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Reducing mine water requirements

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ABSTRACT

Mining is a water intensive activity, and reducing water consumption is a key requirement in moving toward a more sustainable mining industry. This paper identifies mine water reduction, reuse and recycle options, and demonstrates cases where these options have been implemented around the world. A mine water system model is developed and used to show potential water saving strategies through six scenarios. Apart from the base case, these scenarios include the introduction of evaporation reduction strategies, paste tailings disposal, filtered tailings disposal, ore pre-sorting and a combination of the most effective options. The results of the modeling show how an open-pit copper mine with a traditional layout can move from having an average water withdrawal of 0.76 m^3/t of ore processed to 0.20 m^3/t of ore processed or lower. A key result of the modeling is the discovery that a combination of ore pre-concentration and filtered tailings disposal can reduce water consumption by 74% or more. This finding demonstrates an opportunity to significantly lower water consumption on mine sites.

1. Introduction

Mining consumes large quantities of water; the copper mining industry alone withdrew over 1.3 billion m^3 of water in 2006 (Gunson et al., 2010b). On a global scale, however, mine water use accounts for a small portion of overall water use. Even in relatively dry, mining-intensive countries like Australia, Chile, and South Africa, mine water consumption is only 2–4.5% of national water demand (Brown, 2003; Bangerter et al., 2010). Nevertheless, when mining takes place in areas where water is scarce, mine water consumption can severely impact local supplies. Acid rock drainage, leaks from tailings or waste rock impoundments, or direct disposal of tailings into waterways can additionally contaminate surface and groundwater (MMSD, 2002; Nedved and Jansz, 2006; Akcil and Koldas, 2006; Cohen, 2006). Mines require large pumping, treating, heating and/or cooling water systems, which are often large energy consumers. Better mine water systems can reduce both water and energy consumption. Improving water system design and practice are key strategic requirements in moving toward a more sustainable mining industry.

This paper addresses conventional base-metal or precious-metal mine sites, which typically consist of an underground and/or open pit mine and a mineral processing plant, or mill. Ore is extracted from the mine and processed through the plant to produce a saleable concentrated product. Tailings, or waste material, are then deposited in a tailings storage facility (TSF). Any rock removed from the mine with no economic value, or waste rock, is stored without being processed. Most mills use wet processes, such as froth flotation, in order to separate valuable minerals from the non-valuable minerals in the ore. Wet processes can use large quantities of water. Flotation, the most common separation process, typically takes place at 25–35% solids by mass. A plant not reusing or recycling any water would thus require 1.9–3.0 m^3 of water per tonne of ore processed. In addition to flotation, water is used for various applications including grinding, screening, dust scrubbing, wash water, dust suppression, pump gland seal water (GSW), and reagent mixing. However, most major mines now practice at least some water reuse and recycling. Modern mines often recycle all available water; in Canada, metal mines recycle a higher percentage of water than any other industry (Statcan, 2008). The high rate of water recycling means water consumption depends not on the amount of water required for individual unit operations, but the amount of water lost to permanent water sinks, such as evaporation, seepage or retention in the concentrate or tailings material. Brown reported that average mine water use currently ranges from 0.4 to 1.0 m^3/t of ore processed (2003). A cross-sectional study of water usage in the copper mining industry in 2006 found that conventional flotation-based copper mines' water withdrawals ranged from 0.34 to 2.07 m^3/t of ore processed, with a weighted mean of 0.96 m^3/t (Gunson et al., 2010b).

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Key terms in this paper are defined as follows:

- Raw water refers to water that is brought to or captured on site and has not been previously used for any purpose within the site. Typical sources include surface water, groundwater, sea water or water from an external industrial or municipal site.
- Water withdrawal refers to any raw water captured or brought to site.
- An operation in a mine that involves water, such as dust suppression, is referred to as a task or a water user (ADRET, 2008). A water user requires water directly from a raw water source or from reused or recycled water.
- Reuse is when water from one user is passed directly to another user without transformation. An example would be using discharged cooling water directly for another task in a plant.
- Recycling is when water is treated to improve its quality before it is reused, through a method like clarification or filtration.
- Water consumption refers to raw water that has been made unavailable for reuse in the same basin, such as through conversion to steam, losses to evaporation, seepage to a saline sink, or contamination (Gleick, 2003).
- Water stores are facilities on the site that hold and/or capture water (Cote et al., 2009).

This paper first details past approaches used or suggested to improve mine water system performance by reducing mine water consumption and reusing or recycling water available on site. A mine water system model is developed and six scenarios are used to show the potential water and energy saving achievable using these approaches. This paper demonstrates how to quantify the individual and combined potential impact from different water saving approaches.

While all the water saving options described here have been described elsewhere, this is the first model that allows a quantitative estimate of the individual and combined effects of a variety of different water saving options. A key finding is that the combination of ore pre-concentration and filtered tailing disposal can dramatically reduce mine site water consumption.

2. Mine water and energy use in the context of sustainable development

Over the past two decades, civil society and governments have encouraged the global mining industry to move toward sustainable development, a move now largely accepted by the industry (NRCan, 1994; MMSD, 2002; ICMM, 2003; MAC, 2004). With respect to mining, sustainable development has encompassed a number of areas including corporate social responsibility, human rights, risk management, health and safety, biodiversity and the environment, recycling, community relations and transparency. Much has been written about applying sustainable development industrial or business models to the industry to allow companies to address these areas (Hilson and Murck, 2000; Damigos, 2006; Basu & van Zyl, 2006; van Berkel, 2007a; van Berkel, 2007b; Handelsman, 2009). Kemp et al. (2010) focus specifically on the impact of mine water use on human rights.

Continual improvement of environmental performance and environmental management systems in mining is a key facet of the push toward sustainability (MMSD, 2002; ICMM, 2003; MAC, 2004; Hilson and Nayee, 2002; Hilson, 2003; Driussi and Jansz, 2006a,b). Hilson (2000) has also discussed the significant legislative, technical, and economic barriers the mining industry faces in implementing cleaner technology. van Berkel (2007a) undertook a comprehensive review of efforts to integrate sustainability into the mining industry. He described five hierarchical levels of models for environmentally friendly sustainable business operations and categorized commonly known models such as Industrial Ecology, The Natural Step, Green Engineering, Eco-Efficiency and Cleaner Production within these levels. A common theme in these models is the need for the mining industry to improve the efficiency of water use.

Several efforts have been made to quantify and understand mine water use, with a focus on life cycle analysis and key indicators (Azapagic, 2004; Norgate and Lovel, 2004; Suppen et al., 2006; Mudd, 2008, 2009; Tejos and Proust, 2008; Worrall et al., 2009; Cote and Moran, 2009; Cote et al., 2009; Norgate and Haquea, 2010). For mining companies aiming to improve the efficiency of their water use, there are dozens of options available, including water recycling, reducing evaporation and reducing the water content in concentrates and tailings (Gunson et al., 2010a). Some companies, such as Rio Tinto, have well thought-out water management policies (Rio Tinto, 2010). However, little work has been done on how to systematically design water systems specifically related to the mining industry. The best available efforts include The Centre for Water in the Minerals Industry at the Sustainable Minerals Institute, University of Queensland, which has developed a "hierarchical conceptual systems approach" to analyze mine water management (Cote et al., 2007a), and the South African Department of Water Affairs and Forestry best practice guidelines on mine water management (DWAF, 2006a). In addition, the World Resource Institute has released a working paper on water-related risks associated with the mining industry (Miranda et al., 2010).

