



# Report

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## **Water Use in Metal Production: A Life Cycle Perspective**

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**CSIRO Minerals**

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## **A life cycle perspective**

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### **EXECUTIVE SUMMARY**

While the Australian mining industry consumed only about 2% of Australia's total water consumption in 2000-01, many of these mining operations are located in regions of low water supply and are in competition with other users for access to water resources. In 1996-97, 95% of the water consumed by the mining industry was sourced locally from groundwater, with only 5% being supplied through mains infrastructure. Water reforms currently taking place in Australia are based on the principles espoused in the National Water Initiative recently established by the Council of Australian Governments (COAG), and may result in restricted access to water and reduced security of supply. Consequently water issues are likely to become more concerning to the minerals industry.

Mining and mineral processing are the first two of several stages in the life cycle of metal production. These stages are generally followed by smelting and refining stages, which can also consume significant amounts of water. Furthermore, the various raw material and energy inputs into the various stages may consume significant amounts of water in their production or generation (eg. electricity). In this report, the authors have used Life Cycle Assessment (LCA) to assess the variations in water use associated with different mineral processing options and to add a life cycle perspective to the debate about water resources and their sustainability, particularly with respect to the minerals and metal production industries.

LCA methodology was used to estimate the "cradle-to-gate" (ie. from ore extraction through to refined metal production) water consumptions for the production of a number of metals by various processing routes. The essence of LCA methodology is to account for all inputs, both direct (ie. within a process stage) and indirect (ie. external to a process stage) in the life cycle of a process or product. Data on the amounts of water consumed in the various stages in the production life cycle of the various metals was sourced from publically available literature, and then incorporated into the LCA spreadsheet models previously developed for each metal processing route. The results for the "cradle-to-gate" water consumption ranged from 2.9 m<sup>3</sup>/t for steel up to 252,087 m<sup>3</sup>/t for gold. The results are strongly correlated to the grade of the initial ore used to produce each metal, and can be approximated by the following equation:

$$W = 167.7 G^{-0.9039} \quad (R^2 = 0.916)$$

where  $W$  = “cradle-to-gate” water consumption ( $\text{m}^3/\text{t}$  refined metal)  
 $G$  = grade of ore used to produce metal (% metal);

Indirect water consumption in the metal production life cycle, in particular that associated with electricity generation, made a significant contribution to the “cradle-to-gate” water consumption for aluminium, and to a lesser extent titanium. When the “cradle-to-gate” water consumptions were expressed in terms of  $\text{m}^3/\text{t}$  ore, the mean value for the water consumption of all metals considered was  $2.1 \text{ m}^3/\text{t}$  ore, while the mean value for the water consumption for the mining and concentrating stage was  $0.7 \text{ m}^3/\text{t}$  ore, indicating that “cradle-to-gate” water consumption is, on average, three times that of the mining and concentration stage for the metals considered. This observation illustrates the importance of using a life cycle approach when evaluating the amount of water extracted from the environment for metal production.

Water recycling is a candidate to help reduce water consumption in the minerals industry, however issues such as the recycling of organic molecules, inorganic and microbiological species, and the build-up of collectors, among others, will influence the extent to which this can be achieved. The use of dry or near-dry processing technologies, for which the demand for water is small or zero, may offer a solution to the water consumption problem, however the introduction of dry processing will bring with it a new set of problems, including dust.

It is emphasised that given the wide range in water consumption data between mining, mineral processing and metal production sites often reported in the literature, even when using the same processing route (partly explained by the above correlation and also by varying degrees of water recycling), the results presented in this report should be considered as first estimates only.

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## 1 INTRODUCTION

Without water there cannot be life, and therefore it can be argued that water is the world's most valuable resource. Population growth, changing weather patterns, increased industrialisation and competition among users have recently changed the reliability of water supply and society is beginning to recognise that water is a finite resource.

*“In many countries, both developing and developed, current pathways for water use are often not sustainable. There is clear and convincing evidence that the world faces a worsening series of local and regional water quantity and quality problems, largely as a result of poor water allocation, wasteful use of the resource, and lack of adequate management action. Water resource constraints and water degradation are weakening one of the resource bases on which human society is built” (from the United Nations Commission on Sustainable Development report Comprehensive Assessment of the Freshwater Resources of the World, 1999).*

Numerically, the world has plenty of fresh water. However its uneven distribution combined with human activity over the last century has seriously threatened local availability (Brown, 2002).

Globally, 66% of all water withdrawn for human use each year is used for agriculture, 20% is used for industry, with 10% for municipal or domestic use (Shiklomanov, 2000), although these averages vary a great deal between regions. In Australia 79% is used for irrigated farmland and other rural uses, 9% for industry and 12% for domestic use (Nowland, 2003). Mining accounted for about 3% of the total water consumed in Australia in 1996-97 (Chartres and Williams, 2003), but this decreased to about 1.6% in 2000-01 (see Appendix A). Many mining operations are located in regions of low water supply, and the minerals industry may be in competition with other users for access to water resources. Permission to access water resources is gained through allocations, rights or licences of a variety of types. Water allocation systems generally evolved at a time when there was less concern for, or awareness of, human impacts on the environment and there were fewer water users. Consequently, some people believe that water has been over-allocated and that inequity between users has resulted.

Many issues and drivers can influence the future of water use. Dunlop (2001a) grouped many of them into the following categories:

- domestic and export market driven growth in commodity production;
- social attitudes toward water use (and re-use) and the environment;
- government policy;
- uncertainty associated with global climate change.

Global climate change is very likely to have some significant effects on water resources in Australia, and current allocation procedures will need to become adaptive enough to cope with increasing climatic variability. However, issues

such as changing water allocation procedures may be complicated by the fact that water resources in Australia are the constitutional responsibility of the State and Territory Governments.

The water debate is raging in many sectors, and the national and state water reforms currently occurring in Australia are attempting to balance these issues, primarily by guaranteeing an allocation to the environment and establishing markets for water trading.

The purpose of the study described in this report was to add a life cycle perspective to the debate about water resources and their sustainability, particularly with regard to the life cycles and supply chains of metal production. Life Cycle Assessment (LCA) methodology was used to estimate typical water consumptions (in terms of fresh or raw water consumed per tonne of refined metal) for the production of a number of metals, and in some instances by alternative processing routes (eg. pyrometallurgical versus hydrometallurgical). The work was Appropriation-funded, and was carried out as part of the Social and Economic Integration (SEI) project at CSIRO Minerals.

## 2 WATER AND THE MINERALS INDUSTRY

As noted in Appendix A, the mining industry consumed 401 GL or 1.6% of Australia's total net water consumption in 2000-01, down from 570 GL (ie. 3%) in 1996-97 (Chartres and Williams, 2003).<sup>1</sup> Information on the water cycle and Australian water resources is given in Appendix A.

In the minerals industry, relatively little water is used in most types of mining, and the majority of water is used in mineral processing, refining and the associated tailings disposal (Brown, 2002). Mineral processing operations such as grinding, flotation, gravity concentration, dense medium separation and hydrometallurgical processes all consume substantial amounts of water.

Three factors are said to make water the fluid of choice for mineral processing (Brown, 2002: Napier-Munn and Morrison, 2003):

- water is an efficient (low energy, low cost) way of transporting particles within and between processes, mixing particles, and supplying reactants to the site of a reaction;
- water is a medium which can provide a suitable vehicle for the selective action of a distributed force field, eg. gravity or centrifugal force;

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<sup>1</sup> Net water consumption refers to the amount of water used and not discharged back to existing water bodies (ie. it includes any losses within the plant such as evaporation seepage and other discharges). Thus the words "use" and "consume" are used interchangeably in the remainder of this report to mean the net amount of raw water extracted from a water source (ie. the raw water makeup) for use by the operations.

- water is an essential chemical ingredient in some processes.

Grinding generally uses water to convey the particles being ground along the mill and to remove heat. Flotation exploits the chemical nature of mineral surfaces to separate them by reverse sedimentation through the selective attachment of bubbles to those minerals naturally hydrophobic or rendered so by the addition of reagents. Water is essential to the chemistry of the method of discrimination, the medium of separation by gravitational force, and the transport of the particles in the process. Water is also essential to many chemical processes in which minerals are concentrated through a change of state. Hydrometallurgical processes, such as leaching and electrowinning, require aqueous solutions of reagents to dissolve and re-precipitate minerals and metals to concentrate and purify them (Miller, 2003).

Tailings disposal is another major consumer of water on most mine and mineral processing sites. In many cases it is also the largest source of water loss as well as representing a major environmental risk. Water may be lost through either evaporation or seepage.

Refining processes used to extract and purify the valuable metals from the concentrates produced by mineral processing can also use large amounts of water. The main refining processes may be classified as being either pyrometallurgical or hydrometallurgical. Table 1 compares several aspects of water use in mineral processing and in pyrometallurgical and hydrometallurgical processes in base metals refining (Marr and Petrie (2002) – as reported by Brown (2002)).

Table 1. Aspects of water use in base metals refining.

Aspect	Mineral processing	Pyrometallurgical	Hydrometallurgical
Water use	Transport	Utilities (cooling) Pollution abatement Granulation	Reaction medium Transport Utilities Pollution abatement
Inventory	Very large	Small	Large
Re-use	Very high	High	Moderate to high
Water quality	Raw to potable	Raw to potable	Potable to demineralised
Losses	Entrainment Evaporation	Evaporation	Inventory Evaporation Spills/releases Products
Environmental impact	Consumption Suspended solids	Consumption Thermal Acidification (via atmospheric transport)	Consumption Ecotoxicity Eutrophication Acidification Chemical oxygen demand Suspended solids

The sources of water supplies for the above uses within the minerals industry are varied. They may come from local water authority reticulation systems, purpose-built dams, rivers, lakes and groundwater sources of several kinds, including artesian water as at Olympic Dam. Sometimes the supply is located some distance from the mine site, requiring the use of purpose-built pipelines. According to Chartres and Williams (2003) and Anon (2004a), only about 5% of the water consumed by the Australian mining industry in 1996-97 was supplied through mains infrastructure, with 95% sourced locally from surface and groundwater.



## 2.1 Mine site water balance

As the mineral processing stage uses a large proportion of the total water required in the life cycle of metal production, it is of interest to consider the mine site water balance<sup>2</sup>. A simplified mine site water balance (excluding internal mill water recycles, eg. from thickener overflows, dewatering and filtering operations) is shown in Figure 1, although there are many variations on this figure in practice. The common sources of water used on mine and processing sites are (Brown, 2003):

- groundwater extracted from bores;
- groundwater inflows into the mine;
- reclaimed, treated and recycled water;
- purpose-built dams and/or pipelines;
- surface run-off and storm water collected on site
- rivers or lakes;
- reticulated supplies from local water companies or authorities.

