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Tailings Cover Hydrology for the Central Manitoba Mine Site

Alexandra Nan, Golder Associates Ltd., Canada
Pascal Saunier, Draintube Afitex-Texel, Canada

Abstract

This paper examines the hydrology of the proposed cover system, under varying drainage-layer conditions, for the Central Manitoba Mine (CMM) site-rehabilitation project located in southeastern Manitoba. The proposed 1 m thick engineered soil cover included a 0.2 m thick, highly permeable basal granular drainage layer, which was ultimately replaced with a man-made synthetic drain tubes planar drainage geocomposite. Four different levels of potential clogging of the man-made drainage layer were analyzed, equivalent to 99, 90, 50, and 0 percent of the original material. The purpose of the analyses was to observe the flow dynamics and change trends in the hydrology of the engineered soil-cover system located above the drainage layer, over a period of ten years, and from there, estimate future trends in the cover-system hydrology and its impacts. The SVFlux™ finite-element modeling software was the main numerical tool used to model the hydrologic regime. The results of the analyses are presented and show increasing trends in the net percolation, flux, and saturation in the topsoil, and decreasing trends in the sandy clay and drainage layer saturation as the drainage layer became more clogged. The results also show that the soil cover would perform with minimal associated risks up to an equivalent 90 percent clogging of the drainage layer, which is due in part to the high capacity of the DRAINTUBE™ drainage system and conservative design levels in the soil cover.

Introduction

The site that is the subject of this paper is the Central Manitoba Mine (CMM) site, located in Nopiming Provincial Park, 220 km northeast of Winnipeg, Manitoba, Canada. The mine was in production from 1927 to 1937, generating approximately 5,000 kg of gold (using cyanide) from 480,000 tons of ore (Richardson and Ostry, 1996).

During the 1990s, an Orphaned and Abandoned Mine Sites Program (OAMS) was developed by the Manitoba Mines Branch (MMB) to address the issue of abandoned mine sites. MMB contracted AMEC to evaluate and classify approximately 149 out of 250 mine sites as abandoned. Due to a high number of abandoned mine sites, AMEC further developed a hazard-based framework model which ranked and prioritized the sites based on criteria established for public safety and human health. Based on this model, 31 out of 149 abandoned mines sites were classified as high hazard (Priscu et al, 2010). In 2007 AMEC was appointed to conduct a hazard assessment on the CMM site, and determined it to be one of the thirty-one high hazard sites (Priscu, 2011). These findings prioritized the site for rehabilitation under OAMS and in 2008, AMEC commenced a site investigation program to propose rehabilitation methods for the abandoned mine site.

The results indicated that the tailings and waste rock material were acid generating and metal leaching into the surrounding environment when unoxidized sulfide-bearing tailings were exposed to oxygen through the erosion processes. These were expected to potentially impact the environment should the erosion process continue. Human health hazards were related only to direct contact and/or ingestion of soil or tailings. Consequently a rehabilitation plan for covering the tailings was proposed as Phase 2 of the project.

The objectives for Phase 2 at the CMM site included the removal of public-safety concerns, provision of a good medium for revegetation, and implementation of erosion-control measures to accelerate water collection away from the site and limit water infiltration into the tailings, all based on the construction of an engineered soil cover on top of the tailings. Also, based on the fact that permeable natural materials were not found on site, the design had to consider alternate solutions in order to keep the project cost efficient and environmentally viable.

This paper examines a specific hydrologic behavior of the selected soil cover that was placed on top of the tailings in 2013, and which includes a Drain Tubes Planar Drainage Geocomposite (PDG) in its structure to replace natural drainage granular material. Analysis of the hydrologic behavior under varying flow and slope parameters presented in the paper is an extension to the previous analyses completed by AMEC and will focus on the efficiency of the cover system in the long term.

Project Scope

The main scope of work was to analyze the long-term effectiveness of a soil cover composed of topsoil, overlying sandy clay, and a drainage layer in which crushed rock was replaced with a Drain Tubes PDG called DRAINTUBE™ (AMEC, 2011). A sensitivity analysis for the hydrology of the cover was undertaken to examine the behavior of the soil cover system with changing drainage layer effectiveness, including constraints and complexities associated with the fill (natural) materials, and also—in particular—the geosynthetic (man-made) materials that are part of the cover.

