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Accounting for Water Footprint of an Open-Pit Copper Mine

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Received: 30 September 2020; Accepted: 16 November 2020; Published: 19 November 2020

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Abstract: Water is a crucial input for any production system, and mining is no exception. A huge amount of water is being used in the various phases of mining activities. In the coming decades, the competition in using a sufficient amount of fresh water will become a major hurdle for the mining industry. Water footprint (WF), an accounting framework for tracking the amount of water used to produce a unit of product, can be useful to the mining companies by quantifying their water resource appropriation and identifying ways to reduce the consumption. In this study, we accounted for the green, blue, and grey water footprint of an open-pit copper mine that is located in Laos. The input–output water flows of the mine are also developed from the inventory of water use. Moreover, we have calculated the uncertainty in the water footprint accounting to check the robustness of the findings. According to the results, the green, blue, and grey WF of the studied mine are 52.04, 988.83, and 69.78 m^3/tonne of copper concentrate, respectively. After the installation of a passive effluent treatment system in 2013, the calculated grey WF of the mine was 13.64 m^3/tonne, a fivefold decrease than before. The uncertainty in the footprint ranges between 8% to 11% which shows the robustness of the analysis. Although green WF is ignored by most studies, we suggest incorporating it into the accounting. The responsible share of a supply-chain WF to the total blue WF is about 98%, which is quite huge. Water embedded in the hydroelectricity is mainly responsible for such a huge amount of blue WF. Evidently, the use of electricity from hydropower results in the consumption of a large amount of water in exchange for a reduction in carbon emissions. Thus, the article attempts to demonstrate the escalating importance of WF accounting of this mine.

Keywords: copper mining; water footprint; environmental impact; sustainability; sustainable resource management

1. Introduction

Mining activities use an extensive amount of water in their various phases of production, with copper mining itself using more than 1.3 billion cubic meter water during 2006 [1,2]. The recent trend of declining ore grade along with stringent water regulations is putting sustainability challenge to this industry [3]. Understanding and utilizing the resources efficiently is a key for sustainable resource use and management, which is being put forward by the international and national community [2,4]. If a reduction in mine water use could be done, this will surely help to warrant that the water requirements are met without posing further encumbrance on the available resource. However, in order to reduce the resource use, the operation must know how much resource it uses with their incoming and outgoing flows [5,6]. One way of quantifying the anthropogenic pressure on the natural environment is to estimate the environmental footprint where the resource appropriation and the waste generation are measured [7]. Researchers have developed several footprint accounting approaches over the years, e.g., ecological footprint (EF), carbon footprint (CF), material footprint (MF), and water footprint (WF). EF, which measures humanity's demand on the ecosystem, can be defined as the area of biologically productive land and water needed to produce goods and to assimilate pollution [8]. On the other hand, CF is the total amount of CO_2 released to the atmosphere by human activities, which is also related to the concept of EF [9]. The global allocation of used raw material extraction to the final demand of an economy is termed as MF [10]. WF, a specific environmental footprint, is considered as a comprehensive indicator of the water resource appropriation and the assimilation of waste caused by human activities in the spatiotemporal dimension [7,11]. A WF analysis adds the global dimension in effort to understand the pattern of water use, scarcity, and pollution. It also paves the way for analyzing what can be done elsewhere than locally to improve the sustainability of water use on top of the existing practices [12]. The footprint of a product is dependent not only on the direct resource use on-site but also on the resource use along the supply chain, which in many cases are much bigger [7]. Surprisingly, only a handful of studies have considered this fact when performing footprint accounting [13].

There is limited understanding regarding the variability and magnitude of water resource use between mining regions, despite the importance of mining industries to global economies. This limitation makes it challenging to define what is an acceptable or appropriate level of water resource consumption for any mining entity [14]. Although the situation is changing as there is growing interest in both civil society and the business communities about sustainable water use, the lack of transparency of companies to report the direct and indirect water use is a major drawback that needs proper attention [15]. Northey et al. (2016) [16] pointed out the opportunities of WF assessment to the mining industry; for instance, a standardized assessment about the water use impact associated with mining will enable a meaningful and fair comparison with other sectors while contributing to developing a water efficiency benchmark scheme for mineral processing facilities. The recent development of WF methodology offers new scopes to quantify and help reduce the impacts associated with mined commodities [17]. However, several limitations exist in the WF for the mining industry, e.g., quality mine-site inventory data of water use, indirect WF, and unplanned pollution events, such as tailing dam failure, which are not accounted for in the present inventory [16].

A detailed WF assessment framework was prepared by the Water Footprint Network (WFN) [11]; it is an indicator of freshwater use and considers the direct water use of the consumer/producer as well as the indirect water use. WF is a multidimensional environmental indicator that shows the volumetric water consumption and the water pollution associated with the production process [11,18,19]. The comprehensiveness of the WF as an indicator lies in the adoption of supply chain thinking while performing the accounting [20] and providing spatiotemporally explicit information about how water is appropriated for various human uses [11]. Green, blue, and grey WFs are the three subdivisions of the total water footprint of a production or process according to the assessment manual. Blue WF refers to the surface water and groundwater consumed along the supply chain of the product, whereas green WF is the consumption of the rainwater. On the other hand, grey WF refers to the pollution, which is defined as the volumetric freshwater required to assimilate the pollutants load [11]. The merit of WF accounting is the value addition by creating interdisciplinary water management strategies to reduce the consumption of water [4,6,21].

Despite the merit of the WF from the viewpoint of sustainability, only a few research studies have considered this for mining products [2–6,21]. Moreover, the scope of those studies was confined to the calculation of a blue WF, and in some cases both blue and grey WFs. Green WF, which should have a share in the total WF if precipitated or runoff water is used in the system, was ignored by the studies. In this case, the knowledge of remote sensing (RS) could be particularly helpful to analyze the land use of the mine site, which in turn will provide the required data to calculate green WF. We opted for this approach to overcome the limitation of green WF accounting and make WF accounting comprehensive. On top of that, the uncertainty in WF accounting was mostly not reported, although Peña and Huijbregts (2014) [21] was an exception. Therefore, the aim of this study is to calculate the WF of mining by incorporating all the three subdivisions. Other than WF accounting, this study also explains the effect of water treatment on grey WF. In addition, the uncertainty involved in WF accounting is also discussed. We apply the methods to an open-pit copper mine and provide recommendations as to which areas the WF could be reduced in future endeavors. Moreover, we also discuss the comparison among blue WF, carbon emission, and the gross energy requirement of the mine from its various processes.

