Description of MINEDW Calculation Code

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MINEDW is a three dimensional (3D) finite-element groundwater modeling code developed specifically for mining and civil engineering applications. This white paper outlines the mathematical basis of the groundwater flow code, boundary conditions, and features, such as the ones listed below, developed specifically for simulating common mining scenarios. The information in this white paper is supplemented by the ***MINEDW*** manual, which gives in-depth information about how to construct a groundwater model using ***MINEDW***.

Key features include the following built-in functions, which allow the user to simulate common mining scenarios with efficiency and accuracy:

1. Progressive open-pit excavations with the ability to simulate multiple intersecting open pits by collapsing elements in the finite-element grid,
2. Zones of Relaxation, where rock hydraulic properties are altered by open-pit excavation or block-cave mining,
3. Backfill, which is commonly added to excavations and has different hydraulic properties than in-situ material, and
4. Pit-lake development after the cessation of open-pit mining.

1.0 INTRODUCTION

For mining operations that are conducted below the water table, there are two important water-related problems that mine operators may face: the amount of groundwater inflow into an underground excavation or an open pit if the country rock is relatively permeable or, if the rock is impermeable, the effect of pore pressure on the stability of open-pit and underground mine walls. For economic and safety purposes, it is important to be able to predict the nature and magnitude of these potential problems so that appropriate dewatering and/or depressurizing systems may be installed.

Numerical groundwater flow models are now routinely used to predict inflows to both open-pit and underground mines and to help design mine dewatering and depressurization systems. Although adequate for addressing broad issues such as the impact of mining operations on regional water resources, available finite-difference groundwater numerical codes are limited in their ability to quantify the more detailed problems of the phreatic surface in highwalls and inflows to both open-pit and underground excavations. These limitations arise primarily from limitations in model discretization inherent in finite difference codes:

1. The discretization used in a numerical model can strongly affect the predictions of inflow and the shape of the water table near an open-pit or underground excavation. Not only must discrete features, such as faults and contacts between significantly different hydrogeologic materials, be included in the discretization, but predicting the essentially radial flow toward an excavation is more accurately performed by using small, approximately logarithmic horizontal and vertical grid spacing.
2. The seepage face—the surface of the open-pit highwall through which lateral flow occurs—is difficult to estimate using finite-difference codes (i.e. MODFLOW). The height of the seepage face affects both the amount of lateral inflow and the height of the water table behind the highwall. A poor estimate of the height of the seepage face can introduce significant errors to the predicted inflows and pore-pressure distribution.

To overcome limitations such as those described above, Itasca Denver, Inc. (Itasca) developed ***MINEDW***, a three-dimensional (3D) finite-element groundwater flow code. The core of the code is based on algorithms previously developed by Durbin and Berenbrock (1985) for the United States Geological Survey (USGS) code *FEMFLOW3D*. As of early 2018, ***MINEDW*** had been used successfully at more than 75 mines located throughout the world and in diverse hydrogeologic and climatic conditions. The code has been in use for approximately 30 years, and its predictions have been validated by field data collected over many years and the Sandia National Laboratory (Corbet et al. 1998).

2.0 GROUNDWATER FLOW

MINEDW can be used to evaluate potential inflows and pore-pressure distributions near open-pit and underground mining operations. It has been widely used in a variety of climatic, geologic, and hydrogeologic settings. Described below is the formulation of the calculation code that is used to simulate the groundwater system in a ***MINEDW*** model.

Groundwater flow in ***MINEDW*** is governed by the 3D equation for groundwater flow shown below:

$$\frac{\partial}{\partial x}\left(K'_{xx}k_R\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K'_{yy}k_R\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K'_{zz}\frac{\partial h}{\partial z}\right)-S'_s\frac{\partial h}{\partial t}-W=0 \qquad (2.1)$$

Where:

h = hydraulic head [L],
K'_{xx} = effective hydraulic conductivity in the *x* direction [LT^{-1}],
K'_{yy} = effective hydraulic conductivity in the *y* direction [LT^{-1}],
K'_{zz} = effective hydraulic conductivity in the *z* direction [LT^{-1}],
k_R = relative hydraulic conductivity [L^0],
S_s' = effective specific storage, a parameter that accounts for specific storage and specific yield, as defined below in Equation 2.7 [L^{-1}],
W = source-sink discharge per unit volume [T^{-1}],
x = coordinate in the *x* direction [L],
y = coordinate in the *y* direction [L],
z = coordinate in the *z* direction [L],
t = time [T],
S_s = specific storage [L^{-1}],
S_y = specific yield at the phreatic surface [L^0],
V = specified volume of media [L^3], and
A = area of the phreatic surface within the specified volume of water [L^2].

The governing groundwater flow equation shown above assumes that the coordinate system is aligned with principal components of the hydraulic conductivity (*K*) tensor. The effective hydraulic conductivity (K') in the groundwater flow model is derived using the Forchheimer equation for a two-regime (Darcian and non-Darcian) flow that has the following form:

$$\frac{dh}{dl}=\frac{1}{K}q+\frac{R}{K^2}q^2 \qquad (2.2)$$

Where:

q = groundwater discharge in the direction of the hydraulic gradient [LT^{-1}],

l = direction of groundwater flow [L],
K = hydraulic conductivity flow under Darcian flow conditions [LT^{-1}], and
R = Ratio of Non-Darcian to Darcian flow, a value of 0 indicates flow is completely Darcian [L^0].

For a general case of saturated groundwater flow, and where the porous media is anisotropic and *i* is arbitrarily oriented within a rectangular coordinate system, the Forchheimer equation can be rewritten as the following:

$$q_i = \sum_j \left[\frac{1}{\frac{1}{K_{ij}} + \frac{R}{K_{ij}^2} q}\right] \frac{\partial h}{\partial x_j} \tag{2.3}$$

Where:

q_i = component of groundwater discharge in the i direction [LT^{-1}], and
K_{ij} = hydraulic conductivity tensor for Darcian flow [LT^{-1}].

From the rewritten Forchheimer equation the *K'* tensor can be described by the following equation:

$$K'_{ij} = \frac{1}{\frac{1}{K_{ij}} + b_{ij} q} \tag{2.4}$$

Where:

b_{ij} = tensor form of *b* in the Forchheimer equation, such that $b_{ij} = \frac{R}{K_{ij}^2}$, [$L^2T^{-2}$].

