



Water consumption in modern copper production

Internship report

Sustainability Sciences at PSL

Lucas Lau Grady

May 2026

Internship supervisor: Dr. Edouard Asselin

Abstract: Copper is central to the energy transition, yet its production is highly water-intensive and often located in water-scarce regions. This paper reviews water consumption across the two main copper refining pathways: pyrometallurgy for sulfide ores and hydrometallurgy for oxide ores. On a direct consumption basis, pyrometallurgy is consistently more water-intensive, with estimates ranging from roughly 89 to 228 m³/tonne of copper, compared to 32 to 70 m³/tonne for hydrometallurgy. These figures narrow considerably when upstream inputs, particularly sulfuric acid production, are included. In pyrometallurgy, the tailings storage facility accounts for the vast majority of water losses. In hydrometallurgy, evaporation from leach pads is the dominant loss point. Across both pathways, ore grade is the primary driver of water intensity. As accessible high grade deposits are depleted, consumption is expected to rise. Three mitigation strategies are reviewed: improved tailings management, seawater substitution, and a longer-term shift toward secondary copper production.

TABLE OF CONTENTS

1. INTRODUCTION.....	3
2. DIFFERENTIATING COPPER PROCESSING TECHNIQUES: PYROMETALLURGY & HYDROMETALLURGY.....	4
2.1 Pyrometallurgical pathway.....	4
2.1.1 Milling.....	4
2.1.2 Froth flotation.....	4
2.1.3 Smelting.....	5
2.1.4 Refining.....	5
2.2 Hydrometallurgical pathway.....	5
2.2.1 Heap leaching.....	5
2.2.2 Solvent extraction (SX).....	6
2.2.3 Electrowinning (EW).....	6
3. QUANTIFYING WATER USE BY PROCESS.....	7
4. IDENTIFYING WHERE AND WHEN WATER IS BEING USED.....	15
4.1 Pyrometallurgy: the concentrator as the dominant water consumer.....	15
4.2 Hydrometallurgy: evaporation from leach pads.....	16
4.3 Factors driving variability.....	17
5. EXAMINING MITIGATION STRATEGIES: ADDRESSING WATER STRESS IN ARID REGIONS AND REDUCING EFFLUENT WATER.....	18
5.1 Reducing water consumption: tailings management.....	19
5.2 Alternative water sources: seawater.....	19
5.3 Geographical considerations and broader context.....	20
6. CONCLUSION.....	21
7. BIBLIOGRAPHY.....	22

1. INTRODUCTION

As we aim to steer away from fossil fuels and into an energy transition, copper has made the USGS's 2025 critical minerals list and is included on the European critical raw materials list as a strategic raw material. Its conductive properties and relatively low costs make it a central commodity to electric vehicles, renewable energy infrastructure, and power transmission grids. Global copper demand is expected to rise to significant heights over the upcoming decades (Mudd, 2008; Månberger & Stenqvist, 2018), with one projection estimating an increase of up to 350% between 2010 and 2050 (Elshkaki et al., 2016). Meeting this demand requires primary production at scale, a process that requires extensive volumes of water, and is frequently located in regions where water is already scarce.

In 2024, Chile accounted for 24.3% of global copper mining, and has done so for at least the past decade (COCHILCO, 2024). Much of that production is concentrated in the Atacama desert which is one of the driest regions on Earth. Moreover, as high grade deposits are progressively exhausted, more ore must be processed per tonne of copper produced, and water consumption rises accordingly. With demand for copper expected to grow substantially in the coming decades, water consumption in copper mining is a pressing concern.

This paper seeks to understand how copper production uses water and what can be done to reduce the use. Section 2 distinguishes two primary pathways for copper production: pyrometallurgy for sulfide ores and hydrometallurgy for oxide ores. These two pathways have water consumption profiles and must consequently be treated differently. Section 3 reviews current estimates of water consumption across the two pathways, taking into account methodological differences that complicate comparison. Section 4 identifies what steps in each pathway are the most water intensive, focusing on water losses in tailing storage facilities (TSF) for pyrometallurgy and evaporative losses in hydrometallurgy. Finally, section 5 investigates potential mitigation strategies: reducing water intensity of processes, changing sources for water, and potential shifting towards secondary copper production. Many studies reviewed focused on evidence from Chile as it has the most extensive mine level water use reporting in the literature (Bernal, 2020), although its challenges are not unique to that country.

2. DIFFERENTIATING COPPER PROCESSING TECHNIQUES: PYROMETALLURGY & HYDROMETALLURGY

There are two main types of copper ores, each with its own refining process. Sulfide ores are the most common (Singh, 2010) and include chalcocite and covellite (pure ores), and bornite and chalcopyrite (mixed copper-iron ores). Oxide ores less common and include minerals such as cuprite and tenorite. The refining process from copper ore (0.5-1% copper) to London Metal Exchange (LME) standard copper cathode (99.99%) differ significantly depending on the ore type. Sulfide ores are typically refined through a pyrometallurgical pathway, while oxide ores undergo hydrometallurgical processing.

2.1 Pyrometallurgical pathway

The pyrometallurgical pathway involves subjecting the ores under high temperatures to then extract the metals. This pathway first includes a concentrator, where ore passes through milling and froth flotation; secondly a smelter, where the ore is thickened and smelted into a concentrate; thirdly, a refinery, where copper is finally converted into a copper cathode.