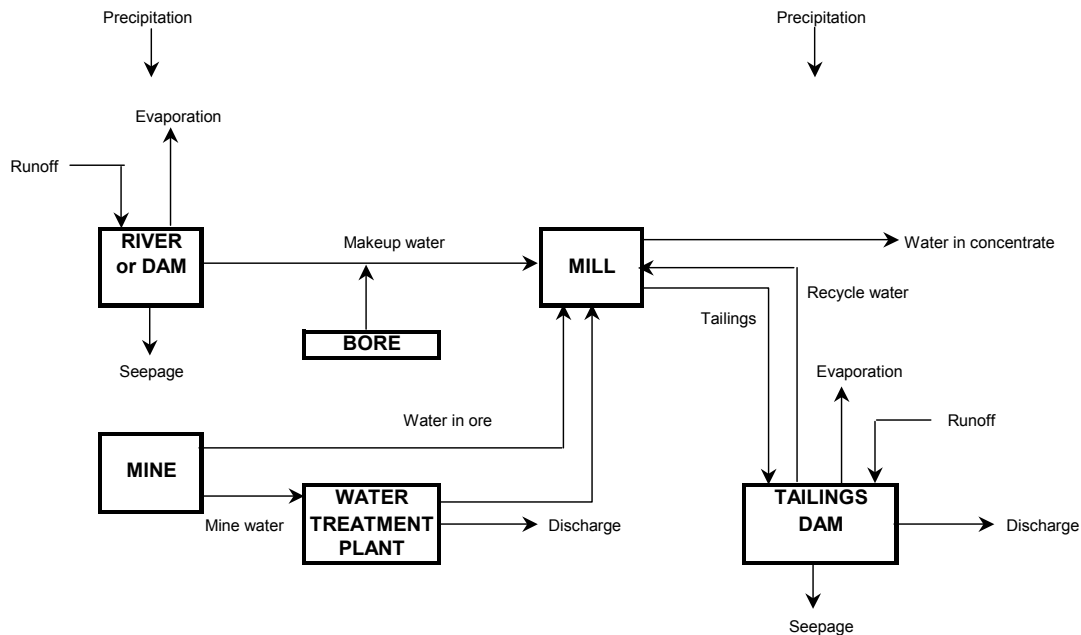


Figure 1. Mine site water balance.

McQuade and Riley (1996) gave a typical water balance for a mine makeup water or tailings dam according to the following equation:

$$\Delta \text{ Dam storage} = \text{Rainfall} + \text{Groundwater flow} + \text{Runoff} + \text{Returns from process} - \text{Inputs to process} - \text{Evaporation} - \text{Seepage} - \text{Discharge} \pm \Delta \text{ Pump transfers}$$

Historically, in Australia and elsewhere, many mining projects have failed because of a lack of adequate supplies of water on the one hand, or an

<sup>2</sup> Refining may or may not be carried out on the same site as mining and mineral processing.

inability to control inflows of water into mining excavations on the other. Australian mining lore and history is filled with stories of explorers and miners suffering from a lack of water and having to go to great lengths to transport water to newly discovered mining fields. A classic example of this is the search for, and eventual supply of, water to the Eastern Goldfields in the Kalgoorlie-Coolgardie district of Western Australia. A more recent example is given by Gibson et al (2003) who report that water shortages caused a loss of 100,000 t of plant feed to the Northparkes mine in NSW in 1998. Conversely, gold mining in central Victoria has been disrupted by too much water for much of the 20<sup>th</sup> Century.

The development of a mining operation often has an impact on local and regional groundwater systems (Hair, 2003). Impact occurs when mining progresses below the groundwater table, thereby creating a groundwater “sink” and altering the local flow regime. The altered flow regime drives inflows into open cut operations and underground mining voids which must be minimised and controlled in order to provide safe and dry working conditions. In drier situations, ie. when rainfall is low and evaporation is high, surface water storages (dams) are not a reliable water supply, and the mining operation may have to rely on a borefield, often located a considerable distance from the mining operation itself.

Many mining operations use water unsuitable for agriculture and re-use water within the constraints imposed by quality requirements, water availability, and discharge considerations as discussed later (Section 5.2). The water balance for a Bayer plant for alumina refining has been reported by Stegink et al (2003) and software tools have been developed for managing mine water balances (Anon, 2004b).

### **3 LIFE CYCLE ASSESSMENT**

Life Cycle Assessment (LCA) is one of a number of methodologies that have been developed in recent years to assess the potential environmental impacts associated with a product, process or activity during its entire life cycle. It essentially involves the compilation of an inventory of relevant exchanges during the life cycle and evaluating the potential impacts associated with those exchanges. LCA has also been referred to as “cradle-to-grave” analysis. The objective of most LCA studies is to find the design option that minimizes the life cycle impact of the process.

The LCA methodology has four distinct stages:

- the goal definition and scoping stage, where the goals and scope of the proposed study are described and agreed upon with reference to the intended application;
- the inventory stage, where the material and energy inputs and outputs to and from the system are quantified;

- the impact assessment stage, where the results of the inventory analysis are interpreted in terms of the potential impacts they have on the environment;
- the improvement assessment stage, where potential areas of improvement are identified.

The most time-consuming stage of a LCA is the inventory stage. There is generally a paucity of publicly available LCA inventory data, although this issue is slowly being addressed. Furthermore, published inventory data are rarely mass-balanced for a particular plant or process, and data must be combined from different sources. This is particularly true for water consumption, as this is currently one of the least reported operating parameters of a plant or process. The growing practice of companies to issue Environmental/Sustainability reports has improved this situation, but even then the reported data are often aggregated over a company's plant or total operations, with very little stage-by-stage detail on water consumption.

The inventory results are classified according to the kind of problems to which they contribute during the impact assessment stage. Attempts are then made to quantify the contributions to each impact category. Assessing environmental impacts often requires equivalency factors to indicate how much a particular substance contributes to an environmental impact compared to a reference substance. Some of the environmental impacts commonly considered are:

- global warming – measured relative to the effect of 1 kg of CO<sub>2</sub>;
- acidification - measured relative to the effect of 1 kg of SO<sub>2</sub>;
- photochemical oxidant formation - measured relative to the effect of 1 kg of ethylene;
- nitrification - measured relative to the effect of 1 kg of phosphate;
- resource depletion – measured relative to world reserves.

### 3.1 Goal and scope

LCAs of various metal production processes have been carried out by CSIRO Minerals (eg. Norgate and Rankin, 2000; Norgate and Rankin, 2002) to assess the environmental impacts associated with greenhouse and acid rain gaseous emissions along with the Gross Energy Requirement of the processes. To expand the environmental impacts included in these LCAs and to add life cycle perspective to the debate about water resources and their sustainability, LCA methodology has been used to estimate typical life cycle water consumptions for the production of a number of metals by the processes shown in Table 2.

The system boundary for the study described here was restricted to “cradle-to-gate”, i.e., the processes have only been considered to the point where refined metal is available to the secondary manufacturing sector. For

simplicity reasons the functional unit chosen for the study was m<sup>3</sup> (or tonnes) of fresh or raw water consumed per tonne of refined metal.

LCA spreadsheet models of each process flowsheet were previously set up using CSIRO Minerals in-house, Excel-based, LCA software (LCA-PRO). The flowsheets were constructed at a level of detail consistent with available process data, generally resulting in flowsheets of 3-4 process steps; mining, mineral processing, smelting and refining.

Table 2. Metal production processes included in the LCA.

Metal	Process	Feed
Copper	Smelting/converting & electrorefining	Sulphide ore (3% Cu)
	Heap acid leaching & SX/EW	Sulphide ore (2% Cu)
Nickel	Flash furnace smelting & Sherritt-Gordon refining	Sulphide ore (2.3% Ni)
	Pressure acid leaching & SX/EW	Laterite ore (1% Ni)
Lead	Blast furnace	Sulphide ore (8.6% Zn; 5.5% Pb)
	Imperial smelting process	Sulphide ore (8.6% Zn; 5.5% Pb)
Zinc	Imperial smelting process	Sulphide ore (8.6% Zn; 5.5% Pb)
	Electrolytic process	Sulphide ore (8.6% Zn; 5.5% Pb)
Aluminium	Bayer/Hall-Heroult processes	Bauxite (17.4% Al)
Titanium	Becher/Kroll processes	Mineral sands (9.8% Ti)
Iron/steel	Blast furnace & Basic Oxygen furnace	Iron ore (64% Fe)
Stainless steel	Electric arc furnace / argon oxygen decarburization	Ferronickel (23% Ni, 69% Fe)
	Electric arc furnace / argon oxygen decarburization	Nickel (100% Ni)
Gold	CIL cyanidation & EW/smelt	Gold ore (3.6 g Au/t)

### 3.2 Inventory and assumptions

The water consumption data used for input to each LCA spreadsheet model were derived solely from publicly-available literature, with the data being cross-checked with more than one source where possible. These data are summarised in Table 3 and given in detail in Appendix B. It should be appreciated that there can be a wide range of water consumption data between sites, even for the same metal production route, and the data given in Table 3 are meant to be average or typical values only for each process. In addition to the direct water consumption data shown in Table 3, LCA methodology also requires indirect water consumption to be included, ie. water consumed in producing some of the other raw materials used in the various process stages, eg. ammonia in the Sherritt-Gordon refining stage for nickel, lime in the Bayer alumina refining stage for aluminium, and also in generating the electricity consumed in the various stages of a metal's life cycle. While these indirect water consumption amounts were included in the LCAs, they are not shown in Table 3.

The following assumptions were made in deriving the indirect water consumption data for electricity generation and consumption for the various metal production processes:

- electricity in the State grids was assumed to be generated in conventional coal-fired power plants;
- water consumption (via evaporative losses) for conventional coal-fired power plants was assumed to be 1.76 m<sup>3</sup>/MWh (ACARP, 2001);

- water consumption for diesel-fuelled generating sets was assumed to be small (air-cooled and/or sealed water cooling systems) and hence can be ignored;
- 60% of Australian gold production is from small to medium operations (Tyrwhitt et al, 1993) and it was assumed that these operations generate their electricity on-site using diesel-fuelled generating sets – large operations were assumed to obtain their electricity from State grids;
- based on the above assumptions, the indirect water consumption value for electricity consumption for small to medium gold operations is 0.70 m<sup>3</sup>/MWh (ie. 0.6 x 0 + 0.4 x 1.76).

Table 3. Water inventory data used in study.

Metal	Process	Stage	Water consumption	
Copper	Smelting/convertng & electrorefining	Mine & concentrator	0.37	m <sup>3</sup> /t ore
		Smelting	7.8	m <sup>3</sup> /t Cu
		Refining	0.6	m <sup>3</sup> /t Cu
	Heap acid leaching & SX/EW	Mining & heap leaching	23.0	m <sup>3</sup> /t Cu
SX/EW		6.4	m <sup>3</sup> /t Cu	
Nickel	Flash furnace smelting & Sherritt-Gordon refining	Mine & concentrator	0.93	m <sup>3</sup> /t ore
		Smelting	0.81	m <sup>3</sup> /t conc
		Refining	7.16	m <sup>3</sup> /t matte
	Pressure acid leaching & SX/EW	Total all stages *	3.4	m <sup>3</sup> /t ore
Lead	Blast furnace	Mine & concentrator	0.64	m <sup>3</sup> /t ore
		Smelting	4.85	m <sup>3</sup> /t Pb
		Refining	0.47	m <sup>3</sup> /t Pb
	Imperial smelting process	Mine & concentrator	0.64	m <sup>3</sup> /t ore
		Smelting	12.73	m <sup>3</sup> /t Pb
		Refining	0.47	m <sup>3</sup> /t Pb
Zinc	Imperial smelting process	Mine & concentrator	0.64	m <sup>3</sup> /t ore
		Smelting	12.73	m <sup>3</sup> /t Zn
		Refining	0.54	m <sup>3</sup> /t Zn
	Electrolytic process	Mine & concentrator	0.64	m <sup>3</sup> /t ore
		Electrolytic refining	12.33	m <sup>3</sup> /t Zn
Aluminium	Bayer/Hall-Heroult processes	Mining	0.03	m <sup>3</sup> /t bauxite
		Bayer alumina refining	2.9	m <sup>3</sup> /t alumina
		Hall-Heroult smelting	1.5	m <sup>3</sup> /t Al
Titanium	Becher/Kroll processes	Mine & concentrator	5.16	m <sup>3</sup> /t ilmenite
		Becher process	6	m <sup>3</sup> /t S rutile
		Kroll process	40	m <sup>3</sup> /t Ti
Iron/steel	Blast furnace & Basic Oxygen furnace	Mine & concentrator	0.21	m <sup>3</sup> /t ore
		Sintering	0.15	m <sup>3</sup> /t sinter
		BF & BOF	1.94	m <sup>3</sup> /t steel
Stainless steel	Electric arc furnace / argon oxygen decarburization – ferronickel feedstock	Smelting & refining	2.24	m <sup>3</sup> /t s steel
	Electric arc furnace / argon oxygen decarburization – nickel feedstock	Smelting & refining	2.24	m <sup>3</sup> /t s steel
Gold	CIL cyanidation & EW/smelt	Total all stages *	0.74	m <sup>3</sup> /t ore

\* Stage-by-stage data not available.

