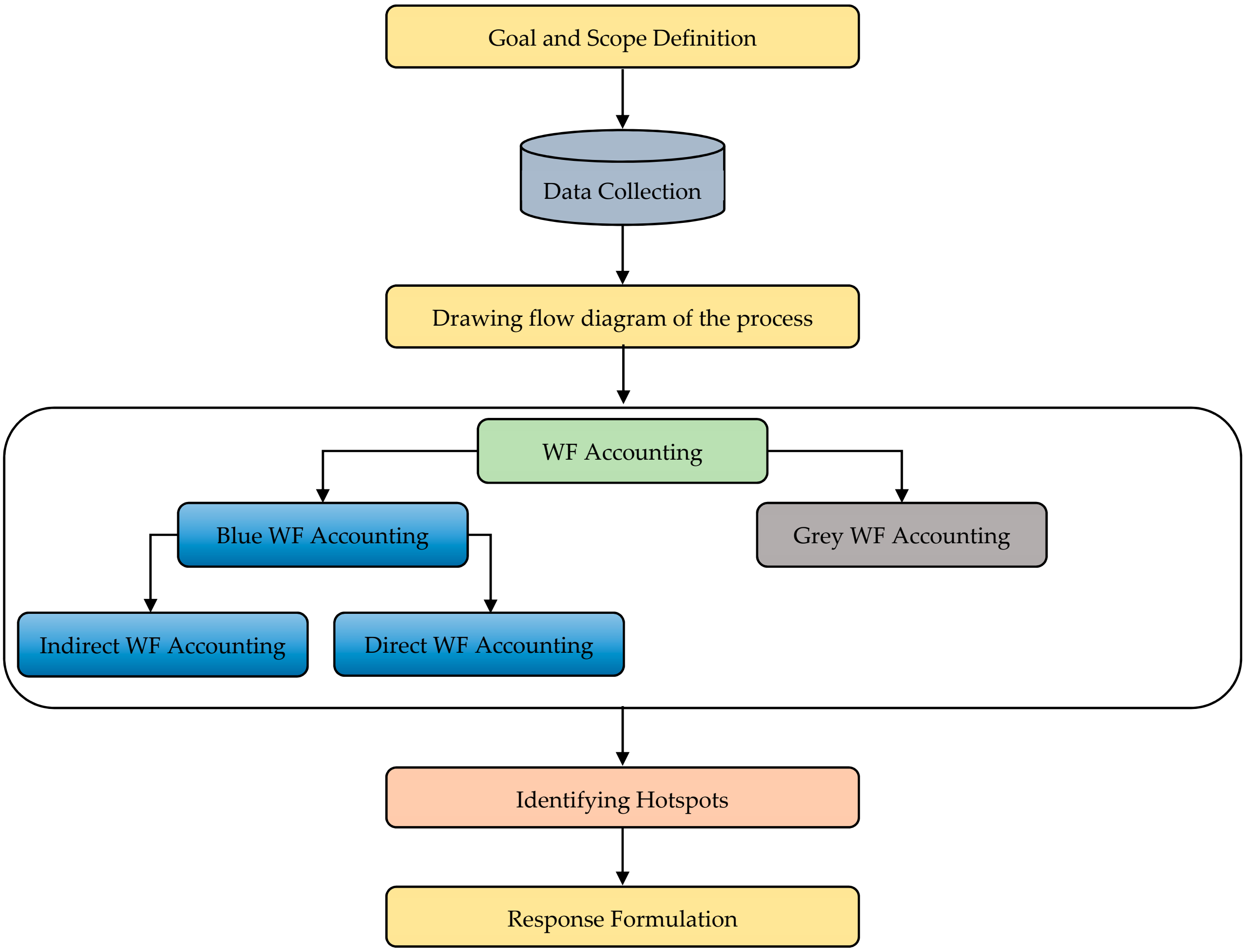

Figure 3. Flow diagram of the study.

2.3. *Water Footprint Accounting*

In this study, the blue and grey WFs of the mine were calculated. Green WF is not included in the study because this type of WF is mostly used for agriculture and forestry activities, and, according to its definition, there is no information that can cause a green WF in the field.