2. Materials and Methods

2.1. Goals and Scope

We followed the detailed guideline of the WFN [11] to estimate the WF of the studied mine. The WFN suggests the following phases while accounting for the WF of a product, industry, organization, or nation, which are (a) settings goals and scope, (b) water footprint accounting, (c) water footprint sustainability assessment, and (d) water footprint response formulation [11].

The goal of this study is to estimate the WF of the Phu Kham copper–gold mine of Laos, which will enable us to determine the operational water use and how to reduce the volumetric water consumption. The studied mine consisted of an open-pit mine that feeds the ore to a conventional milling and floatation process. It produces copper concentrate with by-products of gold and silver and then exports it to the pyrometallurgical producers in Asia (e.g., Thailand and Vietnam). The ore grades for copper, gold, and silver are 23%, 6 g/t, and 47 g/t respectively [22,23]. Phu Kham mine uses the surface water from a nearby river named the Nam Mo River, mostly for domestic purposes and specialized cooling systems for the equipment in the concentrator plant. Most of the water entering the tailings storage facility (TSF) is the rainfall run-off from the upper catchments and a small portion from pit dewatering. About 95% of the water in the site is recycled for further use in the production, and the excess water is discharged to the surrounding environment [22]. Figure 1 shows the system boundary of this research.

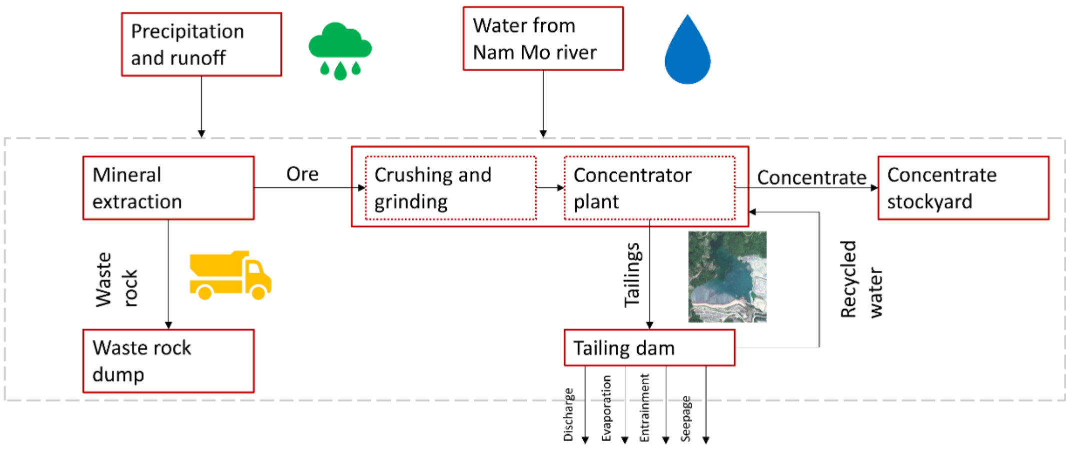

Figure 1. The schematics of copper concentrate production in the studied mine.

The scope of the WF accounting includes the blue, green, and grey WF. Since the mine uses a significant amount of materials in its production process, the indirect WF along the supply chain is also accounted for. The total WF was allocated as 83.1%, 15.14%, and 1.76% for copper, gold, and silver in concentrate respectively, based on the economic allocation following Islam et al. (2020) [23]. The functional unit of the accounting is the volumetric water consumption (m^3) to produce 1 tonne copper in concentrate. We considered the copper concentrate production and water use data for 2008–2010 [24–26] in the studied mine. The reason behind selecting the data for the aforementioned period is the availability of a full inventory only for those years. However, water discharge data are available for 2013, and a passive water treatment system was installed in the same year;

therefore, we calculated the grey WF of 2013. This also serves the purpose of explaining the effect of water treatment by a change in grey WF of the studied mine. Supplementary Table S1 shows the detailed inventory of materials for 2008–2010 period.

2.2. Water Footprint Accounting

The total amount of water used either directly or indirectly to produce a product is defined as the WF, according to the WFN [11]. Since the mine produces a single product as the output, we considered the chain-summation approach to calculate the WF. The following formula is used in this regard following Hoekstra et al. (2011) [11]: The WF for one tonne of a product p, $WF_{prod}[p]$, is estimated as shown in Equation (1), where $WF_{proc}[s]$ is the process WF of process step s (volume/time), and $P[p]$ is the quantity production of product p (mass/time).

$$WF_{prod}[p] = \frac{\sum_{s=1}^{k} WF_{proc}[s]}{P[p]} \quad \left[m^3/tonne\right], \tag{1}$$

The total WF is the sum of the green, blue, and grey WFs. The rainwater that is used in the production process, which could have been stored in the topsoil temporarily, is considered as the green water. Most of the study ignores this WF, simply stating that the amount is not that significant. However, this is not always true; for example, if the surrounding environment has tropical vegetation, then the water-holding capacity of the soil will be greater than the arid environment. In addition, according to the sustainability report of the mining company, it uses precipitated water. Therefore, the green WF part could not be just ignored. The calculation of the green WF is quite complicated. We overcame this limitation by utilizing the average precipitation from the sustainability report [24–26] while integrating the value in the land use of the study site obtained from the RS analysis of our previous work [23]. The estimated value of the green WF was then subtracted from the total water use to avoid double accounting. Equation (2) was used to estimate the green water utilization of the mine according to the MCA (2014) [27] framework.

$$V_{Rainfall} = 0.01 \times R \times SA, \tag{2}$$

where $V_{Rainfall}$ is the volume of rainfall (ML), R represents the average annual rainfall (mm) in the site obtained from the sustainability report, SA denotes the surface area (ha) of the mine estimated from Islam et al. (2020) [23], and the coefficient 0.01 converts the volume into ML.

Blue water is the fresh water, i.e., surface water and groundwater that are not returned to the same source. The studied mine withdraws water from the nearby Nam Mo river as the surface water source. In addition, the groundwater entrained in the ore is also used. The mine uses 95% of the total water as recycled water, which was considered in the blue WF. Blue WF can be calculated as the sum of the evaporated water, water incorporated into the product and the water lost in the process. The mine also uses tons of materials that have the embedded virtual blue WF. Therefore, to get a detailed and actual picture of the blue WF, the supply-chain WF needs to be considered. A significant amount of energy is being used to run the mine, which means that the share of the supply-chain WF for the energy should be larger than others. The electricity used in the mine comes from the nearby hydroelectric project. Moreover, fossil fuel, e.g., diesel and petrol, are also used in a larger volume. The blue WF of the electricity was estimated based on the hydroelectricity produced from the nearby three dams of Laos, viz. Nam Ngum, Nam Leuk and Houayho, based on Hogeboom et al. (2018) [28]. We used the representative value of the blue WF for the supply chain based on the literature and the Ecoinvent database. Table 1 shows the detailed blue WF per unit of material used in the Phu Kham mine. The detailed data for the supply-chain WF are provided in Supplementary Table S2.