3. Options to improve mine water system performance

The first step toward improving or designing mine water systems is to develop a good understanding of the mine's existing system. No effort should be undertaken to improve a mine water system until a reasonably accurate site water balance has been completed. Putting effective water metering technologies or methods in place and having an accurate site water model is critical (ERS, 2008; Mayer et al., 2008; ICMM, 2009; DWAF, 2006b). Mining companies should consider implementing a comprehensive water management strategy; Gibson et al. (2003) describe an example of such a strategy. Any water management plan should ensure that existing facilities are well run and maintained. Basic steps such as fixing leaky pipes and valves, replacing undersized or worn-out pumps, and improving thickener or clarifier operation can lead to inexpensive and impressive improvements (Chambers et al., 2003; Stegink et al., 2003; Thompson and Minns, 2003).

Better water system design revolves around two key concepts: first, running all processes at the highest solids density possible without negatively impacting the process and, second, supplying all processes with the poorest acceptable quality water, that does not impact process performance (Bagajewicz, 2000; DWAF, 2006a).

Past efforts to improve mine water system performance by reducing mine water consumption and reusing or recycling water available on site can be categorized into the three components of the decades-old waste management hierarchy: reduce, reuse, and recycle.

Efforts to reduce mine water use include:

- Reducing wet area/open area in the TSF
- Reducing clay generation during grinding to lower tailings water retention
- Improving tailings thickener performance
- Reducing water losses through thickened tailings or paste tailings disposal

- Reducing water losses through the installation of drains in the TSF
- Reducing water losses through tailings compaction
- Reducing water losses through selective tailings size classification
- Reducing water losses by using tailings filtration
- Reducing the concentrate moisture content
- Reducing evaporation through covers (tanks/thickeners/tailings pond)
- Reducing evaporation through alternative dust suppressants
- Ensuring no unplanned pipeline water losses
- Eliminating evaporative cooling
- Reducing pump GSW usage
- Reducing site employee/contractor water use
- Reducing water consumption through ore pre-concentration
- Reducing water use through dry processing

The largest water sink at most mine sites is the TSF; water is lost to evaporation or seepage, or is entrained within the tailings (Brown, 2003; Wels and Robertson, 2003). Significant water savings can be achieved by reducing the available wet and/or open water area, which can be done by carefully managing the placement of the tailings (Chambers et al., 2003; Soto, 2008).

Water entrained within the tailings can be reduced by a number of methods, including lowering the amount of clays generated during processing (Mwale et al., 2005; de Kretser et al., 2009). Many mines have tailings thickeners to recycle water and reagents – increasing the solids density of the thickener underflow can reduce the amount of water sent to the TSF, thus potentially reducing the amount of water lost to evaporation, retention or seepage (Chambers et al., 2003; Mayer et al., 2008; Soto, 2008; ICMM, 2009). Furthermore, increasing the solids density of the thickener underflow reduces the amount of water pumped back from the TSF to the plant, and hence the amount of energy consumed by the reclaim water system. Some mines, such as Barrick's Bulyanhulu Mine in Tanzania and Breakwater's Myra Falls Mine in British Columbia, have installed high-density thickeners to dispose of tailings as a low water paste (Engels and Dixon-Hardy, 2009). At mine sites with high water costs or which have a need for high tailings storage stability, filtered tailings or dry stack tailings storage has been successfully implemented (Davies, 2004; Brown, 2003). Davies reported that 55 metal or industrial mineral operations used dry stack tailings storage by 2004. Reducing the water content of the concentrate by improving filter performance also lowers water losses, and reduces concentrate shipping costs (Soto, 2008).

Barrera and Ortiz (2010) describe a number of other options to reduce water losses in tailings, including installing drains underneath the TSF and compacting tailings through co-disposal with waste rock or even explosives. They also highlighted the effect of size classification on reducing water entrainment in tailings. Hydro-cyclones are often used on mine sites to separate the coarse fraction of the tailings for use in impoundment construction. As water in the coarse sand drains quickly, the overall amount of water retained in the tailings may be lower than the amount in the coarse and fine tailings deposited together. To further reduce evaporation at tailings facilities, some mines have placed floating covers on open water in tailings ponds, in addition to covering water storage tanks and thickeners (Soto, 2008; Mayer et al., 2008). Alternatives such as floating plastic balls may work as well (AWTT, 2010).

Typically, mining operations require a significant focus on handling dust, both on mine roads and in the plant. Mines generally have a number of water trucks which spray the haul roads and other transportation routes to minimize dust generation. Some mines have experimented with additives or alternative dust suppressants to reduce water consumption (McIntosh and Cronin, 2003; Xstrata, 2007; Mayer et al., 2008; Soto, 2008; GE, 2010). There are several dust suppressant alternatives, including salts, surfactants, soil cements, bitumens, and films (Organiscak et al., 2003). GE reported dust suppression water savings of 67%–90% by using organic binders to harden road surfaces (GE, 2006, 2010). For crushing, screening and conveying dust suppression, there are a number of common and widely available alternatives to traditional water sprays. These include fogging systems and foam, which can significantly reduce water consumption (Kissell, 2003).

Many operations have long pipelines delivering water to the mine site. These pipelines may have significant water losses due to leaks. In addition, impoverished communities along pipeline corridors have been known to extract significant quantities of water. Where possible, pipelines should be repaired to reduce leaks. In areas where communities are using the water, a formalized water distribution system should be implemented to minimize waste and improve community relations.

Many mines use evaporative cooling methods, such as cooling towers, to cool major mill equipment. However, due to the large volume of makeup water required in a conventional mine, most sites have enough cool water to meet all of their cooling needs with open water-based heat exchangers (Gunson et al., 2008).

Slurry pumps are often fitted with GSW systems to flush abrasive particles from the pump packing, while also cooling and lubricating the packing. Often GSW is ineffectively used, leading to leaking and excessive water consumption. Mechanical seals can be used to replace gland seals, or systems can be put in place to monitor and limit gland seal water consumption (Savage, 2007). As GSW is not lost to the system, but flows into the slurry, mechanical seals present an opportunity to reduce clean water requirements, not overall water requirements. Mines have also implemented common off-the-shelf water saving techniques such as low water showers and low or zero water toilets (Thompson and Minns, 2003; ERS, 2008).