Blue WF is an indicator of consumptive water use. Consumptive water use, on the other hand, represents 3 states, and the blue WF is the sum of these 3 states. These states are, as seen in Equation (1), evaporated water (Blue Water Evap.), water that is incorporated into the product (Blue Water Incorp.), which is known as the virtual-water content or embedded water, and water that does not return to the same catchment area or in the same period (Lost Return Flow) [14]

$$WF_{proc,blue} = \text{Blue Water Evap.} + \text{Blue Water Incorp.} + \text{Lost Return Flow} \quad (1)$$

Equation (2) was used to calculate and measure the evaporation from the tanks and tailing dam in the facility. This formula is taken from the Water Accounting Framework (WAF) methodology developed by The Minerals Council of Australia. In the equation, V_{Evap} (ML) indicates evaporation losses, S_{Evap} represents the average surface area covered by water (ha) during the calculation period, PanEvap is the value of the evaporation rates (mm) measured during the reporting period, and f is the correction factor to be converted.

The correction factor for pan evaporation rates measured with a Class A pan is usually around 0.75 [36].

$$\mathrm{VEvap} = 0.01 \times \mathrm{SEvap} \times \mathrm{PanEvap} \times \mathrm{f} \quad (2)$$

Rainwater rains directly on open water surfaces in the facility, and measures are not taken to increase the water holding capacity of the soil at the facility. Therefore, the amount of rain falling on the tanks was considered as rain harvest. It is suggested that this type of water use should be evaluated as a blue water footprint.

Equation (3) was used to calculate the rainwater collected in the field [36]:

In Equation (3), V_{Rainfal} (ML) is the volume of rainfall, R (mm) is the precipitation measured during the calculation period, and $SA_{\mathrm{R,M}}$ (ha) is the open surface area.

$$V_{\mathrm{Rainfall}} = 0.01 \times \mathrm{R} \times SA_{\mathrm{R,M}} \quad (3)$$

The entrained water, V_{ent} (ML), is also considered blue water in the ore. To find the amount of water for this, Equation (4) is used, where P is the incoming ore processed during the reporting period (Mt) and m is the moisture content as a fraction [36].

$$V_{\mathrm{ent}} = 1000 \times \mathrm{P} \times \mathrm{m} \quad (4)$$

To include the entire supply chain in the study, many indirect water sources have been considered. The amount of water required for employees to meet their daily needs is also included in the blue water footprint. In addition, the amount of water used to suppress the dust generated as a result of the process in the crusher unit in the facility is another source included in the blue water footprint. In addition, the blue WF obtained for the chemicals, the electricity and fuel, and the amounts of explosives used to extract gold from the mine are included in the study.

When calculating the annual indirect water footprint (WF_{Ind}), the amount of resources (R_i) required to produce 1 kg of gold is found by multiplying the embodied water amount estimates (W_i) in these resources with the annual production amount (P), and the formula for this is the following:

$$WF_{Ind} = \sum_{i=1}^{n} R_i W_i P \quad (5)$$

After the chemical destruction cycle to reduce the concentration of cyanide and heavy metals remaining in the waste to certain limits, wastes are sent to the tailing dam. Some of the water accumulated in the tailing dam is reused in the process and some is discharged. Therefore, the facility has a grey WF. Equation (6) is used to calculate the grey water footprint in a process step [14]:

$$WF_{\mathrm{proc,grey}} = \frac{\mathrm{L}}{C_{\mathrm{max}} - C_{\mathrm{nat}}} \quad (6)$$

In Equation (6), $WF_{\mathrm{proc,grey}}$ (volume/time) shows total grey water footprint of a product, where L (mass/time) is the pollutant load, C_{max} (mass/volume) is the maximum acceptable concentration of the pollutant in the receiving freshwater body, and C_{nat} (mass/volume) indicates natural concentration in a receiving water body [14].

3. Results

The study was carried out to find the blue and grey WF of a gold mine in Turkey that produces gold using the CIP method in its process facility. For all calculations, 1 kg of gold is taken as a functional unit. This section of the paper comprehensively presents the obtained results and research findings in three subsequent sections as direct and indirect blue WF and grey WF values, the contribution of blue WF and grey WF to the total WF, and the distribution of total blue WF to the process steps.