Table 1. The supply-chain blue WF in the studied mine.

Unit Process	Materials	Unit	Value	Reference
Blasting	Explosives	m^3/kg	0.0338	[4]
Excavation, loading and hauling	Diesel	m^3/kg	0.0013	[4]
	Petrol	m^3/L	0.0033	[20,29]
	Lubricants	m^3/L	0.0014	[30]
Concentration	Electricity	m^3/GJ	76.68	[28]
	Cyanide	m^3/kg	0.036	[31]
	Hydrate lime	m^3/t	0.6	[21,29]
	Quick lime	m^3/t	0.3	[3]
	Cement	m^3/kg	0.002	[32]
	Hydrochloric acid	m^3/kg	0.0254	[4]
	Hydrogen peroxide	m^3/kg	0.172	[31]
	Sulphuric acid	m^3/kg	0.0541	[4]
	Frother	m^3/t	0.71	[21,29]
	Collector	m^3/t	2.19	[21,29]
	Grinding media	m^3/t	7.09	[33]

The mine discharges the excess water to the surrounding environment, which signifies that it has grey WF. Grey WF characterizes the pollution caused by the production entity and is defined as the volumetric amount of freshwater required to assimilate the load of the pollutants given natural background concentrations and the existing ambient water quality standards. In other words, the virtual amount of water that is required to assimilate the pollutant in the receiving water body is termed as the grey WF. We used the water discharge data from the sustainability report, whereas the concentration of the pollutants was sourced from Hedin et al. (2015) [34] (Supplementary Table S3). The following formula in Equation (3) was used to calculate the grey WF [11,35]. Based on the concentration of the pollutants, the equation provides the grey WF. We selected the representative grey WF for this study as the highest value obtained from the calculation.

$$WF_{grey} = \frac{C_{effl} - C_{act}}{C_{max} - C_{nat}} \times Effl, \tag{3}$$

where $\frac{C_{effl}-C_{act}}{C_{max}-C_{nat}}$ is the dilution factor, C_{effl} is the concentration of the contaminant in the effluent (mg/L), C_{act} shows the concentration of the contaminant in the receiving water body before the abstraction (mg/L), C_{max} represents the maximum allowable concentration of the contaminant in the surface water (mg/L), C_{nat} denotes the natural concentration of the contaminant in the surface water (mg/L), and *Effl* is the part of the abstracted water that returned to the surface water (m^3).

2.3. Water Inventory Development

The computation of the WF requires water inventory development. The Sustainable Minerals Institute has developed a comprehensive guideline called the Water Accounting Framework (WAF) [27] to identify, measure, record, and report the information about water. We integrated the WAF within the WFN to develop the inventory of the water use data of the mine and its accuracy and limitations. The WAF has three components, namely the input–output model, the operational model, and the water quality descriptions. In input–output model, the flows between the environment and the system boundary of the mining site is described. The volumetric water flows based on their sources and end points are classified and reported as the input, output, or diversion. Input water volume is the volume of water received by the mining site and categorized as the surface water, groundwater, sea water, or third-party water based on its source of origin. The volume of water removed from the site is considered as the output, which could be classified as the surface water, groundwater, sea water, third party water, evaporation, entrainment, and other. Both the input water and the output water are allocated a water quality category based on the characteristics of the water. Three water quality categories (Categories 1, 2, and 3) are used to allocate the receiving and discharge water of the site. To justify the water quality category, we used the WAF guideline. Since the data regarding the inflows and outflows are often estimated, the accuracy of the data needs to be described. This is done by declaring whether the flows are measured, calculated, or estimated. The operational model on the other hand provides guidance to the facility by defining the various water (i.e., raw water, worked water, and treated water). However, due to data unavailability, we did not consider it in this study. We used the formulae in Equations (4)–(6) while following the MCA (2014) [27] framework to calculate the volumetric water from different sources.

$$V_{Runoff} = 0.01 \times R \times A \times \beta, \tag{4}$$

where V_{Runoff} is the volume of runoff (ML), R represents the average rainfall (mm) in the site obtained from the sustainability report, A denotes the disturbed/undisturbed catchment area (ha) of the mine estimated from Islam et al. (2020) [23], and β is the volumetric runoff/rainfall factor [27] ($\beta_{disturbed} = 0.15$; $\beta_{undisturbed} = 0.05$).

$$V_{Evap} = 0.01 \times S_{Evap} \times PanEvap \times f, \tag{5}$$

where V_{Evap} is the evaporation loss (ML), S_{Evap} represents the surface area (ha) occupied by water in the site obtained from Islam et al. (2020) [23], $PanEvap$ denotes the value of measured rates of pan-evaporation (evaporation rate of nearby Nam Ngum reservoir of Laos was used according to Mekonnen and Hoekstra (2012) [36]) and f is the correction factor to convert the measurement of pan evaporation into evaporation losses from the open surface (a correction factor of 0.75 was used according to MCA (2014) [27]).

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

where V_{Ent} is the volume of water (ML) entrained in the ore, P denotes the ore processed (Mt) in the studied period, and m represents the moisture content of the ore body (0.02 was used according to MCA (2014) [27]).

Groundwater from pit dewatering is often used within the mining process. How much water is being used from pit dewatering is extremely difficult to estimate, mainly due to missing information. The pit dewatering rate is also highly dependent on the geography and hydrology of the mine site. In most cases, the water from this source is used for dust suppression, but there is no evidence that all dewatered water is used. Since the mine does not report the volume of water derived from pit dewatering, we used the dewatering rate provided by Northey and Haque (2013) [37]. A dewatering rate of 0.15 m^3/tonne ore was considered while calculating the groundwater input flows from pit dewatering. We also reported the confidence of the estimation.