A more radical opportunity to reduce water use is to pre-concentrate run-of-mine (ROM) ore using such methods as dense media separation and sorting technologies. For some ores, over half of the ROM ore can be rejected with minimum loss of valuable mineral (Bamber, 2008). Test work reports on copper porphyry ores from several mines found conductivity sorting achieved up to 50% waste rejection by mass from the ores, at recoveries from 85 to 92% (Miller et al., 1978). Reducing the amount of ore sent to the mill reduces the size of the mineral processing plant and associated energy requirements, the amount of water required for processing, the amount of cooling water required, and the corresponding evaporation and water retained in the tailings material. Pre-concentration can also lead to a reduction of fines generated, thereby lowering water losses in the tailings (de Kretser et al., 2009). Pre-concentration of gold ores can dramatically reduce cyanide consumption and associated water treatment requirements.

An extreme option to reduce water consumption would be to implement more dry processes or an entirely dry processing plant (Brown, 2003). Dry processing currently has some significant limitations. Wet processes are typically more effective, consume less energy, and create fewer dust-related health concerns than dry processes. Furthermore, there are no real dry alternatives to flotation or hydrometallurgical processes. Further research and development may make dry processes more feasible in the future (Napier-Munn and Morrison, 2003).

Efforts to reuse mine water include:

- Collecting and reusing surface runoff water
- Reusing mine dewatering water
- Reusing offsite waste water

- Reusing cooling water
- Reusing grey water

Any site with precipitation can investigate the usefulness of implementing a watershed management plan to collect site precipitation and any other water runoff for mine use. Storing precipitation in reservoirs, or in the TSF, can significantly reduce offsite water requirements (DWAF, 2007). Mount Isa Mines recently built a 20,000 m^3 reservoir to collect rainwater (Lévy et al., 2006). Barrick's Buzwagi gold mine in Tanzania built a 75 ha high-density polyethylene lined rainfall harvesting area, which drains into a storage pond with a floating cover system to reduce evaporation (Mayer et al., 2008). Mines below the water table are required to dewater around their pits or underground. This water is generally suitable for use, and is commonly used for process water or by other water consumers. Similarly, seepage water from a TSF may be reused in the plant or mine.

Alternative sources for water available to a mine may be valuable to examine. Nearby municipal or industrial sites may have waste water available that is less expensive or more responsible/politically astute to use than local freshwater or groundwater sources. In Australia's Hunter Valley, Xstrata built a 16 km pipeline linking several mines together to enable water sharing (Lévy et al., 2006). Queensland Alumina, Cadia Hill mine and the Commodore Coal Mine in Australia all use treated effluent from nearby sewage treatment plants for their water supply (Kent and McCreath, 2003; Schumann et al., 2003; Stegink et al., 2003). Queensland Alumina also planned on replacing freshwater evaporative cooling with sea water cooling towers paired with heat exchangers during a period of intense water restrictions (Stegink et al., 2003). A corollary to this concept is for mines with a positive water balance to sell/give any mine discharge water to a nearby industrial or municipal consumer, rather than discharging the water directly to the environment, thus offsetting another user's freshwater requirements. Phosphate mining operations in Jordan have successfully used waste water for irrigation of fodder crops with no reported ill effects (Rimawi et al., 2009). In Nevada, Newmont owns the Elko Land & Livestock Co., which manages the 450,000-acre TS Ranch outside of Carlin. Water discharged from their nearby mining operation is used at the ranch to irrigate crops (ERS, 2008). Xstrata's Ulan coal mine in Australia uses its waste water to irrigate 242 ha of perennial pastureland (Lévy et al., 2006). Newmont's Yanacocha mine in Peru converted a mined-out pit to a treated water reservoir for regional agricultural use (Newmont, 2009).

Some mines use water-based cooling systems, such as "tube and shell" or plate heat exchangers to cool major equipments' electrical, gear or lubrication systems. This water is generally clean and can be used for a wide variety of mill water consumers, including dust scrubbers, pump GSW, spray water, reagent mixing water, and flotation or grinding dilution water (Gunson et al., 2008). In the oil sands industry, Syncrude uses spent cooling water to pre-heat the process water required for bitumen separation (Matte and Velden, 2005). Brunswick Mine similarly reuses spent cooling water (Roberts et al., 2008). Mine sites also have the opportunity to reuse grey water from showers or washing utilities in toilets or for watering green space around the site (Thompson and Minns, 2003).

Efforts to recycle mine water include:

- Recycling TSF surface water
- Recycling TSF seepage water
- Recycling tailings thickener overflow
- Recycling concentrate or intermediate thickener overflow
- Recycling potential mine effluent water

Water is commonly recycled when it drains out of deposited tailings and collects in TSF collection ponds. Likewise, any collected seepage or drainage from a TSF is commonly returned to the plant. Tailings thickeners are often used in mines around the world, and the effluent is recycled as process water. Concentrate thickeners and intermediate thickeners or clarifiers are also common within plants and the overflow is available to recycle.

Mines with a positive water balance by definition discharge excess water into the local environment. However, some mines with a positive balance may still import raw water onto site for clean water users, such as pump GSW. Due to regulatory requirements, the discharge water may be of higher quality than the raw water available to the mine. Recycling the water to the mine reduces the overall water consumption of the site and may also reduce overall water treatment costs.

There are a few cases of plants reporting negative process impacts from using recycle water for process water. Examples include multi-stage flotation circuits (Johnson, 2003) and the buildup of salts in coal mines in Australia (Moran and Moore, 2005; Cote et al., 2007b). Often, however, there are no major process impediments to using recycle water and there may be significant benefits, such as the recycling of reagents. Johnson undertook a review of past literature regarding the process implications of using recycle water and documented how to determine the impact of this use (2003). Schumann et al. studied the impact of changing the blend of recycle and makeup water on flotation recovery at the Cadia and Ridgeway concentrators in Australia (2003). Bahrami et al., 2007 investigated water treatment to eliminate the negative process impacts of recycle water at a gold plant in Iran (2007). Levay and Schumann (2006) described a systematic approach to managing water quality between different fresh and recycle water streams and their impact on process variables (2006). If recycle water needs to be further treated, often treating a small side stream will achieve acceptable results (Johnson, 2003).

4. Water reduction model

The following model is used to quantify the potential individual and combined impacts of several of the key water reduction options discussed above. The model describes potential water savings for a hypothetical 50,000 tonne per day (tpd) low grade copper deposit in an arid region. The mineral processing plant uses conventional froth flotation separation to processes 50,000 tpd of copper sulfide ore, with a grade of 0.5% Cu. The final concentrate grade is 28% copper, with a 90% copper recovery. Fig. 1 shows a simplified flow sheet describing the process. The ROM ore is crushed and ground with a gyratory crusher and a SAG Mill circuit with two closed circuit ball mills. The copper sulfide is then separated from the gangue in a flotation circuit at 30% solids. The flotation circuit consists of two lines of ten 160 m^3 rougher/scavenger cells, a line of ten 80 m^3 cleaner/scavenger cells, two 5 m diameter cleaner columns and a regrind mill. The copper concentrate is dewatered in a 15 m diameter thickener followed by a pressure filter and then shipped off site. ROM ore typically has a moisture content of 2%–5%, even in arid locations. In this model, the ROM moisture content is assumed to be 2%. The major process ore and slurry flows are shown in Table 1. The plant is loosely based on a SAG mill design described by Vanderbeek et al. (2006). Overall, the model builds upon the models described previously in Gunson et al. (2008, 2010c).