This paper does not reevaluate or redesign the soil cover system, but rather analyzes how its long-term performance could be impacted by changes in the expected hydrological conditions and/or man-made material properties or performance.

Methodology

The hydrology of a proposed cover system, under varying drainage layer conditions, for a mine site rehabilitation project located in southeastern Manitoba was analyzed with Lymphéa™ software and SoilVision, SVFlux software. The proposed 1 m thick engineered soil cover included a 0.2 m thick, highly permeable basal granular drainage layer, which was replaced with a man-made tubular PDG (as shown in Figure 1).

Figure 1: DRAINTUBE™ (Afitex Texel, 2013)

Designing with Drain Tubes PDG

The water at the surface of the cut slope is collected by the nonwoven drainage layer and transported to the mini-pipes after having passed through the filter. The geocomposite dimensions must take into consideration the head loss when: i) passing through the filter; ii) flowing through the drainage layer and the mini-pipes; and iii) entering the mini-pipes.

The head losses when passing through the filter are not taken into consideration when calculating the drain dimensions, as is generally the case for all types of drainage. The nonwoven drainage layer is considered to be saturated and the most important characteristic parameter is the transmissivity. For simplicity, the flow in this layer is assumed to be perpendicular to the direction of the mini-pipes. This assumption is safe because the gradient created by the slope is not taken into account when determining the head losses into the geotextile drainage layer. The flow Q1 transported per unit of width is given by equation (1).

$$Q_1 = V_1 T_1 = \theta i_1 \quad (1)$$

Where:

V1	=	flow transported by the layer
Tg	=	thickness of the layer
θ	=	transmissivity of the layer
I	=	hydraulic gradient.

Laboratory tests have been carried out to establish the head loss when entering the mini-pipes. These tests illustrated that the head loss is negligible because it corresponds to several millimeters of flow—at most—in the nonwoven layer. For this application, mini-pipes are in the direction of the slope. They are considered to be unsaturated. The slope is sufficient to facilitate a free surface flow inside the mini-pipes. The laboratory results indicate that the flow rate in the mini-pipes may be characterized by the following form relationship.

$$Q_2 = q_d i = \alpha i^{(n+1)} \quad (2)$$

Where:

Qd	=	discharge capacity of the mini-pipe
i	=	hydraulic gradient in the mini-pipe
α, n	=	experimental constants.

Calculation of the maximum length of drainage for the mini-pipe to stay unsaturated

A uniform flow of intensity V is assumed to enter the drainage layer perpendicularly over a width 2B, corresponding to the distance between mini-pipes as illustrated in Figure 2.

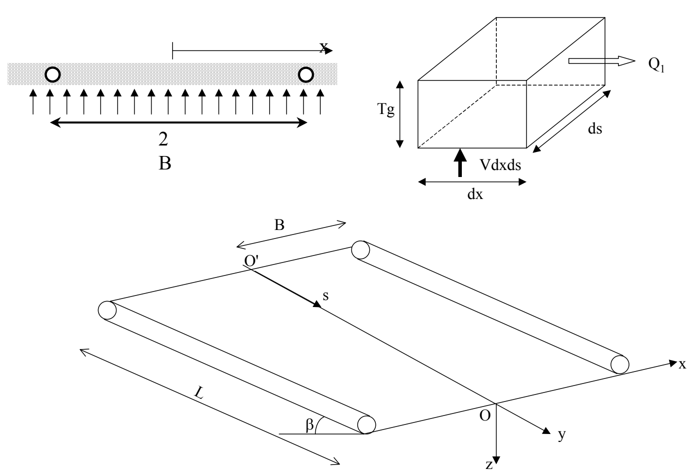


Figure 2: Flow Model

The flow, dQ1, which enters perpendicularly via a surface element (dx.ds) of the nonwoven layer is:

$$dQ_1 = Vdxds \tag{3}$$

Where the volume through the layer element (ds Tg) is:

$$Q_1(x,s)ds = V_1 T_g ds = -\theta \frac{dh_1}{dx} ds \tag{4}$$

Where:

Tg	=	thickness of the layer
θ	=	transmissivity of the layer
V	=	flow entering the layer
V1	=	flow transported by the layer
h1	=	hydraulic head in the layer.

