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Development of a waste rock simulation model to mitigate environmental impacts of acid rock drainage

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ABSTRACT

A dynamic simulation model (TMSim) was recently developed to evaluate tailings dewatering technologies on their ability to meet reclamation and closure goals. TMSim and other similar models do not incorporate ARD and related rock overburden waste management strategies specifically encountered during hard rock mining operations. This paper will detail the development of new sub-models in order to incorporate a waste-rock deposition and hydrogeology sub-model within the TMSim modeling framework. Doing so will allow for the analysis of the efficacy of various ARD prevention strategies such as traditional end dumping of waste-rock (base case), encapsulation of potentially acid generating (PAG) material with non-acid generating (NAG) material, and progressive capping of waste-rock with NAG. The model will utilize a top-down, dynamic system approach to incorporate all systems within a mine plan. It will be implemented by using the GoldSim software coupled with Muk3D to account for the development and configuration of waste-rock piles.

RÉSUMÉ

Un modèle de simulation dynamique (TMSim) a récemment été mis au point pour évaluer les technologies de déshydratation des résidus sur leur capacité à atteindre les objectifs de remise en état et de fermeture. Cependant, TMSim et d'autres modèles similaires n'intègrent pas de stratégies de gestion du drainage minier acide (DMA) ni des stratégies de gestion des haldes à stériles spécifiquement rencontrées au cours des opérations d'exploitation de roches dures. Cet article détaillera le développement de nouveaux sous-modèles afin d'intégrer un sous-modèle de dépôt des roches stériles et d'hydrogéologie dans le cadre de modélisation de TMSim. Cela permettra d'analyser l'efficacité de diverses stratégies de prévention du DMA telles que le déversement à la benne traditionnel des roches stériles (cas de base), l'encapsulation de matériaux potentiellement générateurs d'acides (PGA) avec des matériaux non générateurs d'acides (NGA) et capsulage progressif des roches stériles avec du NGA. Le modèle utilisera une approche système descendante et dynamique pour incorporer tous les systèmes dans un plan de mine. Il sera mis en œuvre à l'aide du logiciel GoldSim associé à Muk3D afin de prendre en compte le développement et la configuration des haldes des roches stériles.

1 INTRODUCTION

One of the main environmental concerns with hard rock mines is acid rock drainage (ARD) generation in waste rock piles. The process occurs when sulphurous rock reacts with atmospheric oxygen and water. The rate of sulphide oxidation in waste-rock piles is slow initially, but if oxygen and water continually enter the waste rock pile, the rate of acid generation increases rapidly as the pH decreases (Bussiere 2007). One of the current accepted ARD management techniques is the construction of cover systems that limit oxygen and/or water infiltration (Johnson and Hallberg 2005). This strategy is often implemented once the entire waste rock pile has been constructed. However, the operation and construction of a waste rock pile can occur over many years or decades. The process of ARD generation starts the moment water and oxygen are introduced to sulphide materials within the waste rock (Wilson 2011). In order to minimize the generation of ARD it is important to decrease the oxygen or water present within the pile during construction (Johnson and Hallberg 2005). ARD mitigation strategies that can be implemented during construction include encapsulation, layering, progressive capping, blending and co-disposal (INAP 2009).

Modeling techniques in the field of mine waste management are predominately process-based approaches that typically study only one aspect of the mining and waste interactions (e.g. water balance, ARD, tailings dewatering, storage embankments). Each of these processes are typically modelled separately using complex analytical tools and are focused on one detail of the mine design, not the overall mine waste management plan performance. There are few available models or approaches that look at the whole system of mine waste management over the mine lifespan. One such tailings management simulation model (TMSim) developed by Beier (2015) uses a system dynamics approach to evaluate tailings dewatering technologies on their ability to meet reclamation and closure goals. System dynamics philosophy allows the user to simulate large complex inter-related systems that cannot be modelled with a traditional process-based software. When modelling systems, there must be a balance between the level of detail and the breadth, or scope of a model. As seen in Figure 1, as the level of detail and number of processes increase, the breadth of the model decreases. In system dynamics modelling, simplifications are necessary in order to model large scale systems. TMSim and the other models, however, do not incorporate ARD and related rock overburden waste management strategies specifically encountered at hard rock mining operations.

