Real-time and Stochastic Estimation of Mine Site Water Balance

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ABSTRACT

This paper presents a modeling tool that has been utilized for water management at two Barrick mines in Africa. The modeling approach includes two functions: historical tracking and future projection. First, past and current water inflows, outflows and storage volumes at mine site water storage facilities are estimated based on hydrological and operational conditions. Second, hydrological parameters in the model are adjusted until good agreement between observed and modeled pond volumes is achieved. Finally, short-term (2 years) future conditions are projected in a probabilistic manner by using the calibrated model.

For mine sites where ARD is a concern, realistic predictions of flow rates and volumes of the ARD streams can aid the selection of the most suitable treatment method and capacity. To make the tool more comprehensive, future development of the model will include links to site water quality monitoring databases.

Additional Key Words: Mine site water balance, time-series, deterministic model, stochastic model.

INTRODUCTION

Water is essential to metal mining operations. The control of mine contact water and minimizing/eliminating unwanted mine water discharge are often the core tasks for mine site environmental management. Real-life mine site water management systems may substantially differ from those initially planned or established. Differences can arise from the progress of mineral resource development and from variation of other factors such as tailings characteristics and water quality. In parallel with tracking the quality of water, quantifying flows and storage is the first step of managing real-life mine water systems. For mine sites where ARD is a concern, realistic predictions of flow rates and volumes of the ARD streams can aid the selection of the most suitable treatment method and capacity.

Hydrology, the expression of climate and local water resources as flow of surface water, strongly influences the design and operation of mine site water management systems. The emphasis of mine water management generally shifts from maximizing water security in dry environments to minimizing effluence or environmental impact in wet environments. If local hydrology is accurately incorporated into the design of water management systems, the ponds, channels and pumps should provide adequate capacity to make up water shortfalls under dry conditions and absorb surplus under wet conditions. The ability to properly operate the system is just as important as the design. This ability can be expressed in two components: proper understanding of system feedbacks with local hydrologic conditions and the capability for proactive management action to sustain normal operation.

A vital link between operators and water management system is a tool that aids both of the above-mentioned capabilities. In the mining industry, this tool is referred to as a site water balance model, which incorporates local hydrology with mine water management processes. Variables such as precipitation and temperature are inherently uncertain and are best expressed in probabilistic terms; as a result, any predictive tool used for water management planning, i.e. a water balance model, needs to be probability based.

In contrast to uncertain hydrologic variables, ore processing related flows are mostly continuous and precisely controlled. Process operators and environmental managers also need assurance that a water balance model continuously and accurately reproduces historical/current water system behavior. This means that the model must be calibrated to time series data recording periodically. In summary, a functional water balance model must demonstrate acceptable accuracy by reproducing past and current time-series of flow and storage and be able to predict future time-series conditions in probabilistic terms.

In current practice, a majority of water balance models for mining applications lack one or more of the above mentioned elements: time-series, calibration and probabilistic prediction, making model applications less useful. For example, some design-focused models only provide snap-shots or are based on over-simplified conceptual scenarios; other more complex, but un-calibrated, ones may give time-series simulations of deterministic or probabilistic flow and water storage. Without the continuous agreement between modeled and observed flows and storage volumes, these “comprehensive” models are generally less utilizable by operators as hands-on decision making tools.

This paper describes the development and application of water management tools designed to continuously track real-time flow and storage as time-series and make probabilistic predictions of mine water management systems at two Barrick mines in Tanzania.

MODEL DEVELOPMENT

Hydrology Engine

The hydrology engine refers to the method used in the model to estimate runoff from precipitation within given watersheds. A modeler generally selects either empirical formulas or theoretical approaches. The simplest approach is to assume a rainfall-runoff relationship, such as the SCS (Soil Conservation Service, USDA 1986) curve number method, or to assign a runoff coefficient and/or runoff threshold. Although these methods are very attractive and widely used due to their simplicity, they must be used with caution because the simplified relationship of rainfall-runoff represents a combination of many factors such as land cover, soil type and initial losses etc. Changes to any of the above factors will affect the rainfall-runoff relationship.

