Sustainable water use in minerals and metal production

Sustainable Water Use in Minerals and Metal Production

T E Norgate[1] and R R Lovel[2]

ABSTRACT

In this paper, life cycle assessment methodology has been used to assess the variations in water use associated with different metal production and processing routes and provide insights into the value derived from water usage in the minerals sector. Using water consumption data derived from the literature it has been shown that the 'cradle-to-gate' water consumption (or embodied water) for production of the various metals considered in the study ranged from 2.9 m^3/t for steel up to 252 087 m^3/t for gold. The results largely reflect the grade of the initial ore used to produce each metal, and can be approximated by the following equation:

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

where:

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

G = grade of ore used to produce metal (per cent metal)

The study showed that indirect water consumption in the metal production life cycle, in particular that due to electricity generation, can make a significant contribution to the embodied water value, eg aluminium production. When expressed in terms of m^3/t ore, the results for all metals considered indicated that the embodied water is roughly, on average, three times the water consumption of the mining and concentration stage. It was also shown that the economic value per m^3 of water consumed for the minerals industry exceeds that for the agricultural and industrial sectors, supporting the view that allocating water resources to the minerals industry has a strong underlying economic basis.

Water reforms currently taking place in Australia aim to address issues such as competition for water access, reduced security of supply and increase in cost. Consequently the minerals industry, along with others, can be expected to come under increasing pressure to reduce fresh or raw water use and to integrate water use across sectors. While water recycling is an obvious candidate to help reduce water consumption in the minerals industry, issues such as water quality, among others, will influence the extent to which this can be achieved.

In addition, wastewater volumes can be minimised using techniques such as pinch analysis to establish and use the minimum water requirement for the process. The use of dry or near-dry processing technologies, for which the demand for water is small or zero, may be a more radical solution to the water consumption problem; however, it is possible that the introduction of dry processing would bring with it a new set of problems, including dust.

INTRODUCTION

Without water there cannot be life. However, population growth, changing weather patterns, increased industrialisation and competition among users continues to affect the reliability of water supply and society is beginning to address issues pertaining to our finite water resource.

Internationally the United Nations General Assembly proclaimed the years 2005 to 2015 as the International Decade for Action: 'Water for Life'. The UN concluded that water is essential for life, that water is crucial for sustainable development, including the preservation of our natural environment and the alleviation of poverty and hunger and that water is indispensable for human health and well-being. The primary goal of the 'Water for Life' decade is to promote efforts to fulfill international commitments to reduce by half the proportion of people without access to safe drinking water by 2015, to stop unsustainable exploitation of water resources, to develop integrated water resource management and water efficiency plans (by 2005) and to halve the proportion of people who do not have access to basic sanitation by 2015 (Secretariat of UN-Water, 2005).

Australian experts[†] co-opted onto an 'Australian Water Futures Panel' (Dunlop, Foran and Poldy, 2001a) raised drivers of change in water use that the workshop conveners (CSIRO Sustainable Ecosystems) grouped into four categories (Dunlop, Foran and Poldy, 2001b):

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

In Australia, global climate change is expected to affect water resources and allocation procedures will need to become adaptive enough to cope with increasing climatic variability. The water debate is raging in many sectors, and the national and state water reforms currently occurring in Australia are addressing sustainability issues by providing an allocation to the environment and establishing markets for water trading. It is against this background that the mining, mineral processing and metal production industries are endeavouring to maintain current water supplies and seek new sources of water for their existing and future operations.

This paper describes a study that was carried out 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 water (fresh or raw) 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 paper concludes with a brief discussion of other issues affecting the ability of the minerals industry to meet its water needs, including water recycling, water quality and dry processing.

AUSTRALIAN WATER RESOURCES

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). Static freshwater 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 potentially unfavourable ecological consequences. Renewable water resources include the water yearly replenished in the process of water turnover (precipitation) on the earth. The annually renewed volume, usually measured as volume per unit of time (eg km^3/year) consists mainly of the regional run-off and the inflow of groundwater into the river network. Australia is characterised by large variations in its water cycle, receiving a yearly average of

1. CSIRO Minerals, Box 312, Clayton South Vic 3169. Email: terry.norgate@csiro.au

2. CSIRO Minerals, Box 312, Clayton South Vic 3169. Email: roy.lovel@csiro.au

† Attendees including representatives from state and territory water and environment agencies, irrigation and urban water industry representatives and water consultants.

about 3300 km^3/year of rainfall (Dunlop, Foran and Poldy, 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 exceeds rainfall, but there are also large areas in northern Australia that have large seasonal surface run-off.