Consequently,

$$\frac{d^2h_1}{d^2x} = -\frac{V}{\theta} \tag{5}$$

Furthermore, the volume collected in an element of length «ds» of mini-pipe is given by:

$$dQ_s(s) = 2VBds \tag{6}$$

With:

$$Q_s(s) = q_d i\lambda(s) = \alpha i^{(n+1)}\lambda(s) \tag{7}$$

With:

$$0 < \lambda(s) < 1 \; and \; \lambda(0) = 0; \; \lambda(L_0) = 1$$

Where:

Q2	=	flow transported by the mini-drain
qd	=	discharge capacity of the mini-drains
i	=	hydraulic gradient in the mini-drain
α, n	=	experimental constants
L0	=	maximum length for the pipe staying unsaturated

So,

$$2VB = \alpha i^{(n+1)} \frac{d\lambda(s)}{ds} \tag{8}$$

$$\lambda(s) = \frac{2VB}{q_d i} s + c_1 \tag{9}$$

With the boundary conditions, we obtain:

$$L_0 = \frac{\alpha i^{(n+1)}}{2VB} \tag{10}$$

And the maximum hydraulic head into the drainage layer (between the mini-pipes) is:

$$(h_1)_{max} = \frac{VB^2}{2\theta} \tag{11}$$

Specific design for CMM Phase 2

In the CMM Phase 2, the following assumptions were taken into account for calculation of the drainage of the tailings including the maximum length of drainage (100 m), the slope (1 percent), the maximum load on the geocomposite (50 kPa), the spacing of 25 mm diameter mini-pipes into the product (1 m) and the transmissivity of the geotextile drainage layer under load ($1.00.10^{-5}$ m^2/s). From Darcy's law (12), the maximum flow of water to be drained per unit of surface under the conditions of the project is:

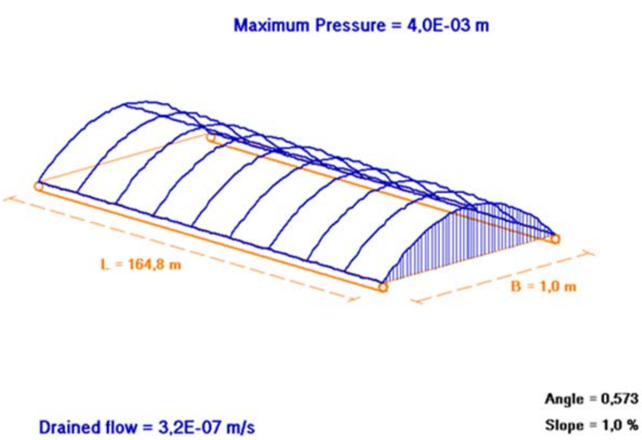
$$F = \frac{Kei}{L} \tag{12}$$

Where

K	=	hydraulic conductivity of the stone (m/s)
e	=	thickness of the stone layer
(m) / i	=	hydraulic gradient
L	=	length of drainage (m)

In this project, with a given K of 0,1 cm/s, the flow to the drain was F = $2.00.10^{-8}$ m/s.

Lymphéa software allows the evaluation of the DRAINTUBE™ drainage geocomposite performance, and particularly in accordance to the design shown below (Figure 3):



Overall Infiltration rate		Safety factor	Value used in design
Value	Unit		
1000	mm / year	SF > 10,00	10000
2,00E-08	m3/s/m2		3,17E-07

Figure 3: Lymphéa Design Sheet and Table

The maximum flow to be drained used in the design is $3.17.10^{-7}$ m/s for a maximum slope of 1 percent. DRAINTUBE FT1 D25 will be able to drain that flow along a maximum length of 164 m with no saturation in the pipes and a maximum hydraulic pressure between the pipes of 4 mm, offering an overall safety factor higher than ten (almost sixteen in this specific case).

