A Pit-Lake Module for FEFLOW

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ABSTRACT

A plug-in module, called "PitLakeBC", has been developed for FEFLOW using the Interface Manager API. The module was developed to simulate the formation of one or more unconnected pit-lakes in deep, conical open pits after excavation and dewatering operations have ceased. Predicted transient pit-lake levels are used in studies of groundwater and geochemical impacts, including evaluation of flow-through or hydrosink conditions, and of acid generation or evapoconcentration. The user defines the 3D geometry of the pit, and the rates of precipitation, runoff and evaporation. PitLakeBC uses an explicit approach. The lake level at the beginning of the current time step is estimated from the saturation of lake elements based on results from the previous time step. The module then computes the net contribution of non-groundwater hydrologic components (precipitation plus run-off minus evaporation) and updates boundary condition fluxes to/from the pit-lake. FEFLOW then solves the groundwater condition based on the updated lake level and fluxes. This module may also be useful for simulating lakes in other environments.

INTRODUCTION

The PitLakeBC plug-in module for FEFLOW (WASY, 2015) was developed to address pit lake recovery for a specific model, but it can be used as a more general tool. The module was developed to simulate the transient formation of lakes in multiple, unconnected mine pits after mining and dewatering has ceased in each pit. Steady-state calculations with the module are not supported. A FEFLOW plug-in lake module (ifmLake, WASY, 2012) also simulates lakes, but the lakes must be located on top of the groundwater model, which does not allow for direct interactions between deep aquifers and the lake body. Given the importance of being able to predict transient pit-lake levels, an alternative was needed. Pit-lake levels are used in studies of groundwater and geochemical impacts, including evaluation of flow-through or hydrosink conditions, and of acid generation or evapoconcentration.

The PitLakeBC module accommodates inflow from precipitation and overland runoff, and outflow due to evaporation, which are applied in appropriate model layers in a 3D triangular mesh model. Lake level, area, and volume are tracked for each user defined pit-lake. The pit-lakes are defined using model elements. PitLakeBC uses an explicit approach where the lake level at the beginning of each time step is estimated from the saturation of pit-lake elements based on results from the previous time step or the initial condition. With an estimated lake level, the module computes the net contribution of precipitation on the surface of the lake, run-off into the lake from precipitation falling onto the dry walls of the pit, and evaporation from the surface of the lake, and then updates nodal boundary condition fluxes to and from the pit-lake. The new boundary conditions are passed back to FEFLOW, which then solves for groundwater flow based on the updated pit-lake fluxes. In addition, PitLakeBC requires that the model be three-dimensional, transient and simulates variably saturated flow modeled using triangular elements.

MATHEMATICS

The surface water and groundwater interface presented in the PitLakeBC module uses an explicit, rather than an implicit, approach like MODFLOW's (Harbaugh, 2005) LAK2 (Council, 1999) and LAK3 (Merritt and Konikow, 2000) modules. Studies by Anderson et al. (2002) suggest that both explicit and implicit approaches can yield similar results, though the implicit approach may be more efficient and flexible.

To model a mine pit, a 3D, multilayer model is appropriate. Mine pits can extend more than 1,000 feet (300 m) into the ground. These features may intersect both shallow and deep aquifers. This implies that the mine pit will penetrate multiple model layers.

During and after mining, often the groundwater levels around the dewatered pit have been highly depressed. After pit dewatering ceases, groundwater-levels can recover, rapidly at first and then more gradually over time. An issue with modeling a mine pit and pit-lake creation is that, before the mine pit is created, the model elements representing the pit have materials with some hydraulic conductivity (K) and specific yield (S_y). Afterwards the K is essentially infinite and the S_y is 100%. In FEFLOW it is possible to modify K and S_y of the pit elements through time to mimic the excavation of the pit, but simulation of precipitation, runoff and, and evaporation is not possible because the pit-lake area changes over time.

In the MODFLOW modules LAK2 and LAK3, an implicit approach is used where the pit cells are defined as no-flow cells with a lake boundary condition such that groundwater levels around the lake interact by way of flow across the interface between the lake cells and the active groundwater cells. In PitLakeBC, an explicit approach is used and a "lake model" is superimposed on the groundwater domain.

The calculations for defining the pit-lake level (L), area (A_L), volume (V), precipitation (P), run-off (RO), and evaporation (E) stress between the groundwater and the pit-lake are as follows:

Pit-Lake Level: The user has two options for selecting the L: 1) to use the minimum value of the head over all the pit-lake nodes at which the saturation is 100%, or 2) to use the minimum value of the averaged head over all the pit-lake elements that have at least one pit-lake node with a saturation of 100%. If L is below the bottom of the pit, the pit is dry.

