A review of the effect of water quality on flotation

Wenying Liu*, C.J. Moran, Sue Vink

Centre for Water in the Minerals Industry, Sustainable Minerals Institute, The University of Queensland, Brisbane, Queensland 4072, Australia

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As water resources become scarcer and society's demands to reduce freshwater extraction have increased, mine sites have been increasing water reuse and accessing multiple water sources for mineral processing to save freshwater, particularly in froth flotation. Implementation of either strategy may lead to water quality variation that may impact flotation efficiency. A large number of studies have been carried out to enhance the understanding of water quality variation in flotation. However, these studies tend to be performed on a case by case basis. There is a lack of a framework to put together these existing studies, which makes it difficult to understand the topic comprehensively and therefore difficult to identify gaps and directions for future research. This would eventually hinder the ongoing implementation of water conservation practices and thus lead to more pressure being placed on freshwater. In this paper, a review of the existing studies on water quality variation in flotation is given in three aspects: causes of water quality variation, consequences of water quality variation and solutions for problems caused by water quality variation. Based on the three aspects, a framework was developed, with which these studies were categorized and structured. Organizing literature in this way makes it possible to identify gaps in current research and future research directions.

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1. Introduction

The minerals industry is being driven to save freshwater and minimize mine water discharge by a combination of water challenges, such as limited freshwater availability (Peters and Meybeck, 2000; Ridout and Pfister, 2010), environmental pollution from mine water discharge (Carlson et al., 2002; Johnson et al., 2002), increasing competition for water among multiple users (Boulay et al., 2011; Rijsberman, 2006), community concerns over water security and cultural or spiritual issues regarding water (Jenkins and Yakovleva, 2006; Kapelus, 2002), and corporate sustainability policies and goals (Amezaga et al., 2010; Moran, 2006). Two important strategies being implemented to improve water efficiency are increasing water reuse and accessing alternatives to freshwater for mineral processing, particularly in flotation. Implementation of either strategy has been shown to increase the tendency for water quality to change, which, in turn, may affect flotation efficiency. In general, flotation is most effectively undertaken with clean water. As a second preference, metallurgists seek
a consistent water quality so that reagent regimes for flotation can be developed and applied consistently. Variation in water quality is undesirable because it could complicate operating conditions and compromise flotation performance (Broman, 1980; Hoover, 1980; Levay et al., 2001; Malysiak et al., 2003; Rao and Finch, 1989).

A significant body of research seeks to understand issues associated with water quality in flotation. These studies focus mainly on three aspects: (1) understanding the reasons for water quality variation in flotation, (2) quantifying the effect of water quality variation on flotation efficiency and investigating the underlying mechanisms to explain the effect, and (3) testing different solutions to deal with the effect. However, one common limitation of these studies is that they approach the multifaceted topic on a case by case basis. Lacking of a method to organize these existing studies hinders the understanding of this topic in a holistic way and therefore makes it difficult to identify gaps in this area and possible directions for future research. Given the limitation stated above, after reviewing the existing research on water quality variation in flotation, a framework was developed to organize these studies. This framework can enhance the comprehensive understanding of this topic by showing the emphasis of current research. This helps identify gaps in current research and directions for future research.

2. Existing research on water quality variation in flotation

Water quality for flotation on a mine site can vary significantly over time (Levay and Schumann, 2006; Luukkanen et al., 2003; Stén et al., 2003). The composition of flotation water depends on the ore being processed, the reagent suite, the water source and the way the site water system is managed. The entire water system is also affected by climate. Fig. 1 shows a conceptual view of a site water system which puts the mineral concentrator in perspective with the main water system components. The system consists of raw water stores, worked water stores, tailings facilities, other site water tasks (operational uses of water), the concentrator itself and a blender. The blender is a virtual representation of site infrastructure used to demonstrate that worked water might need to be diluted with raw water or treated water prior to its use in a specific water task. Raw water is water that has not been previously used for any purpose within the site (Cote and Moran, 2009). In contrast, worked water is water that has been used for a purpose on site and is returned for potential future use (Cote and Moran, 2009). A detailed explanation of Fig. 1 is given in Section 2.1.

2.1. Causes of water quality variation

Factors that cause water quality variation in flotation can be grouped into two categories by reference to the concentrator: internal and external (Fig. 1). Internal factors include the ore being processed by the concentrator, reagents added into the concentrator and water internal reuse, where water is recovered from the concentrator with the help of different kinds of concentrate/tailings thickeners, local storage tanks, etc. and used again by the concentrator. External factors are divided into “external to concentrator” and “external to site”. “External to concentrator” factors refer to factors that are within the site boundary, which include the raw water stream and water external reuse, where water is recovered from different site water tasks (tailings storage facilities and other site water tasks), stored in an appropriate place and used again in the concentrator. Raw water and worked water stores are open systems that interact with the surrounding environment and local climate. These interactions result in mass and energy transfer processes taking place across the site boundary. These processes are defined as “external to site” factors, which are shown as “inputs” and “outputs” in Fig. 1. The possible inputs and outputs of raw water and worked water stores are summarized in Table 1 (Cote and Moran, 2009).

