A preliminary water footprint assessment of copper production in China
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ABSTRACT
Scarcer water resources, stricter water regulations, decline in ore grade and increasing controversy on water use between local communities and mining operators have raised awareness of good water stewardship as being vital to running commercially viable mining operations. Water footprint assessment (WFA) is a holistic methodological framework that allows detailed quantification of direct and indirect water use in different sectors at various spatial and temporal scales. The ultimate aim of this study is to identify water footprint (WF) reduction targets, formulate response strategies to minimize water consumption and pollution and therefore improve the environmental, social and economic sustainability of the mining processes. The assessment will eventually serve as a model for other mines in northern China with water scarcity issues. The paper describes the preliminary WFA of copper cathodes, with particular emphasis on the methodology, approach, degree of details and areas for consideration. It focuses from ore extraction to final discharge to the river. Significant WF contribution is found in the process rather than the supply chain. The explorative approach applied in this real case scenario and the findings contribute to the literature body of the WFA field. This case study can provide helpful guidance for WFA practitioners when applying this methodological framework in addressing particular issues in mining processes.

Key words | copper, mining, supply chain, sustainability, water footprint

INTRODUCTION
China’s renewable water resources are the sixth largest in the world, however, two-thirds of Chinese cities lack water due to unevenly distributed resources and pollution, with the national resource amount per capita only equaling 28% of the average globally (Xie 2009). Mining is a water intensive industry. Scarcer water resources, stricter water regulations and decline in ore grade have posed a major sustainability challenge for the mining industry. Furthermore, mining operations cannot be relocated, making the sector susceptible to changing local water availability (Barton 2010), which leads to increasing controversy on water resource disputes between local communities and mining operators. These have raised the awareness of good water stewardship as being a vital part of running commercially viable mining operations. In order to ensure regulatory compliance and maximize efficiency for all key commodities, it is vital that mining companies optimize their water usage, and minimize the interference with natural water sources and the impact on water quality.

Although mining operation may use a considerable amount of water, the industry overall consumes a relatively small quantity of water at national and global levels (Rankin 2011). Due to its impacts on local resources and its surroundings, companies carried out water accounting to keep track of their water consumption, wastewater discharge, water use efficiency and total amount of recycled water. They have been largely driven by a desire to maximize operational efficiencies. However, this general measure of physical supply is widely considered inadequate to determine the company’s actual access to water supplies and services or whether environmental and human needs are being met (Molle & Mollinga 2003; Chenoweth 2008).
The water footprint (WF) is an indicator showing detailed quantification of water use directly and indirectly in different sectors (Hoekstra et al. 2011). It is intended to allow better understanding of the relationship between water consumption and watersheds, make informed management decisions, and spread awareness of water challenges worldwide (Morrison et al. 2009). It is formulated in the context of a variety of considerations, including local environmental impact, global sustainability, equity, and economic efficiency, given the priority of WF reduction (Hoekstra & Mekonnen 2012). WFs are divided into three separate components – the blue, green, and grey WF – all of which are expressed in terms of water volume. Blue WF is an indicator of the volume of consumptive water use taken from surface or groundwater. Green WF is an indicator of the volume of rain water (often found in soils) consumed generally by crops, fruit plants and trees to be harvested for timber production. Grey WF is defined as the volume of freshwater that is required to assimilate pollutants based on natural background concentrations and existing ambient water quality standards. Studies in the current water footprint assessment (WFA) literature body mostly focus on the WF of countries, cities, agricultural products and consumer goods while relatively limited information regarding the WF of industrial production can be found. WFA in the mining industry will provide useful information and reference for other industries in their assessment.

The overall objective of this work is to explore the potential of using WF as an indicator in mining industry, to minimize the impacts of the mining production on the natural water resources from both quantity and quality perspectives. Critical WF components can be identified to support setting up WF reduction targets. The assessment will serve as a model basis to be applied on other mines within China, especially in the northern part where water scarcity is more prominent. This present paper describes the methodology, approach and challenges and learns from this real case scenario to explore the degree of detail required in such studies.

METHODS AND APPROACH

The general approach is based on the methodology described in the WFA Manual (Ercin et al. 2011; Hoekstra et al. 2011). It consists of four distinct phases: (1) setting goals and scope, (2) WF accounting, (3) sustainability assessment, and (4) response formulation.