3.1. Direct and Indirect Blue WF and Grey WF

As a result of the study, both direct and indirect WF calculations were made for the blue WF. The grey WF was calculated for nine contaminants. It should be noted that the only place that causes a grey WF in the facility is the tailing pond. Detailed information on each contributor of the mine's direct and indirect blue WF and grey WF values is presented in Table 3.

Table 3. Direct and indirect blue WF and grey WF values.

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	2300.69

This table can be considered as a summary of the results obtained in the study. As mentioned, while there are seven contributors that directly cause the blue WF of the mine, there are eight contributors that cause an indirect blue WF. Among all the values, the lost return flow value has the highest blue WF, while the blue WF value due to the use of lime has the lowest value. On the indirect side, it is seen that the oxygen consumption used for the leaching process has the highest value. When an evaluation is made by considering the unit WF values in Table 1, it is seen that oxygen has the second lowest value. On the other hand, it has the largest indirect WF value. The reason for this is that oxygen consumption is used much more in the mine than other indirect contributors. It is also seen in the table that the grey WF value originates only from the tailing pond.

3.2. The Contribution of Blue WF and Grey WF to the Total WF

The results show that 84% of the total water footprint of the mine, which is the subject of the study, is grey WF, while 16% is blue water footprint. When this result is compared with the studies in the mining sector where grey and blue WF measurements were made at the same time, it is seen that the same situation is reached. The contribution of blue WF and grey WF to the total WF can be seen in the Figure 4.

In these previous studies, the grey WF value has a higher percentage than the blue WF value [17,20,22,37]. Another graph for the results obtained is presented in Figure 5. This graph shows the amount of rain water held by open surfaces and the amount of water evaporated from these surfaces on a monthly basis. In addition to these values, the monthly blue WF value is also included in the chart.

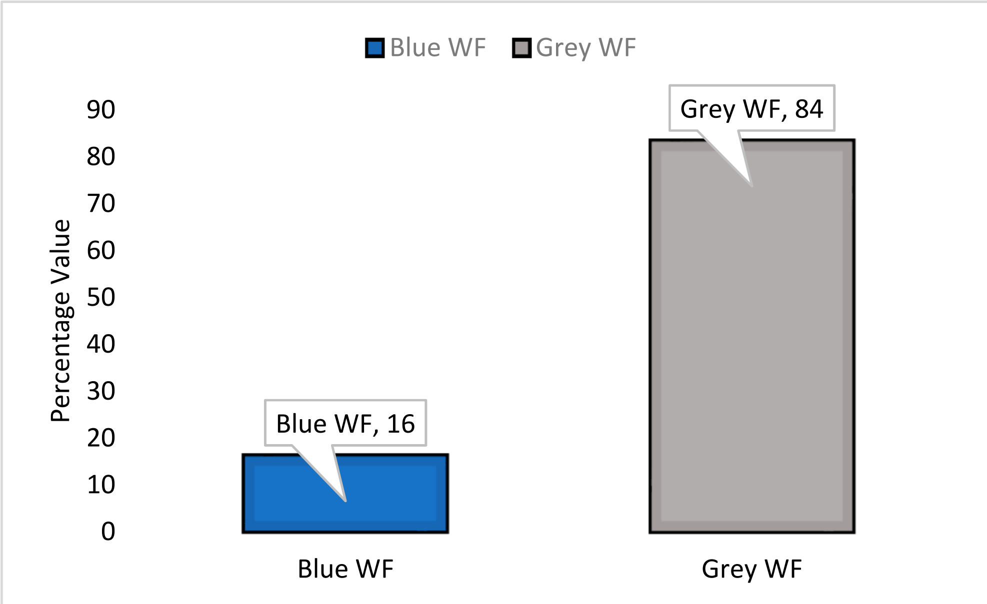

Figure 4. Contribution of blue WF and grey WF to the total WF.

