

# Geochemical Model and Simulation of Water Balance for Mining Operations: Svappavaara Iron Mine

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**Abstract:** A model and simulation of water balance for Svappavaara iron mining operation were carried out. This water balance is an accounting in quantity and quality of all water inputs and outputs and includes a detailed collection of information on raw material and various water quality streams in the whole operation. The first objective was to simulate changes in solution composition as mineral undergoes transformation in contact with the water (e.g. dissolution or precipitation) by incorporating a reaction path modeling. The distribution of species in water streams was calculated by solving the set of mass balance equations, transformation reactions of the solid phase, given water and ore composition, percentage of water recirculation and using the simulation software HSC Chemistry. The reactions were defined for the raw material, i.e. ore, and products (concentrate, tail), in contact with water, air, gases, reagents and other input components. Therefore, various parameters were considered such as changes in pH, temperature, storage and processes, seasonal variation (precipitation and evaporation), variation in characteristics of the mined ore, recycling water percentage, and raw water quality.

The predicted water quality of a facility determines the mitigation measures to implement in order to prevent pollution in the discharge or negative effect in treatment processes. Therefore, a second objective was the simulation of a water balance after a water treatment was implemented targeting one of the main undesirable species in water such as sulfate.

**Key words:** modelling, simulation, water balance, mining operations

## 1. Introduction

Accurate information and prediction on mine hydrological balance with quality water balance is needed for management and strategic planning to be used to assess the environmental impact and operational changes in mining operations. However, the complexity of each mine operation needs a water balance showing accuracy, representativeness and flexibility to changes in the system.

The necessity of gathering chemical data with a hydrological balance is mainly due to two factors. First the mine and process water discharged to the

environment have to meet permissible limits and regulatory standards regarding water quality and second, mine and process water can affect the mineral recovery. Those two factors make the tracking and prediction of geochemical characteristics of water and through a combined hydrogeochemical and production model indispensable.

From the environmental point of view, there is a necessity to reduce fresh water consumption and final effluent discharges. It makes water recirculation an important aspect in a water balance. However, increased recirculation usually implies low dilution and probably species such as salts will accumulate in the system until they reach new, higher, equilibrium concentration levels [1]. This new equilibrium may impact on processing plant efficiency and quality of

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water discharged. Therefore, the chemical equilibrium modeling is necessary for the more reactive species incorporating reactions and residence/contact times (kinetic) where the exposure scenario evaluation is needed. For example, water in tailing dams may occupy exposed areas for a long time and the concentration of contaminants may increase as a result of precipitation, evaporation and dissolution/oxidation reactions.

A flow-path geochemical mass balance has been attempted before by Chen et al. [2] and in the influence area of the mine an understanding of the geochemistry in Kiirunavaara mine water was developed by Lundkvist [3] and Westerstrand [4]. Also, Hagemalm [5] created a water balance for the processing plant in Svappavaara. They have predicted a broad outline for specific units of the operation and ore (system boundaries and deducted quality flow rates in a simple process unit). However, there is no attempt to simulate water balances for systems that involves multiple processes, recirculation, water volume flows, quality, solid phases and losses to the environment in form of gases at the same time as occurs in a mining operation.

Without modeling and simulation tools it will not be possible to envisage sudden changes and trends in water quality and to quantify the effects due to changes in the operation or to assess the streams needing treatment. Moreover, it has been stated [6] that the costs and risks involved in monitoring and assessment of complex systems like a mine operation can be reduced by developing models. Those are the reasons to undertake the present work.

## **2. Methodology**

A methodology integrating water flows and quality together with composition of the solid phase (mineral and waste) has been developed. It initiates by accounting all inflows to the operation (including raw materials) and chemical reactions between the defined phases; then outflows, middle streams and losses for each process unit and quality are simulated.

### *2.1 Svappavaara Operation Mine*

A whole balance in Svappavaara mining operation involves an assessment of operating units, including water sources (Gruvberget and Leveäniemi mine) processing plant (CA), pellet plant (KA), tailing dam, clarification pond, water storage reservoirs (Lake), thickeners, and also, seepage and runoff with regard to seasonal variations.