Different water constituents associated with both the internal and external factors can be introduced into flotation water by either simple mixing or complex physical and biophysicochemical water–mineral interactions during mineral processing. Further, chemical reactions may occur among constituents from different water streams when coexisting in flotation water. The processes of different constituents being introduced into flotation water are given below.

2.1.1. Internal factors

2.1.1.1. Ore oxidation and dissolution. The chemical composition of the ore being processed by a mine can be very complex and usually includes a variety of minerals. Ore oxidation and dissolution during mineral beneficiation processes can introduce various substances into flotation water, which may alter the chemistry of the system and thereby influence flotation efficiency. The exact nature of the reaction products depends on reaction conditions, such as Eh and pH.

There are examples in the literature showing the dissolution of ore and its potential implications for flotation. For example, surface oxidation of copper ore (chalcopyrite, enargite and tennantite) leads to the dissolution of copper (II) to different extents

![Fig. 1. A conceptual view of a site water system showing the internal and external factors causing water quality variation in a flotation plant.](image-url)
at different pH values (Sasaki et al., 2011). Thiourea and copper ions are released into flotation water from copper ore, which may have beneficial effects on flotation by depressing pyrite (Liu et al., 1993), and improve the selectivity of nickel–copper separation (Kirjavainen et al., 2002a, b). At lower pH and in a stronger oxidative environment, chalcocite oxidation produces copper (II) and soluble sulfur species (Chander and Fuerstenau, 1983), which may affect the subsequent adsorption of polymeric dispersant onto chalcocite particles (He et al., 2011). The rate and extent of galena dissolution depends on pretreatment conditions, with air treatment having the highest dissolution rate and extent, followed by oxygen and nitrogen (Fornasiero et al., 1994). The production of lead ions by dissolution leads to the subsequent formation of lead hydroxide precipitates onto galena surfaces, which could affect galena flotation (Chernyshova, 2003). Dissolution of galena also produces dissolved sulfur species, with sulfate and sulfide being the major species with and without air, respectively (Hsieh and Huang, 1989). Another example is molybdenite oxidation, which produces molybdate ions and sulfur (Chander and Fuerstenau, 1983).

The ore itself contributes substances to flotation water that are normally minimal in quantity due to their low solubility and low availability from limited oxidation of valuable and gangue minerals (Johnson, 2003). However, these constituents can build up in flotation water through water reuse, and eventually affect flotation performance, e.g., the accumulation of dissolved copper leading to inadvertent activation of sphalerite (Slatter et al., 2009).

The grinding media employed might also affect flotation water quality if they are not inert materials (Huang and Grano, 2006; Peng and Grano, 2010). For example, Eh and dissolved oxygen of the slurry has been found to decrease immediately after grinding upon application of reducing steel grinding media (Grano et al., 1990). Conversely, iron hydroxide is produced due to the oxidation of electrochemically reactive steel media (Adam et al., 1984; Grano, 2009). As a result, flotation performance can be affected because of the strong dependence of thiol collector adsorption on Eh and the presence of iron hydroxide (Freeman et al., 2000; Grano, 2009).

2.1.1.2. Reagent addition. Reagent addition can introduce various inorganic or organic substances into flotation water in the form of residue reagents, reaction by-products, and impurities (Schumann et al., 2009). For example, lime is added in flotation of molybdenite–copper ore to maintain an alkaline pH for pyrite depression, which causes the release of calcium ions into solution (Raghavan and Hsu, 1984). Water for reverse flotation of iron ore contains a significant concentration of amine flotation reagents used to remove silica particles (Batisteli and Peres, 2008; Stapelfeldt and Lima, 2001). Copper cyanide complexes are often found in water for galena–sphalerite flotation because of the addition of sodium cyanide in the milling circuit (Seke and Pistorius, 2006).

Similar to ore dissolution, flotation reagents themselves may contribute a small portion of water constituents (Slatter et al., 2009), but these constituents can be accumulated in water in an altered or unaltered state during water reuse and eventually reach a concentration high enough to impact flotation performance. For example, flotation selectivity of copper–lead–zinc ore is compromised by the accumulation of the decomposition products of a xanthate copper collector Z-200 due to water reuse and its subsequent non-selective adsorption (Ozkan and Acar, 2004).