## 4 RESULTS

The LCA “cradle-to-gate” results are summarised in Table 4 (column 3) and Figure 2. By far the largest “cradle-to-gate” water consumption was for gold production at 252,087 m<sup>3</sup> water/t gold, followed by nickel produced by the hydrometallurgical (pressure acid leaching) route at 377 m<sup>3</sup> water/t nickel. Steel production had the lowest water consumption at 2.9 m<sup>3</sup> water/t

steel. Figure 2 shows both the direct and indirect water consumptions for each metal production process, with the sum of the two values representing the “cradle-to-gate water consumptions given in Table 4. Because of the high value for gold compared to the other metals, the actual value could not be plotted in Figure 2, however the relative proportions of direct and indirect water consumptions for gold shown in Figure 2 are the correct proportions, having been scaled from the actual values. In order to see the direct and indirect relativities better for the other metals, the results in Figure 2 are reproduced in Figure 3 without the gold and nickel hydrometallurgical results.

Table 4. Life cycle (“cradle-to-gate”) water consumption for metal production.

Metal	Process	Water consumption		Metal \$ value /m <sup>3</sup> water consumed
		(m <sup>3</sup> water/t metal)	(m <sup>3</sup> water/t ore)	
Copper	Smelting/converting & electrorefining	25.9	0.7	158
	Heap acid leaching & SX/EW	38.0	0.5	105
Nickel	Flash furnace smelting & Sherritt-Gordon refining	79.0	1.4	250
	Pressure acid leaching & SX/EW	376.6	3.5	52
Lead	Blast furnace	12.6	0.5	95
	Imperial smelting process	21.7	0.9	55
Zinc	Imperial smelting process	21.2	1.5	66
	Electrolytic process	26.3	1.8	53
Aluminium	Bayer/Hall-Heroult processes	35.9	6.2	68
Titanium	Becher/Kroll processes	110	5.4	216
Iron/steel	Blast furnace & Basic Oxygen furnace	2.9	1.8	125
Stainless steel	Electric arc furnace / argon oxygen decarburization – ferronickel feedstock	74.0	13.7	25
	Electric arc furnace / argon oxygen decarburization – nickel feedstock	13.4	2.0	139
Gold	CIL cyanidation & EW/smelt	252087	0.8	80

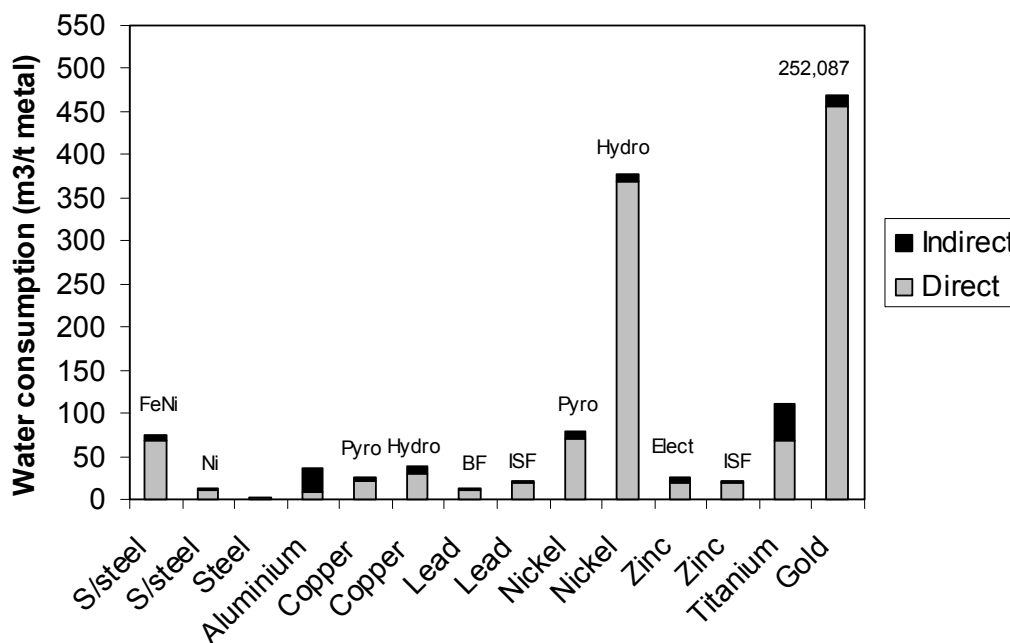


Figure 2. Life cycle water consumptions – all metals (m<sup>3</sup>/t refined metal).

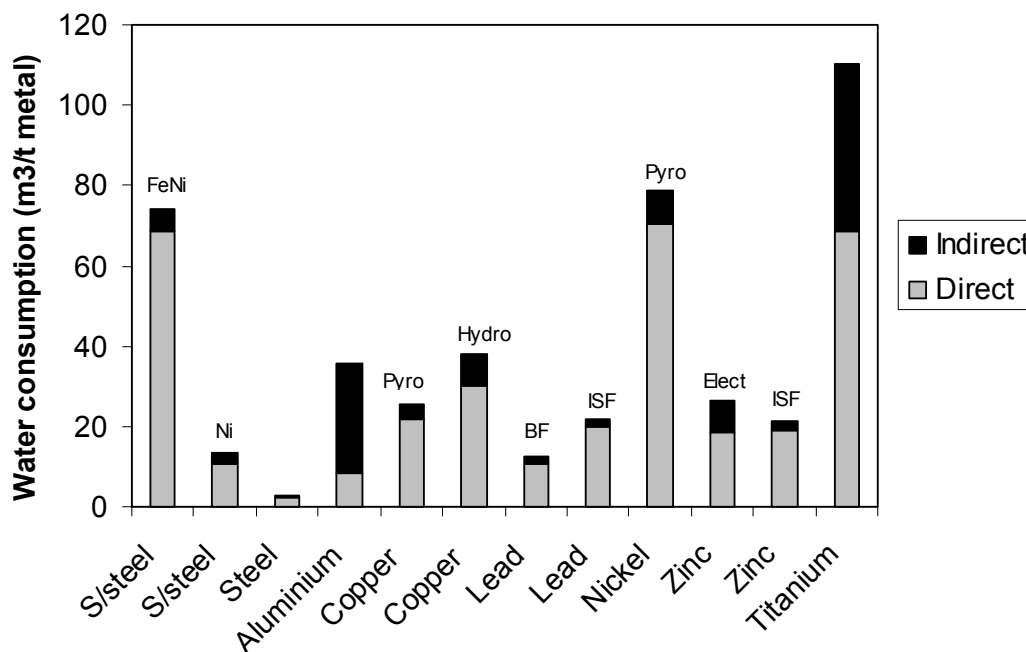


Figure 3. Life cycle water consumptions – excluding gold and nickel hydro (m<sup>3</sup>/t refined metal).

Figure 3 highlights the finding that indirect water consumption makes a significant contribution to the “cradle-to-gate” results for those metals requiring substantial inputs of electricity in their production, eg. aluminium and titanium.

The “cradle-to-gate” water consumptions largely reflect the grade of the initial ore used to produce each metal as shown in Figure 4, using the data presented in Tables 2 and 4, but excluding the two stainless steel results as more than a single ore is used to produce this metal (ie. iron ore, chrome ore and nickel ore). The equation of the line fitted to the data in Figure 4 is given below, and may be used to give a rough first estimate of the “cradle-to-gate” water consumption for the production of most refined metals.

$$W = 167.7 G^{-0.9039} \quad (R^2 = 0.916)$$

where  $W$  = “cradle-to-gate” water consumption (m<sup>3</sup>/t refined metal)  
 $G$  = grade of ore used to produce metal (% metal)

While the functional unit of the LCAs was one tonne of refined metal as outlined earlier, Table 4 also includes the results expressed per tonne of ore extracted from the ground (column 4). When expressed in this way, there is less spread in the results, once again reflecting the influence of ore grade. The mean value of “cradle-to-gate” water consumption for all metals was 2.1 m<sup>3</sup>/t ore, and the mean value of water consumed in the mining and concentration stage for all metals was 0.7 m<sup>3</sup>/t ore, identical to the mean value quoted by Brown (2003) of 0.7 m<sup>3</sup>/t ore (range 0.4 – 1.0 m<sup>3</sup>/t ore) for the amount of water typically consumed in mining and concentrating operations

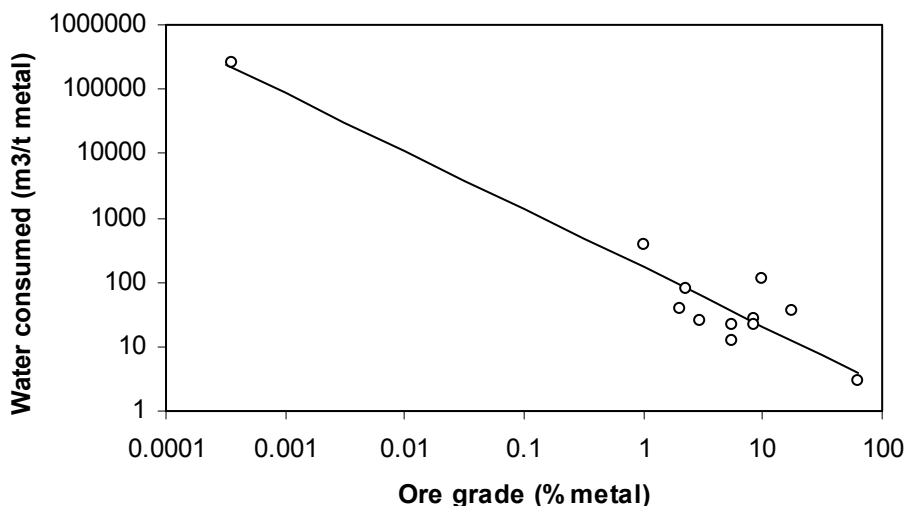


Figure 4. Cradle-to-gate water consumption as a function of ore grade.

The economic or monetary value of each metal per m<sup>3</sup> of water consumed in their production is also included in Table 4 (column 5) and plotted in Figure 5. Despite its high price (viz. US\$400/oz or US\$14.1 M/t), gold has a relatively low \$/m<sup>3</sup> water value due to its high “cradle-to-gate” water consumption. Nickel produced via the pyrometallurgical route had the highest \$/m<sup>3</sup> water value, followed by titanium. Stainless steel produced using ferronickel feedstock had the lowest \$/m<sup>3</sup> water value of all the metals considered.