The goal of this work is set to study the WF of a copper product within a geographical area (Zijinsghan mine) in one particular year, with the purpose of raising awareness and identifying a reduction target. The bioheap leaching at Zijinsghan mine is the first commercial bioleaching plant in China (Ruan et al. 2013) due to its low cost operation, in particular for low grade copper ore. Copper cathode from bioheap leaching, solvent extraction and electrowinning processes were chosen as the WF of a product for this study. The WF of a product is the volume of freshwater used to produce the product, measured over the full supply chains. It is a multi-dimensional indicator, showing water consumption by volumes by source and polluted volumes by type of pollution; all components of a total WF are specified geographically and temporally (Hoekstra et al. 2011). The WF study from the pilot scale bioheap leaching plant will give more insight into the sustainability of this process and the production. Considering the characteristics of the production processes, the blue and grey WFs will be our main focus for this study while the green WF is neglected due to the fact that the green water (rainwater or precipitation that is stored in the soil or temporarily stays on top of the soil or vegetation) is not used in processes under study.

Description of the mine

Many metals are found in mineral-containing ores in the earth’s crust and they are usually situated in remote areas. After they are mined, ores undergo crushing, grinding, milling and various processes that require large volumes of water and chemicals to effectively extract the desired metals. Given the tiny amounts of desired metals contained in most ores, with average ore grade for copper being 0.5–1.0%, the rest of all the material mined will become waste and is stockpiled in the vicinity.

The Zijinsghan opencast gold/copper mine, started in the 1990s, is one of a number of large mining concerns operated by the Zijin Mining Group in China. The mine is located within some 2500 ha of mountainous country beside the Ting River 14.6 km north of the large town of Shanghang (500,000 population), Fujian province, and approximately 200 km northwest of Xiamen on the South China Sea. The area has a temperate climate, subject to heavy rainfall (1,700 mm/annum), particularly in spring and summer. The
mine is based on low grade porphyry-type deposits containing free gold in an upper (secondary oxidation) zone (600–1,100 m elevation) and copper sulfides, mainly chalcocite, covellite and pyrite, in a lower zone (elevation 600–700 m). Ore from the mine goes to various processing units for recovery of gold and copper, while waste rocks go to a stockpile adjacent to the open pit. Gold is processed by gravity separation and heap leaching with cyanide. Copper is concentrated by crushing, grinding and froth flotation (higher grade) for off-site smelting and is also produced as cathode from lower grade ore (<0.3%) through bioheap leaching, solvent extraction and electrowinning.

**Production process**

*Figure 1* shows a simplified diagram of the process. The production process begins with large open pit mining for raw material. It is followed by primary crushing and further grinding to obtain the right particle size for the heap. The waste rocks (below the cut-off grade) will be stockpiled in the waste rock dump. Due to weathering and exposure to air and rain, oxidation of metal sulfides (usually pyrite) occurs within the stockpile and generates acidity – acid mine drainage (AMD) – a very common phenomenon in copper mining. With its high copper content in the AMD, it was collected (from the waste rock dump and other areas within the mine site) and used as leaching solution in the heap. The crushed ore is conveyed and stacked as an 8 m high heap, equipped with piping at the top. The heap is irrigated with AMD for a period of 8 months and the Pregnant Leach Solution (PLS - copper rich solution) is collected in the solution pond. Once a sufficient copper concentration is reached, PLS is pumped to the solvent extraction plant for copper cathode production. Some of the raffinate (copper lean solution) will return to the heap, another stream of raffinate will be neutralized with lime before discharge to the river. The data collected from last year were from the trial heap before the full scale production this year.

### Geographical boundary

The WF is spatially and temporarily explicit. The WF sustainability assessment needs to be placed in an appropriate geographical context. Therefore, defining the geographical boundary is crucial for the assessment. There are three gold processing and three copper processing plants producing four different products (gold loaded carbon, copper cathode, copper concentrate and sulfur concentrate) at Zijinshan.
mine. Water is shared among these operation processes. For this preliminary study, the decision is made to set the boundary according to the processing plant for a specific product. For the copper cathode product, the geographical boundary is from open pit ore extraction (raw material), processing (ore preparation and hydrometallurgy process) and wastewater treatment (neutralization) before discharge to the river (Figure 1). All the processes involved in the production in this geographically delineated area are considered.