Pit-Lake Surface Area: The pit-lake module assumes the mesh is based on triangular elements. Such elements have vertical sides and have three top nodes and three bottom nodes located at the element corners. To simplify area and volume calculations, the elevations of the top and bottom of a pit-lake element are set equal to the average elevation of the top three and bottom three nodes respectively. For each pit-lake element, if the pit-lake level is at or above the average bottom element elevation (e_{abe}), the entire area of the pit-lake element (A_i) is added to A_L. The surface area of the pit-lake is defined as:

$$A_L = \sum_{i=1}^{n_{ws}} A_i$$

where n_{ws} is the number of *wet-surface* pit-lake elements. A *wet-surface* pit-lake element is one in which at least one node is 100% saturated, and which has no fully or partially saturated elements above it. The area of the pit (A_p) is:

$$A_P = \sum_{i=1}^{n_t} A_i$$

where n_t is the number of pit elements in the top layer of the model.

Pit-Lake Volume: The pit-lake volume (V) is not used in calculations for evaluating flow between the pit-lake and the groundwater model, but it is reported in the pit-lake output file. The water volume in an element is defined:

$$V_i = \begin{cases} A_i\left(e_{ate} - e_{abe}\right) & : L \geq e_{ate} \\ A_i\left(L - e_{abe}\right) & : L \geq e_{abe} \text{ and } L < e_{ate} \\ 0.0 & : L < e_{abe} \end{cases} \qquad \text{and} \quad V = \sum_{i=1}^{n_w} V_i$$

where

e_{ate} = average nodal-elevation at the top of the element
e_{abe} = average nodal-elevation at the bottom of the element
n_w = number of *wet* pit-lake elements which are either fully or partially saturated

Pit-Lake Flux: The pit-lake flux (Q_L), which can be either positive or negative, is:

$$Q_L = \frac{\left(Q_p * A_L\right) + \left(Q_{ro} * \left(A_P - A_L\right)\right) - \left(Q_E * A_L\right)}{A_L}$$

where

Q_p = the precipitation rate over the lake surface
Q_{ro} = the run-off rate into the lake from the dry wall of the pit
Q_E = the evaporation rate from the lake surface

The module is based on the assumption that groundwater recharge due to infiltration of precipitation on the dry walls of the pit is zero. This is reasonable if the walls are steep or if such recharge essentially contributes to the overall run-off into the lake. To interact with the groundwater model, the total pit-lake flux is equally divided between, and assigned to, all the saturated pit-lake well nodes:

$$q_{s_n} = \frac{Q_L}{n_{s_n}}$$

where

q_{s_n} = the injection or extraction rate for each pit-lake node at which saturation is 100%
n_{s_n} = the number of saturated pit-lake nodes

After the pit-lake calculations are complete and pit-lake nodes are updated, FEFLOW evaluates groundwater flow for the next time step.

When the PitLakeBC module becomes active, it starts to monitor the head and saturation of the pit-lake nodes and elements. When pit-lake nodes start to become saturated (i.e. they are at or below the level of the lake), a pit-lake has formed. The PitLakeBC process loop is shown in Figure 1.

A pit-lake simulation is configured as follows:

- All nodes touching pit-lake elements (pit-lake nodes) are specified as pumping well nodes with a rate of zero. As a simulation progresses, these pit-lake nodes are used to inject or extract water from the pit-lake if they are at or below the level of the lake.
- At the time a pit-lake becomes active the K of the pit-lake elements should be set to a large value such that calculated hydraulic gradients across the pit are very small. The S_y of the pit elements should be set to 100% to simulate open water.
- At the time the pit-lake becomes active, the head for all pit-lake nodes should be set to the elevation of the pit bottom or the elevation to which the pit was dewatered.
- Recharge over the area of the pit is set to zero.

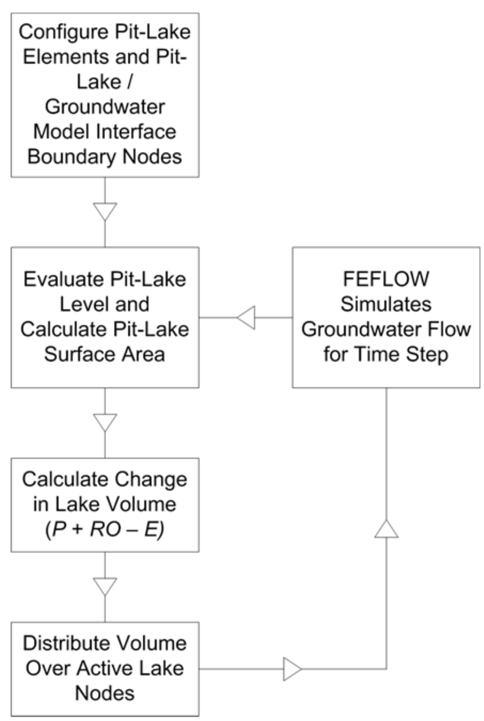


Figure 1: Process loop for PitLakeBC.