2.1.1 Milling

Milling is the process of reducing the size of the ore particles to liberate valuable minerals. This is achieved through mechanical means, typically in a large grinding mill. The ore is crushed into smaller pieces which allows for more efficient separation of the copper minerals from the surrounding rock.

2.1.2 Froth flotation

Froth flotation exploits the differences in hydrophobicity between the desired mineral and the waste material (which will become gangue). In this process, the now finely grinded down ore is mixed with water and chemicals that make the copper minerals hydrophobic. Air bubbles are introduced into the mixture, and the hydrophobic particles attach to these bubbles, rising to the surface to form a froth. Then, the froth which contains the concentrated copper minerals is skimmed off, resulting in a copper concentrate. Meanwhile, the gangue sinks to the bottom. Concentrate percentages typically range from 25-30%.

2.1.3 Smelting

Concentrates are typically the form in which mines export copper. After froth flotation, the concentrated ore undergoes a thickening process, where additional water is removed to increase the density of the slurry. This step enhances the efficiency of smelting by reducing the volume of material that will go through the smelter. Once the ore is thickened, the ore is transferred to a smelter, where it is subjected to high temperatures that foster the separation of metal from impurities. During this smelting process, the molten metal is separated from the slag, which is a by-product that consists of oxidized impurities that melt alongside the ore. This separation allows for the extraction of copper at a higher grade. At this stage, the copper achieves a purity of approximately 98.5% to 99.8%, resulting in what is known as copper anode (Cook et al., 2024).

2.1.4 Refining

After smelting, copper anodes undergo electrorefining. In this process, the anodes are placed in an electrolytic cell alongside cathodes made of pure copper. An electric current is applied causing copper ions to dissolve from the anodes and migrate to the cathodes. This electrochemical reaction effectively removes impurities, resulting in high-purity copper cathodes that meet the London Metal Exchange (LME) grade specifications of 99.99% purity. These cathodes are then ready for various applications in industries such as electrical, construction, and manufacturing.

2.2 Hydrometallurgical pathway

The hydrometallurgical pathway offers an alternative way of refining copper to its pyrometallurgical counterpart, using heap leaching and solvent extraction processes to isolate the copper before undergoing electrowinning to reach a copper cathode, the same end product as the pyrometallurgical pathway.

2.2.1 Heap leaching

Heap leaching uses chemical reactions to allow an acidic solution, typically sulfuric acid, to dissolve metals from the ore. Beforehand, the ores may be crushed to smaller sizes to increase the surface area for the leaching. The crushed ore is then piled into large heaps on an impermeable surface to prevent leakage of the chemicals into the ground. The sulfuric acid is

then poured onto the heaps, dissolving and collecting the copper, as copper sulfate, as it passes through. The leached solution is collected at the bottom of the heap.

2.2.2 Solvent extraction (SX)

Solvent extraction isolates the targeted metal from the leached solution, producing a more concentrated solution of copper. It does so by transferring the copper ions from the aqueous solution obtained during the leaching process into an intermediate organic phase, leaving behind impurities. The reaction is then reversed as the copper in the organic solvent is transferred back into another aqueous solution, ready for electrowinning.

2.2.3 Electrowinning (EW)

Much like the refining process in the pyrometallurgical pathway, electrowinning uses electrochemical properties to collect the copper as a highly pure copper cathode. It does so by recovering the dissolved copper ions from the aqueous solution. The solution is added into an electrolytic cell, consisting of two electrodes. As an electric current is applied to the cell, copper ions are reduced at the cathode, where they gain electrons and deposit as a solid metal.

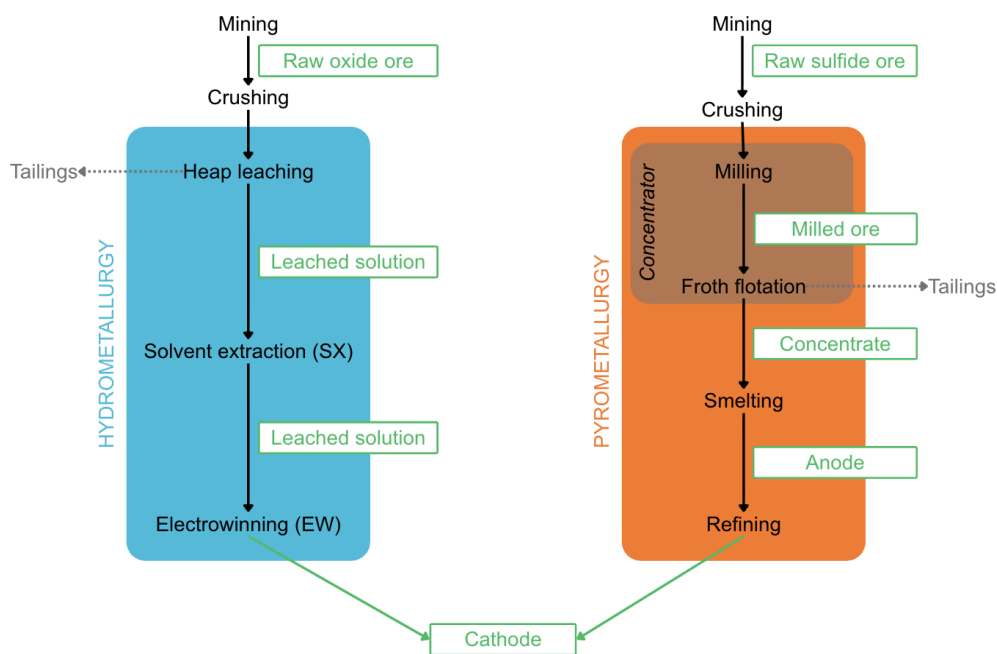


Figure 1: Sulfide and oxide ores follow distinct pathways to produce copper cathodes. Adapted from Figure 9 (Stanley et al., 2015), Figure 1 & Figure 2 (Peña & Huijbregts, 2013), and Figure 8 (Montes, 2021).