Data sources and assumption

The WF of a product is defined as the total volume of fresh water that is used directly or indirectly to produce the product (Hoekstra et al. 2011). For a simple production system, the WF of the product \( p \) is equal to the sum of the relevant process WFs divided by the production quantity of the product \( p \)

\[
WF_{prod} = \frac{\sum_{s=1}^{n} WF_{proc}[s]}{P[p]} \quad \text{[volume/mass]} \quad (1)
\]

in which \( WF_{proc}[s] \) is the process WF of process step \( s \) (vol/time), and \( P[p] \) is the production quantity of product \( p \) (mass/time). In our case, there is only one output product (copper cathode) within our set boundary. For industrial processes, few ingredients from agriculture or forestry are involved in the processes or supply chain, the green WF is not considered in this context, so only blue and grey WFs are analyzed. Water is required for drilling, dust suppression during ore extraction, for used as leachate during heap leaching and ore processing, to support the workforce and to compensate for water lost to evaporation and leakage (Bleiwas 2012). From Figure 1 the process WF is the total from the two plants: crushing and hydrometallurgy process.

Blue WF

The blue WF in a process consists of three components as shown in Equation (2):

\[
WF_{proc, \text{blue}} = \text{Blue water evaporation} + \text{Blue water incorporation into the product} + \text{lost return flow} \quad \text{[volume/time]} \quad (2)
\]

In an industrial process, each component from the above equation can be measured directly or indirectly. In the case of the copper cathode process, there is no water incorporation into the product, nor any non-return flow. The processed blue WF is blue water evaporation (from Equation (2)) from the heap leach pad (area of 104,000 m² and various solution storage ponds, areas range from 19,000 to 40,000 m²). In the hydrometallurgy process, rain data and ore moisture content are also taken into consideration. All the flow measurement from abstraction to final disposal is measured directly from flow meters installed.

Grey WF

The grey WF can be calculated from:

\[
WF_{proc, \text{grey}} = \frac{\text{Pollutant Load (L)}}{\frac{\text{Maximum Acceptable conc (C}_{\text{max}}) - \text{Natural Conc (C}_{\text{nat}})}{\text{Maximum Acceptable Conc (C}_{\text{max}}) - \text{Natural Conc (C}_{\text{act}})}} \quad \text{[vol/time]} \quad (3)
\]

Part of the wastewater produced during the production steps is treated with neutralization before discharge. The rest of the effluent is recycled for use in the process. During the rainy season, when there is a positive water balance, more water has to be treated and discharged which will in turn contribute to the grey WF. As for the maximum acceptable concentration for discharge, it is recommended to use the most critical receiving water body standard. The Environmental Quality Standard for Surface Water in China (GB5838-2002 2012) is used as the ambient water quality standards. When a waste flow concerns more than one form of pollution, the grey WF is determined by the pollutant that is most critical (Hoekstra et al. 2011). From analyses for different contaminants in the effluent, the total copper concentration is associated with the largest pollutant-specific grey WF. Therefore, it is the most critical pollutant.
Supply chain WF

The WF of a product is incomplete without considering its supply-chain WF. Lime, caustic soda and sulfuric acid are the main supply chains in this study. Lime comes from local suppliers whereas sulfuric acid is a byproduct from processing gold concentrate in the nearby region. The blue WF of lime and grey WF of sulfuric acid were calculated using the information given by the suppliers. Since the process of sulfuric acid production is a commercially known Contact Process, the blue WF of sulfuric acid presented in the Tata WFA report (Unger et al. 2013) was used in this study. Data for WF calculation are shown in Table 1.

Overhead process WF

The overhead operation WF is the water consumed or polluted as a result of:

- dust suppression in drilling, extraction and roads;
- transportation (vehicles and fuel) of ores from open pit to processing plants;
- water consumption by employees (labour).