Fig. 2 and Table 2 detail the major water users in the plant, including the flotation process water, SAG mill, ball mills, air compressor cooling water, froth wash water, pump GSW, reagent mixing water, dust suppression, and hose stations for mill cleanups. In the mine, water is primarily used for haul road dust suppression and in the truck maintenance shop. In the office, water is used for

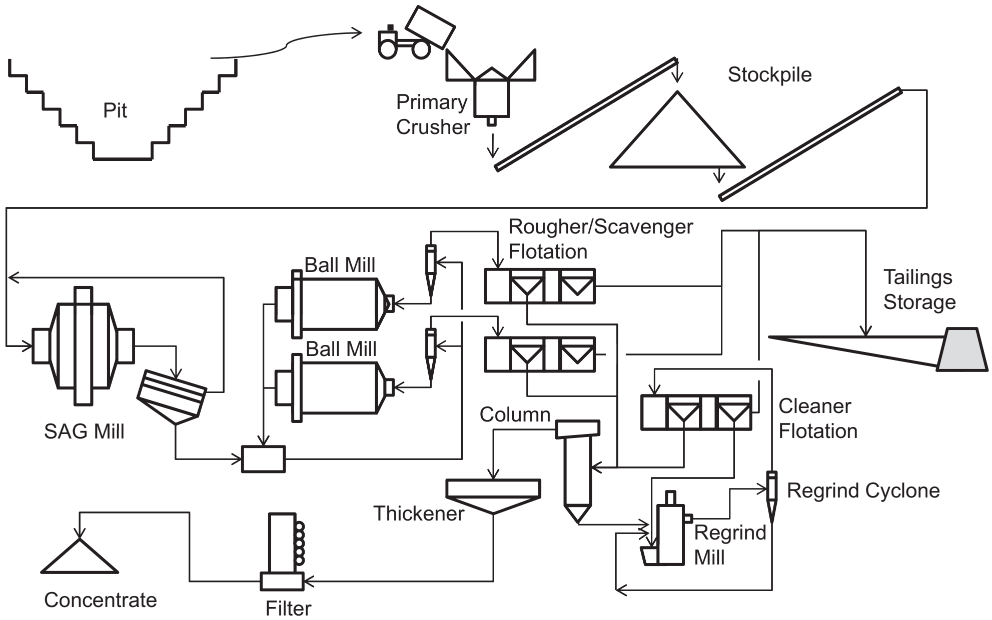

Fig. 1. Basic Process Flow Sheet.

washrooms, showers, food preparation, and drinking. For this model, the maintenance shop water consumption is assumed to be negligible, as it is assumed to be contained and that water is reused after being treated by removing waste sand and oil. Wash water from the hose stations is assumed to be negligible. All process areas with hose stations are assumed to be contained, with sump pumps returning any water and material back to the process where the spill originated. The only available sources of water are assumed to be the moisture in the ROM ore and a nearby river. Precipitation and mine dewatering flows are assumed to be negligible.

The following six scenarios quantify the impact of different options to reduce mine water withdrawals.

4.1. Scenario 1 – Base case

In the base case, no effort is undertaken to reduce water evaporation or otherwise lower water consumption beyond reclaiming water from the TSF and the concentrate dewatering processes. Table 3 outlines the water losses and the raw water required to balance the losses.

As shown in Table 2, the process water requirement for flotation is 116,667 m^3/d, based on a flotation density of 30% solids by mass. This water requirement is met by a mixture of raw water, reused raw water discharged from primary uses such as cooling systems, and recycle water from the TSF or thickeners, shown schematically in Fig. 3. In scenario 1, the recycle water requirement is assumed to be equal to the flotation process water requirement subtract the water initially present in the ROM ore, and the other water consumers in the plant.

Road-dust suppression water use is determined by the area of road to be treated, the amount of water used per application, and the number of applications per time period. The application requirement is typically 1–2 l/m^2 and each application can be effective for a period of 1 h (Tannant and Regensburg, 2001; Organiscak, 2003). However, dust suppression is only needed during some seasons and at some times of the day. For the purposes of the model, the mine is assumed to have 10 km of 32 m wide haul roads and 10 km of 8 m wide service roads (Tannant and Regensburg, 2001). For the base case the haul roads are watered an average of 10 times per day and the service roads are watered an average of 4 times per day. The application requirement is assumed to be 1 l/m^2 leading to a total water use of 3520 m^3/day.

On a mine site, employees and contractors use water for drinking, sanitation, bathing and food preparation. As mines are generally located outside of urban areas, they typically install water and sewage systems on site. During the design phase of a mine, typically an engineering firm will estimate water demand and design appropriately sized systems to accommodate the estimated demand. Water demand estimates vary by project and location. An environmental review for a proposed mine in Canada indicated water use of 250 L per person per day (l/p/d) (Taseko, 2009), whereas the Washington State Department of Health (2009) Water System Design Manual suggests average construction site water consumption is 189 l/p/d (2009). For the traditional scenario, the site is assumed to have 500 people on site, 355 of whom require access to showers. Water use is assumed to be 120 l/p/d and 200 l/p/d for people needing access to shower facilities. Each person works an average of 240 days per year, leading to a total water use of 58 m^3/d. All waste water is assumed to be treated and disposed of through a septic system and is not available for reuse or recycling.

Any exposed body of water, such as thickeners, water tanks, flotation cells or ponds, will experience evaporation. Basic site climate information typically includes average evaporation rates, either on an annual basis or a more detailed time period basis. For

Table 1
Major Ore Flows in Mill Model.

Process Slurry Flows	Solids Content (tpd)	Solids Content (%)	Water Content (m^3/day)
ROM → Comminution	50,000	98	1020
Comminution → Flotation	50,000	30	116,667
Flotation Concentrate → Concentrate Dewatering	804	30	1875
Concentrate Dewatering → Final Concentrate	804	90	89
Flotation Tailings → Tailings Storage Facility	49,196	30	114,792