3. QUANTIFYING WATER USE BY PROCESS

Estimating water consumption in copper production is far from straightforward as water consumption is inconsistently defined across the literature (Gunson, 2013). While some studies report total withdrawal, others report net consumption after discharge, and many do not specify how recycled water is treated. System boundaries also vary. Some studies include only on-site processing water, while others incorporate upstream inputs such as electricity generation or reagent production, and others include mine dewatering. These inconsistencies mean that figures from different studies are rarely directly comparable, and the wide spread of reported values should be read with this in mind.

The earliest systematic LCA-based estimate for copper is provided by Norgate & Lovel (2004), who study nine mineral commodities on a cradle-to-gate basis. For copper, they find water consumption of 25.9 m³/tonne of copper for the pyrometallurgical pathway and 38.0 m³/tonne of copper for heap leaching and SX/EW. These are quite low relative to the other studies reviewed here. We should note that the ore grades assumed of 3% for pyrometallurgy and 2% for hydrometallurgy are significantly higher than the 0.5-1% range that is typical of modern operations (Cochilco Yearbook, 2024). This could at least partially explain the discrepancy. Across all nine commodities, results are strongly correlated with ore grade, yielding the equation $W = 167.7G^{-0.9039}$ ($R^2 = 0.916$), where W is water consumption in m³/tonne of refined metal and G is ore grade as a percentage. Gunson (2013) identifies three additional limitations: the underlying data may not be representative of the wider industry; shared water consumption between primary metals and by-products risks double counting; and the insufficient definition of "water consumption" hampers comparison with later work.

Singh (2010) analyses water consumption at copper mines in Arizona over 2004-2008. The average is calculated to be 236.5 m³/tonne of copper cathode, but also rising to 263.9 m³/tonne if the Morenci mine is excluded. The authors explain that Morenci's low average of 45.1 m³/tonne reflects an exceptionally high recycling rate, with process water recycled on average three times before discharge. However, the author does not specify which processing pathway this relates to, although the data does appear to be primarily pyrometallurgical. Singh also writes that water losses in the concentrator are overwhelmingly concentrated in the tailings stream. This is consistent with the findings of several other studies (Gunson, 2013; Norgate & Lovel, 2004; Northey & Haque, 2013).

Mudd (2008) compiles reported water consumption data from 36 mining companies across a range of mineral commodities, including 48 years for copper. He finds an average of 172 m³/tonne of copper, with an almost equivalent standard deviation of 154 m³/tonne. This high standard deviation illustrates the extent of variability between operations even using the same processing route. Like Norgate & Lovel (2004), Mudd identifies ore grade as the primary predictor of water intensity. He also highlights persistent weaknesses in sustainability reporting: many companies do not separately report recycled water, as GRI indicator EN10 was voluntary at the time. This makes it difficult to determine whether reported totals reflect gross withdrawal or net consumption, and the data cannot be assumed equivalent across operations.

Peña & Huijbregts (2013) offer the most detailed pathway-specific comparison, examining Codelco Norte's operations in northern Chile in 2009 using a blue water footprint methodology. They find a footprint of approximately 96 m³/tonne of copper for the pyrometallurgical pathway and 40 m³/tonne of copper for the hydrometallurgical pathway. The concentrator plant is identified as the dominant water consumer in pyrometallurgy at 57 m³/tonne of copper, though this value is said to be highly plant-specific. When upstream water consumption associated with sulfuric acid production is included for the hydrometallurgical pathway, the authors estimate an additional 150 m³/tonne of copper, raising the total to approximately 190 m³/tonne of copper and closer to the pyrometallurgical figure. The paper itself cites this combined value as 230 m³/tonne of copper, which appears to be an arithmetic inconsistency in the original text. According to the authors, the relevance of this upstream contribution is debatable from a regional water stress perspective: if sulfuric acid is sourced from third parties elsewhere, the additional burden does not fall on the water-scarce Atacama region.

Gunson (2013) provides the most geographically and operationally diverse dataset, drawing on water withdrawal estimates from 78 mining companies across 23 minerals over 2006–2009. For copper concentrators (pyrometallurgical pathway), he reports an average of 89.29 m³/tonne of copper across 128 datasets, with a standard deviation of 79.76 m³/tonne. For copper SX-EW (hydrometallurgical pathway), the average is 40.32 m³/tonne of copper across 22 datasets, with a standard deviation of 19.40 m³/tonne. The narrower spread for the hydrometallurgical pathway may partly reflect the smaller and less diverse sample. Gunson also writes that discharge is substantially harder to measure than consumption, which goes some way to explaining the variability seen across the literature, and that by-product allocation remains an unresolved methodological challenge.

Northey & Haque (2013) apply LCA methodology to copper, gold, and nickel at an assumed ore grade of 0.75% copper for both pathways. They find direct water consumption of 91 m³/tonne of copper for pyrometallurgy and 70 m³/tonne of copper for hydrometallurgy. Once indirect water consumption, primarily embedded in sulfuric acid production and estimated at approximately 189 m³/tonne of copper, is included, total embodied water rises to 128 m³/tonne of copper for pyrometallurgy and 267 m³/tonne of copper for hydrometallurgy, reversing the apparent relative intensity of the two pathways. On a direct consumption basis, their results are broadly consistent with Gunson (2013) and Peña & Huijbregts (2013). They also confirm that ore grade and tailings solids density are the two key variables governing direct water consumption.