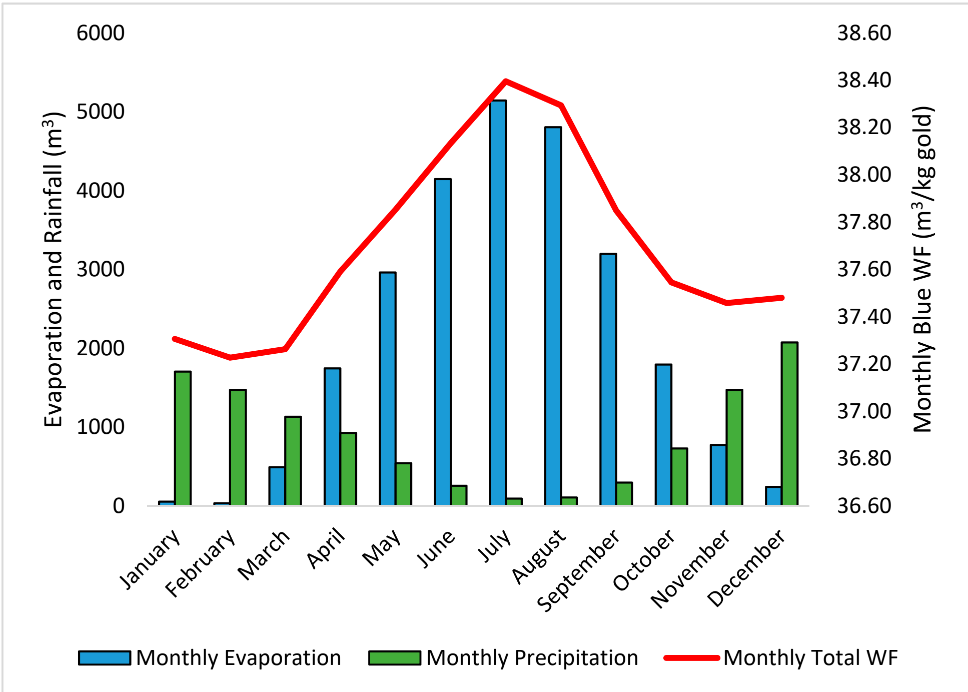

Figure 5. The relationship between the monthly precipitation amount, the evaporation amount, and blue WF [26].

As can be seen, the month with the highest blue WF of the mine is July, with approximately 38.40 m^3/kg Au. This month is also the month with the highest evaporation and the least precipitation. The month with the lowest blue WF value is February, with 37.23 m^3/kg Au. Contrary to July, this month has the lowest evaporation amount. At the same time, the linear relationship between the total WF and the evaporation rate is remarkable. When all these comments are evaluated, it is obvious that the blue WF in this mine is caused by evaporation rather than the amount of precipitation. This is the main reason why the blue WF is the highest in July, because the evaporation rate is the highest in this month, as seen in Figure 2. Therefore, more water is lost through evaporation this month and more blue water is needed to replenish the lost water.

Another result obtained from the graph (Figure 2) is that while there is a noticeable difference between monthly evaporation and precipitation changes, the blue WF values are close to each other in the different months. This implies that the contributors, other than evaporation and precipitation, increase the total blue WF value more.

3.3. Distribution of Total Blue WF in the Process Steps

It can be seen in the chart shared in Figure 6 that evaporation and precipitation values among direct and indirect WF values contribute less to the total blue WF compared to other contributors. In terms of percentage, it is seen that the contribution of evaporation and precipitation to the total blue WF is 1.76% and 0.75%, respectively. The highest value on the direct WF side belongs to lost return flow, while on the indirect WF side this value belongs to the blue WF due to oxygen consumption.