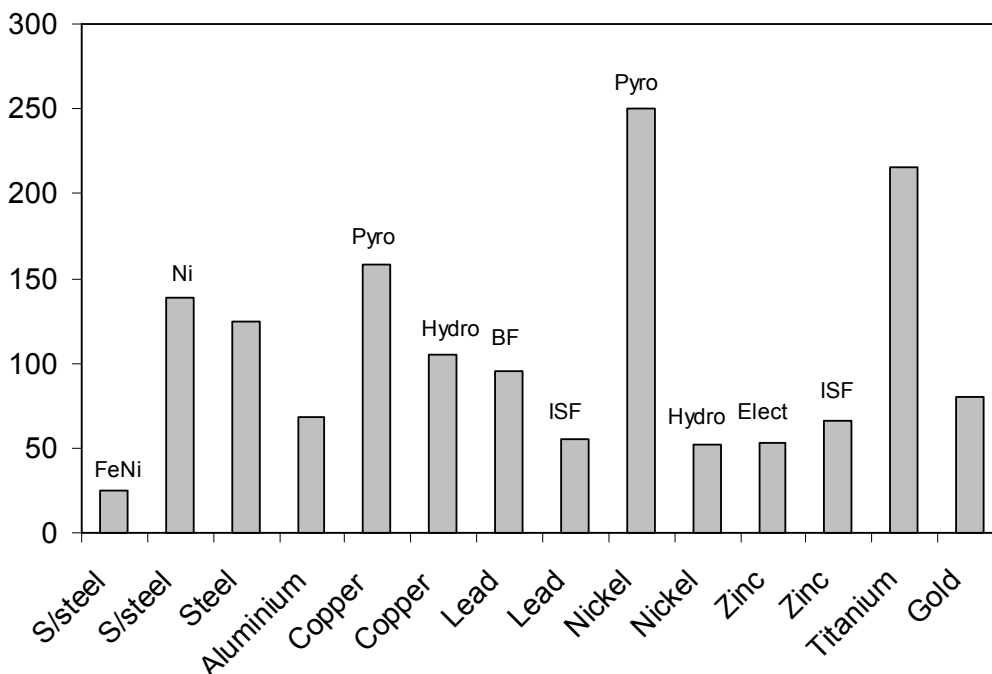


Figure 5. Metal economic value/m<sup>3</sup> water consumed in production.

The contributions of the various process stages to the “cradle-to-gate” water consumptions are shown in Appendix C for all metals considered in the study,



with the exception of nickel by the hydrometallurgical route (pressure acid leaching) and gold, for which the water consumption data were not broken down into individual process stages.

## 5 DISCUSSION

Using a life cycle approach enables a more accurate assessment of the consumption of water over the supply chain of metal production to be made. In the processes studied, the mean “cradle-to-gate” water consumption was approximately three times the mean for the mining and concentration stage (when expressed in terms of m<sup>3</sup>/t ore) – a result not readily obtained without using LCA. This illustrates the contribution that LCA methodology can make to the debate about sustainable water resources and their allocation. Other issues related to water allocation and use in the minerals industry are discussed in the next sections.

### 5.1 Economic value of water

The minerals industry is generally said to provide a greater financial return per unit of water used than the agricultural industry, which is the largest user of water in Australia (see Appendix A - Figure A3). This is shown in Table 5, where the economic value per m<sup>3</sup> (or kL) of water consumed is shown for a range of goods and services across a number of industry sectors, taken from various sources. Values for the various metals from Table 4 are also included in Table 5, with mean values shown where there are competing processes in Table 4.

However, economic measures are not the sole criteria for allocating water resources. For example, water can be allocated on a more “sustainable” basis by allowing for the other two components (viz. environmental and social) of the “triple-bottom-line” concept when determining water resource allocation. The provision of minimum flows to sustain healthy wetlands, the allocation of minimum water volumes for recreation and tourism and the allocation of water to the production of food crops are all examples that suggest short term economics is not the only factor applied to water allocation.

Water reform in the Australian states is taking place on the basis of the principles espoused in the National Water Initiative Agreement (Anon, 2004a; DPMC, 2004) established in 2004 by the Council of Australian Governments (COAG) for the efficient and sustainable reform of the Australian water industry. The key elements of the Agreement are:

- improve the security of water access entitlements, including by clear assignment of risks of reductions in future water availability and by returning overallocated systems to sustainable allocation levels;
- ensure ecosystem health by implementing regimes to protect environmental assets at a whole-of-basin, aquifer or catchment scale;

Table 5. Economic value per m<sup>3</sup> of water consumed for various sectors.

Industry sector	A\$/m <sup>3</sup> water consumed			
	This study	Farmweb website	Urban ecology website	Foran & Poldy (2002)
<b>Agriculture</b>				
Rice		0.19	0.13	0.13
Wheat & grain				4.08
Beef cattle			2.60	1.23
Dairy cattle & milk			1.47	0.68
Sugar cane		0.42	0.81	0.81
Cotton		0.61	0.63	0.63
Fruit & vegetables		1.60	9.70	2.64
<b>Mining &amp; metal production</b>			33	
Copper	132			
Nickel	151			
Lead	75			67
Zinc	60			
Aluminium	68			
Titanium	216			
Iron & steel	125			
Stainless steel	82			
Gold	80			67
Black coal				45
Crude oil				77
Iron ore				43
Bauxite				2.7
<b>Industrial</b>				
Pulp & paper			33	20
Basic chemicals				28
Cement & concrete				67
<b>Services</b>				
Health & education			143	143
Banking			143	111
Community service				37

- ensure water is put to best use by encouraging the expansion of water markets and trading across and between districts and States (where water systems are physically shared), involving clear rules for trading, robust water accounting arrangements and pricing based on full cost recovery principles;
- encourage water conservation in our cities, including better use of stormwater and recycled water.

The implications of water reforms for the mining industry are discussed by Gilbert and Fenton (2003) who suggested that::

- in areas where water resources are limited and systems are already stressed, reform plans will restrict or ban access to new entitlements and access to water may become solely dependent on being able to acquire water entitlements from existing users under trading rules;
- for new mining projects or projects undergoing expansion, and which are located in areas subject to developing water planning, it is likely that

moratoriums on new water development will be imposed pending the outcome of catchment hydrological assessments and subsequent operational plans;

- in other areas where water sharing plans are in force (typically current for ten years) it will be important to understand and monitor changes in supply reliability, especially for entitlements which amount to a share of a variable resource – the assumption of guaranteed supply is not valid.

These water reforms will likely see increased pressure on the minerals industry, along with others, to reduce raw water consumption. Some of the issues associated with achieving this goal are discussed below.

## 5.2 Water quality

Water quality is an important operational issue in mineral processing operations such as flotation, flocculation, and agglomeration, and can also be significant in gravity and magnetic separations, as well as in grinding, classification, thickening and filtration. In general, water quality is relevant whenever the chemical nature of the mineral surface is important. However, relatively little research effort has been devoted to understanding and controlling the influence of water quality on these processes. Historically, this probably stems from the perception of water as an inert transport medium. However, the changing attitude towards water as a valuable resource has given impetus to increasing requirements to use relatively impure make-up water supplies (Schumann et al, 2003).

The quality of water can range from very high quality, soft water derived from melting snow, to poor quality hard water (high levels of dissolved calcium and magnesium) from underground aquifers and to even lower quality seawater (very high levels of dissolved solid including sodium chloride). Some underground water is much more saline than seawater, a phenomenon well known in Western Australia. High quality water is not always required. For example, gold projects in Western Australia have operated effectively with water qualities up to almost 300,000 mg/L total dissolved solids (TDS) together with pHs as low as 3.0-3.5 for CIP/CIL processing, while the Mt Keith nickel project uses a process water supply that ranges up to well over 100,000 mg/L TDS despite the optimum water quality for the project being specified as between 15,000 and 20,000 mg/L (Dundon, 2000).

Laboratory flotation tests on a copper-gold ore (Schumann et al, 2003) indicated that while copper recovery is generally unaffected by the type of water used, both gold and sulphur recovery are influenced by the water used during flotation. The results suggested that gold recovery in particular appears to be lower in water where the salinity is very low (dam water). Sulphur recovery was dependent on water TDS, with those waters having higher TDS resulting in higher recovery. Gold recovery showed a similar but much less significant effect, while copper recovery was independent of TDS in the water used for flotation. While these observations suggest that salinity (ie. TDS)

improves gold recovery within certain limits, the authors advocate that further research be carried out to better understand the impact of water quality on sulphide flotation. The effect of water quality on flotation has also been studied by Levay et al (2001), while Janssen (2003) examined the effect of sediment in water on mining and mineral processing operations.

In light of the above comments, the water strategy that should be adopted by mining, mineral processing and metal production operations is to use water that is “fit for purpose”, an approach that is used by Rio Tinto (O’Reilly, 2003).

### 5.3 Water recycling

The two main objectives of water recycling in the mineral process industry are to reduce the demand for fresh or raw water and to reduce the volume of effluent. Re-use of water is not a new concept, with the re-use of process water, generally without treatment, long being a feature of water management in mineral processing plants internationally (Brown, 2002).

The treatment and re-use of process, mine, domestic and industrial waters is now becoming a significant means of minimising overall water consumption and the volume of contaminated water that may require treatment prior to transfer to long-term water storages, streams or sale to a third party. The effect of recycled water properties on plant performance, including issues regarding the recycle of organic molecules, inorganic and microbiological species, and the build-up of collectors, is discussed by Johnson (2003).

Typically, treatment before re-use is required to reduce acidity or to remove metals, dissolved salts or suspended solids, including biological materials and micro-organisms. The major contaminants and their typical sources are listed in Table 6 (Brown, 2002). There are a wide range of water treatment options available and Table 7 lists those methods with very low capital and operating costs that are favoured by the minerals industry (due to the prevailing low value of the metal products in general) as reported by Johnson (2003).

Table 6. Contaminants on mining sites and their sources (Brown 2002 – from Pulles et al 1995)

Contaminant	Typical source
Metals – iron, manganese, zinc, lead, copper	Pyrite oxidation in underground stopes & surface rock and sand dumps & slimes dams with dissolution of metals
Sulphate	Pyrite oxidation in underground stopes & surface rock and sand dumps & slimes dams to produce sulphates
Cyanide	Spillage from plant areas, ruptured slimes delivery pipelines and slimes dams
Suspended solids	Inadequate underground settling, runoff from surface rock, sand dumps & slimes dams
Sodium	Fissure water, addition of sodium-based neutralisation chemicals
Chlorides	Fissure water
Nitrogen compounds	Waste explosives, gas by-products from explosives, sewage and contaminated runoff from hostels
Phosphates	Sewage and contaminated runoff from hostels
Acidity	Pyrite oxidation underground, surface dumps (rock, sand & slimes), spillage from plant areas
Radionuclides	Pyrite oxidation in underground stopes & surface rock and sand dumps & slimes dams with dissolution of radionuclides

Microbes – faecal coliforms, coliphages	Faecal contamination of underground mine service water, poorly treated sewage, runoff from hostel areas, livestock grazing
-----------------------------------------	----------------------------------------------------------------------------------------------------------------------------

Table 7. Methods for water treatment (Johnson 2003 – from Rao and Finch 1989).

Category	Method	Application
Chemical reaction	Chemical precipitation	Removal of alkaline earth and heavy metal ions
	Chemical oxidation, eg. by ozone	Oxidation of most high molecular weight organics to simpler molecules
Adsorption on solid or at an interface	Adsorption on active carbon or coal	Removal of most organics
	Adsorption on mineral slimes	Removal of metal ions and some organics depending upon the slime composition
	Adsorption on bentonite clay	Removal of metal ions and amines
	Adsorption at gas-liquid interface	Removal of highly surface active organics (eg. alkyl sulphates)
Other methods	Biological oxidation	Removal of biodegradable organics
	Ion exchange resins	Removal of ionic species
	Reverse osmosis	Removal of electrolytes
	Atmospheric freezing	Removal of electrolytes and organics

The contribution of recycled water, including both internally recycled (ie within the mill or concentrator) and externally recycled (ie. external to the mill or concentrator, eg. from the tailings dam) water to the total amount of water consumed on a mining and mineral processing site varies from location to location. Thompson and Minns (2003) reported that the average percentage of water recycled for Newmont Australia's operations in 2002 was 44%, while the average percentage of water recycled for Rio Tinto's worldwide operations in 2002 was 25% (O'Reilly, 2003). A water recycling rate of 80% was reported by Schumann et al (2003) for Newcrest Mining's Cadia Hill gold mine in central NSW.