Lutter & Giljum (2019) draw on COCHILCO data for 31 Chilean copper mines in 2018, reporting a national average water intensity of 92.9 m³/tonne of copper. There is considerable variation between individual mines: Escondida, the world's largest copper mine, operates below the national average at 82.7 m³/tonne of copper, while Salvador and Sierra Gorda reach 369.8 and 280.7 m³/tonne of copper respectively. The authors attribute this variation to differences in processing pathway, ore grade, recycling rates, and technical equipment. The reported figures represent total water abstraction rather than net consumption, and do not distinguish between water incorporated into the product, evaporated, or returned to the environment, a limitation the authors explicitly acknowledge.

Islam & Murakami (2020) apply water footprint accounting to an open-pit copper mine in Laos, using production data from 2008 to 2010. They report a blue water footprint of 988.83 m³/tonne of copper concentrate. This figure is not comparable to the estimates discussed above for two reasons: it is expressed per tonne of concentrate rather than per tonne of cathode, and approximately 98% of the total blue water footprint is attributable to indirect water embedded in hydroelectric electricity generation rather than to operational water use. The study is not directly usable as a benchmark, but it illustrates how the choice of energy source can dominate a water footprint estimate, and reinforces the importance of distinguishing direct from indirect consumption.

The most comprehensive estimate to date is provided by Lutter et al. (2025), who use machine learning to estimate site-level water withdrawal across 507 copper mine sites globally between 2015 and 2019, covering 94% of global copper production. Their approach is novel in that it incorporates a wide range of site-specific predictors, including production quantity, ore

grade, mine type, process route, geological setting, and potential evapotranspiration, rather than relying on a single variable as most prior studies have done. The dataset distinguishes between "new water" (water withdrawn from the environment and not previously used on-site) and "total water" (which includes recycled process water).

Their main finding is that between 2015 and 2019, copper mines globally withdrew an average of 152 m³/tonne of copper in new water, with new water use growing at a rate approximately 50% higher than copper production over the same period. In 2019, more than half of global copper production occurred at sites where water use was increasing while freshwater availability was declining.

Lutter et al. (2025) also benchmark their results against earlier studies and find that previous assessments substantially underestimated global water withdrawal. Tost et al. (2018), for example, reported an average intensity of 69.2 m³/tonne based on a review of existing literature. For the same year (2016), Lutter et al. estimate nearly double: 137 m³/tonne. The authors attribute this to the reliance of earlier studies on uniform water use coefficients linked primarily to ore grade, which fails to capture variability introduced by differences in processing technology, climate, and operational practice. They further note that their machine learning model is itself conservative, meaning even 152 m³/tonne may understate the true global average.

This has significant implications for the studies reviewed above. The estimates from Gunson (2013), Northey & Haque (2013), Peña & Huijbregts (2013), and Lutter & Giljum (2019), which cluster in the range of 40–130 m³/tonne for direct consumption, may reflect not only genuine operational variation but also systematic underreporting. Of the 507 mine sites in the Lutter et al. dataset, only 97 reported new water use for at least one year, and just 38 reported total water use, giving data coverage of 26% and 8% respectively. The global copper industry's water footprint remains largely unmonitored at the site level, and estimates derived from voluntary sustainability disclosures are likely to be biased downward.

It is important to keep in mind that, that Lutter et al. (2025) do not disaggregate their estimates by processing pathway. The 152 m³/tonne figure is a global average across both pyrometallurgical and hydrometallurgical operations, and cannot be used to draw conclusions about the relative water intensity of the two routes. For that question, the process-specific studies discussed above remain the best available evidence.

Using data from Cochilco's 2004–2024 Yearbook: Copper and Other Mineral Statistics, and assuming a concentrate grading of 30% copper, we calculated that the pyrometallurgical pathway had an average water intensity of 227.95 m³/tonne of copper cathode, excluding water consumption from the mining process. Including this consumption raises the water intensity to 695.59 m³/tonne of copper cathode. In comparison, the average water intensity for the hydrometallurgical pathway was calculated to be 31.50 m³/tonne of copper cathode, though the data for this pathway were less comprehensive and the figure should be interpreted with caution. These averages were computed using data from 2015 to 2024. Taking the average of the pyrometallurgical figure (excluding mine water) and the hydrometallurgical figure gives 129.73 m³/tonne of copper cathode.

Table 1. Summary of water consumption estimates for copper production (m³/tonne of copper cathode unless otherwise stated)

Study	Geography	Year(s) of data	Pyrometallurgy	Hydrometallurgy	Unspecified	System boundary / notes
Norgate & Lovel (2004)	Australia	~2004	25.9	38.0	—	Cradle-to-gate LCA; ore grades 3% (pyro) and 2% (hydro) — unusually low
Singh (2010)	Arizona, USA	2004–2008	—	—	236.5	Operational withdrawal; pathway unspecified, likely predominantly pyro