Use of SoilVision, SVFlux software

The modeling software, SVFlux Version 2.1.19 developed by Soil Vision Systems Ltd., was used to simulate flow through the composite soil cover at the CMM site by estimating percolation rates, assessing pore water pressures, and evaluating saturation levels in a one-dimensional system under steady-state conditions.

The hydrology of the soil cover was simulated with four different flow systems in the HDG through varying the hydraulic conductivity in the HDG to simulate a progressive clogging of geotextile/pipes. The four cases below were drawn and modeled in SVFlux (Figure 4).

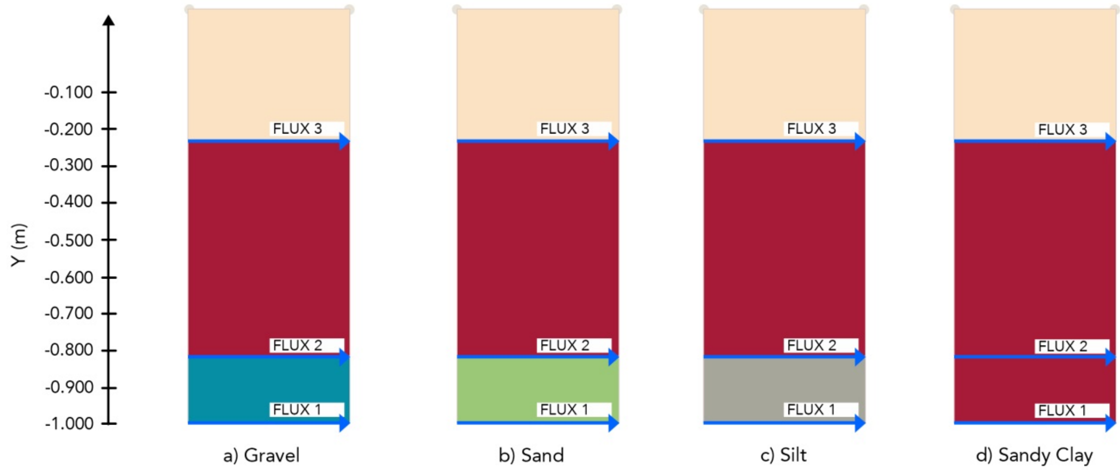


Figure 4: SVFlux Models with Varying Bottom-Layer Hydraulic Conductivity

Case a) Assuming drainage layer is a clean granular drainage layer: this simulation would be equivalent to a 0 percent clogging of the pipes or the geotextile.

Case b) Fine sand drainage layer – equivalent to 50 percent of the geotextile/pipes clogged.

Case c) Silt drainage layer – equivalent to 90 percent of the geotextile/pipes clogged.

Case d) Sandy clay drainage layer – equivalent to 100 percent of the geotextile/pipes clogged.

Three different layers of varying material properties were used in the cover modeling: topsoil, sandy clay, and clean sand. To estimate the unsaturated soil property functions of each layer, borrow materials were sampled and used as a basis for fitting soil water characteristic curves (SWCC). The laboratory-based curves were compared to similar material values to ensure a representative fit.

However, several limitations can be present in the lab tests. One of these is a long duration period (of up to two months) for the development of accurate moisture contents if the soil has significant plasticity. For this reason, several empirical formulas have been developed to accurately predict SWCC lab data. This paper uses the Fredlund and Xing (1994) empirical method to predict the SWCC and unsaturated hydraulic conductivity function in terms of soil water retention parameters. The Fredlund and

Xing fit provides a realistic representation of the curve at high suctions (SVOffice, 2008). The fit is based on the following formulas:

$$\theta(h) = \theta_s \left[1 - \frac{\ln\left(1 + \frac{h}{h_r}\right)}{\ln\left(1 + \frac{10^6}{h_r}\right)}\right]\left[\frac{1}{\left[\ln\left[\exp(1) + \left(\frac{h}{a_f}\right)^{n_f}\right]\right]^{m_f}}\right] for\ h < 0$$

