GROUNDWATER FLOW MODELING OF AN ABANDONED MINE LANDS SITE SCHEDULED FOR RECLAMATION[1]

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Abstract. Groundwater flow models represent one tool that can be used in evaluating the hydrologic conditions of abandoned mine land (AML) sites, and they can be used to preview the probable hydrologic outcomes of reclamation designs. A three-dimensional, variably saturated groundwater flow model was used to characterize the hydrology of a 47 ha AML site in southwestern Indiana. Of particular concern was the flow field extending through a tailings deposit to a large seep contributing acid mine drainage to the local stream. The model was then used to evaluate a potential reclamation plan that would redirect the acidic flow into an onsite lowland area for passive treatment.

A transient model was calibrated by adjusting the model parameters until a minimum residual was achieved between simulated and observed water table elevations in 6 observation wells over a time period of 50 days. The best-fit model had a root mean squared error (RMSE) of 0.195 m. Modeling results show that the seep is fed from a ground watershed of approximately 7.7 ha which spans across the tailings into the coarse-grained refuse bordering the deposit. Further results show that minor alterations of surface topography within the tailings deposit could potentially redirect and contain the acidic groundwater on site for passive treatment prior to discharging into the local drainage network. This study demonstrates the utility of using groundwater flow models to preview hydrologic conditions at AML sites and to anticipate the results of reclamation alternatives.

Additional Key Words: Mine hydrology, acid mine drainage.

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Introduction

Reclamation projects that incorporate hydrologic manipulation are currently being explored by abandoned mine land (AML) programs to address the issue of acid mine drainage (AMD) (Brown et al., 2002; Ziemkiewicz et al., 2003). The goal is to alter the internal flow of water at the site in order to minimize chemical contamination of surrounding areas. Unfortunately, the hydrology of reclaimed surfaces is complex and some consequences of reclamation are not always expected. Groundwater flow models represent one often underutilized tool that can be used as part of a site assessment and to evaluate possible outcomes to land alterations employed during reclamation.

There are many diverse mathematical techniques for simulating the hydrologic response of groundwater basins to various natural and human induced stresses. The most common techniques employ simplifying assumptions such as two-dimensional or quasi three-dimensional flow in only fully saturated porous media. Such models are unable to effectively incorporate topography or surface water flux (rainfall infiltration or evapotranspiration) into the analysis, but a fully three-dimensional, variably saturated groundwater flow model such as that described by Freeze (1971) represents a flexible alternative for hydrologic characterization of AML sites.

The purpose of this study is to evaluate the current hydrology of an AML site located in what is now called the Minnehaha Fish and Wildlife Area, Sullivan County, Indiana and to generate a probable outcome of land-altering reclamation. A numerical groundwater model was calibrated to the study site under current conditions using known water table elevations collected from monitoring wells. The calibrated model was then used to preview the current flow field of groundwater leading to AMD and how the flow field would change under a reclamation design that involved land surface alteration.

Study Area

The study site (called Minnehaha in this paper) is located approximately 6 km northwest of Dugger, Indiana (Fig. 1). The elevation of the site is approximately 134 m above mean sea level and it encompasses an area of about 47 ha. The dominant hydrological feature is Mud Creek, which flows northwest along the eastern and northern boundary of the Minnehaha abandoned refuse deposit. Most of the refuse is barren of vegetation, but a small portion of the site contains grasses and sparse tree cover (Fig. 2). A major zone of seepage from the saturated zone of the refuse occurs along a levee that is adjacent to Mud Creek.

