Snowmelt and Runoff Simulation at Mine Sites in Cold Climates using Probabilistic Methods

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Abstract

A methodology for stochastic simulation of snowmelt and runoff for water balance modelling at mine sites in cold climates is presented in this paper. A stochastic climate model is combined with the Swedish Meteorological and Hydrological Institute's (SMHI) Hydrologiska Byråns Vattenbalansavdelning (HBV) model, which uses a degree-day method is applied to predict snow melting, and a simplified thermal analysis to predict ice formation and melting. The modelling objective is to represent random fluctuations in both precipitation and temperature as the main drivers in the rate and volume of spring meltwater generation. The model has been successfully implemented to support strategic decision making at the Kevitsa mine in Lapland, Northern Finland. The model performance and future model applications are discussed.

Keywords: snowmelt, mine water balance, stochastic simulation

Introduction

For mines in cold climates managing water supply and storage through the winter period, when precipitation falls as snow, and the seasonal meltwater influx in spring presents huge challenges. This carries associated risks to the mine operation, and potentially to the environment, if the spring peak flows cannot be managed. The prediction of snow and ice accumulation in winter and associated melt water generation in spring is critical to water balance calculations that facilitate the management of risks to mining operations.

It is generally recognised that good practice for water balance assessment for mine water management requires a holistic assessment of the side-wide water balance in dynamic modelling tools which are able to simulate interdependent system responses and responses to short term climate variability. For sites in cold climates, these hydrological models must incorporate the freeze and thaw cycle to be of value in understanding flood risk.

The primary goal of mine water balance studies is usually to predict conditions in future periods in the mine life. While models are often run by 'looping' or sampling historical data, to be truly predictive, stochastic climate generators are necessary to simulate the response of hydrologic systems beyond the limits of the historical record. Stochastic generators attempt to reproduce the statistical characteristics of the historical record in synthetic sequences of arbitrary length.

The model described in this study was developed to simulate the water balance of a site in artic Finland, where average temperatures are below freezing for 6 months of the year. This study implemented a hydrological model, the SMHI HBV model (Bergström, 1976, 1992) in GoldSim^{TM}, coupled with stochastic climate simulation to provide probabilistic simulation of snow accumulation, snowmelt and catchment runoff. This was further augmented by a model for ice formation and melting in water storages, driven by the stochastic temperature record.

Climate and Catchment Runoff Modelling Methodology

The most important element of the stochastic climate model is the stochastic precipitation simulator. The GoldSim model implements the Australian CRC for Catchment Hydrology's Stochastic Climate Library Daily Rainfall Model for a single site (Srikanthan and McMahon, 1985; Siriwardena et al., 2002) and has been previously described in O'Hara (2012). The model uses the State-Markov Transition Probability Matrix (TPM) method (lag-1 day) with shifted-gamma distributed top state rainfall. This type of model assumes that the climate state is binary, and is either wet or dry. Each state has an independent rainfall distribution, assumed to be Gaussian; transitions between states are governed by the TPM. Annual seasonality is imposed by computing separate transition probability matrices and gamma parameters for each calendar month. The TPM is developed by simple transition counting in the historical record; done separately for each calendar month to impose seasonality. A long period daily climate precipitation record is necessary to define the TPM.

The stochastic model for temperature is relatively simplistic, but is more sophisticated than a model based only on sampling statistical distributions derived from the historical record. The primary objective was to replicate short period correlation in temperature and seasonal variation in the degree of short range temperature fluctuation. The temperature model has two elements:

- A (non-stochastic) representation the seasonal temperature trend as a sinusoidal function fitted to mean average daily temperature.
- A stochastic temperature fluctuation modelled as deviation from the seasonal mean, represented as a probability density function (PDF) of deseasonalised temperature, with autocorrelation between daily values defined based the historical record.

The autocorrelation factor is determined by regressing daily deseasonalised temperature against the previous days' deseasonalised temperature. PDFs of deseasonalised temperature are derived based on observed data, seasonally or monthly depending on the degree of variability.

Evaporation is simulated according to the methodology described in the SMHI HBV model. Evaporation of each day is calculated from the seasonal mean value plus or minus an adjustment correlated to the deviation of temperature from the seasonal mean.

