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Opportunities for reducing the supply chain water footprint of metals used in consumer electronics

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ABSTRACT

Consumer electronics contain a broad spectrum of materials whose production requires water and potentially discharges contaminants into the water supply, exacerbating freshwater scarcity and pollution. These water impacts have not yet been fully studied, as much of the literature on consumer electronics focuses on supply chain energy or carbon footprint. This study evaluates life cycle water consumption and degradation impacts associated with extracting and producing base, precious, hazardous, and critical metals that are typically found in electronic products. Water impacts were analyzed for individual metals and for the representative material profile of smartphones and laptop computers to identify "hotspots" for future improvement. Results indicate that, at the level of individual materials, precious metals have the highest impacts, due to water consumed directly for mining operations and indirectly for energy production, and water degradation attributed to metal emissions during mine tailings management. At the product level, precious metals also have the highest contribution per smartphone, whereas aluminum has a higher contribution per laptop, accounting for about 40% of the total water scarcity footprint. On the other hand, for water quality impacts, precious metals are responsible for the highest contributions for both products. Scenarios are evaluated to assess improvement potential associated with product design changes, including alternate supply chains, material substitution, and use of recycled content. The greatest potential opportunities for reducing water impacts were sourcing metals from lower water scarcity regions (19% reduction over the baseline water scarcity footprint) and increasing recycled content to the maximum theoretical potential (20% reduction).

1. Introduction

Rapid technological innovation has introduced a broad spectrum of materials to consumer electronics, including base metals such as steel and aluminum, precious metals such as gold and platinum, critical metals like indium and rare earth elements (REEs) (Cucchiella et al., 2015; Işıldar et al., 2018), and hazardous metals such as lead or mercury (Chen et al., 2011; Kiddee et al., 2013). These materials play an essential role in providing the form, finish, or functionality that consumers demand (Cucchiella et al., 2015; Ryen et al., 2014; Tansel, 2017). For example, lighter and thinner touch-enabled flat panel technology used in phones, tablets, and TVs relies on scarce metals like indium (Boundy et al., 2017). Lithium-ion batteries are widely used to power consumer electronics because of their high energy density, which is provided by materials such as lithium and cobalt (Zubi et al., 2018). Due to rapid innovation cycles, declining product lifespans (Bakker et al., 2014), and introduction of new technologies, the demand for a diverse array of materials is expected to continually increase and evolve (Althaf et al., 2020).

While materials have transformed the consumer electronics industry, increasing demand has also led to new sustainability challenges. Consumer electronics literature has addressed supply chain security (Gaustad et al., 2018), physical resource availability (Olivetti et al., 2017), supply chain energy usage (Deng et al., 2011; Ryen et al., 2015; Socolof et al., 2001; Williams, 2004; Yu et al., 2010), carbon footprint (Hischier and Baudin, 2010; Huang et al., 2009; Moberg et al., 2014; Ryen et al., 2015; Teehan and Kandlikar, 2013), and improper end-of-life management impacts (Chen et al., 2011; Kiddee et al., 2013). This body of research has indirectly addressed water impacts, but not fully evaluated the connection between related sustainability issues and water consumption or pollution. For example, the highest contributing factor towards carbon emissions in the electronics supply chain is

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electricity usage, which also consumes and degrades water resources during fossil fuel combustion (Mekonnen et al., 2015). Further, mining residues, or tailings, can release harmful compounds to water that exacerbate health impacts and contribute to social and political disruptions (Adonteng-Kissi and Adonteng-Kissi, 2017). Therefore, it is essential to understand how electronic material supply chain activities contribute towards water impacts and to identify opportunities to reduce these impacts.

Water is a critical input for extracting and producing metals. It is required for mining and refining activities such as grinding, floatation, gravity concentration, medium separation, and hydrometallurgical processes (Gunson et al., 2012; Haggard et al., 2015; Northey et al., 2016, 2014). Water usage in these processes depends on various factors, such as mining site, type of ore being processed, processing techniques, and the local climate (Glaister and Mudd, 2010; Gunson, 2013; Haggard et al., 2015; Northey et al., 2016, 2014). For instance, pyrometallurgical processing of copper ores consumes 91 m^3 of groundwater per tonne of copper, whereas hydrometallurgical processing consumes about 70 m^3 per tonne (Northey et al., 2014). Water is also used in auxiliary activities such as dust suppression, cooling, washing equipment, and human consumption at the mining sites (Northey et al., 2016). Furthermore, mining is an energy-intense process, and water is required at multiple steps in the energy life cycle: from drilling and extracting fossil fuels to boilers, cooling towers, and emission control systems at thermoelectric power plants (Mekonnen et al., 2015). In the U.S., for example, thermoelectric power plants are responsible for over 40% of all water withdrawals, 3% of which is ultimately lost and not returned to surface water systems (Dieter et al., 2018).

Further, metal extraction and processing often take place in water-scarce regions, putting pressure on local water resources. In the past decade, China, one of the major producers of various consumer technology metals (U.S. Geological Survey, 2020), has experienced severe water scarcity driven by rapid industrialization (Wang et al., 2017). Not only do mining processes deplete local watersheds, but they also result in downstream water degradation. Acid main drainage, release of heavy metals and processing chemicals, or improper management of mine tailings may result in potentially harmful emissions to surface and groundwater systems (Gunson, 2013; Gunson et al., 2012; Northey et al., 2016). An analysis of water samples surrounding the gold mines in the Lower Pra Basin of Ghana suggest that the release of heavy metals, including cadmium, mercury, and copper from gold mining processes, is responsible for polluting groundwater resources (Dorleku et al., 2018).

Potential water impacts from mining are compounded by increasing population (Liyanage and Yamada, 2017), expansion of agricultural activities (Parris, 2011), and climate change impacts such as altered weather patterns, droughts, and flooding (Gosling and Arnell, 2016; Haddeland et al., 2014). These external factors often lead to resistance to mining projects from local communities. One example is seen in Peru, a water stressed country in South America. The Conga mine in the Cajamarca region, Peru, had been planned for the production of gold and copper, which are widely used in consumer electronics; however, the project was shut down due to public opposition (Jamasmie, 2016). This resistance was mainly due to planned open pit mining, which risked endangering lakes and wetlands in the region that were the main source of water for the public (Jamasmie, 2016). Addressing these sustainability issues and preserving water resources will require a greater understanding of how water-intense sectors, like mining and manufacturing in the consumer electronics sector, contribute to water quantity and quality risks across different regions.

Given the social, economic, and environmental concerns surrounding water impacts, a growing body of research has begun quantifying the water footprint of consumer electronics. Case studies have been carried out to quantify the life cycle volumetric water consumption for personal computers (Alafifi, 2010), printed circuit boards (Alcaraz Ochoa et al., 2019), lithium-ion batteries (Gong et al., 2018), and semiconductors (Cooper and Pafumi, 2010). When considering the full product life cycle, material extraction contributes about 10% to total volumetric water consumption (Alafifi, 2010), but may actually be responsible for disproportionately high regional water stress impacts because mining and refining processes often take place in water stressed regions, rather than regions where water is abundant (Cooper et al., 2011; Frost and Hua, 2017). To our knowledge, the spatial variability in water stress impact for consumer electronics materials has not yet been analyzed. Further, materials with low volumetric water consumption could ultimately have higher degradative impacts to water quality. Studies have shown a link between material supply chains and impacts associated with water systems, including eutrophication, ecotoxicity, and acidification, in case studies on televisions (Song et al., 2012), desktop computers (Duan et al., 2009), mobile phones (Moberg et al., 2014), and RAM components (Liu et al., 2010). By combining the analysis of water consumption and degradation impacts, there is an opportunity to more holistically analyze consumer electronics materials and then identify strategies to minimize supply chain impacts.

The method of life cycle assessment (LCA) is well suited for such an analysis, as it provides a framework to quantify the cumulative resource inputs, emission releases, and resulting environmental impacts across a full material supply chain and/or product life cycle. These impacts can include the consumption of freshwater resources and the degradation of water quality due to pollutant releases. Measuring consumptive and degradative water impacts has been enabled by advancements in life cycle water impact assessment methods (e.g. Boulay et al., (2018); Boulay et al. (2011); Pfister et al. (2009); Ridoutt and Pfister (2010)). The ISO 14046 (ISO, 2020) standard was developed to provide a framework for analyzing water footprint encompassing of consumption, pollutant release, and attendant impacts (Kounina et al., 2013). The ISO water footprint methodology has been applied to a wide range of products and sectors, including food (Hess et al., 2016; Manzardo et al., 2016; Silalertruksa et al., 2017), automobiles (Berger et al., 2012), metal production (Buxmann et al., 2016), plant products (Musikavong and Gheewala, 2016), and dairy products (Ridoutt and Hodges, 2017). These examples show the utility of water footprint methods for evaluating sustainability solutions, and highlight an opportunity to more widely apply these methods to the electronics sector.