Mudd (2008)	Global	Various	—	—	172 (SD=154)	Operational withdrawal; pathway unspecified; 48 data-years for copper
Peña & Huijbregts (2013)	Northern Chile	2009	96	40 (190 incl. H ₂ SO ₄)	—	Blue water footprint; direct consumption only unless stated
Gunson (2013)	Global	2006–2009	89.3 (SD=79.8)	40.3 (SD=19.4)	—	Operational withdrawal; 128 pyro datasets, 22 hydro datasets
Northey & Haque (2013)	Australia	~2013	91 (direct); 128 (total)	70 (direct); 267 (total)	—	LCA; indirect water dominated by H ₂ SO ₄ for hydro pathway
Lutter & Giljum (2019)	Chile	2018	—	—	92.9	Total abstraction; 31 Chilean mines

This study, calculated from Cochilco (2024)	Chile	2015–2024	227.95 (695.59 incl. mine water)	31.50	129.73	Calculated from COCHILCO Yearbook; assumes 30% concentrate grade; hydro data less comprehensive
Islam & Murakami (2020)	Laos	2008–2010	—	—	988.83 (per t concentrate)	Blue water footprint per tonne of concentrate, not cathode; 98% indirect via hydropower
Lutter et al. (2025)	Global	2015–2019	—	—	152 (new water)	Machine learning estimate; 507 mine sites; pathway not disaggregated

Synthesis:

Several patterns emerge from the studies reviewed above. On a direct consumption basis, the pyrometallurgical pathway is consistently more water-intensive than the hydrometallurgical pathway. Pyrometallurgical estimates from process-specific studies range from roughly 89 to 228 m³/tonne of copper, while hydrometallurgical estimates range from 32 to 70 m³/tonne of copper. This distinction narrows considerably when upstream inputs are accounted for. Both Peña & Huijbregts (2013) and Northey & Haque (2013) show that including the water embedded in sulfuric acid production raises the hydrometallurgical total to approximately 190 and 267 m³/tonne of copper respectively, potentially exceeding the

pyrometallurgical figure. Whether this upstream burden is relevant depends on where and how the acid is produced, and most operational studies do not include it.

Ore grade is the most consistently identified driver of water intensity across all studies. As grades decline from the 2–3% assumed in early LCA work towards the 0.5–0.75% typical of modern operations, water consumption per tonne of copper rises sharply. This trend is expected to continue as accessible high-grade deposits are exhausted. Tailings management, water recycling rates, and climate also contribute significantly to site-level variability, which is large: standard deviations frequently equal or exceed the mean in studies that report them.

The spread of reported values reflects both genuine operational differences and persistent methodological inconsistencies. Definitions of water consumption vary, system boundaries differ, and voluntary reporting means that recycled water is often not separately disclosed. This is illustrated by the contrast between the COCHILCO-derived pyrometallurgical figure calculated here, 227.95 m³/tonne of copper, rising to 695.59 m³/tonne when mine water is included, and the lower estimates of 89–96 m³/tonne estimated by Gunson (2013) and Peña & Huijbregts (2013). This discrepancy likely reflects differences in which process stages are included within the system boundary, as well as the more recent timeframe of the COCHILCO data, during which ore grades in Chile have continued to decline. The COCHILCO-derived hydrometallurgical figure of 31.50 m³/tonne sits at the lower end of the literature range, though as demonstrated above this figure is based on less comprehensive data and should be interpreted with caution.

Lutter et al. (2025) suggest that these methodological issues have led earlier studies to systematically underestimate global water use, with their machine learning estimate of 152 m³/tonne of copper roughly double prior global averages. This figure is not disaggregated by pathway, and should be read as a global operational benchmark rather than a process-specific estimate. It is nonetheless consistent with the upper end of the process-specific range identified here, and lends weight to the view that copper production is more water-intensive than much of the earlier literature suggested.

Taken together, the available evidence suggests that a reasonable estimate for direct water consumption in modern pyrometallurgical copper production lies in the range of 89–228 m³/tonne of copper, and for hydrometallurgical production in the range of 32–70 m³/tonne of copper, rising to 190–267 m³/tonne of copper if upstream acid production is included. The true

global average across both pathways is likely closer to 150 m³/tonne of copper, and may be higher still given the underreporting identified by Lutter et al. (2025). No single figure can be treated as definitive. The appropriate benchmark depends heavily on which process stages are included, which pathway is used, and the ore grade and geographic context of the operation in question.

4. IDENTIFYING WHERE AND WHEN WATER IS BEING USED

Understanding where water is lost in each processing pathway helps explain both the magnitude of water consumption and the variability between studies. In pyrometallurgy, the dominant loss point is the concentrator and its associated tailings storage facility (TSF); in hydrometallurgy, it is evaporation from the leach pads.

4.1 Pyrometallurgy: the concentrator as the dominant water consumer

In the pyrometallurgical pathway, the concentrator plant is the largest water consumer by volume (Chilean Copper Commission, 2008; Northey & Haque, 2013; Norgate & Lovel, 2004; Singh, 2010; Gunson, 2013). Water is used throughout the comminution stage to produce a slurry, typically containing 35-40% solids (Northey & Haque), which is then processed through froth flotation, classification, and thickening. Additional water is added during flotation as copper minerals are separated from gangue. The resulting tailings slurry is then transported to the TSF (Singh, 2010), containing around 50% solids after thickening.

The TSF is where the vast majority of water is lost. Northey & Haque (2013) write that only limited amounts of water can be recycled back from this stage, making it the dominant water loss in pyrometallurgical production. This finding is consistent across several studies with Singh (2010), Norgate & Lovel (2004), and Gunson (2013) all identifying the tailings stream as the primary loss point. According to Bernal (2020), this account for approximately 99.5% of concentrator water losses. In the TSF, water is lost through three main ways: entrainment in the tailings solids, evaporation from the water surface, and seepage into the ground. The effect size of each contribution depends on site-specific factors which include climate, tailings density, and TSF design. Gunson (2013) notes that water lost from tailings can range from over 2 m³/tonne of ore for open tailings systems to less than 0.25 m³/tonne for dry stacked tailings, which shows the large impact of tailings management on the overall water consumption.