2.4. Uncertainty in WF Accounting

Uncertainty in water footprint accounting is common due to use of numerous data sources and estimation. Moreover, the upstream WF accounting for the materials used in the supply chain also creates uncertainty in the analysis. We used certain assumptions based on the data source and the derivation method to estimate the uncertainty of the WF accounting. Data used from the sustainability report of the mining company are considered to have less uncertainty, and therefore an uncertainty range of ±10% is assigned to it. However, we also used data from secondary sources and some databases, and in this case, we assigned the uncertainty to be ±30%. Supplementary Table S4 shows the assumptions of the details regarding the uncertainty estimation. We applied the Gauss law of error propagation to propagate the error based on the nature of the estimation and calculated the uncertainty in the green, blue, grey, and the total WF as the standard deviation (Equations (7) and (8)).

$$\sigma_x = \sqrt{\sigma_a^2 + \sigma_b^2 + \sigma_c^2}\,, \tag{7}$$

$$\frac{\sigma_x}{x} = \sqrt{\left(\frac{\sigma_a}{a}\right)^2 + \left(\frac{\sigma_b}{b}\right)^2 + \left(\frac{\sigma_c}{c}\right)^2}\,, \tag{8}$$

where a, b, and c are the measured variables, and $\sigma_a, \sigma_b,\ and\ \sigma_c$ are the standard deviations of the variables.

The estimated uncertainty was then used in the Monte Carlo Simulation (MCS) to check the robustness of the WF accounting. We ran the MCS 1000 times for the blue, green, grey and total WF individually to determine the uncertainty (standard deviation, σ). The model input data were treated as the mean of the normal distribution, and the uncertainty range was assumed as discussed above. We also estimated the uncertainty in the total WF accounting, which is presented in Equations (9)–(11):

$$WF^{mc} = Green\ WF^{mc} + Blue\ WF^{mc} + Grey\ WF^{mc}, \tag{9}$$

where WF^{mc} is the total water footprint from the MCS, $Green\ WF^{mc}$ denotes the green WF from the MCS, $Blue\ WF^{mc}$ represents the blue WF from the MCS, and $Grey\ WF^{mc}$ is the grey WF from the MCS.

$$\overline{WF} = \frac{1}{n}\sum_{i=mc}^{n} WF^{mc}, \tag{10}$$

where $\overline{WF}$ represents the mean value of the total water footprint;

$$\sigma_{WF} = \pm\sqrt{\frac{1}{n}\sum_{i=mc}^{n}\left(WF^{mc} - \overline{WF}\right)^2}, \tag{11}$$

where σ_{WF} shows the uncertainty (as standard deviation) of the total water footprint.

3. Results

3.1. The Water Footprint

The green WF of the studied mine was 62.62 m^3/tonne where copper, gold, and silver in the concentrate shared 52.04 m^3/tonne, 9.48 m^3/tonne, and 1.10 m^3/tonne, respectively (Figure 2). The contribution of green WF to the total WF was approximately 5%, which was the lowest amongst the three WFs (Figure 3). Even though most studies ignored green WF, the estimated value suggests incorporating green WF into the accounting if a significant amount of precipitated water is used in the production.

Like many other products, the blue WF constitutes the lion's share of the total WF of the open-pit copper mine. The calculated value for the blue WF of copper concentrate, gold in concentrate, and silver in concentrate of the Phu Kham mine was 988.83 m^3/tonne, 180.15 m^3/tonne, and 20.94 m^3/tonne, respectively (Figure 4). By summing up the responsible WF of the metal concentrate, the total blue WF of the mine was estimated to be 1189.93 m^3/tonne. Blue WF contributed to about 89% of the total WF of the mine where the supply-chain water footprint dominated the accounting with an estimated value of 1169.87 m^3/tonne of concentrate. On the other hand, the blue WF from the direct water use from the nearby river source was calculated to have a WF value of 20.06 m^3/tonne of concentrate. It was evident that the use of hydroelectricity was responsible for the huge supply-chain blue WF. The water embedded in the production of hydroelectricity was huge, and its share in the total blue WF was approximately 97%. This result has a broader implication; for example, if the mine replaces a certain share of the energy mix with other sources with less WF, the blue WF will drop dramatically. We describe this phenomenon with more details in the discussion section.

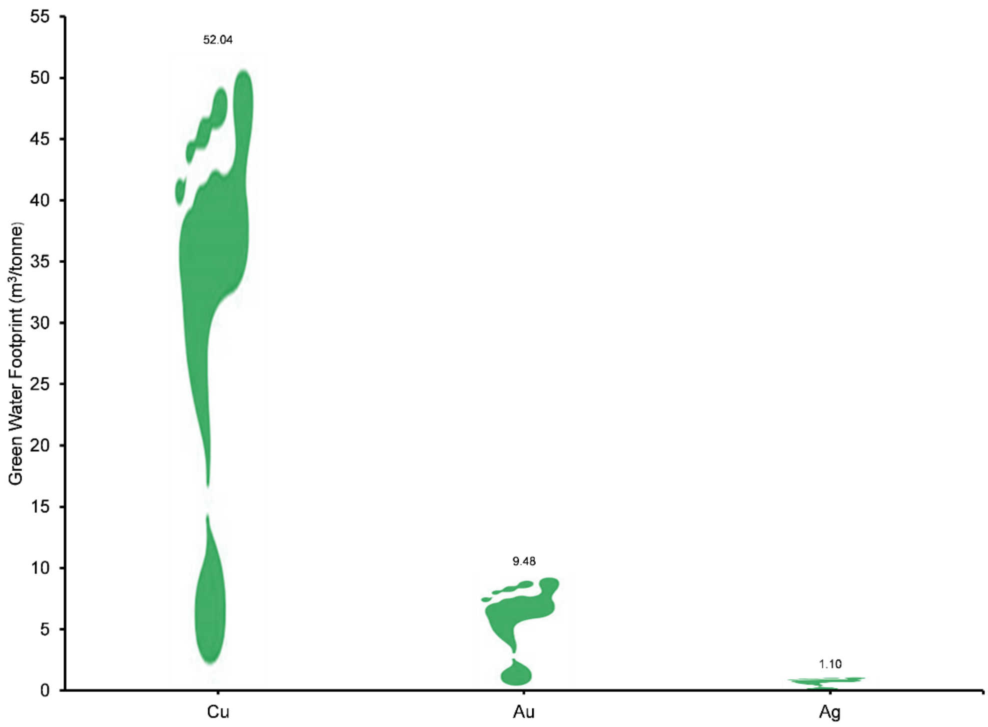

Figure 2. The green water footprint (WF) of the studied open-pit mine.