2.1.1.3. Water internal reuse. Water internal reuse is a typical water management strategy targeting a concentrator. For example, the Rosh Pinah mine in Namibia recovers water from the lead rougher tailings thickener and lead concentrate thickener, and uses the recovered water for milling and lead flotation (Seke and Pistorius, 2006). Water recovered from concentrate filtration/drying is used again in the ore grinding circuit in Olympic Dam (Torris and Trotta, 2009). Water internal reuse may cause issues related with processing, e.g., ore dissolution and reagent addition, to later become water quality issues due to the recirculation of these substances in processing plants. However, this strategy could, to some extent, simplify water chemistry because the water is generally re-circulated rapidly without experiencing significant alterations (Rao and Finch, 1989).

2.1.2. External factors

2.1.2.1. Multiple sources of raw water supplies. Water quality variations in the raw water stream is defined as one of the “external to concentrator” factors that can contribute to water quality variation in the concentrator. The reason why water quality varies in raw water stores can be tracked down to “external to site” factors, because raw water stores receive water inputs from multiple sources of different quantity and quality from outside of the site boundary. These sources, as shown in Table 1, include surface water, ground-water, sea water and third-party water.

The use of multiple sources of raw water supplies of different quality is very common for many mine sites. For example, primary water supplies containing high levels of salinity including calcium, magnesium and iron salts are being used in several remote areas (Levay et al., 2001). Humic acids, abundant in natural waters associated with dead vegetation decomposition, have been found to exist in flotation water, which could depress molybdenite flotation (Lai et al., 1984), and coal flotation (Arnold and Aplan, 1986). Tannic acid, commonly found in ground water, is a potential depressant which may be introduced into flotation water from raw water streams (Levay and Schumann, 2006). Some mine sites are using treated effluent (third-party water) as a make-up water.
supply, e.g., Mt Arthur coal mine (Brereton et al., 2007), Cadia Valley gold–copper mine (Schumann et al., 2003), and Mogalakwena platinum mine (Slatter et al., 2009). This water source may contain high levels of total organic carbon (TOC) and microbes, which may affect flotation performance (Levay et al., 2001). Apart from these inputs, a variety of outputs can also contribute to water quality variation in the raw water stream (Table 1). For example, water constituents can be concentrated due to evaporation and diluted due to rainfall/runoff which may vary seasonally (Rao and Finch, 1989; Vink et al., 2009).

2.1.2.2. Water external reuse. A common external reuse strategy is that water is recovered from tailings storage facilities and other site water tasks, stored in the worked water stores and used again in the concentrator (Department of Resources Energy and Tourism, 2008). Besides the raw water stream, this worked water stream is defined as the other “external to concentrator” factor that can cause water quality variation in flotation. Similarly, this variation can be tracked down to “external to site” factors. As opposed to the raw water stream, there are no inputs but only outputs for the worked water stream (Table 1).

One of the outputs is associated with the local climate, which may raise significant issues regarding water quantity and quality. For example, evaporation can alter concentrations of dissolved and colloidal constituents at different times of the year (Levay et al., 2001). Changes in temperature due to diurnal (day/night) or seasonal (summer/winter) cycles may influence water composition, either directly or indirectly, through chemical, physico-chemical and biological processes, e.g., mineral dissolution and oxidation, solubility of metal precipitates, all of which are affected by temperature (Liu, 1989). These processes may change water constituents in concentration and form. For example, physico-chemical and biological processes mainly related to degradation of flotation reagents could take place in the tailings storage facilities (Chen et al., 2011; Nedved and Jansz, 2006). Tailings particles can contain a high proportion of fine clay and other colloidal materials, which are difficult to separate from water (Ofori et al., 2011). These changes in the tailings storage facilities can be propagated to the concentrator through water external reuse. Similar to water internal reuse, water external reuse may cause initial processing issues to eventually become water quality issues.

2.2. Consequences of water quality variation and associated pathways

Water quality variation is among the factors that can influence flotation efficiency. The consequences of water quality variation in flotation can be grouped into two broad categories based on the type of water constituents: abiotic, meaning not alive (e.g., inorganic metal ions), and biotic, meaning of or related to life (e.g., microorganisms). For each category, the consequences can be either negative or positive effects on flotation efficiency, which can be quantified by different variables, such as recovery, grade and floatability of valuable minerals, and selectivity between valuable minerals and gangue.

The negative or positive effects of abiotic and biotic water constituents can occur through different pathways. Firstly, water constituents could interact with and therefore change the properties of any of the three phases involved in flotation: mineral particle, air bubbles and aqueous solution. These changes could then affect the efficiency of the three sub-processes occurring sequentially in a flotation cell. These sub-processes include collision of mineral particles with bubbles, attachment of mineral particles to bubbles, and formation of stable particle–bubble aggregates which then rise to the surface of the flotation cell forming the froth phase (Dai et al., 1999). Only mineral particles with certain degrees of hydrophobicity, either naturally occurring or artificially rendered by adding certain flotation reagents, can attach to bubble surfaces. The efficiency of the three sub-process are defined as the fraction of particles colliding with a bubble, the fraction of colliding particles which actually attach to the bubble surface, and the fraction of attached particles which are successfully transported across the pulp–froth interface, respectively (Dai et al., 1999; Seaman et al., 2006). Finally, these changes are reflected in the change of the final flotation efficiency. In addition, water constituents can also react with reagents added to flotation circuits, thus changing reagent properties.