Downstream of the concentrator, the smelter and refinery consume comparatively little water. Northey & Haque (2013) estimate smelter and acid plant water consumption at around 10.8 m³/tonne of copper, and refinery consumption at approximately 0.51 m³/tonne of copper. Water in the smelter is used primarily for cooling furnace walls, while the acid plant uses water in the conversion of sulfur dioxide to sulfuric acid. These figures are relatively consistent across operations, in contrast to the highly variable concentrator figures.

Depending on the distance between the concentrator and the filtering and storage installations, process water may or may not be recycled back into the system (Chilean Copper Commission, 2008). Where recycling infrastructure is in place and functioning well, makeup water requirements can be significantly reduced. We can see this in the Morenci mine in Arizona example discussed in Section 3. Its process water is recycled on average three times, resulting in a water intensity well below the industry average (Singh, 2010).

4.2 Hydrometallurgy: evaporation from leach pads

In the hydrometallurgical pathway, water is used much differently. Water is added during the agglomeration stage, where crushed ore is bound together before being stacked onto leach pads. A sulfuric acid and water solution is then irrigated onto the heap, dissolving the copper as it percolates through. The main source of water loss at this stage is evaporation from the leach pad surface (Chilean Copper Commission, 2008). Additional losses occur through entrainment of solution within the heap and seepage through the pad liner.

Downstream, in the SX-EW (i.e. solvent extraction and electrowinning) stages, water losses are small in comparison. The overall water consumption of the SX-EW process is controlled by inputs of pregnant leach solution, water used for washing the organic solvent, and the rate of electrolyte bleed, as identified by Northey & Haque (2013). They write that insufficient data are available in the public literature to disaggregate water losses within the SX-EW circuit further, and model them as occurring from the heap leaching operations as a whole.

Because evaporation is the largest cause for water loss in hydrometallurgy, water consumption in this pathway is strongly influenced by climate. Operations in hot and arid regions, such as the Atacama Desert in northern Chile, will experience substantially higher evaporative losses than those in more temperate settings. This makes direct comparison between hydrometallurgical operations in different geographies difficult.

4.3 Factors driving variability

The large variability in water consumption estimates across the literature, as discussed in Section 3, reflects a combination of operational variability and measurement inconsistency. Several factors contribute.

Firstly, ore grade is most consistently identified as a main driver of water consumption. As ore grade declines, more ore needs to be processed to produce a same amount of copper. This means that more copper needs to pass through the system per tonne of copper output. This relationship is well established across studies (Norgate & Lovel, 2004; Mudd, 2008; Northey & Haque, 2013) and has direct implications for the future. As accessible high-grade deposits are depleted, water intensity is expected to rise.

Water recycling is also a contributing factor to this variability. As expected, sites with reclaim systems, high-density thickeners, and closed tailings circuits report lower makeup water than those relying on more open systems. Moreover, Climate plays a big role in the amount of water lost through evaporation. As identified previously, this is the main driver for water loss in the hydrometallurgical pathway. There are large reasons why two sites might have very different water consumption rates, as identified by Singh (2010).

Finally, measurement and reporting inconsistencies might play the largest role in water consumption variability. Gunson (2013) notes that discharge is substantially harder to measure than consumption. Flow meters can track water inputs, but losses through seepage and evaporation are often estimated rather than directly measured. This introduces uncertainty into net consumption figures, and helps explain why studies using the same methodology can arrive at very different results. Mudd (2008) adds onto this by saying that many companies do not separately disclose recycled water volumes, making it difficult to determine from published reports alone whether a given figure represents gross withdrawal or net consumption. Taken together, these factors mean that reported water consumption figures are best understood as approximate indicators rather than precise measurements, and should always be read alongside information on system boundaries and reporting methodology.

5. EXAMINING MITIGATION STRATEGIES: ADDRESSING WATER STRESS IN ARID REGIONS AND REDUCING EFFLUENT WATER

The previous sections have established that copper mining is water intensive, that the concentrator and its tailings stream account for the majority of freshwater losses in the pyrometallurgical pathway, and that ore grade decline will push consumption higher still. In this next section we turn to what can be done about it. Islam et al. (2025) demonstrate that water availability is not an environmental externality in copper production but a hard physical constraint on production capacity itself. Analysing 3,319 mines globally, they find that total water consumption for geological resource production in 2010 reached 6,739 million m³, equivalent to roughly 7% of all industrial water use that year. Copper accounted for 10% of that total and showed the largest proportion of overconsumption of any resource studied: 37% of current copper production in 2010 already exceeded regional water carrying capacities (RCCs), defined as the water remaining for human use after securing flows necessary for aquatic ecosystem health.

This problem is geographically concentrated in ways that are directly relevant to Chile. Islam et al. (2025) identify Chile and Peru as having the highest overproduction rates, with mines in those watersheds exceeding RCCs by 25–100%. Of the 64 mines located in watersheds with overproduction rates above 75%, 22 were copper mines. Moreover, Chile accounted for 24.3% of global copper mining in 2024 (COCHILCO, 2024), with a large part of that share originating from the Atacama desert which is one of the driest regions on Earth.