MINEDW calculates the phreatic surface and potential seepage face (i.e. where the phreatic surface intersects an open-pit highwall), by simulating both the saturated and unsaturated flow. As shown in Equation 2.1, horizontal effective hydraulic conductivity is scaled by relative hydraulic conductivity, the ratio of unsaturated hydraulic conductivity to saturated hydraulic conductivity. Note that vertical unsaturated hydraulic conductivity is not adjusted unsaturated elements. For the unsaturated zone, this ratio is always less than unity because unsaturated hydraulic conductivity is less than saturated hydraulic conductivity. For elements above the phreatic surface, the k_r is equal to the user-defined relative hydraulic conductivity value (k_r'). Below the phreatic surface, the k_r is equal to unity. For each element which comprises the phreatic surface, the ratio of the element's saturated thickness to its unsaturated thickness is calculated and used as the k_r in subsequent calculations if it is greater than the user-defined k_r' value. Mathematically, the k_r can be expressed as shown in Equations 2.5 and 2.6. Note that pressure head is calculated on model nodes, not elements. Thus, the pressure head within an element is derived from the pressure head calculated on the nodes of that element.

$$k_r = \begin{cases} k_r' \; for \; P < 0 \\ 1 \; for \; P \geq 0 \end{cases} \tag{2.5}$$

$$P = h - z \tag{2.6}$$

Where:

P = pressure head of node associated with element e [L],
z = vertical elevation coordinate [L], and
k_r' = relative hydraulic conductivity in the domain above the phreatic surface [L^0].

The effective specific storage (S_s') has a value that reflects the elasticity of water and the matrix of the porous media (S_s). At the phreatic surface, the S_s' has a value that reflects the specific yield (S_y) due to the movement of the phreatic surface. In ***MINEDW*** the S_s' is defined by the following:

$$S_s' = S_s + S_y \frac{A}{V} \tag{2.7}$$

Where:

S_s' = effective specific storage [L^{-1}],
S_s = specific storage [L^{-1}],
S_y = specific yield at the phreatic surface [L^0],
V = specified volume of media [L^3], and
A = area of the phreatic surface within the specified volume of water [L^2].

The above equations are solved in ***MINEDW*** using the Galerkin finite-element approximation as described in Durbin and Berenbrock (1985). The groundwater solution is solved iteratively based on user-specified closure criteria, solver options, and the maximum allowed iterations. User defined values may vary depending on the groundwater flow model and its application. Users should define closure criterion to minimize water budget residuals in transient simulations or storage change in steady-state simulations.

3.0 BOUNDARY CONDITIONS

MINEDW offers a variety of boundary conditions that can be used to represent the groundwater system. The boundary conditions that are available and the typical uses are as follows:

1. **Specified-Head Boundary Conditions**: Specified-head boundary conditions are used to define boundaries which have a head that is constant or varies in a fixed way with time. ***MINEDW*** can apply two types of specified-head boundary conditions: constant head or drain. A constant-head boundary condition can be used for features that can both discharge water to and receive water from the groundwater system such as rivers, regional flow, lakes, and reservoirs. Drain boundary conditions can be used to define parts of the groundwater system that can receive water from the groundwater system, but not supply water to the groundwater system, such as seeps, springs, and wetlands. In addition to natural components of the groundwater system, underground excavations, sub-horizontal drainholes, and drainage galleries may be simulated using drains.

2. **Recharge and Evapotranspiration**: The recharge and evapotranspiration boundary conditions can be used to simulate flux across the ground surface to or from the groundwater system. The user may directly input a recharge rate that varies spatially and/or temporally, or precipitation rates can be input into ***MINEDW*** and used to calculate a recharge rate. If the phreatic surface is near the ground surface elevation, evapotranspiration can be used to simulate water removed by vegetation (transpiration) and evaporation.

3. **Pumping Wells**: Users can define three types of pumping wells, depending on the pumping situation or desired outcome: (1) Specified-Rate, (2) Specified-Head, and (3) Lowest Pumping Elevation pumping wells.

4. **Variable Flux:** The variable flux boundary condition is a unique boundary condition specific to ***MINEDW*** that can be used to simulate an infinite extent to the regional groundwater system around the model boundary.

5. **River**: The river boundary condition of ***MINEDW*** can be used to simulate rivers, streams, canals, and/or ditches that may have interaction with the groundwater system.

A description of each of these boundary conditions and applicable uses are described below.

3.1 SPECIFIED-HEAD BOUNDARY CONDITIONS

Specified-head boundaries allow the user to simulate locations in the model with a user-determined hydraulic head. This can be used for lakes, streams, seepage faces, underground mining, or other applications. The boundary conditions can take either of the following forms:

1. The boundary head is invariant with time.
2. The boundary head varies with time in accordance with a user-input hydrograph. The user has the option to input a one-year hydrograph which repeats on an annual basis.

Specified-head boundary conditions can be either drain nodes or constant-head nodes. Constant-head nodes can have groundwater flow out of or into the model domain, while groundwater can only flow out of the model domain at drain nodes. Both types of specified-head nodes are discussed below.

3.1.1 Constant-Head Boundary Conditions

The equation for the discharge of water to or from constant-head nodes is shown below:

$$q_h = \sum_{i=1}^{n} C_{hi}(H_{Bi} - H_i) \tag{3.1}$$

Where:

q_h = functional representation of groundwater discharge due to the constant-head boundary condition [L^3T^{-1}],
C_{hi} = leakance factor at node *i* [L^2T^{-1}],
H_{Bi} = boundary head for the node *i* [L],
H_i = computed hydraulic head for the node *i* [L], and
n = number of nodes [L^0].

The leakance factor (C_{hi}) has a non-zero value at constant-head nodes, and a zero value elsewhere, thus discharge (q_{hi}) can be non-zero only at constant-head nodes. The C_{hi} value controls how quickly the computed head (H_i) at node *i* reaches the user-specified boundary head (H_{hi}). The C_{hi} is equal to the user-specified "Leakance" value in ***MINEDW***. This value is related to the source of water to the constant-head node, its distance from the constant-head node, and the hydraulic conductivity of the path from the source water to the constant head node as shown in Equation 3.2 below. The C_{hi} does not need to be determined with a high degree of precision. In general, the C_{hi} value needs to be large enough so that enough discharge is produced that H_i is close to H_{Bi}. However, C_{hi} must not be so large as to cause problems with the precision of the model calculation (e.g. numerical instability). The default C_{hi} value is 1,000.

$$C_{hi} = K\frac{A}{L} \tag{3.2}$$

Where:

K = hydraulic conductivity of material between constant-head node and water source [LT^{-1}],
A = area associated with node *i* perpendicular to flow from water source [L^2], and
L = length from water source [L].