### *2.2 Data Collection*

#### *2.2.1 Water Quality*

Table 1 shows the average value of physical and chemical characteristics of various water streams in the mine operation.

#### *2.2.2 Ore Composition*

There are four types of ores that at the moment are fed to the mineral treatment plant; the mineralogical composition of each ore is shown in the Table 2. Magnetite is the main mineral for three types of ore (Kiruna, Leveäniemi, Mertainen) and hematite is predominant only in Gruvberget ore body, although it is only the magnetite part of Gruvberget that is mined today.

#### *2.2.3 Selecting a Water Balance Model*

When selecting of the modeling software the requirement was set that it must be capable to integrate solid, liquid and gas phases involved or generated in process units. Also, the software should be capable to handle an entire mine comprising of several process units with inflows and outflows that vary in quality. Thus, the whole operation can be assessed simultaneously with unit operations, differing from the approaches used in earlier studies [9]. Besides process units in the mine operation waste rock dam, dewatering pits, residues from treatment plants and other waste sources also need to be included simultaneously to assess the resultant water quality.

HSC-Sim of HSC Chemistry 7.1 was selected to model and simulate the mine water balance [10]. It expands the possibilities for applying HSC Chemistry software on a whole process made up of several

process units and streams. The HSC-Sim module consists of graphical flowsheet and spreadsheet type process unit models. The user-specified variable list, Excel-type unit models and HSC Add-In functions

make HSC-Sim an extremely flexible and easy-to-use simulation tool for a number of applications in different fields and its functionality can be found in the software help [11].

**Table 1 Water composition in Svappavaara mining operation.**

|                                |      | Input water         |                      |                   | Control and validation analysis |               |                        |
|--------------------------------|------|---------------------|----------------------|-------------------|---------------------------------|---------------|------------------------|
|                                |      | Gruvberget open pit | Leveaniemi open pit* | Clarification dam | Outflow tailing dam             | Lake to plant | Leakage from Taili dam |
| Temperature                    | °C   | 5.9                 | 23.1                 | 9.1               | 7.9                             | 7.4           | 5.7                    |
| pH                             | mS/m | 8.1                 | 8.6                  | 7.9               | 8.0                             | 8.0           | 7.4                    |
| Conductivity                   | mg/l | 32.1                | 44.7                 | 147.9             | 183.4                           | 171.0         | 171.5                  |
| Alkalinity (HCO <sub>3</sub> ) | mg/l | 76.2                |                      | 83.9              | 67.8                            | 62.2          | 76.2                   |
| Suspended solids               | mg/l | 111.7               | 24.0                 | 9.6               | 10.3                            | 4.9           | 4.1                    |
| Ca                             | mg/l | 37.3                |                      | 196.3             | 204.1                           | 187.7         | 187.0                  |
| Cl                             | mg/l | 12.2                |                      | 183.2             | 190.7                           | 176.3         | 191.0                  |
| F                              | mg/l | 0.2                 |                      | 1.0               | 1.0                             | 1.0           | 0.8                    |
| K                              | mg/l | 3.4                 |                      | 51.1              | 53.4                            | 47.7          | 48.4                   |
| Mg                             | mg/l | 5.8                 |                      | 25.2              | 26.3                            | 23.4          | 26.0                   |
| Mo                             | mg/l | 5.1                 |                      | 21.8              | 22.2                            | 19.4          | 12.6                   |
| Na                             | mg/l | 9.8                 |                      | 126.0             | 127.9                           | 116.8         | 127.0                  |
| N <sub>2</sub> _tot            | mg/l | 4.9                 |                      | 11.7              | 11.4                            | 9.1           | 4.9                    |
| NO <sub>3</sub>                | mg/l | 3.1                 |                      | 9.1               | 10.1                            | 9.2           | 3.8                    |
| SO <sub>4</sub>                | mg/l | 34.2                |                      | 540.8             | 568.1                           | 523.2         | 530.5                  |
| Sr                             | µg/l | 51.3                |                      | 687.8             | 723.1                           | 641.6         | 616.0                  |
| Ba                             | µg/l | 6.4                 |                      | 44.0              | 43.5                            | 42.8          | 87.0                   |
| C(TOC)                         | mg/l | 2.9                 |                      | 3.1               | 2.4                             | 2.5           | 5.7                    |
| Cr                             | µg/l | 0.030               |                      | 0.05              | 0.1                             | 0.03          | 0.015                  |
| Cd                             | µg/l | 0.008               |                      | 0.03              |                                 | 0.02          | 0.014                  |
| Co                             | µg/l | 0.16                |                      | 0.24              | 0.30                            | 0.29          | 0.46                   |
| Fe <sup>2+</sup>               | mg/l | 0.00108             | 0.099                | 0.01              | 0.0022                          | 0.02          | 0.019                  |
| Mn                             | µg/l | 64.8                |                      | 49.2              | 51.5                            | 72.6          | 174.5                  |
| Ni                             | µg/l | 0.1                 |                      | 3.0               | 1.2                             | 1.1           | 0.9                    |
| PO <sub>4</sub>                | µg/l | 7.0                 |                      | 7.8               | 10.7                            | 8.1           | 1.1                    |
| Pb                             | µg/l |                     |                      | 0.04              | 0.03                            | 0.02          | 0.02                   |
| Zn                             | µg/l | 1.7                 |                      | 37.0              | 2.2                             | 2.2           | 3.9                    |
| Al                             | µg/l | 9.6                 |                      | 6.1               | 12.2                            | 4.1           | 1.6                    |
| Cu                             | µg/l | 9.8                 | 3.3                  | 2.9               | 3.4                             | 2.3           | 3.6                    |
| NH <sub>4</sub>                | mg/l | 0.83                |                      | 0.18              | 0.30                            | 0.28          | 0.03                   |
| Si                             | mg/l | 4.7                 |                      | 3.7               | 4.4                             | 3.8           | 5.1                    |