The pathways by which a particular water constituent affects flotation performance may be different for each mineral and reagent combination. These possible pathways to explain the negative and positive effects of different abiotic and biotic water constituents are given below.

2.2.1. Abiotic water constituents

2.2.1.1. Negative effects.

2.2.1.1.1. Reduction in particle surface hydrophobicity by metal ions. Metal ions are important abiotic water constituents which can impact flotation performance. Metal ions hydrolyze in alkaline pH solutions and precipitate as hydrophilic metal hydroxides, sulfates or carbonates if their concentrations are above their respective solubility limits (Fuerstenau et al., 1985). Formation of metal hydroxides is influenced by aqueous pH (Font et al., 1999). Precipitation of these hydrophilic metal hydroxides on mineral surfaces has been generally described as indiscriminate (Kitchener, 1984), resulting in formation of a hydrophilic barrier to collector adsorption on mineral surfaces (Fornasiero and Ralston, 2006; Senior and Trahar, 1991).

Calcium, iron and aluminum ions are the cations most cited in the literature as precipitated species with a detrimental effect on mineral recovery and grade (Hoover, 1980). The effect of these multivalent ions on coal flotation has been investigated, the result of which shows that multivalent electrolytes depress coal flotation in the pH region of metal hydroxide precipitation (Celik and Somasundaran, 1986; Rao and Finch, 1989; Somasundaran et al., 2000). Sphalerite recovery has been found to be reduced by the presence of zinc ions (200 ppm) due to the formation of colloidal hydroxide on the mineral surface (Williams and Phelan, 1985). Copper (II) acts as the activator at a threshold concentration but a depressant for sphalerite at high concentrations (Fornasiero and Ralston, 2006). A critical concentration of copper sulfate exists where sphalerite gains the maximum recovery. Above that critical concentration, sphalerite recovery decreases as a result of excess copper hydroxide on the sphalerite surfaces (Boulton et al., 2005). Coarse particles are the first particles to be affected by a reduced surface hydrophobicity as they are more easily detached from bubbles in the high turbulent regions of a flotation cell (Ralston et al., 2007).

The reduction in mineral surface hydrophobicity due to the precipitation of hydrophilic metal hydroxides could compromise the efficiency of the particle–bubble attachment sub-process (Koh et al., 2009; Schwarz and Grano, 2005). It can also cause lower contents of mineral particles entering the froth, which might compromise the efficiency of the sub-process of formation of stable particle–bubble aggregates (Ali et al., 2000; Ate, 2012; Johansson and Pugh, 1992; Moolman et al., 1996). The presence of dissolved ions in water can also change the stability of particle–bubble aggregates in the froth phase (Bıçak et al., 2012; Farrokhpay and Zanin, 2012).

2.2.1.1.2. Change in particle surface charge by metal ions. Metal ions in flotation water can alter the surface charge of particles and consequently affect interactions between particles and waste gangue or between particles and collectors. This could affect particle–bubble attachment and also formation of stable particle–bub-

Investigations have been carried out on the role of calcium ions in modulating the surface properties of molybdenite and in controlling the interaction between molybdenite and the most predominant gangue mineral, namely quartz, in copper porphyries. The results show that the floatability of fine molybdenite particles is significantly reduced when calcium ions and silica coexist in the flotation pulp. This is because the adsorption of calcium ions on molybdenite and quartz reduces the magnitude of negative surface charges and thus causes heterocoagulation of molybdenite and quartz (Raghavan and Hsu, 1984). The adsorption of calcium and other metal ions that exist in flotation water leads to a reduction in the negative surface charges and xanthate adsorption on galena, which may have detrimental effects on galena flotation (Ikumapayi et al., 2012). Experimental results suggest that generally, metallic cations present in electrolytes hinder the flotation of pyrochlore, an oxide mineral. This is because the negative surface charge on pyrochlore is reduced by the adsorption of cationic species, which hinders the adsorption of cationic amine collector on pyrochlore surfaces (Espinosa-Gomez et al., 1987; Rao et al., 1988).

