

Life Cycle Based Water Footprints of Selected Mineral and Metal Processing Routes

S Northey¹ and N Haque²

ABSTRACT

Water in mining, mineral processing and metal production on a life cycle basis has been at the top of agendas for various industries, government agencies, research organisations, academic institutions and communities. As a result, a number of water footprint assessment methodologies have been developed. However, their practical applications in mining and mineral processing industries with specific case studies are still rare.

A key objective of the Minerals Down Under Flagship is to contribute to the long-term sustainability of the Australian mining and mineral industries. Researchers in the Mineral Futures theme have developed robust assessment methods to evaluate the impact of mining and minerals technology development on the environment. The future of mining and the mineral industry is strongly linked with its sustainability – better water management strategies will need to be implemented.

Life cycle assessment (LCA) has been a recognised method for measuring the environmental impacts of products, processes and services. It provides a scientifically sound method of comparing products and processes using a common basis and identifies so called ‘hot spots’ and opportunities for reducing environmental impacts. The water footprint of mining, mineral processing and metal production using an LCA basis is still scarce in the literature. Research methodology is now being applied in detail for copper, gold and nickel. A primary focus has been the relationship between ore grade and water use for which mathematical models are being developed. These types of models provide inputs for LCA of mining and mineral processing plants and can identify water saving opportunities through scenarios and process route analysis.

INTRODUCTION

Water in mining, mineral processing and metal production on life cycle basis has been at the top of agendas for various industries, government agencies, research organisations, academic institutions and communities. The *Water Footprint Assessment Manual*, published by Earthscan (Hoekstra, 2011) provides excellent guidelines on the measures of water consumption procedures. In April 2012, the *Water Accounting Framework for the Minerals Industry*¹ was prepared by the Sustainable Minerals Institute of the University of Queensland and was jointly published with the Minerals Council of Australia (SMI and MCA, 2012). This has been based on the *Strategic Water Management in the Minerals Industry* publication by the Minerals Council of Australia (2006). The Government of Western Australia has developed water accounting methods for its mining industry, eg *Pilbara Water in Mining Guidelines* (Government of Western Australia, 2009) and *Western Australian Water in Mining Guidelines* (Government of Western Australia, 2012). UNEP (2012) has published *System of Environmental-Economic Accounting for Water in 2012*. The International Standards Organisation has developed *Water Footprint - principles, requirements and guidelines standard* under the environmental management

category using life cycle assessment approach (ISO, 2013). Water Use in LCA (WULCA, 2013) working group holds regular meetings to develop water impact methods in life cycle assessment (LCA). Investor Group on Climate Change (2011) has published under Carbon Disclosure Project with the title ‘CDP Water Disclosure Australia Report 2011: Shining the Light on Corporate Water Performance’, which reported on behalf of 354 investors with US\$43 trillion asset value. Many of these companies identified water as a significant risk to their business. Furthermore, Global Reporting Initiative (2011) now also clearly requires water consumption details of companies to be reported as part of their sustainability reporting initiative. However, the application in a way that assists to develop better water management strategies in practical terms for mining companies with specific case studies are still rare in Australia and also internationally.

The main objective of the Minerals Down Under Flagship (MDU) is to contribute to the long-term sustainability of the Australian mining and mineral industries and the national economy. The Australia’s Mineral Futures theme under MDU will assist to implement methods to assess the impact of mining

1. Research Project Officer, Minerals Down Under Flagship, CSIRO, Box 312, Clayton South Vic 3169. Email: stephen.northey@csiro.au

2. MAUsIMM, Research Team Leader, Process Science and Engineering, Project Leader, Environmental LCA, Minerals Down Under Flagship, CSIRO, Box 312, Clayton South Vic 3169. Email: nawshad.haque@csiro.au

and minerals technology development on the Australian environment. The future of mining and mineral industry is strongly related with sustainability, including the use of energy, water, generation of solid waste and other impacts as reported by industry surveys and publications. LCA has been a recognised method for measuring the environmental impacts of products, processes and services. It provides a scientifically sound method of comparing products and processes on common grounds and to identify so called 'hot spots' and opportunities for reducing environmental impacts. LCA studies of mining, mineral processing and metal production have been carried out within MDU over the last several years and has gained prominence internally, externally and has an international reputation through published literature. However, there is a significant challenge to apply LCA in the context of the mining and mineral industry with the falling ore grade and dynamic change of the resource and water inputs. The water footprint of mining, mineral processing and metal production on LCA basis is scarce in the literature. Once the precise water footprints of a particular commodity is known then potential water management strategies are devised and recommended to reduce water consumption. Limited work was undertaken by Norgate and Lovel (2006a, 2006b) to determine water footprint using LCA. These results showed the water footprint of various metals on LCA basis. In terms of water usage for metal production, the LCA studies have shown that except gold, which is the most water-intensive, the water intensity of titanium is about five times that of copper. The water footprint of gold is extremely high compared with other metals when expressed in per tonne basis as a functional unit. The breakdown contribution of each of these footprints would provide significant insight on the optimisation of processing option in terms of better water management.

There is a gap in the literature on the estimation of water footprint of major mining and mineral processing routes. Norgate and Lovel (2004, 2006a, 2006b) is the main one of only a handful of studies in this domain. A review of water footprint definition in broader aspect including mining use has been reported (Younger, 2006). The concept was developed in early 2000 and was adopted in LCA methodology to report water footprint. There are research groups who have focused on the overall water balance and cycle. However, there is no study specifically investigating the various types of water used and its footprint following any standard on LCA basis. There is a need for this information by the industry and community stakeholders for decision making about the most potential water saving opportunities based on the data, evidence and LCA. Since energy and water are the main thrust of Mineral Futures, this theme leads the area, based on earlier experience and capabilities of LCA-based studies.

This project is undertaken to determine the water footprint of various metals using LCA, and developing technologies that reduces its consumption. The main objective of this project is to develop a standard framework and use a life cycle based methodology to estimate water footprints for major mineral commodities. Initially, nickel, copper and gold metals have been chosen, based on their relatively high water intensity. The relationship with ore grade and water use has been established by developing mathematical models. These models would be used to provide inputs for LCA and identifying water saving opportunities through the development of various scenarios and configurations in mining and mineral processing plants.

This paper reports on water footprints of mining and mineral processing operations, flotation, pressure oxidation and

integration of tools with mathematical models, LCA for value chain analysis for better water management in the industry. Mining, mineral processing and metal production companies have been consulted to incorporate their viewpoint and to identify opportunities.

METHODOLOGY

Metals have been prioritised based on the importance to the Australian industry under MDU research program. More metals will be included in subsequent future assessments. Life cycle based inventory data on water consumption at various stages have been collected from the open literature. Some embodied water footprints of materials and processes have been compiled from Ecoinvent Database in SimaPro software. Based on this inventory data, direct and indirect water footprints of each metal for a particular process have been estimated on a life cycle basis.

List of selected metal

A variety of production processes are available to produce copper, gold and nickel depending on the mineralogy of ore available. The production processes considered by this study for a range of ore types are shown in Table 1. All figures and data refer to these assumed ore grades unless otherwise specified. The impacts of varying these ore grades are shown in later sections. As a comparison, average milled/treated Australian ore grades for copper and nickel production in 2010 were 0.73 per cent Cu for copper, 1.2 per cent Ni for sulfide ores and 1.3 per cent Ni for laterite ores (Mudd and Weng, 2012).

TABLE 1
Production processes and metals considered by this study.

| Ore type | Ore grade | Process overview |
|---------------------|------------|---|
| Copper sulfide | 0.75% Cu | Pyrometallurgy: mining, beneficiation, smelting and refining. |
| Copper oxide | 0.75% Cu | Hydrometallurgy: mining, heap leaching, solvent extraction-electrowinning. |
| Gold non-refractory | 3.5 g Au/t | Mining, cyanidation, carbon-in-pulp (CIP), electrowinning, smelting and refining. |
| Gold refractory | 3.5 g Au/t | Mining, integrated flotation pressure oxidation, cyanidation, CIP, electrowinning, smelting and refining. |
| Nickel sulfide | 1.3% Ni | Pyrometallurgy: mining, beneficiation, smelting, ammonia leaching and hydrogen reduction. |
| Nickel limonite | 1.3% Ni | Hydrometallurgy: mining, high-pressure acid leaching, sulfide precipitation, ammonia leaching and hydrogen reduction. |

Copper

Copper ores can generally be divided into sulfide ores and oxide ores. Figure 1 shows the copper production processes that have been considered. A detailed overview of copper production processes has been described by Schlesinger *et al* (2011).

Copper mining

The rate of dewatering of mine sites is highly dependent on geographical location. The porosity of surrounding rocks, intersects with both confined and unconfined aquifers, and the rate of aquifer recharge varies from site to site and so it is