On average about 12 per cent of rainfall (ie about 380 km^3/year) flows into rivers (Dunlop *et al*, 2001). Similar figures are reported by Shiklomanov (2000), Gleick (1998) and Dunlop, Foran and Poldy (2001b), giving a mean value of about 370 km^3/year, with about 25 per cent (on average) being divertible (but not necessarily consumed) for human use. Another 15 km^3 or 15 000 GL (Dunlop *et al*, 2001) of the annual rainfall collects underground in artesian[‡] or subartesian[§] basins and about 17 per cent of the water consumed in Australia is sourced from groundwater (ATSE, 2004).

Total net water consumption in Australia in 2000-01 was 24 909 GL (24.9 km^3/year), with the breakdown into various sectors shown in Figure 1 (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 per cent of Australia's total water useage, down from 570 GL (ie three per cent) in 1996-97 (Chartres and Williams, 2003). However, the latter authors project the mining industry will use 810 GL in 2020, while experts at the Australian Water Futures Panel (Dunlop, Foran and Poldy, 2001a) suggest that mining in Western Australia alone may use up to 940 GL by 2020.

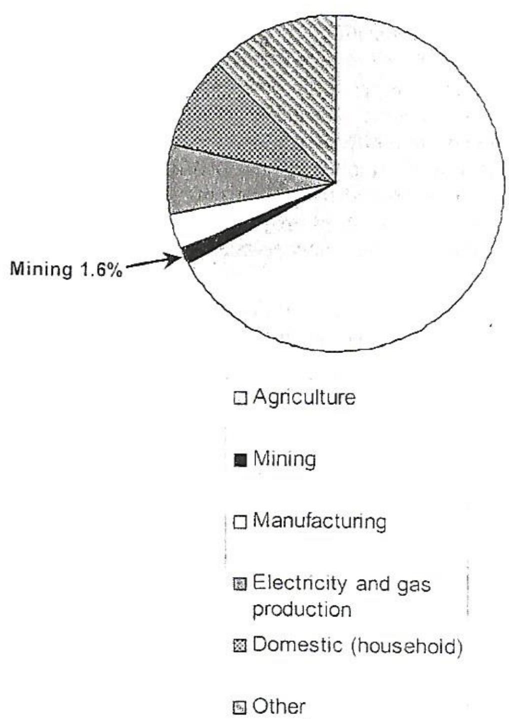

FIG 1 - Australian water consumption by sector (2000-01).

‡ Artesian water – underground water that flows naturally to the surface.

§ Subartesian water – underground water that does not naturally flow to the surface, and which needs to be pumped if it is to be used for human activities.

* Primarily fine-grained host rock after the valuable material has been removed.

Nationally, the data suggests there is not a shortage of water in Australia; however, the uneven distribution creates a mismatch between supply and demand, raising the need for water diversion and allocation procedures. It is the inadequacies of these water allocation systems that is largely responsible for the water crisis now facing Australia, according to the recently released Australian Water Industry Roadmap (2005).

WATER AND THE MINERALS INDUSTRY

The minerals sector uses relatively little water in most types of mining, with the majority of water being used in mineral processing and refining (Brown, 2002). In particular, operations such as grinding, flotation, gravity concentration, dense medium separation and hydrometallurgical processes all consume substantial amounts of water. Three factors said to make water the fluid of choice for mineral processing (Brown, 2002; Napier-Munn and Morrison, 2003) are:

1. 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;
2. water is a medium that can provide a suitable vehicle for the selective action of a distributed force field, eg gravity or centrifugal force; and
3. water is an essential chemical ingredient in some processes.

For example, grinding generally uses water to convey the particles being ground along the mill and to remove heat, while flotation exploits the chemical nature of mineral surfaces to separate them by 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 flotation 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). Water may be lost during mining and mineral processing through either evaporation or seepage. For example, disposal of tailings[*] is a major water loss at most mine and mineral processing sites and in some cases the tailings dams represent the largest source of water loss as well as being a major long-term environmental risk. In addition, refining processes used to extract and purify the valuable metals from the concentrates produced by mineral processing (eg electrolytic refining of zinc) can also use large amounts of water.

The majority of water used by the minerals industry is sourced from 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 (2004), only about five per cent of the water consumed by the Australian mining industry in 1996-97 was supplied through mains infrastructure, with 95 per cent sourced locally from surface and groundwater. According to the Minerals Council of Australia (2004), 80 per cent of water utilised by the minerals industry is sourced from underground water, leaving 15 per cent from surface water.

Mining operations may have a significant impact on local and regional groundwater systems (Hair, 2003), particularly when mining progresses below the groundwater table, creating a groundwater 'sink' and altering the local flow regime. Ironically, an inability to control inflows of water into mining excavations threatens some mining operations and at other sites, water egress into open cut and underground mining voids needs to be minimised and controlled to ensure safe and dry working conditions.