\*Data of sampling during summer, the inclusion of this water system was being tested. Analysis of water quality was provided by LKAB from samples between January 2014 and January 2015.

Table 2 Ore composition

| Group     | Mineral      | Ideal formular                                                                 | Kiruna* | Gruvberget | Leveaniemi | Mertaine |
|-----------|--------------|--------------------------------------------------------------------------------|---------|------------|------------|----------|
| Oxide     | Magnetite    | Fe <sub>3</sub> O <sub>4</sub>                                                 | 60.8    |            | 76.3       | 59.0     |
|           | Hematite     | Fe <sub>2</sub> O <sub>3</sub>                                                 | 0.0     | 72.0       |            |          |
|           | Ilmenite     | FeTiO <sub>3</sub>                                                             | 0.9     |            |            | 1.8      |
|           | Rutile       | TiO <sub>2</sub>                                                               | 0.4     |            |            |          |
| Silicates | Albite       | NaAlSi <sub>3</sub> O <sub>8</sub>                                             | 17.1    |            | 8.4        | 20.9     |
|           | K-feldspar   | KAlSi <sub>3</sub> O <sub>8</sub>                                              | 3.8     |            |            | 4.6      |
|           | Actinolite   | Ca <sub>2</sub> Mg <sub>5</sub> Si <sub>8</sub> O <sub>24</sub> H <sub>2</sub> | 4.1     | 2.2        | 5.0        |          |
|           | Biotite      | KFe <sub>3</sub> (AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub>         | 4.5     |            | 5.5        | 11.7     |
|           | Phlogopite   | KMe <sub>3</sub> (AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub>         | 0.5     |            |            |          |
|           | Quartz       | SiO <sub>2</sub>                                                               | 1.1     | 10.0       | 2.5        |          |
|           | Diopside     | CaMgSi <sub>2</sub> O <sub>6</sub>                                             | 1.9     |            |            |          |
|           | Almandine    | Fe <sub>3</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>                | 0.2     |            |            |          |
|           | Andradite    | Ca <sub>3</sub> Fe <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>                |         | 1.5        |            |          |
|           | Titanite     | CaTiSiO <sub>5</sub>                                                           | 0.3     |            |            |          |
| Other     | Apatite      | Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> F                              | 4.0     | 8.2        | 2.3        | 0.3      |
|           | Calcite      | CaCO <sub>3</sub>                                                              | 0.1     | 6.1        |            | 1.7      |
|           | Gypsum       | CaSO <sub>4</sub> *2H <sub>2</sub> O                                           | 0.2     |            |            |          |
|           | Pyrite       | FeS <sub>2</sub>                                                               | 0.1     |            |            |          |
|           | Chalcopyrite | CuFeS <sub>2</sub>                                                             | 0.1     |            |            | 0.0      |

