Decision Making For Sustainable Tailings and Water Management – A Dynamic Modelling Approach

Björn Sennerfors[1], Patrik Wallman[2]

[1]*Saitec Engineering, Arenavägen 41, 12 tr, SE-121 77 Johanneshov, Sweden, Bjorn.Sennerfors@saitec.se*
[2]*Sweco Environment AB, Drottningtorget 14, SE-211 25 Malmö, Sweden, patrik.wallman@sweco.se*

Abstract

The water system of a mine is complex and its behavior depends on a great number of variables. To obtain a holistic understanding of the water system it is necessary to link all elements in the system together. In this sense, a dynamic modelling of a mine water system needs to integrate the tailing storage facility together with relevant production parameters in the plant, the clarification pond and its interaction with external water sources. Traditionally, the water management for a mine is established through water and mass balances. These balances for tailing storage facilities does not account for the changes in water volumes. This constitutes the main reason why advanced water quality modelling often is omitted for the storage. Hence, a fundamental part and the link between the plant and the clarification pond is missing. This has forced the development of forecasts and prognostics based on simplified assumptions and methodologies for the tailings ponds and do not consider properly its evolution over time. This paper focus on the development on a methodology to build a dynamic model for the tailing storage facility through a coupled hydraulic and a water chemical model, which is integrated as the link between the plant and the clarification pond. The result is a more precise modelling tool that creates the base for decision making to minimize the impact on the environment during both the design and the operation of the system.

Key words: dynamic modelling, integrated model, tailing storage facilities, tailings, water quality

Introduction

The need for dynamic modelling in mining systems is clear. A large number of variables intervene in the operation and can only be properly considered in a dynamic modelling. The mine system should though include the tailing storage facility (herein denominated TSF) in a more detailed manner. A method has been developed by the authors that enables an integrated water balance and water quality modeling that includes essential aspects for the dam safety at the same time. The method is based on the fact that the TSF is a series of an infinite number of storage areas. This method brings light to fundamental parameters that are discussed for the design of the TSF. This is also a requirement to perform advanced modelling of the water quality in the TSF, which explains variations in the outgoing water quality to the clarification pond. The conclusions can be used to optimize the mine water system, to identify critical aspects that could occur during the operation.

Dynamic modelling of mine water systems

Dynamic modelling of mine water systems is discussed by Nalecki and Gowan (2008) and by Lauzon and Paget (2011). Dynamic modelling is required to better understand the mine water system and it needs to integrate essential parameters already during the planning phase of the project but also for the operation of the mine. Mine water systems are composed by production plants, which generates tailings and delivers the slurry to the TSF. The operation of the TSF must take into consideration many factors related to the tailings disposal strategy, dam safety and the management of the water elevations in the storage. The TSF ensures that the water reach an adequate quality before it is delivered further to the clarification pond. From the clarification pond, the water is being pumped up again to the production plant. To the system, the need for additional water make up is also planned.

However, the tailings disposal strategy is a crucial part for the planning of the storage, which affects the storage area's geometry continuously. This influence the management of water elevations and water volumes. Inversely, the change in water volumes affect the tailings slopes, which also affect the storage geometry. Consequently, the water quality is also affected by variations in both the tailing disposal strategy and the management of the water elevations in the TSF.

Given the implications of the water management in the tailings storage facility it is convenient to take into consideration parameters related to the dam safety such as required beach widths, maximum flood elevations, dam heights and spillway structures and its varying capacity over time. Beach widths may have a limiting factor on the water volumes that can be stored in the TSF and hence a direct impact on the water quality that leaves the pond. The minimum required beach widths depends on the tailings disposal strategy.

A dynamic model for a mine water project should consider all the above parameters in order to be able to produce future forecasts for the operation of the system. All these parameters varies over time and can adopt a range of possible values. Therefore, and to cover properly possible future scenarios, the authors have adopted Monte Carlo Simulation techniques that enables probabilistic variations of important variables in the system. The result is an interval of possible results that are an essential part in the decision-making during the design and/or operation of the system.