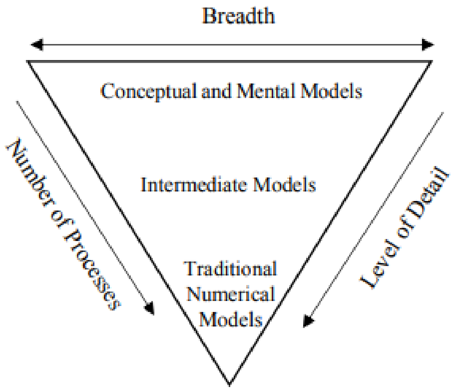

Figure 1. Classifications of Models (Zheng and Beier 2018)

2 OBJECTIVE

The research aims to further develop TMSim to account for ARD phenomena in mine operations. This will be done by incorporating a waste-rock deposition and mass balance sub-model into the TMSim model using the GoldSim software coupled with a volumetric planning software (Muk 3D) to account for the development and configuration of waste-rock piles. Doing so will allow the analysis of the efficacy of various ARD prevention strategies.

This paper will outline the conceptual model and approach to developing the TMSim waste rock sub-model. The waste rock model will be broken down into two separate sub-models, a mine sub-model and an environment sub-model. The mine sub-model will consist of a series of arrays based on the mine plan that will dictate the input conditions into the 1-D seepage, environment sub-model. Specific strategies to be incorporated into TMSim may include traditional end dumping of waste-rock (base case), paddock dumping to prevent segregation, encapsulation or layering of potentially acid generating (PAG) material with non-acid generating (NAG) material, and progressive capping of waste-rock with NAG material to limit seasonal infiltration, these will be discussed further in section 5.2.

3 WASTE ROCK MANAGEMENT

The purpose of the waste rock sub-model is to model the construction of a waste rock pile and the subsequent seepage that occurs based on pile geometry and climate during construction. The model will incorporate the mine plan to track the accumulation of NAG and PAG waste rock available for placement. These materials will then be directed to cells within the waste rock pile to be constructed. The pile geometry will be changed based on the ARD mitigation strategy tested to investigate the subsequent change in pile moisture content and seepage.

One of the most common waste rock pile construction techniques is end-dumping, where the waste rock is tipped off a truck down the edge of a slope. This technique creates two unique structures within the pile; vertical grading due to gravity segregation and inter-bedded dipping layers of coarse- and fine-grained material. These features generate the perfect reactor for the development of ARD, where the fine-grained material retains moisture and the coarse-grained material allows the convective flow of air from the rubble zone at the base of the pile to the surface (Herasymuik 1996). Wilson (2011) discussed the difficulties that arise with the end-dumping technique and recommended that the best ARD prevention strategy is to use improved construction methods that prevent segregation of the waste rock. To align with Wilson's recommendation, the proposed model will include paddock dumping of the waste rock as a mitigation strategy. Paddock dumping is where the waste rock is dumped in-place and shaped by dozers, creating a more homogenous structure with reduced preferential flow paths.

The other ARD prevention strategies focus on the placement of NAG and PAG material in geometries that may reduce waste rock oxidation. The three strategies that will be implemented in the model are encapsulation, layering and progressive capping of the waste rock pile. Encapsulation consists of placing NAG below, beside and above the PAG material to encase it. Layering is a simpler version of encapsulation that places the NAG and PAG material in alternating horizontal layers. Progressive capping of the waste rock would include installing a rudimentary cover over the completed section using NAG material from the excavation or borrow material (INAP 2009).