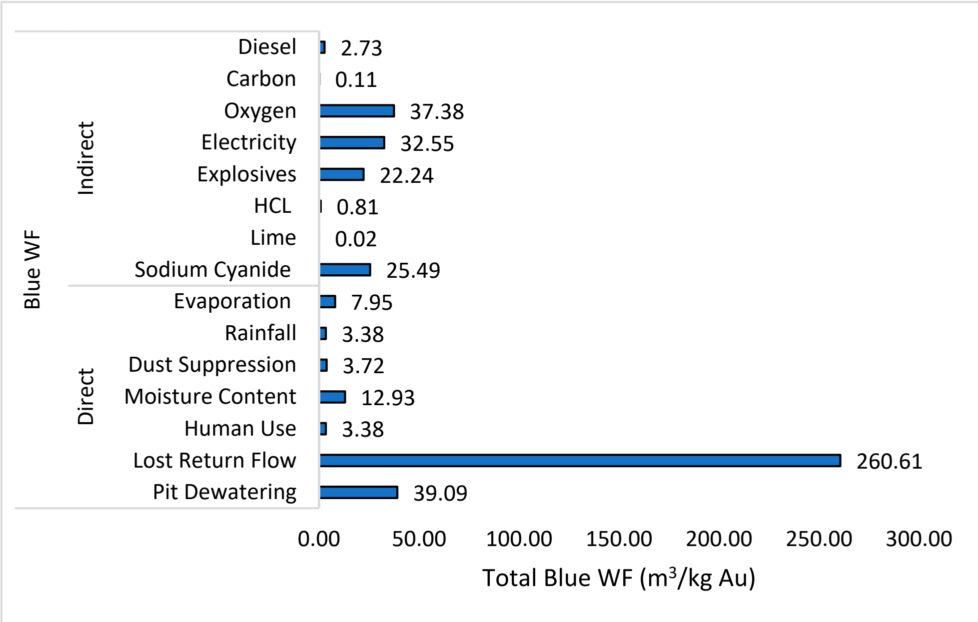

Figure 6. Distribution of the total blue WF between the process steps.

In Figure 7, the blue WF values between operations are shared. Both the extraction and the process facility have been evaluated according to the operations within them. While only the works in the open pit mine and contributing to the blue WF are evaluated for extraction, the process facility is divided into crushing, grinding, dewatering, leaching, adsorption, and tailing dam.

As a result of the calculations, it was determined that the largest blue WF belonged to the 272 m^3/kg Au tailing dam. The second refers to extraction operations, with 86 m^3/kg Au, and the third greatest contribution is from leaching, with 68 m^3/kg Au. It is not surprising that the results are like this because the lost return flow value, which belongs to the highest value in Figure 5, is actually a blue WF value belonging to the tailing dam. Likewise, the contributors with the greatest value in Figure 5 are the blue WF values of the extraction and leaching operations.

When an evaluation was made on the indirect WF side, it was seen that most of the water was caused by the oxygen consumed in the leaching and adsorption unit and the electricity consumption used for production. In the second place, it was determined that the blue WF depends on the amount of cyanide consumed.

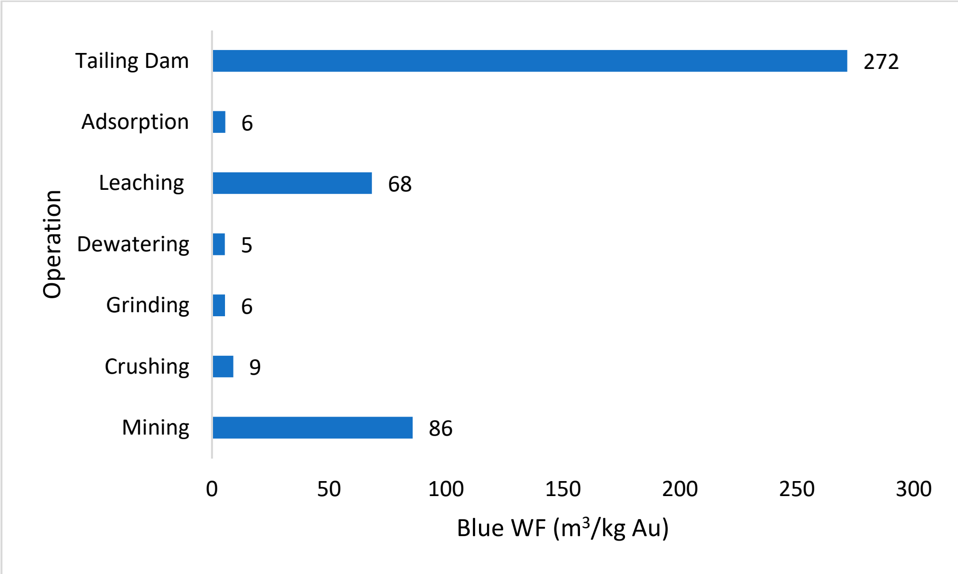

Figure 7. Distribution of the total blue WF between operations.