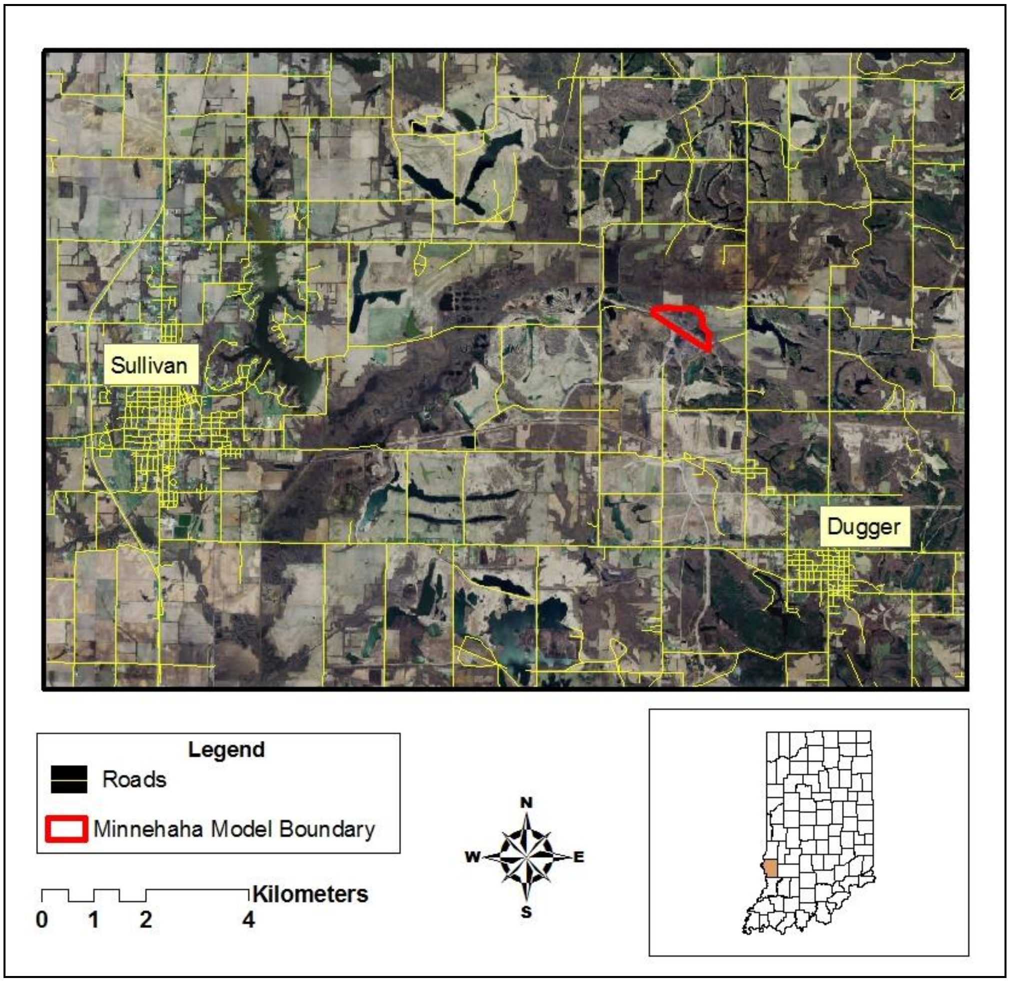

Figure 1. Aerial view of the Minnehaha study area boundary in relation to the towns of Sullivan and Dugger, Sullivan County, Indiana. The aerial photograph is part of the high resolution color orthophotography database for the entire state collected in 2005 and was obtained from the Indiana Spatial Database Service.

The climate of southwestern Indiana is characterized by hot, humid summers and cold winters. In a typical year, temperature extremes range from -18° C to 36° C. The mean annual temperature is 12° C, with a summer mean of 23° C and a winter mean of -1° C. Precipitation occurs year round, although averages are higher for spring and early summer. The average annual amount of rainfall from 1971 to 2000 was 108 cm as taken in part by the National Climatic Data Center at the Terre Haute, IN station (about 50 kilometers north of Minnehaha). Precipitation in the winter months is typically in the form of snowfall.

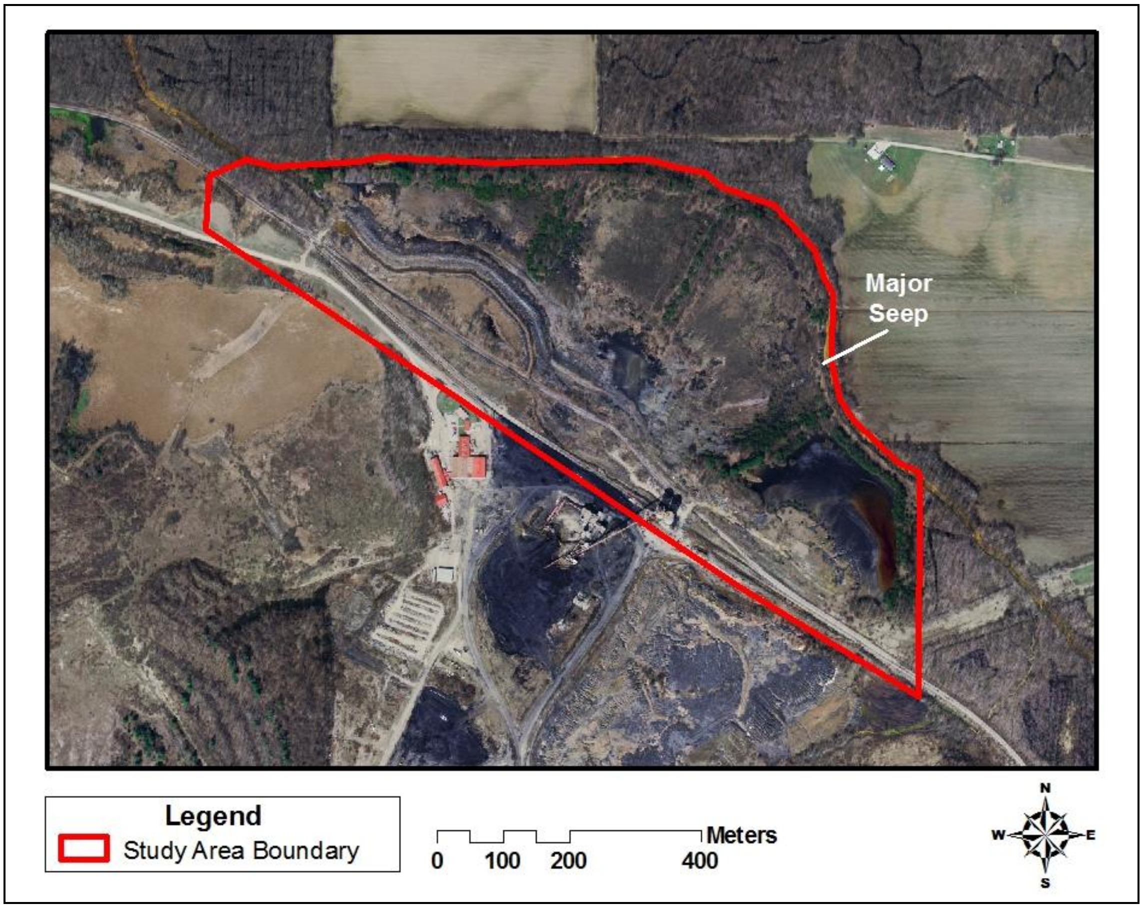

Figure 2. Minnehaha model boundary and location of primary seepage area. The aerial photograph is part of the high resolution color orthophotography database for the entire state collected in 2005 and was obtained from the Indiana Spatial Database Service.