3.1.2 Drain Boundary Conditions

Specified-head boundary conditions can also be drain boundary conditions, meaning that water can discharge out of the groundwater system but not into it. The head value assigned to a drain node can be constant or vary with time. This condition is commonly used to simulate surface seeps and springs, subsurface drains, sub-horizontal drains in an open-pit wall, seepage in an open-pit wall, and underground mine workings.

The equation for calculating discharge from the drain nodes is defined as follows:

$$q_d = \sum_{i=1}^{n} \begin{cases} C_{di}(H_{di} - H_i), for\ H_{di} < H_i \\ 0, for\ H_{di} \geq H_i \end{cases} \quad (3.3)$$

Where:

q_d = functional representation of groundwater discharge due to the drain boundary condition [L^3t^{-1}],
C_{di} = leakance factor at node i [L^2t^{-1}],
H_{di} = specified head for the node i [L],
H_i = computed hydraulic head at node i [L], and
n = number of nodes [L^0].

The H_{di} value must be less than or equal to the elevation at node *i*. The leakance factor (C_{di}) for drain nodes is related to the hydraulic conductivity at the drain node. By default, drain boundary conditions are assigned to all nodes on the ground-surface of the model which do not have another user-specified boundary condition. The boundary head assigned to each ground-surface drain node is equal to the ground-surface elevation at that node. Therefore, the drain boundary condition prevents computed hydraulic head values from exceeding the ground-surface elevation, preventing the simulation of ponded water at surface where it is not explicitly specified by the user. Water which discharges from the ground-surface drain nodes is accounted for in the water budget as surface runoff.

3.2 RECHARGE AND EVAPOTRANSPIRATION

In ***MINEDW***, recharge can be calculated from user-input precipitation rates, or directly specified by the user. Recharge and evapotranspiration are both simulated using boundary fluxes, which are distributed source-sink fluxes that occur on the boundary surface of the flow domain. Recharge and evapotranspiration boundary fluxes are both applied to the upper boundary surface of the model domain. In the 3D finite-element grid, the boundary surface is represented by a collection of individual triangular surfaces that are assembled contiguously in 3D space. Recall that the finite-element grid is formed by an assembly of contiguous triangular prisms, and

selected faces of the triangular prisms form the collection of triangular surfaces that comprise the boundary of the flow domain.

3.2.1 Recharge

The recharge boundary condition is used to simulate precipitation infiltrating into the groundwater system. The user may enter recharge information directly as a recharge rate. In this case, the user may vary the recharge rate spatially by specifying zones, in which different recharge characteristics are specified for different areas of the model. Additionally, the user may specify recharge rates that are constant in time, vary on an annual basis, or vary with time as the user prescribes. The user also has several options for using ***MINEDW*** features to calculate the recharge rate based on precipitation information or the relationship between precipitation and ground-surface elevation.

3.2.1.1 Calculating Recharge Rate from Precipitation Rate

To calculate the recharge rate from precipitation information, the user may directly input precipitation rates which may vary temporally or spatially. Alternatively, the user may fit an empirical curve of the form shown in Equation 3.4 to observed precipitation at a range of ground-surface elevations. ***MINEDW*** will then calculate the precipitation rate at each surface node in the model based on its elevation.

$$P = A + B * z^C \tag{3.4}$$

Where:

P = precipitation rate [LT^{-1}],
A [LT^{-1}], *B* [L^{-C}] and *C* [-] are curve-fitting parameters, and
z = ground-surface elevation [L].

If precipitation rates are entered or calculated by ***MINEDW*** using Equation 3.4, the amount of water from precipitation which enters the groundwater system as recharge can be defined using elevation factors and temporal factors. Elevation factors are the percentage of precipitation that will be applied to the groundwater system in a specified range of ground-surface elevations. The user can specify elevation factors for as many different ground-surface elevation ranges as desired. This method is adapted from Maxey and Eakin (1949). Temporal factors can also be applied to precipitation rate so that the percentage of precipitation that will be applied as recharge is a function of time, using either temporal factors that vary on an annual basis, or temporal factors that vary as the user prescribes. The use of elevation factors and temporal factors to define the recharge rate is shown in the equation below.

$$R = TF * EF * P = TF * EF * \ (A + B * z^C) \tag{3.5}$$

Where:

R = recharge rate [LT^{-1}],
TF = temporal factor [%], and
EF = elevation factor [%].

The empirical relationship shown in Equation 3.4 and the temporal factors formulation shown in Equation 3.5 can both be varied by zone in order to represent spatial variation in recharge.

3.2.1.2 Applying Recharge to Model

Once the recharge rate is determined, recharge is applied to the model in the form of Equation 3.6.

$$q_r = \sum_{e=1}^{n} A_e R_e \tag{3.6}$$

Where:

q_r = recharge discharge [L^3T^{-1}],
n = number of elements [L^0],
A_e = surface area associated with element e [L^2], and
R_e = recharge rate per unit area at element e [LT^{-1}].

Elements which have a user-input recharge rate have a non-zero recharge rate (R_e), all others are zero.

3.2.1.3 Surface Recharge Application

Recharge can be applied either at surface (default option) or to the uppermost saturated model node. If recharge is applied to the model at surface, it infiltrates downward through the unsaturated area between ground surface and the phreatic surface following Darcian flow with an assumed unit vertical hydraulic gradient. Therefore, the maximum infiltration rate (R_e) is equivalent to the hydraulic conductivity of the hydrogeologic unit it is flowing through (recall that the relative hydraulic conductivity coefficient (k_R) is not applied to vertical hydraulic conductivity).

If the recharge rate (defined by the user or calculated by ***MINEDW***) is greater than the hydraulic conductivity of the uppermost hydrogeologic unit, recharge above the maximum infiltration rate is not applied to the groundwater system and is counted as surface runoff in the ***MINEDW*** water budget. An example in which user-specified recharge is directed to surface runoff is illustrated in Figure 3-1.

If there is a high hydraulic conductivity unit on surface underlain by a low hydraulic conductivity unit, recharge may not be able to infiltrate to the phreatic surface at the rate at which it is applied

in the model. In this case, the computed hydraulic head at surface may be greater than the ground-surface elevation, causing water to discharge from the groundwater system at the drain boundary conditions applied to surface nodes. This discharge is also accounted for in the surface runoff portion of the water balance.