For dust suppression, haulage of six trucks is operated three times a day and each truck contains 20–25 m³ of water. The total water consumption in dust suppression is 360–450 m³/day for the entire mine and it is assumed this is all lost in evaporation. The ores from the open cast pit are distributed in a different proportion to various processing plants. Bioheap leaching is just one of the processes. Therefore, only a fraction of the total overhead WF is attributed to this product, based on the ratio of the ores entering the plant with the total amount of ore extraction. In this case, it amounts to 8.3%. Consumption of fuel from trucks in transportation between the open pit mine to the processing plants is also considered here. Trucks are used to haul the overburden and ore from the pit to a dump site, stockpile or to the next stage of the mining process. The blue and grey WFs for diesel from literature (Gerbens-Leens et al. 2008; EPE 2011; Francke & Castro 2013) are used for our calculation. In terms of water consumption by labour, the relevant WF data are obtained from Mekonnen & Hoekstra (2011). Table 1 shows the source of data used for the WF calculation.

RESULTS AND DISCUSSION

Based on the methodology, the flow diagram (Figure 1) set out in the previous section and data collected in 2012, the WF quantification for the copper production at the selected Zijin mining site is made according to the methods described in the WFA Manual (Hoekstra et al. 2011). For water abstraction, only a small amount of water is taken from a local river while the majority is from the collection of runoff resulting from AMD. Instead of letting it run off and contribute to the grey WF, it is passed through the process to recover the valuable metal and discharge after treatment. Due to recirculation system and recovery, the actual consumption of water in the mining operation is relatively low except when there is positive water balance, then water has to be treated and discharged. At Zijinhshan mine there is no water scarcity, but with high annual rain fall, the excess of water will need to be discharged and it will contribute to the grey WF.

Process WF

Crushing only contributed very slightly to the overall WF and the majority of the contribution lies in the hydrometallurgy process. In tropical climates, for a typical heap application rate of 10 L/hr/m², evaporation loss can account for 2–5% of applied solution when using sprinklers. Evaporation from barren and pregnant solutions ponds can range from 5 to 13 mm per day (Kappes 2002). From our results, the processed blue WF contributes significantly to the overall water loss. It is largely due to the evaporation from the heap and solution ponds (70% contribution) since all the processing steps are
mainly in the open, except for the solvent extraction and electrowinning. Evaporation ranges from 3 mm per day in winter to 7 mm per day in the summer months. Part of the water loss can also be due to seepage and leakage. The large heap leaching area is dependent upon the ore grade. The lower the ore grade, the larger the amount of ore piled, hence a larger area for leaching in terms of economic output. Heap leaching requires less energy consumption compared to the traditional flotation method, but it is subject to high evaporation (i.e. water loss). Therefore, a compromise should be made for the energy consumption, evaporation loss and efficient leaching requirement.

Process effluent is treated before discharge. Although the copper concentration in the discharge meets the national discharge limit, it still contributes to the grey WF. It is due to some of the capacity to assimilate pollutants being consumed (Hoekstra et al. 2011). In other words, due to the effluent, the concentration of the chemical in the receiving water increases and moves from $C_{\text{nat}}$ in the direction of $C_{\text{max}}$ (in Equation (3)), therefore, less water is available to assimilate pollutant. Figure 2 shows the contribution of blue and grey WFs in the process. In mining practice, water is normally recycled for internal use in the same process or other processes. However, sometimes when there is too much water (positive water balance), water has to be discharged after treatment. Therefore, water abundance will also pose a problem and contribute to pollution to the environment.

Supply chain and overhead WF

This study shows that the blue WF in the supply chain does not contribute to a great extent to the overall WF due to the majority not being derived from agricultural sources. However, only a small number of parameters have been considered in this study. Other areas such as construction material and machinery, equipment and materials, energy for heating and power of all kinds of onsite equipment (Ercin et al. 2011) can also be taken into consideration. However, it can be difficult to decide where to truncate the assessment, e.g. the production of diesel and the wear and tear of the vehicles.