Mining at the Minnehaha site was carried out in three different coal beds; the Danville and Hymera Members of the Dugger Formation and Springfield Member of the Petersburg Formation, which are all members of the Carbondale Group, Desmoinesian Series (IGS, 2008). The Carbondale Group bedrock is shale and sandstone, with thin beds of limestone, clay, and coal. The overburden was typically Pre-Wisconsin loam to sandy loam till, with some areas of Wisconsin to Holocene eolian deposited loess and Holocene alluvium.

Hydrologic Model

Mathematical Model

A finite-difference groundwater model used to study groundwater-surface water interaction was utilized in this study. The model, based on that of Freeze (1971), is an extension of earlier work by Freeze and Witherspoon (1966, 1968) who attempted to generalize the analytical work of Toth (1962, 1963) that was directed at understanding how topography and geological heterogeneity influenced local groundwater flow. The upper boundary of the groundwater basin is the ground surface, and the flow field is fully three-dimensional with provision for both saturated and unsaturated conditions. The governing equation of flow is (Freeze, 1971, p. 349):

$$\frac{\rho^2 g}{\mu}\left(\frac{\partial}{\partial x}\left[k_x(\Psi)\frac{\partial \Psi}{\partial x}\right]+\frac{\partial}{\partial y}\left[k_y(\Psi)\frac{\partial \Psi}{\partial y}\right]+\frac{\partial}{\partial z}\left[k_z(\Psi)\left\{\frac{\partial \Psi}{\partial z}+1\right\}\right]\right)= \left\{\frac{\rho\theta(\Psi)}{n(\Psi)}[\alpha+\eta(\Psi)\beta]+\rho C(\Psi)\right\}\frac{\partial \Psi}{\partial t} \qquad \textbf{(1)}$$

where x, y, and z are the coordinate directions [m], t is time [s], and Ψ is the pressure head [m of water]. The assumed constants in equation 1 for this study were the mass density of water (ρ) [10^3 kg/m^3], the dynamic viscosity of water (μ) [1.8×10^{-3} Pa·s], the compressibility of water (β) [4.4×10^{-10} Pa^{-1}], and the acceleration due to gravity (g) [9.8 m/s^2]. The hydraulic variables dependent on the pressure head include the volumetric moisture content (θ) [decimal fraction], porosity (η) [decimal fraction], and the specific moisture capacity (C) [m^{-1} of water], where $C(\Psi) = d\theta/d\Psi$. The variable vertical compressibility of porous media (α) is in units of Pa^{-1} and the parameters $k_x(\Psi)$, $k_y(\Psi)$, $k_z(\Psi)$ are the specific permeabilities [m^2] measured in the direction of the three principal axes x, y, and z, respectively. The components of the specific permeability are related to the hydraulic conductivity K_i [m/s] by $k_i = K_i\mu/\rho g$.

Mathematical expressions developed by van Genuchten (1980) were utilized to describe the relationships between the pressure head (Ψ) and the unsaturated hydraulic properties of porous media. The effective saturation (S_e) is related to Ψ by:

$$S_e = \frac{\theta(\Psi)-\theta_r}{\theta_s-\theta_r} = \left(\frac{1}{1+|a\Psi|^n}\right)^m \qquad \textbf{(2)}$$

where θ_s ($\approx \eta$) and θ_r are the dimensionless saturated and residual moisture contents, respectively, and a [cm^{-1}] and n [dimensionless] are empirical parameters describing the shape of the soil-water retention curve. For simplicity, m is related to n by $m = 1\text{-}(1/n)$. An algebraic expression for the unsaturated hydraulic conductivity is then given as:

$$K(\Psi) = K_0 S_e{}^L\left[1-\left(1-S_e{}^{1/m}\right)^m\right]^2 \qquad \textbf{(3)}$$

where K_0 is the saturated hydraulic conductivity [m/s], and L is a dimensionless parameter associated with pore tortuosity and connectivity (traditionally set to 0.5). Also, by differentiating (2) with respect to Ψ, an expression for the specific moisture capacity can be obtained:

$$C(\Psi) = \frac{\partial\theta}{\partial\Psi} = \frac{mna^{n} \cdot (\theta_s - \theta_r) \cdot |\Psi|^{n-1}}{[1 + |a\Psi|^{n}]^{2}} \left(\frac{1}{1 + |a\Psi|^{n}}\right)^{m-1} \tag{4}$$

As illustrated by Freeze (1971, p. 350), the nonlinear partial differential equation of flow (1) can be solved by discretizing the model domain into a three-dimensional, block-centered nodal grid ("brick pile") and approximating the governing equation in finite-difference form. Terms are grouped by vertical position so that the entire flow domain can be solved using Line Successive Overrelaxation (LSOR) subject to any imposed configuration of boundary conditions.

Model output is in the form of a three-dimensional grid of pressure head values (a value for each cell in the finite-difference grid) over the study area. The elevation of the water table at each x, y location is extracted from the vertical column where pressure head is equal to zero or has switched from positive to negative sign.

Geological Model

Geographic Information System (GIS) methods were utilized in the generation of the three-dimensional grid. The model domain was generated from two georeferenced digital elevation model (DEM) raster grids; one representing the ground surface and the other representing an underlying clay layer. Both grids utilized a 5-meter resolution, which was subsequently the horizontal spacing of the finite-difference nodal grid.