3.2.1.4 Phreatic Surface Recharge Application

If recharge is applied to the model at the top of the phreatic surface, the maximum recharge rate is equal to the hydraulic conductivity of the hydrogeologic unit which contains the phreatic surface. If the user-defined recharge rate is greater than the hydraulic conductivity of the hydrogeologic unit, in which the phreatic surface is located, a recharge rate equal to the hydraulic conductivity of that unit is applied. In this case, the difference between the user-defined recharge rate and the recharge rate applied to the groundwater system is accounted for as surface runoff in the water budget. Note that if the phreatic surface rises or falls to a different unit, the maximum recharge rate will change with the hydraulic conductivity of the unit which contains the phreatic surface.

3.2.2 Evapotranspiration

The evapotranspiration boundary condition in ***MINEDW*** is used to simulate the discharge of groundwater from a shallow water table due to evapotranspiration (a combination of evaporation and transpiration) from vegetated areas or from bare-soil areas. The simulation is performed by assuming that groundwater discharge related to evapotranspiration is linearly related to the depth below the land surface to the phreatic surface. The linear relation holds until a maximum depth is reached, which is the extinction depth. At the extinction depth, evapotranspiration ceases. In ***MINEDW***, the evapotranspiration rate depends on the local depth to the phreatic surface, the extinction depth, the potential (maximum possible) evapotranspiration rate, and the size of the groundwater discharge area. The discharge of groundwater from a shallow phreatic surface has the general form shown below:

$$q_{ET} = \sum_{e=1}^{n} \begin{cases} 0, for\ H_e \le H_{ETe} \\ C_{ETe}(H_{ETe} - H_e)\ for\ H_{ETe} < H_e < H_{Le} \\ A_e ET_{max}, for\ H_e \ge H_{Le} \end{cases} \quad (3.7)$$

Where:

q_{ET} = evapotranspiration discharge [L^3T^{-1}],
C_{ETe} = coefficient representing the evapotranspiration at element e [L^2T^{-1}],
H_{ETe} = extinction elevation at element e [L],
H_e = computed hydraulic head at element e for the current time step [L],
H_{Le} = ground-surface elevation at element e [L],
A_e = discharge area of element e [L^2],

ET_{max} = potential evapotranspiration rate [LT^{-1}], and
n = number of elements [L°].

The discharge (q_{ET}) has a non-zero value for nodes where evapotranspiration occurs, otherwise it has a zero value. The coefficient C_{ETe} in Equation 3.7 depends on a number of factors as indicated in Equations 3.8 and 3.9.

$$C_{ETe} = \frac{A_e ET_{max}}{H_{Le} - H_{ETe}} \tag{3.8}$$

$$H_{ETe} = H_{Le} - d_0 \tag{3.9}$$

Where:
d_o = extinction depth, specified by the user [L].

A number of different cases can occur based on the computed hydraulic head for an element e (H_e) as shown in Equation 3.7. First, if H_e is below the extinction depth, then the contribution to q_{ET} from element e equals zero, and no groundwater discharge related to evapotranspiration occurs. Second, if H_e is above the extinction elevation (H_{ETe}) and below the ground-surface elevation, the contribution to q_{ET} depends on the difference between H_e and H_{ETe}, and the value of C_{ETe}. Third, if H_e is at or above the land surface, the contribution to q_{ET} is proportional to A_e and ET_{max}.

3.3 PUMPING WELLS

MINEDW has three different options for pumping wells, described below:

1. **Specified-Rate Pumping Well**– The user can specify a pumping rate at a pumping well either to be constant or vary with time. ***MINEDW*** will pump at the specified pumping rate until the node goes dry. Within the output files, ***MINEDW*** will indicate when a pumping node has gone dry. Specified-rate pumping wells are useful in the groundwater flow model calibration to ensure that the modeled pumping well accurately simulates available pumping records.
2. **Specified-Head Pumping Well** – The user can specify head values to maintain in a pumping well that are constant or vary temporally. ***MINEDW*** will extract water from the pumping well at a rate calculated to maintain the head specified by the user.
3. **Lowest Pumping Elevation (LPE) Pumping Well**- The user can specify a pumping rate at a pumping well either to be constant or vary with time. In addition to specifying a pumping rate, the user specifies a lowest pumping head for the well. ***MINEDW*** will extract water at the specified pumping rate until the lowest head condition is met. Once the lowest head condition is met, ***MINEDW*** will decrease the pumping rate to maintain the lowest head condition. If the groundwater system recovers above the lowest head condition, the user-defined pumping rate will be used.

The pumping well boundary condition is used to specify values related to the source-sink term *W* in Equation 2.1, calculated in the general form of Equation 3.10. Equation 3.10 shows the calculation for sources or sinks that occur at a user specified node, as is typically the case for pumping wells.

$$q_P(t) = \sum_{i=1}^{n} Q_{Pi}(t) \tag{3.10}$$

Where:

q_P = functional representation of the internal source-sink fluxes [L^3T^{-1}],
Q_{Pi} = pumping rate at node *i* [L^3T^{-1}], and
n = number of nodes [L°].

The formulation for the pumping rate at node *i* (Q_{Pi}) is different for each of the three types of pumping well as discussed in the following sections.

3.3.1 Specified-Rate Pumping Wells

For specified-rate pumping wells, the Q_{Pi} is simply equal to the user defined value. If the phreatic surface falls below the pumping node, the pumping rate is zero. This is shown in Equation 3.11.

$$Q_{Pi} = \begin{cases} Q_i, for\ H_i > H_{Li} \\ 0, for\ H_i \leq H_{Li} \end{cases} \tag{3.11}$$

Where:

Q_i = user-specified pumping discharge rate at node *i* [L^3T^{-1}],
H_i = calculated hydraulic head at node *i* [L], and
H_{Li} = elevation at node *i* [L].

3.3.2 Specified-Head Pumping Wells

In the case of specified-head pumping wells, the user specifies the head at the pumping node, and the pumping rate is determined by the difference between the specified head and actual head, and the leakance factor. If the phreatic surface falls below the pumping node, the pumping rate is zero. Equation 3.12 shows the formulation for specified head pumping wells.

$$Q_{Pi} = \begin{cases} C_i(H_i - H_{iP}), for\ H_i > H_{iP} \\ 0, for\ H_i \leq H_{iP} \end{cases} \tag{3.12}$$

Where:

C_i = leakance factor for node *i* [L^2T^{-1}], and
H_{iP} = user-specified head at node *i* [L].