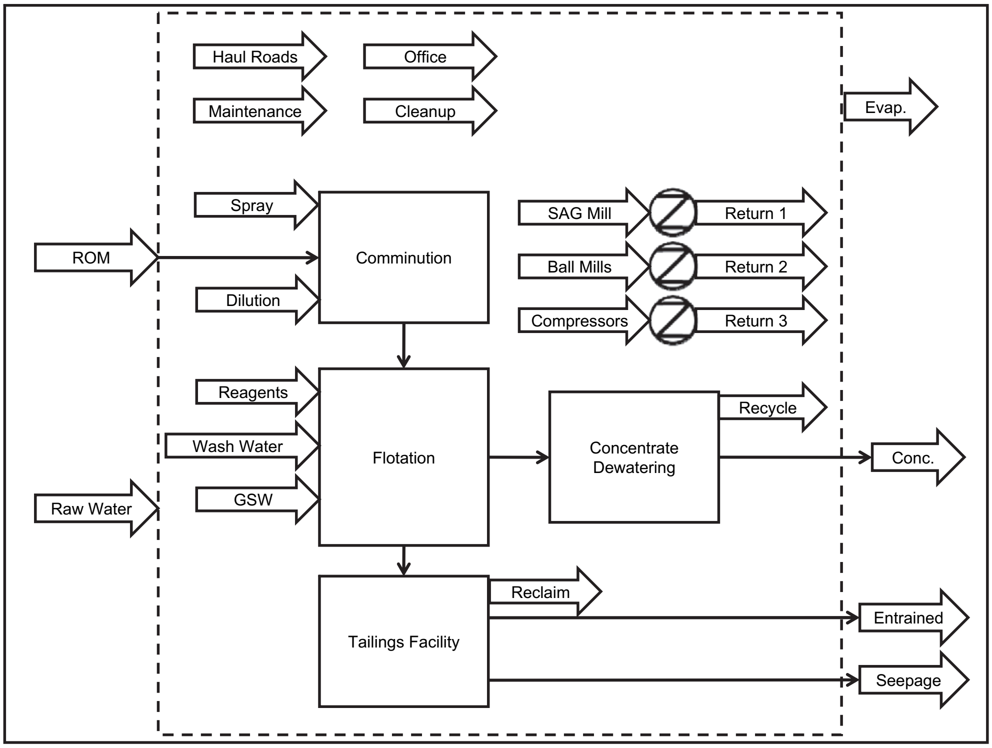

Fig. 2. Site Water Use.

this model, the average annual evaporation rate is 7 mm/d and evaporation quantities are estimated by multiplying the surface area of a body of water by the evaporation rate. The site is assumed to have a 20 m diameter raw water tank, a 25 m diameter process water tank, and flotation cells and a concentrate thickener as detailed above. The evaporation rates are thus 2.2 m^3/d, 3.4 m^3/d, 6.7 m^3/d, and 1.2 m^3/d respectively.

Dust suppression at the primary crusher and ore stockpiles is critical to reduce dust inhalation, to increase visibility, to improve maintenance and to reduce product lost to dust. A traditional dust control system consists of numerous water spray nozzles surrounding a dust generating area such as a primary crusher dump pocket. For this scenario, the primary crusher is assumed to have 30 nozzles and the coarse ore stockpile is assumed to have 10 nozzles, each spraying 1 m^3/h 50% of the time, for a total water use of 360 m^3/d and 120 m^3/d respectively. All of the water used is assumed to evaporate off the ore on the coarse ore stockpile.

The final copper concentrate is dewatered to 90% solids by mass and shipped off site, leading to a water loss of 89 m^3/day.

Table 2
Major Water Users.

Major Water Users	Flow (m^3/d)
Flotation Process Water (30% solids by mass)	115,646
SAG Mill Cooling Water	4100
Ball Mill Cooling Water	4100
Compressor Cooling Water	4100
Road-Dust Suppression	3520
Froth Wash Water	2880
Pump GSW	1440
Reagent Dilution Water	720
Primary Crusher Dump Pocket-Dust Suppression	358
Coarse Ore Stockpile-Dust Suppression	121
Mine/Mill/Office Staff-Domestic Water	58.1
Maintenance Shop	0.0
Hose stations-clean up	0.0

The bulk of water lost is in the TSF. TSF water balances can be extremely complex, with contributing variables including the climate, the geography and geology of the TSF site, the tailings mineralogy, size distribution and water content, the process plant reagents, and the tailings disposal method chosen.

Scenarios 1, 2, and 5 use a water model developed by Wels and Robertson (2003, 2004) to estimate water loss. The model was initially developed for the Collahuasi copper mine in Chile by Robertson GeoConsultants and AMEC and was validated at Collahuasi and Chuquicamata, two large, low grade, open pit copper mines. The Wels and Robertson model is used for this paper because it was developed for mines similar to the model described here. Furthermore, the model is relatively straightforward and focuses on the amount of water available to return to the plant, which is the most relevant aspect when targeting reduced raw water losses. Typically TSF water balances try to account for all

Table 3
Base Case Mine Water Balance Scenario.

Water Withdrawals		Water Losses	
Name	m^3/day	Name	m^3/day
Run of Mine Ore	1020	Road-Dust Suppression	3520
Raw water	37,935	Human Consumption	58
		Raw Water Tank – Evap.	2.2
		Process Water Tank – Evap.	3.4
		Primary Crusher-Dust Supp.	360
		Stockpile-Dust Supp.	120
		Flotation Cell – Evap.	6.7
		Conc. Thickener – Evap.	1.2
		Final Concentrate	89
		Tailings Retained, L_{ENT}	20,792
		Beach Evaporation, L_{EVAP}	9312
		Pond Evaporation, L_{POND}	1890
		Beach Rewetting, L_{REW}	2800
Total	38,955	Total	38,955

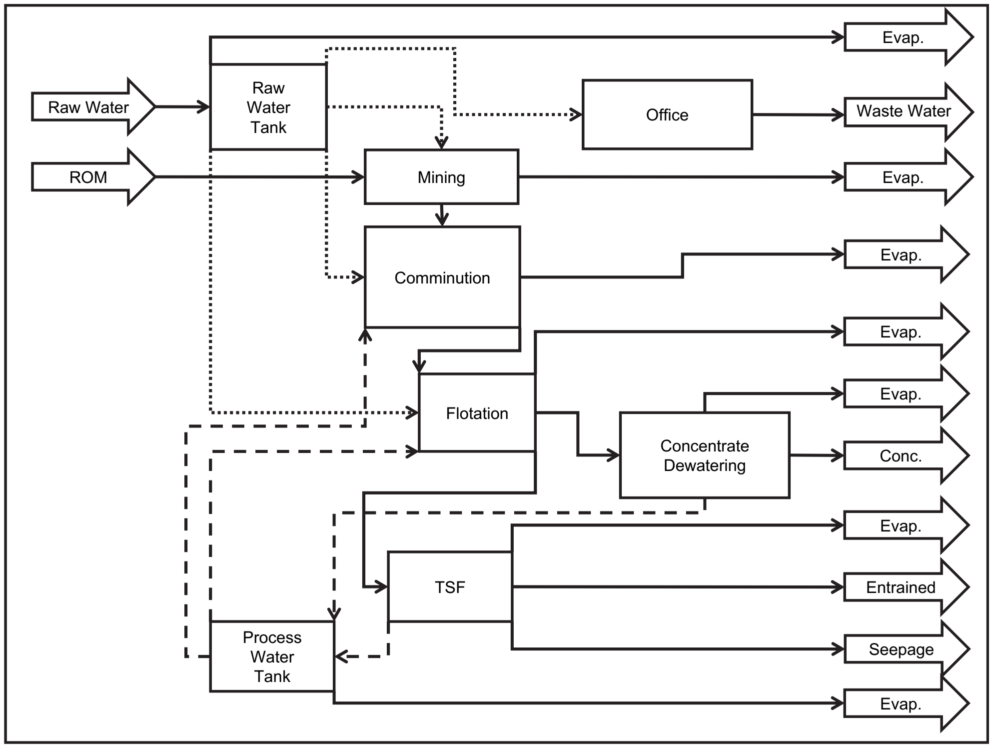

Fig. 3. Water Flow Block Diagram.

water sources and sinks: the models are time dependant and are more complex than required for the purposes of this paper (Truby et al., 2011).

