Water-saving strategies in the mining industry – the potential of mineral processing simulators as a tool for their implementation

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Abstract

As the mining industry is facing an increasing number of issues related to its fresh water consumption, water-saving strategies are progressively being implemented in the mineral processing plants, often leading to variations in the process water chemistry. However, the impact of water chemistry variations on the process performance is rarely known beforehand, thus creating an obstacle to the implementation of those water-saving strategies. To tackle this problem, the effect the different dissolved species present in the process water have on the processing plant performance must be quantified, and this information must be digitalized in a practical and suitable form to be used in mineral processing simulators. To achieve this goal, a methodology to digitalize the influence of the process water composition on the flotation performance is presented in this paper. Using the flotation of a fluorite ore as case study, the relationship between process water composition and the flotation kinetics of that fluorite ore was determined. This relationship was digitalized in HSC Sim, a mineral processing simulator, turning it into a tool capable of simulating the flotation performance under a variety of process water compositions. Finally, the potential of this new tool to help implementing water-saving strategies on the mine site is discussed, and the challenges that need to be overcome in order to apply this tool at industrial scale are being addressed.

Keywords

Water-saving strategies, Water chemistry, Flotation kinetics, Simulation-based optimization.

1. Introduction

There exist a large number of incentives for the mining industry to reduce its fresh water consumption and process water discharge. Those incentives can be legal, social, environmental, or even economical when mining projects or activities are suffering from fresh water scarcity in arid to semi-arid regions of the globe. It is thus tempting to implement water-saving strategies on the mine site, such as using unconventional water sources (*e.g.* seawater) or increase water reuse. However, the implementation of those water-saving strategies can have severe implications, especially for the flotation process because the performance of this mineral beneficiation technique is highly dependent on the process water chemistry, and this dependency is rarely known beforehand.

To date, the traditional approaches to establish the dependency between process water quality and flotation performance can be divided into two major methods:

1. Determination of the shift in the grade – recovery curve as the water chemistry is changing. The shift in such curve is established under a limited number of pre-determined water chemistries, as illustrated in Figure 1a, which helps determine the sensitivity of the flotation process to water quality modifications.
2. Determination of the flotation recovery and/or concentrate grade as a function of dissolved species concentration, as was for example done by Guimarães and Peres (1999) or dos Santos et al. (2010). Once this relationship is established, one can determine a threshold concentration for the dissolved species so that the flotation recovery and/or the concentrate grade are not greatly impaired (Figure 1b).
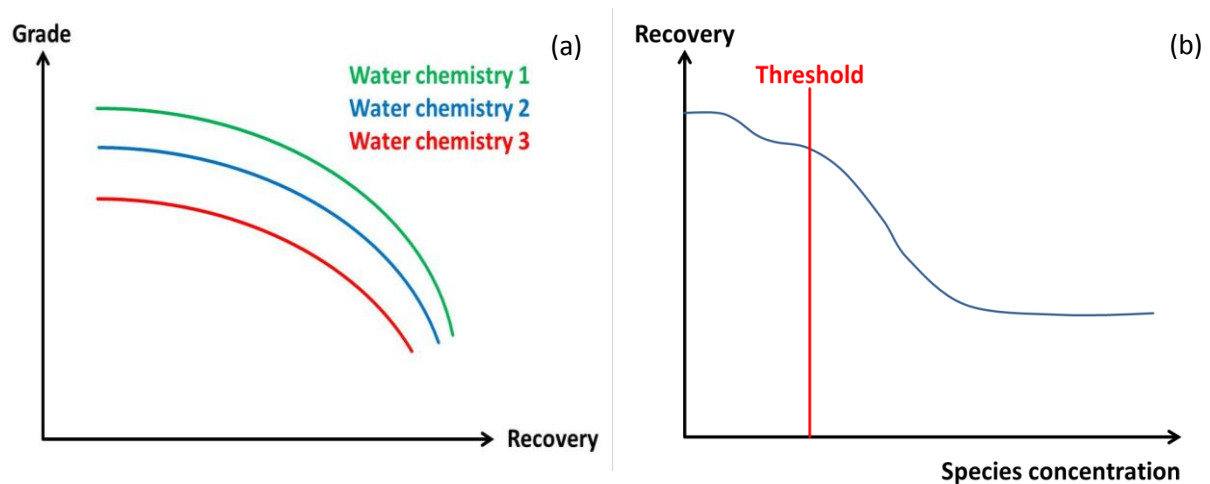

Figure 1 – illustration of current methods to determine the relationship between process water chemistry and flotation performance.

The first method has often been used to determine the potential impact of water recirculation in the flotation circuit or to investigate the possibility of using alternative water sources in the flotation plant (Corin et al., 2011; Levay and Schumann, 2006; Schumann et al., 2009; Slatter et al., 2009). Although it provides valuable insight on the process response when the process water chemistry is changing, the very discrete nature of this approach renders difficult to establish a numerical relationship between process performance and water chemistry. The second method, on the other hand, can yield such relationship. However, as was done in the work of dos Santos et al. (2010), this relationship links the concentration of the dissolved species in the process water to flotation recovery and grade. This relationship is thus implicitly valid only for a system where the residence time in the flotation cell is fixed, where there is no variability in the ore to be processed, etc. Consequently, as was addressed in a

previous paper (Michaux et al., 2018), it would be more practical to establish a numerical relationship between the process water chemistry and the flotation kinetics of the ore under investigation.

Using a kinetic approach does not only allow more flexibility with respect to flotation time and ore variability, it also yields relationships that can be implemented in mineral processing simulators. Implementing those relationships in a mineral processing simulator creates a particularly pertinent tool to address the challenges faced with the implementation of water-saving strategies on the mine site. Indeed, once the whole processing plant has been digitalized in said simulator and the influence of the process water composition has been accounted for in the different unit operations, it becomes possible to simulate how the implementation of different water-saving strategies would impact the global plant performance. Moreover, digitalizing the effect of water chemistry in a mineral processing simulator enables new possibilities in the field of process optimization. As was acknowledged in a recent review by Cisternas et al. (2018), the role of water chemistry is currently not taken into consideration in the process optimization algorithms. Therefore, implementing those process optimization algorithms in a mineral processing simulator that accounts for the role of water chemistry would advance the field of process optimization.