The HBV model is a catchment scale hydrological model for simulation of snow accumulation and melt, groundwater and surface water interaction and catchment runoff. While the model has been applied across

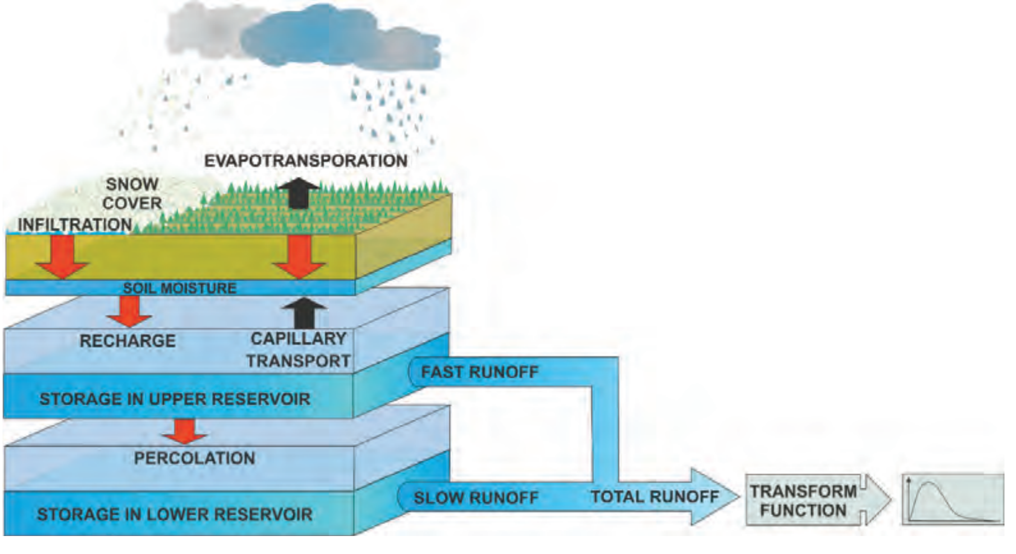

***Figure 1** Schematic representation of the HBV-96 model (modified from Lindström et al., 1997)*

the world, it is well suited for Scandinavian climatic and hydrological conditions. The HBV model comprises a number of routines for system components: snowmelt is calculated by a degree-day method; groundwater recharge and actual evapotranspiration are functions of the calculated soil-water storage; and runoff formation is simulated by linear reservoir functions. Daily values of storages and discharge are simulated using daily precipitation and temperature and long-term averages of potential evapotranspiration as inputs.

The model is calibrated through adjustment of empirical factors in each routine, including the snow melting rate and runoff recession coefficients.

Snow accumulation is defined by a threshold temperature, below which precipitation is snow and above which snowmelt occurs. Snowmelt occurs as a function of temperature based on a rate coefficient C_{FMAX} (mm/°C/day). Snowmelt is retained within the snowpack until meltwater exceeds a certain proportion of the snowpack, after which it is released. If the temperature falls below the threshold temperature, melt water refreezes based on a freezing rate coefficient. Sublimation, although not included in the HBV model, was included in our model as an additional loss from the snow water reservoir calculated as a proportion of snowfall based on calibration.

Ice formation is simulated using a simplification of the method proposed by Comfort and Abdelnour (2013). The method uses a heat-budget analysis based on a 'bulk' heat transfer coefficient which is suitable for application based only on available temperature, snowfall and rainfall data. Ice formation has been simulated as a combination of the following processes:

- Calculation of the lag in ice formation between air temperature reaching freezing and lake temperatures reaching freezing, allowing ice formation to start.
- Calculation of the rate of bottom ice growth through freezing at the basal surface of the ice sheet.
- Calculation of the rate of surface ice growth through:
  - Refreezing of slush in the snowpack following rainfall events; and
  - Freezing of surface ice following flooding events where snow loading results in submersion and flooding of the ice sheet.

The time lag for the onset of ice formation when air temperature falls below freezing has been calculated as in Leppäranta (2010) using an assumed atmospheric cooling rate. The rate of ice formation on the bottom of the ice sheet and surface ice growth is calculated using the following equation (Comfort and Abdelnour, 2013):

$$\frac{dh_i}{dt} = \frac{1}{\rho_i \lambda} \frac{(T_m - T_a)}{\frac{h_s}{k_s} + \frac{h_i}{k_i} + \frac{1}{H_a}}$$

Where subscript i represents ice and s, snow, h is thickness, t is time, T_m and T_a water and air temperature respectively (water temperature assumed to be 0°C), k thermal conductivity and H_a the heat transfer coefficient from the snow surface to the air. The water available to form surface ice is limited by two processes which may provide water for ice formation: rainfall events where precipitation falls as rain on existing snow and ice, and flooding events where snow loading results in submergence of the ice sheet.