The tension is set to worsen. Islam et al. (2025) project that water consumption associated with copper production will increase by up to 241% by mid-century even under the optimistic sustainability scenario (SSP1). This would be driven by rising demand for copper in technologies aimed for decarbonisation. Shifting production to less water-stressed regions is theoretically possible, but when economic competitiveness is factored in, 30-32% of current overconsumption remains unresolvable across scenarios 2 and 3. Market geography and resource geography are stubbornly misaligned. Declining ore grades will only increase this water consumption. As identified in Section 4, ore grade is a primary predictor of water intensity, and grades in Chile are projected to fall from around 0.88% in 2015 to below 0.57% by 2035 (Lagos et al., 2020).

Three broad categories of mitigation strategy emerge from the literature: reducing water consumption within existing processes, substituting freshwater with alternative sources, and relocating water-intensive processing steps away from water-scarce regions.

5.1 Reducing water consumption: tailings management

Since copper sulfide ores are expected to continue dominating supply, and since pyrometallurgy is the more water-intensive pathway as established in Section 3, reducing concentrator water consumption is a most consequential target. As established in Section 4, the tailings storage facility (TSF) is where the vast majority of water is lost. Increasing the solids density of the thickener underflow reduces the amount of water sent to the TSF, thereby reducing losses to evaporation, seepage, and retention (Gunson, 2013). Moreover, filtered dry-stack tailings can reduce water content to a maximum of 15%, compared with up to 70% for conventional tailings. This could simultaneously reduce water losses as well as the risk of catastrophic structural failure (Lagos et al., 2020).

5.2 Alternative water sources: seawater

Another mitigation strategy would be rethinking water sources. By 2019, 14 Chilean mining companies had started to include seawater in their processes. Seawater then represented 25% of total water consumed (Astudillo et al., 2023). There are two main approaches to this strategy: direct seawater use and desalination. Direct seawater use is cheaper since it requires only minor pretreatment. However, the high chloride content can cause corrosion and interfere with certain processing steps where chloride concentrations must be kept below 0.03 g/L to prevent pitting of stainless-steel cathodes (Astudillo et al., 2023). Desalination removes approximately 99% of salts but introduces substantial energy and cost penalties: the average cost of desalinated water in Chilean mining is approximately US\$5.1/m³, compared with US\$1.6/m³ for freshwater, with transportation to high-altitude mine sites often the dominant cost component (Astudillo et al., 2023). Lagos et al. (2020) project that seawater will account for 60.5% of total water use in Chilean copper mining by 2035, an increase from 14.8% in 2015.

Seawater adoption is also being explored at the concentrate refining stage, where it can reduce freshwater dependency further downstream. Bruce and Seaman (2014) present testwork on Teck's CESL hydrometallurgical process, which uses medium-temperature pressure leaching of copper sulfide concentrates in the presence of chloride. Because the process already operates in a chloride-bearing environment, it is well suited to saltwater integration. With 30% saltwater

substitution for freshwater, the CESL process uses 66–80% less freshwater than conventional pyrometallurgical smelting, and copper extraction remained at 97.3% across all test conditions, with no significant metallurgical penalties observed in pilot trials. The economic savings are most pronounced where freshwater is already sourced from desalination, reaching US\$2.3 million per year for a 100,000 tonne per year operation. The CESL process remains at relatively early stages of commercial deployment, and smelting will continue to dominate concentrate refining for the foreseeable future, but it illustrates that saltwater integration may be a legitimate alternative water source to fresh ground water..

5.3 Geographical considerations and broader context

Islam et al. (2025) suggest that relocating production steps that are water intensive to less water-stressed regions might theoretically help substantially reduce overconsumption. However, they note that there are many economic constraints to this approach. It is worth noting that mitigation strategies carry their own environmental trade-offs. Seawater desalination produces concentrated brine waste that poses risks to marine ecosystems if discharged without adequate dispersion infrastructure (Astudillo et al., 2023). The energy required for desalination and pumping generates additional greenhouse gas emissions unless powered by renewables, a transition that Lagos et al. (2020) consider feasible in northern Chile given the region's solar resource but which requires significant capital investment. Recycling, meanwhile, offers a longer-term structural solution. Hong et al. (2018) find that reclaimed copper production in China generates 59-99% lower environmental impacts than refined copper across most categories, though human toxicity is higher due to arsenic emissions during the recycling stage. As secondary copper stocks grow over coming decades, recycling will reduce the pressure on primary production and its associated water demands, though Islam et al. (2025) note this effect will only become material after mid-century, once sufficient stocks have accumulated.

No single strategy resolves the structural mismatch between copper's resource geography and water availability. The evidence reviewed here suggests that a combination of tailings management improvements, seawater substitution, and longer-term shifts toward secondary production represents the most credible path, with the urgency of action determined by the pace of demand growth for copper in the energy transition.

6. CONCLUSION

This paper has traced copper's water problem from the processing plant to the watershed. The two main refining pathways consume water in distinct ways. Pyrometallurgy is the more water intensive route, with losses concentrated overwhelmingly in the tailings storage facility. Hydrometallurgy loses water primarily through evaporation from leach pads. Estimates of water intensity vary widely across the literature, from below 40 m³/tonne of copper to over 600 m³/tonne depending on pathway, system boundary, ore grade, and reporting methodology. Lutter et al. (2025) suggest that earlier studies systematically underestimated water intensity, and that the true average is closer, and maybe even more than , 150 m³/tonne. What is consistent across all studies is the direction of travel: declining ore grades will push consumption upward, and the regions where copper is most abundant are, geographically, the regions least able to sustain it.