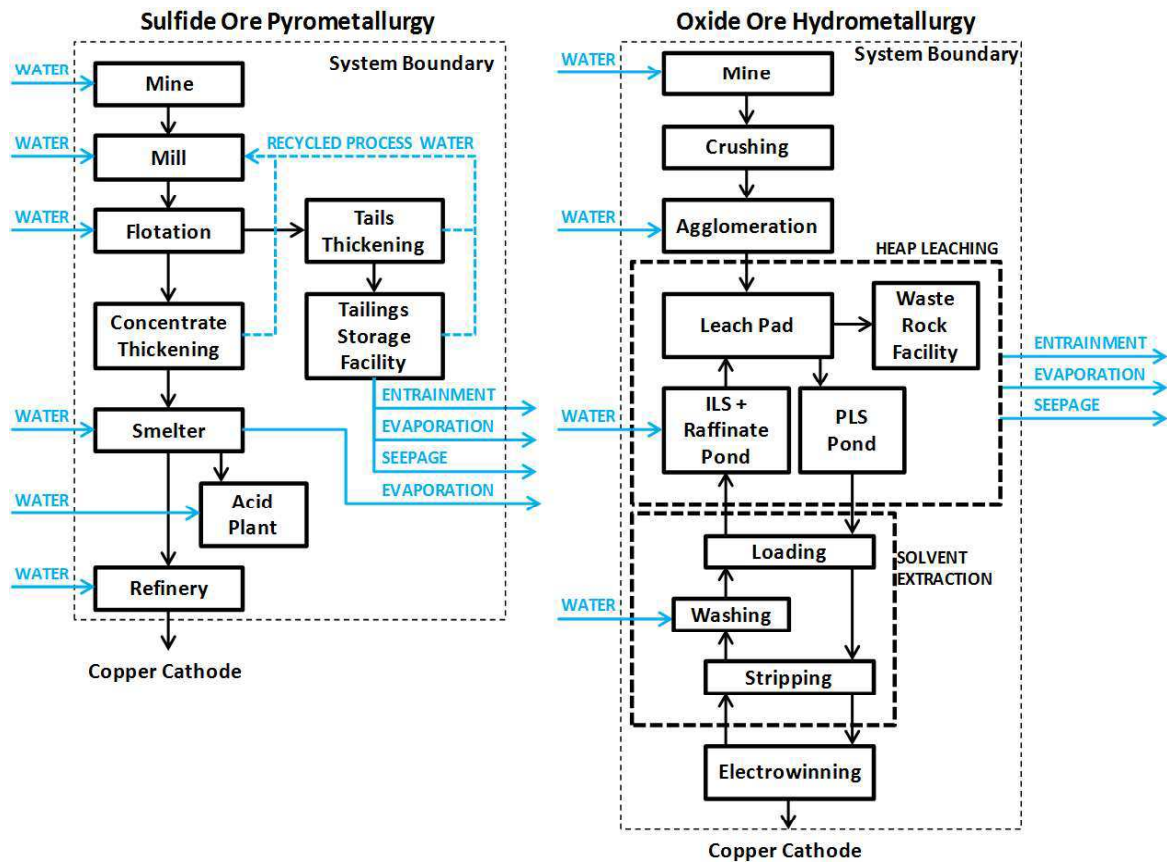


FIG 1 - Copper processing routes and major water flows modelled.

difficult to produce a typical flow rate for underground mine dewatering activities. Table 2 shows estimates for rates of dewatering at several Australian copper mines.

Water entrainment in copper ores entering the system is very site specific. Copper ores are assumed to have a moisture content of two per cent.

Water is used within underground mines primarily for dust suppression. There is little data on the water required for dust suppression activities available within the literature.

Copper pyrometallurgy

The general process for treating sulfide copper ores is to beneficiate the ore, through milling and flotation, to produce a copper concentrate and then smelting to metal. The main consumption of water in this process occurs in the concentration plant (ie milling and flotation stages).

TABLE 2

Copper mine dewatering rates estimated from information provided by Butcher *et al* (2013), Clyde *et al* (2013), Magee *et al* (2013) and Reed *et al* (2013).

| Mine | Type | kt ore/a | L/s | kL/a | kL/t ore |
|--------------|--------------------------------|----------|-----|-----------|----------|
| DeGrussa | Underground | 10 681 | 10 | 315 360 | 0.03 |
| Ernest Henry | Open pit and small underground | 15 000 | 64 | 2 007 500 | 0.13 |
| Mount Lyell | Underground | 2000 | 75 | 2 372 500 | 1.19 |
| Northparkes | Open pit and underground | 5200 | 4 | 126 144 | 0.02 |
| Total | | 32 881 | | 4 821 504 | 0.15 |

Water is added to produce slurry containing approximately 35 - 40 per cent solids. Additional water is also added during the flotation processes as copper minerals are separated from gangue material. Tailings from this process are thickened and then discharged onto the tailings storage facility (TSF). The majority of water losses during copper production occur through the TSF as only limited amounts of sink water can be recycled back to the process from this water sink.

The copper concentrate leaving the flotation cells is thickened and filtered enabling additional process water to be recovered and recycled back to the mill. The filtered concentrate is then fed to dryers attached to smelting facilities. Due to the nature of water consumption in smelting operations, the processes of drying, smelting and converting of concentrate have been consolidated into a single unit process for the modelling. Smelting and converting are essentially two stages of the same underlying physical process; that is the separation of iron and sulfur through oxidation processes. Water is consumed in this stage primarily for cooling of furnace walls. Smelter off-gases high in sulfur dioxide are fed to an acid plant to produce sulfuric acid, a process that requires additional water inputs. The water consumption of the smelter and acid plant have been estimated to be 10.8 kL/t Cu, the average for Chagres smelter from 2003 to 2010 (Anglo-American, 2003 - 2010) and Altonorte Smelter from 2008 to 2010 (Xstrata Chile, Various).

Copper anodes produced from the smelter are electrolytically refined to produce London Metal Exchange (LME) Grade A copper cathodes (>99.99 per cent Cu). This process requires additional water inputs of around 0.51 kL/t Cu, based upon the average for Townsville Refinery from 2003 to 2010 (Xstrata North Queensland, Various).

Copper hydrometallurgy

Copper oxide ores are processed using hydrometallurgical techniques. Various leaching methods exist to extract copper from the ore such as heap leaching, dump leaching, vat leaching and *in situ* leaching. Of these methods heap leaching is by far the most common method globally.

Prior to leaching, mined ore undergoes comminution and subsequent agglomeration processes to ensure adequate porosity and structural integrity of the heap. Water and sulfuric acid are added during the agglomeration stage. Additional sulfuric acid solution is then added via an irrigation system to the constructed heap where it percolates and leaches copper from the ore. The pregnant leach solution (PLS) is recovered from the base of the heap and stored in (PLS) ponds prior to solvent extraction-electrowinning (SX-EW) processes. Entrainment of leach solutions within the heap is a significant area of water and acid losses in the production system.

Solution from the PLS pond is pumped to solvent extraction processes where an organic solvent is loaded with copper from the PLS and the raffinate flows back to a storage pond. The copper in the organic solvent is then stripped into an electrolyte solution that flows to the electrowinning plant. The stripped organic solvent is then washed and recycled back to the loading stage.

The copper-enriched electrolyte is electrowon to produce copper cathodes for sale to the market, with the depleted electrolyte from this process being recycled back to the stripping stage. The overall water balance of the SX-EW processes is controlled by the inputs of the PLS, water inputs for washing of organic solvent and the bleed rate of electrolyte. Electrolyte bleeds have been modelled to return

to the 'ILS + Raffinate Pond' with the wash water. Due to this, the only major water sink for the process is entrainment, evaporation and seepage associated with the leach pads, waste rock facilities, 'ILS + Raffinate Pond' and the 'PLS Pond'. Unfortunately insufficient data is available within the public literature to be able to disaggregate water losses beyond this. Therefore, water losses have been modelled to occur as a whole from the heap leaching operations (see Figure 1 for the relevant process boundary), with assumed water loss to evaporation, entrainment and seepage being the same as for the TSF described by Wels and Robertson (2003).

Gold

Gold ores can generally be classed as either refractory or non-refractory. Non-refractory ores are free milling and can be processed either through gravity separation or carbon-in-pulp (CIP) or carbon-in-leach (CIL) processes. In refractory ores, the gold is bound to a sulfide fraction and requires flotation and additional processes such as roasting, pressure oxidation and bio-oxidation before they can be processed via CIP or CIL processes. Following CIP/CIL or gravity separation the product stream is smelted and then refined to produce refined gold. The process routes considered by this study for gold production and the major water inputs and outputs to this are shown in Figure 2.

Gold mining

Gold-only mines are generally underground operations that target low tonnages of high-grade material. As with copper mines, the rate of dewatering from gold mines is highly variable between sites due to the localised hydrology of individual mine sites. The dewatering rates for a variety

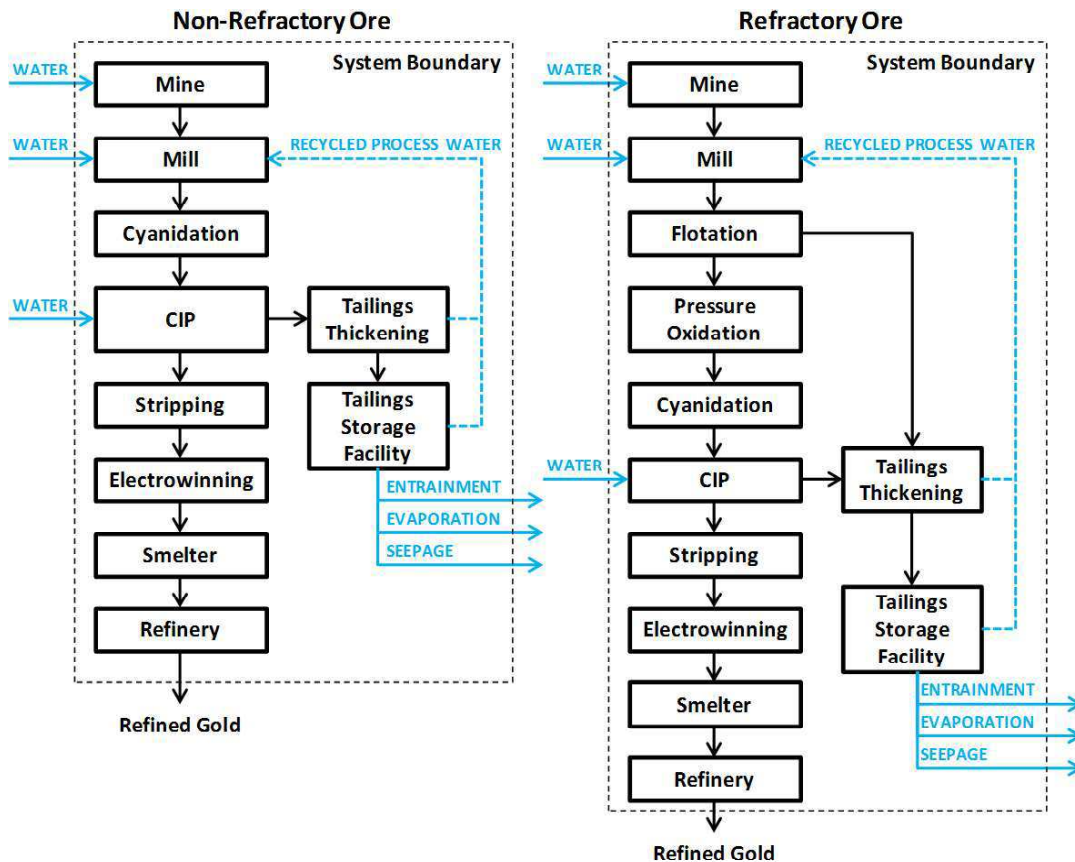


FIG 2 - Gold processing routes and major water flows modelled.