In localities deficient in surface water (eg when evaporation rates exceed rainfall or surface water storages (dams) are not reliable) operations rely on artesian waters that may be sourced a considerable distance from the mining operation itself. Many mining operations use water unsuitable for agriculture and reuse water within the constraints imposed by quality requirements, water availability and discharge considerations, as discussed later.

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 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.

LCAs of various metal production processes have previously 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. More recently, water consumption was added to the environmental impacts of these metal production processes (see Table 1). The system boundary for these LCAs was 'cradle-to-gate', ie the processes were evaluated up 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^3 (or tonnes) of fresh or raw water consumed per tonne of refined metal.

The water consumption data used for input into the LCAs (Table 2) were derived solely from publicly available literature, with the data being cross-checked with more than one source where possible. It should be noted that water consumption data between sites can vary widely, even for the same metal production route, and the data given in Table 2 are meant to be average or typical values only for each process. In addition to the direct water consumption data shown in Table 2, LCA methodology also requires indirect water consumption to be included, ie water consumed in producing the other raw materials used in the various process stages, 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 itemised in Table 2.

RESULTS

The LCA 'cradle-to-gate' water consumption (or embodied water) results are summarised in Table 3 (column 3) and Figure 2. Figure 2 shows both the direct and indirect water consumptions for each metal production process, with the sum of the two components representing the embodied water values given in Table 3. Because of the high value for gold, and to a lesser extent nickel (hydrometallurgical), compared to the other metals, the values for these metals are not plotted in Figure 2. This figure highlights the finding that indirect water consumption makes a significant contribution to the embodied water results for those metals requiring substantial inputs of electricity in their production, eg aluminium.

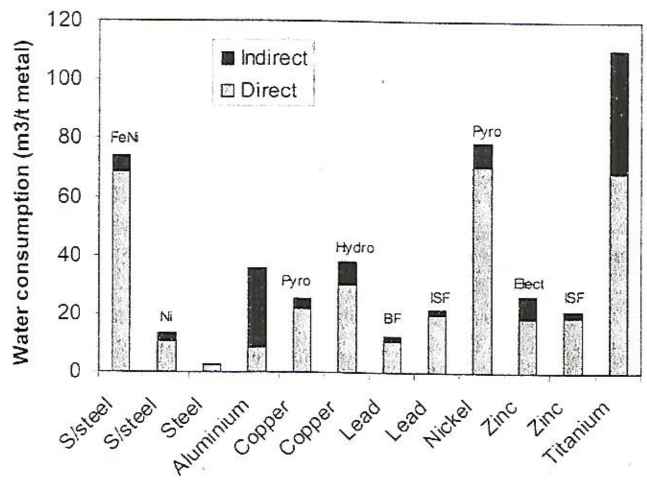

FIG 2 - Life cycle water (embodied) consumptions – excluding gold and nickel hydro (m^3/t refined metal).

TABLE 1

Metal production processes included in the study.

Metal	Process	Feed
Copper	Smelting/converting and electrorefining	Sulfide ore (3% Cu)
	Heap acid leaching and SX/EW	Sulfide ore (2% Cu)
Nickel	Flash furnace smelting and Sherritt-Gordon refining	Sulfide ore (2.3% Ni)
	Pressure acid leaching and SX/EW	Laterite ore (1% Ni)
Lead	Blast furnace	Sulfide ore (8.6% Zn; 5.5% Pb)
	Imperial smelting process	Sulfide ore (8.6% Zn; 5.5% Pb)
Zinc	Imperial smelting process	Sulfide ore (8.6% Zn; 5.5% Pb)
	Electrolytic process	Sulfide 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 and basic oxygen furnace	Iron ore (64% Fe)
Stainless steel	Electric arc furnace/argon oxygen decarburisation	Ferronickel (23% Ni, 69% Fe)
	Electric arc furnace/argon oxygen decarburisation	Nickel (100% Ni)
Gold	CIL cyanidation and EW/smelt	Gold ore (3.6 g Au/t)

TABLE 2
Water inventory data used in study.

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

† Stage-by-stage data not available.

The largest embodied water value was for gold production at 252 087 m^3 water/t gold, followed by nickel produced by the hydrometallurgical (pressure acid leaching) route at 377 m^3 water/t nickel. Producing nickel by the pyrometallurgical route was about five times more water efficient than by the hydrometallurgical route. Steel production had the lowest embodied water value at 2.9 m^3 water/t steel.

The embodied water values for the production of single element metals (ie excluding stainless steel produced from iron, chrome and nickel ores) largely reflect the grade of the initial ore used to produce each metal as shown in Figure 3. The equation of the line fitted to the data in Figure 3 is given below, and may be used to give a rough first estimate of the embodied water value for the production of most refined metals.