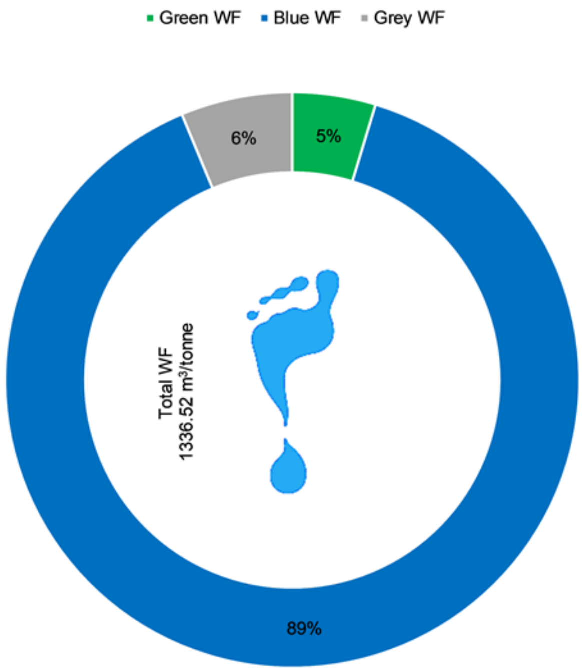

Figure 3. The total WF with its share in green, blue, and grey WFs of the studied open-pit mine.

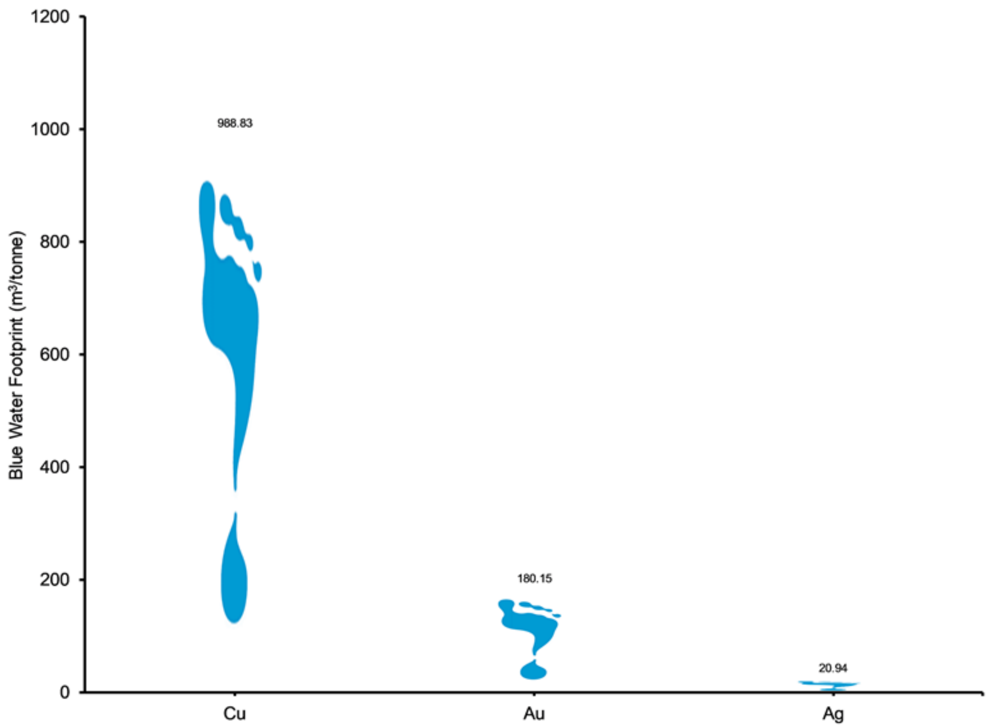

Figure 4. The blue WF of the studied open-pit mine.

Figure 5 shows the grey WF of the mine, which was estimated from the amount of pollutants released to the environment by the mine. All but the concentration of Fe and Mn in the discharged water during the 2008–2010 period were within the maximum allowable concentration limit of the standard water quality guideline (see Supplementary Table S3 for details). The total grey WF of the studied mine in the 2008–2010 period was 69.78 m^3/tonne of concentrate. It was assumed that roughly 69.78 m^3 water would be required to assimilate the contaminant produced from 1 tonne of concentrate. In the case of grey WF, the highest representative value was considered as within this amount of water, and the other contaminant should be diluted in the receiving water source. Even if the mine treats the water to keep the concentration of Mn in the discharged water, the grey WF would be 27.08 m^3/tonne of concentrate, unless it also corrects the concentration of Fe.

The case study mine eventually undertook corrective measures to treat the effluent to remain within the permissible water quality limit. Since all other contaminants were within the limit, the mine installed a passive treatment system in 2013 to treat the discharges from the two toe drains and to reduce the concentration of Fe and Mn in the treated water [34]. Figure 5 also shows the comparison of the grey WF before and after the installation of the passive treatment system. Even though both the discharge and concentrate production increased in 2013 compared to the 2008–2010 period, the grey WF decreased dramatically (see Supplementary Table S3 for details). The grey WF of the mine in 2013 was 13.64 m^3/tonne of concentrate, which is a fivefold decrease than the previous. This also shows the effectiveness of the water treatment facility on one hand and the incentive for similar types of operations to reduce the grey WF on the other hand.

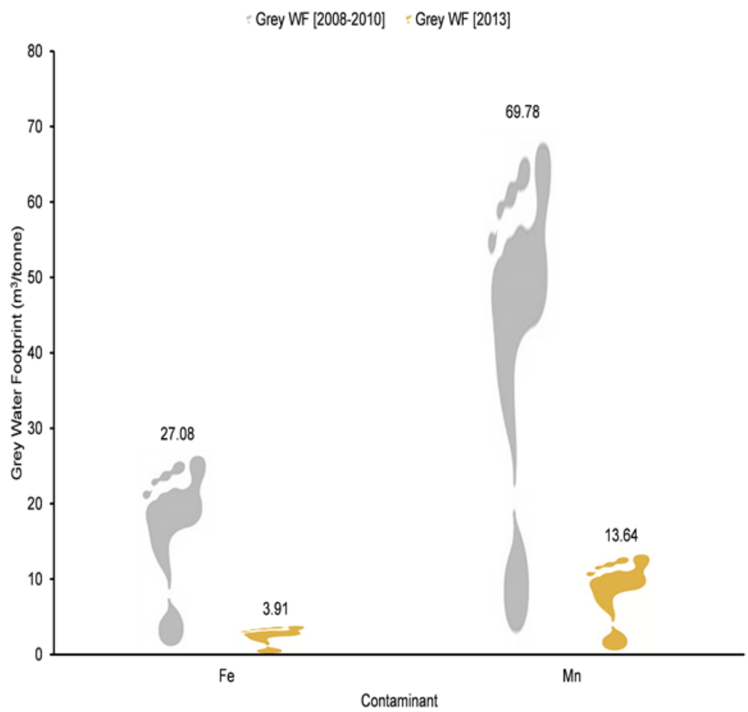

Figure 5. The grey WF of the studied mine before and after the installation of the passive treatment system.