The mitigation strategies reviewed in Section 5 are real but partial. Improved tailings management can reduce losses at the dominant loss point in pyrometallurgy. Seawater substitution is already underway at scale in Chile, projected to account for over 60% of mining water use by 2035, though it introduces energy penalties and marine disposal challenges of its own. Recycled copper offers the most structurally sound long-term response, with Hong et al. (2018) showing environmental benefits of 59–99% across most impact categories relative to primary production, but the effect on water demand will only become material after mid-century as stocks accumulate.

Water is one dimension of a broader sustainability challenge. Energy consumption, greenhouse gas emissions, tailings volumes, and land use all follow similar trajectories as ore grades decline and production scales up. The literature reviewed here focused predominantly on Chile, which is understandable given the quality of its reporting, but the Democratic Republic of Congo has recently overtaken Chile in estimated copper reserves and is likely to account for a growing share of primary production in the coming decades. Whether its water endowment and institutional capacity are better suited to large-scale copper expansion is a question the literature has not yet adequately addressed, and one worth pursuing.

7. BIBLIOGRAPHY

- Astudillo, Á., Garcia, M., Quezada, V., & Valásquez, L. (2023). *The use of seawater in copper hydrometallurgical processing in Chile: A review*. 123.
<http://dx.doi.org/10.17159/24119717/2445/2023>
- Bernal, L. (2020). *Strategy to reduce water consumption in concentrator plants*.
- Bruce, R., & Seaman, T. (n.d.). *Reducing fresh water use in the production of metals*.
<https://www.teck.com/media/CESL-Publication-Copper-reducing-fresh-water-use-in-the-production-of-metals.pdf>
- Chilean Copper Commission. (2008). Best practices and efficient use of water in the mining industry.
<https://www.slideshare.net/slideshow/best-practices-and-efficient-use-of-water-in-the-mining-industry/pdf/263414848>
- Elshkaki, A., Graedel, T. E., Ciacchi, L., & Reck, B. K. (2016). Copper demand, supply, and associated energy use to 2050. *Global Environmental Change*, 39, 305–315.
<https://doi.org/10.1016/j.gloenvcha.2016.06.006>
- Gunson, A. J. (n.d.). *QUANTIFYING, REDUCING AND IMPROVING MINE WATER USE*.
- Hong, J., Chen, Y., Liu, J., Ma, X., Qi, C., & Ye, L. (2018). Life cycle assessment of copper production: A case study in China. *The International Journal of Life Cycle Assessment*, 23(9), 1814–1824. <https://doi.org/10.1007/s11367-017-1405-9>
- Islam, K., Maeno, K., Yokoi, R., Giurco, D., Kagawa, S., Murakami, S., & Motoshita, M. (2025). Geological resource production constrained by regional water availability. *Science*, 387(6739), 1214–1218. <https://doi.org/10.1126/science.adk5318>
- Islam, K., & Murakami, S. (2020). Accounting for Water Footprint of an Open-Pit Copper Mine. *Sustainability*, 12(22), 9660. <https://doi.org/10.3390/su12229660>
- Lagos, G., Peters, D., Lima, M., & Jara, J. J. (2020). Potential copper production through 2035 in Chile. *Mineral Economics*, 33(1–2), 43–56.
<https://doi.org/10.1007/s13563-020-00227-2>

- Lutter, S., & Giljum, S. (n.d.). *Copper production in Chile requires million cubic metres of water*.
- Lutter, S., Maus, V., Luckeneder, S., & Tost, M. (2025). *Increasing Water Use in Global Copper Production Threatens Freshwater Availability* [Application/pdf]. Vienna University of Economics and Business.
<https://doi.org/10.57938/441B6E21-B914-4565-A2AF-623F78ED92C6>
- Månberger, A., & Stenqvist, B. (2018). Global metal flows in the renewable energy transition: Exploring the effects of substitutes, technological mix and development. *Energy Policy*, 119, 226–241. <https://doi.org/10.1016/j.enpol.2018.04.056>
- Mudd, G. M. (2008). Sustainability Reporting and Water Resources: A Preliminary Assessment of Embodied Water and Sustainable Mining. *Mine Water and the Environment*, 27(3), 136. <https://doi.org/10.1007/s10230-008-0037-5>
- Norgate, T. E., & Lovel, R. R. (2004). *Water use in metal production: A life cycle perspective*.
- Peña, C. A., & Huijbregts, M. A. J. (2014). The Blue Water Footprint of Primary Copper Production in Northern Chile. *Journal of Industrial Ecology*, 18(1), 49–58.
<https://doi.org/10.1111/jiec.12036>
- Singh, D. M. M. (2010). *Water Consumption at Copper Mines in Arizona*.
- Stanley, J., Wilkinson, S.T., Moreno Ramírez, D., Maier R.M., & Chief, K. (2015). Tribal Mining Educational Modules: Copper Mining and Processing [PDF document]. Retrieved from
<https://www.superfund.arizona.edu/resources/learning-modules-english/copper-mining-andprocessing>
- Comisión Chilena del Cobre (COCHILCO). (2024). *Anuario de estadísticas del cobre y otros minerales 2005–2024* [Yearbook: Copper and other mineral statistics]. Ministerio de Minería, Gobierno de Chile.
<https://www.cochilco.cl/web/anuario-de-estadisticas-del-cobre-y-otros-minerales/>