#### 5.4 Dry processing

Currently, the price of water fluctuates according to supply and demand conditions, with the average price of water in Australia being about A\$1/kL or A\$1000/ML (Urban Ecology). Pressures on water supply (as discussed above) are anticipated to result in water supplies for the minerals industry to become increasingly compromised. Thus water availability and cost are likely to drive changes in water consumption within the minerals industry.

While increased water recycling is an obvious candidate to help reduce the water consumption of mineral processing plants, there may be a more radical solution to the problem – the use of dry or near-dry processing technologies, for which the demand for water is small or zero (Napier-Munn and Morrison, 2003). If dry processing is to replace conventional mineral processing in applications in which water is scarce, unavailable or difficult to recycle, Napier-Munn and Morrison (2003) have suggested that two major issues will need to be addressed:

- a new paradigm will be required for the design of processing flowsheet - this will need to extend to innovative ways of valuing particular process routes, eg. more emphasis can be placed on achieving selective mineral

liberation in blasting and coarse comminution so that simple (dry) methods can be used to remove waste prior to conventional processing;

- research will be required to develop current dry methods to increase throughput and overcome other disadvantages, and to develop new dry separation methods, perhaps exploiting alternative mineral properties – special attention will have to be paid to efficient energy utilisation.

Dry processing has been applied to many products in the minerals industry including gypsum, salt, phosphate, talc, magnesite, diamonds, limestone, potash, gold, coal, uranium and copper-lead-zinc ores (Brown, 2003). In recent years at CSIRO Minerals, dry particle separation research has focussed on using a vibrating plate separator that classifies particles on the basis of size and density (O'Connor et al, 2002).

The most serious problem with dry processing is currently considered to be dust and its association with health and environmental issues. There are many other unknowns associated with dry processing, and it is likely that the introduction of dry processing would bring with it a new set of problems.

## 6 CONCLUSIONS

Water consumption data derived from the literature have been incorporated into previously developed LCA spreadsheet models to obtain “cradle-to-gate” water consumption values for a number of metals by various processing routes. The following conclusions may be drawn from the work:

- “cradle-to-gate” water consumption for production of the metals considered in the study ranged from 2.9 m<sup>3</sup>/t for steel up to 252,087 m<sup>3</sup>/t for gold;
- these results largely reflect the grade of the initial ore used to produce each metal, and can be approximated by the following equation:

$$W = 167.7 G^{-0.9039} \quad (R^2 = 0.916)$$

where  $W$  = “cradle-to-gate” water consumption (m<sup>3</sup>/t refined metal)  
 $G$  = grade of ore used to produce metal (% metal);

- the above correlation, together with varying degrees of water recycling, partly explains the wide range in water consumption data between mining, mineral processing and metal production sites often reported in the literature, even when using the same processing route ;
- LCA can be used to examine process pathways and highlight possible alternative processing routes with lower water use, eg. up to 80% less “cradle-to-gate” water use for stainless steel using nickel instead of ferronickel feedstock, with reductions of 40% for lead and 20% for zinc also being indicated – however there is often not a choice in determining

the most appropriate processing route for a particular orebody, as it is strongly influenced by mineralogy and grade;

- indirect water consumption in the metal production life cycle, in particular that due to electricity generation, made a significant contribution to the “cradle-to-gate” water consumption for aluminium, and to a lesser extent titanium;
- when expressed in terms of m<sup>3</sup>/t ore, the mean “cradle-to-gate” water consumption was 2.1 m<sup>3</sup>/t ore, while the mean water consumption for the mining and concentrating stage was 0.7 m<sup>3</sup>/t ore, indicating that “cradle-to-gate” water consumption is roughly three times that of the mining and concentration stage;
- water reforms currently taking place in Australia are likely to see issues such as competition for water access, reduced security of supply and increase in cost as major concerns of the minerals industry in the future – consequently the minerals industry, along with others, may come under increasing pressure to reduce fresh or raw water use;
- while water recycling is an obvious candidate to help reduce water consumption in the minerals industry, issues such as the associated recycling of organic molecules, inorganic and microbiological species, and the build-up of collectors, among others, will influence the extent to which this can be achieved, and a “fit for purpose” water strategy should be adopted by mining, mineral processing and metal production operations;
- the use of dry or near-dry processing technologies, for which the demand for water is small or zero, maybe a more radical solution to the water consumption problem, however it is likely that the introduction of dry processing would bring with it a new set of problems, including dust;
- the water-related issues facing the minerals industry represent part of a wider crisis in the availability and management of water resources facing many parts of the world.

While the focus of this study has been on water consumption, it should be borne in mind that when assessing the relative environmental merits of alternative processing routes, broader impacts (eg. greenhouse and acid rain gas emissions, nutrification, community capacity, economics etc.) must be considered in addition to water consumption/resource depletion, with each impact being weighted appropriately.

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**APPENDIX A**

**THE WATER CYCLE AND WATER RESOURCES**

## THE WATER (OR HYDROLOGIC) CYCLE

The water or hydrologic cycle, is driven by the sun's heat. It causes the water held in the oceans and on the surfaces of the land to vaporise (this process is known as evaporation). Rising warm air carries the water vapour with it, and as it rises the water vapour cools and condenses into tiny water droplets which join together to form clouds, that under certain conditions produce rain, hail or snow (collectively termed precipitation). Winds blow the clouds from the water source to other sites prior to precipitation.

Deposited on land, much of the rainwater soaks up into the topsoil of the earth. The roots of plants will absorb some of this water from the topsoil and some of the water will evaporate directly from the land back into the atmosphere. The water that does not evaporate or is not absorbed into the soil will run-off into rivers, lakes and wetlands or will migrate downwards into the groundwater (water held beneath the ground). In addition, the plants that absorbed the water will, under the heat of the sun, release the water back into the atmosphere through a process called transpiration. The collective effect of evaporation and transpiration is termed evapo-transpiration. When the water returns to the atmosphere, the evapo-transpired water forms clouds and the cycle continues. A schematic diagram of the water cycle is shown in Figure A1, while the estimated residence times of the world's water resources are shown in Figure A2 (both figures from UNEP, 2004).

It has been estimated that about 502,800 km<sup>3</sup> (Note: 1km<sup>3</sup> = 1000 GL (gigalitres)) of water evaporates each year over the oceans and seas, of which 458,000 km<sup>3</sup> (or about 90%) returns directly to the oceans through precipitation, while the remainder (44,800 km<sup>3</sup>) falls over land. With evapo-transpiration totalling about 74,200 km<sup>3</sup>, the total volume in the terrestrial hydrological cycle is about 119,000 km<sup>3</sup>. About 35% of this, or 44,800 km<sup>3</sup> is returned to the oceans as run-off from rivers, groundwater and glaciers. Annually the hydrologic cycle circulates nearly 577,000 km<sup>3</sup> of water.

## WORLD WATER RESOURCES

Reliable assessment of the amount of water stored on the Earth is a complicated problem because water is very dynamic. The total amount of water in the hydrosphere consists of the free water in liquid, solid or gaseous states in the atmosphere, on the Earth's surface, and in the crust down to a depth of approximately 2000 m. The world's water resource has been estimated (Shiklomanov, 2000) at approximately 1400 million km<sup>3</sup>. However 97.5% of this is saline water largely in the oceans, with only 2.5% as fresh water. Frozen water in the form of ice and permanent snow cover in polar and mountainous regions accounts for the greater proportion (68.7%) of this fresh water. Of the balance of 11 million km<sup>3</sup>, 90,000 km<sup>3</sup> is concentrated in lakes, reservoirs and river systems while the remainder lies underground. The above values are the natural static or long-term amounts of water stored in the elements of the hydrosphere. In the shorter-term, the values vary as a result

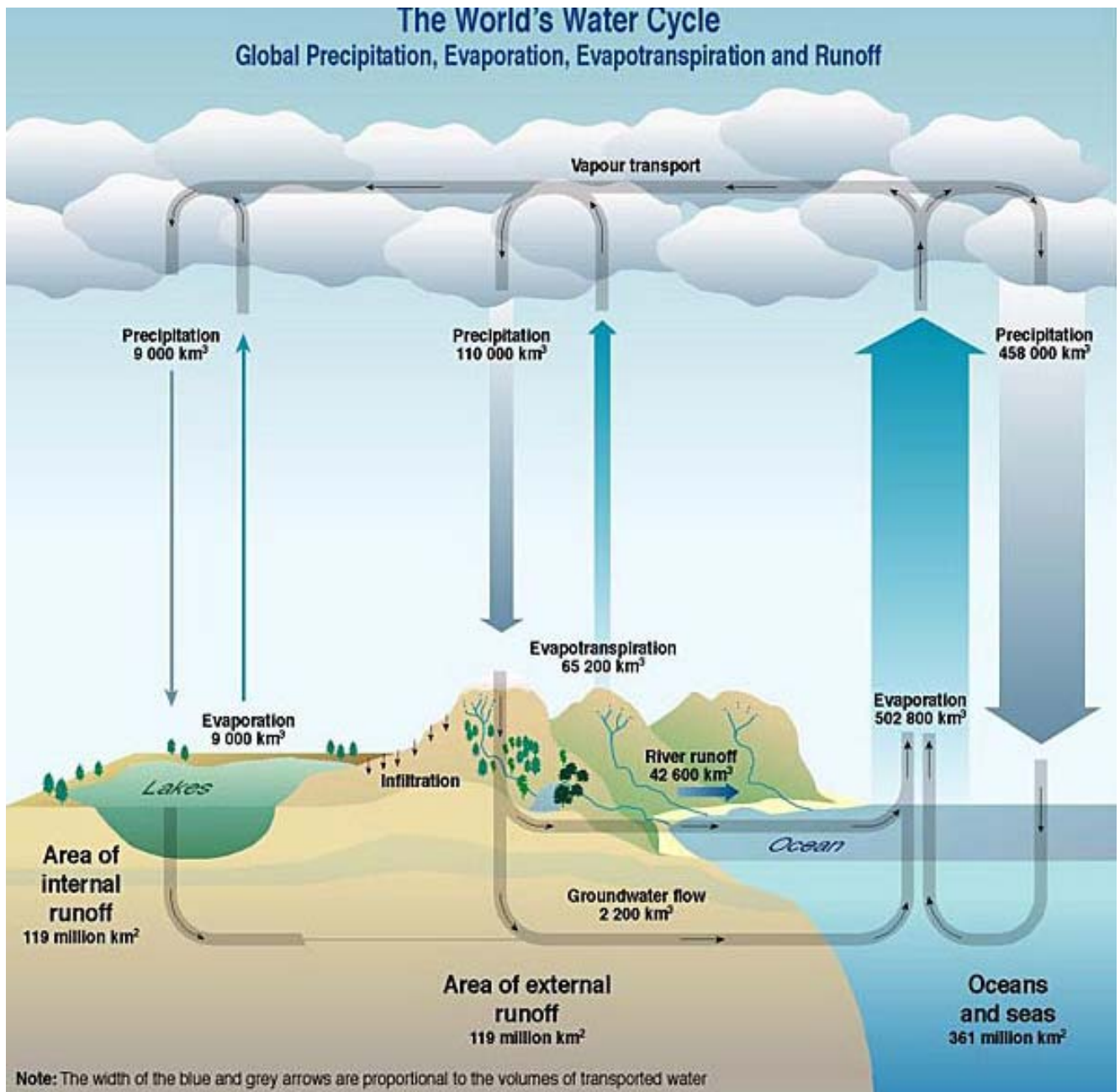
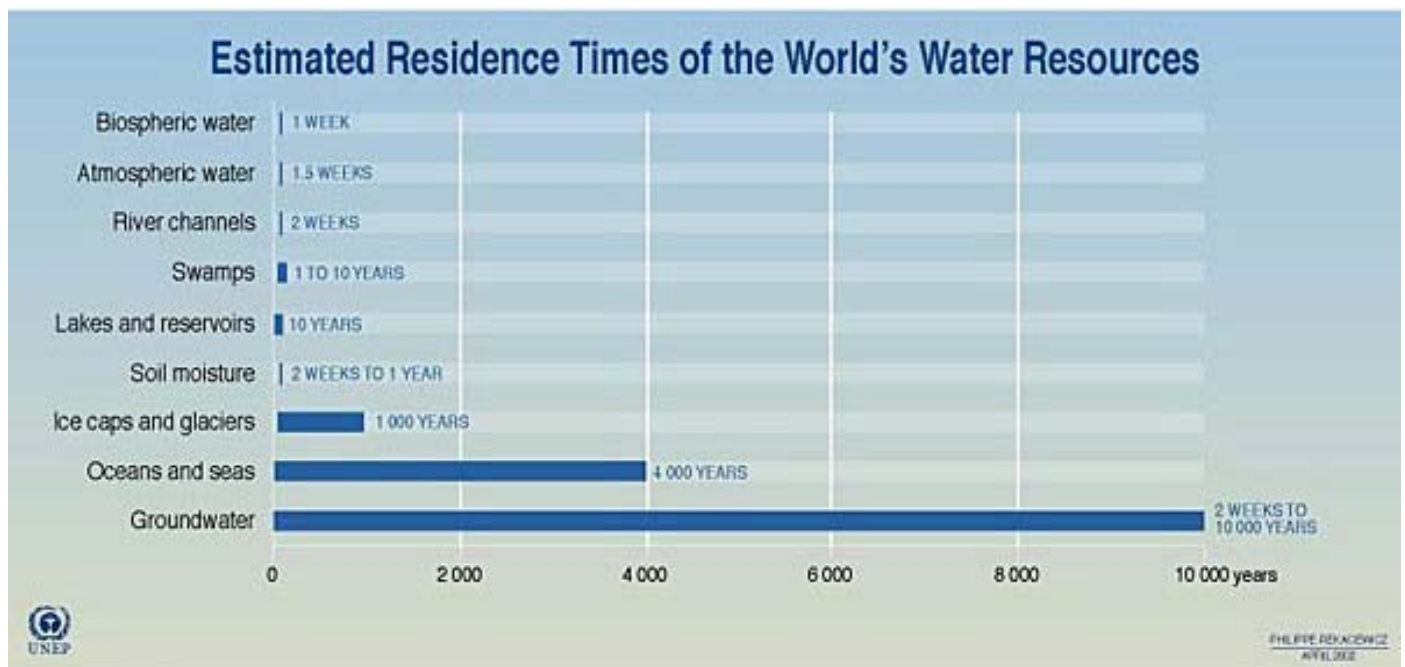