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

where:

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

G = grade of ore used to produce metal (per cent metal)

Although the functional unit of the LCAs was one tonne of refined metal as outlined earlier, Table 3 also includes the results expressed per tonne of ore extracted from the ground. When expressed this way, the reduced spread of results further suggest that embodied water in the metal product is strongly influenced by ore grade. The mean embodied water value for all metals was 2.1 m^3/t ore, with the mean value of water consumed in the mining and concentration stage for all metals being 0.7 m^3/t ore, which agrees with the mean value (0.7 m^3/t ore) of the range (0.4 – 1.0 m^3/t ore) reported by Brown (2003) for the amount of water typically consumed in mining and concentrating operations.

The economic or monetary value of each metal per m^3 of water consumed in their production is also included in Table 3 and plotted in Figure 4. Nickel produced via the pyrometallurgical route had the highest \$/m^3 water value, followed by titanium. Stainless steel produced using ferronickel feedstock had the lowest \$/m^3 water value of all the metals considered.

TABLE 3

Embodied ('cradle-to-gate') water consumption for metal production.

Metal	Process	Water consumption		Metal $ value /m^3 water consumed
		(m^3 water/t metal)	(m^3 water/t ore)	
Copper	Smelting/converting and electrorefining	25.9	0.7	158
	Heap acid leaching and SX/EW	38.0	0.5	105
Nickel	Flash furnace smelting and Sherritt-Gordon refining	79.0	1.4	250
	Pressure acid leaching and 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 and basic oxygen furnace	2.9	1.8	125
Stainless stell	Electric arc furnace/argon oxygen decarburisation – ferronickel feedstock	74.0	13.7	25
	Electric arc furnace/argon oxygen decarburisation – nickel feedstock	13.4	2.0	139
Gold	CIL cyanidation and EW/smelt	252 087	0.8	80

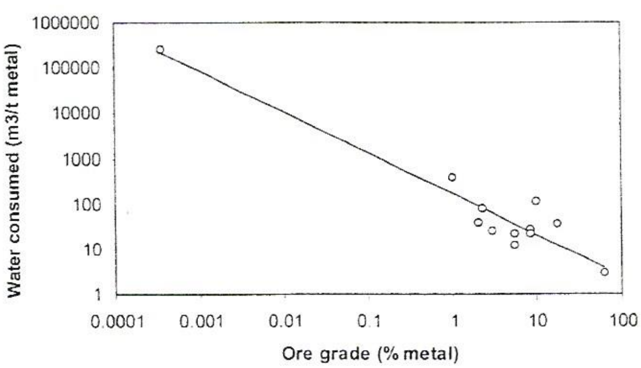

FIG 3 - Embodied water as a function of ore grade.

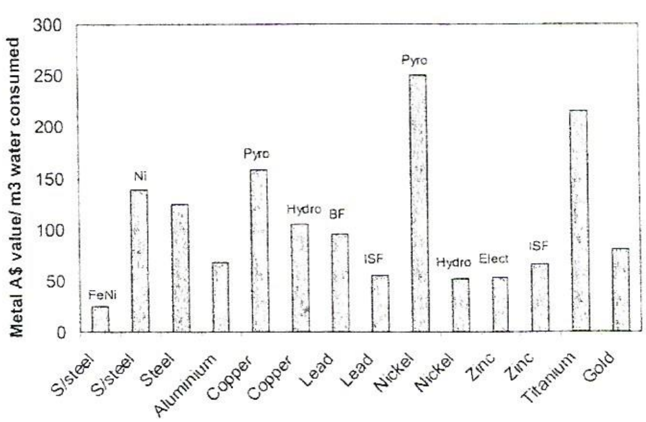

FIG 4 - Metal economic value/m^3 water consumed in production.

The above results show that 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 embodied ('cradle-to-gate') water value was approximately three times the mean for the mining and concentration stage (when expressed in terms of m^3/t ore) – a result not readily obtained without using LCA methodology. This illustrates the contribution that LCA can make to the debate about sustainable water resources and their allocation.

DISCUSSION

Economic value of water

Table 4 presents a summary of the economic value per m^3 (or kL) of water consumed for a range of goods and services across a number of industry sectors, taken from various sources including the values calculated in the current study. All data in this table are life-cycle based, ie represent embodied water, with the possible exception of the Farmweb data, for which the life cycle boundary is unclear. Low water use sectors with high economic outputs, such as the service sectors, have the highest water values, as indicated in Table 4. Averaging all the values for a particular sector in Table 4 for simplicity purposes suggests a mean economic value per m^3 of water of 1.7, 37, 83 and 115 for the agricultural, industrial, mining and metal products and services sector respectively. Foran and Poldy (2002) have suggested that in international trade terms it could be to Australia's advantage to quantify the embodied water content of the goods and services it imports and exports. These authors report that Australia exports an estimated 4000 GL of embodied water more than it imports, (which is roughly double the amount of domestic water used each year in Australia – see Figure 1) and they point out that an important national question to be addressed is whether Australia receives adequate monetary return for this net outflow of water resources.