Characterization of the Tailing storage facility

Nalecki and Gowan (2008) and Lauzon and Paget (2011) consider a continuous tailings disposal throughout the mine projects lifetime. However, it is not clear how the modelling of the tailing storage is performed or how the water volumes evolve with time. TSF need to integrate the tailings disposal strategies for the future operation periods. Past and future geometries of the TSF are necessary to be able to make historical analysis, planning of new projects or for an upcoming maintenance period.

A TSF can be described as an infinite number of storage areas (SA) each of them are associated to a specific time (t, t+1,…, t+n), i.e. SA_t, SA_{t+1},…, SA_{t+n}. Each storage area per time step can be described using conventional stage-storage and stage-area curves (fig 1). In the figure, it can be observed how the bottom line of the storage area, i.e. elevation for volume equal zero, increases continuously with time.

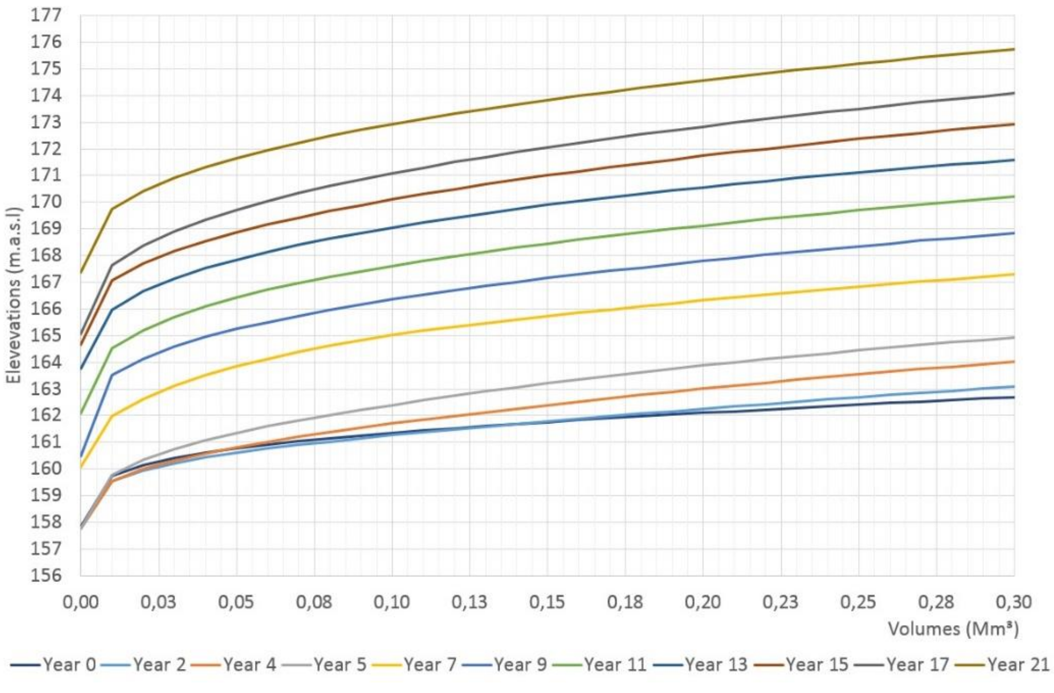

***Figure 1** Examples of a set of stage storage curves for a fictive tailings storage facility. Own elaboration.*

Having the set of stage storage curves defined for a period of time (fig 1), it is possible to carry out a regulation study of the TSF. For a specific volume and time, the water elevation, Z_{water}, can be obtained through a bilinear interpolation between the set of storage curves (fig 2).