TABLE 3

Gold mine dewatering rates estimated from information provided by Corp (2013), Hills (2013), Johnston and Pluckhan (2013), French *et al* (2013) MacNevin *et al* (2013), Semler *et al* (2013) and Stralow *et al* (2013).

| Mine | Type | kt ore/a | L/s | kL/a | kL/t ore |
|----------------------------------|-------------|----------|-----|-----------|----------|
| Randalls | Open pit | 1800 | 2 | 78 400 | 0.04 |
| Cadia Valley operations Ridgeway | Underground | 5000 | 22 | 693 500 | 0.14 |
| Henty Gold Mine | Underground | 260 | 15 | 473 040 | 1.82 |
| Jundee | Underground | 874 | 10 | 315 360 | 0.36 |
| Paulsens Gold Mine | Underground | 188 | 2 | 63 072 | 0.34 |
| Tanami | Underground | 1612 | 25 | 788 400 | 0.49 |
| Tasmania Mine | Underground | 298 | 70 | 2 207 520 | 7.41 |
| Total | | 10 032 | | 4 619 292 | 0.46 |

of gold mines are shown in Table 3 and were aggregated to produce an estimated dewatering rate of 0.46 kL/t ore for Australian gold mines. The moisture content of gold ores has been assumed to be two per cent.

Non-refractory ores

The main water addition is made during the crushing and grinding processes. The density of slurry leaving the mill is generally 25 - 40 per cent solids. The slurry is transported to tanks and treated with cyanide to leach out the gold. CIP technology is used to separate and strip the gold into a solvent; the water is added during the washing processes. Tailings are separated during the CIP process and thickened before being discharged at a TSF. Water is recovered from the thickener and TSF and recycled back to the mill. The gold dissolved in solvent is electrowon to produce gold cathodes. The cathodes are then smelted to produce dore and then further processed using chlorination and electrolysis to produce high-purity refined gold. Norgate and Haque (2012) produced a detailed LCA of gold production processes, which forms the basis of this analysis. Water consumption in the CIP and stripping stage has been estimated to be 65 816 kL/t Au, based upon data for Paulsens Gold Mine (Stralow *et al*, 2013).

Flotation and pressure oxidation of refractory gold ores

Refractory ores require additional processing to separate the gold particles from gangue material in the ore, as a high proportion of the gold is contained within sulfide mineralogy. Generally, refractory ores have to be ground to a smaller particle size to liberate and expose the gold-containing minerals. Sulfide is removed through oxidation processes such as bioleaching, roasting or pressure oxidation. Pressure oxidation is a common process for treating refractory ores and acid inputs to this process are dependent on the sulfur content of the ore. Gold can then be separated from the oxidised material using the cyanidation and CIP processes as described for non-refractory ores.

Nickel

The nickel production processes considered in this study along with major water flows are shown in Figure 3. Currently the majority of nickel production is sourced from two broad categories of ore. These are sulfide ores and laterite ores. Laterite ore deposits are formed through weather

processes that create distinct layers of ore mineralogy. Each of these layers can have a distinct class of ore, with common classifications being limonite, smectite or saprolite ore. Different processes are suitable for different types of laterite ore. This study considers two production processes for nickel: a pyrometallurgical process for sulfide ore and a hydrometallurgical production process for limonite ore. The production processes for nickel are described in detail by Crundwell *et al* (2011) and Norgate and Haque (2010b).

Nickel sulfides

The processing of nickel sulfides is similar to production processes for other base metals such as copper, zinc and lead.

Nickel sulfides can be mined using either underground or open pit methods. Rates of dewatering for mines are highly site specific. Table 4 shows an estimate of dewatering rates for the Flying Fox mine site in Western Australia. Due to limited data availability on the rate of dewatering in nickel mines, it has been assumed that the rate of dewatering for sulfide nickel mines is similar to the value of 0.15 kL/t ore, which was obtained for copper mines.

The natural moisture content is highly dependent on region and is affected by factors such as mine dewatering and localised aquifer hydrology. Assuming that mining occurs in an arid region, a moisture content of two per cent was applied to nickel sulfide ores.

Similar to other metal beneficiation, water is added to produce slurry that is about 35 per cent solids entering the flotation plant. The flotation process generally operates at about pH 8, with additional water being added during these processes. The concentrate produced is thickened and filtered, with this water being reclaimed and recycled back to the milling stage. Overflow water from the tailings thickener is also reused in slurry preparation in the mill. Underflow from the tailings thickener is pumped to the TSF where water is lost through entrainment, evaporation and seepage processes. Some water is recovered from the TSF by decanting of wetted areas.

Filtered concentrates with a moisture content of about seven per cent are fed to a coal bed dryer and then flash smelted and converted to remove the iron and sulfur content via oxidation. Some water is consumed to cool the flash smelter. Converting takes place in a Peirce Smith converter with slag and off-gases are recycled back to the flash smelter. Off-gases high in sulfur dioxide are sent to an acid plant to produce sulfuric acid, a process that also consumes water.

Nickel matte from the flash smelter is refined using ammonia leaching and hydrogen reduction to produce nickel briquettes for sale to the market. The refining process has been estimated to consume 13.8 kL/t Ni.

Nickel laterites

Mining of nickel laterites is almost exclusively conducted using open pit methods. Nickel laterite orebodies can contain layers of different types of mineralisations such as limonite, smectite and saprolite. The most economic process to use is heavily dependent on the proportion of different minerals in the ore. This study considers the processing of a limonite dominant

TABLE 4

Flying Fox nickel mine dewatering rate estimated from information provided by Rich *et al* (2013).

| Mine | Type | kt ore/a | L/s | kL/a | kL/t ore |
|------------|-------------|----------|-----|---------|----------|
| Flying Fox | Underground | 350 | 30 | 946 080 | 2.70 |

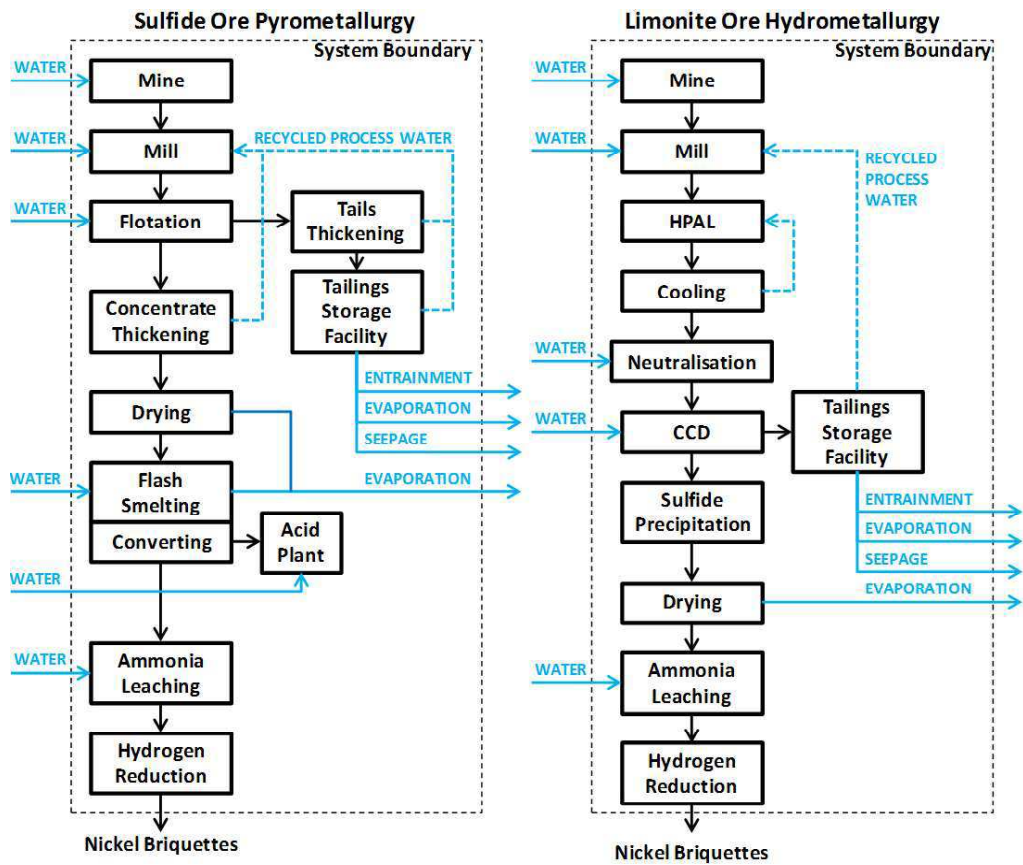


FIG 3 - Nickel processing routes and major water flows modelled.

ore through high-pressure acid leaching (HPAL), sulfide precipitation, ammonia leaching and hydrogen reduction.

Lateritic ores typically have high moisture contents (10 - 30 per cent, see Table 5), a fact that can in part be attributed to the way in which these types of deposits form. Laterite deposits are formed from tropical weathering processes and so naturally occur in regions that lead to high ore moisture contents. Therefore, groundwater brought into nickel production processes through ore entrainment can be expected to be higher for lateritic ores when compared to sulfide ores. As nickel laterite deposits are located close to the surface, dewatering rates are expected to be lower than for nickel sulfide mines. However, in the absence of any reliable data on dewatering rates for nickel laterite mines, the same 0.15 kL/t ore dewatering rate obtained for copper mines has been assumed.

The limonite ore that has been mined is crushed, milled and mixed with water to produce slurry. The slurry is fed to an autoclave where it is leached with sulfuric acid in a high pressure and high temperature environment. Water is generated during the HPAL process as a by-product of reactions involving sulfuric acid. Slurry leaving the autoclave is flash cooled and the steam produced is recycled back to the HPAL to maintain optimal operating conditions. The cooled slurry is neutralised and the solids are separated using counter-current decantation to produce a clarified pregnant leach solution. Wash water is added to this process at a ratio of 1:1 with the slurry. The clarified solution is treated with hydrogen sulfide and a nickel sulfide precipitate is produced.