As the majority of water used in the minerals industry is sourced locally, as pointed out earlier, the price paid for water by the industry is not widely reported. It is generally made up of a water access charge (in the form of an annual licence fee) and a water volume charge. Water for agricultural use is based on a similar pricing structure. Although these fees and charges may vary between locations, the price of water for mining and agricultural purposes is typically in the order of \$0.01/kL (NRM, 2005). This compares with typical prices currently paid in Australia for water for industrial and domestic purposes of about \$0.58/kL and \$1.00/kL respectively. The water values and prices for the various sectors are compared in Figure 5.

TABLE 4

Economic value per m³ of water consumed for various sectors.

Industry sector	$A/m³ water consumed			
	This study	Farmweb web site	Urban Ecology Australia web site	Foran and Poldy (2002)
Agriculture				
Rice		0.19	0.13	0.13
Wheat and grain				4.08
Beef cattle			2.60	1.23
Dairy cattle and milk			1.47	0.68
Sugar cane		0.42	0.81	0.81
Cotton		0.61	0.63	0.63
Fruit and vegetables		1.60	9.70	2.64
Mining and metal production			33	
Copper				
Nickel	132			
Lead	151			67
Zinc	75			
Aluminium	60			
Titanium	68			
Iron and steel	216			
Stainless steel	125			
Gold	82			67
Black coal	80			45
Crude oil				77
Iron ore				43
Bauxite				27
Industrial				
Pulp and paper			33	20
Basic chemicals				28
Cement and concrete				67
Services				
Health and education			143	143
Banking			143	111
Community service				37

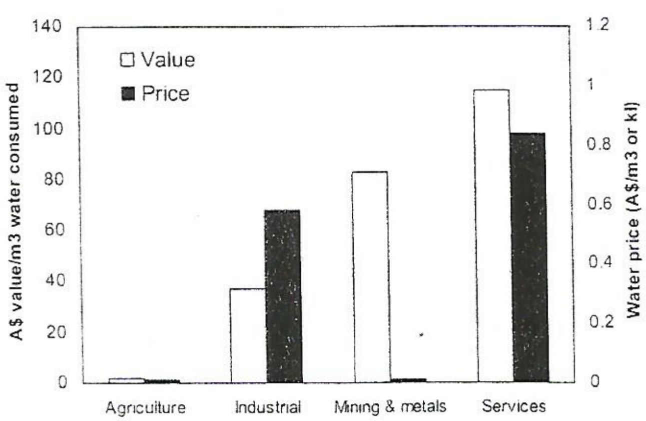

FIG 5 - Comparison of water value and price for various sectors.

Previously, governments in Australia subsidised water infrastructure, but the aim under the National Water Initiative Agreement is for water prices to reflect the cost of supply and management. It is worth noting that the above prices for industrial and domestic water are not high by international standards, as shown in Figure 6 (Australian Water Industry Roadmap, 2005).

Water allocation and reform

While humans presently use 40 per cent of the world's accessible water, Falkenmark (1998) suggests that this will have increased to 80 per cent by 2025 because of anticipated requirement for the dilution of pollution loadings in rivers. Substantial re-allocation of water resources will be required to achieve this. This has already started to occur in Australia, and was one of the driving forces behind the National Water Initiative Agreement (Anon, 2004; DPMC, 2004) established in 2004 by the Council of Australian Governments (COAG) for the efficient and sustainable reform of the Australian water industry. The issue of water resource allocation is a complex one involving many factors, and is beyond the scope of this paper. However, any proposed system for water allocation needs to fit within and encourage behaviour that aligns with the national vision and results in equitable and just water allocation between competing users.

Water reform in the Australian states is taking place on the basis of the principles espoused in the National Water Initiative Agreement, the key elements of which are:

- improve the security of water access entitlements, by clear assignment of risks of reductions in future water availability and by returning over-allocated systems to sustainable allocation levels;