The main scope of this paper is to present how recent developments in the Outotec simulation software HSC Sim have enabled the possibility of using this mineral processing simulator as a tool to implement water-saving strategies on the mine site and optimize the process efficiency with respect to the process water composition. To do so, the flotation of a fluorite ore was selected as a case study. A methodology to establish a numerical relationship between the flotation kinetics of the ore and the composition of the process water is presented, as well as the required procedure to implement this relationship in the mineral processing simulator. Some applications of the new features in the mineral processing simulator are presented, such as a process sensitivity analysis to the process water composition (as in Figure 2) or process optimization with respect to the process water chemistry. Finally, the potential use of this new tool to help implementing water-saving strategies on the mine site is discussed.
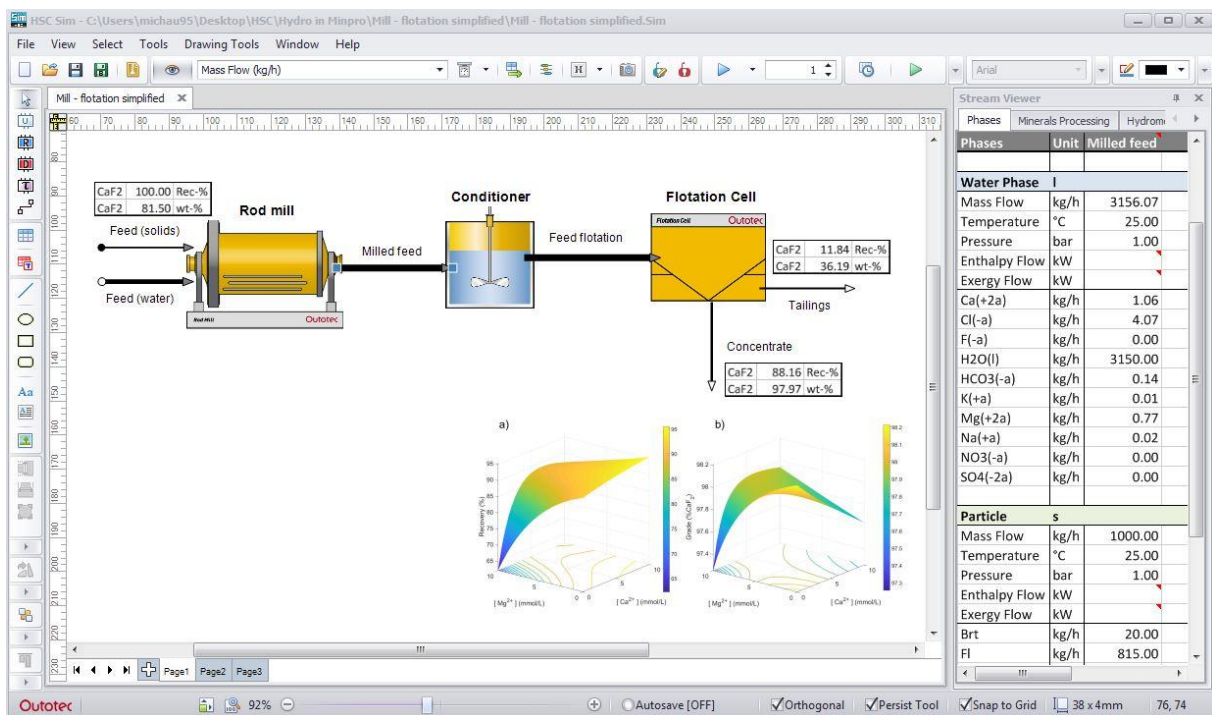

Figure 2 – process sensitivity analysis to the process water composition as performed in HSC Sim.

2. Determination of a numerical relationship between water chemistry and flotation kinetics

In order to implement in a mineral processing simulator the effect of water chemistry on the flotation performance, it is first necessary to determine a quantitative relationship between the process water chemistry and the flotation kinetics of the ore under investigation. To do so, the flotation of a fluorite ore has been investigated as a case study. As presented in this section, kinetic flotation tests were performed on this ore in waters that contain a variety of electrolyte concentrations. The resulting flotation kinetics were then parametrized to be expressed as a function of the process water chemistry, hence yielding the desired relationship to be implemented in the mineral processing simulator.

2.1. Experimental design for kinetic flotation tests

The ore is a fluorite pre-concentrate grading 81.5% CaF_2, 13.5% SiO_2, 2.0% $BaSO_4$, and the remaining 3.0% consists in a mixture of other minerals (mostly sellaite, siderite, and muscovite) which are grouped together and designated as "minor minerals" from here on. Prior to each flotation test, 1kg of this ore was ground at a pulp density of 65wt-% solids with a lab-scale rod mill down to a $d_{80,\,3}$ of 90 μm. The ground material was conditioned for a total of 8 min at pH 8 using HCl as pH regulator, tall oil fatty acids as collector, an alkyl ether phosphoric ester as frother, and calcium lignosulfonate as depressant. With the exception of HCl, the reagent dosage during conditioning was identical in each flotation tests. After conditioning, the material was floated for 30 minutes in a 4 l Outotec GTK LabCell using an impeller speed of 1000 RPM and an air flow rate of 4 l/min. A total of seven concentrates were recovered over the 30 min flotation time and analyzed with XRD to determine their content in fluorite, quartz, and barite, hence providing the flotation kinetics of those three major minerals. The tailings of the flotation tests were also systematically analyzed and the results of analysis were mass balanced to ensure consistency in the data.