Therefore, this research applies life cycle based water footprint methodology to assess the potential freshwater quantity and quality impacts associated with the extraction and production of metals used in consumer electronics. This study is carried out at three levels: first analyzing water impacts for specific metals individually, then for the metals contained in two representative case study products, and finally for the electronics sector in aggregate. The goal is to identify material "hotspots" and then analyze scenarios under which impacts can be reduced, including supply chain shifts, use of recycled content, and material substitution. The insights provided by this research are intended to guide product designers and manufacturers towards reducing environmental impacts of consumer electronics.

2. Methodology

The study analyzed water footprint of material supply chains in the electronics sector, following LCA methods. These methods are carried out in four steps: the definition of study goal and scope, a life cycle inventory to quantify water inputs and emissions, life cycle impact assessment to quantify the resulting potential for environmental damage, and interpretation according to study goal. Each of these steps is detailed further in the following sections.

2.1. Goal and scope

The goal of this research is to assess potential freshwater quantity and quality impacts of metals used in consumer electronics. The study is intended to inform multiple stakeholders who might use results in different ways, including product design, manufacturing, supply chain management, policy development, and materials recycling. Because these audiences would require information at varied scales, the results are ultimately normalized according to three functional units: 1) Per kg of metal produced; 2) Per product; and 3) Per the global electronics sector. The system boundary reflects a cradle-to-gate approach, because materials studied find varied use in a wide array of electronic products. Thus, component manufacturing and assembly, product use, and end-of-life phases are not included in the scope of the study, although this introduces potential limitations that are discussed later. This study specifically focuses on metals because they account for the major share of a typical electronic product's mass composition (Babbitt et al., 2020) and because metal mining and production takes place in many geographical regions, and as a result, variability exists in water consumption and discharges. The system boundary (Fig. 1) includes the physical transformation of metal ores into mineral concentrates (mining and concentration), further transformation into mineral products and intermediates (purification), and subsequent conversion into the final metal or alloy (refining). Input flows are the freshwater withdrawals associated directly with metals processing and indirectly with energy generation and upstream chemical and material processing. Output flows are the pollutant emissions that are directly linked to potential water quality degradation through available life cycle impact assessment methods (see Section 2.3).

2.2. Life cycle inventory

The life cycle inventory was developed in two phases: first, consumer electronic product bills of materials (BOMs) were used to determine specific metals that are of importance to the consumer electronics sector broadly and that are found within specific case study products; and second, production process data were compiled to model water inputs and emissions associated with the processing steps and upstream inputs required to produce all of the identified metals.

2.2.1. Individual materials

Common materials used in consumer electronics were first identified using BOM data obtained from Babbitt et al. (2020), and then augmented with data on detailed composition of complex components such as printed circuit boards (PCBs), display units, and batteries (Buechler et al., 2020; Cucchiella et al., 2015; Işıldar et al., 2018; Wang and Gaustad, 2012). Consumer electronics metals identified were categorized as base metals, precious metals, critical metals, rare earth elements (REEs), and hazardous metals (Table 1). Due to a lack of LCI data, a limited set of materials including vanadium and certain REEs (those other than lanthanum, praseodymium, and neodymium) were excluded.

2.2.2. Case study products

To evaluate how individual material impacts contribute at the product scale, the smartphone and laptop were used as case studies. These devices have high ownership rates and prevalence in the e-waste stream (Althaf et al., 2020, 2019). BOM data were used to quantify the mass of specific materials for multiple product models representing different brands and manufacturing years (Table S1). BOMs included bulk materials such as steel, aluminum, and copper, as well as complex components, including PCBs, batteries, and displays (Babbitt et al., 2020). The mass of individual metals present in those components was determined from a compilation of literature (Bizzo et al., 2014; Boundy et al., 2017; Guo et al., 2011; Hagelüken, 2006; Oguchi et al., 2011; Szalatkiewicz, 2014; Vats and Singh, 2015; Wang and Gaustad, 2012; Yamane et al., 2011; Yazıcı et al., 2010) by Althaf et al. (2020), Tan et al. (2017), Sahan et al. (2019) and Buechler et al. (2020). The data on individual metals are compiled in Tables S2-S9. The complete summary

Table 1
Classification of consumer electronic metals considered in the scope of the study.

Base	Precious	Critical	Rare earth elements	Hazardous
Steel	Gold	Manganese	Lanthanum	Lead
Aluminum	Silver	Gallium	Praseodymium	Mercury
Copper	Platinum	Indium	Neodymium	Chromium
Nickel	Palladium	Cobalt		Cadmium
Magnesium	Rhodium	Lithium		
Zinc		Tantalum		
Titanium		Tin		
		Antimony		
		Barium		
		Tellurium		

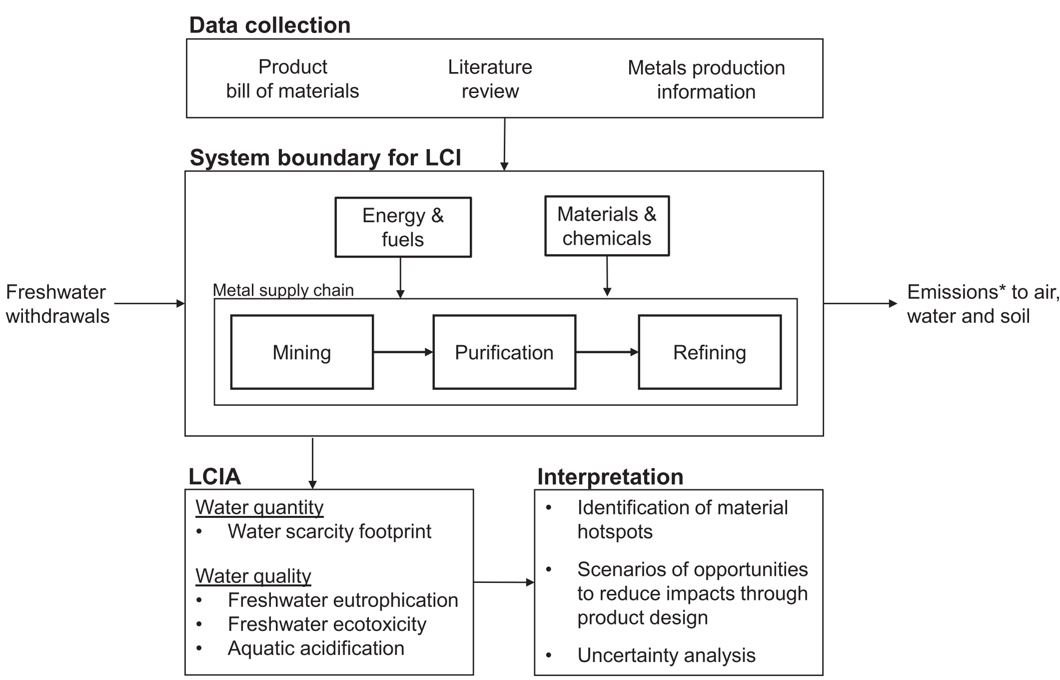

Fig. 1. Life cycle framework adopted in this study to quantify water consumption and degradative impacts of consumer electronic material supply chains. *The specific emissions and impacts analyzed by the study are detailed further in the section on Life Cycle Inventory.

of product material composition is provided in Table S10.

2.2.3. Global electronics sector

To evaluate water impacts of material consumption more broadly, data were also collected on the total global use of metals in the electronics sector. Current global metal production data for the electronics sector were collected from U.S. Geological Survey (2020) and Graedel et al. (2015), and summarized in Table S11. For broader context, these data represent the entire electronics sector, which includes consumer electronics, electronic appliances, and other electric and electronic equipment, including as components found in other products (e.g., the motor of an electric vehicle).

2.2.4. Production processes

Material data were linked to water consumption and emission release using mining and production process data in SimaPro v8.5 using the ecoinvent v3.5 database ("Allocation, cut-off by classification" system model). Ecoinvent data use generic water flows that are allocated to different countries based on the best available knowledge of the location of the unit processes (Classen et al., 2009). The baseline case of material production was modeled according to the average global production market mixes with primary content alone (no recycled content). See Table S12 for the list of process blocks used from ecoinvent, and Fig. S1 for an example process block modeled. Scenario analyses described in Section 2.4.1 were used to model variability around these initial assumptions, including geographic variability and production from secondary sources. While the LCI data used include a wide range of resource inputs and emission releases, this study specifically focused on those with a direct linkage to water impacts discussed in Section 2.3. Specifically, the flows quantified were the volumetric consumption of freshwater to each of the production processes and, following ISO 14046 method, the release of only those emissions to land, air and water that potentially impact water quality.

2.3. Life cycle impact assessment

Water consumption and quality impacts were first evaluated per kilogram of each metal produced and then scaled to the per product and per sector functional units according to the amount of each material contained in a smartphone or laptop and globally used in the electronics industry, respectively. Characterization of these impacts are described further in the sections below.