Although water is used for dust suppression during handling, milling and on stockpiled ore, generally the single largest amount of water for this purpose is used on haulage roads (Bleiwas 2012). The amount varies significantly from operation to operation and is dependent on the nature of the ore, mine capacity, climate, the type of equipment in use, the road base material, the length and width of roads and safety standards. Few actual examples are available in the literature, ranging from 180,000 to 700,000 m$^3$/yr (Mills 2010; Bleiwas 2012). From our assessment, the dust suppression in roads forms 82% of the overall water loss in the overhead component. However, compared with the process WF, this contribution is insignificant. Figure 3 shows the actual values of direct and indirect WF components in copper cathode production. Data cannot be published at the moment for confidential reasons. Although there are no grey WF data of lime and caustic soda shown in Figure 3, the contribution is assumed to be small, therefore comparison of the total blue and grey WF is still valid. Due to all the ingredients in the supply chain being locally sourced and not of agricultural origin, it does not contribute hugely to the indirect WF. Therefore, the WF impact mainly affects the local environment.
**Challenges**

Highlighting the size ofWFs is beneficial in raising awareness of the volume of water required to produce products and goods from source, along with supply chains and overhead processes. As it stands, the numerical value of a WF alone is not a measure of impact. The essence of the WFA is the consideration of the timing and location of the associated resources, information on when, where and how water is used and its type, and the sustainability of the water consumption and pollution. This makes the assessment different from other water use indicators.

Since there are not many WFAs on industrial products, some of the parameters can be different from assessing agricultural products. With declining ore grade, an increase in water consumption in the process is inevitable. The grade of the original material determines the process and will affect its final product footprint. Caution must be taken when comparison of WF is based on tonnes of product. The type of process should be taken into consideration. Secondly, for the grey WF, the environmental quality standard varies in different countries. It could result in a higher grey WF in those regions where ambient water quality standards are more stringent. These factors should be considered when carrying out the WFA.

**CONCLUSIONS**

This is a preliminary study of its kind, using WFA as a tool to look into the sustainability of one of our products in terms of water consumption and pollution. The methodology and approach applied in this study have been highlighted. The level of detail and the geographical areas for the assessment are discussed. A few conclusions can be drawn based on the study so far.

The study shows the process WFs have a significant contribution to the overall water consumption, in particular the blue WF. Due to the nature of this particular heap leaching process, it is subject largely to climate and other natural phenomena, e.g. evaporation, infiltration and run off. The grey WF contributed 40% to the total process footprint due to the discharge made in those summer months. The WF resulting from the supply-chain and overhead processes considered in this study does not significantly contribute to the total WF. Although heap leaching is the most economical way to process low grade ore, consideration must be taken for process efficiency, economic gain and WF reduction, e.g. applying a dripping method rather than spraying, or surface coverage, while at the same time it is vitally important to make sure the operation will have as little impact on the local environment and watershed. Although Zijinshan mine is situated in a water abundant region, given the competition over the globe’s freshwater resources, increasing water productivities (lowering product WFs) in this non-stressed basin will solve the problem of over exploitation of blue water resources in water-stressed catchments (Hoekstra & Mekonnen 2012). In turn it can be an instrument towards sustainability.

At present, most of the publicly available WF database is primarily for agriculture products and processes. A comparable database for the WFs of industrial products is lacking. This poses an immense challenge when carrying out the WFA in the supply chains for the industrial processes and products. Even the water use data existing in company reports often pertain to water abstraction and are geographically non-specific. WFAs for industrial operations highlight a great importance to fill such a data gap and the WF results of such assessments can be helpful to develop benchmarks for specific processes and products in different regions. The approaches, assumptions, data sources – including supply chain and overhead processes – and the level of detail required in this study will certainly be helpful as a reference for others to carry out similar WFA studies. This study can also be applied to other mines of the company located in the north eastern part of China, e.g. Xinjiang where water scarcity is more prominent.

This assessment only reflected the data from the pilot scale heap leaching process in 2012. A full scale production in the current mine site was resumed at the beginning of 2015. This paper presents preliminary results of the study while data collection, WF accounting and sustainability assessment will continue to gain further understanding of its application in this field. In conclusion, the WFA has proven to be useful to highlight major water uses, both in operations and supply chain, and prioritize where the company might focus. Hence, the company not only looks to advance sustainable water management within their fence.
line but also beyond. However, challenges remain, further refinement and standardization of the methodology to address particular issues in industrial process will reinforce the suitability of WFA as a comprehensive tool for all industries worldwide.

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REFERENCES


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