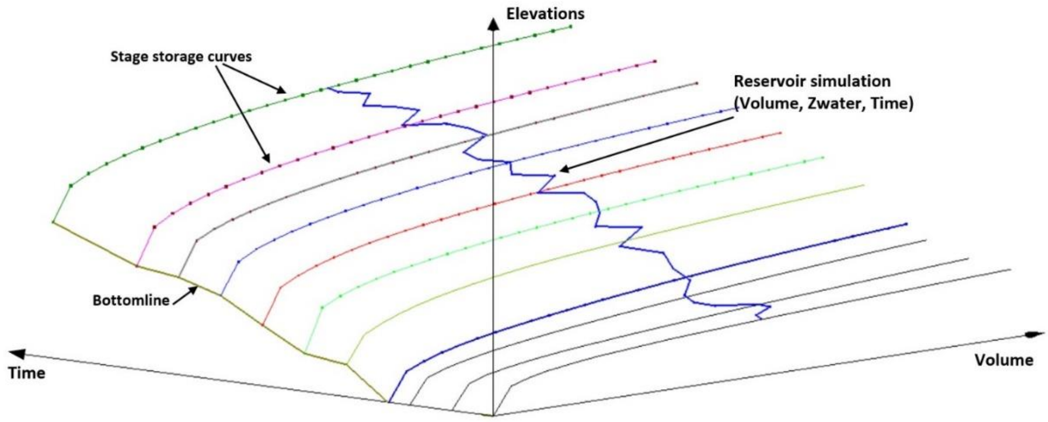

Figure 2 *Example of a reservoir simulation for a period of time for a fictive tailings storage facility. Own elaboration.*

Tailings Storage facility – Regulation study

Current Guidelines ICOLD (2011) indicate that the water balance for a TSF has to consider all potential inputs and outputs to ensure successful operation of the facility. These guidelines also mention that change of storage in the TSF is a potential threat and should be accounted for in the design. Furthermore, the TSF pool storage should be verified for rise in pool levels for change of storages and this can be done for selected intervals during the operation. Established minimum beach widths for each TSF shall be maintained during the any flood event.

The proposed method herein enables traditional reservoir regulation studies, or water balance modelling, for TSF. This study can be done for the TSF's entire lifetime rather than for selected time intervals as indicated in ICOLD (2011). The main objective of such a study consists of defining a design that, on one hand, contains an adequate amount of water to ensure satisfactory functioning of the TSF from a water quality perspective and, on the other hand, to ensure that maximum flood levels are not exceeded. A regulation study for a TSF should take into consideration several aspects such as all inflows and outflows, water levels, minimum operation levels, emergency spillway levels, beach width levels, maximum flood levels, dam crest elevations and the staging of the project (fig 3).