4 SYSTEM DYNAMICS

System dynamics (SD) is a modelling approach that focuses on overall behavior of a system rather than detailed numerical modelling. There are three basic building blocks of a SD system, stocks and flows, feedback structures and delays. Stocks are state variables that track accumulation with the flows representing the increase and decrease in the stock variable. Feedback structures explain the relationship between two variables and delays can be informational or material in nature. The modeller organizes the three structures into causal loop diagrams that visually show the connections and relationships between each component of the model. Model development consists of a qualitative stage and a quantitative stage. The qualitative stage is the construction of causal loop diagrams in the following steps (Zheng and Beier 2018):

i. Familiarization with the system
ii. Construction of specific questions
iii. Identification of variables, stocks and flows
iv. Formulation of causal loop diagrams
v. Iterative revision of causal loop diagrams

Once the causal loop diagrams have been completed, a computer model can be developed in the quantitative stage in the following steps (Zheng and Beier 2018):

i. Conversion of causal loop diagrams to runnable models
ii. Parameter estimation
iii. Sensitivity analysis

iv. Analysis of parameter input and model structures
v. Continued model maintenance

GoldSim is a Monte Carlo simulation software that uses the system dynamics approach to visually model complex systems. The software allows the construction of large hierarchical, top-down models that are easy to understand, navigate and explain to many audiences of varying skill levels (Kossik and Miller 2004) .

5 WASTE ROCK MANAGEMENT MODEL

5.1 Conceptual Model

Figure 2 depicts a simplified conceptual model of the waste rock pile. The waste rock from excavation of the mine pit will be constructed into a pile that will undergo precipitation and evaporation.

One of the strengths of system dynamics modelling is the ability to model systems in a top down approach. The model will utilize the mine plan to simulate the flow of waste rock from the mine pit to the pile. The pile will then be created using a pseudo 3-D structure consisting of a series of 1-D columns similar to Fredlund et al. (2015). The model is separated into two sub-models, a mine sub-model and an environment sub-model. The mine sub-model creates a pseudo 3-D structure by dictating where waste material will be placed within the pile. The environment sub-model is a self-contained 1-D seepage model that is cloned to create the pseudo 3-D structure.

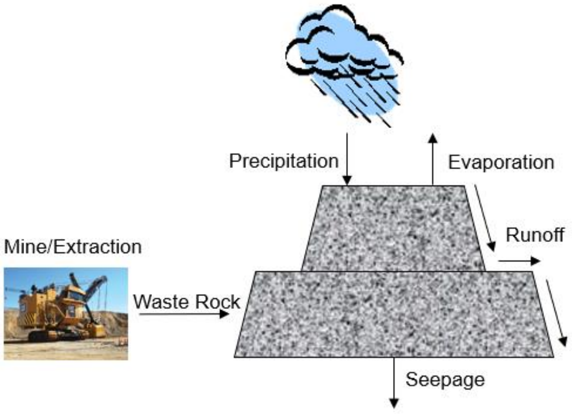

Figure 2. Conceptual Model

Using the concepts of system dynamics modelling, the causal loop diagram was developed, as seen in Figure 3. The stock variables in the model are the volume of excavated waste rock and water storage within the pile. The flow variables are the mine plan excavation schedule and precipitation, evaporation, and seepage out of the pile.