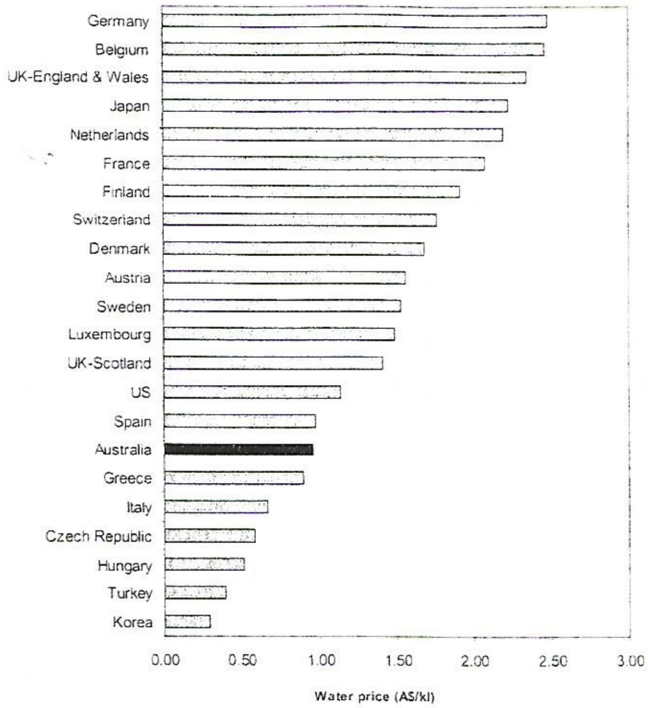

FIG 6 - International water prices.

- ensure ecosystem health by implementing regimes to protect environmental assets at a whole-of-basin, aquifer or catchment scale;
- 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; and
- 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; and
- 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 that 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 total raw water usage, improve recycling and to integrate water use between companies and across industry sectors. The LCA results presented above support the view that allocating water resources to the minerals industry has a strong underlying economic basis.

Water quality

Water quality is an important operational issue in mineral processing operations such as grinding, classification, filtration, thickening and flotation. 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 (Schumann *et al*, 2003).

High quality water is not always required. The quality of water can range from very high quality to poor quality hard water (high levels of dissolved calcium and magnesium) from underground aquifers and to even lower quality saline groundwater# and seawater (very high levels of dissolved solids including sodium chloride). For example, gold projects in Western Australia have operated effectively with water containing close to 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 can be 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 sulfur (in sulfide minerals) 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 (surface collected dam water). Sulfur 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 sulfide 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).

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. reuse of water is not a new concept, with the reuse of process water, generally without treatment, long being a feature of water management in mineral processing plants internationally (Brown, 2002).

The treatment and reuse of process, mine, domestic and industrial waters is now becoming a significant means of minimising overall water consumption, as well as minimising 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) and also by ATSE (2004). Typically, treatment before reuse 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 given by Brown

Some underground water is much more saline than seawater, a phenomenon well known in Western Australia.

…2). There are a wide range of water treatment options …ailable and methods with very low capital and operating costs …hat are favoured by the minerals industry (due to the prevailing …ow value of the metal products in general) are discussed by Johnson (2003).

In addition to considering waste water treatment options, many operators aim to minimise the amount of waste water generated. One of the techniques that can be used to do this (Wang and Smith, 1994; Smith *et al*, 1994) is pinch analysis, an approach adapted from the methodology developed for heat exchanger networks by Linhoff and Hindmarsh (1983). Pinch analysis involves setting maximum concentration limits for each contaminant component in the water at the inlet and outlet of each processing stage, and determining the minimum water flow rate required to achieve these targets. A composite limiting water profile is then derived for the entire process, and by matching the water supply to this profile, the minimum water flow rate for the process is obtained. A worked example of the methodology is given by Smith *et al* (1994)[¤].

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 per cent, while the average percentage of water recycled for Rio Tinto's worldwide operations in 2002 was 25 per cent (O'Reilly, 2003). The highest water recycling rate known to the authors, 80 per cent, was reported by Schumann *et al* (2003) for Newcrest Mining's Cadia Hill gold mine in central New South Wales.

Dry processing

While increased water recycling is an obvious option to help reduce the water consumption of mineral processing plants, a more radical solution to the problem, dry or near-dry processing technologies, may be applicable when water is unavailable. In reviewing opportunities for dry processing to replace conventional mineral processing, Napier-Munn and Morrison (2003) highlighted two areas to be addressed:

- a new paradigm will be required for the design and evaluation of processing flow sheets – this will need to extend to innovative ways of valuing particular process routes, eg more emphasis 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; and
- 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.

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 focused on using a vibrating plate separator that classifies particles on the basis of size and density (O'Connor *et al*, 2002). While health and environmental issues related to dust are serious known problems, there are many other unknowns involved, and it is likely that the introduction of dry processing will bring with it a new set of problems.

¤ Commercial software is available for performing this type of analysis (WATER Version 1.8, UMIST, 2005).