TABLE 5

Nickel laterite ore moisture contents (Whittington and Muir, 2000).

| Mine | Ore moisture content |
|------------------|----------------------|
| Bulong | <35% |
| Cawse | <10% |
| Murrin-Murrin | ~30% |
| Syerston | 13% |
| Moa Bay | >20% |
| Approximate mean | 21.6 |

RESULTS

Direct water footprint

Table 6 has been constructed in accordance with the methodology outlined in the *Water Accounting Framework for the Minerals Industry* (SMI and MCA, 2012). The input-output statement describes the fluxes of water entering and leaving the boundaries of the mine site as a whole. Rainfall has been excluded from this analysis. When preparing this table it was assumed that all external water withdrawals are from groundwater aquifers and that TSF and heap pad seepage is returned to these systems. The groundwater consumption provided in Table 6 is equivalent to the 'direct blue water footprint', as defined by Hoekstra *et al* (2011).

The main process variable that influences the direct water footprint of metal production is the grade of ore being mined. There is a general trend within the industry to mine and process lower-grade ores. As ore grades decline more material has to be processed to produce the same amount of

TABLE 6
Input-output statements based upon base ore grades.

| Inputs | Copper | | Gold | | Nickel | |
|-----------------------------------|--|---|--|------------------------------------|---------------------------------|----------------------------------|
| | Pyrometallurgy m ³ /t Cu | Hydrometallurgy m ³ /t Cu | Non-refractory m ³ /t Au | Refractory m ³ /t Au | Sulfide m ³ /t Ni | Limonite m ³ /t Ni |
| Groundwater | | | | | | |
| - Mine dewatering | 21.6 | 31.1 | 145 758 | 177 971 | 13.6 | 16 |
| - Ore entrainment | 2.94 | 4.24 | 6337 | 7738 | 1.9 | 23 |
| - Withdrawal | 79.2 | 41.9 | 121 123 | 133 346 | 59.6 | 272.7 |
| Total | 103.7 | 77.2 | 273 219 | 319 055 | 75.1 | 311.3 |
| Outputs | | | | | | |
| Tailings storage facilities/heaps | | | | | | |
| - Entrainment | 59.9 | 36.39 | 134 812 | 164 606 | 35.2 | 39.1 |
| - Evaporation | 19.58 | 11.90 | 44 073 | 53 813 | 11.50 | 12.8 |
| - Seepage | 12.7 | 7.7 | 28 518 | 34 820 | 7.4 | 8.3 |
| Task losses | 11.6 | 21.2 | 65 816 | 65 816 | 20.9 | 251.2 |
| Total | 103.7 | 77.2 | 273 219 | 319 055 | 75.0 | 311.3 |
| Consumption | | | | | | |
| Groundwater | 91 | 69.5 | 244 701 | 284 235 | 67.6 | 303.0 |
| - per tonne of ore | 0.62 | 0.32 | 0.76 | 0.72 | 0.73 | 2.8 |

metal product. The impacts of varying ore grade on the direct water footprint for each metal production process are shown in Figure 4. Note that the models do not account for the fact that lower-grade ores may require grinding to finer sizes and that this would have a negative impact on water recovery from thickeners and the TSF.

Another key factor that influences the direct water consumption of metal production is the degree of water recycling that occurs in the concentrator and TSF. The main opportunity to recover and reuse/recycle water is from the tailings dewatering processes. The base model assumes that tailings are dewatered to a solids density of 55 per cent (w/w) before being discharged to the TSF. Figure 5 shows the impacts on direct water consumption for copper sulfide processing from dewatering tailings to different solids densities (similar results are found for gold and nickel). In general, dewatering to higher tailings solids densities will result in lower direct water consumption and as ore grades decline the differences are exacerbated.

Indirect water footprint

The production of the metal products using the various production routes requires the consumption of materials and energy. There is an indirect water footprint associated with the supply of these materials and energy to the production processes. Life cycle inventory tables (shown in Appendix A) were developed for each metal production process to enable an estimate of indirect water consumption. The embodied water consumption for each of the input materials and energy are shown in Table 7. These values were estimated from LCA databases using the LCA software SimaPro. For each of these materials a range of embodied water estimates are available within the databases. Estimates specific to Australia were preferentially selected, although Australian estimates were not available for all materials.

The indirect water consumption was estimated to be less than the direct water consumption for gold production,

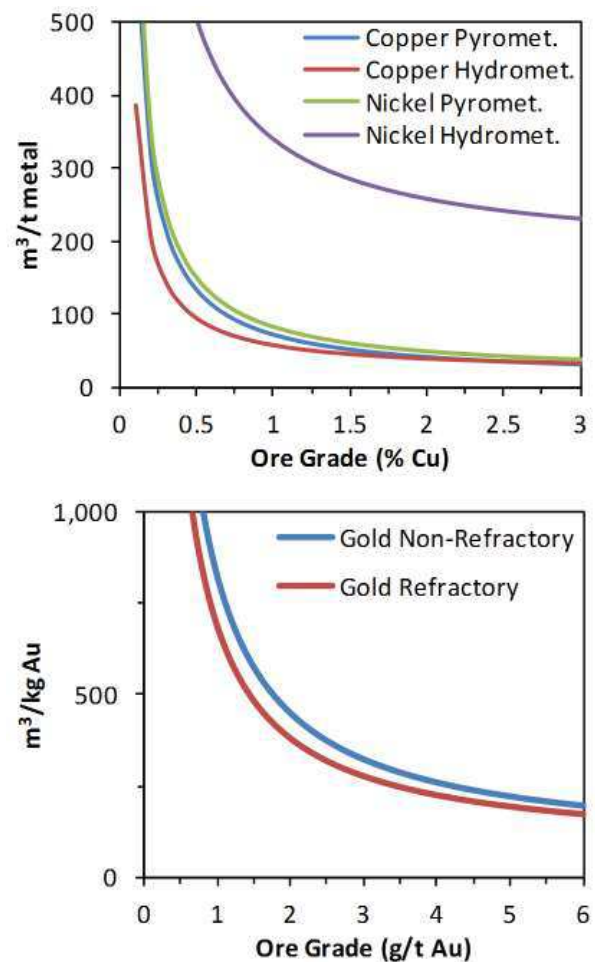


FIG 4 - Estimated direct water consumption for refined metals versus ore grade.

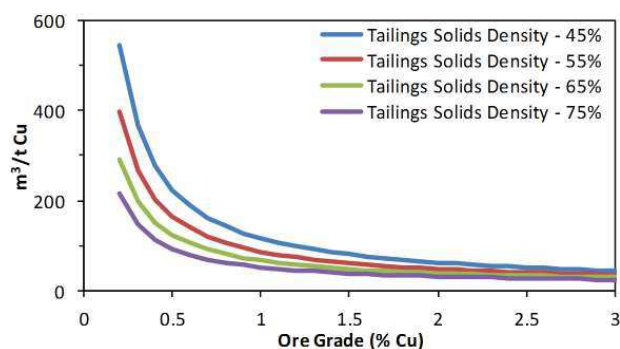


FIG 5 - Variation of copper sulfide processing direct water consumption with tailings solids density.

TABLE 7

Embodied water estimates for common materials consumed during copper, gold and nickel production (SimaPro and LCA databases).

| | | | | | |
|-------------------|--------|---------------------|------------------|--------|--------------------|
| Acetylene | 0.1016 | m ³ /kg | Hydrogen | 0.0025 | m ³ /kg |
| Ammonia | 0.0032 | m ³ /kg | Hydrogen sulfide | 0.0377 | m ³ /kg |
| Carbon black | 0.0005 | m ³ /kg | Lime | 0.0020 | m ³ /kg |
| Chlorine | 0.0614 | m ³ /kg | Natural gas | 0.0000 | m ³ /kg |
| Cobalt | 0.4793 | m ³ /kg | Oxygen | 0.0042 | m ³ /kg |
| Diesel | 0.0013 | m ³ /kg | Silica sand | 0.0015 | m ³ /kg |
| Black coal | 0.0003 | m ³ /kg | Sodium cyanide | 0.1956 | m ³ /kg |
| Electricity | 0.0021 | m ³ /kWh | Sodium hydroxide | 0.0610 | m ³ /kg |
| Explosives | 0.0338 | m ³ /kg | Sulfuric acid | 0.0541 | m ³ /kg |
| Fuel oil | 0.0014 | m ³ /kg | Steel | 0.0027 | m ³ /kg |
| Hydrochloric acid | 0.0254 | m ³ /kg | Vanadium | 0.0010 | m ³ /kg |

copper pyrometallurgy and nickel pyrometallurgy. Figure 6 shows that the indirect water consumption displays the same trend with ore grade as direct water consumption. As ore grades decline more materials and energy has to be processed to achieve the same output of concentrate. Indirect water consumption associated with the smelting and refining stages of production is largely a factor of concentrate grade and mineralogy rather than the original ore grade.

Indirect water consumption is higher than the direct consumption for copper and nickel hydrometallurgical processes. Figure 7 shows the contribution of different materials or energy sources to the indirect water consumption for the base case ore grades (0.75 per cent Cu, 3.5 g/t Au and 1.3 per cent Ni). For copper and nickel pyrometallurgy, the water associated with electricity consumption accounts for almost half of the total indirect water consumption. Interestingly, sodium cyanide, which is sometimes used as a flotation reagent, is also a large source of indirect water consumption for copper pyrometallurgy. No data on the embodied water for some important flotation reagents such as xanthates was found; however, they may be important contributors to the embodied water of metal concentrates.

The production of acid used in hydrometallurgical processes is a water intensive process. The embodied water of sulfuric acid consumed in copper heap leaching was estimated to be approximately 189 m³/t Cu (assuming 3.5 t H₂SO₄/t Cu), or roughly twice the processes' direct water consumption. Sulfuric acid consumption for HPAL of limonitic nickel ores was estimated to account for 1353 m³/t Ni.