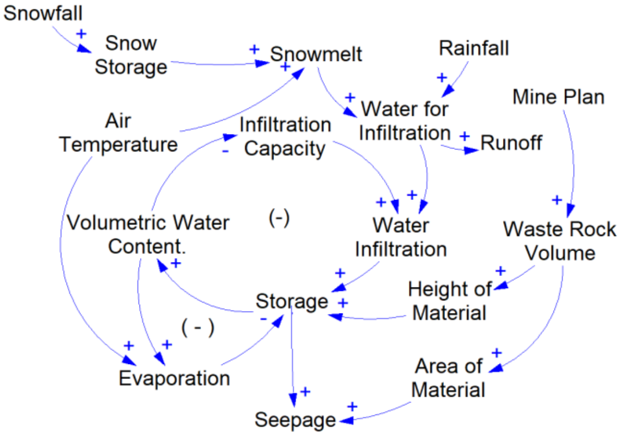

Figure 3. Casual Loop Diagram of Waste Rock Model

5.2 Mine Sub Model

The purpose of this research is not to recreate the exact behavior within a waste rock pile, which is difficult in any modelling software due to the inherent heterogeneity within the structure (Herasymuik 1996). System dynamics modelling allows the user to model large complex inter-related systems that cannot be modelled with a traditional geoenvironmental modelling software. GoldSim is a powerful tool, however, three-dimensional modelling is not possible with the standard software package. Because of this, the mining sub-model needs to be constructed using a series of array functions to simulate a pseudo 3-D structure. Essentially each lift within the waste rock pile is simulated using a grid structure that corresponds to a matrix (array function in GoldSim), as seen in Figure 4. The waste rock pile will then be constructed by the use of discrete events triggering material flow from one cell to another as each cell reaches maximum volume.

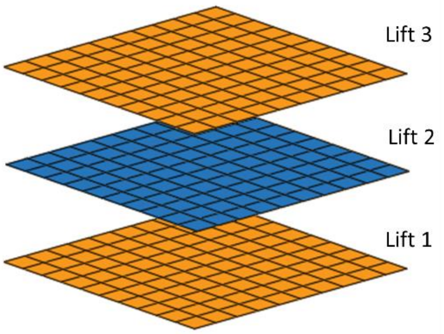

Figure 4. Pseudo 3-D Structure

The sub-model element in GoldSim allows the user to create a self-contained model that can be triggered and run when necessary. The environment sub-model will be implemented in this way to be re-run for every grid section within the waste rock pile that has material in it. This creates a more simplified visual structure of the model for ease of understanding and explanation.

In order to model the construction methods, end-dumping and paddock dumping, the structure needs to be simplified. The end-dumped scenario will have an increasing hydraulic conductivity with depth whereas the paddock dumped scenario will have a homogeneous hydraulic conductivity (Lahmira et al. 2015). The model will also include a compacted, low hydraulic conductivity surface layer of each lift due to the traffic during construction (Martin et al. 2017). This low hydraulic conductivity surface will increase the runoff during high intensity rainfall events.

The model assumes that there is no lateral movement of flow within the pile and water movement is only one dimensional. Any runoff that occurs is assumed to leave the pile. Runoff will not impact the waste rock sub-model; however, this will need to be included in the site wide water balance. The amount of runoff on the slopes of the pile will be larger than the horizontal section of the pile. To account for this, a relationship between runoff and slope will be determined using a software such as SoilVision or Seep/W (Weeks 2006).

The conceptual diagrams of the three mitigation strategies to be implemented in the model can be seen in Figure 5. Essentially the three methods are very similar in principle with the difference being the varying amounts of NAG and PAG material needed. The mine plan will provide the material flows of NAG and PAG and the model will determine which strategies are possible and effective.

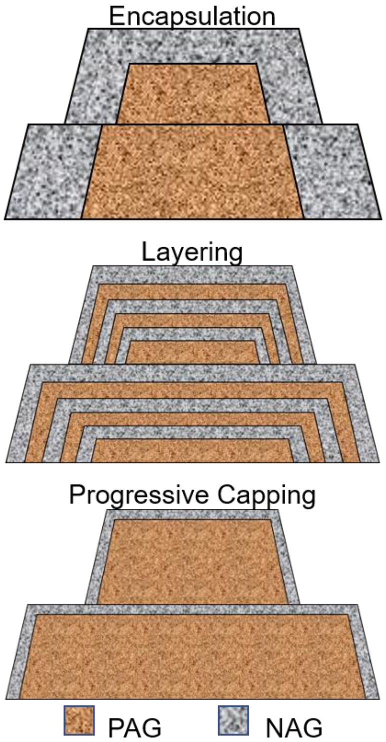

Figure 5. Conceptual Model of ARD Mitigation Strategies

5.3 Environment Sub Model

The environment sub-model is a continuation of the model developed by Zheng (2019) for the unsaturated flow within a cover above consolidating tailings.