Source: Different source from LKAB, mineralogical analyses and \*element to mineral conversion [7, 8].

2.2.4 Conceptual Model

The reaction approach (equation reactions) was used for this study. A conceptual model was developed (Fig. 1) which simplifies the real operational conditions, streams, phases and species in each phase originated from interactions [12]. A set of likely hydrogeochemical reactions and steps were done following the phases proposed by Younger and Sapsford (2006).

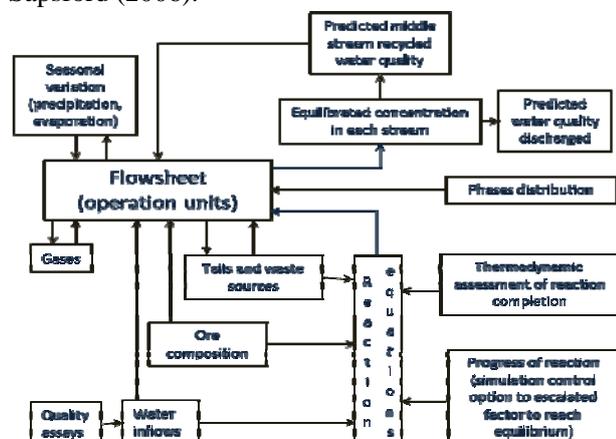


Fig. 1 Conceptual model.

2.2.5 Reaction Equations

The reaction approach from HSC-SIM was used for the water balance simulation. It allows introducing the solid phase transformation and the building up of species in water. The main reactions occurring in various units have to be defined by the user. For instance, accelerated reactions occur in the tailing pond (precipitation, dissolution and oxidation) due to reactions of minerals with liquid and gases and progress towards chemical equilibrium. Also, many reactions occur in the pellet plant (oxidation and reduction). The HSC-SIM program allows adding reaction equations within the reaction model Distribution Wizard/Chemical which evaluates the completion of the reactions in terms of H (enthalpy), K (equilibrium constant) and temperature. In this work a total of 34 reactions were defined and used for the tailing dam and 14 for the pellet plant.

Also, the support database from PHREEQ was used to identify the most important geochemical processes

across the mine site.

### 3. Results and Discussion

#### 3.1 Water Chemistry

Table 1 shows that the main characteristic of Svappavaara process waters with an increment in conductivity indicating increasing of ions in solution.

The concentrations of some species in water increase or reduce (dissolves or precipitates) as water recirculate through different process units. These are divided in two groups and highlighted in gray and dash respectively in Table 1. The first group (gray) is subdivided and highlighted (dark gray) on species increasing in concentration on the infiltrated water in the tailing dam (leakage), which indicates they had more time of retention that may increase oxidation and dissolution.

The sulfate concentration in the input water stream (Gruvberget mine) was 34 mg/l. However, the sulfate concentration in various recycled water streams was higher than > 500 mg/l which indicates oxidative conditions on this place. There is probably sulfate in Leveaniemi water, but at the time of this project, there was no data from monitoring since this water stream is

new within the process.