Total embodied water

The results of the study for the base case ore grades are shown in Table 8. The direct water consumption represents 65 - 80 per cent of the total embodied water for copper and nickel pyrometallurgy and the gold production processes. Whereas for the copper and nickel hydrometallurgy processes the indirect water consumption represents 75 - 82 per cent of the total embodied water.

A breakdown of the contribution of individual unit processes to the embodied water is shown for each production process in Figure 8. The embodied water is mostly associated with the milling and flotation stages of production for all processes, excluding the copper and nickel hydrometallurgy routes. For the hydrometallurgy routes, the indirect water associated with acid consumption is by far the largest contributor to the overall embodied water.

DISCUSSION

Comparisons with other studies

Studies into the embodied water of various metal production processes have previously been conducted (Norgate and Lovel, 2004, 2006a, 2006b; Norgate and Haque, 2012). The results of these studies are plotted alongside this study for comparison in Figure 9.

When differences in ore grades are taken into account, the total water consumption in all cases exceeds the estimates provided by Norgate and Lovel (2006a, 2006b). The direct water consumption found in this study is similar to the total water consumption found in other studies. Indirect water consumption is significantly higher for this study and this is particularly evident for the copper and nickel hydrometallurgical processes. The main source of indirect water consumption in Norgate and Lovel (2006a, 2006b) was associated with electricity production from black coal, and the study did not account for many materials consumed such as sulfuric acid.

The indirect water consumption for the hydrometallurgical processes is highly sensitive to the unit acid consumption and the embodied water of this acid. In Chile it has been shown that the acid consumption required to produce one tonne of electrowon copper has grown from 2.86 t H₂SO₄/t Cu in 2004 to 3.65 t H₂SO₄/t Cu in 2010 (Chilean Copper Commission, 2011). This is expected to increase further to 4.5 t H₂SO₄/t Cu in 2020 as leachable copper ore grades decline.

This study assumes that sulfuric acid consumed by processes has been produced by a stand-alone acid plant with an embodied water consumption of 54.1 L/kg H₂SO₄. Sulfuric acid produced from smelter off-gases are likely to have lower embodied water consumption as the majority of the water consumption are allocated to the primary metal products. For many regions the production of sulfuric acid is largely a by-product of these metallurgical processes. In the Chilean sulfuric acid market 96 per cent of acid is produced as a by-product of smelting and 96 per cent of acid is consumed by copper hydrometallurgy (Chilean Copper Commission, 2011). The supply and demand of acid between copper pyrometallurgy and hydrometallurgy is essentially balanced in this case. This study has assumed no allocation of impacts to the acid produced as a by-product of smelting processes (Figure 10).

Norgate and Lovel (2006a, 2006b) also provided a generic equation that can be used to produce a rough first estimate of

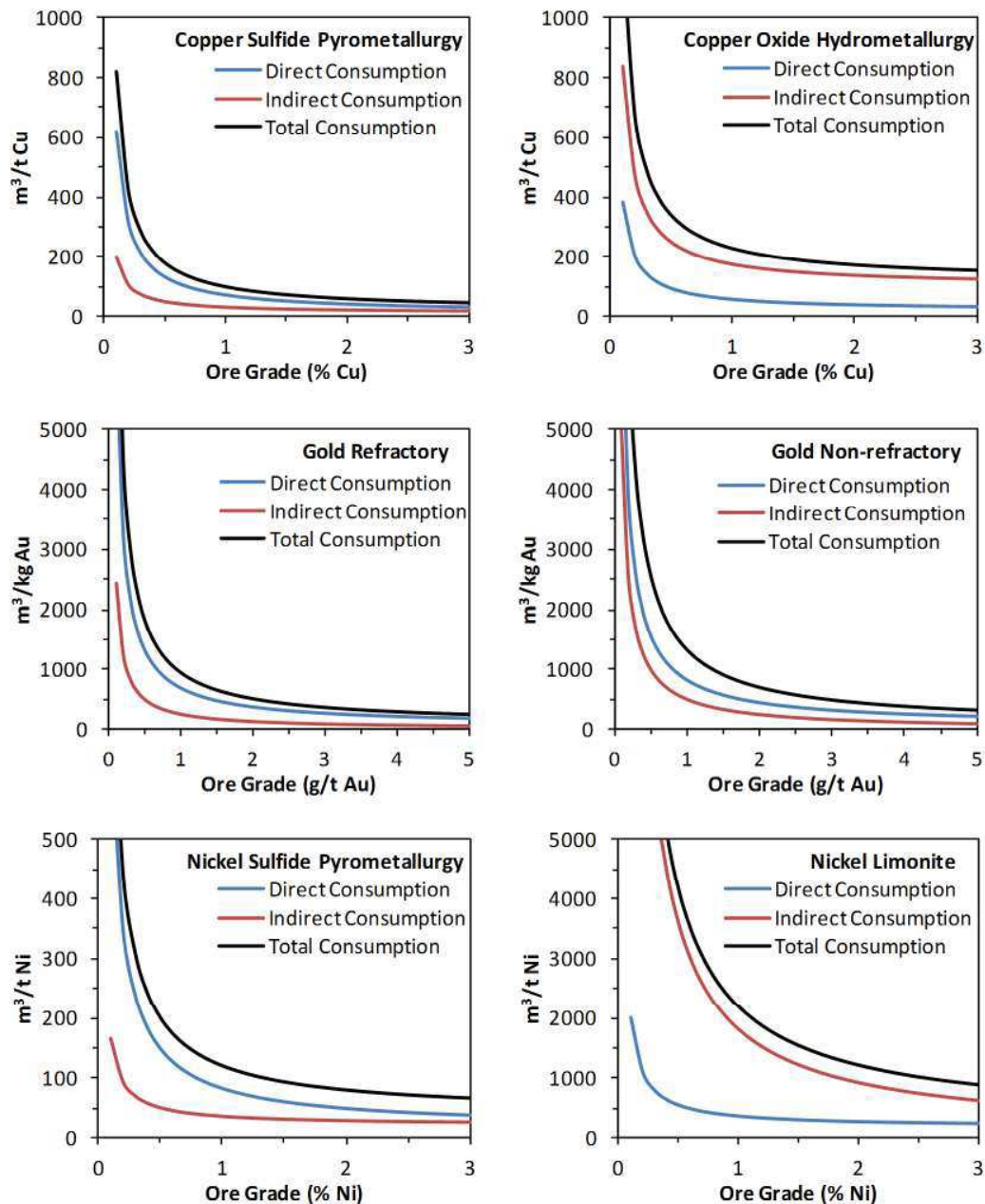


FIG 6 - Estimated water consumption for refined metals versus ore grade. Note the differing axis scales and units.

the embodied water of refined metals, based on ore grades. This equation is shown below:

$$W = 167.7 G^{-0.9039}$$

where:

W = embodied water of (m^3/t refined metal)

G = grade of ore used to produce metal (%)

The equation has been plotted alongside the results of this study for comparison in Figure 11. At higher ore grades (>2 per cent metal) the equation produces similar results for copper and nickel pyrometallurgy, but underestimates the hydrometallurgical processes. At lower copper ore grades (<0.5 per cent Cu) the equation provides reasonable estimates for copper hydrometallurgy and overestimates the pyrometallurgical processes. For gold production the equation underestimates the embodied water, particularly

for non-refractory ores. Despite these differences the equation provides a reasonable order of magnitude estimate of the embodied water of refined metals.

Case studies of copper concentrators

During March 2012 the authors visited an Australian mine and copper concentrator that receives more than 2000 mm of rainfall annually. The biggest focus from an environmental point of view has been on managing water quality issues and also assessing energy and greenhouse gas emissions. Because the site operates a positive water balance there has been little incentive to improve water use efficiency and recycle water on-site. A broad objective of the parent company's sustainability policy is to reduce water consumption across all sites and so there is an aim to better understand water use within their processes. A process flow diagram for the site's concentrator is shown in Figure 12.