The areal extent of the clay layer was generated by integrating information from 20 different soil cores and implementing an inverse distance weighting interpolation model within the ESRI ArcGIS software package. This method interpolated a smooth surface from input data points (location and depth of clay) and numerical approximation analysis. The 5-meter resolution ground surface DEM was generated by resampling (using bilinear interpolation) a 1.5-meter resolution DEM generated from the 2005 Indiana Statewide Orthophotography Project. Field observations of sediment exposures and geomorphic features were used in conjunction with literature on the engineering history of the mining operations to construct a raster of the domain describing the physical properties of the refuse (Fig. 3). The substrate was classified into three categories of sediment; fine-grained refuse (sediment from abandoned slurry pond), coarse refuse, and "clay", and then mapped according to their respective spatial distributions.

The georeferenced top and bottom bounding layers of the study area and the domain raster layer were used in the construction of the three-dimensional finite difference grid for the study area. A computer algorithm read the raster files and assigned each cell of the three-dimensional finite-difference grid spatial coordinates (row, column, layer) and a sediment identification code based on the mapped sediments of the domain layer. By using the surface and clay layer DEMs as the upper and lower boundaries, the algorithm projected the domain assignment down

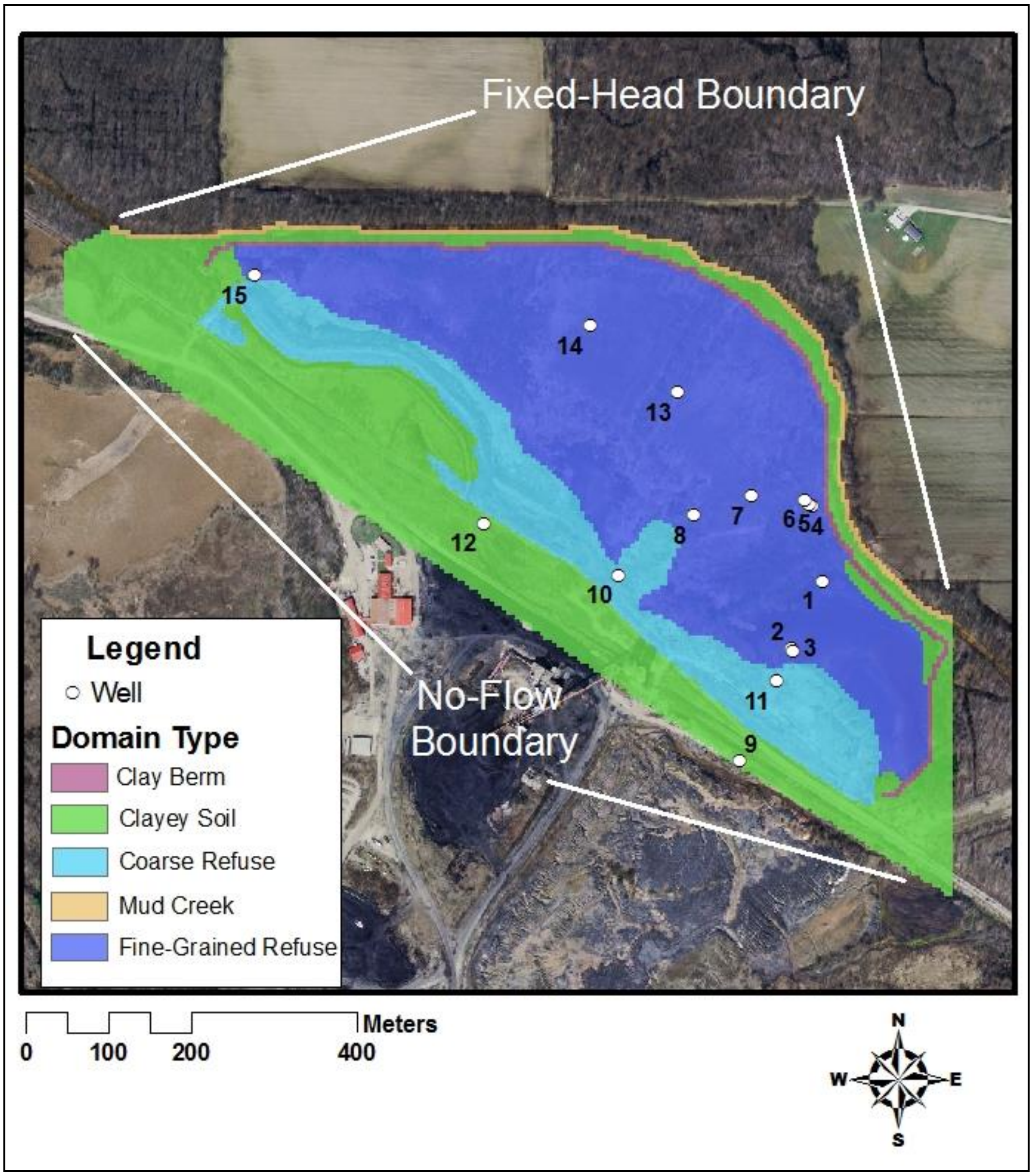

Figure 3. Study area illustrating the well locations and domain types input into the three-dimensional model. Note that the berm is given the same code (hydraulic properties) as the soil domain. Also shown here are the boundary conditions prescribed to the perimeter of the study site. The western edge of the soil domain is prescribed as a no-flow boundary and the northern and eastern perimeter is given as a fixed-head pertaining to the stream elevation (Mud Creek and drainage ditch) as given by the surface DEM.

vertically (z-direction) to fill each cell in the three-dimensional grid between the boundaries with the corresponding sediment identification codes. These identification codes were subsequently assigned specific hydraulic properties for use in the model simulations.