To investigate the effect of electrolytes on the flotation kinetics of the 3 major minerals (*i.e.* fluorite, quartz, and barite), the kinetic flotation tests were performed in synthetic waters containing different amounts of sulfate, fluoride, calcium, and magnesium ions. The water used for the flotation tests was prepared from deionized water, to which a series of salts was added in order to reach the Baseline Synthetic Water (BSW) composition displayed in Table 1. The effect of sulfate, fluoride, calcium, and magnesium ions on the flotation kinetics of the 3 major minerals was then investigated by further addition of Na_2SO_4, NaF, $CaCl_2$, and $MgCl_2$ to the BSW, respectively. The concentration range studied is ranging from 0 mmol/l to 3 mmol/l for the anions, and from 0 mmol/l to 10 mmol/l for the cations.

Table 1 – Baseline Synthetic Water composition

Ion	Na^+	K^+	Ca^{2+}	Mg^{2+}	HCO_3^-	Cl^-	NO_3^-	F^-	SO_4^{2-}	PO_4^{3-}
Concentration (mmol/l)	0.283	0.043	0.207	0.118	0.715	0.226	0.019	0.006	0.005	0

Based on this experimental design, a total of 25 kinetic curves were obtained, each of which relate to a specific water composition. Those curves must then be parametrized so that the flotation kinetics of the ore can be numerically expressed as a function of the process water composition.

2.2. Parametrizing the flotation kinetics under varying water compositions

To parametrize the flotation kinetics under varying water compositions, a flotation model first has to be selected. The model selected in this case is a so-called *three-component batch flotation model* since

it provides a relatively good fit between experimental and modeled data, as illustrated in Figure 3 with the flotation of the fluorite ore in the BSW and in water containing 10 mmol/l MgCl$_2$ (Mg-rich water). This model links the recovery of a mineral R_m to the flotation time t as follows:

$$R_m(t) = m_f\left(1 - e^{-k_f t}\right) + m_s\left(1 - e^{-k_s t}\right) + 0.m_n \tag{1}$$

Where m_f and m_s represent the proportion of fast and slow floating particles, respectively;
    k_f and k_s represent the flotation rate constant of fast and slow floating particles, respectively;
    m_n represents the proportion of non-floating particles such that $m_f + m_s + m_n = 1$.

The plot shows equations:
$$R_{fl}(t) = 0.74(1 - e^{-1.66t}) + 0.19(1 - e^{-0.07t})$$
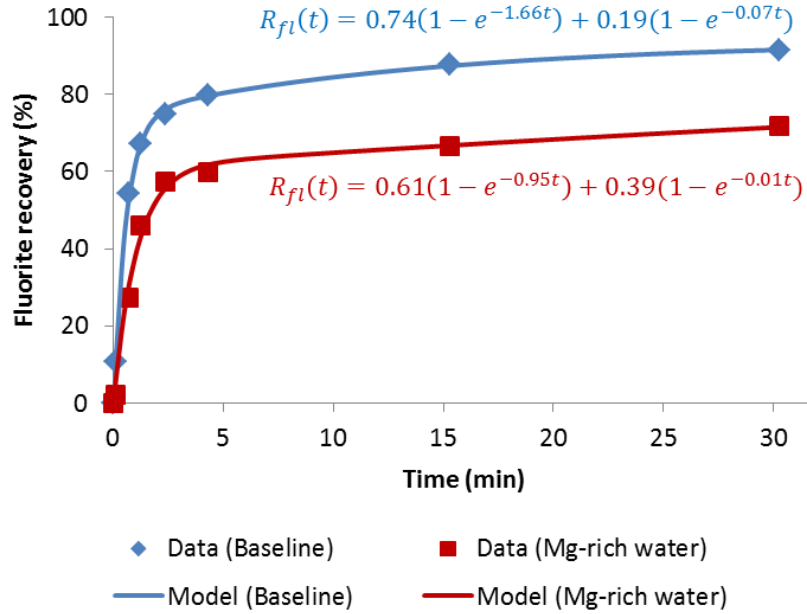$$R_{fl}(t) = 0.61(1 - e^{-0.95t}) + 0.39(1 - e^{-0.01t})$$

Figure 3 – modeling of fluorite flotation kinetics data with the three-component batch flotation equation under baseline conditions and with magnesium-rich water (10 mmol/l MgCl$_2$).

For the 25 different water compositions containing different proportions of the electrolytes under investigation, the kinetic model in equation (**1**) was fitted to the experimental data using the least squares method. This data fitting yielded values for the parameters m_f, m_s, k_f and k_s specific to each water composition and each mineral, and a linear model was arbitrarily selected to link those parameters to the process water composition. This linear model was determined using the forward selection approach which consists in adding variables step by step to the model until none of the remaining variables are significant when added to said model. In other words, the following procedure was applied:

1) Start with a model that includes the most significant variable (as determined by the R² value);
2) Test each variable that is not already in the model for inclusion in said model;
3) Add the most significant variable to the model as long as it provides a significant increase in R² value;
4) Repeat steps 2 and 3 until none of the remaining variables are significant when added to the model.

In this case, the variables are the concentrations in calcium, magnesium, fluoride, and sulfate ions as well as the product of two or more of those ionic concentrations. Applying the forward selection approach, the linear model could systematically be expressed as in equation (**2**), where P represents the parameter m_f, m_s, k_f or k_s. The concentrations in that equation are expressed in mmol/l, the resulting

value for the parameters k_f and k_s is expressed in min^{-1}, and the resulting value for the parameters m_f and m_s is expressed as a fraction of unity

$$P = A + B[Ca^{2+}] + C[Mg^{2+}] + D[F^-] + E[SO_4^{2-}] + F[Ca^{2+}][Mg^{2+}] \qquad (2)$$

The coefficients from equation (**2**) are displayed in Table 2, Table 3, and Table 4 for fluorite, barite, and quartz, respectively.

Table 2 – model coefficients for fluorite.