The hydrology engine used in the models presented here is a theoretical based method - Soil Moisture Accounting (SMA) within the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS version 3.10, US Army Corps of Engineers, 2008). The HEC-HMS SMA model is patterned after Leavesley's Precipitation-Runoff Modeling System (1983) and is described in detail in Bennett (1998). It is freely available to the public. The model simulates water movement and storage change on vegetation, on the soil surface, in the soil profile, and in groundwater layers. Given time-series of precipitation and monthly potential evapotranspiration (ET), the model computes basin surface runoff, groundwater flow, losses due to ET, and deep percolation over the entire basin.

A key advantage of the SMA method is that inputs are physically based, as opposed to empirical inputs such as soil classification and Curve Number used in the SCS method. Some inputs used in the SMA method are measureable soil properties, such as soil air-entry value, porosity and saturated hydraulic conductivity, while others are physically derived properties, such as wilting point, tension storage (field capacity) etc. Since physically based inputs are less dependent on modelers' judgment, ongoing model calibration and improvement processes are expected to be more transparent and more easily handled by different model users.

The linkage between the hydrology engine, HEC-HMS, and the mine site water balance models is through the HEC-HMS output in a MS-Excel file. The application of the HEC-HMS SMA method requires the mathematical representation of different land surfaces, soil types, and watersheds/sub-watersheds. Calculations of unit runoff are carried out for each land surface or soil type. For example, six surface types - natural grassland, waste rock dump, open pit wall, tailings, disturbed bare ground and pond, were analyzed in the two models presented. HEC-HMS runoff outputs are then automatically read as inputs into the water balance model, where total volumes of runoff are calculated.

Input Files and User Interface

The platform of the site water balance model is GoldSim® V9.60 simulation environment (GoldSim Technology Group, 2008). All time-series based information, such as size of land surfaces and production rates etc. are stored in an input file. As described in the previous section, time-series of runoff and evaporation are calculated by HEC-HMS and used as input data in the water balance calculations.

The user-model interface was designed as a hub for navigation between model components such as run-time control, input file, HEC-HMS, and output files within the GoldSim® environment. Inputs and outputs are automatically read and exported by GoldSim. Users don't need any modeling knowledge to modify inputs, run model and review outputs of the GoldSim® water balance model. The GoldSim® component consists of numerous calculation units, each of which represents a flow or a storage (reservoir) element. Flow elements are linked to their corresponding storage components, either as inflows or outflows. The storage components then record the net inflows and calculate spillage based on the upper limit of storage capacity. A network of flow and storage components, plus logic operations and probability functions, form the water balance model.

Tracking (Calibration) and Predictive Module

The water balance model includes a tracking module and a predictive module. The tracking module is used to calibrate the hydrology engine and ensure correct description of site water management systems so that the accuracy of the model is within the acceptable limit. This is done by adjusting HEC-HMS and GoldSim® calculations to match model-estimated flows and pond volumes with real-life observation values. The calibration needs to be performed from the beginning through the latest date when observed data are available.

The predictive module uses the same hydrology engine and calculations as the tracking module. Once the tracking module is proven to be accurate, predictions to a future time can be carried out. Figure 1 illustrates a hypothetical example of the tracking and predictive module outputs as pond volumes. The fundamental difference between the two modules is that the predictive model is developed as a tool to analyze 'what-if' scenarios where management decisions can be made proactively based on desirable model outcomes.