Climate change

Climate change is contributing to the uncertainty of water supplies. There is growing evidence of global warming and current estimates suggest that annual average temperatures in Australia will increase by between 0.4 to 2.0°C by 2030. The projected changes in annual rainfall in the range of -20 per cent to +5 per cent by 2030 in the south-west, and -10 per cent to +5 per cent in parts of south-eastern Australia (Pittock, 2003) are likely to reduce water supplies and accentuate competition between users, including the minerals industry. In addition, higher water temperatures are expected to contribute to a general degradation of water quality as well as lead to increased evaporative losses, particularly in irrigation areas.

CONCLUSIONS

LCA methodology has been used to provide insights into the value derived from water usage within the minerals sector and to add a life cycle perspective to the debate about water resources across industry sectors. Using water consumption data derived from the literature it has been shown that the 'cradle-to-gate' (or embodied) water consumption for production of the various metals considered in the study ranged from 2.9 m³/t for steel up to 252 087 m³/t for gold. The results largely reflect the grade of the initial ore used to produce each metal, and can be approximated by the following equation:

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

where:

W = embodied water (m³/t refined metal)

G = grade of ore used to produce metal (per cent metal)

This correlation between grade and water consumption, 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.

The study showed that indirect water consumption in the metal production life cycle, in particular that due to electricity generation, can make a significant contribution to the embodied water value, eg aluminium production. When expressed in terms of m³/t ore, the results for all metals considered indicated that the embodied water is roughly, on average, three times the water consumption of the mining and concentration stage. It was also shown that the economic value per m³ of water consumed for the minerals industry exceeds that for the agricultural and industrial sectors, supporting the view that allocating water resources to the minerals industry has a strong underlying economic basis.

Water reforms currently taking place in Australia aim to address issues such as competition for water access, reduced security of supply and increase in cost. Consequently the minerals industry, along with others, can be expected to come under increasing pressure to reduce fresh or raw water use and to integrate water use across sectors. While water recycling is an obvious candidate to help reduce water consumption in the minerals industry, issues such as the build-up of organic and inorganic molecules, microbiological species and collectors, among others, will influence the extent to which this can be achieved. While many operations currently use water that is unsuitable for agricultural use and unlikely to be put to any other anthropogenic use, a flexible 'fit for purpose' water strategy that accounts for local conditions and synergies could be more broadly adopted by mining, mineral processing and metal production operations.

In addition, wastewater volumes can be minimised using techniques, such as pinch analysis, to establish and use the minimum water requirement for the process. The use of dry or near-dry processing technologies, for which the demand for water is small or zero, may be a more radical solution to the water consumption problem; however, it is possible that the introduction of dry processing would bring with it a new set of problems, including dust.

While the focus of this study has been on water consumption, it should be borne in mind that when assessing the relative merits of alternative processing routes for metal production, broader impacts (eg greenhouse and acid rain gas emissions, nutrification, community capacity, economics etc) also need to be considered in addition to the water consumption/resource depletion impact considered in this paper. While the paper has been written for an Australian audience, the methodologies used and the findings reported have global relevance.

REFERENCES

Anon, 2004. Miners get tick in COAG water initiative, *Australian Journal of Mining*, July/August, p 30.

ATSE (Australian Academy of Technological Sciences and Engineering, Canberra), 2004. Water recycling in Australia. Available from: <http://www. atse.org.au>.

Australian Water Industry Roadmap, 2005. Barton Group, Canberra. Available from: <http://www.bartongroup.org.au>.

Australian Waterlines, 2004. Australian Statistics – Extract from water account 2000/2001. Available from: <http://www.waterlines.com.au>.

Brown, E, 2002. Water for a sustainable minerals industry, Report to Sustainable Minerals Institute, University of Queensland, Julius Kruttschnitt Minerals Research Centre, Brisbane.

Brown, E, 2003. Water for a sustainable minerals industry – A review, in *Proceedings Water in Mining Conference*, pp 3-14 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Chartres, C and Williams, J, 2003. Competition for Australia's diminishing water resources – Agriculture versus industry versus environment, in *Proceedings Water in Mining Conference*, pp 15-24 (The Australasian Institute of Mining and Metallurgy: Melbourne).

DPMC (Department of the Prime Minister and Cabinet), 2004. National water initiative. Available from: <http://www.pmc.gov.au/docs/national_water_initiative_progress.cfm>.

Dundon, P, 2000. Water in Mining – Where will it come from and where will it go to? in *Proceedings After 2000: The Future of Mining*, pp 103-105 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Dunlop, M, Foran, B and Poldy, F, 2001a. Scenarios of future water use. Report III of IV in a series on Australian water futures. Working Paper Series 01/05. CSIRO Sustainable Ecosystems. Available from: <http://www.cse.csiro.au>.

Dunlop, M, Foran, B and Poldy, F, 2001b. Scenarios of future water use. Report IV of IV in a series on Australian water futures. Working Paper Series 01/05. CSIRO Sustainable Ecosystems. Available from: <http://www.cse.csiro.au>.