Coefficient	m_f	m_s	k_f	k_s
A	0.76	0.20	1.55	4.7E-02
B	1.5E-02	-1.4E-02	-5.6E-02	1.7E-03
C	-1.6E-02	1.7E-02	-5.8E-02	-4.4E-03
D	6.8E-03	-1.4E-02	5.2E-02	1.4E-02
E	0	0	0	0
F	-1.1E-03	1.9E-04	6.3E-03	1.1E-03

Table 3 – model coefficients for barite.

Coefficient	m_f	m_s	k_f	k_s
A	0.18	0.20	1.52	4.4E-02
B	1.2E-02	-1.4E-02	-1.7E-02	4.2E-03
C	0	0	0	0
D	-2.3E-02	-3.3E-02	1.5E-01	4.7E-02
E	3.6E-03	-3.0E-02	7.7E-02	3.5E-03
F	0	0	0	0

Table 4 – model coefficients for quartz.

Coefficient	m_f	m_s	k_f	k_s
A	4.5E-02	0.16	1.70	2.1E-05
B	3.8E-03	-5.3E-03	-3.9E-02	2.1E-05
C	3.1E-04	1.8E-03	-4.3E-02	2.1E-05
D	0	0	0	0
E	0	0	0	0
F	-3.7E-04	5.0E-04	2.9E-03	2.1E-05

As the concentration of the minor minerals in the concentrates was insufficient to be accurately measured or even detected in some instances, those minerals were considered non-floating and entirely reporting to the tailings of flotation. Alternatively, in order to avoid the assumption of minor minerals not floating in the investigated system, it could have been hypothesized that the minor minerals have a similar flotation behavior to that of quartz, hence attributing the same flotation kinetics to all gangue minerals. However, as this alternative does not noticeably affect the simulation results presented in the following sections, the minor minerals were still considered as non-floating.

Having determined the relationship between the model parameters m_f, m_s, k_f, k_s and the water chemistry for each major mineral, it is now possible to estimate the recovery of those minerals as a function of water chemistry and flotation time using equation (1). Knowing the estimated recovery for all minerals, the concentrate purity is also obtained, hence yielding the performance of the flotation system as a function of calcium, magnesium, sulfate, and fluoride ions concentration in the process water.

3. Implementation in mineral processing simulators and direct applications

As the relationship between process water composition and flotation performance has been established in a practical and suitable form to be implemented in a mineral processing simulator, this relationship now has to be integrated in said simulator. Therefore, this section aims at presenting a procedure to integrate the composition of the process water in HSC Sim and implement the relationships established in the previous section in this simulation platform. In addition, applications directly resulting of such implementation are presented, in particular the possibility of performing process sensitivity analysis to the composition of the process water and determining the optimum water composition to maximize flotation recovery under specific constraints.

3.1. Integration of water chemistry effects in HSC Sim

The integration of water chemistry in traditional mineral processing software is by itself a challenge, essentially because such software products are particle/mineral-oriented and tend to consider water as a transport medium only. In other words, the water throughput can be included but the water composition is not yet part of the simulation. However, recent developments at Outotec with the simulation software HSC Sim have enabled the possibility of merging the mineral processing and the hydrometallurgical parts of the simulator, thus rendering possible the inclusion of water chemistry during the simulation of a mineral processing flowsheet. To demonstrate this possibility, the process under investigation (as described in Section 2.1) was digitalized in HSC Sim using the new available software features (Figure 4).
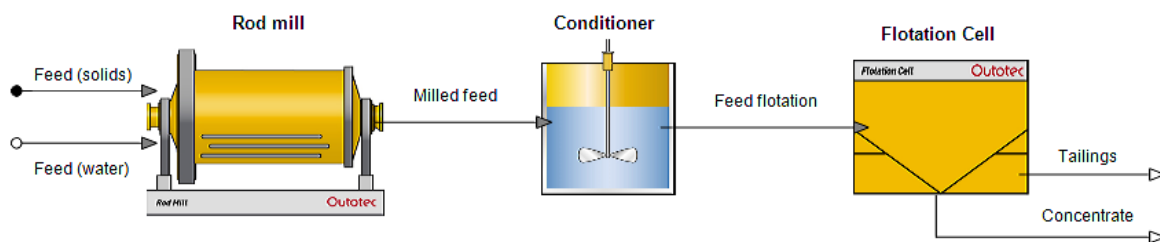

Figure 4 – simple HSC Sim flowsheet including water composition as an input.

In Figure 4, the composition of the ore is defined in a regular mineral processing stream (named *Feed (solids)*) while the water throughput and composition are defined separately in a hydrometallurgical stream (named *Feed (water)*). Those two streams are mixed in the rod mill unit to produce a new stream (named *Milled feed*) that simultaneously carries the information related to the solid and the aqueous phases as is demonstrated in Figure 5 for the case where the BSW is used as process water. This stream information is then carried to the conditioner unit, where equation (1) is selected as flotation model for the simulation to be performed. In this unit, all model parameters (*i.e.* m_f, m_s, k_f and k_s) are linked to the aqueous composition of the *Milled feed* stream according to equation (2), thus yielding the calculated values presented in Table 5 for the baseline conditions. Based on those values, the recovery for each mineral is calculated in the flotation cell unit according to equation (1) for

different flotation times, hence providing the process performance for the baseline conditions (Table 6). It must be noted that mineral dissolution is not considered in the rod mill; therefore, the composition of the process water in the streams *Feed (water)* and *Milled feed* are identical in this case.

Figure 5 – *Milled feed* stream simultaneously carrying information on the solid and aqueous phase.

Table 5 – calculated values for the model parameters m_f, m_s, k_f, and k_s when the Baseline Synthetic Water (BSW) is used as process water.

Mineral	m_f	m_s	k_f	k_s
CaF_2	0.76	0.20	1.53	0.05
$BaSO_4$	0.18	0.20	1.52	0.05
SiO_2	0.05	0.16	1.69	0.00

Table 6 – calculated process performance under baseline conditions.