An increment in the concentrations of salts Na, Cl, K in all streams clearly is generated due to recycling of process water, reagent additions and dissolution of the ore during mineral processing.

Metal ions in the recycled water were generally low probably because these elements are leached to the water through much slower weathering processes than the time that the minerals are in contact with water in the process plants. Also, there is likely metal hydroxide formation and precipitation at pH > 8 on most of the water streams.

#### 3.2 Model and Simulation of Water Balance

The simulated water balance shows graphically the volume flows in each stream (water phase t/h, Fig. 3) and the concentration of major and minor species in every stream (middle stream composition is shown in figures calculated by the software). Fig. 2 shows the concentrations of Ca, Cl, F, K, Mg, Na and SO<sub>4</sub> and Fig. 3 shows the concentrations of Al, Cu, Mn, Fe, NO<sub>3</sub>, NH<sub>4</sub> and TOC. Those are presented as an example, but the user can define the species of interest in the operation.

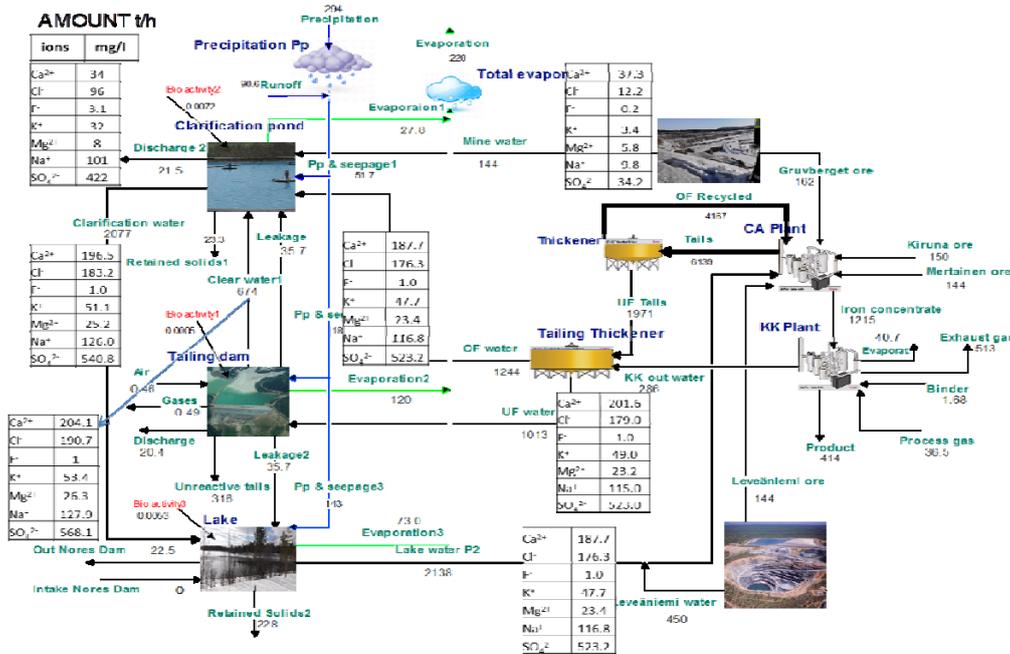


Fig. 2 Water quality balance of major species.

For this case study, mine water (Gruvberget and Leveaniemi) and Nores Dam water are the main input water sources to the system. It is possible to follow the change of the water quality from the mine water to downstream with an increase in concentration for most of the species after the waters mix and pass through clarification pond, tailing dam and lake.

The balance obtained allows seeing the total amount (t/h, Fig. 2) as the sum of all phases in the operation, but it is also possible to visualize the amount of each one (water, solid, gases), for example water t/h (Fig. 3).

The calculated concentrations of those species obtained with the simulation were compared with the chemical assays (Table 2) from the monitoring of the mining operation. For all species there is a good agreement between the simulated and found values.

### 3.3 Implementation of New Technologies

A new water treatment technology was included and tested in the simulation environment with a purpose to assess the flexibility of the system in investigation of different water purification options.