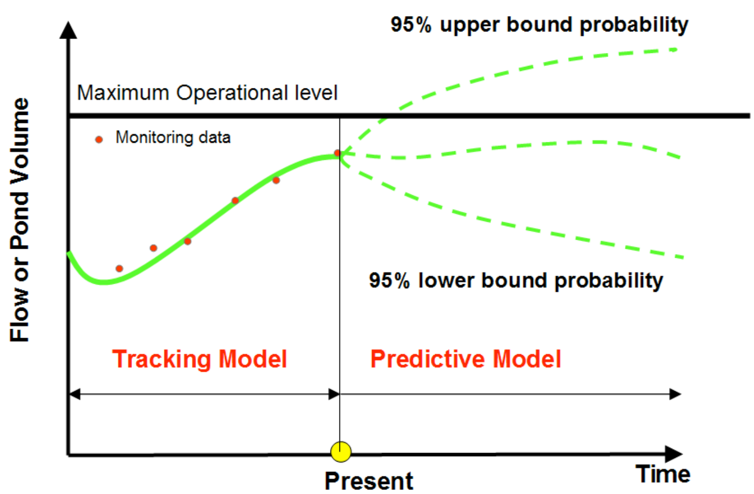


Figure 1. Hypothetical example of tracking and predictive module output.

MODEL APPLICATION

This section describes the application of the water balance model at Barrick's North Mara and Bulyanhulu mines. The description focuses on the specific objectives of the water management system at each mine. The locations of the North Mara and Bulyanhulu Gold mines are shown on Figure 2.

Figure 2. Locations of the North Mara and Bulyanhulu Gold Mines.

North Mara

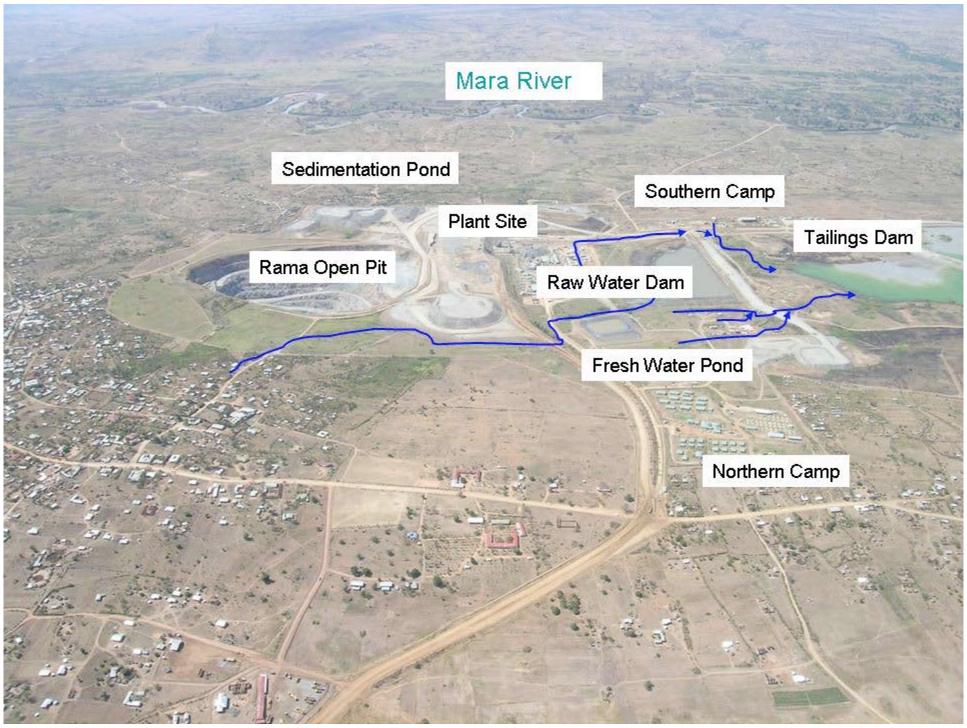
Description of Water Management System

The North Mara Mine (NMM) is located approximately 100 km east of Lake Victoria and 20 km south of the Kenyan border (Figure 2). It is situated in the northwest highlands and the isolated Granitic Mountain region of Tanzania. The topography of the mine and surrounding area is characterised by occasional hills among flat grass and farmlands with slopes ranging from 1% to 15%.

The NMM occupies approximately 7 km^2 of land. The mine consists of three open-pit deposits – Nyabirama (Rama), Gokona and Nyabigena (Gena). The Gokona and the Gena deposits are close by, whereas the Rama deposit is approximately 10 km to the southwest. The total annual milling rate is 2.8 million tonnes. The gold extraction process includes a gravity separation circuit, cyanidation and carbon-in-leach recovery followed by electrowining and gold refining.