3.3.3 Lowest Pumping Elevation Pumping Wells

In the case of LPE pumping wells, the pumping rate is equal to the user-specified rate when the head at the pumping node is greater than the user-specified LPE. If, after pumping at the user-specified rate, the head in the pumping well at the next time step would be equal to or less than the LPE, the pumping rate is reduced in order to maintain the LPE. Thus, the head in the pumping well should not fall below the LPE. This is shown mathematically in Equation 3.13.

$$Q_{Pi} = \begin{cases} C_i(H_i - LPE), \ for\ H_i(\mathrm{Q}_i) \leq LPE \\ Q_i, \ for\ H_i(\mathrm{Q}_i) > LPE \end{cases} \quad (3.13)$$

Where:

LPE = lowest pumping elevation [L],
$H_i(\mathrm{Q}_i)$ = head at node *i* that would result from pumping at rate Q_i [L], and
Q_i = user-specified pumping discharge rate at node *i* [L^3T^{-1}].

LPE wells are commonly used in model simulations for prediction or for testing dewatering well designs because they can give the user information about the maximum pumping rate that can be sustained in a given location.

3.4 VARIABLE-FLUX BOUNDARY

The variable-flux boundary condition simulates boundary fluxes that would result if the modeled flow domain were extended outward a great distance from the actual boundary. This is accomplished by attaching the analytical solution for a semi-infinite linear aquifer to the boundary of the modeled flow domain.

To ensure that the variable-flux boundary conditions are implemented properly, the actual boundary of the model domain should be far enough from the simulated hydraulic stresses such as mining and pumping that their effects at the variable-flux boundary are negligible. The exchange of water at the boundary of the modeled domain related to variable-flux boundary conditions has the general form shown in Equation 3.14.

$$q_v = \sum_{i=1}^{n}[C_{Vi}(H_{Vi} - H_i) + Q'_{Vi}] + \ Q_{V0} \quad (3.14)$$

Where:

q_V = functional representation of the groundwater discharge across the variable flux boundary [L^3T^{-1}],
C_{Vi} = coefficient derived from the analytical solution for a semi-infinite linear aquifer (Equation 3.15) [L^2T^{-1}],
H_{Vi} = steady-state hydraulic head [L],
H_i = computed hydraulic head for the current time step [L],

Q'_{Vi} = discharge across the boundary in the current time step due to head changes at the variable flux boundary in past time steps [L^3T^{-1}],
Q_{V0} = initial discharge across the boundary [L^3T^{-1}], and
n = number of nodes [L°].

The initial discharge across the variable flux boundary (Q_{V0}) must be considered in calculating the discharge across the variable-flux boundaries. This value is typically from the steady-state model, when a constant-head boundary condition was used in place of the variable-flux boundary condition. Therefore, Q_{vo} is the discharge required to achieve the initial head distribution specified for the model.

The coefficient C_{Vi}, the initial discharge Q_{v0}, and the discharge Q'_{Vi} all have non-zero values at each node on the variable-flux boundary and zero values otherwise. The coefficient C_{Vi}, calculated using Equation 3.15, is derived from the analytical solution for discharge from a semi-infinite linear aquifer shown in Equation 3.16.

$$C_{Vi} = \frac{2}{\Delta t}\left[\frac{KBW}{(\frac{\pi K}{S_S})^{\frac{1}{2}}}\right]\Delta t^{\frac{1}{2}} \tag{3.15}$$

Where:
K = hydraulic conductivity of the element associated with node i [LT^{-1}],
B = thickness of the face normal to the direction of variable flux associated with node i [L],
W = width of the face normal to the direction of variable flux associated with node i [L],
S_s = specific storage of the element associated with node i [L^{-1}], and
t = time [T].

The discharge at $x = 0$ for a semi-infinite linear aquifer that extends from $x = 0$ to $x = \infty$ is shown in Equation 3.16 (Carslaw and Jaeger 1959).

$$q_0 = -\left[\frac{KBW}{(\frac{\pi Kt}{S_S})^{\frac{1}{2}}}\right]\Delta h \tag{3.16}$$

Where:
q_o = instantaneous discharge rate at x = 0 [L^3T^{-1}], and
Δh = step change in the boundary head at x = 0 in the semi-infinite aquifer [L].

A positive value of q_o represents discharge from the semi-infinite aquifer into the modeled domain. The average discharge over a specified period of time is found by integrating over the time period and then dividing by the duration of the time period. The integral is shown in Equation 3.17 and evaluated in Equation 3.18.

$$Q_0 = -\frac{1}{\Delta t}\int_{t_1}^{t_2}\left[\frac{KBW}{\left(\frac{\pi K t}{S_S}\right)^{\frac{1}{2}}}\right]\Delta h\, dt \tag{3.17}$$

$$Q_0 = -\frac{2}{\Delta t}\left[\frac{KBW}{\left(\frac{\pi K}{S_S}\right)^{\frac{1}{2}}}\right]\Delta h\left(t_2^{\frac{1}{2}} - t_1^{\frac{1}{2}}\right) \tag{3.18}$$

Where:

Q_0 = average discharge during period t_1 to t_2 [L^3T^{-1}],
t_1 = time to start of a step head change (Δh) [T], and
t_2 = time to end of a step head change (Δh) [T].

Equation 3.18 can be rewritten as shown in Equation 3.19 to demonstrate its consistency with the first term in Equation 3.14.

$$Q_0 = C_{Vi}(-\Delta h_i) \tag{3.19}$$

Where:

$$-\Delta h_i = H_{Vi} - H_i$$

The second term in Equation 3.14, Q'_{Vi}, accounts for discharge related to head changes in all past time steps in which the variable flux boundary condition was applied. The equation for Q'_{Vi}, Equation 3.20, is derived from Equation 3.18 to account for discharge related to head differences in previous time steps.

$$Q'_V = \sum_{j=1}^{m-1}\frac{2}{\Delta t_m}\left[\frac{KBW}{\left(\frac{\pi K}{S_S}\right)^{\frac{1}{2}}}\right]\Delta h_j\left[\left(t_m - t_{j-1}\right)^{\frac{1}{2}} - \left(t_{m-1} - t_{j-1}\right)^{\frac{1}{2}}\right] \tag{3.20}$$

Where:

j = the index for a time step [L°], and
m = the index for the current time step [L°].