3.4. Distribution of Chemicals in Grey WF

In the study, only the tailing pond causes the grey water footprint. A detox process is carried out, the processed water is sent to the tailing dam, and the excess water is discharged to the receiving water body. Figure 8 shows the contribution of nine chemicals causing a grey WF in the mine.

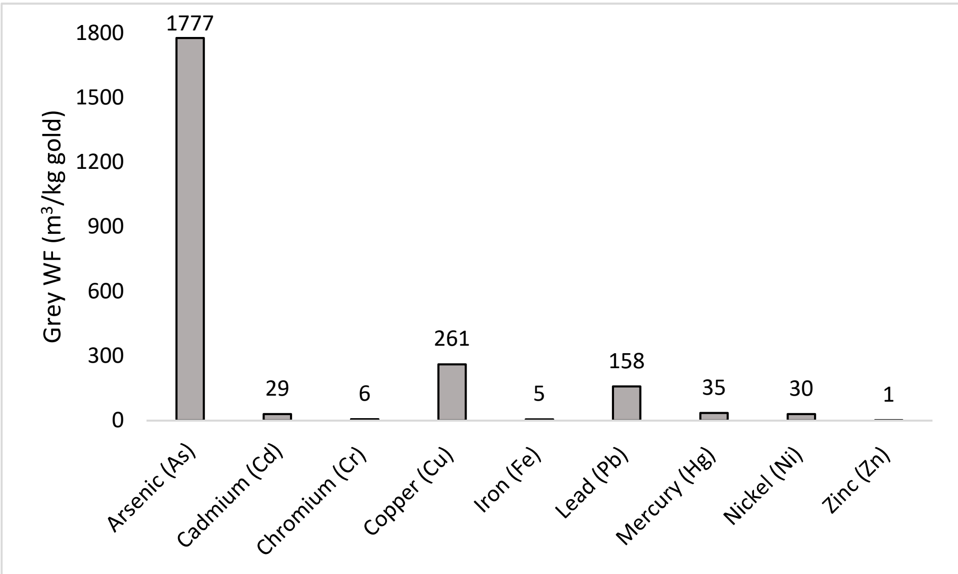

Figure 8. Grey water footprint in the tailing dam based on 9 contaminants.

Among the nine contaminants in the mine tailings, the critical component responsible for the grey water footprint is by far arsenic. Arsenic constitutes 77.23% of the total grey WF, with a value of 1777 m^3/kg Au. By definition, the largest pollutant is that associated with the specific grey water footprint. Here, it will be sufficient to focus on the grey water footprint due to arsenic in order to make a general comment on water pollution and to find an indicator. However, it is of course crucial to formulate a response that targets other contaminants as well.

4. Discussions

The WF value may vary depending on the type of mining methods together with geological and geographical factors. Therefore, with this study, both a region and a process method have been brought to the literature. Considering the results, it is seen that the study has achieved its purpose. The blue and grey WF values of a facility that produces gold using the CIP method in Turkey were calculated, and the contributors and regions with the highest water footprint for sustainable water management were determined. In addition, with this study, a detailed examination of the CIP method was made, and the most water-consuming parts of this method were determined. This study is a first in terms of examining the CIP method in such a detailed way.

4.1. Comparison with the Previous Studies

The values obtained as a result of this study were compared with 2 previous studies on water consumption in gold mining.In the first study, Mudd (2007) examined the resources used in gold mining from 1992 to 2006 based on sustainability reports in his study [38]. In another study, Mudd et al. (2017), there are water use data from 75 different mines for different years [39]. Among these mines, there are 19 mines that produce only gold, and only the values of these 19 mines are taken as a reference for comparison. The maximum, average, and minimum values of the two studies are shown in Table 4.

Table 4. Water Consumption Values of the Studied.

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

When the results obtained in this study are compared with those of the two studies, it is seen that there is a consistency with the other two studies. The 452.40 m^3/kg Au value obtained in this study is between the maximum and minimum values and is below the average value of the study by Mudd (2007). In addition, the amount of water consumed per ton in this study is 1.73 m^3/t ore. This value is still within the range, and the value is higher than the average value. The reason for this difference is the difference in ore grade, processing techniques, precipitation, and evaporation. When the study by Mudd et al. (2017) is considered, the value of 1.73 m^3/t ore is again in the range of the maximum and minimum values and is smaller than the average value.