On average, the area receives annual precipitation of 1,280 mm/year, with a similar magnitude of potential evaporation (PE). The current process water demand is approximately 9,400 m^3/d, of which about 5,000 m^3/d is circulated within the plant and the remaining 4,400 m^3/d must be supplied from external sources. There are three main external sources of process water supply: (1) raw water from the Raw Water Dam, which comes from site runoff, (2) water abstraction from the Mara River and (3) reclaimed water from the Tailings Dam. The mine has a license to extract 4,200 m^3 of water daily from the river. During dry months (June to end of September), water supply from the Mara River can be limited as the river often dries up. Surplus inflows from rainfall and runoff normally occur in the wet season. Photograph 1 shows some key facilities situated at the Rama deposit of the NMM.

The objectives for the current water management system are to reduce the river water abstraction and eliminate any mine effluence. The action plan to achieve the above objectives is to quantify the various water sources and optimize fit-for-use practice.



Photograph 1. Key facilities at the North Mara Mine (South portion) and the Mara River. The blue arrows indicate directions of runoff flow.

Model Setup

The tracking module represents all ponds and flow paths within the NMM water management system using mathematical functions. Synthetic rainfall records were generated based on regional rainfall records and used in probabilistic simulations.

Model Calibration and Prediction Results

The NMM water balance tracking model has been calibrated to achieve agreement between model output and monitoring data at the following two key facilities:

- Tailings Dam –quarterly surveyed pond and tailings elevation (July 2003 to October 2008); and
- Raw Water Dam – weekly surveyed pond volume and elevation (August 2002- October 2008.

Calibrated results indicate that the current water balance model is able to reproduce key flows and seasonal variations of two pond volumes for the calibration period. Predicted pond volumes with various probabilities of exceedence are also shown on Figure 3. Results show that since 2003 surplus water has been accumulated in the Tailings Dam, which is the designated collection point for site contact water with poorer water quality. As expected the variation in the probabilistic distribution of pond levels are much wider for the Raw Water Dam than for the Tailings Dam, since the former is closely linked to rainfall-runoff and the latter mostly controlled by slurry inflow and reclaim.

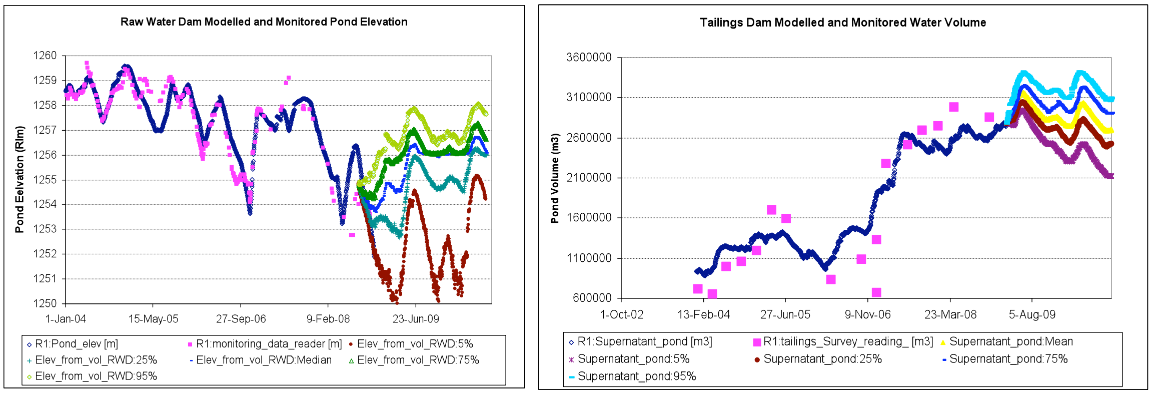


Figure 3. Combined results of Tracking Module (calibration) ending in August 2008 and Predictive Module starting in August 2008 and ending August 2010 - the Raw Water Dam (left) and the Tailings Dam (right).

Based on the model results, the mine has made significant changes to water supply and consumption. The implications of predicted pond levels are described in the following section.