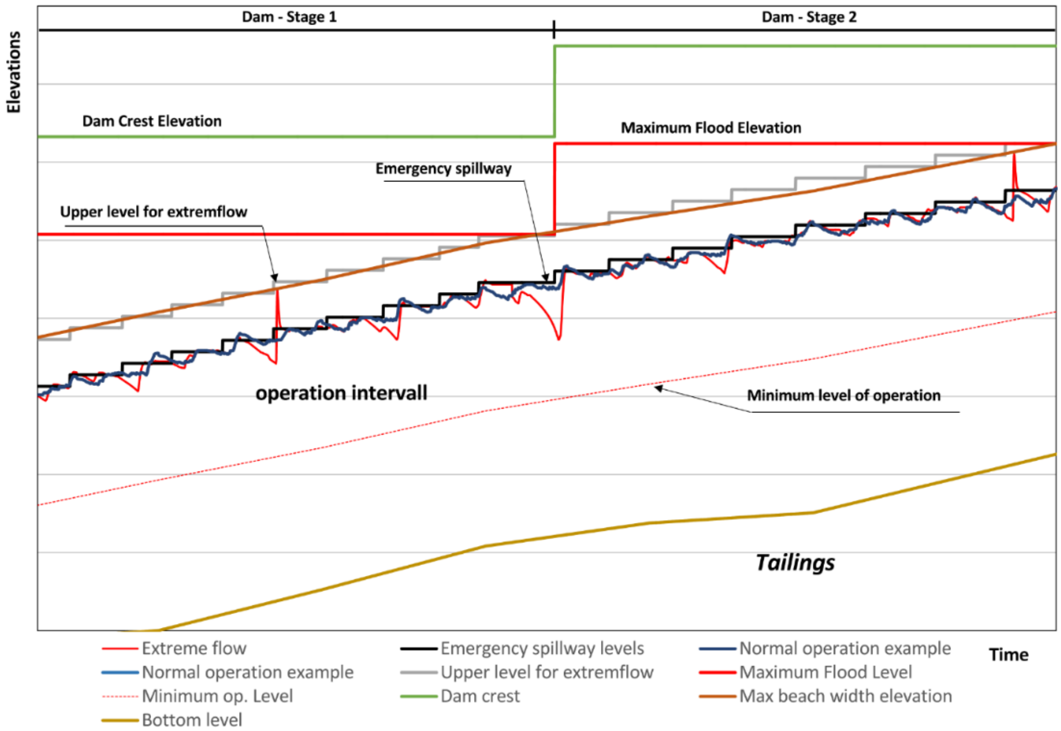

Figure 3 *Example of a design of a fictive tailing storage facility. Own elaboration.*

The construction of TSF is divided into stages and the maximum flood level is normally set to one level per each stage (fig 3). This maximum flood is however only reached in the end of each phase but the flood event can occur at any time during the projects lifetime. This means that the water operation levels could be tested for design floods a long its lifetime. This would generate the Upper Level for Extreme flow limit (fig 3), which should be compared, for instance, with the minimum beach width elevation. In the end of each stage the upper level of extreme flow would coincide with the maximum flood level. This information is important to consider when determining the planning of the different constructions stages of the dam.

What is an adequate interval of water volumes in the TSF, how shall it be determined and what limitations must be taken into consideration? The interval of volumes is the result from an iterative process between tailings management, water quality and water balances. The necessary water volumes could follow from a water regulation study based on limiting factors from the tailings management, which should be verified through detailed water quality analysis. For instance, the result from the water quality results adjustments might be necessary for water volumes and tailing disposal strategy. The disposal of tailings throughout time changes the geometry of the TSF, which for instance means that a constant water level would generate a loss of water volume for a certain time period. The authors have implemented this method in two projects in Sweden. Both studies included an analysis on possible future water operation levels considering probabilistic sampling of relevant parameters in the study. This applied for instance for different substances and for hydrological variations in the rainfall to evaluate the sensitivity of certain results such as water elevations and water volumes in the TSF. The analysis was useful to determine critical periods and levels for the operation.

The quantity of tailings and the amount of process water that reach the TSF has to be considered in the dynamic model. The production rates in the plant such as the amount of incoming product from the mine, percentage of ready product, which finally gives the amount of tailings, varies considerably. The quantity and characteristics of the tailings influence the water quality in the mine water system.

Water quality modelling

Water quality modelling of mine water systems is generally considered a challenging topic, both because of its technical complication and inherent uncertainties (Maest et al. 2005) but also because of natural phenomena and their variability.

A TSF or a clarification pond can be considered to work as a continuous stirred tank reactor (CSTR) in the ideal case. This means that the concentration of a substance is equal everywhere in the tank and that the effluent water has the same concentration.

The material balance equation for such a reactor looks like:

$$In + Prod = Out + Acc$$

This means that for a certain substance that what goes in (*In*) and what is produced (*Prod*, usually through chemical reactions) must equal what goes out (*Out*) and what is accumulated (*Acc*) in the reactor.

For substance A the equation can be written:

$$Q_0 \cdot C_{A,0} + r_A \cdot V = Q \cdot C_A + V \cdot \frac{dC_A}{dt}$$

where Q_0 and Q denote the volumetric flow in and out of the system respectively and $C_{A,0}$ and C_A the concentration of A in the inflow and outflow respectively. r_A is the reaction rate for the conversion of substance A and depends on the concentration of A if the chemical reaction is of the first order.