2.2.1.1.3. Inadvertent activation of unwanted minerals by metal ions. Some metal ions can also inadvertently activate unwanted minerals, thus affecting flotation selectivity in varying degrees. For example, metal ions such as lead, silver and iron are present in flotation water as impurities and can inadvertently activate sphalerite surfaces (Chandra and Gerson, 2009; Finkelstein, 1997). The undesirable activation by metal ions, copper (II), iron (II) and calcium (II), causes pyrite to float together with sphalerite in sphalerite flotation circuits, leading to poor selectivity (Boulton et al., 2003; Zhang et al., 1997). Inadvertent activation of sphalerite and pyrite by copper ions in water leads to a low copper grade in copper flotation circuits (Bromon, 1980; Rao and Finch, 1989). Copper (I) cyanide could activate sphalerite in flotation of lead–zinc sulfide ore reducing lead grade (Seke and Pistorius, 2006).

2.2.1.1.4. Slime coatings on mineral surfaces. The formation of a slime coating on valuable mineral surfaces can lead to depression of flotation of valuable minerals. For example, positively charged serpentine gangue minerals, such as chrysotile and lizardite, has been found to severely reduce the flotation of negatively charged (unoxidized) pentlandite by forming a hydrophilic slime coating on pentlandite surfaces (Edwards et al., 1980). The coverage of colloidal iron oxide (hematite) slimes originating from the steel grinding media, iron sulfide minerals and non-sulfide gangue, on galena surfaces can reduce the mineral surface hydrophobicity and therefore have a significant depressing effect on the flotation of galena particles (Bandini et al., 2001). The slime coating of montmorillonite clay on coal is detrimental to coal flotation (Xu et al., 2003).

2.2.1.1.5. Interactions with flotation reagents. Like metal cations, anions may also have a negative effect on flotation performance by interacting with flotation reagents. For example, anions in treated effluent have been identified as having a negative effect on copper and molybdenum recoveries (Fisher and Rudy, 1976). Sulfide ions have been found to decompose xanthate collector in the presence of oxygen (Shen et al., 2001). Under solution conditions which favor rapid xanthate decomposition by sulfite, xanthate adsorption onto galena is significantly reduced and galena flotation strongly depressed (Grano et al., 1997a,b). Salts in water are particularly liable to react with fatty acid reagents and form insoluble complexes (Ozkan and Acar, 2004). Calcium ions react with the collector used in apatite flotation, thus reducing its concentration for flotation, leading to a decline in apatite recovery (dos Santos et al., 2010).

Variations in pH and Eh usually affect the chemistry of flotation reagents and species present in flotation water. For example, pulp pH can alter the form of some frothers and thus influence their effectiveness. Cresol, with the optimum performance in the molecular form, has been found to be converted into ionized form at high pH, which then does not act as a frother. Quinoline exists in ionized form in acid pH, and consequently has poor frothing properties (Bulatovic, 2007). Dissolved oxygen is also important in controlling the composition of the mineral surface of some minerals and the effect of the reagents on the minerals in flotation systems (Gaudin, 1974).

2.2.1.2. Positive effects.

2.2.1.2.1. Compression of electrical double layer. The presence of electrolytes can improve particle–bubble attachment efficiency through compressing the electrical double layer and thus reducing the electrostatic repulsion between particles and bubbles (Kurnia-wan et al., 2011). Investigation of oil agglomeration of coal in inorganic salt solutions shows that coal recovery increases markedly as salt concentration (NaCl) is raised (Yang et al., 1988). Coal recovery is improved by using saline water (Ofori et al., 2005; Wang and Peng, 2013). Flotation of methylated quartz is improved with increasing KCl concentration (Laskowski and Kitchener, 1970). The efficiency of the attachment of methylated quartz particles to nitrogen bubbles has been found to increase with the increase in KCl electrolyte concentration (Dai et al., 1999). Flotation improvement in the presence of electrolytes is explained by the compression of the electrical double layer by electrolytes, thus reducing electrical repulsion and subsequently facilitating the particle–bubble attachment process. The reduction in electrostatic repulsion between particles or between particle and bubbles may in turn decrease the adsorption of positively charged hydrophilic slimes such as magnesium silicates and thus increase bubble-particle attachment (Bremmell et al., 2005; Hewitt et al., 1994; Morris et al., 1995).

2.2.1.2.2. Formation of smaller bubbles. Electrolytes are favorable to the formation of smaller stable bubbles due to the influence of the electrolytes on surface tension and gas solubility (Pugh et al., 1997). Smaller bubbles increase the particle–bubble collision probability (Bournival et al., 2012; Pugh et al., 1997), and also improve particle–bubble attachment efficiencies (Hewitt et al., 1994). Finer gas bubbles in high salt concentrations may result in reduced reagent consumption (Quinn et al., 2007). However, it is noteworthy to mention that along with the benefits discussed above, an increase in ionic strength can cause a negative effect by enhancing frothability and therefore increasing gangue recovery (Manono et al., 2012, 2013).