Improvements to Water Management

The results of the model quantified the surplus of inflows from different sources at the mine site resulting in a continual rise of water level in the Tailings Dam. The mine management has since made significant changes to site water management by diverting clean runoff off of the property and maximizing the use of contact water collected in the three open pits and from waste rock storage facilities. The fit-for-use effort has maximized the use of site runoff as make-up process water, thereby eliminating the need for water extraction from the Mara River.

Direct benefits of these changes are significant to the overall mine operation. These include (1) reduction of the environmental footprint of mine operation by reducing water extraction from the Mara River, (2) termination of long-term water accumulation in the Tailings Dam, and (3) reduction of the risk of the release of surplus water from the property. These beneficial outcomes are indicated in the predictive model results (Figure 3), which shows more stabilized water level in the Tailings Dam over a future period of two years.

Apart from the above direct benefits, the utilization of the water balance model also raised the awareness for water conservation and improved the quality and record keeping of monitoring data. The water balance model has become a living tool that will be continuously checked and improved by the mine operators.

Bulyanhulu

Description of Mine Water Management System

The Bulyanhulu Gold Mine (BGM) is located approximately 55 km south of Lake Victoria (Figure 2). It lies on a flat plain occupying approximately 50 km^2 of land. On average, the area receives annual rainfall of about 950 mm/year with a much higher PE of 1700 mm/year. Most of the rainfall is concentrated within a wet season. This climate pattern requires the water management system to cope with both wet and dry conditions.

The mine consists of underground mine, mineral processing, surface paste tailings disposal and water management areas with an average daily ore processing rate of 2,300t/day. Approximately 82% of the process water can be circulated within the processing circuit with remaining make-up water of 900 m^3/day. A pipeline brings fresh water from Lake Victoria to supply potable and process water to the mine.

The BGM has a complex water management system that is able to transport water among seven water storage facilities (photograph 2), depending on daily water quality and quantity in each facility. With the newly commissioned Return Water Pond #2, the storage capacity within the two return water ponds (600,000 m^3) at the tailings storage facility represents 83% of the total on-site capacity.

The water management mandate at the BGM is to maintain acceptable water quality in the facilities and eliminate discharge during upset conditions. Since mine dewatering from the underground workings and the supplemental water supply from Lake Victoria are fairly reliable water sources, water supply in the dry season is generally not a concern.

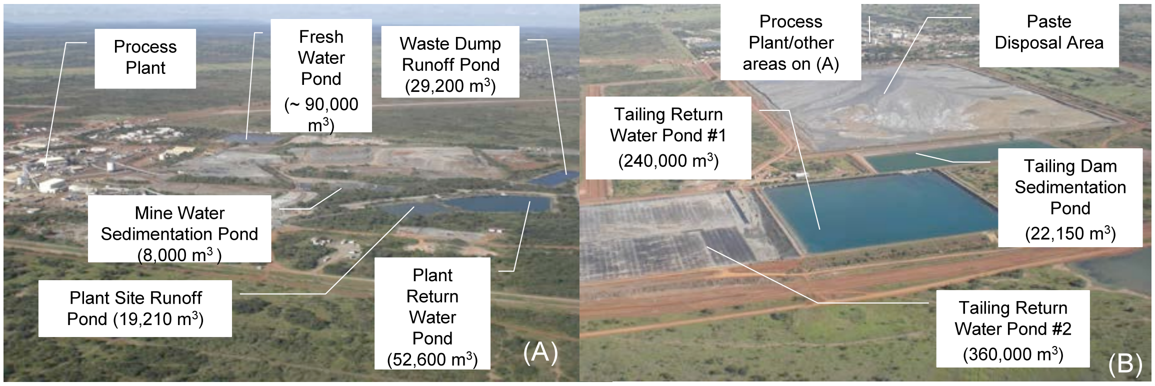
Model Setup

In the past, two consulting companies were commissioned to build water balance models. These previous models were to reproduce the complex flow logic and numerous what-if scenarios to capture all possible flow directions; however, these efforts made their models difficult to follow and extremely hard to calibrate.