A study of the equation reveals that both the volume of the reactor (in this case the TSF, the clarification pond or for that matter a lake that receives effluent water) and the concentration of substance A influence the chemical processes in the system. Substance A can be involved in several reactions, for example ammonium (NH_4^+) is involved in nitrification (transformation of NH_4^+ by bacteria to NO_2^-/NO_3^-), volatilization ($NH_4^+$is transformed to gaseous ammonia which goes off to the air), ammonification (NH_4^+ is produced when organic material is decomposing) and also taken up as a nutrient by vegetation, plankton et cetera. All of these processes depend more or less on the concentration of ammonium in the water, which in turn depends on the volume of water. Considering this, it is evident that from a water quality modelling perspective it is of greatest importance that volumes of the different ponds in a mine water system and the water flows between them are as correctly estimated as possible. As seen above (fig 2 and fig 3) the water volume in a TSF can vary considerably over time. This also means that the volumes of other ponds and the flows in the system will vary and hence influence the chemical reactions. Many reaction rates do not only depend on concentrations of the reactants, other physical and chemical characteristics of the water such as e.g. temperature but also pH are important and change when flows are mixed or a flow is emitted into a lake.

An example from a study of an existing mine water system is shown (fig 4). In this case only inert suspended solids were modelled, but also from this rather simple case it is evident that the water volume in the TSF plays a major role for the overall cleaning performance of the system. In this case the production was fluctuating which has not been shown separately in the figure. The zero concentration values stem from production intermissions. It should be noted that the observed concentrations were analyzed in one single grab sample.