2.2.2. Biotic water constituents

2.2.2.1. Negative effects. Biotic water constituents in flotation water, including organics and microorganisms, may be surface active, or act as dispersants or flocculants, which can interfere with flotation process (Levay et al., 2001; Rao and Finch, 1989). Residue reagents such as xanthate and their decomposition products in flotation water could absorb non-selectively on most sulfides and reduce flotation selectivity (Seke and Pistorius, 2006).

There are cases in literature showing the effect of organic species on flotation efficiency through different pathways. For example, humic acids, abundant in some natural waters, have been found to readily adsorb on molybdenite surfaces and result in decreased hydrophobicity and floatability of molybdenite (Lai et al., 1984). The presence of a small amount of strongly hydrophilic lignosulfonates is sufficient to render molybdenite surfaces hydrophilic, which hinders the attachment and spreading of an oily collector over the molybdenite surface (Ansari and Pawlik, 2007a,b). The presence of organic species, the exact composition of which is not known, has a negative effect on pyrochlore flotation selectivity by promoting the flotation of silicate minerals along with pyrochlore (Espinosa-Gomez et al., 1987; Rao et al., 1988). The accidental incorporation of oils and lubricants into the mill feed
at a copper–gold concentrator has been shown to promote liberated gangue particles, leading to uncontrollable frothing associated with a drop in selectivity (Bos and Quast, 2000). Copper and gold flotation has been found to be negatively affected by total organic carbon (TOC) in flotation water (Schumann et al., 2003).

A variety of microorganisms at meaningful concentrations can be introduced into flotation water due to the use of alternative water sources that contain microorganisms, such as treated effluent. Furthermore, flotation circuits can provide conditions conducive to microbial growth, given that there is potential nutrition from reagent addition, appropriate oxygen levels and suitable temperature. For example, the total bacterial count in the plant flotation pulp on a mine site can be as high as $10^9$ cfu/mL (Levay et al., 2001), where cfu stands for colony-forming units. Unlike direct microscopic counts (cell/mL) where all cells (dead and viable) are counted, cfu only estimates viable cells. Thus the concentration of dead plus viable bacterial cells in the flotation pulp may be higher than $10^9$ cell/mL. For comparison, $E.\ coli$ concentration in typical raw sewage (i.e., untreated municipal wastewater) is at a magnitude of $10^7$ cell/mL (Carr et al., 2004). The presence of bacteria in flotation water could pose potential risks to flotation performance (Levay et al., 2001; Slatter et al., 2009). For example, bacteria ($\gamma$-Proteobacteria) have been shown to reduce the floatability of apatite due to their interactions with calcium-containing minerals and strong flocculation (Evdokimova et al., 2012). $E.\ coli$ has been found to have a negative effect on copper flotation mainly due to its attachment onto chalcopyrite surfaces and the resulting reduction in chalcopyrite surface hydrophobicity (Liu et al., 2013a; Liu et al., 2013c).

### 2.2.2.2. Positive effects

In some cases, biotic water constituents may bring positive effects on flotation efficiency. Two types of biotic water constituents can exemplify the positive effects: residue reagents and bacteria. Residue reagents brought to flotation circuits through water external reuse allows retention of some reagents and therefore lowers reagent consumption. For example, the dosage of amine collector in the reverse flotation of iron ores can be reduced by up to 50% through water external reuse (Batistelli and Peres, 2008; Stapelfeldt and Lima, 2001). Bacteria could be used to reduce the recovery of one mineral over that of another in situations where a selective flotation is required (Elmahdy et al., 2011; Evdokimova et al., 2012; Pecina-Trevino et al., 2012). Further research will advance and refine the search for suitable solutions to take advantage of the positive effects of biotic water constituents.

#### 2.3. Solutions for water quality variation

As flotation efficiency can be affected by water quality change, different strategies are required to manage water quality change to avoid compromising flotation efficiency. Solutions that can be applied to deal with flotation problems caused by water quality can be divided into two categories by reference to the concentrator: internal and external ("external to concentrator" and "external to site").

##### 2.3.1. Internal solutions

Generally, flotation problems from water quality are dealt with by internal solutions, which focus on the flotation operation itself. One conventional internal solution to deal with the problems is to adjust the reagent regime. There are examples of reagents added to control flotation problems caused by water quality in literature. Zinc hydroxide precipitants can be dissolved by acids, thus improving sphalerite–galena separation (Levay et al., 2001). Removal of calcium ions by oxalic acid improves pyrochlore recovery (Rao et al., 1988). The addition of citric acid has been found to eliminate the detrimental effects of calcium ions and to restore the selectivity of chalcopyrite–galena separation with dextrin (Liu and Zhang, 2000). Chemical dispersants, e.g., polyphosphate, can be used to disperse precipitated colloidal species from mineral surfaces (Levay et al., 2001). Addition of complexing agents, such as amine complexes, can help to revert inadvertent activation effects of metal ions on the selective flotation of pentlandite–pyroxene (Shackleton et al., 2003). The selectivity of sphalerite and pyrite can be increased by the use of sulfoxyl depressants against pyrite that has been inadvertently activated by metal ions (Chandra and Gerson, 2009). Dithionite has been used as a reducing reagent to control electrochemical reactions in flotation, notably to prevent oxidation of sulfide minerals (Sui et al., 2000). Activation of sphalerite by copper species during the selective flotation of galena and sphalerite can be eliminated by removing copper with sodium cyanide (Seke and Pistorius, 2006). Soda ash is added to precipitate calcium and other interfering cations from the pulp for flotation of phosphate ore (Nanthakumar et al., 2009). Changing the slime surface charge by chemical additives, such as carboxy methyl cellulose, has been shown to be effective in reducing the adverse effect of the slime on pentlandite flotation (Edwards et al., 1980). Coal flotation recovery increases significantly by removing the fine fraction from the feed using a hydrocyclone (Oats et al., 2010).