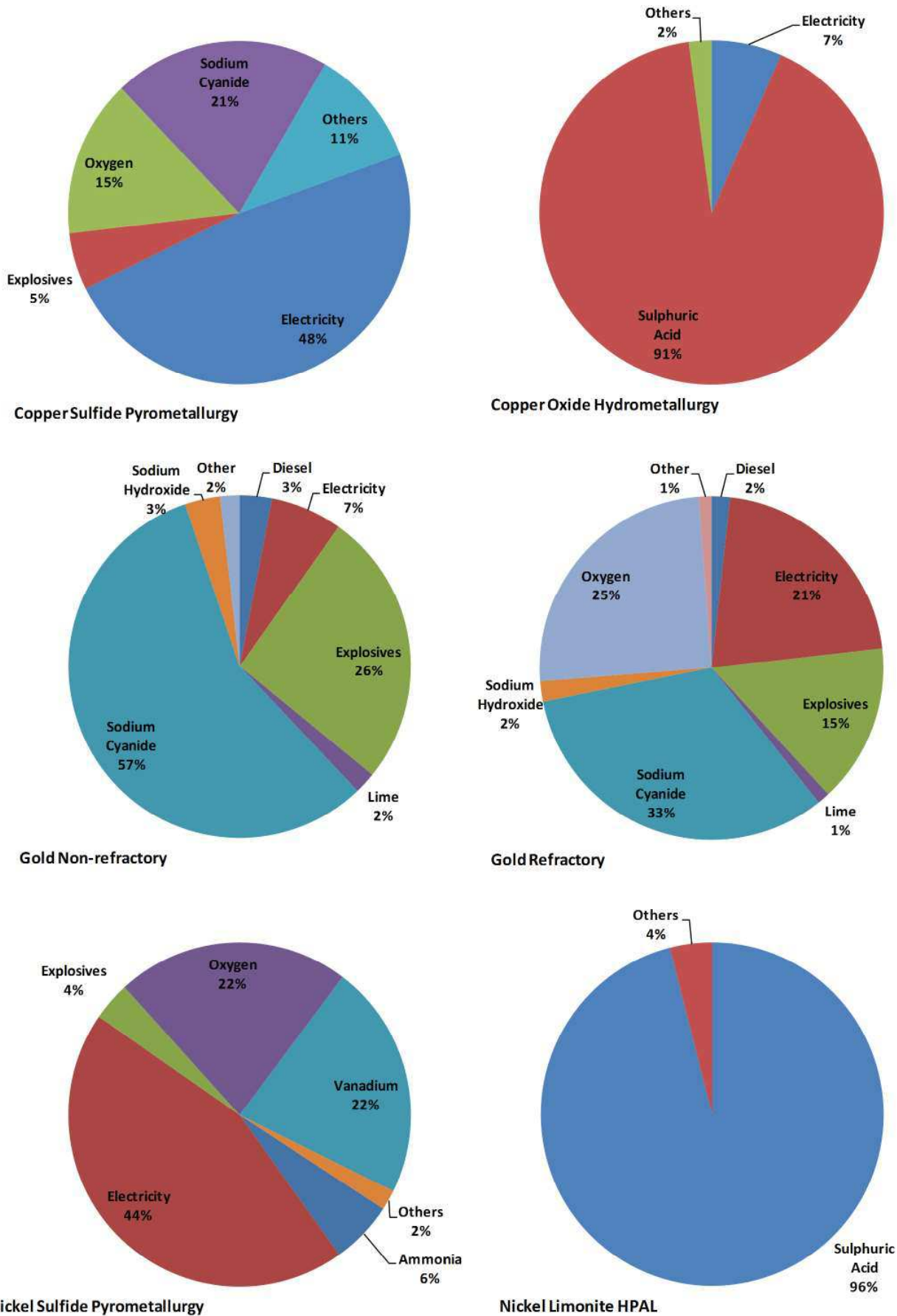


FIG 7 - Contribution of materials and energy to indirect water consumption.

TABLE 8

Summary of the embodied water of copper, gold and nickel production processes.

| Ore type | Ore grade | Process | Direct (m ³ /t) | Indirect (m ³ /t) | Total (m ³ /t) |
|---------------------|------------|-------------------------|----------------------------|------------------------------|---------------------------|
| Copper sulfide | 0.75% Cu | Pyrometallurgy | 91 | 37 | 128 |
| Copper oxide | 0.75% Cu | Hydrometallurgy | 70 | 198 | 267 |
| Gold non-refractory | 3.5 g Au/t | CIP | 244 701 | 69 732 | 314 433 |
| Gold refractory | 3.5 g Au/t | Pressure oxidation, CIP | 284 235 | 149 112 | 433 347 |
| Nickel sulfide | 1.3% Ni | Pyrometallurgy | 68 | 35 | 102 |
| Nickel limonite | 1.3% Ni | Hydrometallurgy (HPAL) | 303 | 1409 | 1712 |

Note: CIP – carbon-in-pulp; HPAL – high-pressure acid leaching.

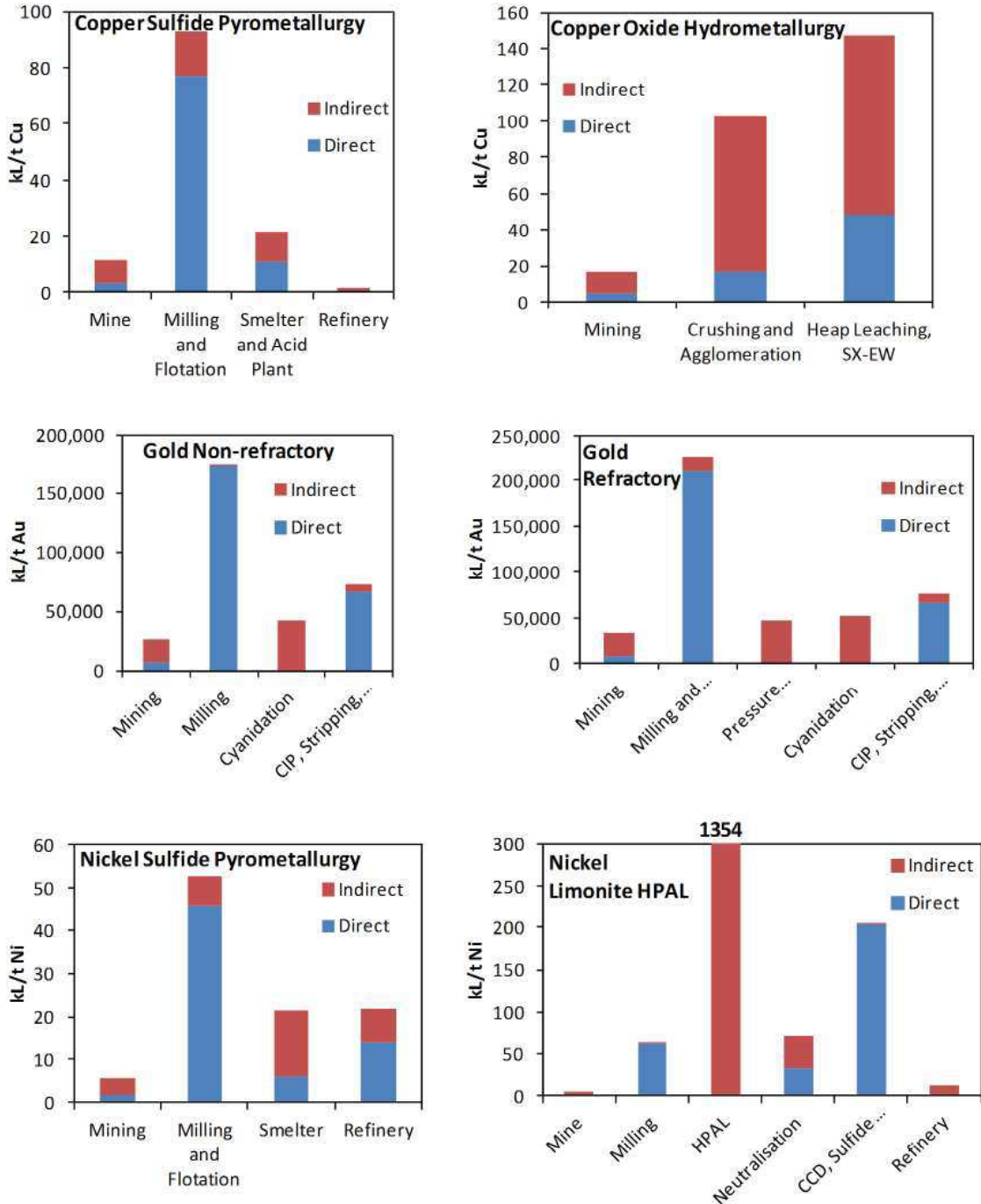


FIG 8 - Direct and indirect water consumption by unit processes.

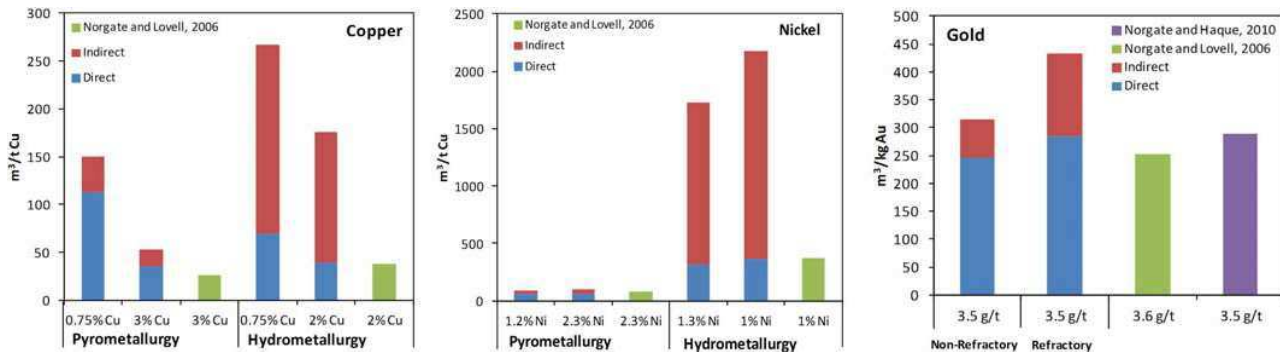


FIG 9 - Comparison between this study and others.

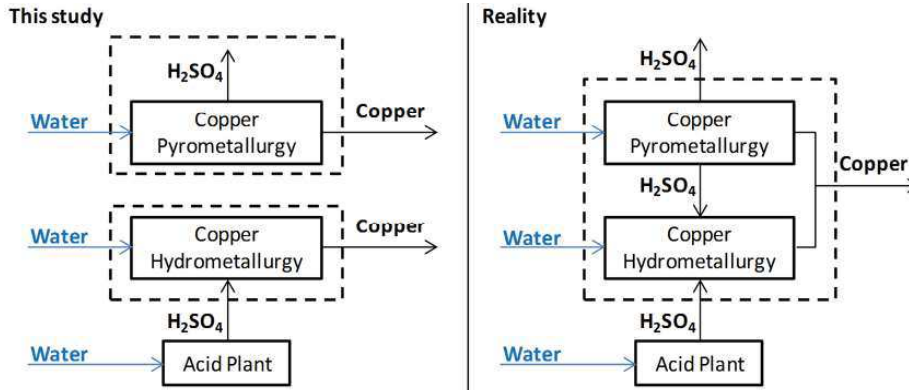


FIG 10 - Flows of sulfuric acid for copper production processes assumed by this study (left), compared with reality (right).

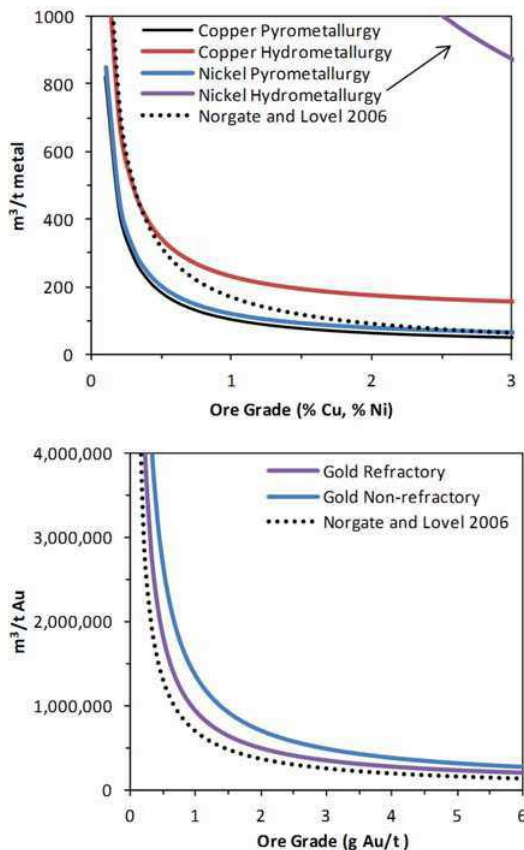


FIG 11 - Comparison with Norgate and Lovell's (2006) embodied water equation.