3.5 RIVERS

The river function of ***MINEDW*** is an approximation of river flow and its interaction with the groundwater system that can be used to simulate rivers, streams, canals, and/or ditches. The use of the river package in place of a constant-head boundary is dependent on the hydrogeologic setting. For example, if the river depth and head are expected to be unchanging, it is likely that a user should simulate the stream as a constant-head boundary instead of using the river package.

For simplicity, the terms listed below will be used to describe the river package of ***MINEDW***. The terms are also shown in an example river network in Figure 3-2.

River: refers to a surface-water flow body that interacts with the groundwater system such as a river, stream, canal, and/or a ditch.

Reach: refers to the region between user-defined surface-water nodes where interaction between a river and the groundwater system occurs, and river flow properties do not change significantly

Riverbed: area beneath a stream that has physical properties that describe the area of flux between the river and groundwater system.

The river function of ***MINEDW*** is designed to be flexible for users. It includes the following features:

1. Rivers can be automatically assigned based on input files or manually input.
2. The user may define slopes based on ground-surface elevation (i.e. automatically calculating slope depending on the topography assigned in the model) or based on a user-defined constant slope.
3. Riverbed hydraulic conductivity can be defined for each reach or set constant for an entire river.
4. External flow to a river (i.e. external input to a river from a tributary or discharge) can be applied along any river at a constant or time-varying rate.

MINEDW users can define a river based on a series of connected nodes in the model. Numerous rivers can be defined within the ***MINEDW*** model as a river network. River flow is routed from one river to another in the river network. External sources of water (i.e. pipe discharges or river diversions) can be applied along a river. Figure 3-2 shows an example of a network of rivers within a ***MINEDW*** model, including reaches, and tributaries.

Discharge into or out of the model domain related to groundwater exchange with river nodes is calculated using Equation 3.21.

$$q_R = \sum_{i=1}^{n} \begin{cases} C_{Ri}\,(H_{Ri} - H_i), for\ H_i > H_{BOTi} \\ C_{Ri}\,(H_{Ri} - H_{BOTi}), for\ H_i \leq H_{BOTi} \end{cases} \quad (3.21)$$

Where:

q_R = discharge into or out of the groundwater system related to surface water [L^3T^{-1}],
C_{Ri} = riverbed conductance [L^2T^{-1}],
H_{Ri} = elevation of stream water level [L],
H_i = Computed head at node *i* [L], and

H_{BOTi} = elevation of the bottom of the streambed at node *i* [L].

Riverbed conductance (C_{Ri}) is based on four properties: the hydraulic conductivity of the riverbed, the length of the reach, the width of the river, and the thickness of the riverbed. Equation 3.22 shows how riverbed conductance is calculated. Figure 3-2 shows a diagram of the parameters used in the calculation of surface water exchange with the groundwater system.

$$C_{Ri} = \frac{K_S LW}{B} \tag{3.22}$$

Where:

K_s = vertical hydraulic conductivity of the streambed at node *i* [L],
L = length of reach associated with node *i* [L],
W = width of river associated with node *i* [L], and
B = thickness of streambed directly above node *i* [L].

Using Manning's Equation, the flow in the river can be related to the channel geometry in the following equation:

$$Q = \frac{Conv}{n} A R_H^{2/3} S^{1/2} \tag{3.23}$$

Where:

Q = river discharge [L^3T^{-1}]
n = Manning's roughness coefficient [$TL^{-1/3}$],
A = cross sectional area of the river [L^2],
R_H = hydraulic radius (defined in Equation 3.24) [L],
S = slope between adjacent river nodes [L^0], and
Conv = constant for unit consistency [L^0].

The hydraulic radius (R_H) and cross-sectional area (A) in Equation 3.23 are defined as follows:

$$R_H = \frac{wd}{w+2d} \tag{3.24}$$

$$A = wd \tag{3.25}$$

Where:

w = width of the river [L], and
d = depth of the river [L].

Water must be conserved between the surface and groundwater systems, thus the difference between discharge at the upstream and downstream end of the river reach is equal to q_R. This is shown in the water balance in Equation 3.26. In Equation 3.26, Q_{in} is equal to Q_{out} of the immediately upstream reach.

$$q_R = Q_{out} - Q_{in} \tag{3.26}$$

Where:

Q_{out} = discharge at the downstream end of the stream reach [L^3T^{-1}], and

Q_{in} = upstream inflow to the stream reach, including tributary inflow [L^3T^{-1}].

Because the discharge into or out of the groundwater system resulting from interaction with surface water (q_R) is dependent on both the local groundwater head distribution and the elevation of water in the stream, as shown in Equation 3.21, the river function is nonlinear. Using Equations 3.21, 3.23 and 3.26 a non-linear, iterative solution may be found for river depth, which is then used to calculate the amount of discharge into or out of the groundwater system.

4.0 MINING AND CLOSURE

MINEDW was specifically designed for groundwater flow problems related to mining, whether open-pit or underground mining operations. As such, ***MINEDW*** has a specific set of boundary conditions and features that can be applied for mining simulations. For open-pit mining, ***MINEDW*** has the ability to simulate the development of an open-pit mine over time by adjusting the finite element grid and adding drain boundary conditions to simulate seepage from the open-pit walls. Open-pit mining features include:

1. **Open-Pit Development:** Open-pit designs (i.e. contours of the topography) through time can be applied in the groundwater flow model simulations.

2. **Open-Pit Mining Seepage:** ***MINEDW*** can be used to calculate the amount and location of seepage into the open pit over time.

3. **Dewatering and Depressurization**: ***MINEDW*** is capable of easily simulating numerous dewatering and depressurization techniques used in open-pit mining.

4. **Pit Lake after Mining**: After mining and dewatering ends at an open pit, the groundwater system begins to recover. ***MINEDW*** is capable of simulating the infilling of open pits.

5. **Open-Pit Backfilling**: At the end of mining, it is common for mines to backfill their portions of an open pit prior to pit-lake infilling. ***MINEDW*** is capable of simulating a backfill plan through time.

6. **Zone of Relaxation (ZOR)**: Mining and blasting operations in open-pit mines commonly form a ZOR, or an area of altered hydrogeologic properties surrounding the open pit. The ZOR is important when modeling stress release behind the open-pit high wall. ***MINEDW*** has a built-in feature which allows the user to easily simulate a ZOR around an open pit.