3.2. The Input–Output Flows of Water

The WAF provided a detailed guideline by which the mining water requirements with their inflows and outflows could be estimated. We integrated the WAF to estimate the input–output flows of water in the studied mine and calculated the accuracy and confidence of the accounting. Table 2 shows the input–output water flows of the studied mine. Out of 23.37 Mm^3 water per year that was used in the mine in the 2008–2010 period, roughly 18.93 Mm^3 water used have moderate water quality (Category 2). We estimated similar values for output water flows (19.78 Mm^3 per year) having the moderate water quality. In the input water flows, a significant amount of water accounting for 48% of the total input water flows was derived from the precipitation and runoff. The contribution of water from river was about 5%, whereas the water entrained in ore shared approximately 1% of the total input flows. Input water from pit dewatering also remained low, which was less than 1%. It was noticeable that evaporation, seepage, and task loss altogether contributed to nearly 95% of the total output water flows. Evidently about 3% of the total output water flows was discharged to the environment, which was responsible for the grey WF of the mine.

Table 2. The input–output water flows in the Phu Kham mine for 2008–2010.

Input–Output	Source/Destination	Inputs/Outputs	Volume of Water in Quality Category Number			Total (Mm^3)	Accuracy (Measured, Estimated, Simulated) and Confidence * (High, Medium, Low)	Notes
			1 (Mm^3)	2 (Mm^3)	3 (Mm^3)			
Input	Surface water	Precipitation and runoff	3.06	8.07		11.13	Estimated, medium	1
		Rivers and creeks	1.23			1.23	Measured, high	
	Groundwater	Entrainment			0.14	0.14	Estimated, low	2
		Pit dewatering			0.01	0.01	Estimated, low	3
	Other	Other		10.85		10.85	Estimated, low	4
	Total Inputs		4.30	18.92	0.15	23.37		
Output	Surface water	Discharge			0.67	0.67	Measured, high	
	Other	Evaporation	2.23			2.23	Estimated, low	5
		Entrainment			0.68	0.68	Estimated, low	6
		Seepage, task loss		19.78		19.78	Estimated, low	7
	Total Outputs		2.23	19.78	1.36	23.37		

* High: >75%; Medium: 50–75%; Low: <50%. Notes: (1) Precipitation was estimated based on the average rainfall from the sustainability report of the company and the land use data from Islam et al. (2020) [23]; runoff was estimated following the formula of the WAF. (2) Water entrained in the ore was calculated based on the formula provided by WAF. (3) Input water from pit dewatering was estimated using the pit dewatering rate data provided by Northey and Haque (2013) [37]. (4) Value was estimated based on subtracting the inflows of surface and ground water from the total water flow reported by the company. (5) Evaporation was estimated according to the formula of WAF and the land use data from Islam et al. (2020) [23]. (6) Same as note 4. (7) Value was estimated to match the total outflow with the inflow.

The mining company only measures the volume of water from the river and discharges back to nearby creeks. Therefore, most of other parameters for input–output flows must be estimated due to which the confidence level of the accounting got lower. The accuracy of the accounting for high, medium, and low confidence level of the total water flows were 4%, 24%, and 72%, respectively (see the footnote in Table 2 for a detailed description of confidence). Supplementary Table S5 shows the accuracy statement of the water footprint accounting.

3.3. Water Use and Ore Grade of Minerals

The direct water used by the mine is also dependent on the ore grade. Figure 6 shows the contribution of ore grade to the total water consumption by the studied mine. The ore grade of the minerals of the mine for the fiscal year (FY) 2008–2018 was sourced from [38], and the water use in the process was collected from the sustainability report [22,24–26,39–45]. Thus, each data point in Figure 6 represents the ore grade and water use in a single FY. The declining ore grade means more ore is needed to be processed to produce the same amount of concentrate. Therefore, more materials are also needed to sustain the production due to which the responsible water consumption increases over time. It is also evident from Figure 6, however, that the relationship as found in this study remains quite moderate. This declining ore grade will have significant influence on the competing water uses by the mining companies and the neighboring residents.

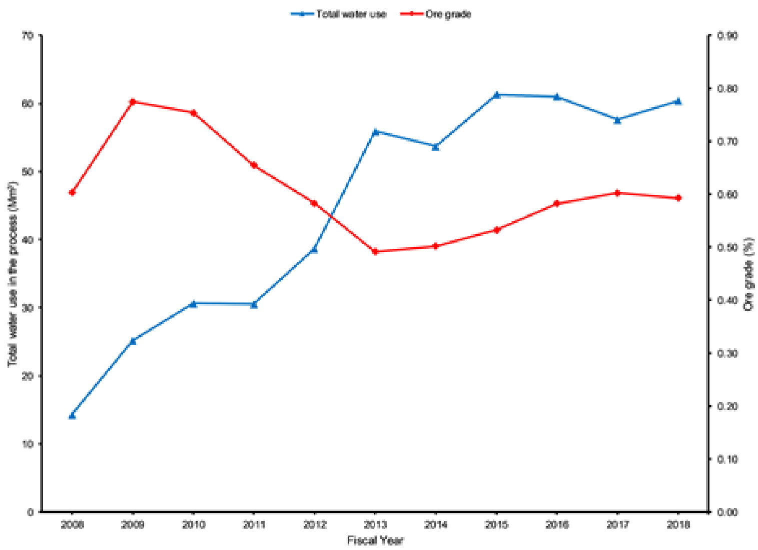

Figure 6. The relationship between ore grade and water use in the mining process.

3.4. The Uncertainty in the Water Footprint Accounting

The uncertainty in the WF accounting is obvious due to the unavailability of measured water flow data. We used the MCS to calculate the uncertainty of the WF accounting to show the robustness of the results. Table 3 shows the uncertainty of the accounting of the studied mine. The green WF of the Phu Kham mine for copper concentrate was 52.33 ± 5.63 m^3/tonne, which implies an uncertainty of 11% in the accounting. On the other hand, the blue WF for copper concentrate was 987.81 ± 92.25 m^3/tonne with an uncertainty of 9%. Since the uncertainty of the WF accounting does not exceed more than 11%, the results from the footprint analysis is robust. Overall, the total WF of the mine for copper concentrate, gold in concentrate, and silver in concentrate were found to be 1110.14 ± 92.51 m^3/tonne, 203.26 ± 18.07 m^3/tonne, and 23.47 ± 2.07 m^3/tonne, respectively (Table 3).

Table 3. Uncertainty in the water footprint accounting of the Phu Kham mine.