4.2. Response Formulation to Reduce Blue WF

Considering the results obtained from the study, it was seen that evaporation and blue WF values moved proportionally. It was also found that the blue WF values were more dependent on other contributors than on evaporation and rainfall compared to the values obtained. As a result, it was seen that the amount of lost return flow with 260.61 m^3/kg Au among values contributed much more than other contributors. In fact, this value has the largest value among both direct and indirect WF values. The fact that this value is so large has caused the tailing dam to have the highest blue WF value, 272 m^3/kg Au, among the operations and parts of the facility. For this reason, it is necessary to work to reduce the lost return flow on the direct blue WF side. As a starting point for sustainable water management, recycling more water from the tailing dam to be used in operations can reduce the lost return flow. Since the lost return flow value is discharge water from the tailing fam to the receiving environment, the discharge value will be reduced with more recycling. In this way, less water will be drawn from the wells to obtain the required water for the process plant. At the same time, a final filtration process before sending the wastes to the tailing dam will also reduce the lost return flow value. Regionally, solutions should be taken to prevent evaporation, especially in the summer months, when the tailing dam is the largest surface area [40]. On the indirect WF side, oxygen consumption (37.38 m^3/kg Au) and electricity consumption (32.55 m^3/kg Au) are the sources that contribute the most. In addition, when the blue WF value obtained for cyanide consumption (25.49 m^3/kg Au) is evaluated, the leaching operation stands out. To reverse this situation, remedial solutions should be found for the amount of electricity and oxygen consumed in the mine. When both the direct and indirect blue water footprint values are evaluated together, it is seen that the blue WF value for the extraction operation is also high. Here, it was determined that the pit dewatering with 39.09 m^3/kg Au made the greatest contribution to the extraction operation. For example, using pit dewatering for dust suppression in the mine or in the process facility will reduce the blue WF value.

4.3. Response Formulation to Reduce Grey WF

Only the tailing dam is responsible for the grey WF. Among the nine contaminants that cause the grey WF, the biggest contributor belongs to arsenic, with 1777 m^3/kg Au. Arsenic is a highly toxic and accumulative element. World Health declares arsenic as one of the main pollutants in aqueous waste streams. Therefore, it is important to reduce the arsenic concentration before it is introduced into a natural system with wastewater. Since the arsenic content causes the greyest WF, the arsenic concentration in the water must be further reduced using new methods before the wastewater is released into the environment. These measures can be taken with the use of new technologies for arsenic removal. In the study by Langsch et al. (2012), 14 arsenic removal methods are given with their advantages and disadvantages. The arsenic concentration can be reduced by evaluating these methods and applying the appropriate one to the mine waste [4,41].

5. Conclusions and Recommendations

In this study, the WF of a gold-producing mine using the CIP method was calculated, hotspots were determined, and the research objectives have been successfully achieved. At the end of the study, blue a WF of 452.40 m^3/kg Au and a grey WF of 2300.69 m^3/kg Au belonging to the mine were found. For the blue WF in the mine, the lost return flow on the direct WF side and the oxygen and electricity consumption on the indirect blue WF side have the highest values. Among the process steps, the tailing dam was identified as by far the largest source of blue WF. However, on the indirect WF side, it has emerged that, first of all, measures to reduce the blue WF should be taken for the leaching operation. When the two blue WFs were examined jointly, it was revealed that measures to reduce the blue WF should be taken for pit dewatering after lost return flow. The tailing dam is the only source of grey WF. Among the nine pollutants that are sources of grey WF, arsenic is the largest pollutant. Here, it is revealed that necessary studies should be done to reduce the concentration of arsenic in the waste dam. In order for the mine to reduce WF values and produce in a more environmentally sustainable way, a water management system should be established, and these hot spots should take the necessary measures.

This study can be made more efficient by collecting more detailed data from a mining site operating with the CIP method and taking the necessary measurements. At the same time, with a study in which Life Cycle Assessment Methodology is integrated, the environmental impact of the mine in relation to the water consumed can be clearly seen by selecting certain categories. In this way, the measures to be taken can be built on a more solid foundation with the understanding of sustainable production, which is an emerging issue for today's mining industry under the upcoming water crisis.

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