The vertical spacing of the finite-difference grid (model layers) was set to 0.5 meters for the lower fifth of the domain and 0.25 meters for the remaining cells. The smaller vertical spacing was used to ensure the topography and unsaturated-saturated interface was realistically modeled. At this spacing, it took a total of 64 layers to incorporate the entire vertical grid. The x-y grid spacing of the finite-difference model consisted of 175 cells longitudinally (rows) and 215 cells laterally (columns). Approximately 2.4 million cells for the entire three-dimensional finite-difference grid resulted from the given spatial parameters.

Boundary Conditions

For transient simulations in this study, the upper node of each vertical prism (described by the surface topography) was subject to a daily surface moisture flux using precipitation data and potential evaporation estimates from the Penman (1948) method. The bottom surface of the brick pile was assumed to be an aquitard corresponding to the position of the georeferenced clay layer. The initial condition for the transient model was the results of a steady-state simulation employing a fixed head (set to a negative value to represent unsaturated conditions) at the ground surface. In all simulations, the head along streams was set equal to the ground elevation of the cell that intersected the stream channel.

As shown in Fig. 3, the northern, eastern, and southeastern edges of the study area are bounded by a stream (Mud Creek) which was assigned a fixed-head. The western edge of the study area was treated as a no-flow boundary. This is not an unrealistic assumption because this border of the study area contains undisturbed clayey soil like that which underlies the coal refuse deposit.

Methods

In this study, initial estimates of K_0 were obtained through slug test data and estimates of θ_s, θ_r, n, and a were attempted through calibration that involved modeling simulated water levels to those observed in monitoring wells at the study site. Additionally, a sensitivity analysis was conducted to evaluate model performance.

Table 1 lists the spatial information for all 15 monitoring wells at the study site. A pressure transducer (Level Troll 700) was used to collect water level data during each slug test. Data were then imported into a commercial software program (AQTESOLV) for conductivity analyses. The values of hydraulic conductivities ranged from 1.0×10^{-4} cm/s to 3.6×10^{-3} cm/s. This range of values is typical of a fine sand soil (Esling et al., 1996; Hawkins 1998; Schaap et al., 2000), which agrees with the description of the abandoned slurry sediment from field investigations.

Table 1. Spatial information for each of the 15 monitoring wells installed at Minnehaha. Northing and Easting (m) values are based on the UTM83 coordinate system. Note the asterisks (*) indicate the wells that contained calibrated pressure transducers to continuously monitor water levels.

Well	Northing (UTM83)	Easting (UTM83)	Elevation (m)	Depth (m)	Material
1*	4329362.1	475068.3	131.6	5.6	fine-grained refuse
2	4329280.6	475029.3	131.6	4.6	fine-grained refuse
3*	4329278.1	475032.4	131.6	6.0	fine-grained refuse
4	4329452.5	475054.7	131.3	4.7	fine-grained refuse
5*	4329455.0	475051.5	131.3	4.8	fine-grained refuse
6	4329460.1	475045.4	131.3	4.7	fine-grained refuse
7	4329465.0	474981.6	131.8	5.2	fine-grained refuse
8*	4329441.6	474911.9	132.5	6.1	fine-grained refuse
9	4329144.1	474967.2	135.6	9.9	clayey soil
10	4329368.8	474821.4	133.5	5.2	coarse refuse
11	4329241.2	475011.9	136.6	7.6	coarse refuse
12	4329431.9	474657.6	130.3	4.2	clayey soil
13	4329590.4	474893.0	132.4	4.9	fine-grained refuse
14*	4329670.5	474787.0	132.1	5.1	fine-grained refuse
15*	4329731.7	474380.2	131.5	4.2	fine-grained refuse

* equipped with pressure transducer

Model Calibration and Sensitivity Analysis

The observed water table elevations used for analysis in transient simulations were obtained from calibrated pressure transducers that were installed in the fine-grained deposits of the study site (Wells 1, 3, 5, 8, 14, and 15, Fig. 3). The root mean squared error (RMSE) was the statistical function used to measure the degree in which the measured and predicted water levels differed for each adjusted parameter. The RMSE is expressed as:

$$RMSE = \sqrt{\frac{\sum_i^N (x_i - x)^2}{N}} \quad \textbf{(5)}$$

where x_i and x are simulated and observed water table elevations, respectively, and N is the total number of comparisons.

An initial sensitivity analysis found K_0 to have the strongest effect on generated water levels. Increasing the conductivity by just one order of magnitude (common values range over multiple orders of magnitude) compared to an initial estimate (1.0E-03 cm/s) increased the mean water table elevation within the fine-grained refuse domain by 1.04 m. Therefore, K_0 was utilized as the primary calibration parameter.

The hydraulic conductivity was adjusted incrementally (over a range of representative values for the fine-grained refuse) until the RMSE for the water elevations in the 6 wells within this domain were minimized during a time period of 50 days. The simulated water table elevations for the 6 monitoring well locations were generated for each daily time-step. The best-fit simulation resulted in a RMSE of 0.296 m when the value of conductivity was equal to 5.0E-04 cm/s.

Further parameterization for each of the other four parameters only decreased the RMSE by 0.101 m. Table 2 shows the parameter values for the calibrated model, which resulted in a RMSE of 0.195 m for the 50-day simulation.

Table 2. Parameter values for transient simulations. The simulations had a time-period of 50 days. The values correspond to both tailings and gob. The RMSE for this simulation was 0.195 m.