The water treatment technology was

electro-coagulation that is being investigated by Mamelkina (2015). The content of sulfate in water in the Lake water P2 stream was 523 mg/l before the simulation of the treatment (Fig. 2). After installing virtually the electro-coagulation treatment in the simulation system and setting the efficiency of sulfate removal to 30% (Fig. 4) the sulfate concentration decrease to 240 mg/l when the equilibrium was reached and therefore sulfate concentration decrease in the whole operation as illustrated in Fig. 4.

### 3.4 Probabilistic balance with time and seasonal variation

Precipitation, evaporation and runoff (t/h) was calculated using the monthly precipitation (mm/month) for Svappavaara and water receptor areas. It this way it was possible to simulate dynamic variation of water quality fluctuation due to seasonal variation.

Fig. 5 shows the annual variation of water flow in Lake water. The volume flow increases in months with high precipitation (June, July or corresponding days in Fig. 5) and concentration of SO<sub>4</sub> is decremented due to high dilution.

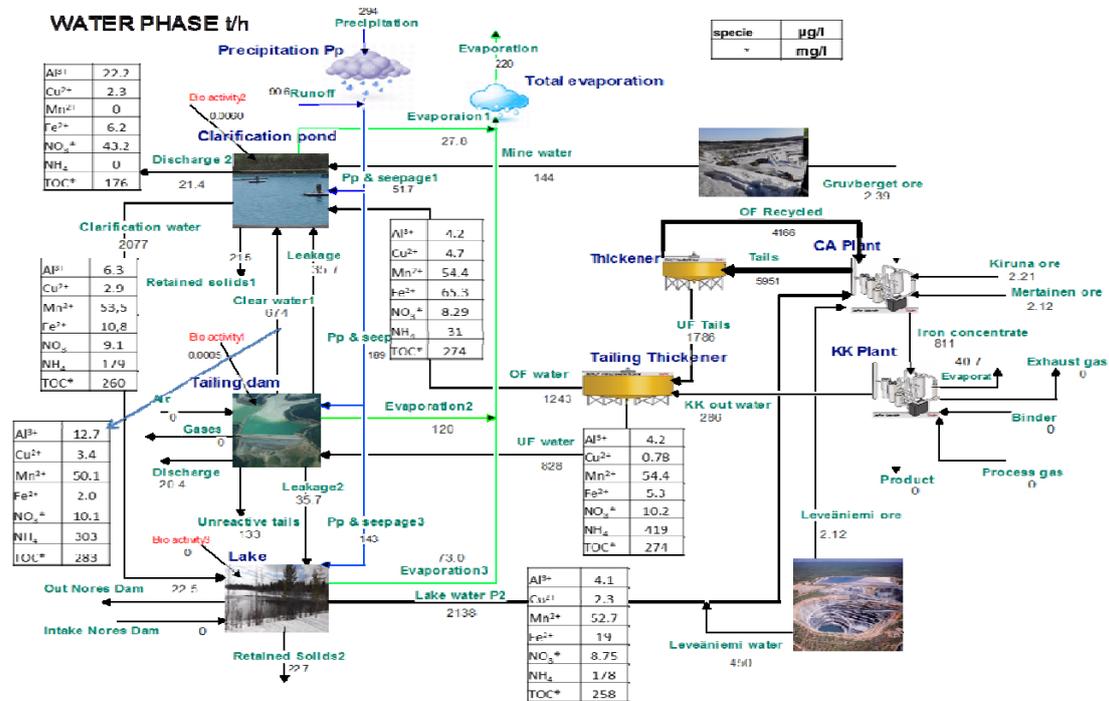


Fig. 3 Water quality balance of minor species.