Dunlop, M, Hall, N, Watson, B, Gordon, L and Foran, B, 2001. Water use in Australia. Report I of IV in a series on Australian water futures. Working Paper Series 01/02. CSIRO Sustainable Ecosystems. Available from: <http://www.cse.csiro.au>.

Falkenmark, M, 1998. Dilemma when entering the 21st century – Rapid change but lack of sense of urgency. Water Policy, 1, pp 421-436.

Farmweb web site. Available from: <http://www.farmweb.au.com>.

Foran, B and Poldy, F, 2002. The future of water. From future dilemmas: Options to 2050 for Australia's population, technology, resources and development. CSIRO Sustainable Ecosystems. Available from: <http://www.cse.csiro.au>.

Gilbert, L and Fenton, C, 2003. Water reform, tradeability and understanding the value of water for large-scale resource projects, in *Proceedings Water in Mining Conference*, pp. 67-69 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Gleick, P, 1998. *The World's Water 1998-1999* (Island Press: Washington, DC). Avialable from: <http://www.worldwater.org/table1.html>.

Hair, I, 2003. Groundwater issues in the mining industry, in *Proceedings Water in Mining Conference*, pp 173-179 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Janssen, R, 2003. Ignore sediment at your peril – Sediment issues in water management, in *Proceedings Water in Mining Conference*, pp 113-121 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Johnson, N, 2003. Issues in maximisation of recycling of water in a mineral processing plant, in *Proceedings Water in Mining Conference*, pp 239-245 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Levay, G, Smart, R and Skinner, W, 2001. The impact of water quality on flotation performance, *Journal of The South African Institute of Mining and Metallurgy*, March/April:69-75.

Linhoff, B and Hindmarsh, E, 1983. The pinch design method of heat exchanger networks, *Chemical Engineering Science*, 38:745-763.

Miller, G, 2003. Water consumption optimisation in copper heap leach-SX-EW projects, in *Proceedings Water in Mining Conference*, pp 279-284 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Minerals Council of Australia, 2004. Australian Minerals Industry, Position paper for Australia's water reform agenda.

Napier-Munn, T and Morrison, R, 2003. The potential for the dry processing of ores, in *Proceedings Water in Mining Conference*, pp 247-250 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Norgate, T E and Rankin, W J, 2000. Life cycle assessment of copper and nickel production, in *Proceedings MINPREX 2000*, pp 133-138 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Norgate, T E and Rankin, W J, 2002. An environmental assessment of lead and zinc production processes, in *Proceedings Green Processing 2002*, pp 177-184 (The Australasian Institute of Mining and Metallurgy: Melbourne).

NRM (Natural Resources and Mines), 2005. Water Management: Water resource charges – frequently asked questions. Available from: <http://www.nrm.qld.gov.au/water>.

O'Connor, M, Clout, J and Nicholson, R, 2002. Dry particle separation – A contribution to sustainable processing, in *Proceedings Green Processing 2002*, pp 291-297 (The Australasian Institute of Mining and Metallurgy: Melbourne).

O'Reilly, J, 2003. Towards excellence in water management within Rio Tinto, in *Proceedings Water in Mining Conference*, pp 25-28 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Pittock, B (ed), 2003. Climate change – An Australian guide to the science and potential impact. Available from: <http://www.greenhouse.gov.au/science/guide>.

Schumann, R, Levay, G, Dunne, R and Hart, S, 2003. Managing process water quality in base metal sulfide flotation, in *Proceedings Water in Mining Conference*, pp 251-259 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Secretariat of UN-Water, United Nations Department of Economic and Social Affairs, Division for Sustainable Development, 2 UN Plaza, Room DC2-2024 New York, NY 10017, USA, UN Department of Public Information. DPI/2378–March 2005–10M. Available from: <http://www.un.org/esa/sustdev/publications/water_for_life.pdf> [Accessed: 1 March 2006].

Shiklomanov, I, 2000. Appraisal and assessment of world water resources, *Water International*, 25(1):11-32.

Smith, R, Petela, E and Wang, Y, 1994. Water, water everywhere, *The Chemical Engineer*, May:21-24.

Thompson, M and Minns, A, 2003. Mine water usage eco-efficiency, in *Proceedings Water in Mining Conference*, pp 301-304 (The Australasian Institute of Mining and Metallurgy: Melbourne).

UMIST, 2005. University of Manchester, UK. Available from: <http://www.ceas.manchester.ac.uk>.

Urban Ecology Australia web site. Available from: <http://www.urbanecology.org.au>.

Wang, Y and Smith, R, 1994. Wastewater minimisation, *Chemical Engineering Science*, 49(7):981-1006.