Transient Model Calibrated Parameters				
K_0 (cm/s)	a (cm^{-1})	n	θ_s	θ_r
	0.02	2	0	0.
5.0E-04	5	.25	.46	065

Results

Current Configuration

The simulated mean elevation of the water table within the fine-grained refuse domain was calculated to be 130.7 m. A three-dimensional representation of the flow field under present conditions at Minnehaha (Fig. 4) was generated by resolving the three spatial components of specific discharge (generated for each grid cell within the model using Darcy's Law). The resultant vectors plotted in Figure 4 indicate the magnitude and direction of flow immediately below the water table. The vector field shows that the dominant flow is generally toward Mud Creek throughout the study area, with a small amount of internal flow towards the existing ditch, demonstrating some effect of internal drainage on groundwater flow. Notice there is a large groundwater shed (approximately 7.7 ha) contributing flow towards the main zone of seepage into Mud Creek.

Effects of Topographic Alteration

As part of the reclamation feasibility study, we explored the possible hydrological effects of carving a surface drainage network into the refuse deposit. The hypothesis is that by driving the water table down along the valley bottoms, the overall water table would be lowered and the direction of groundwater flow would be altered away from Mud Creek. A minimal amount of land alteration was desired in order to decrease the cost of reclamation and the disturbance of existing weathering profiles. The hypothetical drainages are depicted in Fig. 5. One arm of the network was extended up to the major seep in an effort to starve it of groundwater. The down-gradient portion of the stream network extended to the local minimum elevation, adjacent to Mud Creek. This design would involve the displacement of approximately 35,000 m^3 of refuse sediment.

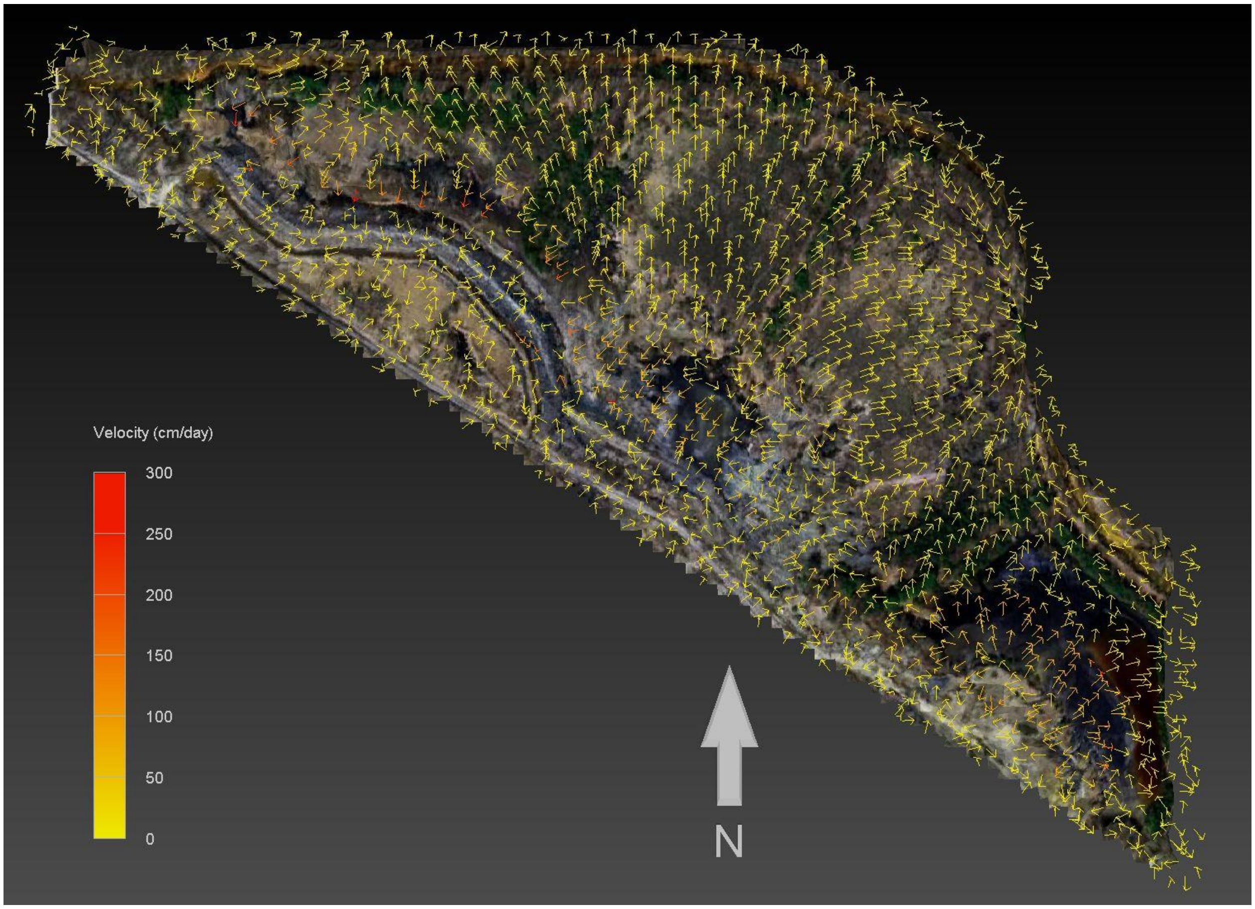

Figure 4. Groundwater flow field under current conditions at the Minnehaha study area. Note for visualization purposes, only every eighth vector throughout the map view domain was plotted (results were too crowded otherwise). The vector components were plotted using Mining Visualization System (MVS) software.