Figure A1. The world's water cycle (UNEP, 2004).

of water exchange between the oceans, the land and the atmosphere as part of the global hydrological cycle.

In hydrology and water management, two concepts are often used to assess water resources in a region – static freshwater storage and renewable water resources (Shiklomanov, 2000). The static storage conventionally includes freshwater with a period of full renewal of many years or decades (large lakes, groundwater, glaciers, etc.) Its intensive use unavoidably results in storage depletion and unfavourable ecological consequences. Renewable water resources include the water yearly replenished in the process of water turnover on the earth. The annually renewed volume, usually measured as



Source: Igor A. Shiklomanov, State Hydrological Institute (SHI, St. Petersburg) and United Nations Educational, Scientific and Cultural Organisation (UNESCO, Paris), 1999; Max Planck, Institute for Meteorology, Hamburg, 1994; Freeze, Allen, John, Cherry, *Groundwater*, Prentice-Hall: Englewood Cliffs NJ, 1979.

Figure A2. Estimated residence times of the world's water resources (UNEP, 2004).

volume per unit of time (eg.  $\text{km}^3/\text{year}$ ) consists mainly of the regional runoff and the inflow of groundwater into the river network.

Estimates of renewable water resources and availability by continent Shiklomanov (2000) are shown in Table A1. The mean global value of renewable water resources is estimated at  $42,780 \text{ km}^3/\text{year}$ , and it varies greatly in time and space. Australia (with Oceania) has the smallest volume ( $2400 \text{ km}^3/\text{year}$ ). Further breakdown of the data in Table A1 on a country-by-country basis is given by Shiklomanov, 2000). Globally, about 45-55% of the run-off that forms the total renewable resource occurs during periods of flooding, which means that some of the potential water supply shown in Table A1 is not actually available for use. The unevenness of river runoff distribution during a year leads to the desirability for human regulation through the creation of different types of reservoirs.

In considering water use, it is necessary to distinguish between the amounts of water withdrawn from the hydrosphere and the amount consumed. Water consumed is the amount of water loss after taking into account the water returned to the system. Shiklomanov (2000) reported that in 1995 total global water withdrawal was  $3788 \text{ km}^3/\text{year}$  while consumption was  $2074 \text{ km}^3/\text{year}$ , or 55% of withdrawal. This was predicted to increase to  $5235 \text{ km}^3/\text{year}$  and  $2764 \text{ km}^3/\text{year}$  (ie. 53% of withdrawal) respectively in 2025. The amount of water withdrawal in Australia in 1995 was estimated by Shiklomanov (2000) at  $27.1 \text{ km}^3/\text{year}$  and was predicted to increase to  $35 \text{ km}^3/\text{year}$  in 2025. Dunlop et al (2001a) give an estimate of  $22 \text{ km}^3/\text{year}$  for Australian water withdrawal.

Table A1. Renewable water resources and water availability by continent (Shiklomanov, 2000).

Continent	Area (10 <sup>6</sup> km <sup>2</sup> )	Population (millions, 1994)	Water resources (km <sup>3</sup> /year)			Potential water availability (1000 m <sup>3</sup> /year)	
			Average	Maximum	Minimum	Per 1 km <sup>2</sup>	Per capita
Europe	10.46	685	2900	3410	2254	277	4.23
North America	24.3	453	7890	8917	6895	324	17.4
Africa	30.1	708	4050	5082	3073	134	5.72
Asia	43.5	3445	13510	15008	11800	311	3.92
South America	17.9	315	12030	14350	10320	672	38.2
Australia & Oceania	8.95	28.7	2400	2880	1891	269	83.7
<b>(Australia)</b>	<b>(7.68)</b>	<b>(17.9)</b>	<b>(352)</b>	<b>(228)</b>	<b>(701)</b>	<b>(45.8)</b>	<b>(19.7)</b>
World	135	5633	42780	44750	39780	316	7.60

## AUSTRALIAN WATER RESOURCES

Australia is characterised by large variations in its water cycle, receiving a yearly average of about 3300 km<sup>3</sup>/year of rainfall (Dunlop et al, 2001b), however this is distributed very unevenly across Australia, throughout the year and between years. Evaporation also varies widely across the country, in vast areas of Australia surface evaporation can exceed rainfall, but there are also large areas in northern Australia that do have large seasonal surface runoff. On average about 12% of rainfall (ie. about 380 km<sup>3</sup>/year) ends up as runoff (Dunlop et al (2001a)). The latter figure compares with the values of 352 km<sup>3</sup>/year given by Shiklomanov (2000) in Table A1, 343 km<sup>3</sup>/year given by Gleick (1998) and 397 km<sup>3</sup>/year given by Dunlop et al (2001b).

Australia has vast underground water resources, which can be grouped into two main categories:

- artesian water – underground water that flows naturally to the surface
- sub-artesian water – underground water that does not naturally flow to the surface, and which needs to be pumped

Australia's potential annual groundwater supplies are about 15 km<sup>3</sup> or 15,000 GL (Dunlop et al, 2001a). About 150 GL/y (0.15 km<sup>3</sup>/year) of groundwater is used by the mining industry in Western Australia (Johnson and Commander, 2003) from an annual renewable groundwater source of 2500 GL (Water and Rivers Commission, 1998), with about 80 GL/y being used in the gold industry (Johnson and Commander, 2003). The mining industry extracts about 11 GL/y of groundwater from the Great Artesian Basin (Hillier et al, 2003).

Total net water consumption in Australia in 2000-01 was 24,909 GL (24.9 km<sup>3</sup>/year), with the breakdown into various sectors shown in Figure A3 (Australian Waterlines, 2004). Net water consumption refers to the amount of water used and not actively discharged back to existing water bodies. The mining industry consumed 401 GL or 1.6% of Australia's total water consumption, down from 570 GL (ie. 3%) in 1996-97 (Chartres and Williams, 2003). However the latter authors give a projected use of 810 GL for the mining industry in 2020. Dunlop et al (2001b) examined a number of different



scenarios in which the the total water consumption in Australia increased by up to 28,800 GL in 2050 and commented on the likely effects on Australia's water resources. As noted by Dunlop et al (2001a) – *“In gross terms Australia has more than enough water available to support rapid economic growth and healthy ecosystems for a considerable period – the reality is however that the mismatch between the natural variation and our production systems greatly limit that scope of growth”*.

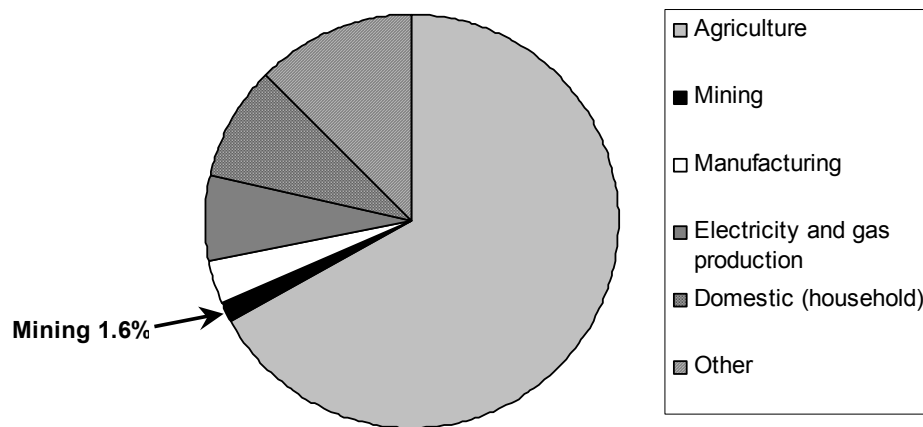


Figure A3. Australian water consumption by sector (2000-01).