2.3.1. Water scarcity footprint

Water consumption impacts were quantified by the Water Scarcity Footprint (WSF), which represents the product of the inventory flow (volume of water consumed in m^3 per functional unit) and the water stress characterization factors (Eq. (1)).

$$\begin{aligned} \textit{Water scarcity footprint (WSF)} &= \textit{Water consumption}\left(m^3/\textit{functional unit}\right) \\ &\times \textit{Water stress charactericationfactor}\left(m^3\textit{equivalents}/m^3\right) \end{aligned} \quad (1)$$

Two water stress characterization factors were used: Pfister et al. (2009) and AWARE (Boulay et al., 2018). The Pfister et al. (2009) water stress characterization factors used here (m^3 eq./m^3 consumed) is based on the ratio of total annual freshwater withdrawals to the hydrological availability of freshwater resources at a country level (Pfister et al. 2009). The AWARE method water stress characterization factors used here (m^3 eq. /m^3 consumed) is based on the inverse of the AMD (availability minus demand), which indicates the relative available water remaining per area in a watershed (i.e., determining the water availability minus the demand of humans and environmental water requirements) aggregated to a country and annual resolution (Boulay et al., 2018).

These methods were used because they provide country-level characterization factors that allow for an assessment of geographic variability in metal sourcing. The WSF was initially based on the assumption that consumer electronic materials are sourced according to the global average production mix. However, water availability and withdrawals vary spatially, and assuming an average global production mix might under- or over-estimate the impact. To capture this geographic variability, we analyzed WSF across the wide range of producer countries from which electronics metals are known to be sourced (U.S. Geological Survey, 2020). The water stress characterization factors of each producer country were estimated again using the AWARE method (Boulay et al., 2018) and presented for an equivalent volume of water consumption (Table S14). While water scarcity can vary significantly within a country itself, capturing water impacts at this detailed level was not possible due to lack of ecoinvent LCI data on water consumption for processes specific to individual mining sites.

2.3.2. Water quality impacts

Human activities influence water quality in varied ways, from the direct release of contaminants that degrade water resources to the long-term climate impacts on water temperature and aquatic organism health (Khatri and Tyagi, 2015). Here, we specifically focus on the impacts to freshwater quality that are directly linked to chemical emissions resulting from metals production. Specifically, we analyzed freshwater ecotoxicity and eutrophication (using ReCiPe midpoint (H) characterization factors; Huijbregts, 2016), and aquatic acidification (Impact 2002+ midpoint characterization factors; Jolliet et al., 2003). While geographic variability in water quality impacts can still be studied through the differences in underlying country-specific LCI data, the impact characterization factors used here represent an average value that does not vary by location.

2.4. Interpretation

Interpretation of results was first carried out to identify material "hotspots" – those metals contributing the greatest water consumption and degradative impacts per metal, per product, and per sector. Then, scenario analysis was used to evaluate potential opportunities to reduce the impacts of representative material hotspots, as described below. Results were also interpreted through the lens of potential variability and uncertainty in modeling choices and the extent to which these factors may influence the ultimate water impact results.

2.4.1. Scenario analysis

Scenarios were created around potential strategies that might be applied during the design and manufacturing stage for consumer electronic products to reduce water impacts. The three scenarios, described below, were aimed at addressing materials and processes that the baseline results showed to have a significant water impact. While the nature of these impacts is described in the Results section, we note an example here to clarify our approach: in the product case studies, gold and aluminum were identified as water impact hotspots for the smartphone and laptop, respectively. Therefore, scenarios examined how model results might change according to strategies specifically applied for these materials, namely, sourcing materials from alternative supply chains (in the case of gold), substituting with a lower impact material (in the case of aluminum), or increasing the recycled content (for both elements). The three scenarios are described below.

2.4.1.1. Alternate supply chains. This scenario examined the overall impact reduction potential that may be achieved by specifying that gold be obtained from supply chains in regions with lower water stress. The WSF is governed by both volumetric water consumption and the country-specific water stress index. Given available LCI data, it is not possible to estimate how water consumption for mining and metals processing would change due to supply chain shifts, especially for countries not yet modeled in ecoinvent. Thus, the water consumed for extraction and production of 1 kg of gold was assumed to be constant regardless of country. But the water stress associated with that water consumption could be varied according to country-specific AWARE characterization factors. Thus, WSF per kg of gold was calculated as if it were produced solely from one of three countries with low water stress risks: Canada, Russia, and Brazil. These countries currently contribute to the global production of gold and have available resources that could meet demand from the electronics sector (U.S. Geological Survey, 2020). The country-specific results for gold, scaled according to mass of gold per smartphone, were combined with the previously calculated contributions of the other elements present in the smartphone (as modeled for the baseline) (Table S24 and Table S25). Results were interpreted on a per smartphone basis and provide a theoretical upper bound on the extent to which a single material supply chain can influence the overall WSF of materials contained within a consumer electronics product.

2.4.1.2. Material substitution. This scenario examined the potential impact reduction potential that may be achieved by material choice during product design. The BOM data showed aluminum to be a common laptop casing material, but other materials are also feasible for this application, including plastic and magnesium (Babbitt et al., 2020). A representative model (i.e., 14-inch laptop) containing 444 g of aluminum in the casing was used as the reference. An equivalent laptop of the same size but with an alternative casing material would contain 336 g of acrylonitrile butadiene styrene (ABS) or 388 g of magnesium, according to example product BOMs (Table S26 and Table S27) and due to different properties of the materials. Other sources of aluminum identified in the BOM (wiring, battery, hard drive, etc.) were not changed, as these are not easily substituted during product design, a common issue for many electronics materials that provide unique properties and functionality (Babbitt et al., 2021). Results were interpreted on a per laptop basis, relative to the degree of improvement over the reference all-aluminum case.

2.4.1.3. Material recovery in a circular economy. Our baseline results captured impacts associated with primary production of metals, representing a worst-case scenario. Circular economy aspirations will require pathways to recycle materials, even for demanding, high-purity applications like electronics. Here, we modeled use of recycled content aluminum and gold recovered from e-waste (Bakas et al., 2016; Bigum et al., 2012) following open loop allocation, cut-off principles (refer to SI section 1.5). According to these principles, the original material extraction and production of a material were allocated to the primary user (i.e., first life cycle), but the processes required to collect, recover and purify a material from the electronics scrap were allocated to the second life cycle (Nicholson et al., 2009). Fig. S3 shows the extended scope of LCI carried out for e-waste recycling processes and the materials recovered. Industry-specific recovery rates were collected from (Bigum et al., 2012; Caffarey, 2012; Hagelüken, 2008) to estimate water scarcity footprint of 1 kg of a recycled material. Then, WSF of gold and aluminum from both primary and secondary material supply was estimated. Ranges of secondary supply that can theoretically be specified for electronics applications were based on realistic values and optimistic upper bounds of potential recycled content: 45–90% for aluminum and 35–70% for gold (Ashby, 2012; Graedel et al., 2011).

2.4.2. Uncertainty analysis

This study relied on a comprehensive database of electronic product BOMs (Babbitt et al., 2020), and aggregate data on material production processes (ecoinvent). Uncertainties in results may stem from data limitations around elemental composition of specific materials contained in composite components like lithium-ion batteries or printed circuit boards. The elemental concentration of a metal in such a component depends on the type, manufacturer, and age of the product, and such estimates are additionally confounded by variability in the empirical methods and instrumentation used to detect and quantify elemental concentrations (Guo et al., 2011; Sethurajan et al., 2019; Yang et al., 2011). For example, the literature sources used to estimate elemental concentration in a typical smartphone PCB reported gold content ranging from 0.003 to 0.18% by mass (Oguchi et al., 2011; Sahan et al., 2019; Tan et al., 2017; Vats and Singh, 2015) (Table S3 and Table S41). The influence of variability in material concentration on baseline results was assessed again using the example of gold content in a smartphone. Multiple data points from literature were compiled (Table S3) to establish maximum, minimum, and average values of gold content in a smartphone (Table S41). The baseline WSF per smartphone was then re-analyzed across these ranges.

3. Results and discussion

3.1. Baseline material-level impacts

Results show that when analyzing individual materials, precious metals (rhodium, platinum, gold, palladium) have the highest water scarcity footprint per kg, particularly in comparison to that of base metals (steel, copper, aluminum) (Fig. 2a). The WSF results calculated with Pfister et al. (2009) water stress characterization factors range from 0.007 m^3 eq. for 1 kg of steel to 93.1 m^3 eq. for 1 kg of rhodium, whereas WSF calculated with AWARE water stress characterization factors ranges from 0.53 to 7518 m^3 eq. for the same metals, which represent the lowest and highest material-level impacts. While the absolute values of WSF vary between approaches, the relative rankings of metals in terms of water scarcity impact are the same for both methods. Further, the metals with highest WSF results were also found to represent the largest ecological risks due to pollutants released from metal extraction processes. Specifically, precious metals have the highest impacts per kg for all three water quality impacts quantified: freshwater ecotoxicity, freshwater eutrophication, and aquatic acidification (Fig. 2b).

Precious metals are typically found in low concentrations in ores, and as such often require higher quantities of water and energy to extract and refine (Calvo et al., 2016; Mudd, 2008). These impacts are anticipated to continue to grow with increased demand for scarce elements in electronics, as resource requirements for extraction and production processes increase with declining ore grade (Calvo et al., 2016; Miranda et al., 2010; Norgate and Jahanshahi, 2010). Another factor that influences baseline WSF results is the underlying LCI data used to model water consumption (detailed further using gold as an example in Table S13). Ecoinvent processes for metals are typically constructed using economic allocation methods to partition impacts for materials created from joint production processes (Classen et al., 2009; Frischknecht et al., 2007). Because precious metals have high economic value, they typically are allocated a greater degree of impacts (Classen et al., 2009), although this is an area that requires future methodological study (Bustamante et al., 2016).