$\theta(h) = \theta_s\ for\ h \geq 0$

$$k(h) = (K_s - K_{\min})[\left[1 - \frac{\ln\left(1 + \frac{h}{h_r}\right)}{\ln\left(1 + \frac{10^6}{h_r}\right)}\right][\frac{1}{[\ln[\exp(1) + [\frac{h}{a_f}]^{n_f}]]^{m_f}}]]^p + K_{min}$$

Where

θ_r = residual volumetric moisture content

θ_s = saturated volumetric moisture content

h = hyraulic head

h_r = hydraulic head at which residual water content occurs

a_f, n_f, m_f = SWCC fitting parameters

K_s = saturated hydraulic conductivity

K_{min} = calculated minimum hydraulic conductivity

The above equations describe the existence of various parameters in the modeling. The saturated volumetric content can be defined as the greatest amount of water storage while the residual volumetric constant is the maximum soil suction without seepage occurring. Three different fitting parameters (a_f, n_f, and m_f) were correlated with the SWCC for each material layer.

Sensitivity Analysis

The method used in this sensitivity analysis was the finite element method (FEM). The hydrology of the soil cover was simulated with the different flow systems in the HDG, as shown in Figure 2. The sensitivity analysis was based on varying the hydraulic conductivity in the HDG layer to simulate a progressive clogging geotextile. The cases used in the sensitivity analysis are shown below with topsoil, sandy clay, and a changing drainage layer. The hydrology of each case is presented in the results section.

Two boundary conditions or driving forces behind the finite element analysis were used in the model. The top boundary condition consisted of an atmospheric boundary from climatic forces to simulate meteoric conditions and the bottom boundary consisted of free drainage so as to provide a conservative overestimation of percolation (Bohnhoff et al., 2009).

To analyze the long-term flow in the soil cover, the modeling was based on a ten-year performance simulation. Hydrologic plots were formulated for each given case including a summary of the water balance, net percolation into the soil cover, saturation in each layer, and flux along the soil boundaries.

The water balance depicts the slopes of various hydrological parameters in cubic meters per year. These parameters are plotted as cumulative slopes and include precipitation, runoff, potential evaporation and transpiration, actual evaporation, transpiration sink, flux, boundary flux, net percolation, water volume change, water balance without boundary flux, water balance without flux, and maximum storage.

As stated above, the net percolation, saturation, and flux are the three parameters examined. The CMM site has a high water table, located approximately 0.5 to 1.5 m below the top of the tailings. Saturation and flux are both plotted for each layer. The change in saturation levels is displayed in the figures below where the gravel layer is depicted by different materials as stated by the various cases. The flux simulated in this model is equivalent to the sum of precipitation and actual evaporation minus the runoff. Flux 2 is the main flux analyzed in this paper.

Results

The results of the sensitivity analysis are depicted below.

The gravel case is the base case (Case A) in this paper and is therefore the reference for analysis for all three of the other cases. The bottom gravel layer (Figure 4) represents an equivalent HDG layer with no clogging in the pipes. Figure 5 shows the saturation in each layer over time. The y axis represents the degree of saturation while the x axis shows the time in days for a period of ten years. Saturation in the topsoil appears to fluctuate with climatic conditions causing saturation levels to increase with seasonal precipitation. The saturation in the sandy clay layer at time zero is approximately 58 percent and constantly increases to 84 percent after ten years. In the drainage layer, the saturation is constant at less than 10 percent, which is consistent with the expected performance of the HDG.

The cumulative flux along the sandy clay – gravel boundary increases from 0 to approximately 0.014 m^3 in ten years with the greatest increase in the first half of the first year (Figure 6). This shows that the sum of the precipitation and actual evaporation was much greater than the runoff in the first year. This high flux indicates a large positive flow into the drainage layer during the first half of the year. Subsequently, the trend increases at a lower rate.

The net percolation is presented in Figure 7 and shows an increase from $1.5.10^{-6}$ m^3/day to $4.5.10^{-6}$ m^3/day in the first year, decreases to approximately $3.0.10^{-6}$ m^3/day after 2,000 days and increases to $5.0.10^{-7}$ m^3/day after ten years.