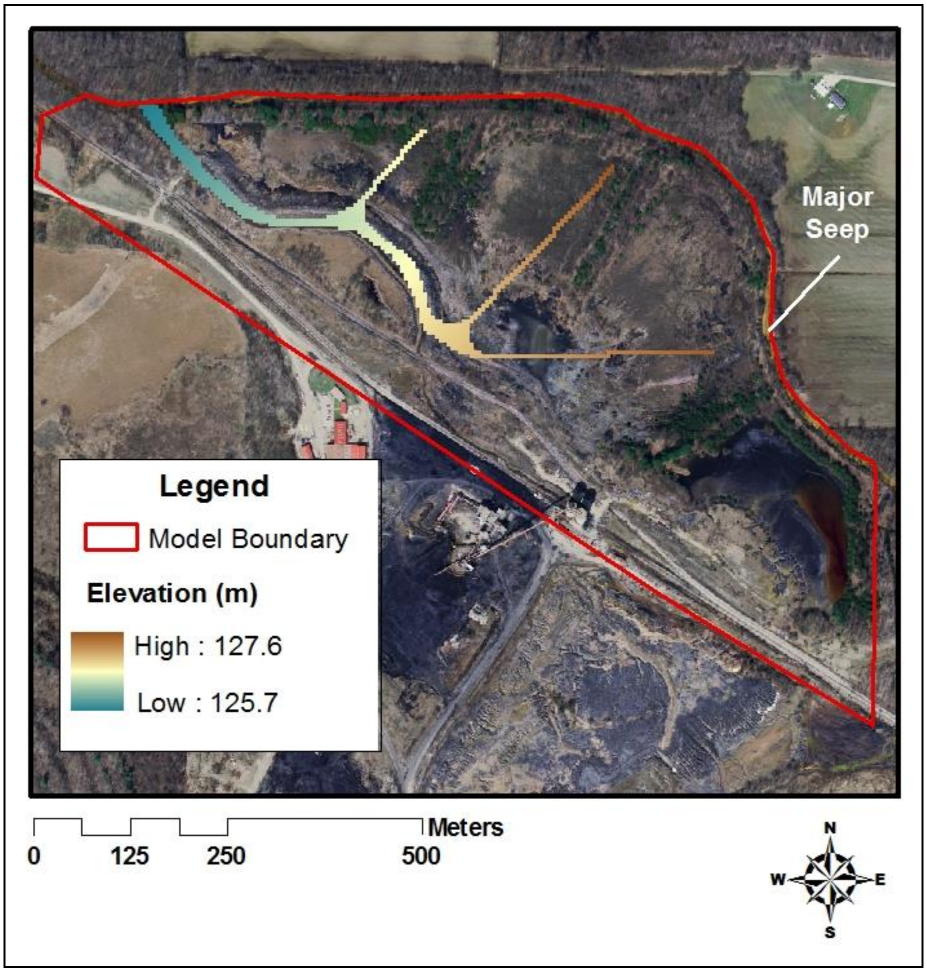

Figure 5. Color-ramped elevations of the proposed stream network used for a reclamation alternative.

A groundwater simulation was performed using exactly the same boundary conditions that were employed in the base model (current conditions), but with the new surface topography. The resulting simulated mean elevation of the water table within the fine-grained refuse domain was calculated to be 129.7 m (a reduction of 1 m), but the drawdown was much greater in the vicinity of the valleys (Fig. 6). Furthermore, the simulation showed that the internal drainage network strongly altered the flow field and intercepted groundwater over a large area of the refuse, most notably near the problem seep (Fig. 7).