However, the underlying processes that contribute to material level WSF results vary by metal, according to the processes in which the greatest amounts of water are consumed. For example, 46% of the WSF for gold is attributed to water consumed directly for mining and production activities, and 36% to indirect water consumption associated with producing the energy used in mining and production (Fig. 3). Fuel and electricity consumption occur widely across the metal supply chain, including opening mine pits, crushing, grinding of ores, refining metals, and for general plant operation. Upstream water impacts of producing chemicals and materials needed for mining and process operation contributed 16% of the total WSF for gold, with the remaining 2% associated with other activities (Fig. 3). On the other hand, aluminum, which is an energy intensive material, owes 84% of its WSF to indirect water consumption associated with energy generation, with only 6% of the impact attributed to water consumed directly for mining and production activities, 6% to upstream water impacts of materials and chemicals, and the remaining 3% to other activities. Conversely, cobalt,

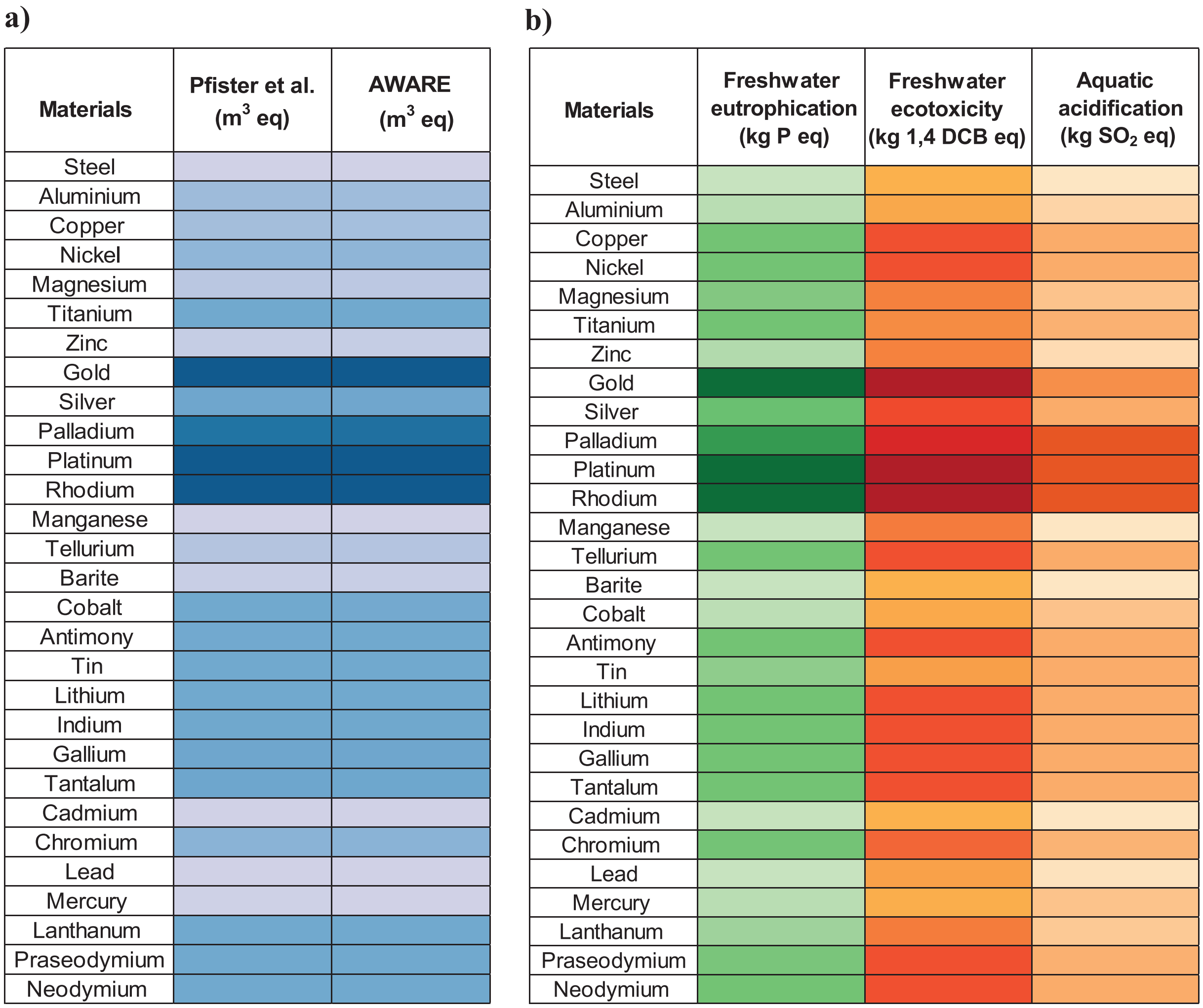

Fig. 2. Heat map showing the comparison of material hotspots identified for a) water scarcity footprint (m^3 eq) calculated per kilogram of each metal using Pfister et al. (2009) and AWARE impact assessment methods; and b) water quality impacts per kilogram of each metal: Freshwater ecotoxicity potential (kg 1,4-DCB eq), Freshwater eutrophication potential (kg P eq) and Aquatic acidification potential (kg SO_2 eq). The color scale is based on the relative percentile (90th, 50th and 10th) to which each metal belongs according to its ranking within the impact category (numeric values are provided in the Supplemental Information file). For example, metals in the 90th percentile range are those with the highest impacts and are shown in the darkest color.

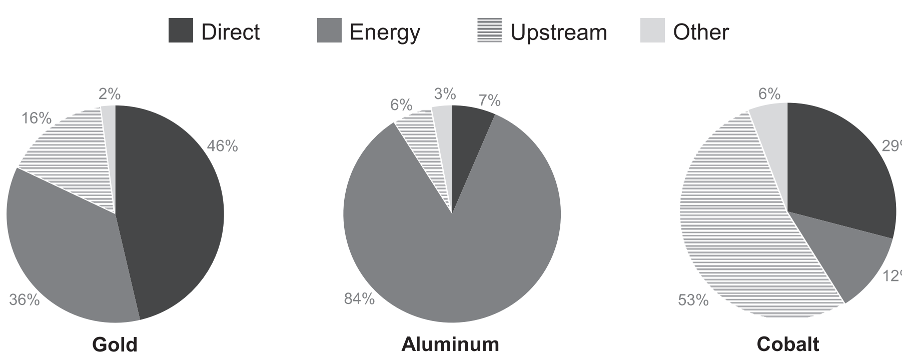

Fig. 3. Relative contribution to material level WSF results for specific metals, as estimated using AWARE (m^3 eq/kg of each material). Contributions are disaggregated into four categories: direct (process) water use, water associated with energy conversion and fuel extraction, upstream water inputs (associated with producing chemicals or materials required in the metal's supply chain), and all other types of water consumption.

a critical metal with moderate water scarcity impacts (in the 50th percentile range in Fig. 2), has 53% of WSF attributed to upstream water impacts of producing chemicals and materials, 29% due to direct water consumed during mining and production, with the remaining fractions associated with energy production (12%) and other activities (6%) (Fig. 3).

For water quality impacts, process contribution analysis identified pollutant releases during the treatment of sulfidic mine tailings as being the primary cause of freshwater ecotoxicity and eutrophication impacts (98% of the total impacts for gold, Figs. S5 and S6). Water quality impacts are also influenced by fossil fuel extraction and combustion to produce the energy needed for mining processes. These upstream energy systems are a contributing factor for acidification impact across all elements and for the eutrophication and ecotoxicity impact across base metals including copper, nickel, lead, and manganese. Acidification impacts are also attributed to the blasting process used to open mines, which releases nitrogen oxide, carbon monoxide, and ammonia into the environment (this process represents 43% of water quality impacts for gold, see Fig. S7). Results do not include any impact on water quality from the particulates of rock created during blasting, as they are omitted from the LCI database, suggesting a potential opportunity for future study and data collection.

3.2. Geographic variability in baseline material results

The baseline WSF results are also influenced by the global average production mix of metals, due to the spatial variations in water consumption in different mining operations, as modeled by the available inventory data, and regional water demand and availability, as captured by country-specific water stress characterization factors (see Table S13 for further comparisons of these underlying factors). While geographic variation in inventory flows cannot be evaluated extensively due to LCI data limitations, we can analyze variability in water stress. To this end, Fig. 4 shows the "relative" WSF for 1 m^3 of water consumed for each producer country, thus holding volumetric water consumption constant and allowing for direct comparisons of country-level water stress based on the AWARE characterization factors (Boulay et al., 2018). The variability shown in Fig. 4 accounts for freshwater availability within a region and the marginal demand of human and aquatic ecosystems on those water resources. This variability in WSF provides an opportunity to leverage alternate material sourcing decisions that can potentially reduce life cycle water impacts, an opportunity that is explored through scenario analysis in Section 4.1.