Time (min)	Mineral recovery (%)			Concentrate grade (%CaF_2)
	CaF_2	$BaSO_4$	SiO_2	
10	83.5	25.7	4.8	98.3
20	88.3	30.3	5.0	98.3
30	91.3	33.3	5.2	98.2

3.2. Analysis of process sensitivity to the water composition

Since the process performance is now linked to the composition of the process water, it becomes possible to analyze the process sensitivity to the concentration of the four different ions under

investigation: Ca^{2+}, Mg^{2+}, F^- and SO_4^{2-}. This analysis can be performed directly in HSC Sim using the Scenario Editor, or by calling the process flowsheet from a MATLAB script. In this case, two different MATLAB scripts were written: one to display the sensitivity of the process to the presence of the two cations in the process water (Figure 6), the other for the process sensitivity to the two anions (Figure 7). Both scripts considered all possible concentrations of the ions investigated with the restriction that those concentrations must be within the experimental range (*i.e.* 0 to 10 mmol/l for the cations and 0 to 3 mmol/l for the anions).
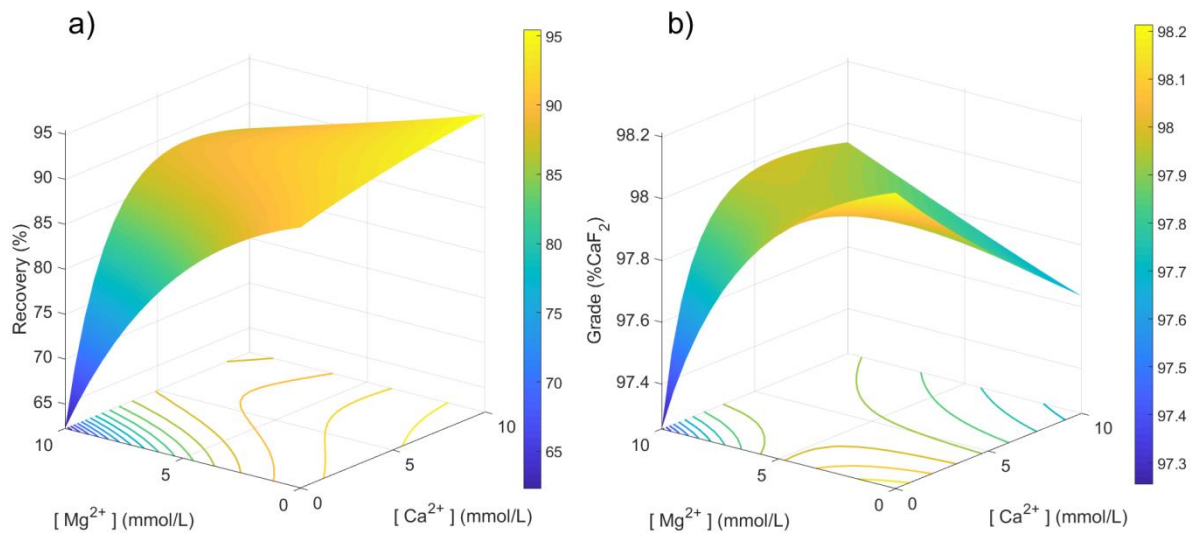

Figure 6 – fluorite recovery (a) and concentrate grade (b) as a function of $[Ca^{2+}]$ and $[Mg^{2+}]$, where $[F^-] = 0$ mmol/l and $[SO_4^{2-}] = 0$ mmol/l.
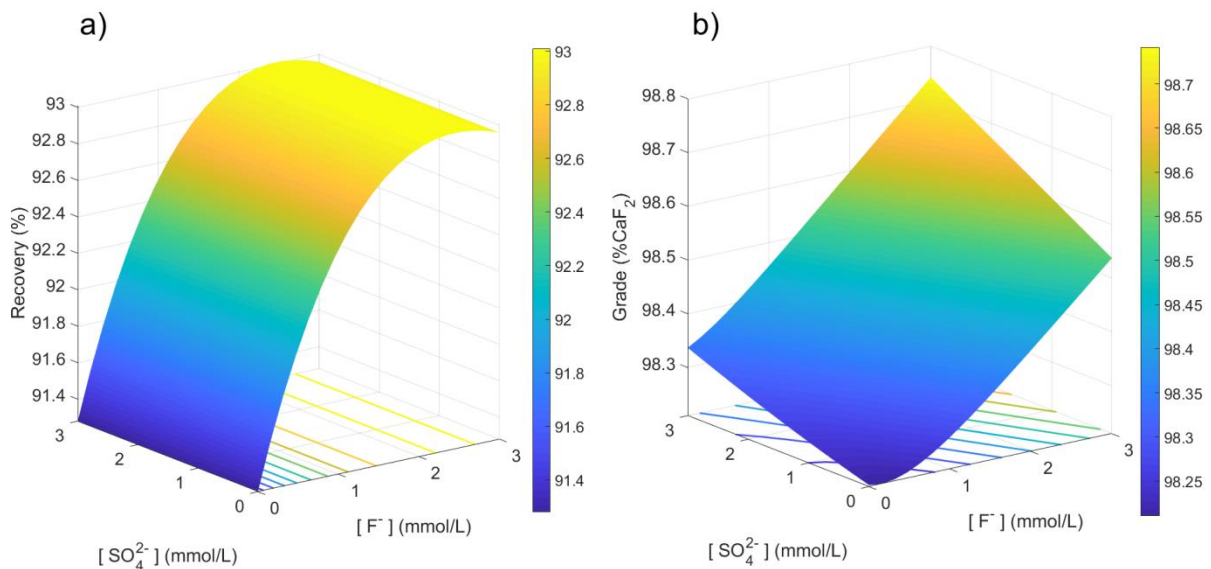

Figure 7 – fluorite recovery (a) and concentrate grade (b) as a function of $[F^-]$ and $[SO_4^{2-}]$, where $[Ca^{2+}] = 0$ mmol/l and $[Mg^{2+}] = 0$ mmol/l.