The point at which the ice sheet becomes neutrally buoyant due to the overlying snow load is calculated as (Comfort and Abdelnour, 2013):

$$h_s = \left(\frac{\rho_w}{\rho_s}\right)\left(1 - \frac{\rho_i}{\rho_w}\right)h_i$$

Where definitions are as above, and ρ_w and ρ_s are the densities of ice and snow, respectively.

The resulting model is a simplified representation of ice formation and melting processes, neglecting some aspects of the Comfort and Abdelnour (2013) model as well as more sophisticated thermodynamically based models. It was found to perform well for ice growth, but not for ice melting.

Ice melting was simulated using Zubov's law (Zubov, 1945 in Leppäranta, 2010), a modification of Stefan's equation which includes an adjustment factor to allow for the insulating effect of the near-surface air-snow buffer.

Case Study: Kevitsa Mine

Kevitsa Mine is located near to Sodankylä in the Lapland region of Finland and is operated by Boliden Kevitsa Mining Oy. The Site lies north of the Artic circle and experiences average temperatures below freezing for more than 6 months of the year. At present, the ultimate catchment of the mine will be approximately 10.6 km^2. The catchment is gently undulating, lying at an elevation of between 200 m and 315 m above sea level, and is surrounded by areas of wetland. Groundwater is near to ground surface in many parts of the Site, which is underlain by superficial deposits comprising peat and glacial till, underlain by Paleoproterozoic basement rocks.

The mine is an open pit operation, with a waste rock dump, tailings storage facility, crusher (located underground) and processing plant, which began operation in 2012. The Site has a water reservoir for storage. Process water is taken from the water reservoir and also directly from the tailings decant pond. Water from all the mine facilities and small areas of catchment within the mine Site ultimately discharges to the water reservoir, from which excess water is treated and discharged under an Environmental Permit to the Kitinen River approximately 3.5 km west of the mine. A small amount of raw water is taken from the Kitinen River to augment the water supply.

Calibration was undertaken of the following aspects of the climate and runoff model in the Kevitsa study:

- Stochastic precipitation: mean and standard deviation, and predicted rainfall for the 1 in 10 year, 1 in 50 year and 1 in 100 year 24 hour events.
- Stochastic temperature: visual fit to observed, replication of 10%ile, 50%ile and 90%ile of observed record over an extended time period.
- Snow and ice thickness: snow accumulation as snow water equivalent, and ice thickness.

Historical data for surface flows at Kevitsa mine did not include runoff data for any natural catchment areas, and catchment runoff data for the region was not available from the Finnish Meteorological Institute. As such, the runoff model could not be directly calibrated to available data. The mine collects data for discharges from the major mine facilities, from the treatment plant and off site discharge location. The water balance was calibrated to these flows and to water inventory data where available. The model calibration therefore gives an indication of the accuracy of specific parts of the climate and runoff model, and of the site wide balance as a whole, but not of the runoff model directly. The HBV module incorporated into the model has been previously applied at site in Sweden and was found to perform well with calibration to a historical catchment runoff series.

Calibration of the stochastic precipitation module to 24 hour peak rainfall events is shown in Table 1. At the longer return periods, the model slightly over-predicts the rainfall intensity, but is within the 95%ile upper bound of the observed values. The daily, monthly and annual mean and standard deviation of simulated rainfall showed a good match to observed.

Predicted and observed snow pack thickness and ice thickness for the recent period are shown in Figure 2. The annual maximum snow pack was also calibrated over a much longer historical record. A degree-day method is unlikely to provide a good fit to observed conditions in all years as it neglects some key

Table 1: *Predicted and Observed 24-Hour Return Period Events, Stochastic Precipitation Module*

Return Period	Probability of Occurrence	Calculated Value (mm)	Observed Value, Average (mm)	Observed value, 95%ile Upper Bound (mm)
10 years	0.027%	41.8	39	45
20 years	0.014%	47.4	43	50
100 years	0.0027%	62.6	54	63