However, these factors do not account for any additional developments in infrastructure that may be required to make water widely available to all its users. As a result, some countries, such as the Democratic Republic of the Congo (DRC), are observed to have low WSF (Fig. 4), but in fact lack the water infrastructure needed to expand mining in this region, due to under-investment in water systems and conflict-related destruction (Partow, 2011). Sourcing metals from the DRC also faces other barriers, such as social and geopolitical risks from the mining industry in this region (Althaf and Babbitt, 2021), underscoring the importance of considering broader tradeoffs in supply chain decisions. When changing a supply chain to water abundant countries is not feasible, companies can invest in infrastructure to improve water quality treatment in mining and manufacturing areas. This treatment infrastructure would improve quality and also help tackle water scarcity in a region, thereby reducing overall water impacts of products and benefiting local communities (Damania et al., 2019). Scenario analysis on alternate supply chains are further explored below to understand if regional variability may be leveraged to reduce the impacts of materials in consumer electronics.

3.3. Baseline product-level impacts

Results discussed so far focus on the water impacts per kg of each material. However, materials are used in widely varying amounts within common electronic products. On a per product level, material hotspots

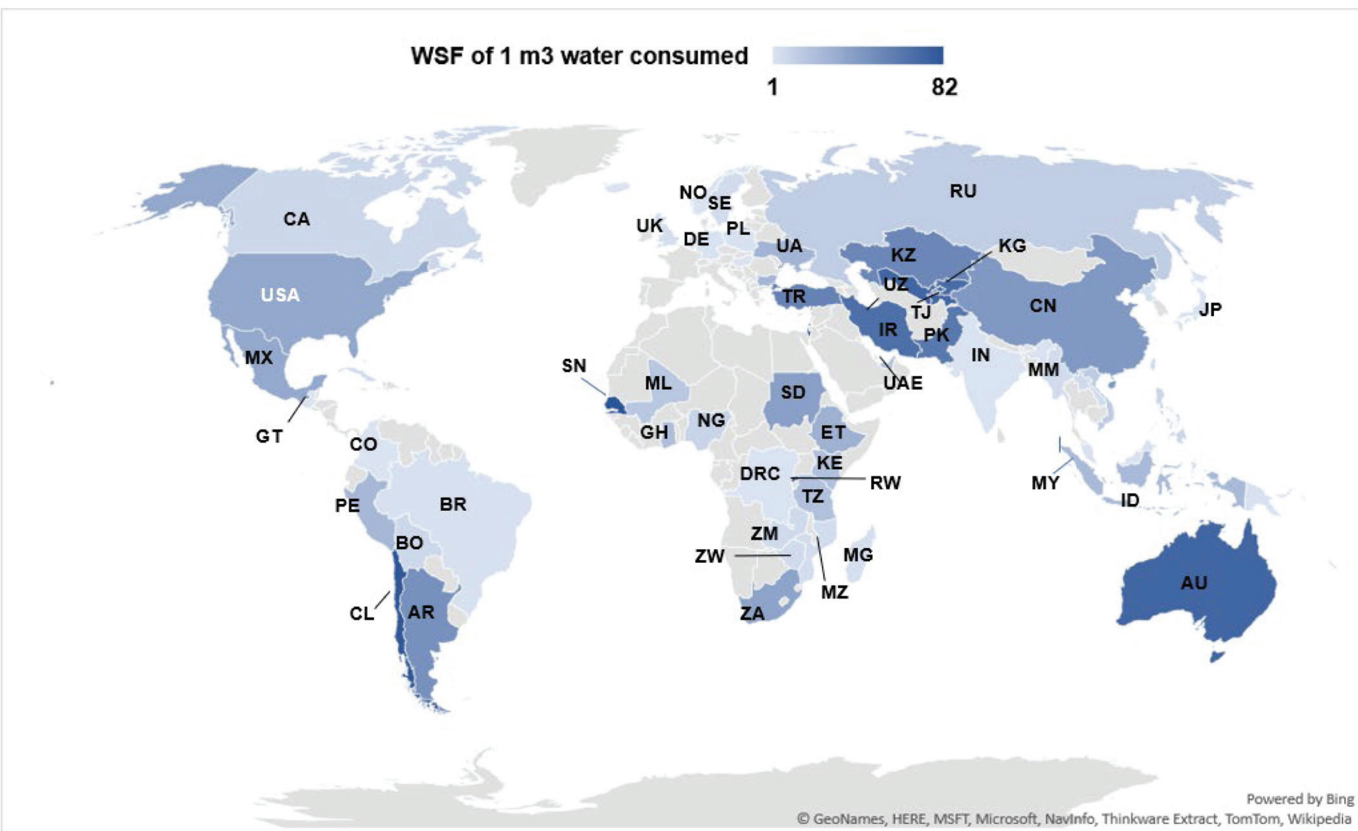

Fig. 4. Relative WSF (m^3 eq/1 m^3 water consumed) for countries known to produce electronic materials. Color intensity corresponds to relative magnitude of impacts, where darker shades suggest greater water stress risks. Here, the shading associated with a value of "1" represents the world average WSF, and all darker shades reflect the factor by which each country analyzed is relatively greater than the world average. For example, the country corresponding to the value of "82" has the highest relative impact of all analyzed (82 times greater than world average). Countries shown in gray were not analyzed.

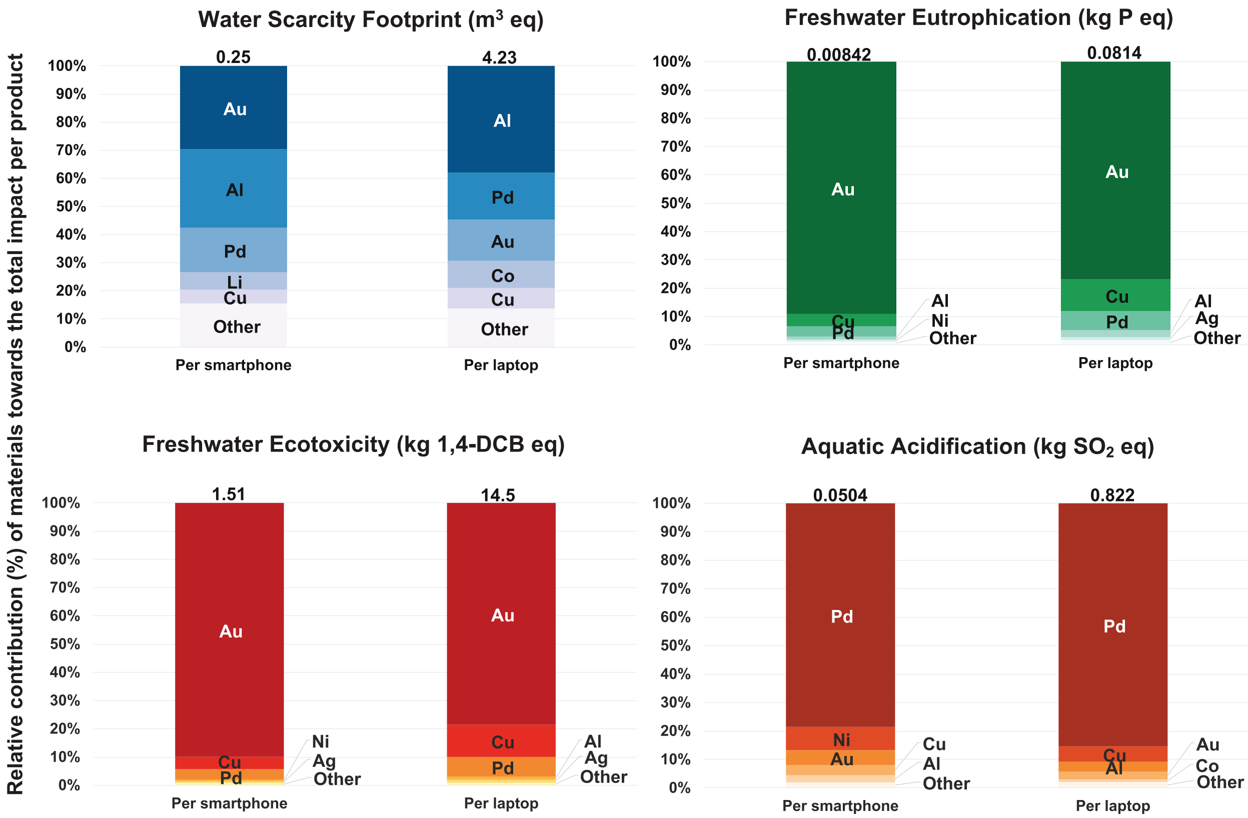

Fig. 5. Relative contribution of metals per smartphone and per laptop towards the total water scarcity footprint (m^3 eq), freshwater ecotoxicity (kg 1,4-DCB eq), freshwater eutrophication (kg P eq), and aquatic acidification (kg SO_2 eq) for all metals per product. The value on top of each bar shows the impact for all metals cumulatively in a product. The relative magnitude of a laptop is higher than a smartphone due to overall mass of a product. Note that for all the impacts, the contribution of the top five metals is shown, and the rest of metals are aggregated as "Other." The color intensity corresponds to the relative degree to which each metal contributes to the total on a ranked basis.