5.3.1 Snowmelt

Zheng (2019) did not originally include snowmelt, therefore it was added to better model the environmental conditions at Canadian mine sites. The model accounts for the delayed infiltration that occurs from snow accumulation during winter and snowmelt during spring. Within the model, snowfall occurs when precipitation occurs below a critical temperature (+1°C) (Martinec et al. 1983).

The degree-day method for snowmelt was chosen for its simplicity as the only exogeneous variable is the mean daily air temperature. The degree-day method is outlined in the system dynamics model for predicting floods from snowmelt by Li and Simonovic (2002). The change in snowpack with time is given in the following equation:

$$\frac{dS}{dt} = P_s(SWE) - \alpha T \qquad [1]$$

where S (cm) represents the water in snow storage, P_s (cm day^{-1}) is precipitation as snowfall identified by a critical temperature (T_{crit}), SWE (cm snow/cm precipitation) is snow-water equivalent coefficient, α (cm $°C^{-1}$ day^{-1}) is the degree-day factor for snowmelt, and T (°C) is daily mean temperature (Li and Simonovic 2002).

In order to determine the snow water equivalent (SWE) and degree-day factor (DDF), historical measured snowpack depth data is required to use the optimization tool in GoldSim. The optimization is run by changing the parameters to maximize the coefficient of determination (R^2) between the modelled and measured snowpack depth. Due to the simplicity of the model, these parameters must be assumed constant throughout the year in order to maintain mass conservation. The upper and lower bounds of the SWE and DDF were based on values obtained from literature. The density of settled snow is approximately 200-300 kg/m^3 (Paterson 2016) which corresponds to a SWE of 0.3-0.5. The degree-day factor is a scaling factor for how many centimetres of snowmelt occur per incremental degree above a threshold temperature per day. Based on literature the degree-day factor ranges from 0.2 for light, fresh snow and 0.8 for dense, wet snow (Anderson 1976, Martinec et al. 1983, Li and Simonovic 2002, Graveline and Germain 2016). The degree-day method does not account for melt that occurs during the warmest hours of the day. To align the spring melt to the measured snowpack melt, the threshold temperature where melt begins for March to May was included as an empirical variable in the optimization.

5.3.2 Evaporation

The evaporation within the model created by Zheng (2019) was derived from Wilson et al. (1997), where the actual evaporation rate at the soil surface is dependent on the relative humidity of the air and soil voids. The relative humidity in the soil voids is determined based on the thermodynamic relationship between relative humidity of soil voids and total soil suction head given by Edlefsen and Anderson (1943), as follows:

$$\mathrm{h_r} = \exp\left(\frac{\Psi \mathrm{g} \mathrm{W_v}}{\mathrm{R} \mathrm{T_a}}\right) \qquad [2]$$

where, h_r is the relative humidity in the unsaturated soil voids, ψ (m) is the equivalent matric suction taken as a negative value, T_a (°C) is the mean air temperature, W_v (0.018 kg mol^{-1}) is the molecular weight of water, R (8.314 J mol^{-1} K^{-1}) is the universal gas constant, and g (9.81 m s^{-2}) is the gravitational acceleration. Wilson et al. (1997) formulated an expression for the ratio of actual evaporation to potential evaporation assuming the same temperature applies to the air, water and soil:

$$\frac{\mathrm{AE}}{\mathrm{PE}} = \frac{\mathrm{h_r} - \mathrm{h_a}}{1 - \mathrm{h_a}} \qquad [3]$$

where h_a is the relative humidity of the air. Actual evaporation (AE) rate is given by multiplying the potential evaporation (PE) rate by the AE/PE ratio. The potential evaporation (PE) rate in the Zheng model requires a user inputted monthly PE value. In early stages of a project, this information may not be available and therefore the model was expanded to allow for PE calculation using the Thornthwaite (1948) method, which only requires the mean daily temperature and can be corrected for latitude written as:

$$PE = K * 16\left(\frac{10T_a}{I}\right)^{\alpha} \qquad [4]$$

$$I = \sum \left(\frac{T_a}{5}\right)^{1.514} \qquad [5]$$

$$\alpha = 6.75x10^{-7}I^3 - 7.71x10^{-5}I^2 + 1.79x10^{-2}I + 0.49 \qquad [6]$$

where PE (mm/month) is the monthly potential evaporation, K is the latitude correction factor for total sunlight hours in a month, T_a (°C) is the mean monthly air temperature, I is the sum of 12 monthly heat indices (i), and α is a constant. In order to determine the mean monthly air temperature in GoldSim, the publicly available sub-model "Monthly and Annual Totals" was modified and used. The Thornthwaite (1948) method uses a sum of the 12 monthly heat indices to determine monthly evaporation in a given year. Because future data is required during the calculation, the PE had to be inserted as its own GoldSim sub-model container, which allows the contents of the container to be run before the rest of the model. The PE sub-model outputs the monthly evaporation in mm/day to be then used with equation 3 to determine the actual evaporation rate.

5.3.3 Hydrogeology

The hydrogeology model created by Zheng (2019) was a replication in GoldSim of a previous study on system dynamics modelling of infiltration and drainage in layered coarse soil (Huang et al. 2011). The conceptual set-up of the model seen in Figure 6 shows the stock variable of water storage and the various flow variables between soil layers and the boundary inflows and outflows. Figure 7 shows the model setup between each soil layer using the finite difference method.

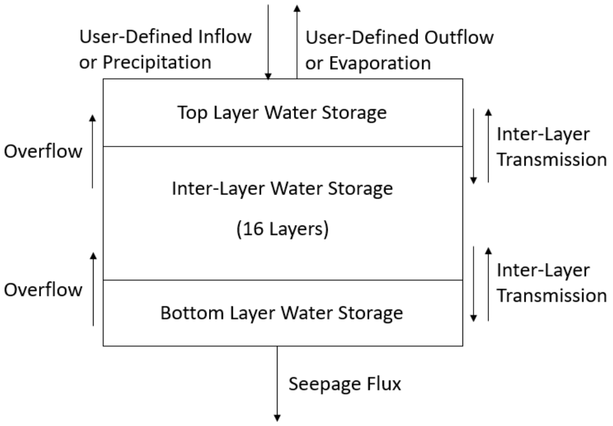

Figure 6. Conceptual set-up of the hydrogeology model (Modified from Zheng 2019)

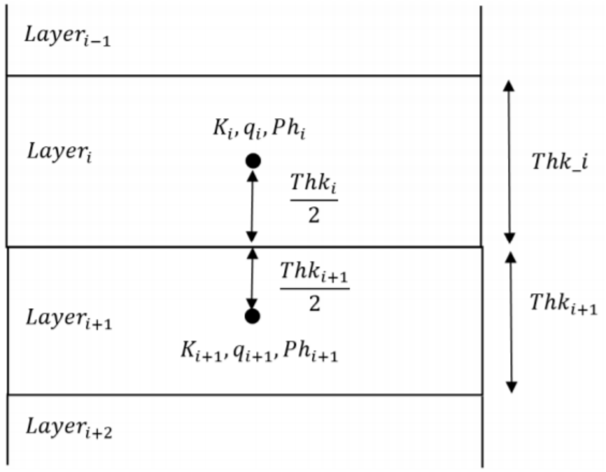

Figure 7. Geometric setup of the hydrogeology model (Zheng 2019)

Using the setup in Figure 7, the transmission rate (f_i) between two layers can be calculated using a modified version of the Darcy's equation, where the inter-layer hydraulic conductivity is assumed to be the average of the two layers, as follows (Huang et al. 2011):

$$f_i = \frac{K_{i-1}+K_i}{2}\left(\frac{Ph_i - Ph_{i-1}}{\frac{1}{2}(Thk_i + Thk_{i-1})} + 1\right) \quad [7]$$