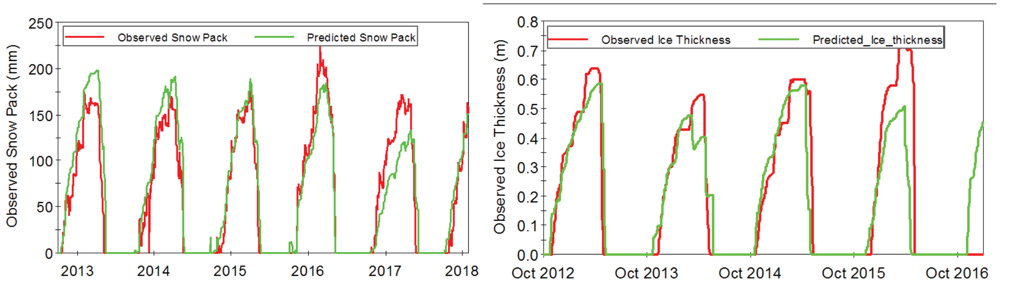

***Figure 2** Kevitsa Mine Model Calibration, Snow Depth (as Snow Water Equivalent) and Ice Thickness*

variables in terms of energy balance. However, an acceptable calibration was obtained through fitting of the threshold temperatures and adjustment of the observed record snow density within a defined range.

A good fit to observed temperature was achieved using the stochastic temperature module, but the extremes of the generated temperature record resulted in a poor calibration for snow and ice formation. The module was therefore modified to reduce the modelled extremes, resulting in a better calibration for snow and ice formation and melting.

The calibration of the Site's annual discharges is illustrated in Table 2. The normal operational demand for make up water is an input into the model: though the model can generate additional make up water if required, no additional make up water was generated in the calibration period. There are many factors in the calibration of the Site wide water balance that are unrelated to the climate and runoff model performance, and the overall model performance cannot be used to validate the climate and runoff model.

The water balance model has thus far been utilised to assist the mine in strategic decision making regarding the future water treatment requirements for the mine, and to evaluate the risk profile of the Site's major water storages. Golder continues to work with the mine to improve the water balance model performance and develop confidence in the model predictions. As further data is collected, this will include further calibration of the run off model.

Other Considerations

The catchment runoff and ice storage model described has the potential to provide a useful tool for stochastic generation of future runoff sequences for mine water balances, but is based on historical climate. While for operations, climate change impacts may be of little significance, for design of long term infrastructure and in particular for closure, climate change modelling results may significantly affect decision making and consideration of climate change factors is mandated.

A range of approaches to adopting modelled climate change impacts to support mine design and impact assessment can be found in literature; Fraser et al. (2017) includes a regionally appropriate example at a Boliden property in the region (Aitik Mine, Northern Sweden). In order to practically adapt this basis, Golder has previously presented a

***Table 2:** Observed and Predicted Annual Treatment and Off Site Discharge Volumes*

	Year	Calculated Volume (m^3/yr)	Recorded Volume (m^3/yr)	Variance (m^3)	Percentage Error
Off Site Discharge	2014	3 335 580	3 199 350	136 230	4.3%
	2015	3 624 740	3 652 090	-27 350	-0.7%
	2016	3 785 730	3 718 540	67 190	1.8%
ETP Flow	2014	2 709 200	2492560	216 640	8.7%
	2015	2 848 790	2 490 700	358 090	14.4%
	2016	2 553 870	2 406 890	146 980	6.1%

ETP – effluent treatment plant.

method which can be used to include climate change signals into future planning for water resource management within a GoldSim model (O'Hara et al, 2012).

The process of incorporating climate change scenarios can be summarised in 3 steps:

Analyse key parameters in Site and local historic and current baseline datasets, compare to longer term regional records and characterise anomalies to support selection of longer term future climate trend inputs.

Determine a regionally appropriate source of climate change scenario data. This may incorporate reference to industry and scientific best practice (e.g., IPCC publications, SMHI Report No. 116, 2014), technical experts and consultation with regulatory agencies and stakeholder groups. For the Kevitsa mine, the Rossby Centre (SMHI 2014) is a regional source for climate change scenario results which can provide downscaled, daily data for all required parameters, obtained via the CORDEX (COordinated Regional climate Downscaling EXperiment) system.

Derive seasonal and annual adjustments to precipitation and temperature for inclusion in the stochastic climate model from the future climate model data and adjust accordingly.

Conclusions

This paper presents a methodology for the stochastic simulation of snow and ice melting and runoff, implemented using the GoldSim™ Monte Carlo simulation platform. Application of the model for the water balance at the Kevitsa mine has provided encouraging results regarding the model performance, though runoff rates have yet to be validated due to a lack of suitable data. The methodology proposed could be readily adapted to consider future climate scenarios, and as such has the potential to be valuable in long term planning.

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