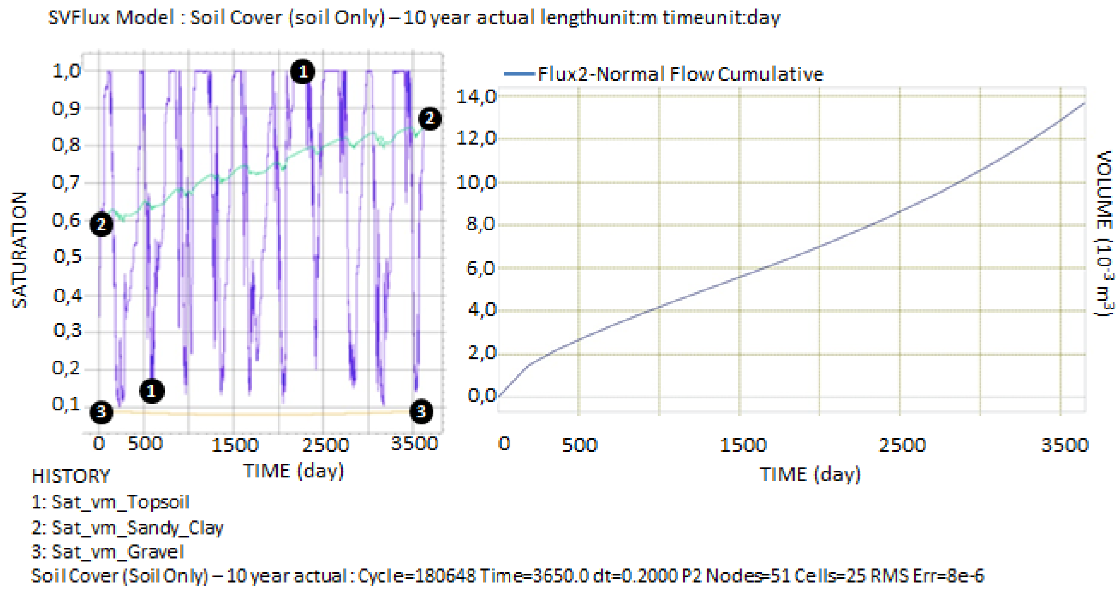


Figure 5: Saturation vs Time in Case Cover layers for Gravel

Figure 6: Flux vs Time for Gravel Case

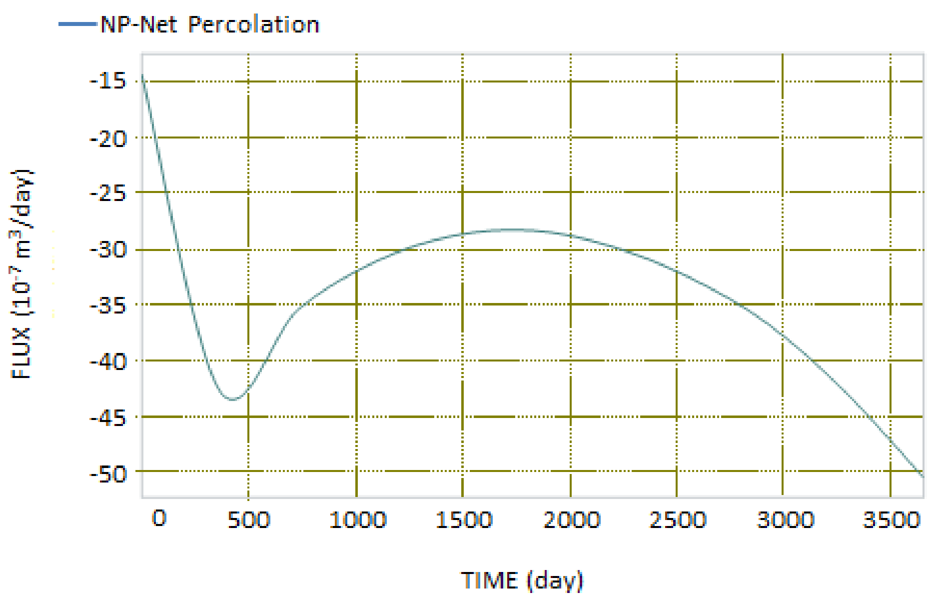


Figure 7: Net Percolation vs Time for Gravel Case

The sandy clay case is the least desirable case and highly unlikely; however, it has been plotted for the purpose of simulating a clogged drainage layer. The model geometry (Figure 4) displays a bottom sandy clay layer representing an equivalent HDG layer with 99 percent of the pipes clogged.