where, K (cm/min) is the unsaturated hydraulic conductivity of the soil layer, Ph (cm) is the pressure head within the soil layer, as a positive number for model simplicity, Thk (cm) is the thickness of the soil layer and subscript i varies from 2 to n and n is the total number of soil layers (Romano et al. 1998). The unsaturated hydraulic conductivity can be calculated using the van Genuchten parameters that are estimated using the soil water characteristic curve (Mualem 1976, Van Genuchten 1980). This model ignored the effect of hysteresis on the SWCC and only the drying curve parameters are used. The van Genuchten equations were re-arranged in GoldSim by Zheng (2019) into the following equations:

$$K = K_{sat} S_e^{\frac{1}{2}}\left[1 - \left(1 - S_e^{\frac{1}{m}}\right)^m\right]^2 \quad [8]$$

$$Ph = \frac{\left[\left(\frac{1}{S_e}\right)^{\frac{1}{m}} - 1\right]^{\frac{1}{n}}}{a} \quad [9]$$

$$S_e = \frac{q - Q_r}{Q_s - Q_r} \quad [10]$$

$$m = 1 - \frac{1}{n} \quad [11]$$

$$q = \frac{S_i}{Thk_i} \quad [12]$$

where, K_{sat} (cm/min) is the saturated hydraulic conductivity, S_e is the normalized effective volumetric water content, a (1/cm), n and m are van Genuchten model fitting parameters, q is the volumetric water content of the layer, Q_r and Q_s are the residual and saturated volumetric water contents and S_i (mm) is the amount of water stored in the soil layer. Zheng (2019) expanded the model to include overflow if the soil layer becomes fully saturated, allowing for the following equation for change in water storage:

$$\frac{dS_i}{dt} = f_i + \mathrm{Overflow}_{i+1} - f_{i-1} \quad [13]$$

where Overflow (cm/min) is the overflow from layer i+1 to layer i and the subscript i varies from 2 to n-1 as there is no overflow into the bottom layer. The total water storage (S_T) within all the soil layers is determined as the sum of the water storage in each layer.

$$S_T = \sum S_i \quad [14]$$

6 FUTURE WORK

The environment sub-model was previously validated by Zheng (2019). The next steps in this research is to implement the mine sub-model within GoldSim, which corresponds to step i of the qualitative stage of system dynamics model development. Once the model is complete, the mine sub-model and changes to the environment sub-model will be validated using data from an Eastern Canada gold mine. System dynamics modelling requires that the model be constantly improved as new information and knowledge becomes available. This is the first iteration of a waste rock sub-model to be implemented into the TMSim model. Many assumptions and simplifications were made to aid in model development that could be improved in the future. Currently the snowmelt is determined using only the mean air temperature, if more information is known for a site, the model could be updated to use the energy balance method that gives more accurate snowmelt (Anderson 1976). The potential evaporation is also determined using only the mean air temperature and could be improved using a method that requires wind speed, solar radiation, and relative humidity for increased accuracy. The hydrogeology of the model could be improved by adding a lateral flow component. A lateral flow component would be useful for any mitigation strategy that relies on increased runoff and lateral flow within NAG layers to minimize PAG moisture content (Aubertin et al. 2009; Broda et al. 2014; Dawood and Aubertin 2014). For the mining sub-model, the mitigation strategies of blending or co-disposal could be included in a future iteration (INAP 2009).

7 CONCLUSION

Development of a typical mine waste management plan would require the use of multiple models and tools to individually model each process with limited coupling or interactions between the models. With the use of system dynamics modelling software, the many systems within a mine can be modelled concurrently to simulate performance of the entire system. Various operational strategies can then test the performance of the mine waste management plan over the life of the mine. The updated TMSim model will include a waste rock deposition sub-model and an environment sub-model that includes precipitation, snowmelt, evaporation, runoff and unsaturated seepage within a 1-D column. The environment sub-model has been implemented and validated; the mine sub-model is currently under development. The model will then be validated using operational data from an Eastern Canada gold mine. The completed model will apply a system dynamics approach to allow the analysis of the efficacy of the various ARD prevention strategies that can be implemented for waste rock piles.

8 ACKNOWLEDGMENTS

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