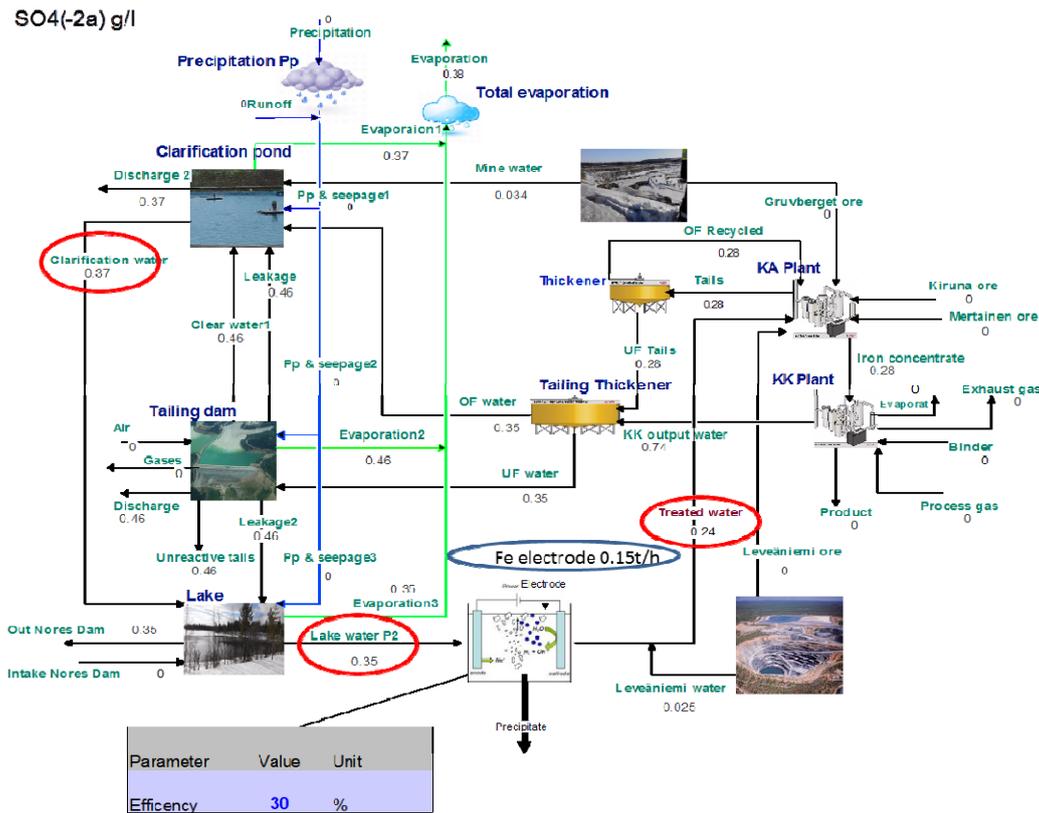


Fig. 4 New technology implementation.

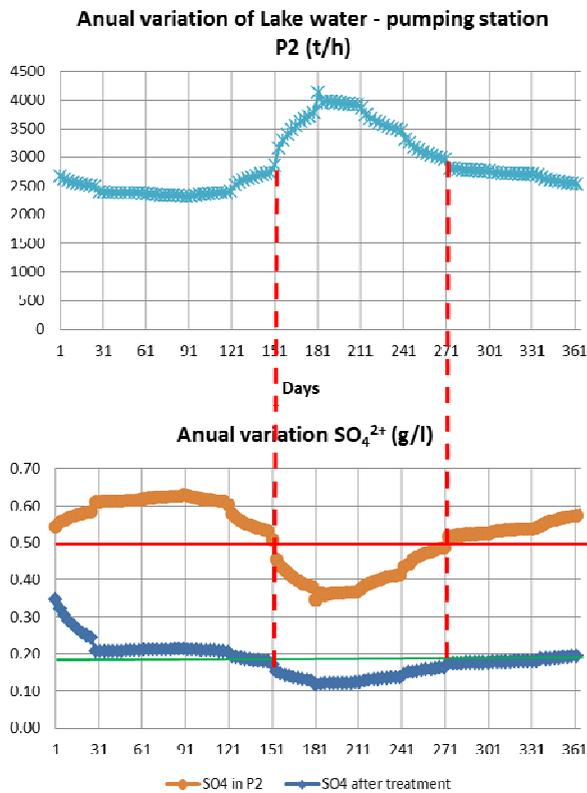


Fig. 5 Simulation of the water flow and quality fluctuation versus time.