Fig. 4 details the basic components of the Wels and Robertson Model. A typical TSF consists of an impoundment with several tailings discharge points located around the perimeter. Water is primarily lost through evaporation and seepage from the tailings as they are deposited on the beach of the TSF, through evaporation and seepage from the pond that forms from runoff water as the tailings are deposited, and through water entrainment in the pore spaces of the tailings. Water collected in the pond can be pumped back to the plant and reused or recycled. Not all discharge points are active at the same time - operators will switch discharge points every few weeks or months to keep the tailings evenly deposited across the impoundment. When tailings are deposited from the discharge point, the tailings form a fan-shaped wetted area which grows over time until the discharge point becomes inactive. The Wels and Robertson Model focuses on water losses from the active discharge points; while water retained in tailings at inactive discharge fans continues to evaporate or seep into the ground after deposition, this water is assumed to be non-recoverable from a practical standpoint.

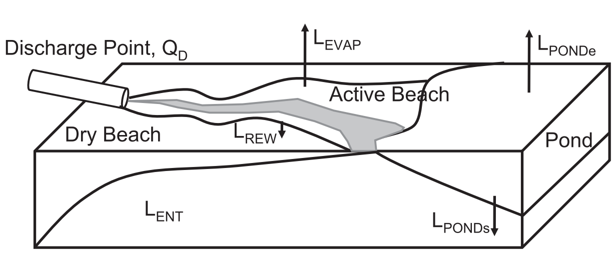

Fig. 4. Tailings Storage Facility.

The basic concept of the Wels and Robertson Model is that the water available for recovery to the mine equals the total discharged water in the tailings minus the total water losses in the TSF. The modified model only accounts for the initial rewetting losses, not the repeated rewetting losses that Wels and Robertson found to be negligible at the similarly-sized Collahuasi mine. Table 4 outlines the Wels and Robertson parameters used in scenarios 1, 2 and 5.

Overall, the site described in Scenario 1 withdraws 37,935 m^3/d of water from the local river, using 0.76 m^3 of water per tonne of ore processed. As shown in Gunson et al. (2010b), this is somewhat below the mean water usage for copper mines around the world.

4.2. Scenario 2 – Traditional case with water conservation

In Scenario 2, the mine has the same processes and equipment as the traditional case, but has eliminated as many sources of water

Table 4
Modified Wels and Robertson Model Parameters.

Parameter	Units	Value
Specific Gravity of Tailings Solids, G_s		2.65
Void Ratio of Tailings after Completion of Initial Settlement, e_0		1.12
Pan Evaporation, PE	mm/day	6
Pan factor, f_{PAN}		0.9
Initial Flooded Area, A_1	Hectares	30
Final Flooded Area, A_{30}	Hectares	90
Average effective depth of rewetting, D_{rw}	Meters	0.5
Final void ratio of Tailings (after consolidation), e_f		0.79
Average saturation of inactive tailings beach prior to rewetting, S_{dry}	Percent	80%
Surface Area of Recycle Pond, A_{POND}	Hectares	30
Vertical Permeability of Slimes underlying pond, K_{POND}	Meters/second	2.0E-09

loss as possible, with a focus on evaporation. Table 5 details the water savings achieved in Scenario 2.

To reduce water losses for dust suppression on the mine roads, the mine has applied an organic binder to the site roads. The binder is assumed to reduce the water requirements by 78.5%, the median of the water savings reported by GE (GE, 2006, 2010). This effort reduces road dust suppression water requirements to 757 m^3/d, a saving of 2763 m^3/d.

To reduce water lost due to human consumption, the mine has redirected all available waste water, or grey water, after treatment, directly to the process water tank. Gleick (1996) recommends a basic water requirement of 50 l/p/d, based on 5 l/p/d for water consumption, 20 l/p/d for sanitation, 15 l/p/d for bathing and 10 l/p/d for food preparation. Of this water, a relatively small portion is lost through perspiration and breathing. For example, in a hot environment, a 70 kg person will sweat 4–6 L/d (Gleick, 1996). The water required for showers and toilets can also be reduced by using off-the-shelf low water use toilets and shower heads. This scenario assumes that 10 l/p/d is irretrievably lost to the mine site due to perspiration, breathing, and evaporation, for a total of 3.3 m^3/d, a savings of 55 m^3/d.

To reduce water lost to evaporation due to dust suppression at the primary crusher dump pocket, the mine has installed a fog dust suppression system. Fog dust suppression systems produce fine water particles in the less than 30 micron size range, are effective at capturing dust, and consume little water. Fog dust suppression systems have proven effective in dump pocket installations, provided that the pocket can be protected from the wind (TRC Group, 2010). Water addition rates are in the range of 1 L/t of material (VSR, 2010). Thus the water requirement is reduced to 50 m^3/d, a savings of 310 m^3/d.

It is difficult to contain the dust from the discharge conveyor to the coarse ore stockpile, limiting the usefulness of a fog dust suppression system. However, the entire coarse ore stockpile can be covered to eliminate dust emissions, as has been done at Teck's Highland Valley Copper Mine (Teck, 2008). Teck is also planning on building a similar cover at its Andacollo Mine, similar to the scale of the mine described in this example, for $8 million (Teck, 2010). A covered coarse ore stockpile would eliminate the need for a separate dust control system, providing a water savings of 120 m^3/d. If the copper in the dust can be recovered, reduced dust losses may also increase the mine's copper production.

Evaporation from the concentrate thickener, the water tanks, the flotation cells and the TSF pond can also be eliminated by covering the open areas. The covers can either be created by placing a cover or roof over the open area or in the case of thickeners or ponds by placing a floating cover on the surface. Floating covers can take the form of balls or tiles and can provide coverage of up to 95% of the surface area (AWTT, 2010). Mines also can manage the size of the TSF pond by careful management of the tailings deposition plan (Wels and Robertson, 2004), allowing reduced evaporation and reduced coverage requirements. This scenario assumes that the flotation cells and the concentrate thickener are completely covered, that the TSF pond is covered with tiles and that the pond size has been reduced to 15 ha, providing additional savings of 6.7 m^3/d, 1.2 m^3/d and 1843 m^3/d respectively. The remaining assumptions regarding the TSF are unchanged from Scenario 1.

The concentrate filter performance can be improved to reduce the water content of the final concentrate. This could be achieved by upgrading filtration equipment, increasing filtration time or improving filter operation. Candelaria mine in Chile, among others, has reduced water consumption by improving filter performance (Soto, 2008). An additional benefit to improved filter performance is that lower water content reduces the concentrate weight and thus the concentrate shipping costs. This scenario assumes that the concentrate filter performance was improved, increasing the solids content from 90% solids to 93% solids, providing additional water savings of 29 m^3/d.