In some cases, the internal solution of adjusting reagent regime is an efficient way to deal with flotation problems associated with both internal and external factors. However, this solution requires much time, energy and attention to be spent on the selection of reagents and control of reagent additions to ensure proper concentrations and the most effective separation. In addition, operational efficiency cannot be guaranteed. For example, despite continuous process improvement, the problem of pyrite activation by metal ions and its misreporting to sphalerite concentrates still remains (Boulton et al., 2003; Zhang et al., 1997). Chemical side-reactions between the reagents added and flotation water constituents, metal ions for example, may also affect mineral surface properties and thus their floatability (Sui et al., 2000).

Water treatment by conventional technologies and operational techniques to meet flotation requirements is also considered as an internal solution. A wide variety of technologies and techniques are available for the minerals industry. The main types of water treatment and their application domains in mining operations can be found in The Water Management Handbook (Department of Resources Energy and Tourism, 2008). A few examples of water treatments employed to meet mineral processing requirements are given here. Metal ions can be removed using ion exchange and membrane technologies. For example, the adverse effect of zinc ions on sphalerite flotation is eliminated by treating flotation water to remove zinc ions before the water enters the mill (Williams and Phelan, 1985). The use of low-cost natural iron ore has been shown to be effective in removing arsenic from water (Aredes et al., 2012). Laboratory experimental results show that a combination of activated carbon and ion exchange to remove Ca$^{2+}$, Mg$^{2+}$ and organic species appears to be an effective means for improving selective flotation of pyrochlore (Espinosa-Gomez et al., 1987; Rao et al., 1988). Pretreatment of water with aeration or with activated carbon has been found to significantly improve molybdenite recovery in the presence of humic acid (Lai et al., 1984). Removal of organic species from flotation water by activated carbon can produce a statistically significant improvement in nickel grade and recovery (Levay et al., 2001).

Each water treatment technique has its own advantages and limitations. Therefore, the optimum treatment approach should be selected according to the water quality requirements for a specific water task. For example, treatments for most mineral processing applications would not require potable grade water. A
combination of different approaches may be used to deal with difficult or complex water quality issues. The selection of water treatment approaches, which match the water quality requirement for specific water tasks, can be challenging. The cost of water treatment and the undesirable additional energy incurred may pose a challenge for maintaining an environmentally and economically sustainable mining operation.

2.3.2. External solutions

Although they may efficiently deal with flotation problems from water quality, the technologies and processes implemented by internal solutions have not considered the connectivity of the site water system, leading to a constrained view of opportunities to deal with the problems. In contrast, external solutions attempt to consider opportunities across the entire water system to deal with flotation problems caused by water quality. External solutions have generally received less attention compared to internal solutions. Therefore, there is a lack of literature on external solutions that could be applied to manage water quality problems.

Flotation water quality is dynamic because of the influence by the internal and external factors discussed in Section 2.1. The water system on a mine site acts as a complex system with feedbacks and interactions between the local climate and the engineered reticulation (Vink et al., 2009). Therefore, solving flotation problems caused by water quality requires an understanding of the properties of different water streams and their connectivity. If this information is known, in some cases relatively simple external water management practices can be applied to help stabilize plant operations without overreliance on chemical additions. For example, taking water from a location in the water store that provided water of consistent quality was proposed as a possible "external to concentrator" solution to control the risk posed by water salinity variation to a coal washing plant (Liu et al., 2011). Using tailings as a potential adsorbent to bacteria was considered as a possible "external to concentrator" solution to mitigate the risk posed by water-borne bacteria to copper and gold flotation (Liu et al., 2013b). In this case study, one possible "external to site" solution might be to treat the bacteria-containing water stream before it enters the mine.

It is understandable that more attention has been paid to internal solutions simply because it is simpler to do so. It takes more effort to think about external factors and interconnectivities of the system. Looking at external solutions may require a change in paradigm or change in the way of thinking.