The inputs and outputs of water were estimated for each of the major process areas within the concentrator (Table 9). The majority of water inputs occur during the milling stage where ore of about 2.4 per cent moisture content is converted to slurry containing 38.5 per cent solids (w/w). Within the flotation circuit, water additions are highest in the roughing and cleaning flotation cells, with only a minor addition of ~4.8 m³/t concentrate occurring in the scavenger and regrind circuits. Concentrates are thickened to 50 - 57 per cent solids and then filtered to a moisture content of 7.5 - 8 per cent for export to an international copper smelter. Tailings slurry containing ~43 per cent solids are pumped and discharged to the site's TSF.

The concentrator's water usage has been highly variable through time, as reported, based on site-specific data. The exact reasons for this are poorly understood by site staff, but are likely to be a combination of a number of factors. These factors could include errors in measurement of water flow rates, variability in thickener and pump performances, changes in water levels in the tank that gravity feeds the concentrator, maintenance taking equipment off-line and rainfall occurring on the thickeners.

Case studies exist in the literature for other copper concentrators. Olivares *et al* (2012) used the methodology presented by Hoekstra *et al* (2009) to estimate the direct blue and grey water footprint of copper concentrate produced by Codelco's El Teniente division in central Chile. The average blue water footprint of the site was found to be 29.5 m³/t concentrate when the TSF was excluded from the system boundary, or only 8.7 m³/t concentrate when the TSF was included. The grey water footprint of the site (the water required to dilute discharges to below certain standards) was found to be 31.5 m³/t concentrate.

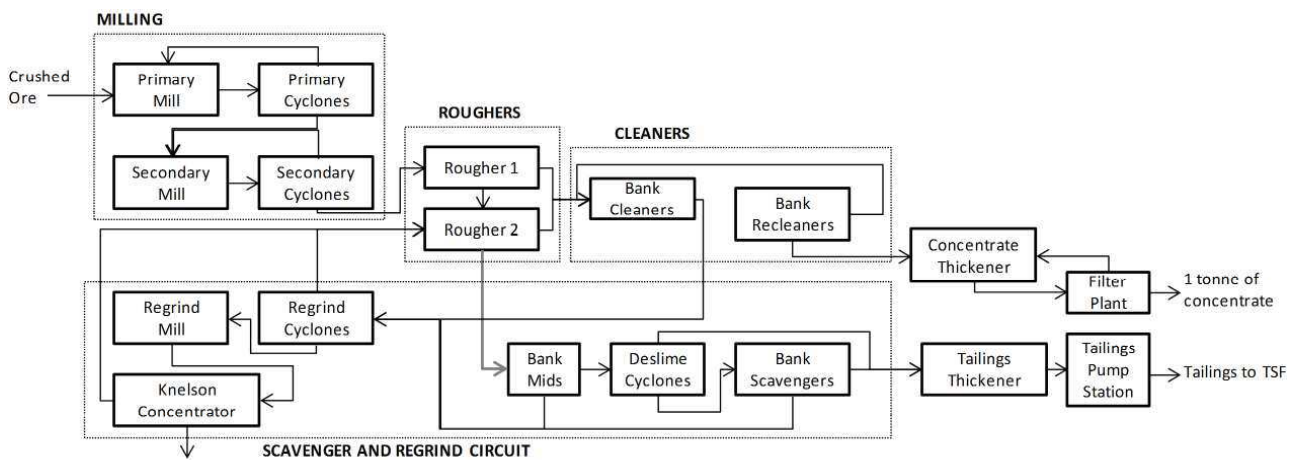


FIG 12 - Process flow diagram for an actual Australian copper concentrator.

TABLE 9

Estimated water inputs and outputs per tonne of concentrate.

| Water inputs | | |
|---------------------------------------|-------|-------------------------------|
| Ore entrainment | 0.6 | m ³ /t concentrate |
| Milling | 35.6 | m ³ /t conc |
| Roughers | 12.1 | m ³ /t conc |
| Cleaners | 9.8 | m ³ /t conc |
| Scavenger and regrind circuit | 1.9 | m ³ /t conc |
| Tailings pump station | 4.8 | m ³ /t conc |
| Total | 64.8 | m ³ /t conc |
| Water outputs | | |
| Concentrate entrainment | 0.1 | m ³ /t conc |
| Concentrate thickener (recycled) | 2.7 | m ³ /t conc |
| Tailings entrainment | 26.5 | m ³ /t conc |
| Tailings thickener (recycled to mill) | 35.5 | m ³ /t conc |
| Total | 64.8 | m ³ /t conc |
| Makeup water required | | |
| - Per tonne of ore milled | 1.2 | m ³ /t ore |
| - Per tonne of Cu in concentrate | 102.2 | m ³ /t cu |

The US Geological Survey released a report describing the typical water requirements for the conventional flotation of copper ores (Bleiwas, 2012). Water requirements for the process were shown to range from 1.5 to 3.5 m³/t ore, with makeup water constituting anywhere from ten per cent to 100 per cent of this. The study found that for a 50 000 t ore/day copper concentrator operating in a semi-arid environment, processing an ore grade of 0.5 per cent Cu and discharging tails at 50 per cent solids, raw water requirements are approximately 38 m³/t concentrate.

CONCLUSIONS

The general growth of the mining and mineral processing industries coupled with declining ore grades will continue to place pressure on water resources. Integrated management approaches to water use within the industry is essential to maintain the long-term sustainability of these water resources.

The water consumption at mine sites is highly variable due to a range of factors including climate, process configuration

and the competition between water users in an area. The key variables that influence direct water consumption for metal production processes are the ore grade being processed, the tailings solids density and the rate of reuse/recycling within concentration facilities. In all cases, the overall site water balance is highly dependent on the climatic conditions. These affect not only water availability and inflows into the site, but also the ability to reuse and recycle water within process facilities.

Prior studies were found to underestimate the direct and indirect water footprints of the metal production processes considered. This is particularly the case for the copper and nickel hydrometallurgy processes, where acid consumption was found to be a significant contributor to the indirect and total embodied water. The results for these two processes are, therefore, highly sensitive to assumed embodied water of the sulfuric acid.

Reported data and the case study provided for a copper concentrator highlight the significant variability in direct water consumption, both within and between mine sites. Improved assessment of the potential for individual sites to reduce their water consumption is essential for reducing the overall impact of the industry. It is hard to generalise but depending on processing routes, indirect water consumption may be higher compared with direct (ie hydrometallurgical), thus saving opportunities may exist outside the immediate process boundary. The choice of materials and energy has a large influence on water footprints. Further assessment will be made on finding strategies to reduce water consumption, based on these results for selected metals.

REFERENCES

- Anglo-American, 2003 - 2010. Anglo-American sustainability reports, Anglo-American Plc, London.
- Clyde, S, Pitt, T, Kemp, P, Cordery, G, Manley, J and DeRoss, J, 2013. Mount Lyell, Vedanta Resources CMT, in *Australasian Mining and Metallurgy Operating Practices, The Sir Maurice Mawby Memorial Volume*, third edition (ed: W J Rankin), pp 901-914 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Butcher, A, Cunningham, R, Edwards, K, Lye, A, Simmons, J, Stegman, C and Wyllie, A, 2013. Northparkes Mines, Rio Tinto, in *Australasian Mining and Metallurgy Operating Practices, The Sir Maurice Mawby Memorial Volume*, third edition (ed: W J Rankin), pp 861-878 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Bleiwas, D I, 2012. Estimate water requirements for the conventional flotation of copper ores, US Geological Survey (USGS), Open-File Report 2012-1089, 17 p.