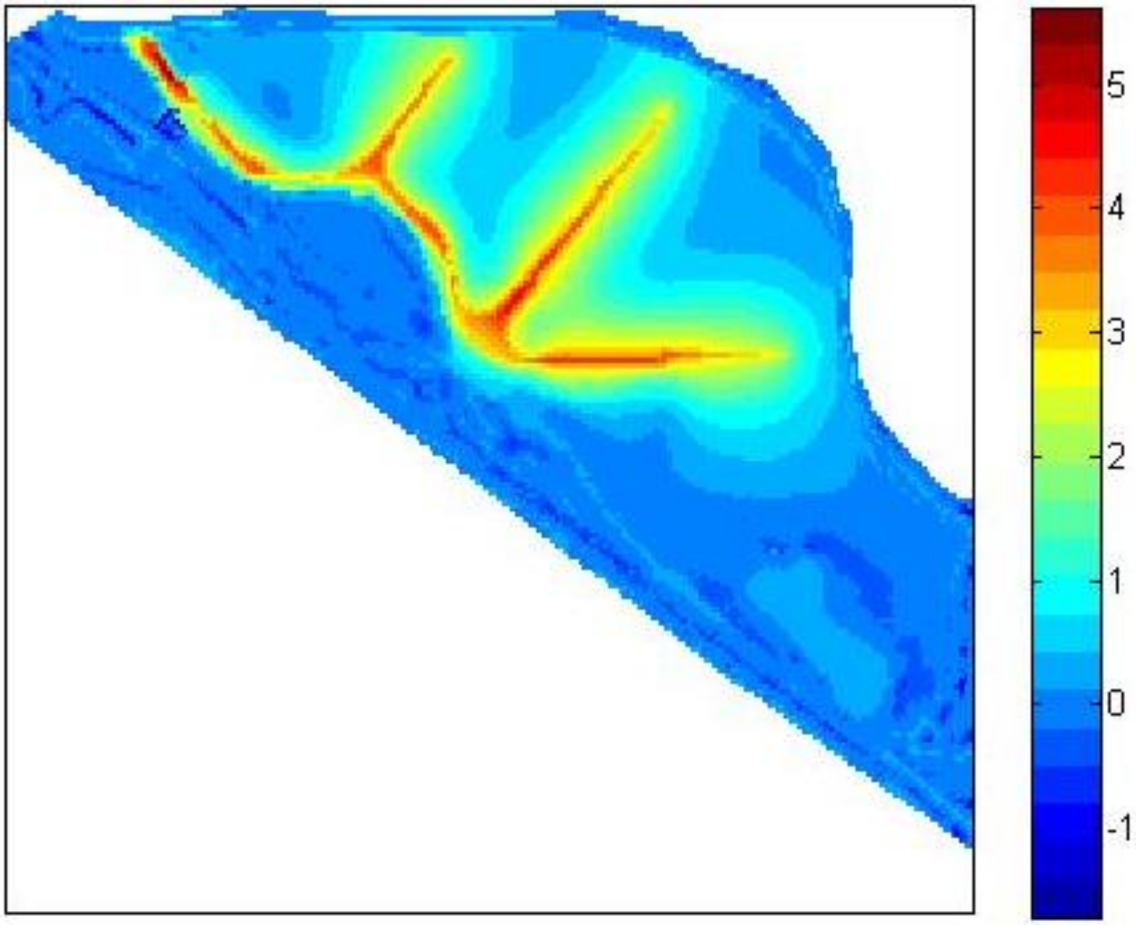

Figure 6. Color-ramped image of the simulated water table under current condition minus that simulated under the reclamation design. The values are in meters.

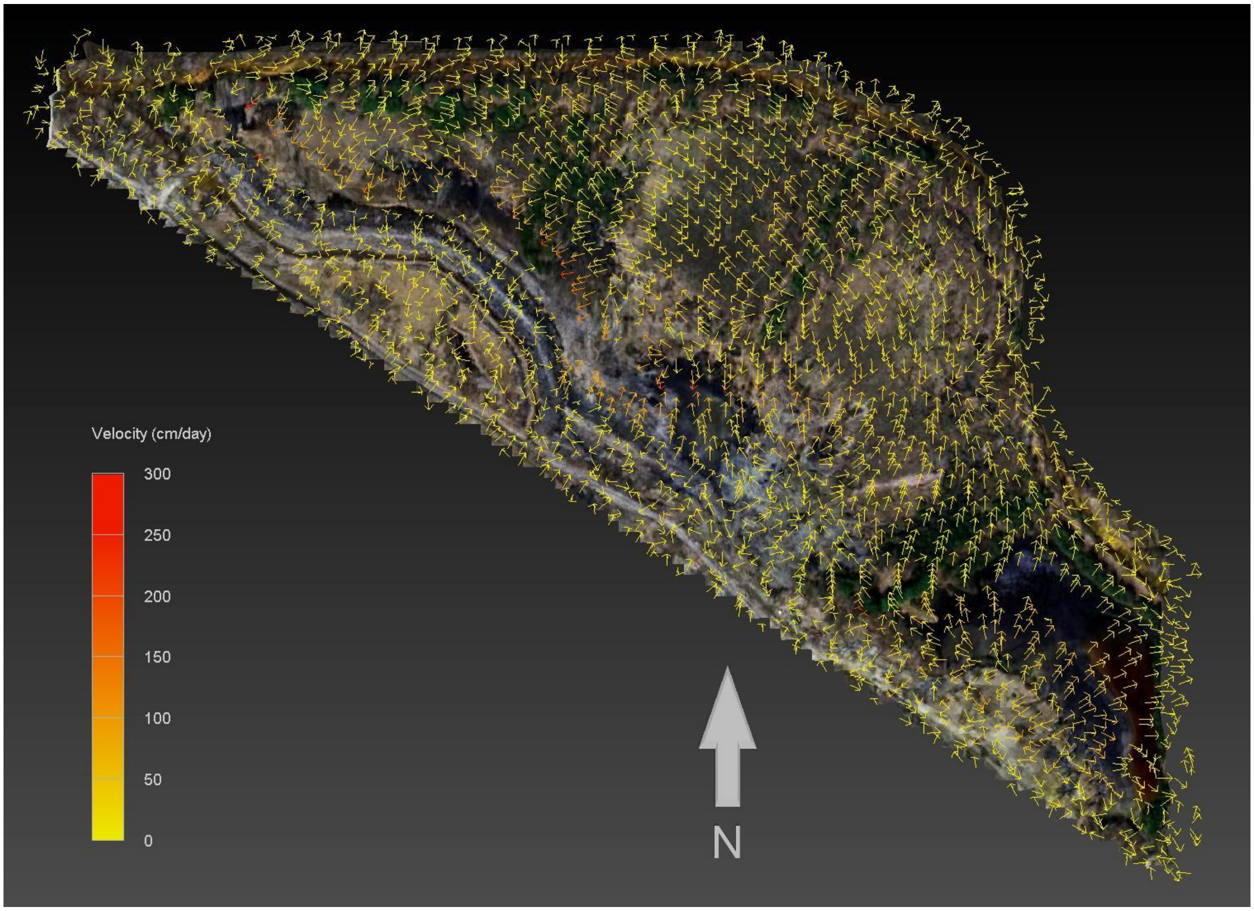

Figure 7. Groundwater flow field under hypothetical reclamation design for the Minnehaha study area. Note for visualization purposes, only every eighth vector throughout the 2D domain was plotted (results were too crowded otherwise). The vector components were resolved and plotted using Mining Visualization System (MVS) software.

Conclusion

This study illustrates the potential utility of undertaking groundwater modeling exercises as part of reclamation feasibility studies. The model applied to the Minnehaha site showed that by only making minor alterations to the surface topography of the site, the flow field of groundwater can be redirected away from problem AMD areas and into an area where it could be treated by passive methods before discharging into the local stream network.

Further refinements to this study could be made by coupling the physical hydrologic model with a geochemical model for the reaction and transport of solutes. In addition, geophysical investigations could improve the model by providing a basis for quantifying spatial variability of the hydraulic properties.

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