MINEDW also can be used to simulate underground mining, using a feature in the GUI that allows to the user to easily create an underground mine plan with drain boundary conditions. The inflows to these drain boundary conditions is the seepage into the underground mine workings. The pore pressure distribution around the mine workings may also be estimated. Additional features available for underground mine simulations include:

1. **Underground-Mine Development:** Underground mining through time can be simulated through the use of drain nodes. ***MINEDW*** features assist the user with tracking seepage in different areas of the mine over time.

2. **Water Level Recovery after Mining (with or without backfilling):** the water level recovery after the cessation of mining may be estimated for workings filled with backfill and without backfill.

3. **Block-Cave Zone**: a common technique in underground mining operation is the use of block caving to extract ore. ***MINEDW*** is capable of simulating the block cave zone and its potential impact on pore-pressure distributions and inflows.

Provided below are the details of each of the mining features and boundary conditions that are available in ***MINEDW***, including their mathematical formulation and common usages.

4.1 OPEN-PIT MINING

MINEDW is capable of simulating open-pit mining through a unique feature specifically designed for ***MINEDW***. ***MINEDW*** collapses the finite-element mesh based on the ground-surface elevations (i.e. open-pit designs) of the open pit. For open-pit mining in ***MINEDW***, the user can define the following:

1. Open-Pit Designs
2. Open-Pit Schedule
3. Multiple Pits
4. Intersecting Open Pits

Any number of open-pit designs can be imported to ***MINEDW***, at any date interval. The user also may simply specify the depth of the pit bottom on certain dates. The open-pit shape between time steps with specified pit plans or depths is determined through interpolation.

MINEDW uses the interpolated mining plans and schedules to simulate the progressive excavation of an open pit during model simulations. The excavation is simulated by collapsing specified elements and their corresponding nodes in the finite-element grid at each time step. The elements and nodes are collapsed such that their elevation is decreased to match the elevation of pit specified in the open-pit mine plans, but their x and y locations are unchanged. Elevation increases of open-pit nodes are not allowed, and in the case of intersecting pits, the lowest elevation is simulated.

4.1.1 Open-Pit Mining Seepage Calculation

The seepage face is represented in terms of the refined finite-element grid, with drain boundary conditions implemented on the ground surface of the open pit. Equation 4.1 shows how seepage from open-pit drain nodes is calculated.

$$q_s = \sum_{i=1}^{n} \begin{cases} C_{Si}(H_{Si} - H_i), & H_i > H_{Si} \\ 0, & H_i \leq H_{Si} \end{cases} \tag{4.1}$$

Where:

q_s = functional representation of the seepage-face discharge [L^3T^{-1}],
C_{Si} = coefficient representing the node *i* on the seepage face [L^2T^{-1}],

H_i = computed hydraulic head at the node *i* [L],
H_{Si} = elevation of node *i* [L], and
n = number of nodes [L^o].

Note that seepage from the groundwater system has a negative sign convention because it is leaving the modeled domain. Seepage discharge is accounted for in the "Mine" portion of the water balance. The seepage-face specified head (H_{Si}) equals the elevation of the node *i* on the open-pit surface if the seepage face is not impacted by the formation of a pit lake, as discussed in Section 4.1.3.

The coefficient C_{si} is non-zero only at nodes on the surface of the open pit. It is sufficient to choose a value that is large enough such that H_i will become close to H_{Si} within a reasonable timeframe. Nevertheless, the value should not be so large such that the difference between H_i and H_{Si} is lost in the precision of the computations.

4.1.2 Dewatering and Depressurization

MINEDW can be used to simulate common dewatering and depressurization techniques such as perimeter dewatering wells, in-pit dewatering wells, sub-horizontal drains, and drainage galleries. Users may easily track the effect of these techniques on dewatering rates, seepage into the open pit, and the pore-pressure distribution. Thus, ***MINEDW*** is a valuable tool for evaluating the effectiveness of various proposed dewatering and depressurization schemes.

4.1.3 Pit-Lake Filling

After the cessation of open-pit mining, the formation of a pit lake may be simulated. During open-pit excavation, drain nodes are used to simulate seepage to the open pit. If a pit lake is simulated, the drain nodes at the surface of the open pit convert to "lake nodes." The head at lake nodes is specified according to the predicted elevation of the pit-lake surface. If the pit-lake elevation is sufficiently high, water may discharge into the groundwater system (this would not be possible if the nodes were still drain nodes). Equation 4.2 shows the formulation for calculating discharge into or out of the pit lake.

$$q_S = \sum_{i=1}^{n} \begin{cases} C_{Si}(H_L - H_i), for\ H_{Si} < H_L \\ C_{Si}(H_{Si} - H_i), for\ H_{Si} \geq H_L\ and\ H_{Si} < H_i \\ 0, for\ H_{Si} \geq H_L\ and\ H_{Si} \geq H_i \end{cases} \quad (4.2)$$

Where:

q_S = functional representation of discharge to or from the pit lake [L^3T^{-1}],
C_{Si} = coefficient representing the node *i* on the open-pit surface [L^2T^{-1}],
H_i = computed hydraulic head at the node *i* [L],

H_{Si} = elevation of node *i* [L],
H_L = water-surface elevation of pit lake [L], and
n = number of nodes [L^o].

The coefficient C_{Si} is the same coefficient used for each node in simulating seepage to the pit while the pit was being excavated. C_{Si} is non-zero for nodes on the surface of the pit and zero elsewhere.

In the first case of Equation 4.2 ($H_{Si} < H_L$), the open-pit node *i* is under the surface of the pit lake. In this case, discharge goes into the groundwater system if the head calculated at the open-pit node is less than the elevation of the pit-lake surface. Discharge exits the groundwater system if the head calculated at the open pit node is greater than the elevation of the pit lake surface.

The second case in Equation 4.2 ($H_{Si} \geq H_L \; and \; H_{Si} < H_i$) describes a scenario where the open-pit node is above the pit-lake surface, and the head calculated at that node is greater than the elevation of the node. In this case, water discharges from the groundwater system to the pit lake.

The third case in Equation 4.2 ($H_{Si} \geq H_L \; and \; H_{Si} \geq H_i$) corresponds to open-pit nodes which are above the pit lake and have a head value less than their corresponding ground-surface elevation. In this case, there is no discharge into or out of the groundwater system.