The combined water-saving efforts reduce the water loss from 38,955 m^3/d to 33,822 m^3/d - a savings of 5133 m^3/d. This allows the raw water requirements to be reduced from 37,935 m^3/d to 32,801 m^3/d, a savings of 13.5%. 54% of the savings are due to reducing evaporation from the mine roads and 36% of the savings are due to covering and reducing the size of the TSF pond.

Table 5
Traditional Mine with Conservation Water Savings.

Name	Scenario 2 m^3/day	Scenario 1 m^3/day	Savings m^3/day
Road-Dust Suppression	757	3520	2763
Human Consumption	3.3	58	55
Raw Water Tank – Evap.	0.0	2.2	2.2
Process Water Tank – Evap.	0.0	3.4	3.4
Primary Crusher-Dust Supp.	50	360	310
Stockpile-Dust Supp.	0.0	120	120
Flotation Cell – Evap.	0.0	6.7	6.7
Conc. Thickener – Evap.	0.0	1.2	1.2
Final Concentrate	60	89	29
Tailings Retained, L_{ENT}	20,792	20,792	0
Beach Evaporation, L_{EVAP}	9312	9312	0
Pond Evaporation, L_{POND}	47	1890	1843
Beach Rewetting, L_{REW}	2800	2800	0
Total	33,822	38,955	5133

4.3. Scenario 3 – Paste tailings case

Thickening the tailings prior to deposition can reduce the evaporation and rewetting losses in the TSF (L_{EVAP}, L_{POND} and L_{REW}) by wetting a smaller area. The solids content of the tailings can be increased to the point of forming paste, thus eliminating any TSF pond. A thickener producing lower solids content non-paste slurry would still reduce water requirements in comparison to the base case. However, paste disposal represents the most extreme reduction likely through using thickeners.

In Scenario 3, the mine has installed a 75 m diameter tailings thickener to produce paste, but left everything else as per Scenario 1. All of the flotation tailings flow to the new thickener – the overflow water is pumped to the process water tank and the paste tailings, at 65% solids by mass, is pumped to the TSF.

Installing the paste thickener reduces the water discharged with the slurry to the TSF from 114,792 m^3/d to 26,490 m^3/d. However, thickening does not change the properties of the tailings material, and so does not change the amount of water retained in the tailings. This scenario assumes that no reclaim water is available to return to the plant, as the paste tailings is already close to its final moisture content of 70% solids. Any excess water would evaporate from the paste beach. No pond is formed in the TSF. The paste thickener creates a new open area of 4418 m^2, leading to an evaporation of 31 m^3/d.

Installing the tailings thickener thus reduces the water lost from 38,955 m^3/d to 30,682 m^3/d, a savings of 8273 m^3/d. This allows the raw water requirements to be reduced from 37,935 m^3/d to 29,662 m^3/d, a savings of 21.8%, due to the loss of the pond in the TSF and reduced rewetting losses and beach evaporation.

4.4. Scenario 4 – Filtered tailings case

In Scenario 4, the mine has installed a 75 m diameter tailings thickener to feed a bank of tailings filters, but with no further change to Scenario 1. All of the flotation tailings flow to the new

Table 6
Combined Water Reduction Scenario.

Name	Scenario 6 m^3/day	Scenario 1 m^3/day	Savings m^3/day
Road-Dust Suppression	757	3520	2763
Human Consumption	3	58	55
Raw Water Tank – Evap.	0.0	2.2	2.2
Process Water Tank – Evap.	0.0	3.4	3.4
Primary Crusher-Dust Supp.	50	360	310
Stockpile-Dust Supp.	0	120	120
Flotation Cell – Evap.	0.0	6.7	6.7
Conc. Thickener – Evap.	0.0	1.2	1.2
Final Concentrate	59	89	30
Tailings Thickener – Evap.	1.5	0	−1.5
Tailings Retained, L_{ENT}	9803	20,792	10,989
Beach Evaporation, L_{EVAP}	0	9312	9312
Pond Evaporation, L_{POND}	0	1890	1890
Beach Rewetting, L_{REW}	0	2800	2800
Pre-Sorting Rejects	204	0	−204
Total	10,878	38,955	28,077

thickener with the overflow water pumped to the process water tank. The thickened tailings are then filtered to 80% solids by mass, and deposited by a stacker conveyor in the TSF. The filtrate can be reused or recycled.

Installing the tailings filter reduces the water placed in the TSF from 114,792 m^3/d to 12,299 m^3/d. As the tailings are below their saturation limit, no reclaim water is available to return to the plant. No pond is formed in the TSF. The thickener creates a new open area of 4418 m^2, leading to an evaporation of 31 m^3/d, as in Scenario 3.

Installing the filtered tailings system thus reduces the water lost from 38,955 m^3/d to 16,491 m^3/d, a savings of 22,464 m^3/d. This allows the raw water requirements to be reduced from 37,935 m^3/d to 15,471 m^3/d, a savings of 59.2%, due to filtering the tailings to below their saturation limit and the elimination any water losses in the TSF.

4.5. Scenario 5 – Ore pre-sorting case

In Scenario 5, the mine has installed an ore pre-sorting system after the primary crusher with the purpose of rejecting any ore

Table 7
Impact of Combining Sorting with Filtered Tailings on Water Withdrawals (m^3/t ore).

Ore Pre-Sorting (% Rejected)	Filtered Tailings Solids Density (%) 75%	80%	85%	90%
10%	0.29	0.22	0.16	0.10
20%	0.26	0.20	0.14	0.09
30%	0.23	0.17	0.12	0.08
40%	0.20	0.15	0.11	0.07
50%	0.17	0.13	0.09	0.06

below a certain grade. This model conservatively assumes that 20% of the ore can be rejected while retaining 98% of the copper. While the mine could increase production to keep the mill running at 50,000 tpd, for the purposes of comparison, the mine production in the model will remain unchanged, dropping the post-sorter mill feed rate to 40,000 tpd. This would allow much of the mill equipment to be reduced in size. However, for simplicity, the surface area of the flotation cells and the fresh and process water tanks will be unchanged. Pre-sorting may also require an additional crushing step not addressed here.

As a result of the reduced mill feed, the tailings production drops from 49,196 tpd to 39,213 tpd and reduces the water discharged with the slurry to the TSF from 114,792 m^3/d to 106,293 m^3/d. This model does assume that the reduced volume of slurry being deposed in the TSF reduces the size of the flooded deposition areas by a proportional amount. Thus the flooded deposition area after 1 day of discharge is lowered from 30 ha to 23.9 ha and the flooded deposition area after 30 days of discharge is lowered from 90 ha to 71.7 ha (variables A_1 and A_{30} respectively). The smaller wetter area reduces the beach evaporation to 7422 m^3/d and the beach rewetting to 2232 m^3/d. The TSF pond area is also assumed to be reduced from 30 ha to 23.9 ha, lowering the pond evaporation to 1506 m^3/d. Some moisture is also contained in the rejected ore, leading to an additional loss of 204 m^3/d.