Figure 8 shows the saturation in each layer in time. The y axis represents the degree of saturation while the x axis shows the time in days for a period of ten years. Saturation in the topsoil seems to fluctuate with climatic conditions, starting at 34 percent at time zero to complete saturation after one hundred days and down to 10 percent at 250 days. The saturation in the sandy clay layer at time zero is approximately 60 percent and increases to 90 percent after ten years. In the drainage layer, the saturation starts at 50 percent and increases linearly to 60 percent after ten years.

The cumulative flux along the sandy clay – sandy clay boundary increases exponentially from 0 to approximately 0.0015 m^3 after the first year as shown in Figure 9, slope A. The slope decreases between 500 and 2,000 days and starts to increase again thereafter. Slope A is the steepest out of the three as a result of the initial climatic conditions. This means that the sum of the precipitation and actual evaporation is much greater than the runoff in the first year. A high flux indicates a large positive flow into the drainage layer. The flatness in slope B shows that the flux is much lower from the first half of the second year to the end of the sixth. The graph shows an increase in slope C from 0.005 m^3/d to 0.0078 m^3/d between year six and ten respectively.

The net percolation is presented in Figure 10 and shows an increase from 0 to 3.0.10^{-7} m^3/day in the first year, 4.5.10^{-7} m^3/day after 2,500 days, and 6.0.10^{-7} m^3/day after ten years.