Equation 4.2 describes discharge to and from the pit lake due to groundwater interactions (q_S). The total discharge to or from the pit lake (q_T) also includes additional user-specified pumping to or from the pit lake (q_P), and evaporation from the pit-lake surface (q_E). The mass balance relationship that defines the q_T is shown in Equation 4.3.

$$q_T = q_S + q_P - q_E \tag{4.3}$$

Where:
q_T = total discharge into or out of open pit [L^3T^{-1}]
q_P = additional pumping to or from pit lake [L^3T^{-1}], and
q_E = discharge related to evaporation [L^3T^{-1}].

The q_P is specified by the user and is not dependent on pit-lake surface area or elevation, though the user may specify a pit-lake elevation at which pumping initiated. The q_E is calculated as shown in Equation 4.4. The evaporation rate from the pit lake may be specified by the user. The q_E is dependent upon the surface area of the pit lake, which changes over time based on the pit-lake elevation (H_L).

$$q_E = r_E A_t \tag{4.4}$$

Where:
r_E = evaporation rate from pit lake [L^1T^{-1}], and

A_t = surface area of pit lake at time step t, which is a function of H_L [L^2].

The cumulative discharge to or from the pit lake over time (Q) is calculated throughout the model run using the average discharge rate over the current time step and the previous time step, as shown in Equation 4.5.

$$Q^t = Q^{t-1} + \frac{q_T^{t-1} + q_T^t}{2} \Delta t \tag{4.5}$$

Where:

Q = cumulative discharge into lake [L^3],
q_T = total discharge rate to the pit lake [L^3T^{-1}],
Δt = time-step length [T].

Each term of Equation 4.5 depends on the pit-lake elevation. Since the pit-lake elevation at a given time step *t* both depends on and informs the local groundwater head distribution, it must be determined iteratively, such that error is minimized within the local groundwater head distribution and the pit-lake formulation.

4.1.4 Zone of Relaxation

Mining activities commonly alter rock properties by unloading stress through the removal of overburden, and by blast damage. Both of these processes increase hydraulic conductivity and porosity through increases in fracture density and aperture. The increase in hydraulic conductivity is generally accepted to be up to three orders of magnitude, and is dependent on rock properties and mining activities (Read and Stacey 2009).

The ZOR is a function in the ***MINEDW*** GUI that enables the user to efficiently simulate altered rock properties due to mining activities. To use the ZOR function, the user specifies a scaling factor (α_j) which the hydraulic conductivity of each affected unit is multiplied by, as shown in Equation 4.6.

$$K_{zj} = \alpha_j K_{0j} \tag{4.6}$$

Where:

K_{zj} = hydraulic conductivity of unit j in ZOR [L^1T^{-1}],
α_j = scaling factor for unit j in ZOR [L^0], and
K_{0j} = initial hydraulic of unit j [L^1T^{-1}].

For simulations of open-pit mining, the thickness of the ZOR around the open pit can be specified by the user, or it can be calculated as a function of the depth of the open pit. This is explained in detail in the ***MINEDW*** manual. The user-specified ZOR has a large effect on the pore-pressure

distribution around the open pit. This tool may be useful for slope-stability analysis which is performed with a pore-pressure input from ***MINEDW***.

4.1.5 Open-Pit Backfill

The filling of an open pit with backfill after the cessation of mining also may be simulated in ***MINEDW***. The user specifies the hydraulic properties of the backfill material. The backfill can be added to the open pit to a constant or varied elevation that the user specifies. Backfilling may occur in any time step following the last pit excavation time step, and is assumed to occur during only one timestep. The pit-lake formation may start on the next time step.

4.2 UNDERGROUND MINING

MINEDW has built in tools to help the user simulate underground mining over time with drain boundary conditions. Additionally, ***MINEDW*** can simulate changes in hydraulic conductivity related to underground mining activities (i.e. block-cave mining), and water-level recovery in underground excavations

4.2.1 Underground-Mine Development

The user specifies drain nodes, as discussed in Section 3.1.2, through which water can discharge from the groundwater system but not into it, to achieve a user-specified head. To simulate an underground mine, the user specifies drain nodes at which the head is equal to the elevation of the mine workings. The nodes are grouped into mining tunnels or workings so that the user can track how much seepage is coming from different mine areas over time.

Each drain node has a user-specified leakance factor C_{di}, as shown in Equation 3.3. The C_{di} is related to the local hydraulic conductivity of the mine walls. For example, a low C_{di} value may be chosen to simulate mine workings which have been grouted, while a high C_{di} value may be chosen for freshly blasted mine workings.

4.2.2 Underground-Mining Recovery and Backfill

The recovery of the water level in and around underground mine workings can be simulated with or without backfill. If backfill is not used, groundwater discharges from the modeled domain into the empty mine workings. This volume cannot be simulated using hydrology concepts because the mine workings are not porous media. In this case, water level recovery is simulated in the same way as pit lakes, using an iterative approach to minimize error between the local groundwater head distribution and the mine working volume to water level relationship. Surface area input is not required because evaporation is assumed to be negligible underground.

In the case of mine workings filled with backfill, the user specifies the hydraulic conductivity and specific yield of the backfill material, as well as the time step at which the mine workings are backfilled. Once water-level recovery begins, all drain nodes which are related to mining are turned off. Seepage into the mine workings fills porosity contained in the backfill material, and the water level in the mine workings is simulated using the same general groundwater flow equations as in the rest of the groundwater model.

4.2.3 Block-Cave Zone

Block-cave mining typically increases the hydraulic conductivity of rock in its vicinity. Block-cave mining can be simulated using a ZOR, similar to the ZOR in open-pit mining (Equation 4.6). The user specifies the elements which are impacted by block-cave mining, a factor to multiply the affected elements by, and the time step at which to apply the factor. The user can specify multiple ZOR units, so that different areas of the block caving zone have different hydraulic conductivity factors. For example, the inner portion of the block caving zone may have a larger hydraulic conductivity factor than the outer portion.

5.0 CLOSURE

MINEDW is a robust groundwater flow code with many built-in features to assist the user in simulating common mining scenarios. The features discussed above allow the user flexibility to simulate groundwater conditions from pre-mining conditions, open pit or underground mine development, and mine closure.

Please refer to the ***MINEDW*** manual and tutorial for more information on constructing and running a ***MINEDW*** model, and contact Itasca with any questions or comments.

6.0 REFERENCES

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