Installing the pre-sorting system thus reduces the water lost from 38,955 m^3/d to 32,096 m^3/d, a savings of 6859 m^3/d. This allows the raw water requirements to be reduced from 37,935 m^3/d to 31,076 m^3/d, a savings of 18.1%, due to the reduced tailings production.

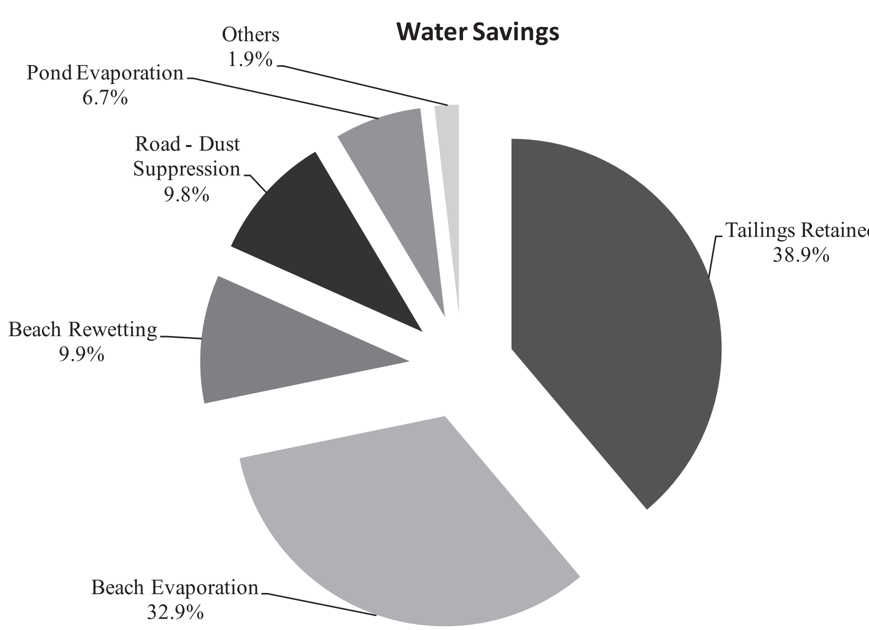

Fig. 5. Scenario 6 Water Savings.

Table 8
Scenario Summary.

Water Withdrawal	Scenario 1 Base Case	Scenario 2 Conservation	Scenario 3 Paste	Scenario 4 Filtered	Scenario 5 Sorting	Scenario 6 Combined
m^3/day	37,935	32,801	29,662	15,471	31,076	9858
m^3/t ore	0.76	0.66	0.59	0.31	0.62	0.20
m^3/t Cu	157.4	136.1	123.0	64.2	140.9	44.7
% reduction	0	13.5	21.8	59.2	18.2	74.0

4.6. *Scenario 6 – Combined water-reduction case*

In this final scenario, the water savings options which most reduced water withdrawals in the previous scenarios are combined. The scenario includes the water conservation methods included in scenario 2, the filtered tailings system described in scenario 4, and the ore pre-sorting system described in scenario 5. To summarize the process, the ore is pre-sorted, rejecting 20% of the ore while retaining 98% of the copper, and the flotation tailings are filtered to a solids content of 80% by mass. In addition, an organic binder is applied to the site roads, all site grey water is directed to the process water tank, a fog dust suppression system is installed on the primary crusher dump pocket and the coarse ore stockpile is covered. The concentrate thickener, the water tanks and the flotation cells are covered. Finally, tiles are placed on the tailings thickener to reduce evaporation by 95% and the final concentrate is filtered to 93% solids by mass.

Table 6 details the savings achieved through combining the different water reduction options.

Installing the combined system thus reduces the water lost from 38,955 m^3/d to 10,878 m^3/d, a savings of 28,077 m^3/d. This allows the raw water requirements to be reduced from 37,935 m^3/d to 9858 m^3/d, a savings of 74.0%. Fig. 5 shows the savings achieved in the different water sinks at the mine. The combination of pre-sorting and filtered tailings led to 88.4% of the water savings. Reducing water lost on road dust control contributed 9.8% of the savings and the other efforts reduced water losses by 1.9%.

Furthermore, if the percentage of ore rejected could rise above 20% or if the filtered tailings solids content could reach above 80% solids, the water withdrawals could be further reduced significantly. Table 7 shows how the water consumption, in m^3/t of ore, changes when varying the percentage of ore rejected and the filtered tailings solids content, with all other variables unchanged from Scenario 6. Improving the filtered tailings solids density or the percent of ore rejected by pre-sorting alone reduces water consumption linearly, but combining the two leads to dramatic reductions in water requirements. If the mine could achieve a filtered tailings solids density of 90% solids by mass while rejecting 50% of the ore through pre-sorting, water consumption could reach as low as 0.06 m^3/t of ore mined, allowing the 50,000 tpd mine to withdrawal only 3051 m^3/day of raw water.

5. Conclusion

The results from all six scenarios are summarized in Table 8. The base case scenario, representing common practice at open pit copper mines, achieved a water withdrawal of 0.76 m^3/t of ore processed. Scenario 2 implemented a water saving strategy of reducing evaporation throughout the mine site, lowering the water withdrawal to 0.66 m^3/t. Scenario 3 implemented tailings paste thickening, approximating the maximum water savings achievable through implementing tailings thickening technologies, and reduced water withdrawals to 0.59 m^3/t. Scenario 4 introduced filtered tailings disposal and achieved a water withdrawal of 0.31 m^3/t by filtering the tailings to 80% solids by mass. Scenario 5 introduced ore sorting to reject 20% of the ore, reducing the water withdrawals to 0.62 m^3/t. Scenario 6 combined the efforts of scenarios 2, 4, and 5 to achieve a water withdrawal of 0.20 m^3/t of ore. Further increasing the portion of ore rejected in ore sorting and/or the final solids density achieved by tailings filtration could bring water withdrawals significantly below any existing conventional major copper mine and into the range of the water consumption of the best performing SX/EW operations (Gunson et al., 2010b).

The results of the different scenarios highlight the obvious importance of tailings disposal in mine water management – most other options have comparatively minor impacts on overall water consumption. However, the key finding of the study is the massive potential water savings from combining ore pre-concentration and filtered tailing disposal. It is still comparatively rare to test ore for amenability to pre-concentration, but in areas with high water costs, evaluating pre-concentration as an option may be reasonable. Filtered and paste thickened tailings disposal options are relatively expensive and difficult technically. However, they would be significantly more attractive if a large portion of the ore could be rejected prior to comminution. There may also be considerable plant capital and operating cost reductions if pre-concentration is viable.

These low levels of water consumption may seem unrealistic to many in the mining industry today. However, these scenarios were developed by combining currently available off-the-shelf mining technology. While not all of these options may be suitable for many mine sites, these scenarios outline how the mining industry can work toward dramatically reducing its water requirements.

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