Once configured, the pit-lake level and surface area are calculated. The change in pit-lake volume is calculated, $P + RO - E$, and then distributed over the saturated pit-lake nodes to be injected or extracted during the next time step. Once the setup is complete, FEFLOW simulates groundwater flow for the next time step.

EXAMPLE

A simple case was designed to test the PitLakeBC module (Figure 2). The test model is 100 feet by 100 feet by 50 feet with 20 equal thickness layers (2.5 feet per layer). It has a triangular mesh with 1024 elements per layer, all of the same size and shape. Fixed heads are specified on the north and west sides at 50 feet. Pit #1 is in the southeast corner and extends from the surface (50 feet) down to an elevation of 12.5 feet. Pit #2 has steeper walls, is in the center of the model, and extends down to an elevation of 22.5 feet. Pit #1 is dewatered from days zero to 100, and Pit #2 is dewatered from days 10 to 60. The bedrock is simulated using a K of 0.1 feet/day and a S_y of 0.01. In the pits, a K of 1,000 feet/day and a S_y of 1.0 are specified (a model of an actual site might simulate transient K and S_y as pits are mined). The model was run for a total of 500 days.

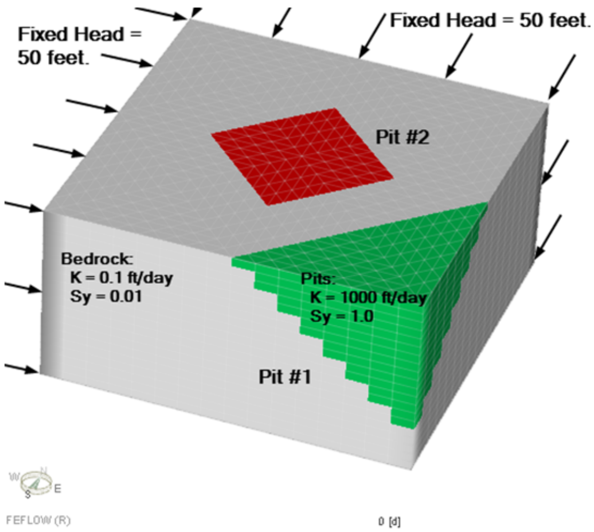


Figure 2: Example model configuration with mine pits.

The model results are shown at 100 days (Figure 3, when Pit #1 starts to fill) and at 500 days (Figure 4). In Figure 5, the pit-lake levels and volumes are shown over time. The step-like responses are caused when a lake level rises into the next model layer so that the area of the lake expands rapidly. More model layers, smaller time steps, and smaller elements would result in smoother curves.

SUMMARY

The PitLakeBC module was developed for a specific type of mining project to simulate the formation of lakes in mine pits. Future enhancements might include conversion to an implicit approach similar to MODFLOW's LAK3 module, expansion to a mine-pit module that handles both dewatering and flooding over time, support for different element shapes, and support for 2D horizontal and cross-sectional models.

REFERENCES

Anderson, M.P., Hunt, R.J., Krohelski, J.T., and Chung, K., 2002. Using high hydraulic conductivity nodes to simulate seepage lakes, Groundwater, 40(2), pp 117-122.

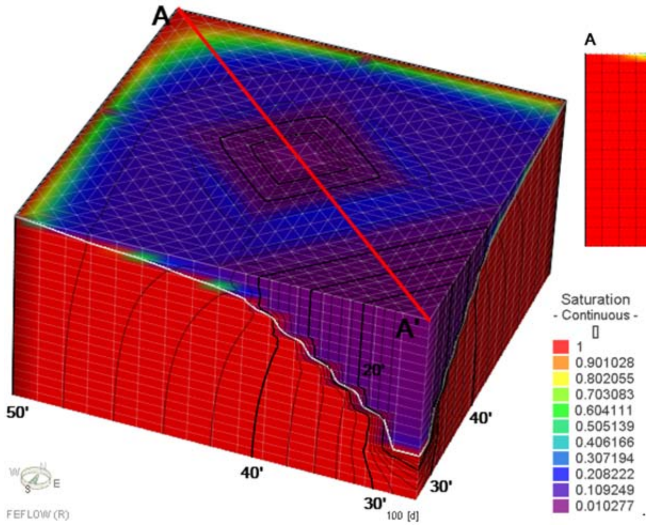
G. W. Council, 1999. A Lake Package for MODFLOW (LAK2)—Documentation and User's Manual, HSI Geotrans - A Tetra Tech Company, Sterling, Va, USA.