(Fig. 5) had both similarities and distinctions from those identified above, depending on the product considered. In the case of a smartphone, precious metals gold and palladium collectively contributed nearly 45% of the total WSF (0.25 m^3 eq. for all metals in the product), followed by aluminum (28%), and lithium (6%). For the laptop, on the other hand, base metals aluminum and copper collectively contributed

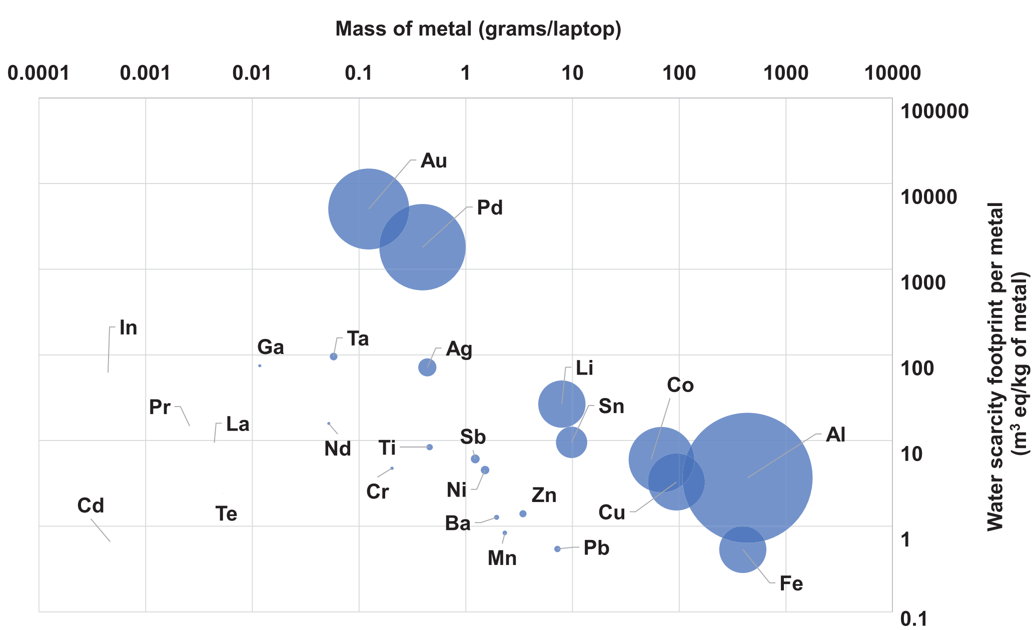

Fig. 6. Comparison of material concentration in a laptop (g/laptop) and WSF for each metal (m^3 eq/kg metal). Both axes are presented on a log scale. The circle size corresponds to the material's overall contribution to the total WSF for all laptop materials (from 1 to 100%). A similar analysis is provided for the smartphone in the Supplemental Information file.

almost 45% of the total WSF (4.23 m^3 eq. unit for all metals), followed by palladium and gold collectively (31%), and cobalt (10%). The WSF of metals per product is influenced by both the magnitude of water consumption per material and the mass of that material contained in the product. For example, base metals have a small WSF impact per kg, but they contribute almost 45% of the WSF impact of a laptop because they comprise a significant fraction (>25%) of this product's mass (Fig. 6). On the other hand, precious metals account for almost 45% of the WSF of a smartphone because the magnitude of impact per kg (see Table S22, and Fig. S8) offsets the relatively low mass (0.4% of an average smartphone). Precious metals were also observed to be the dominant contributors for all three water quality metrics, for both the products analyzed (Fig. 5). As material trends in consumer electronics products continue to evolve, the anticipated hotspots will likely vary in the future. For instance, the overall concentration of gold in electronics is declining with changes to product design (Althaf et al., 2020; Kasulaitis et al., 2019). As a result, the contribution of gold to WSF and other environmental impacts may similarly change in the future.

Beyond the materials discussed thus far, other metals to note are lithium and cobalt, which are also observed to be key contributors towards WSF of a smartphone and laptop, respectively (Fig. 6 and Fig. S8). These elements are used in the electrodes of lithium-ion batteries found in mobile devices, and their use is expected to rapidly grow due to both the continued adoption of electronics and the projected demand for electric vehicle batteries (Fu et al., 2020). Both metals present unique challenges to water scarcity impacts. Globally, the majority of lithium is currently produced via brine extraction (Liu et al., 2019) and primarily extracted in Chile, in particular Salar de Atacama, which holds almost 30% of the world's lithium resources (Agusdinata et al., 2018). However, this region is already one of the driest places on earth, and increasing demand for lithium is leading to overexploitation of water resources (Liu and Agusdinata, 2020). Further, brine extraction may emit pollutants from evaporation pools into the water supply, leading to increased water quality impacts and exacerbating tensions between the local communities and mining companies (Liu and Agusdinata, 2020). On the other hand, more than 60% of world's cobalt is sourced from the DRC, where concerns have grown about the interaction of mining activities and socio-political vulnerabilities (Rustad et al., 2016). Added impacts from water extraction and pollutions may aggravate existing social concerns over cobalt extraction in vulnerable regions (Kemp et al., 2010; Olivetti et al., 2017). Increased demand for cobalt and lithium should be met in ways that reduce both water scarcity impacts and interconnected impacts to society.

3.4. Baseline sector-level impacts

Finally, to provide broader context on water impacts from electronics materials, WSF and quality metrics were also estimated relative to the current background situation of global metal use in the electronics sector. In the case of WSF, base metals (Fe, Al) contribute nearly 80% at the sector level (see Fig. S4), primarily because they are used in larger products and appliances (Işıldar et al., 2018; Morf et al., 2007), which are not distinguishable from consumer electronic devices in the underlying data (U.S. Geological Survey 2020, Graedel et al., 2015). For water quality impacts, base metals again contributed over 75% of the cumulative impact for acidification, but for eutrophication and ecotoxicity, trends show that gold, along with base metals, are materials of concern (Fig. S4), largely due to the emissions released during mining and mine tailings management. The variation in results across the scales of analyses suggests that a wide array of strategies will be needed to alleviate water impacts, including product design by strategies discussed in the following section, lifespan extension for components containing elements with high individual impacts (Babbitt et al., 2021; Cordella et al., 2021), product remanufacturing (Ardente et al., 2018; Nasr et al., 2018; Quariguasi-Frota-Neto and Bloemhof, 2012), and increased commodity recycling (Hertwich et al., 2019; Menikpura et al., 2014). However, any evaluation of such solutions would require an expanded analysis beyond the estimation presented here, as they would likely involve large-scale sectoral shifts involving 'non-marginal' changes in material use and the corresponding demand for water resources in different basins or countries (Pfister et al., 2017).

4. Interpretation and scenario analysis

Results presented thus far have been interpreted and compared internally, by identifying relative material hotspots for different water resource impacts and different scales (per material, product, and sector). These results can also be interpreted using the context provided by other studies, although much of the existing literature has focused on carbon and energy footprints, rather than water. But, even using studies on other metrics as a point of reference, we do find parallels in results. For example, this study demonstrated that precious metals have the largest impacts to WSF and water quality at the material level, a finding that is mirrored in studies on global warming potential and cumulative energy demand of material production (Nuss and Eckelman, 2014). The similarity in findings can be traced to the fossil fuel-based energy used during material extraction and refining, which contributes to climate, energy, and water impacts. This interconnection demonstrates the importance of an energy-water nexus perspective on material supply chains (Elshkaki, 2019) and highlights the importance of transitioning to energy sources that have low carbon and water impacts.

At the product level, the ranking of material hotspots from WSF results are generally comparable to materials of concern identified from analyses of carbon and energy impacts for a smartphone (Ercan, 2013; Yu et al., 2010) and a laptop (Deng et al., 2011). While there are small differences in the absolute ranking of materials when evaluating different environmental metrics, these can also be attributed to variability and evolution in product design and material choice (Kasulaitis et al., 2015). Water quality impacts have also been quantified as a part of broader LCA studies for both laptops (Ciroth and Franze, 2011; Grzesik-Wojtysiak and Kukliński, 2013) and smartphones (Moberg et al., 2014). However, the approach in this study disaggregates impacts to determine specific material contributions, whereas past work typically treats material impacts collectively, since the studies' scopes often include the full product life cycle. This difference represents a key opportunity for future study, to extend results presented here to understand how material impacts–and the solutions to reduce them–relate to water impacts during product use and end-of-life management.

To further interpret results, three scenarios were analyzed to determine how findings may vary with product design changes. These scenarios focus on strategies that could be employed during the design and manufacturing stage: sourcing materials from lower WSF countries via alternate supply chains, using recycled materials to displace primary production, and substituting high-impact materials with alternatives expected to have lower water impacts. These scenarios were explored for two case study metals, gold and aluminum, which were identified as hotspots in the results described above.