- Chilean Copper Commission**, 2011. The Chilean sulphuric acid market, estimations through 2020 (revised to June 2011), DE/05/2011, Research and Policy Planning Department, Chilean Copper Commission.
- Council on Minerals and Petroleum Resources**, 2006. Strategic water management in the minerals industry, 36 p (Minerals Council of Australia).
- Corp, D**, 2013. Cadia Valley Operations, Newcrest Mining Limited, in *Australasian Mining and Metallurgy Operating Practices, The Sir Maurice Mawby Memorial Volume*, third edition (ed: W J Rankin), pp 1131-1146 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Crundwell, F K, Moats, M S, Ramachandran, V, Robinson, T G and Davenport, W G**, 2011. *Extractive Metallurgy of Nickel, Cobalt and Platinum-Group Metals*, 586 p (Elsevier: UK).
- French, D, Harris, G, Lorrigan, A, Mattiske, A, McArthur, A and McLean, R**, 2013. Henty Gold Mine, Unity Mining Limited, in *Australasian Mining and Metallurgy Operating Practices, The Sir Maurice Mawby Memorial Volume*, third edition (ed: W J Rankin), pp 1361-1370 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Global Reporting Initiative (GRI)**, 2011. Sustainability reporting guidelines, third edition [online], (Global Reporting Initiative: Amsterdam). Available from: <<https://www.globalreporting.org/reporting/sector-guidance/mining-and-metals/pages/downloads.aspx>> [Accessed: 08 October 2012].
- Government of Western Australia**, 2009. Pilbara water in mining guidelines: looking after all our water needs, Department of Water, Report 34, 65 p.
- Government of Western Australia**, 2012. Western Australian water in mining guidelines: draft for public comment, Department of Water, Report 12, 67 p.
- Hills, P B**, 2013. Tasmania Mine, BCD Resources NL, in *Australasian Mining and Metallurgy Operating Practices, The Sir Maurice Mawby Memorial Volume*, third edition (ed: W J Rankin), pp 1011-1025 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Hoekstra, A Y, Chapagain, A K, Aldaya, M M and Mekonnen, M M**, 2009. *Water Footprint Manual, State of the Art 2009* (Water Footprint Network: Enschede, the Netherlands).
- Hoekstra, A Y, Chapagain, A K, Aldaya, M M and Mekonnen, M M**, 2011. *The Water Footprint Assessment Manual: Setting the Global Standard* (Water Footprint Network, Earthscan: London).
- Investor Group on Climate Change**, 2011. Carbon Disclosure Project water disclosure Australia report 2011: shining the light on corporate water performance, 24 p (Carbon Disclosure Project).
- International Standards Organisation (ISO)**, 2013. Environmental management standards. Available from: <http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=43263> [Accessed: 13 August 2013].
- Johnston, R and Pluckhan, J**, 2013. Randalls Gold Project, Integra Mining Limited, in *Australasian Mining and Metallurgy Operating Practices, The Sir Maurice Mawby Memorial Volume*, third edition (ed: W J Rankin), pp 1085-1091 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- MacNevin, W, Tassone, M, Price, N and Waugh, G**, 2013. Tanami Operations, Newmont, in *Australasian Mining and Metallurgy Operating Practices, The Sir Maurice Mawby Memorial Volume*, third edition (ed: W J Rankin), pp 1207-1219 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Magee, M, Theobald, A, Callaghan, B, Christen, P, Donovan, K, Magee, F, Wilson, V, Stark, A, Wass, B, McCutcheon, K and Duck, C**, 2013. Ernest Henry Mining, Xstrata Copper, in *Australasian Mining and Metallurgy Operating Practices, The Sir Maurice Mawby Memorial Volume*, third edition (ed: W J Rankin), pp 915-930 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Mudd, G M and Weng, Z**, 2012. Base metals, in *Materials for a Sustainable Future* (eds: T M Letcher and J L Scott), pp 11-59 (Royal Society of Chemistry: London).
- Norgate, T and Haque, N**, 2010a. Energy and greenhouse gas impact of mining and mineral processing operations, *Journal of Cleaner Production*, 18:266-274.
- Norgate, T and Haque, N**, 2010b. Assessing the environmental sustainability of nickel laterite processing, CSIRO Minerals Down Under Flagship, DMR-3816.
- Norgate, T and Haque, N**, 2012. Using life cycle assessment to evaluate some environmental impacts of gold production, *Journal of Cleaner Production*, 29-30(2012):53-63.
- Norgate, T E and Lovel, R R**, 2004. Water use in metal production: a life cycle perspective, CSIRO DMR-2505, 39 p.
- Norgate, T E and Lovel, R R**, 2006a. Sustainable water use in minerals and metal production, in *Proceedings Third International Conference on Sustainable Processing of Minerals and Metals Conference (Green Processing)*, pp 133-141 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Norgate, T E and Lovel, R R**, 2006b. Sustainable water use in minerals and metal production, in *Proceedings Water in Mining Conference 2006*, pp 331-340 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Northey, S and Haque, N**, 2012. Copper LCA case studies, CSIRO EPublish Report 121195.
- Olivares, M, Toledo, M, Acuña, A and Garcés, M**, 2012. Preliminary estimate of the water footprint of copper concentrate production in central Chile, in *Proceedings Third International Congress on Water Management in the Mining Industry*, Santiago, Chile, 6-8 June 2012, pp 390-400 (Gecamin: Chile).
- Reed, M, Dawson, C, Bamforth, S, Knoblauch, J, Sime, T, Ryan, S, Rankine, G and Armstrong, J**, 2013. DeGrussa Copper Project, Sandfire Resources, in *Australasian Mining and Metallurgy Operating Practices, The Sir Maurice Mawby Memorial Volume*, third edition (ed: W J Rankin), pp 879-896 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Rich, A, Haywood, J, Bower, J, Fitzmaurice, C, Coulson, D, Chisholm, R, Donnelly, O and Jones, W**, 2013. Flying Fox Nickel Mine, Western Areas NL, in *Australasian Mining and Metallurgy Operating Practices, The Sir Maurice Mawby Memorial Volume*, third edition (ed: W J Rankin), pp 1743-1759 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Semler, B, Pendergast, J, Rautenbach, G, Uren, G, Abbott, C and Cupac, A**, 2013. Jundee Operations, Newmont, in *Australasian Mining and Metallurgy Operating Practices, The Sir Maurice Mawby Memorial Volume*, third edition (ed: W J Rankin), pp 1177-1190 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Stralow, D, Clarey, S, Ekers, B and McGovern, P**, 2013. Paulsens Gold Mine, Northern Star Resources, in *Australasian Mining and Metallurgy Operating Practices, The Sir Maurice Mawby Memorial Volume*, third edition (ed: W J Rankin), pp 1241-1252 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Schlesinger, M E, King, M J, Sole, K C and Davenport, W G**, 2011. *Extractive Metallurgy of Copper*, fifth edition (Elsevier: UK).
- The Sustainable Minerals Institute (SMI) and Minerals Council of Australia (MCA)**, 2012. Water accounting framework for the minerals industry, user guide version 1.2:2012, 54 p (University of Queensland).
- United Nations Environment Programme (UNEP)**, 2012. System of environmental-economic accounting for water in 2012, 216 p (Department of Economic and Social Affairs).
- United States Geological Survey (USGS)**, 2004. Flows of selected materials associated with world copper smelting, open file report 2004-1395 [online]. Available from: <<http://pubs.usgs.gov/of/2004/1395/>> [Accessed: 20 January 2012].

- Water Use in Life Cycle Assessment (WULCA)**, 2013. Assessment of use and depletion of water resources within LCA. Available from: <<http://www.wulca-waterlca.org>> [Accessed: 13 August 2013].
- Wels, C** and Robertson, A MacG, 2003. Conceptual model for estimating water recovery in tailings impoundments [online]. Available from: <<http://www.nep.rgc.ca/publications/welcmf.pdf>> [Accessed: 22 May 2013].
- Whittington, B I** and Muir, D, 2000. Pressure acid leaching of nickel laterites: a review, *Mineral Processing and Extractive Metallurgy Review: An International Journal*, 21(6):527-599.
- Xstrata Chile**, Various. Xstrata Chile sustainability reports, 2008-2010. Xstrata Plc, London.
- Xstrata North Queensland**, Various. Xstrata North Queensland sustainability reports, 2003-2010. Xstrata Plc, London.
- Younger, P L**, 2006. The water footprint of mining operations in space and time - a new paradigm for sustainability assessments?, in *Proceedings Water in Mining 2006*, pp 13-22 (The Australasian Institute of Mining and Metallurgy: Melbourne).

APPENDIX A – INDIRECT WATER INVENTORY DATA

TABLE 10

Underground copper mining material and energy consumption
(Norgate and Haque, 2010a).

| Mining material | Energy consumption | |
|-----------------|--------------------|-----------|
| Diesel | 2.8 | kg/t ore |
| Explosives | 0.4 | kg/t ore |
| Electricity | 20.4 | kWh/t ore |

TABLE 11

Copper sulfide pyrometallurgy inventory data.

| Process/input | Value | Unit | Reference or assumption |
|---------------------------------------|-------|---|--|
| Milling | | | |
| Electricity | 18.5 | kWh/t ore | Norgate and Haque, 2010a |
| Grinding media | 1.4 | kg/t ore | Norgate and Haque, 2010a |
| Flotation | | | |
| Recovery | 93.7 | % | |
| Reagents | 1.7 | kg/t ore | Norgate and Haque, 2010a |
| Tailings | | | Dependent on ore grade |
| Smelter, converter and casting | | | |
| Concentrate | 3.60 | t conc./t anode | Recovery 98.7%, concentrate grade 27.3% Cu |
| Natural gas | 2.5 | GJ/t anode | Northey and Haque, 2012 |
| Fuel oil | 0.7 | GJ/t anode | USGS, 2004. 'Mixed fuel' assumed fuel oil |
| Silica | 312 | kg/t anode | Northey and Haque, 2012; Schlesinger <i>et al</i> 2011 |
| Refractories | 6.3 | kg/t anode | Northey and Haque, 2012; Schlesinger <i>et al</i> 2011 |
| Oxygen | 0.35 | t/t conc. | Mass balance. El Teniente's consumption is 320 kg/t conc. Northey and Haque, 2012 |
| Slag generated | 2.6 | t slag/t conc. | Mass balance. Concentrate 27.3% Cu, anode 97% Cu, slag 0.5% Cu |
| Acid plant | | | |
| Sulfuric acid | 3.90 | t H ₂ SO ₄ /t anode | Concentrate grade 35% S, 98% SO ₂ recovery and 98% H ₂ SO ₄ concentration |
| Electricity | 1.25 | GJ/t H ₂ SO ₄ | Outotec brochure |
| Vanadium oxide | 230 | L/t H ₂ SO ₄ | Outotec brochure |
| SO ₂ emissions | 13 | kg/t H ₂ SO ₄ | 98% SO ₂ recovery |
| Refinery | | | |
| Cu anode | 1.03 | t anode/t Cu | Anode 97% Cu, cathode 99.99% Cu |
| Electricity | 410 | kWh/t Cu | Townsville Refinery, 2008 to 2010 (Xstrata North Queensland, Various) |
| Natural gas | 0.97 | GJ/t Cu | Townsville Refinery, 2008 to 2010 (Xstrata North Queensland, Various) |
| Gelatin | 72 | g/t Cu | Townsville Refinery, 2007 to 2010 (Xstrata North Queensland, Various) |
| Acetylene | 0.4 | kL/t Cu | Townsville Refinery, 2010 (Xstrata North Queensland, Various) |
| Lime | 0.09 | kg/t Cu | Townsville Refinery, 2010 (Xstrata North Queensland, Various) |
| Sulfuric acid | 5.13 | kg/t Cu | Townsville Refinery, 2007 to 2010 (Xstrata North Queensland, Various) |
| Thiourea | 9.6 | g/t Cu | Townsville Refinery, 2007 to 2010 (Xstrata North Queensland, Various) |