Accounting Type	Cu			Au			Ag		
	Mean	Standard Deviation	Uncertainty (%)	Mean	Standard Deviation	Uncertainty (%)	Mean	Standard Deviation	Uncertainty (%)
Green WF	52.33	5.63	11%	9.48	1.04	11%	1.10	0.12	11%
Blue WF	987.81	92.25	9%	181.02	17.95	10%	20.90	2.07	10%
Grey WF	70.00	5.33	8%	12.76	0.98	8%	1.47	0.11	8%
Total WF	1110.14	92.51	8%	203.26	18.07	9%	23.47	2.07	9%

Note: The unit of the WF is m^3/tonne.

4. Discussion

This study successfully accounted for the WF of an open-pit copper mine. While most studies reported only blue WF and grey WF [3,5,6,21], this study also included green WF, and therefore the WF accounting could be considered as complete and comprehensive. The integration of WAF with the WF enabled us to develop an inventory for water usage with its input and output. We relied on the raw water use data from the sustainability report of the mining company. Northey et al. (2013; 2019; 2016) [14,16,46] discussed the prospects and challenges of sustainability reporting to perform a water footprint. The present reporting framework could be revised by providing more detailed sectoral water use data other than reporting only the total water abstraction, water use, and discharge. Due to this limitation, we could not develop an operational model that is recommended in the WAF. The internal operational model is helpful to identify the routes of internal water use and thus helps to reduce the volumetric consumption of water. In the coming decades, the competition for fresh water will become a major hurdle for the mining industry. Therefore, the reduction of water usage by identifying the leakage routes should be considered.

The studied mine uses approximately 95% of the total water as recycled water, which is undoubtedly a positive aspect [22], but there are some issues that could be considered in the future, not only for this mine but also applicable for other mines. For example, the evaporative loss of water was quite huge—about 2.23 Mm^3 per year. Other major routes of water loss was seepage and task loss, which was the highest for the Phu Kham mine. If this significant amount of water was reused in the system, e.g., for cooling and dust suppression, the total WF would be reduced dramatically. The mine discharges roughly 0.67 Mm^3 grey water per year to the nearby water sources due to which the responsible grey WF was 69.78 m^3/tonne of concentrate during the 2008–2010 period. The concentration of the pollutants (e.g., Mn and Fe) in the discharged water exceeded the standard water quality limit due to which the mine has grey WF. However, the mine installed a passive treatment system in 2013 to remain compliant with the standard water quality guideline. The comparison of the grey WF before and after the installation makes it clear that the treatment facility is contributing to reduce the grey WF of the mine. It also means that a mine site could reduce its grey WF by adopting necessary corrective measures. Morera et al. (2016) [47] also showed that the grey WF was greatly reduced after treating the water in a wastewater treatment plant. Among the three WFs, grey WF could impact the surrounding aquatic environment drastically. Several reports already discussed the mining water discharge as a major point source of water pollution in the rivers of Laos. However, this type of impact could be avoided if the water is treated sufficiently by following the standard water quality guideline and reducing the discharge volume by reusing it in nonproductive purposes.

Performing WF accounting often requires estimation, especially for the water embedded with the products, which creates uncertainty in the estimation. Therefore, the uncertainty in the estimation should be reported while conducting a WF study. The important contribution of this study is the detailed accounting of WF with its uncertainty and the adoption of supply-chain thinking for blue WF. A significant amount of materials are being consumed by the mine, many of which come from thousands of kilometers away from the geographic space of the mine. Unless the supply chain of the materials is considered, the product WF is incomplete. We found from the analysis that the share of the supply-chain WF (WF embedded with the materials) to the total blue WF was about 98%. It is also noteworthy to mention that the use of hydroelectricity is solely responsible for about 99% of the supply-chain WF and roughly 97% of the total blue WF. The reduction of supply-chain WF requires the commitment of producers to practice sustainability, which is growing gradually worldwide. Although the use of freshwater from the river was not that much compared to the virtual water embedded into the materials, we recommend reduction of the existing amount by utilizing more from the green water. The existing climate surrounding the mine is very much capable of providing an ample amount of green water supply.

It is clear that blue WF dominates the WF due to the usage of tons of materials in the mining process. Table 4 shows the comparison of the blue WF, global warming potential (GWP), and gross energy requirement (GER) of the studied mine from different unit processes. The GWP and GER data were collected from our previous work [23] to show this comparison. Excavation, loading and hauling, and concentration were the major processes that consumed most of the materials and energy due to which the respective footprint was also higher. The GWP of the mine was lower mainly due to the use of hydroelectricity, which was about 8% (272.63 kg CO_2 eq./tonne copper in concentrate; see Supplementary Table S6 for details) of the total carbon emission. On the other hand, the use of hydroelectricity was solely responsible for the huge blue WF in exchange for a reduction in the GWP. On-site combustion, grinding media, and explosives were the top three processes sharing roughly 40%, 17%, and 11%, respectively, of the total GWP. The energy requirement of the mine from the excavation and the loading and hauling process was 20,262.46 MJ/tonne copper in concentrate, and it was about 57% of the total GER.

Table 4. The comparison of WF, carbon emission, and gross energy requirement from different processes in the studied mine.

Unit Process	Blue WF (m^3/tonne Cu)	GWP (kg CO_2 eq./tonne Cu)	GER (MJ/tonne Cu)
Blasting, Excavation, loading and hauling	2.48	2013.87	20,262.46
Concentration	971.09	1400.29	15,122.59

Hydroelectricity is one of the cleanest sources of energy, considering the lower CO_2 emission, which was also evident from Islam et al. (2020) [23]. However, from the WF analysis, we were able to show another side of the story of hydropower. Even though the carbon emission from the mine was lower due to hydroelectricity, the blue WF was too huge due to a higher amount of embedded water to produce a unit of electricity using hydroelectric dam. Here, we consider how certain energy mixes impact the total blue WF by taking 6 hypothetical situations. These six hypothetical scenarios are (a) Scenario 1 with 100% hydroelectricity; (b) Scenario 2 with 90% hydroelectricity and 10% coal; (c) Scenario 3 with 80% hydroelectricity, 10% coal, and 10% photovoltaics; (d) Scenario 4 with 80% hydroelectricity, 5% coal, 5% photovoltaics, 5% concentrated solar panel, and 5% nuclear; (e) Scenario 5 with 70% hydroelectricity, 5% coal, 5% oil, 5% natural gas, 5% nuclear, 5% concentrated solar panel, and 5% photovoltaics; and (f) Scenario 6 with 65% hydroelectricity and 35% coal. The WF data to produce electricity from different sources were collected from Mekonnen et al. (2015) [48] and were adopted in the hypothetical conditions to compare the total blue WF of the mine. The water embedded in the materials from the supply chain and the direct water used in the mine were also included. Figure 7 shows the hypothetical blue WF of the mine. By adding a certain percentage of nonrenewable energy source in the electricity grid, blue WF could be reduced substantially. For example, the WF in Scenario 1 was 1189.93 m^3/tonne of concentrate, whereas it was 1077.17 m^3/tonne of concentrate in Scenario 2—a 9% reduction in WF. The lowest blue WF was noticeable in the case of Scenario 6 due to the larger share of nonrenewable energy source. Photovoltaics and wind energy have one of the lowest WF, though considering the long-term cost-effectiveness, not much of either was added in the grid [48].