The current water balance model greatly simplifies the site water management system by treating all flows between facilities as internal transfers which are not included in the calculations; thereby the outputs of the model use the combined volumes of water in all seven ponds. Because most of the contact water is stored in the two tailings return water ponds, the combined storage volume is a meaningful parameter for the mine operators.

Model Calibration and Predictive Results

The Bulyanhulu water balance model has been calibrated for the period between January 2008 and February 2009 when required records are available. As indicated on Figure 4, the estimated total pond volume closely follows the observed volumes for the entire period, except for the period between June and August 2008, during which the rainfall and water consumption data are lacking. The results indicate that there may be a slight surplus of the site water on annual basis, so that on going removal of excess water by forced evaporation is required to maintain long-term water balance.



Photograph 2. Layout of key water management facilities at the Bulyanhulu Gold Mine.

Improvement to Water Management

The water balance model has been integrated into the management system by the process operators, who are also responsible for day-to-day production. Real-life tracking and predictive model results have guided the management to add more forced evaporation sprinklers to remove surplus water. The predictive results allow the operators to act proactively in keeping the storage level below the storm freeboard at all the ponds.

The quality of the model, to a large degree, depends on the quality and frequency of survey data. Since the implementation of the water balance model, the mine survey team has completed a detailed survey of geometry for all the ponds, standardized survey documentation and increased the survey frequency from once a month to once a week. This has significantly improved the model reliability making it a robust and accurate predictive tool.

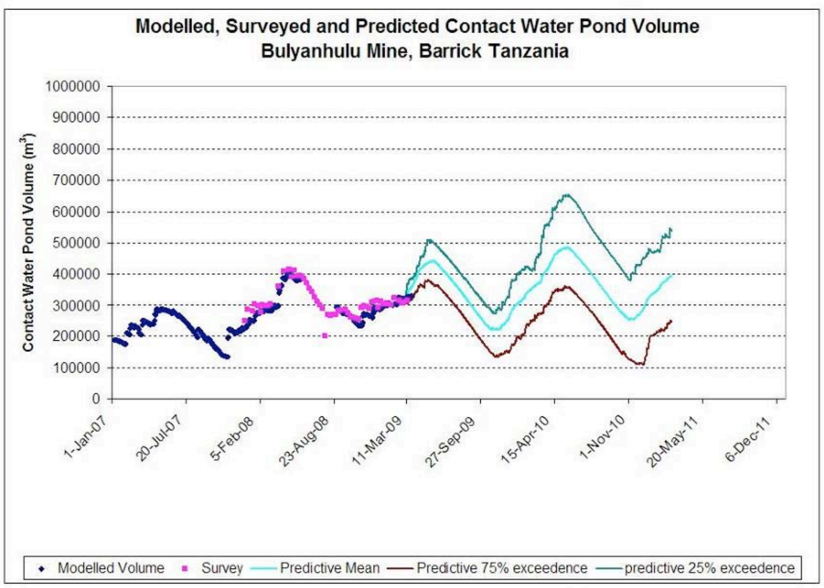


Figure 4. Combined results of the Tracking Model (calibration), ending in February 28, 2009 and the Predictive Model, starting in March 1 2009 and ending in February 28, 2011.

CONCLUSIONS

The applications of the tracking and predictive water management model at the NMM and the BGM confirm that the value of the water balance models lies in time-series analysis, real-time tracking and calibration, and probabilistic prediction. Operations can gain a better understanding of the existing water management system by implementing a systematic monitoring program and carrying out periodic model calibrations.

Future expansion of the model application will include the tracking and prediction of water quality in parallel with water quantity. This feature will allow the operator to fully evaluate environmental risks and maintain good water quality to meet various mine water needs. Management of ARD flows can then be improved by initiating necessary water treatments prior to the undesired conditions with high flows and full pond volumes.

ACKNOWLEDGEMENTS

The Authors wish to thank the staff at the environmental department and the processing department of the Bulyanhulu Gold Mine and North Mara Gold Mine for their support and corporation during the model development and application.

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