Harbaugh, A.W., 2005, MODFLOW-2005, the U.S. Geological Survey modular ground-water model -- the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6-A16.

Merritt, M.L., and Konikow, L.F., 2000. Documentation of a computer program to simulate lake-aquifer interaction using the MODFLOW ground water flow model and the MOC3D solute-transport model, U.S. Geological Survey Water-Resources Investigations Report 2000-4167.

WASY, 2012, IfmLake Plug-In, http://www.mikepoweredbydhi.com/-/media/shared content/mike by dhi/flyers and pdf/product-documentation/feflow-plugins.pdf, DHI Worldwide.

WASY, 2015, FEFLOW, http://www.mikepoweredbydhi.com/products/feflow, DHI Worldwide.



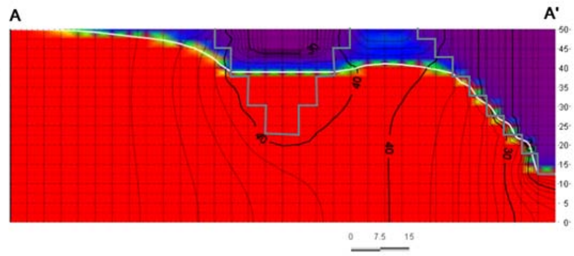
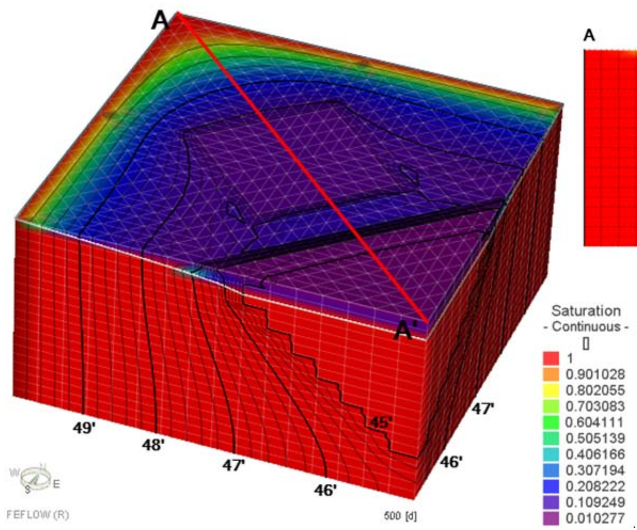


Figure 3: PitLakeBC results after 100 days. Head, black 2 ft contour lines. Water-table (zero pressure), white line.



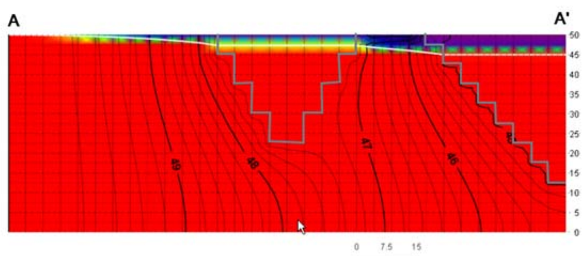


Figure 4: Pit-Lake results after 500 days. Head, black 0.2 ft contour lines. Water-table (zero pressure), white line.

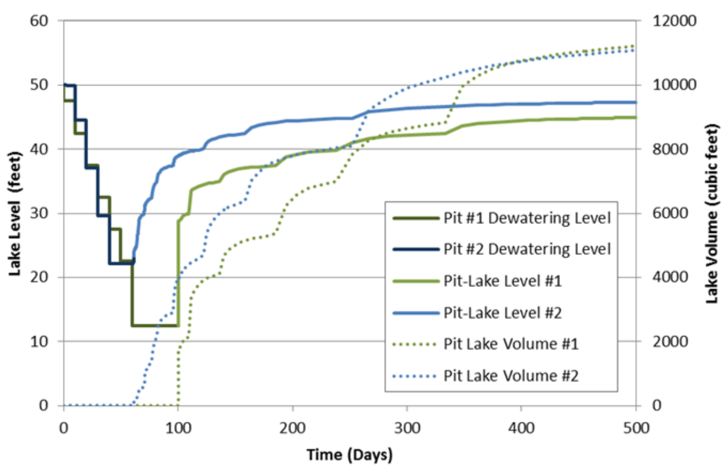


Figure 5: Pit level and pit-lake level and volume through time.