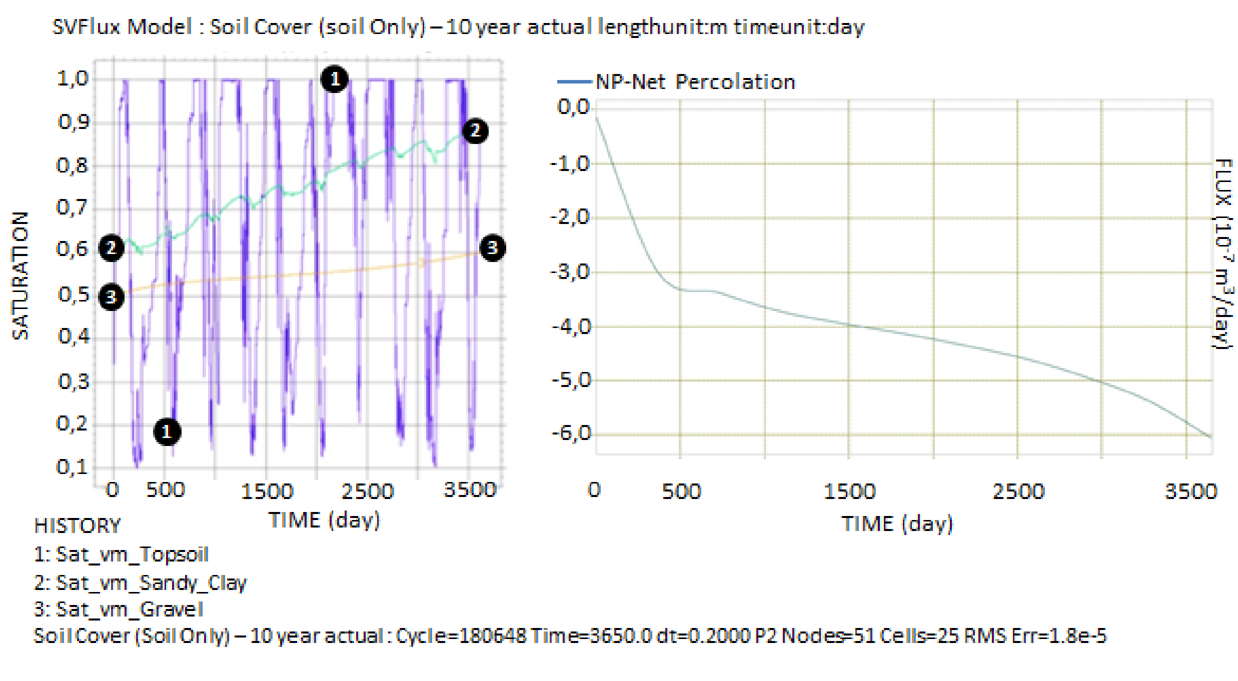


Figure 8: Saturation vs Time **Figure 9: Flux vs Time for Sandy Clay**
Case in Cover layers for Sandy Clay Case

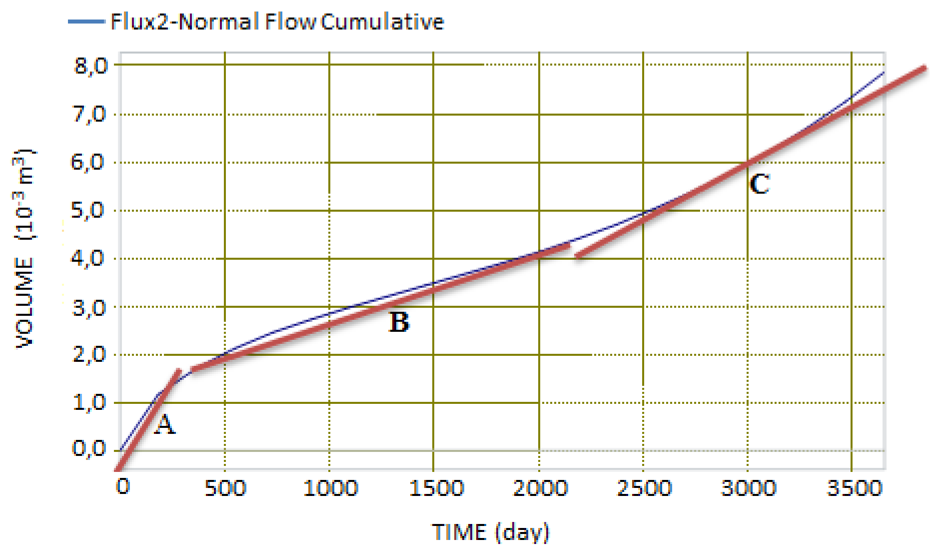


Figure 10: Net Percolation vs. Time for Sandy Clay Case

Plots were produced for the bottom layer as sand, silt, and sandy clay. Table 1 below shows the trend for each of the layers in the four cases. Although case A and D have a similar number of full saturation in the topsoil, it must be noted that the duration of the saturation in Case D significantly increases over the ten years, while case A remains irregular.

Case	Layer Properties	Top Soil	Sandy Clay	Drainage Layer
A	Gravel	Increases (fully saturated 12 times)	Increases	Constant
B	Sand	Increases (fully saturated 20 times)	Decreases	Decreases
C	Silt	Increases (fully saturated 25 times)	Decreases	Decreases
D	Sandy Clay	Increases (fully saturated 12 times)	Increases	Increases

Table 1: Degree of Saturation over Ten Years

Conclusion

The modeling performed for each given case with SVFlux showed increasing flow trends over time as the hydraulic conductivity was reduced. The software results illustrated that the least desirable case and most extreme case showed that if the drainage system were to fail by becoming completely clogged in the long term; more than 50 percent of the drainage layer would be saturated and an increasing trend over twenty years could increase water percolation rates into the tailings. However, the system has some level of flexibility in terms of drainage-layer clogging. Even with a 50 percent clogging of the drainage layer, the cover system would still be performing as designed, with a minor increase in saturation levels and a limited increase in percolation rates. From this perspective the system as designed, with a design safety factor higher than ten on the PDG, has a built-in safety factor that allows good long-term performance and should perform according to original requirements such as limiting erosion, limiting direct human exposure to tailings, shedding water away, and supporting the vegetative cover.

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