The sensitivity analysis in Figure 6 highlights that magnesium and calcium ions have a fundamentally different effect on the flotation of the fluorite ore. Although both cations slightly decrease the purity of the concentrate, Mg^{2+} has an adverse effect on the fluorite recovery whereas Ca^{2+} tends to increase

9

said recovery. In addition, it can be observed that the negative effect produced by the presence of Mg^{2+} in the process water can be buffered upon addition of Ca^{2+}, thus suggesting a relatively simple water treatment option if the process water is found to be magnesium-rich. In Figure 7, it can be observed that sulfate ions have no effect on the fluorite recovery but tend to increase the purity of the fluorite concentrate. This observation is due to the fact that SO_4^{2-} was only found to depress barite in the flotation of the fluorite ore, thus not affecting fluorite recovery but improving the fluorite concentrate purity. Fluoride ions, on the other hand, were found to simultaneously increase CaF_2 recovery and improve the flotation selectivity towards CaF_2.

3.3. Maximization of process performance through water chemistry optimization

As was demonstrated in Section 3.1, the merging of the mineral processing and hydrometallurgical parts of the simulation platform HSC Sim has enabled the inclusion of the water composition as an input during the simulation of a mineral processing flowsheet, thus to link the process performance to the composition of the process water. This development, coupled with the possibility of calling an HSC Sim flowsheet from MATLAB, provides unique features in the field of mineral processing simulation such as process performance maximization through water chemistry optimization.

To demonstrate this new feature, an optimization problem for the flowsheet presented in Figure 4 was defined in a MATLAB script. The optimization problem is to find the optimal process water chemistry so that the fluorite recovery is maximized under the constraints presented in Table 7. Thus, the optimization problem can be presented in the form:

Objective function:

max CaF_2 Recovery [%] (x, y)

where x = ([Ca^{2+}], [Mg^{2+}], [F^-], [SO_4^{2-}]), y = flotation time (fixed here at 30 min)

subject to the constraints in Table 7.

Table 7 – constraints for the optimization problem.

Constraint type	Constraint definition
Boundaries on input variables	$0 \leq [Ca^{2+}] \leq 10$ mmol/l $0 \leq [Mg^{2+}] \leq 10$ mmol/l $0 \leq [F^-] \leq 3$ mmol/l $0 \leq [SO_4^{2-}] \leq 3$ mmol/l
Solubility limits	$[Ca^{2+}][F^-]^2 \leq 3.45 * 10^{-11}$ $[Mg^{2+}][F^-]^2 \leq 5.16 * 10^{-11}$ $[Ca^{2+}][SO_4^{2-}] \leq 4.93 * 10^{-5}$
Concentrate quality	Fluorite content $\geq 97\%$ Quartz content $\leq 1\%$ Sulfur content $\leq 0.1\%$

In Table 7, the acceptable range for the input variables was defined to be the same as the one used in the experimental design to avoid finding solutions outside of the concentration range studied, which constitutes a constraint. Another constraint is fixed by solution thermodynamics since cations and anions sometimes form insoluble species (*e.g.* CaF_2 or MgF_2), thus the solubility of those species may not be exceeded. The thermodynamic constants for those constraints were taken from Lide (2003). Finally, to avoid maximizing recovery at the expense of the fluorite grade in the concentrate, common constraints on the purity of the fluorite concentrate for it to be classified as "acid grade fluorspar" have also been imposed (British Geological Survey, 2011).

Under the constraints presented in Table 7, the flowsheet in Figure 4 was called from MATLAB, and MATLAB's Global Optimization Toolbox (MATLAB, 2017) and its genetic algorithms were used to solve the presented optimization problem. The solution to this optimization problem revealed that, under the specified constraints, a maximum of 93.0% CaF_2 recovery could be achieved. To reach this maximum, the water composition in Table 8 should be targeted.

Table 8 – required water composition to maximize fluorite recovery under given constraints.

Species	Concentration (mmol/l)
Ca^{2+}	0.006
Mg^{2+}	0.000
F^-	2.449
SO_4^{2-}	2.675

The result in Table 8 is coherent with the sensitivity analyses in Figure 6 and Figure 7. Indeed, to obtain a high fluorite recovery, the concentrations in Ca^{2+} and F^- should be maximized. However, due to the restrictions on the solubility limits, the concentration in those two ions cannot be simultaneously maximized. Therefore, as the restrictions on the concentrate purity require a high concentration in F^- and SO_4^{2-} in the process water, it is coherent to find that the solution to the optimization problem requires a water composition with high concentrations of F^- and SO_4^{2-} while the concentrations in Ca^{2+} and Mg^{2+} are kept low.

4. Mineral processing simulators as a tool to implement water-saving strategies on the mine site

The inclusion of water chemistry in a mineral processing simulator and the possibility to link the simulation platform to optimization algorithms provide a powerful tool that could be used to help implementing water-saving strategies on the mine site. To illustrate this possibility, two different scenarios were considered in this section:

- Use of multiple water sources as process water in order to reduce the fresh water intake;
- Online control of the process water composition to avoid the rejection of "process-friendly" water out of the processing plant.

For illustration purposes, the flowsheet in Figure 4 was considered to be representative of the whole processing plant, and the relationships determined in Section 2.2 were assumed to be accurate and contain all relevant water chemistry parameters. It is evident that both those assumptions are

erroneous. Indeed, the flowsheet of a mineral processing plant is unquestionably much more complex than the one in Figure 4. Also, the model presented in Section 2.2 contains a limited number of electrolytes that can be found in the process water, and it does not account for other potentially critical parameters such as water pH and temperature, the presence of residual reagents or colloidal material in the process water, etc. However, since the tool presented in this paper was shown to work with a flowsheet containing only three unit operations and with a relatively simple model linking water chemistry to the flotation performance, it is also evident that this tool can be applied to a whole processing plant with more complex relationships between process water composition and process performance.