4.1. Alternate supply chains

This scenario examined the potential to reduce water scarcity by sourcing materials from different regions, thus leveraging the geographic variability in water scarcity impact discussed in Section 3.2 (Fig. 4). Here, gold is used as a case study, due to its wide production geography and high WSF and quality impacts. When gold is modeled as being produced solely from Canada, Russia, or Brazil, the net WSF of materials per smartphone is reduced by 19–28% (Fig. 7). These results reflect a change in gold supply chains alone, while other materials are held constant (modeled according to their global production mix as calculated in the Baseline scenario). Optimizing the production mix of other materials may theoretically reduce the estimated WSF further, but benefits are likely to be less significant, because other materials

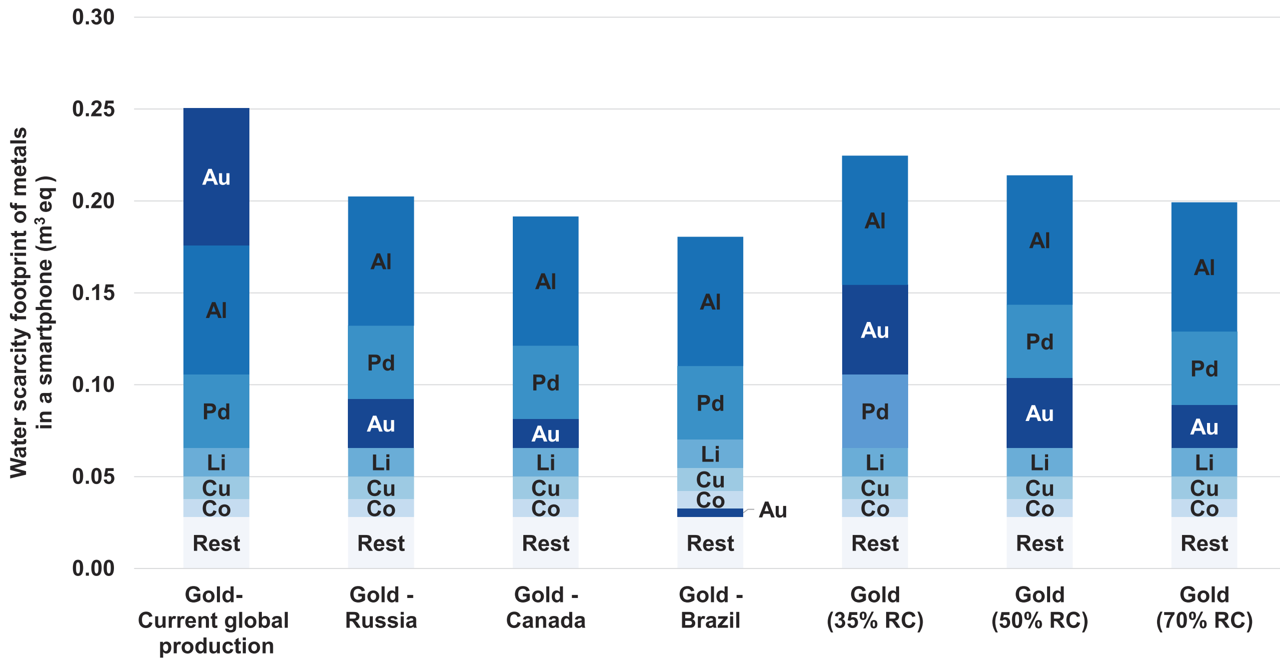

Fig. 7. Potential opportunities for reducing WSF (m^3 eq) impact per smartphone: alternate supply chains and material recycling scenarios applied to gold as a representative case. The contribution of gold is represented in the darkest bar segment. The six elements with the highest individual contributions are shown in each bar, with "Rest" including the contribution of all other metals in the smartphone.

contribute less to WSF results and are characterized by lower supply chain variability. Note, however, that this scenario may also serve as a theoretical maximum of impact reductions, since supply chains are unlikely to so dramatically shift to a single country unless significant economic benefits overcome logistical barriers (Yokoi et al., 2021).

Further, limiting material sourcing to the one or a few of the lowest impact countries may create tradeoffs in economic and social aspects, such as job loss in producer countries or reduced supply chain diversity, which can leave material resources vulnerable to geopolitical disruptions (Althaf and Babbitt, 2021). Alternatively, these results can also be

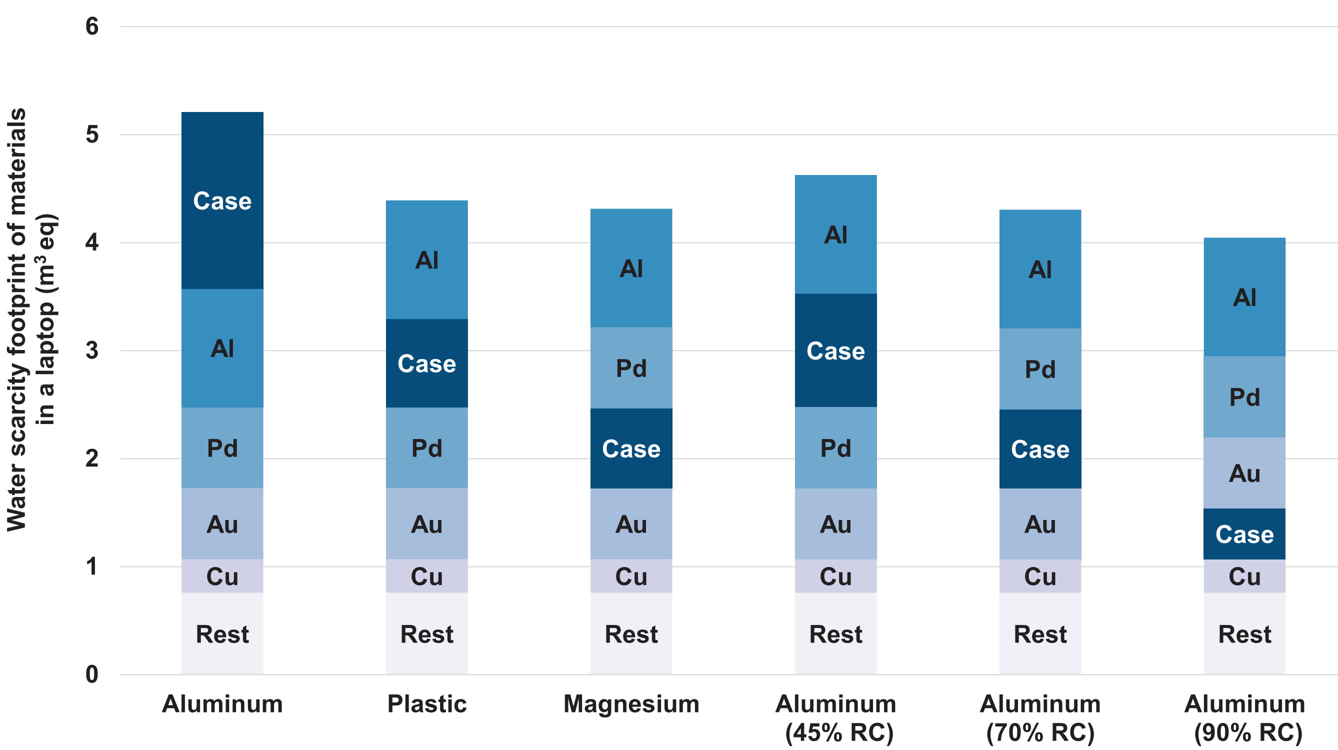

Fig. 8. Potential opportunities for reducing WSF (m^3 eq) impact per laptop: material substitution and material recycling scenarios applied to aluminum used as a laptop casing material. The contribution of the select casing material is represented in the darkest bar segment, and the specific "Case" material analyzed corresponds with the x-axis labels. Other non-casing uses of aluminum in the laptop are designated with "Al." The five materials with the highest individual contributions are shown in each bar, with "Rest" including the contribution of all other metals in the laptop.

interpreted as a call for a multi-stakeholder engagement to invest in sustainable water management systems, which can help build resilience for the future. Further, the electronics industry should integrate water into their business strategy, develop suitable metrics to evaluate water risks, engage in addressing shared water risks by raising awareness in their supply chain, and contribute to policy development that supports investments in water management solutions (Hoekstra, 2014; Morgan, 2018; Stuckenberg and Contento, 2018). While these integrated strategies may take longer to bear results than others discussed below, they may ultimately be more scalable than fundamentally altering material extraction infrastructure, which faces bottlenecks to scale-up, particularly for critical materials (Olivetti et al., 2017).

4.2. Material substitution

Compared to other strategies, product design changes may offer more immediate potential for reducing water impacts. One such opportunity is substituting lower impact materials for those materials used in large quantities in products, such as the aluminum commonly used in laptop casing. Aluminum was observed as a hotspot in the average laptop in our baseline scenario, but bill of material data (Babbitt et al., 2020) show that functionally equivalent casings can also be made with other materials, including plastic (typically acrylonitrile butadiene styrene (ABS)) and magnesium. Substituting either of these materials results in at least a 17% reduction in the overall impact of materials relative to a reference laptop with an all-aluminum case (Fig. 8). This decrease in impact is driven in part by a reduction in net mass: for the same 14-inch laptop, magnesium casing weighs 13% less than the aluminum casing, and plastic casing weighs 24% less (Table S26).