**APPENDIX B**

**WATER CONSUMPTION DATA**

Metal	Process	Stage	Water consumption		Reference	
Copper	Smelting/converting & electrorefining	Mine & concentrator	0.53	m <sup>3</sup> /t ore	2002 MIM Environment and Community Report (Ernest Henry) 2002 MIM Environment and Community Report (McArthur River) Valenzuela copper (Chile) Falconbridge 2002 Sustainable Development Report (Kidd Mine) MEAN	
			0.34	m <sup>3</sup> /t ore		
			0.38	m <sup>3</sup> /t ore		
			<u>0.22</u>	m <sup>3</sup> /t ore		
			0.37	m <sup>3</sup> /t ore		
	Smelting		7.8	m <sup>3</sup> /t Cu	Boliden Environmental Facts 2003 (Ronnskar)	
	Refining		0.6	m <sup>3</sup> /t Cu	2002 MIM Environment and Community Report (Townsville)	
	Heap acid leaching & SX/EW	Mining & heap leaching		23.0	m <sup>3</sup> /t Cu	Miller (2003)
		SX/EW		6.4	m <sup>3</sup> /t Cu	By difference
		Total		23.1	m <sup>3</sup> /t Cu	Valenzuela (2003)
			30.0	m <sup>3</sup> /t Cu	Giurco et al (2001)	
		<u>35.0</u>	m <sup>3</sup> /t Cu	2003 BHP Billiton HSEC report (Cerro Colorada)		
		29.4	m <sup>3</sup> /t Cu	MEAN		
Nickel	Flash furnace smelting & Sherritt-Gordon refining	Mine & concentrator	0.92	m <sup>3</sup> /t ore	2000 WMC Business report and site data (Mt Keith) 2000 WMC Business report and site data (Leinster) 2000 WMC Business report and site data (Kambalda) Johnson & Commander (2003) Wright (1993) MEAN	
			0.93	m <sup>3</sup> /t ore		
			0.97	m <sup>3</sup> /t ore		
			0.92	m <sup>3</sup> /t ore		
			<u>0.90</u>	m <sup>3</sup> /t ore		
	0.93	m <sup>3</sup> /t ore				
	Smelting		0.81	m <sup>3</sup> /t conc	2000 WMC Business report and site data (Kambalda)	
	Refining		7.16	m <sup>3</sup> /t matte	2000 WMC Business report and site data (Kwinana)	
	Pressure acid leaching & SX/EW	Total all stages *		2.3	m <sup>3</sup> /t ore	Taylor & Cairns (1997)
				4.5	m <sup>3</sup> /t ore	Johnson & Commander (2003)
			3.4	m <sup>3</sup> /t ore	MEAN	
Lead	Blast furnace	Mine & concentrator	0.65	m <sup>3</sup> /t ore	2000 Pasminco Environment report (Broken Hill) 2000 Pasminco Environment report (Elura) 2002 MIM Environment and Community report (McArthur River) Milligan et al (2003) MEAN	
			0.95	m <sup>3</sup> /t ore		
			0.34	m <sup>3</sup> /t ore		
			<u>0.63</u>	m <sup>3</sup> /t ore		
			0.64	m <sup>3</sup> /t ore		
	Smelting		4.85	m <sup>3</sup> /t Pb	2000 Pasminco Environment report (port Pirie)	
	Refining		0.47	m <sup>3</sup> /t Pb	2002 MIM Environment and Community report (Northfleet)	
	Imperial smelting process	Mine & concentrator		0.65	m <sup>3</sup> /t ore	2000 Pasminco Environment report (Broken Hill) 2000 Pasminco Environment report (Elura) 2002 MIM Environment and Community report (McArthur River) Milligan et al (2003) MEAN
				0.95	m <sup>3</sup> /t ore	
				0.34	m <sup>3</sup> /t ore	
<u>0.63</u>				m <sup>3</sup> /t or		
0.64				m <sup>3</sup> /t ore		
Smelting		15.3	m <sup>3</sup> /t Pb	2002 MIM Environment and Community report (Avonmouth)		
		<u>10.15</u>	m <sup>3</sup> /t Pb	2000 Pasminco Environment report (Cockle Creek)		
		12.73	m <sup>3</sup> /t Pb	MEAN		
Refining		0.47	m <sup>3</sup> /t Pb	2002 MIM Environment and Community report (Northfleet)		

Zinc	Imperial smelting process	Mine & concentrator	0.65 0.95 0.34 <u>0.63</u> 0.64	m <sup>3</sup> /t ore m <sup>3</sup> /t ore m <sup>3</sup> /t ore m <sup>3</sup> /t ore m <sup>3</sup> /t ore	2000 Pasminco Environment report (Broken Hill) 2000 Pasminco Environment report (Elura) 2002 MIM Environment and Community report (McArthur River) Milligan et al (2003) MEAN
		Smelting	15.3 <u>10.15</u> 12.73	m <sup>3</sup> /t Zn m <sup>3</sup> /t Zn m <sup>3</sup> /t Zn	2002 MIM Environment and Community report (Avonmouth) 2000 Pasminco Environment report (Cockle Creek) MEAN
		Refining	0.54	m <sup>3</sup> /t Zn	Mean of copper (pyro) & lead (pyro)
	Electrolytic process	Mine & concentrator	0.65 0.95 0.34 <u>0.63</u> 0.64	m <sup>3</sup> /t ore m <sup>3</sup> /t ore m <sup>3</sup> /t ore m <sup>3</sup> /t ore m <sup>3</sup> /t ore	2000 Pasminco Environment report (Broken Hill) 2000 Pasminco Environment report (Elura) 2002 MIM Environment and Community report (McArthur River) Milligan et al (2003) MEAN
		Electrolytic refining	12.33	m <sup>3</sup> /t Zn	2000 Pasminco Environment report (Hobart)
	Aluminium	Bayer/Hall-Heroult processes	Mining	0.03 <u>0.03</u> 0.03	m <sup>3</sup> /t bauxite m <sup>3</sup> /t bauxite m <sup>3</sup> /t bauxite
Bayer alumina refining			2.6 2.2 2.9 3.0 <u>3.8</u> 2.9	m <sup>3</sup> /t alumina m <sup>3</sup> /t alumina m <sup>3</sup> /t alumina m <sup>3</sup> /t alumina m <sup>3</sup> /t alumina m <sup>3</sup> /t alumina	Mean of various miscellaneous sources 2002/2003 Worsley Aluminium HSEC report 2002 Alcan gove HSEC report 2002 Alcoa Sustainability report p 20 & 52 Stegink et al (2003) MEAN
Hall-Heroult smelting			1.5 <u>1.4</u> 1.5	m <sup>3</sup> /t Al m <sup>3</sup> /t Al m <sup>3</sup> /t Al	2003 Comalco sustainable development report 2002 Alcoa Sustainability report p 20 & 52 MEAN
Becher/Kroll processes		Mine & concentrator	5.16	m <sup>3</sup> /t ilmenite	By difference from data for Mine & Conc & Becher process in 2002 Iluka Sustainability report of 14.6 m <sup>3</sup> /t S rutile (mid & south west)
		Becher process	6	m <sup>3</sup> /t S rutile	Formanek et al (1997)
Iron/steel	Blast furnace & Basic Oxygen furnace	Kroll process	40	m <sup>3</sup> /t Ti	DRD report 1994, p. 19
		Mine & concentrator	0.3 0.21 <u>0.13</u> 0.21	m <sup>3</sup> /t ore m <sup>3</sup> /t ore m <sup>3</sup> /t ore m <sup>3</sup> /t ore	2003 Robe Social & Environment report 1999 Rio Tinto Social & Environment report 2003 bhpbilliton HSEC report MEAN
		Sintering	0.12 <u>0.16</u> 0.15	m <sup>3</sup> /t sinter m <sup>3</sup> /t sinter m <sup>3</sup> /t sinter	Sheng (1993) remas data sheet MEAN
	BF & BOF	1.94	m <sup>3</sup> /t steel	By difference from data for Mine & Conc, sintering & BF/BOF of 2.4 m <sup>3</sup> /t steel from various sources	
Stainless steel	Electric arc furnace / argon oxygen decarburization – ferronickel feedstock	Smelting & refining	2.24	m <sup>3</sup> /t s steel	bhpbilliton 2002 HSEC report (Samancor) bhpbilliton 2002 HSEC report (Eastern Chrome Mines Nickel Development Institute LCI Tables (2000)

	Electric arc furnace / argon oxygen decarburization – nickel feedstock	Smelting & refining	2.24	m <sup>3</sup> /t s steel	bhpbilliton 2002 HSEC report (Samancor) bhpbilliton 2002 HSEC report (Eastern Chrome Mines Nickel Development Institute LCI Tables (2000)
Gold	CIL cyanidation & EW/smelt	Total all stages *	1.14 0.89 0.50 0.81 <u>0.37</u> 0.74	m <sup>3</sup> /t ore m <sup>3</sup> /t ore m <sup>3</sup> /t ore m <sup>3</sup> /t ore m <sup>3</sup> /t ore m <sup>3</sup> /t ore	2000 WMC Business report and site data (Agnew) 2000 WMC Business report and site data (Central Norseman) 2000 WMC Business report and site data (St Ives) 2002 Placer Dome Sustainability report (Granny Smith) Barrick Gold, 2003 Responsibility report MEAN

\* Stage-by-stage data not found.

**APPENDIX C**

**PROCESS STAGE CONTRIBUTIONS TO THE “CRADLE-TO-GATE”  
WATER CONSUMPTIONS FOR TARGET METALS.**



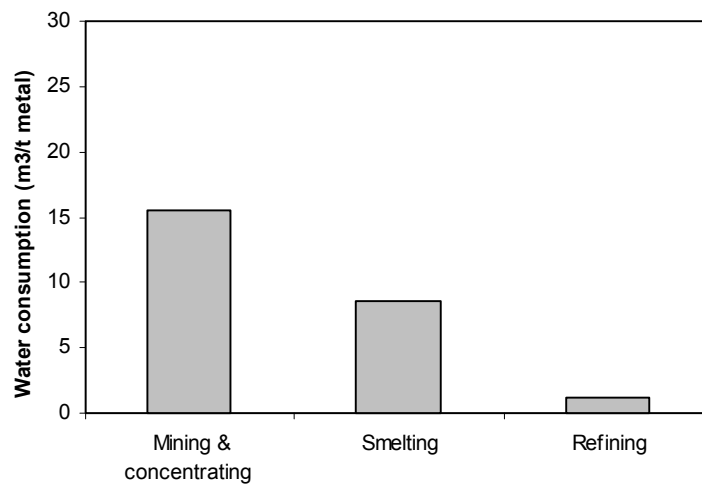


Figure C1. Process stage contributions to water consumption for copper production (pyrometallurgical route).

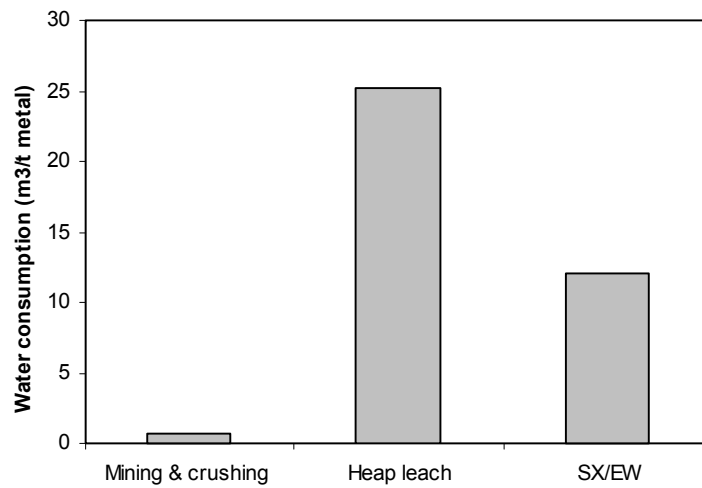


Figure C2. Process stage contributions to water consumption for copper production (hydrometallurgical route).

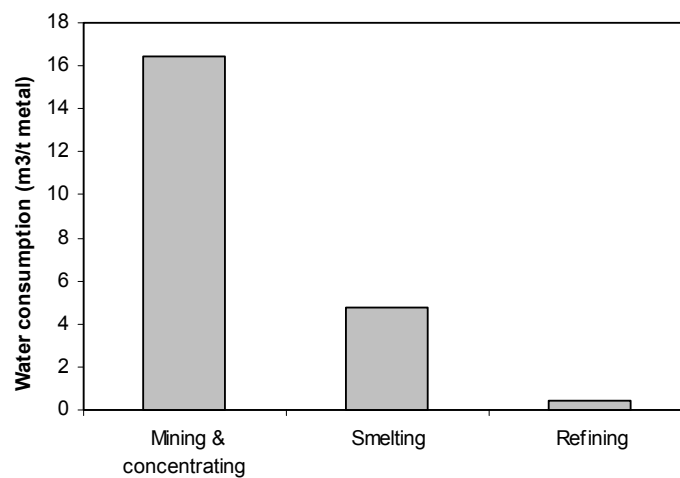


Figure C3. Process stage contributions to water consumption for lead production (Imperial smelting furnace).