4.1. Water sources management on the mine site

To reduce fresh water consumption on the mine site, a solution would be to use "impure" water sources that are available on or near said mine site. Traditionally, this solution is investigated through lab flotation tests using the alternative water sources as process water, and the flotation performance in each of those water sources is thereby determined (Castro and Laskowski, 2015; Slatter et al., 2009; Yousef et al., 2003). An alternative to this traditional approach would be to use the tool presented in this paper. Indeed, once the composition of the available water sources has been documented, the process performance can be simulated using any of those water sources, thus highlighting what the potential candidates to be used as process water are. Moreover, using for example the flowsheet in Figure 8, it is possible to simulate how different mixtures of those water sources would affect the process performance.
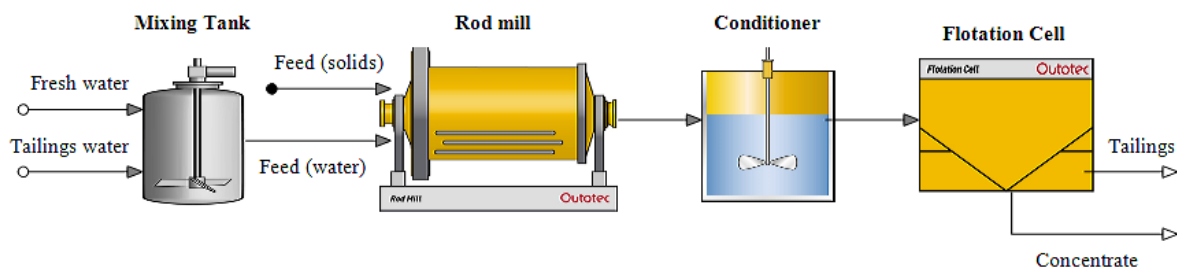

Figure 8 – consideration of two water sources as process water in HSC Sim.

In Figure 8, it is assumed that there are only two water sources available on the mine site: a fresh water source and water coming from the tailings dam (named *Tailings water*). The composition of those water sources was analyzed (see Table 9) and introduced in the *Mixing Tank* unit. In this water mixing unit, the proportion of fresh water and tailings water used to make up the feed water for the process is defined, and this proportion can be varied using the Scenario Editor integrated in HSC Sim. By varying this proportion, the process performance was simulated for any possible mixture of the two water sources, and the result presented in Figure 9 was obtained. This result highlights that increasing the recirculation intensity of the water coming from the tailings dam leads to an increase in fluorite recovery at the expense of the concentrate purity. If this reduction in concentrate purity can be tolerated, it is clear that intensifying process water recirculation in the processing plant would have a beneficial impact on the process performance.

Table 9 – composition of the two available water sources on the mine site.

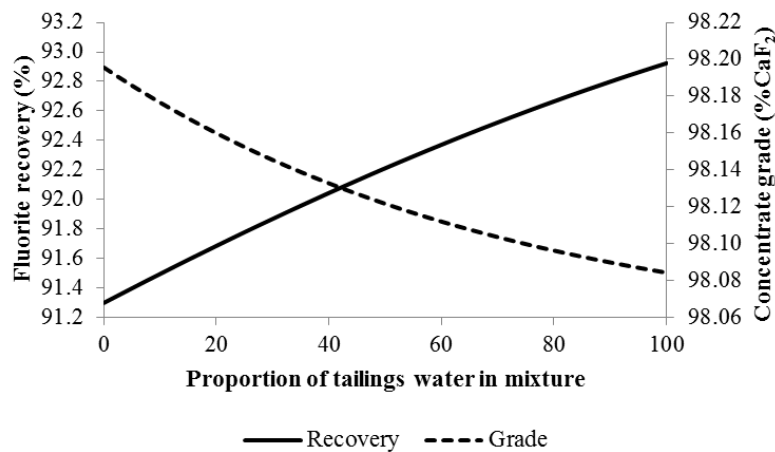| Species	Concentration (mmol/l)	
	Fresh Water	Tailings water
Ca^{2+}	0.207	2.171
Mg^{2+}	0.118	0.452
F^-	0.006	0.253
SO_4^{2-}	0.005	0.666

Figure 9 – variation of process performance as a function of tailings water recirculation intensity.

When solely two water sources are considered, the HSC Sim Scenario Editor is sufficient to determine their ideal mixture so that the process performance is maximized. However, as the number of water sources being considered is increasing, this problem gets exponentially more complex. In such a case, it is worth using the optimization tool presented in Section 3.3. Indeed, finding the optimum mixture of the water sources available so that the process performance is maximized constitutes an optimization problem where at least the following constraints need to be implemented:

- The solution to the optimization problem is limited by the composition of the different water sources available;
- The amount of water originating from the different water sources is restricted by the availability of said water sources;
- The concentration of inorganic ions in the water mixture cannot exceed the solubility limits fixed by solution thermodynamics.

Solving this optimization problem would thus lead to an improved management of the water sources on the mine site. Additional restrictions can also be applied, so that the contribution of the fresh water source is minimized in this "ideal" water mixture, hence reducing fresh water consumption in the processing plant.

4.2. Improved process control

Process control is crucial in the mining industry: it ensures that the desired process operating conditions are maintained in the processing plant (*i.e.* disturbance rejection), but it can also be used to adjust those operating conditions based on the specifications of the ore to be processed. In the second case, the relationship between the plant operating conditions and the process performance must have

been established, and this relationship should ideally be digitalized in a simulation platform. This digitalization then helps the plant operator to determine through simulation how the process operating conditions (*e.g.* the throughput of material in the grinding circuit) should be adjusted when the mineralogy of the feed material is changing, and thus ensure an efficient beneficiation of the mineral resources.