This decrease is also attributed to lower WSF per kg for the alternate materials. The WSF of aluminum is 34% greater than that of ABS and 48% greater than that of magnesium. Both aluminum and magnesium are energy intensive processes, however, process contribution analysis showed that for aluminum, nearly 84% of the total impact is attributed to electricity production, which only contributed 66% to the net WSF of magnesium (Fig. 3 and Fig. S9). These differences can be traced to the energy grid mix associated with global material production. For aluminum, the majority of electricity input is sourced from hydropower, while fossil fuel sources are used more in magnesium production (Classen et al., 2009). While fossil sources certainly create greater water quality impacts, further investigation into the underlying inventory data found that hydropower electricity generation for aluminum was mainly modeled on power stations with reservoirs having significantly higher evaporative losses when compared to the water losses associated with the same amount of energy produced from coal combustion (see Fig. S10), a dichotomy that was also shown in previous studies (Mekonnen et al., 2015; Zhao and Liu, 2015).

While material substitution may offer more immediate reduction potential, it also introduces new tradeoffs that should be considered further. Substituting plastic for aluminum may reduce the upstream WSF impact of materials in a laptop, but it introduces the need for chemical additives such as brominated flame retardants, which may pollute water resources if emitted to the environment at product end-of-life (Chen et al., 2012). Further, material choices may have cascading impacts into other life cycle stages. For example, the high energy footprint of aluminum means that it is a costly metal to produce from primary resources alone (Sverdrup et al., 2015), creating an economic motivation for its recycling that is evidenced by global average recycling rate of 76% (Bloxsome, 2020). Plastic, on the other hand, has higher costs to recycle and sees limited recovery in the current market (Di et al., 2021; Sahajwalla and Gaikwad, 2018), which may negate initial WSF savings. Further, consumer attachment to electronics, and thus their willingness to repair and extend the product lifespan, is driven by both functional and emotional durability, both of which are thought to be enhanced by durable metallic casings (Lobos and Babbitt, 2013). While the water footprint of lifespan extension is not evaluated here, it may see benefits from reduced resource extraction and waste generation as well as impacts from added energy–and likely water consumption–required over a longer use phase. For some materials, substitution is not effective or practical, as seen in the case for gold. While copper or silver are lower WSF alternatives, neither provides equivalent quality or functionality as gold wiring in printed circuit boards (Gan and Hashim, 2015; Graedel et al. 2015).

4.3. Material recycling

The baseline results capture WSF impacts associated with primary material content, but material recovery in a closed-loop circular economy presents tremendous opportunity to reduce environmental impacts of material supply chains. This opportunity is explored for both gold and aluminum. For gold, increasing the secondary content from 0% to 35% (realistic estimate of average recycled content) results in a 10% reduction of the overall WSF of materials in a smartphone (Fig. 7). Further increasing the recycled content of gold to 50% or 70% reduces WSF proportionally (by 15% or 20%, respectively), but would require overcoming critical barriers now facing the electronics recycling industry. Such challenges include products that are not designed for disassembly or recycling (Tansel, 2017), low recycling rates (Forti et al., 2020), and low collection rates of electronics after consumer use (Shittu et al., 2021; Tesfaye et al., 2017).

For aluminum, increasing the recycled content of aluminum in laptop casing to 45% (current estimate of average global recycled content) reduces the overall WSF of materials in a laptop by 11% (Fig. 8). Doubling this recycled content (to 90%) can reduce the total WSF of metals in laptop by up to 22%. While this target is ambitious, current products on the market achieve this level and suggest broader feasibility (e.g., Macbook Air laptop, Apple, 2020). While the benefits of using recycled content aluminum are lower than those for substituting aluminum with plastic or magnesium, it may offer a more realistic pathway, as aluminum is a highly recycled material with a well-established recovery infrastructure. On the other hand, combining material substitution and recycling can also result in greater benefits. For instance, replacing the aluminum casing with magnesium containing up to 90% recycled content could theoretically reduce the overall WSF of materials in a laptop by 30% (Table S40).

A preliminary analysis was also conducted with available LCI data to estimate if scenarios discussed above provide similar benefits in reducing water quality impacts. Using 35% recycled content of gold in a smartphone reduces both freshwater ecotoxicity and eutrophication by 31%, and doubling this recycled content (70%) reduces the impacts by nearly 63% (Table S33 and Table S34). For aluminum, increasing recycled content of aluminum in a laptop casing only provides about 3% savings for both ecotoxicity and eutrophication, since this material did not have significant impacts in these categories in the baseline model (Table S38 andTable S39). However, all of these estimates should serve as a theoretical maximum of the extent to which impacts can be reduced by recycling, because recycling rate is an optimistic proxy for recycled content and because available LCI data only included pollutant emissions from upstream processes and energy generation, not directly from the recycling process itself. Substituting aluminum in a laptop casing by ABS reduces the total impact of metals in a laptop by only 1–2% (Table S28 and Table S29). On the other hand, using magnesium instead of aluminum in a laptop slightly increases ecotoxicity and eutrophication impacts by the same magnitude, due to the added emissions from fossil energy sources used in magnesium production, as discussed above (Table S28 and Table S29). Scenario analysis underscores the importance of systems-level analysis to identify potential tradeoffs that may arise across environmental impact categories.

4.4. Uncertainty analysis and limitations

While this study used comprehensive BOM data, potential sources of uncertainty include inconsistent data on elemental composition of select components and variability in product design. To capture this variability, minimum, maximum, and average amounts of gold present in a smartphone were estimated by collecting data points from multiple literature sources (Table S41 and Table S42). In our baseline product-level analysis, using average mass concentration of gold per smartphone, gold contributes 0.0746 m^3 eq (30% of total WSF of smartphone materials). At the highest mass concentration, this contribution more than doubles to 0.171 m^3 eq (49% of total WSF of smartphone materials), while at the lowest mass concentration, gold only contributes 0.003 m^3 eq (2% of total WSF of smartphone materials) (Table S42). For high gold content, the key material hotspots (gold and aluminum) for a smartphone remain the same as in our baseline scenario. However, at the lowest concentration, other materials (palladium, lithium, copper) become dominant contributors to the total WSF. This variability underscores the need to comprehensively analyze material hotspots for electronics, particularly capturing evolution over time, which may demonstrate the shifting role of precious metals as they become more dispersed and diluted across products (Kasulaitis et al., 2019).

More broadly, evaluating the water footprint of metal commodities has other general limitations associated with LCA modeling, LCI databases, and impact assessment methods. For instance, volumetric withdrawals and consumption of freshwater for extraction and production processes vary from region to region. The ecoinvent data do not fully capture this variability for metal production processes due to lack of publicly available data on water withdrawals and discharges. In such cases, water consumption per unit output of material is assumed to be the same in all regions where the metal is extracted. Even within the same country, water stress can vary seasonally and between catchments, but this level of disaggregation is not currently captured in LCI data. Such limitations are inevitable, but equally applicable to all materials analyzed here, so the associated uncertainties are not expected to change the underlying findings on material hotspots. Other key uncertainties requiring future study are the extension of material-focused findings to the water footprint of a full electronic product life cycle. Use and end-of-life management will require additional water inputs and create different emissions that degrade water quality, but these are also subject to immense variability that are beyond the scope of this study, including evolving product lifespans (Babbitt et al., 2009) and product consumption and discard scenarios (Althaf et al., 2020; Ryen et al., 2015).

5. Conclusion

Materials enable the functionalities and features of modern electronic products on which our society depends. However, producing these materials comes at a cost to water resources. The majority of metals used in these devices are mined from regions that are already water stressed, motivating the need for analysis using life cycle based water footprint methods. Findings suggest that direct water consumed for mining and production activities, indirect water consumed for fuel extraction and energy production, and disposal of sulfidic mine tailings contribute the greatest towards the water impacts of metals, particularly for precious metals, which were identified as materials of concerns across all metrics evaluated. These results emphasize a need for the consumer electronics industry to implement sustainable water management programs with their suppliers to promote supply chain water use efficiency, proper management of mine tailings, and increased use of low-carbon and low-water energy sources and conversion technologies. Furthermore, leveraging spatial variability in metal resources through alternate supply chains can reduce WSF of metals like gold by 19% or more if it is feasible to obtain these resources from countries with lower water stress. Such information can drive policies to reduce water impacts holistically, for example, through supplier selection based on water intensity, water stress of the local region, and potential tradeoffs to supply chain disruptions.

Minimizing material supply chain impacts and building resilience towards the future demand of both water and primary metal resources also requires transitioning to a circular economy model. Promoting the use of recycled content materials in new smartphones and laptops can potentially reduce WSF by 20% or more. Sustainable product design, as seen through these strategies and the substitution or reduction of high impact materials, will be a key enabler for reduced water impacts, but such solutions may also introduce sustainability tradeoffs that should be proactively analyzed and mitigated. These solutions will also require collaboration across all levels of the supply chain to better connect design and material choices to product usage, lifespan, and end-of-life management. Achieving these goals will likely require additional interventions, including extended producer responsibility policy to catalyze product recovery, consumer engagement to increase product collection, and increased transparency in the supply chain to fully calculate the water impacts for the growing electronics industry.

Credit author statement

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Callie W. Babbitt: Conceptualization, Writing-Review & Editing, Funding acquisition

Erinn G. Ryen: Conceptualization, Writing-Review & Editing

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2021.105926.

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