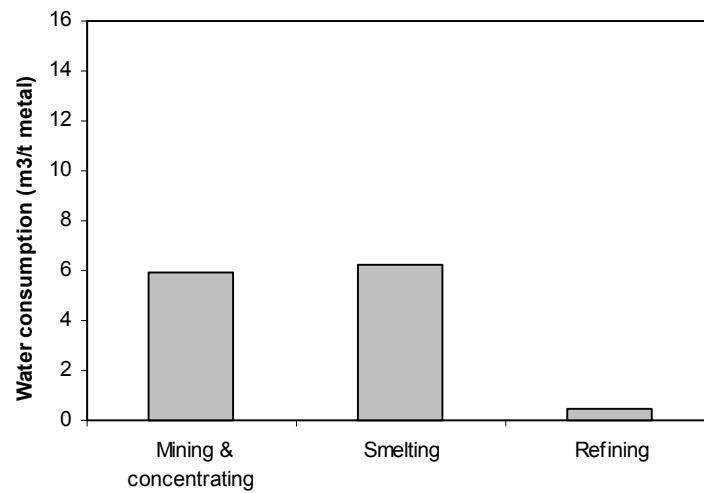


Figure C4. Process stage contributions to water consumption for lead production (blast furnace).

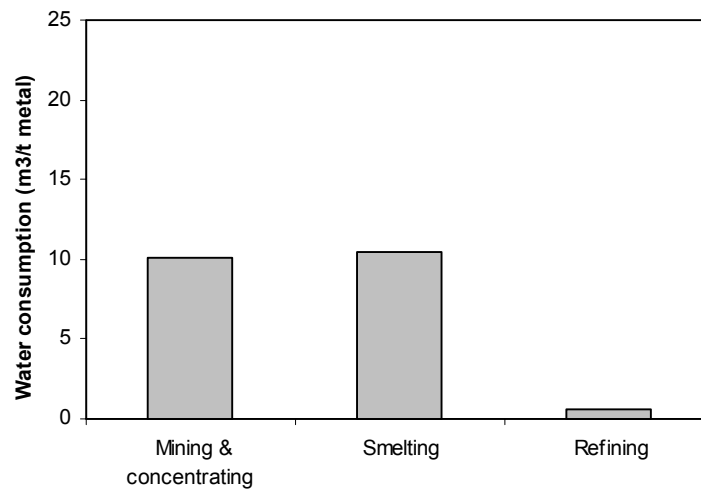


Figure C5. Process stage contributions to water consumption for zinc production (Imperial smelting furnace).

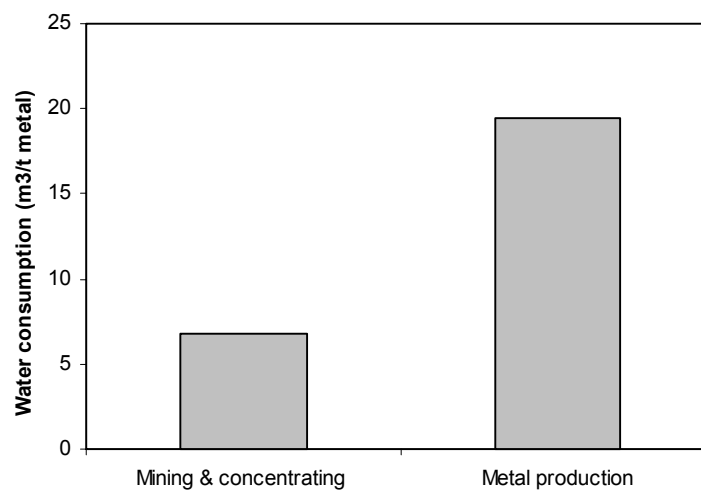


Figure C6. Process stage contributions to water consumption for zinc production (electrolytic process).

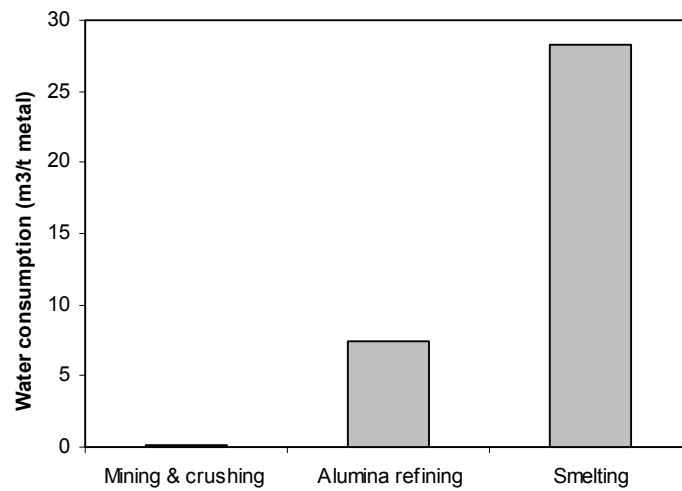


Figure C7. Process stage contributions to water consumption for aluminium production.

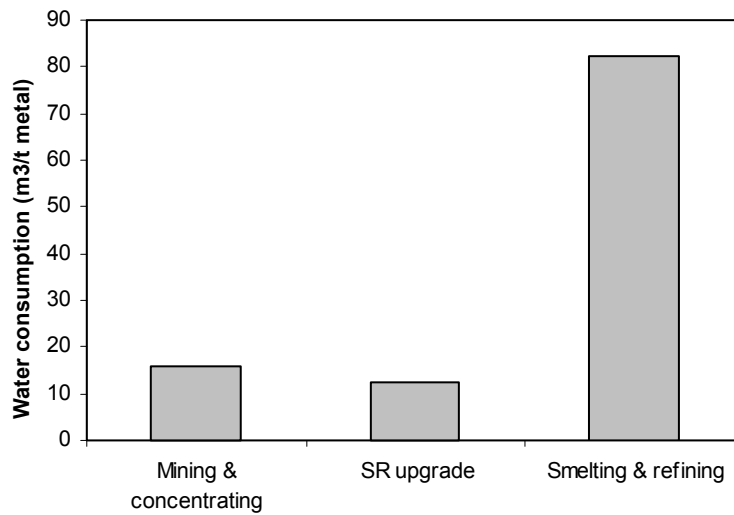


Figure C8. Process stage contributions to water consumption for titanium production.

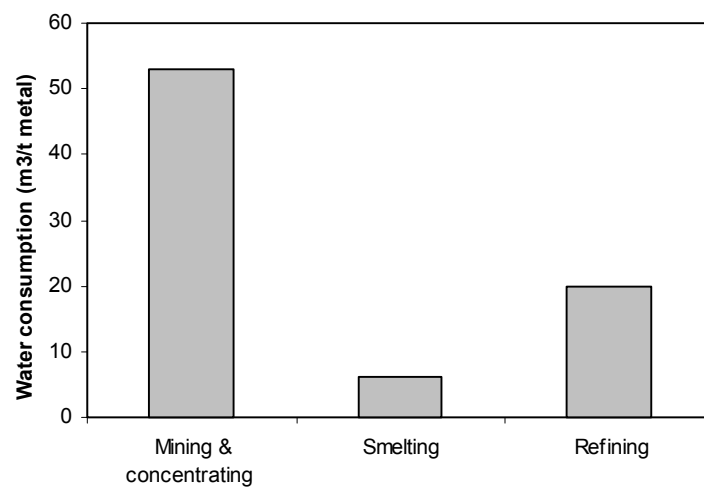


Figure C9. Process stage contributions to water consumption for nickel production (pyrometallurgical route).

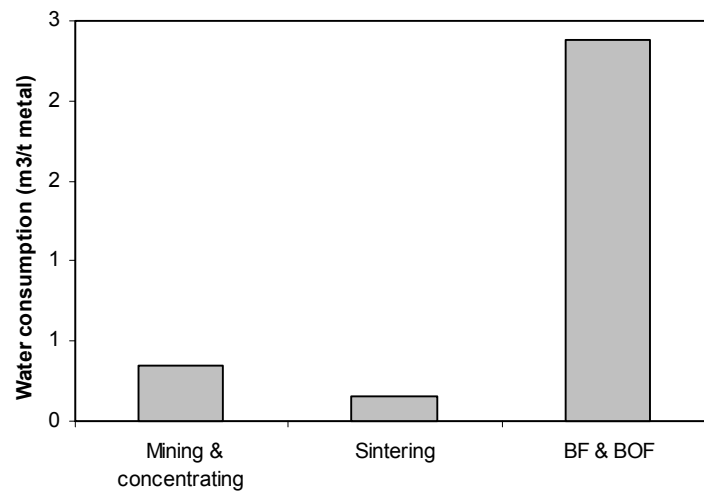


Figure C10. Process stage contributions to water consumption for steel production.

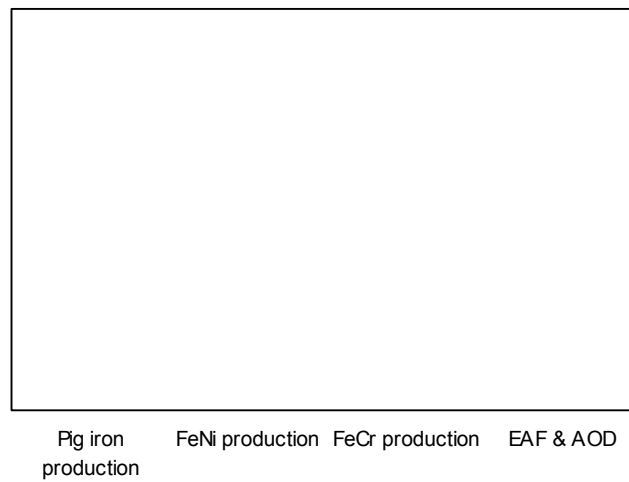


Figure C11. Process stage contributions to water consumption for stainless steel production (ferronickel feedstock).

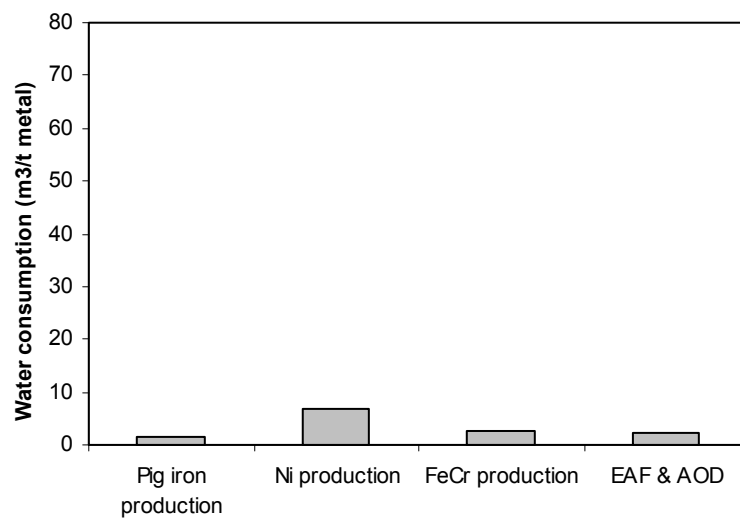


Figure C12. Process stage contributions to water consumption for stainless steel production (nickel feedstock).

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