### 4. Conclusions

The model and simulation of the water balance for Svappavaara mine developed in HSC-SIM allowed calculating the flow and quality of water in streams for each process unit and as a whole system. The fluctuations due to the addition of a new process treatment unit implementation were simulated making a link for varying efficiency of treatment technologies and consumption of main reagents or material for treatment. Also, the fluctuations in water quality and flows due to seasonal variations and changes in the operation were simulated.

Integration of water flows, raw material, waste and emissions were included in the model and interaction between water-solid-gases (reaction approach) was simulated. It allows generating data for reporting requirements, water quality prediction and a balance for decision making.

HSC Chemistry was proven to be suitable and versatile tool for modeling and simulation of water systems in mines. It offers diverse reporting tools and addition of new process units, like potential water treatment operations, was easy.

Collecting and evaluating water balance input data and reactions are of high importance, especially to develop and calibrate the model and also to ensure that the mine has a reliable and appropriate water balance. It is important to maintain operational water balance models regularly so that they represent current conditions such as continual operational changes during the active phase of the mine life.

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### References

- [1] G. McPhail, Getting the water balance right, in: *Tailings & Paste Management and Decommissioning*, Section 14, 2005, pp. 1-11.
- [2] M. Chen, C. Soulsby and P. Younger, Modelling the evolution of mine water pollution at Polkemmet Colliery, Almond catchment, *Scotland. Q. J. Eng. G.* 32 (1999) 351-362.
- [3] A. Lundkvist, The process water geochemistry of the Kiirunavaara magnetite ore, Luleå University of Technology, 1998.
- [4] M. Westerstrand, Process water geochemistry and interaction with magnetite at the Kiirunavaara iron mine, Northern Sweden, Luleå University of Technology, 2013.
- [5] J. Hagemalm, Flow balance for the processing plants in Svappavaara, Luleå University of Technology, 2012.
- [6] S. A. Banwart, Malmström Hydrochemical modelling for preliminary assessment of mine water pollution, *J. Geochemical Explor.* 74 (2001) 73-97.
- [7] C. Lund, P. Lamberg and T. Lindberg, Practical way to quantify minerals from chemical assays at Malmberget iron ore operations — An important tool for the geometallurgical program, *Miner. Eng.* 49 (2013) 7-16.
- [8] M. Parian, P. Lamberg, R. Mockel and J. Rosenkranz, Analysis of mineral grades for geometallurgy: Combined element-to-mineral conversion and quantitative X-ray diffraction, *Miner. Eng.* 82 (2015) 25–35.
- [9] B. Usher, R. Strand, C. Strachotta and J. Jackson, Linking fundamental geochemistry and empirical observations for water quality predictions using GoldSim, in: *Mine Water and Innovative Thinking*, IMWA, 2010, pp. 313-316.
- [10] A. Roine, HSC chemistry 7.0 user's guide — Chemical reaction and equilibrium software with extensive thermochemical database and flowsheet simulation, Vol. 1/2, 2009.
- [11] T. Kotiranta, Sim reaction example, in: *Help HSC Chemistry 7.0*, Vol. 41, 2009, pp. 1-9.
- [12] M. Sinche-Gonzalez and P. Lamberg, Geochemical water balance by modeling and simulation in mining — Water conscious mining (WASCIOS) project, in: *Conference in Minerals Engineering*, Lulea, 2016, pp. 14-156.
- [13] P. L. Younger and D. J. Sapsford, Acid drainage prevention guidelines for Scottish opencast coal mining: The primacy of the conceptual model, in: *7th International Conference on Acid Rock Drainage*, 2006, pp. 2558-2570.
- [14] M. Mamelkina, Electrocoagulation new approach, in: *Wascios Meeting*, Lappeenranta University 2015.