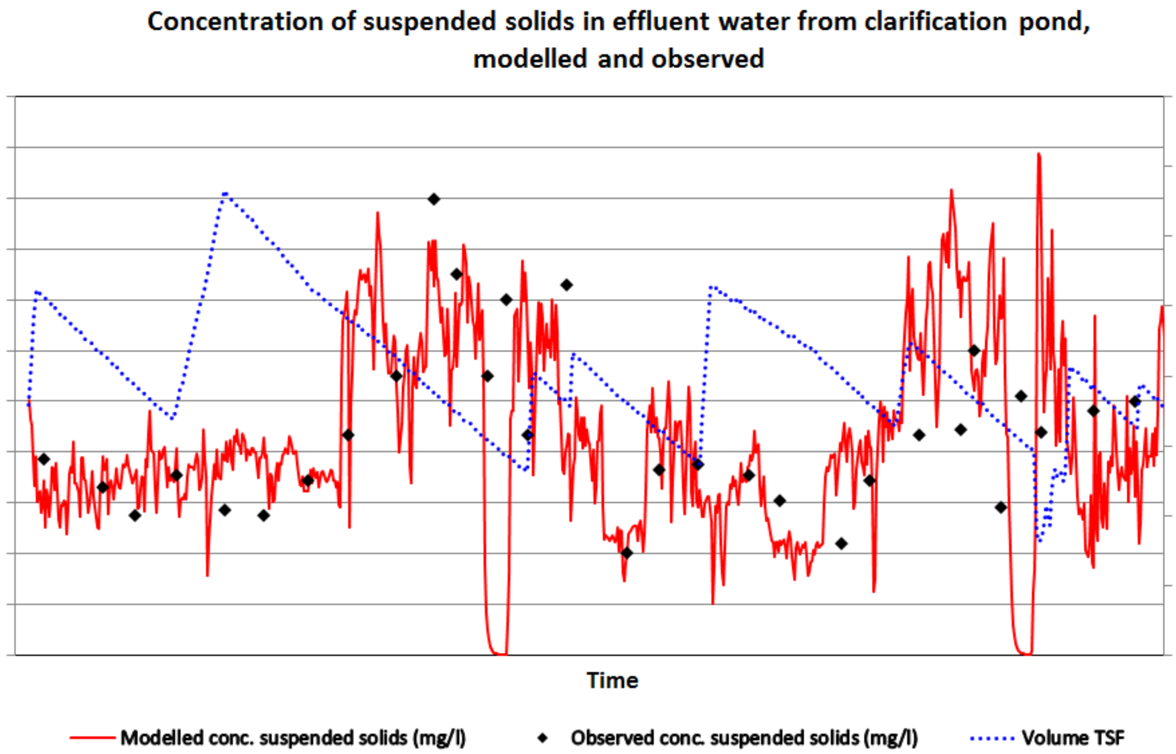

Figure 4 *Example of results from an actual project where the described method of combining detailed water regulation studies with water quality calculations.*

Results from another water quality example where the proposed method has been used is shown below (fig 5). In this case, the water quality modelling is more complex since it involves the nitrogen cycle with both chemical reactions and biological processes, but the production scenario in the mine is less varying than in the former case (fig 4). The nitrogen model was developed from a model presented by Chlot et al. (2011). The influence of the volume in the TSF can be seen even clearer in these model results, also in the recipient (fig 5), which is a lake of notable volume. For easily realized reasons these model results have not been validated.

Uncertainty in models that involve the natural environment is usually significant. Uncertainty can be divided into two types, variability, the uncertainty that comes from nature's true fluctuations and true uncertainty, uncertainty due to lack of knowledge. The size of both types must be quantified, but normally only true uncertainty can be reduced. Variability can best be described as the natural randomness, e.g. in weather conditions. Variability cannot be reduced by more extensive studies, but it is possible to describe better. Uncertainties that have to do with our knowledge and our models can in many cases be reduced by more studies or by using expertise. It is therefore important to follow up on model results to verify (or falsify) the model results but also to gain more knowledge of how the system works in order to continuously improve the models and the understanding.