Since the influence of the process water composition on the process efficiency can now be included in the simulation of a mineral processing flowsheet, it is possible to improve the quality of the process control by monitoring not only the mineralogy of the feed, but also the composition of the process water in the processing plant, and include both online measurements in the simulation platform. This improvement would lead to an even more efficient beneficiation of the mineral resources by adjusting the process operating conditions according to both the ore properties and the composition of the process water being used. Moreover, as illustrated in Figure 10, by monitoring the composition of the process water and including the measurements in the simulation platform, it is possible to turn the mineral processing simulator into an on-line decision-making tool for the fate of the currently used process water, hence allowing a more efficient use of the water resource as well.
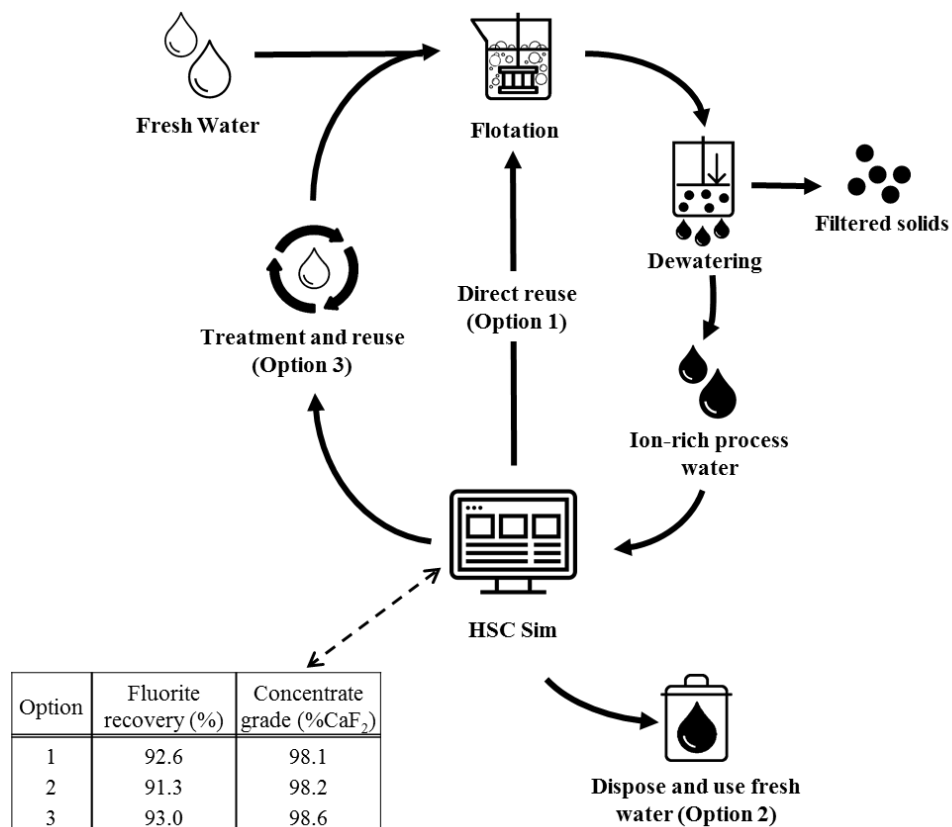

Option	Fluorite recovery (%)	Concentrate grade (%CaF$_2$)
1	92.6	98.1
2	91.3	98.2
3	93.0	98.6

Figure 10 – integration of HSC Sim in a flotation plant to help deciding on the fate of the currently used process water.

In Figure 10, three different options with respect to the fate of the process water are considered:

1) Direct reuse of the process water in the flotation plant;
2) Disposal of the process water and use of fresh water as process water only;
3) Water treatment prior to reuse.

Each of those options has a certain impact on the process performance, and this impact can be simulated in HSC Sim. In this example, it was assumed that the water fed to the flotation plant for

each of the previously presented options has the composition displayed in Table 10. Based on this information, the process performance for each of the three options was simulated, thus providing quantitative information to decide on the fate of the currently used process water.

Table 10 – water composition fed to the processing plant according to the selected option.

Species	Concentration (mmol/l)		
	Option 1	Option 2	Option 3
Ca^{2+}	0.207	2.171	0.006
Mg^{2+}	0.118	0.452	0.000
F^-	0.006	0.253	2.449
SO_4^{2-}	0.005	0.666	2.675

The application presented in Figure 10 is particularly relevant for the implementation of water-saving strategies at the level of the processing plant. Indeed, by monitoring the composition of the process water and associating the process water chemistry to the process performance, the rejection of potentially "process-friendly" water out of the system can be avoided, hence helping reducing the consumption of fresh water while maintaining or increasing the process efficiency. Finally, factors other than the process performance can be taken into account, such as the cost associated with each option (*e.g.* treatment cost and pumping cost). Therefore, using the link between HSC Sim and MATLAB, an objective function aiming at maximizing revenue can be coded in MATLAB and the optimization algorithms can be used to determine which option would financially be the most sensible.

5. Summary and outlook
The development of HSC Sim as a mineral processing software capable of taking water components in consideration during the process simulation has enabled the possibility of simulating the impact of process water chemistry variations on the process performance. To demonstrate this possibility, the flotation of a fluorite ore in a variety of water compositions was selected as a case study. A specific methodology to parametrize the relationship between the flotation kinetics of the ore and the process water composition was presented, as well as a procedure to implement this relationship in the mineral processing simulator. With this implementation, along with the possibility of calling an HSC Sim flowsheet from MATLAB, it was shown with the simplified case study that the mineral processing simulator could be used as a tool to help implementing water-saving strategies in the mining industry. However, to implement those water-saving strategies with this tool in a real case, at least two challenges need to be overcome:

- The whole processing plant needs to be digitalized in the simulation platform, and all unit operations that influence / are influenced by the composition of the process water require a model that properly reflects such influence (*e.g.* modeling the mills as "chemical reactors" where the dissolution of minerals influence the process water composition).
- Online sensors used to monitor the composition of the aqueous and the solid phases need to be combined for improved process control in the processing plant, and the data resulting from such monitoring should be used to develop sufficiently accurate models for each unit operation where the influence of the process water composition needs to be considered.

In the wake of process digitalization and in view of a water-constrained society, it appears clear that those challenges can and must be overcome in order to optimize resource efficiency (both minerals and water) and to minimize the environmental footprint of the mining industry.

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