3. Identifying gaps and future directions

A review of the literature shows that a significant amount of research has been carried out on each of the three aspects of water quality variation in flotation (reasons, effects and solutions). The reasons why water quality varies are explained by internal and external factors. The consequences of water quality variation are either negative or positive effects on flotation efficiency, which can be quantified by different variables, such as recovery, grade and floatability of valuable minerals, and selectivity between valuable minerals and gangue. Solutions to deal with the effect are divided into internal and external solutions.

Given the absence of a method to organize these case-by-case studies, we developed a three-component framework to classify the existing literature. This three-component framework consists of causes of water quality variation, consequences of water quality variation and solutions for problems caused by water quality variation (Fig. 2). The framework structures the literature in such a way that makes it possible to identify gaps in each component and associated research directions. Fig. 3 shows the emphasis of current research on each of the three components by different levels of color. Darker color equals more research work. Accordingly, research gaps were identified in three broad areas.

The first gap lies in the focus of current research on the two types of water constituents. Compared to abiotic water constituents, there is a lack of an understanding on the impacts, processes and solutions associated with biotic water constituents (Rao et al., 2010). This could be a barrier for mine sites sourcing alternative water sources that contain biotic water constituents of concentrations sufficiently high to affect flotation efficiency, such as treated effluent, when attempting to reduce freshwater withdrawal. Consequently, more pressure would be put on the limited freshwater resources and the people and ecosystems that rely upon it. Therefore, further research is needed to understand how biotic water constituents affect flotation and the optimal solutions that can be adopted to deal with the effect. It is important for mine sites to be aware that the effect of biotic water constituents may be site-specific. Different mine sites may have different external water sources with different biotic constituents. Some mines are located near populated areas with an option of treated effluent and may need to study the impact of fecal bacteria, etc. Other mines are in forested areas, which may have a water source containing different types of bacteria, algae or tannic acids (from plant decomposition) that may affect flotation.
The second gap is about the solutions applied to deal with water quality problems in flotation. Currently, water quality problems in flotation are generally dealt with by internal solutions that focus on the flotation operation itself or more or less haphazardly, that is, without a diagnostic and proactive understanding of the causes for water quality variation. This may lead to a constrained view of opportunities to deal with the problems and thus hinders the ongoing implementation of good water management practices that conserve freshwater. Therefore, further research work is required to explore multiple external solutions that consider opportunities across the entire water system as opposed to the flotation operation itself. The ultimate solution might be the best combination of internal and external solutions. Finding such a solution requires mine sites to have a good understanding of the connectivity of the site water system and the properties of different water streams. This leads to the third gap.

The third gap is associated with understanding the reasons why water quality varies. This relies on water quality monitoring information and an understanding of the connectivity of the site water system. Even though water quality monitoring is conducted on mine sites, in some cases, the monitoring tends to be performed without clear objectives and consideration of the connectivity of different water streams, and not at the desired locations or at the desired frequency. This poses a potential challenge for subsequent utilization of these data to analyze water quality variation. Therefore, there is an essential need to develop a method which could help set up clear objectives and therefore target the monitoring at the desired water streams. The way the information on water quality variation in flotation is organized, i.e., from the perspective of internal and external factors, could be a starting point for developing such a method. After understanding the internal and external factors that cause water quality variations, mine sites can design a monitoring program that measures the chosen components at the right locations and for a suitable long time period.

The applicability of this three-component framework may not be limited to optimizing research on water quality problems in flotation but extended to broader “external to concentrator” and “external to site” areas involving water quality change, such as the impact of water quality variation on heap leaching within the site boundary and on the local ecosystem outside mine sites. Further research is required to test the applicability of this framework.

From the perspective of water management, integrated water management requires water issues be treated as a risk management exercise. This is because water is one of the risk factors that increase the likelihood of mining operations having accidents which could injure or kill people, damage the environment and cause serious loss of production and profits (Byrne et al., 2012; Cat- alan et al., 2000; Cote and Moran, 2008; Saleh and Cummings, 2011). As for water quality management in flotation, a previously published risk-based approach was suggested as a tool to assist mine sites in managing the risk of water quality variation in flotation in a consistent and structured manner (Liu et al., 2011). This approach integrates the three components stated above to quantify the risk posed by water quality variation to flotation and evaluate different scenarios for risk mitigation. The potential of the approach as such a management tool that can be put in place has been tested using two flotation case studies. The first is to manage the risk of saline water to coal flotation (Liu et al., 2011). The second deals with the risk posed by water-borne bacteria to copper and gold flotation (Liu et al., 2013a). The two case studies demonstrate the potential of the risk-based approach to deal with complexity and allow specific situations to be considered in a generic manner. They also show that water quality problems can be dealt with more effectively by considering opportunities from the entire water system rather than only focusing on the local area where the problems occur.

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