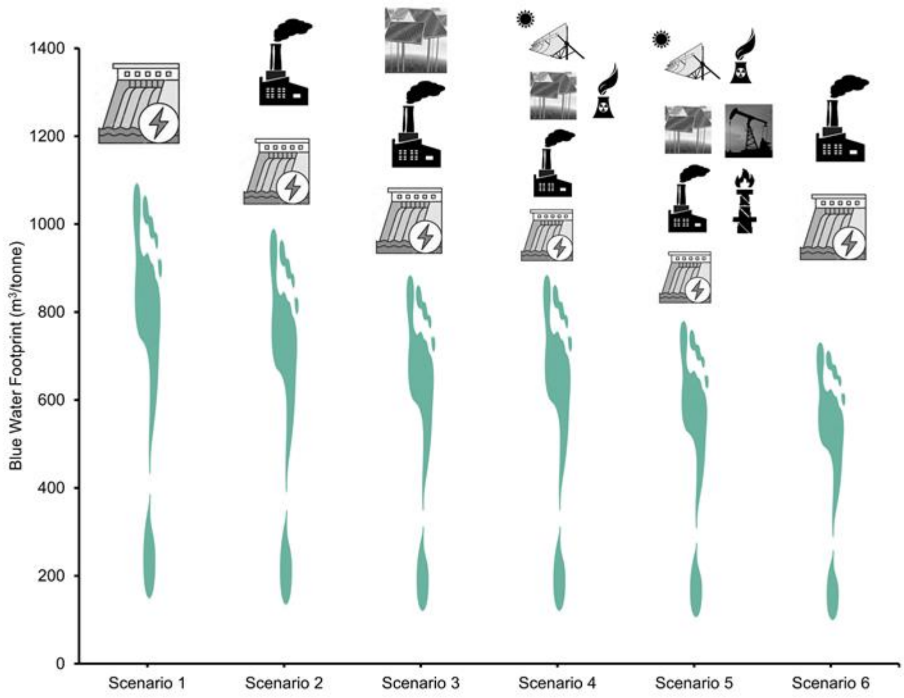

Figure 7. The hypothetical blue WF from different energy mixes.

The mineral resource, copper, is still available and may meet the demand for the coming decades. For now, the critical issue is the environmental footprint of the metal supply and use rather than the resource availability itself [49]. Using renewable energy could certainly reduce the greenhouse gas (GHG) emission; for example, the reported GHG emission for the Phu Kham mine was 3.4 kg CO_2 eq./kg of copper concentrate, which was mainly due to hydroelectricity. However, the use of hydroelectricity increases the WF significantly. The choice of renewable energy in this case is very critical. Only the solar energy has the lower GHG emission factors for electricity generation (0.05 kg CO_2 eq./kWh) [49] and lower WF (303 m^3/TJ) [48]. A suitable energy mix could reduce both the WF and GHG emission, as opting for solar energy fully as of now is not economically feasible.

There is no such standard or reference value as to which the mining company should follow to keep their WF within the limit. The very first step to reduce the footprint should be the accounting of the WF, and if possible, comparing it within a similar production system that is occurring elsewhere. Depending on the type of mining methods with geologic and geographic factors, the WF should vary. We compiled the existing WFs of different mining products and provided it as Supplementary Table S7. From the comparison, it is clear that the scope of the studies regarding WF calculation was limited. Both the steel (unalloyed and alloyed) and PGM (platinum group metals) have higher blue WF than that of our present study, which is quite obvious. Angel (2016) [50] conducted a literature survey and found that the average WF for primary copper production was 97.2 ± 164 L/kg of metal. The uncertainty in the average WF value and for the individual case study was extremely high, which could be due to the use of global data. In this case, the use of site-specific data is very useful to reduce the uncertainty, as evident from this study.

5. Conclusions

The representative value for green, blue, and grey WFs of the studied mine were 52.04, 988.83, and 69.78 m^3/tonne of copper concentrate. Due to the installment of the passive treatment facility in 2013, the grey WF of the mine reduced greatly, and the calculated value was 13.64 m^3/tonne of concentrate, a fivefold change lower than before. Fortunately, an abundant water resource allows the case study mine to use less carbon-intensive hydroelectricity, but the water embedded in the hydroelectricity production was mainly responsible for the huge blue WF. Adding a certain percentage of electricity from a nonrenewable energy source could reduce the WF in this regard. Given that the uncertainty ranges between 8% to 11% and that the calculations of all the subdivisions of the WF were performed, the findings from the WF accounting are robust. It is evident from the analysis that the mine could avoid the grey WF if it opts for a zero-discharge policy by reusing the discharge volume in other works or simply discharging the water after ensuring that the concentration of the contaminants does not exceed the standard limit.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/22/9660/s1, Table S1: Inventory of materials used in the mine, Table S2: Blue water embedded in the production of the materials, Table S3: Characteristics of the contaminants released to the surrounding environment in the studied mine, Table S4: The detailed uncertainty assumptions considered to estimate the WF, Table S5: Accuracy statement of the water flows in the studied mine, Table S6: A detailed comparison of the blue WF, global warming potential and gross energy requirement in different unit processes of the studied mine, Table S7: Comparison of water footprint of different mining products.

Author Contributions: Conceptualization, K.I.; methodology, K.I.; software, K.I.; validation, K.I. and S.M.; formal analysis, K.I.; investigation, K.I.; resources, K.I.; data curation, K.I.; writing—original draft preparation, K.I.; writing—review and editing, K.I. and S.M.; visualization, K.I. and S.M.; supervision, S.M.; project administration, S.M.; funding acquisition, S.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by JSPS KAKENHI grant number 18KT0010.

Acknowledgments: The first author of this study is grateful for the PhD scholarship provided by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), Japan. The authors would like to thank two anonymous referees for helpful comments in an earlier version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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