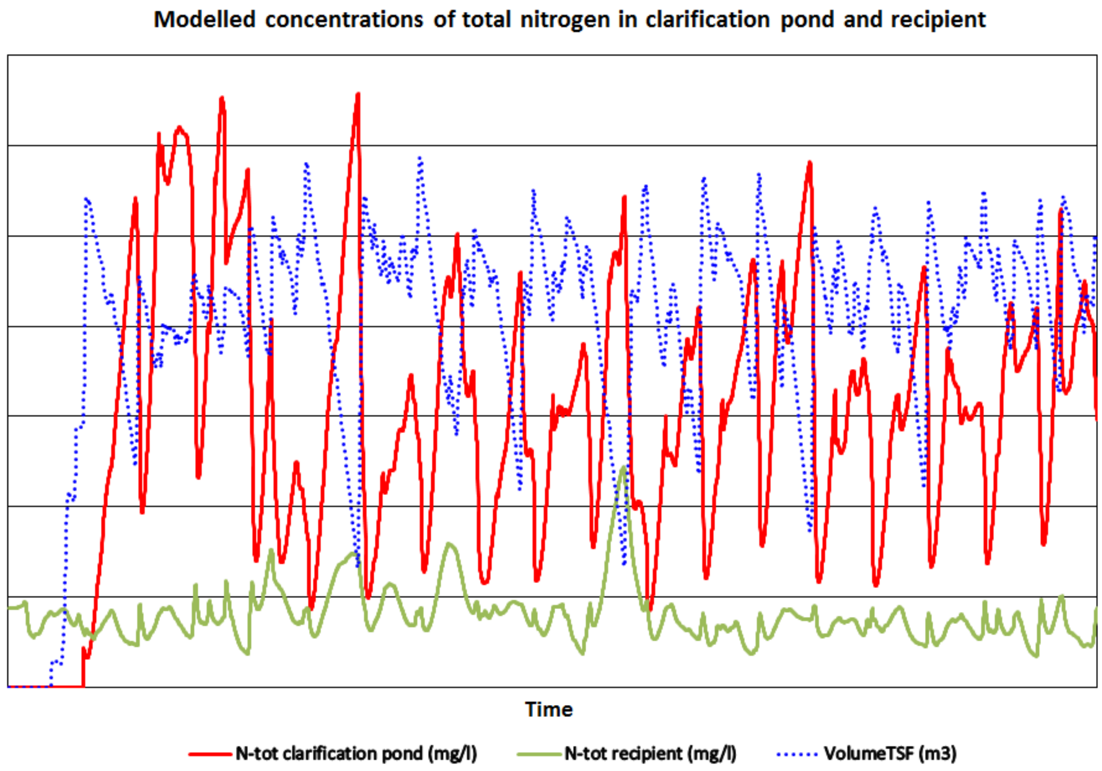

Figure 5 *Example of model results from a project aiming at evaluating the performance of the water system in a planned mine.*

Conclusions

The method developed by the authors consists of considering the tailings pond in the system as a conventional dam storage together with the clarification pond. The TSF is characterized using past and future geometries of the tailings storage, rather than using a mass transport approach, why dynamic hydraulic and water chemistry modelling of the whole system of ponds can be made and is necessary. The geometries of the tailings pond are based on the tailings disposal strategy, why the study includes relevant and limiting factors such as minimum required beach widths etc. and its variation with time. Future operation strategies can be tested and optimized; staging of dam raisings can be done considering the production in the plant, tailings management, water resources and water quality questions. Hence, future deficiencies in the system can be identified and efficient remedial measures proposed ensuring that environmental conditions and requirements are fulfilled.

This method has been tested in one existing and in one new project. From an environmental point of view, the water quality variations in the tailings pond can be determined adequately and related to parameters in the plant and hence how it influences the water quality in the clarification pond and the discharged waters. From a dam safety perspective, both operation rules and an extreme flood event may be “tested” throughout the entire lifetime of the project ensuring thus that spillways works adequately during normal operation and flood events. The interaction between the operation- and tailings disposal strategies is decisive since it affects beach slopes and hence the geometry of the pond.

The functioning of a tailings pond is a close interaction between tailings management, water quantities and water quality. Through an iterative approach, an optimum operation strategy can be determined. The dynamic modelling approach is useful to not only ensure that the environmental requirements are met but its level of detail also provides mining companies with a complete tool for holistic planning and design approach of sustainable mine water systems. Decision-making processes regarding issues such as predicting future needs for raisings of tailings dams, the effect of increased production rates, etc. can now be made environmentally sustainable. It is the authors opinion that an integrated operation strategy of tailings ponds is important to ensure that water volumes in the tailings pond is maintained within an acceptable interval in order to improve the control of concentrations of contaminants in the effluents.

Acknowledgements

We would like to thank the mining companies that supported this initiative and allowed us to develop integrated solutions for their projects.

References

Chlot S, Widerlund A, Siergieiev D, Ecke F, Husson E, Öhlander B (2011) Modelling nitrogen transformations in waters receiving mine effluents, Science of The Total Environment, Volume 409, Issue 21, p. 4585–4595

Lauzon N, Paget M (2011) Report on Guidance Document on Water and Mass Balance Models for the Mining Industry. Yukon Government, Environment. http://www.env.gov.yk.ca/publications-maps/documents/mine_water_balance.pdf.

Maest A, Kuipers, J, Travers C, Atkins, D (2005) Predicting Water Quality at Hardrock Mines: Methods and Models, Uncertainties, and State-of-the-Art

Nalecki, P, Gowan M (2008) Mine Water Management – Dynamic, Probabilistic Modelling Approach. International Mine Water Association. 10th International Mine Water Association Congress. Proceedings 2008. p. 469-472.

ICOLD (2011) Improving Tailings Dam Safety. Guidelines. Bulletin 139. International Commission on Large Dams. ISSN 0534-8293.