

# Integrated Modeling Innovations for Mining and Underground Infrastructure: Dynamic Mesh Adaptation and Tunnel Boundary Conditions for Surface–Groundwater Systems

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## Abstract

Mining and underground engineering alter coupled surface–groundwater systems, yet their representation remains limited by static meshes and simplified boundary conditions. This study presents an integrated modeling framework within HydroGeoSphere that enables continuous simulation of evolving excavation geometry without model reinitialization and improves tunnel inflow estimation under coarse regional discretization. The dynamic mesh enables continuous simulation of evolving topography during excavation and reclamation, while the boundary formulation improves inflow estimation for underground openings under coarse discretization. Verification and synthetic mining applications demonstrate that the proposed framework reduces discretization-induced inflow errors and improves representation of transient groundwater responses during excavation and reclamation. These developments enhance reliability in mine water management and support safer design of underground infrastructure.

**Keywords:** Integrated modeling, dynamic mesh, tunnel boundary condition, groundwater seepage, groundwater–surface water interaction

## Introduction

Mining and underground construction activities substantially modify hydrologic systems by altering both land surface geometry and subsurface flow pathways. Excavation, tunnelling, and material placement processes introduce significant disturbances to the natural balance between groundwater and surface water systems. These disturbances can lead to changes in groundwater levels, redistribution of surface water, and modification of exchange fluxes between surface and subsurface domains. Such hydrologic alterations are closely linked to environmental protection, water resource sustainability, and the structural safety of engineering systems, particularly in regions where mining operations or underground infrastructure development are extensive.

Accurate prediction of these coupled processes remains challenging due to the complexity of the physical system and the limitations of conventional numerical modeling approaches. Most existing models rely on fixed spatial discretization, where the computational mesh remains unchanged throughout the simulation. While this assumption is reasonable for natural systems with relatively stable geometry, it becomes inadequate in engineering environments where topography evolves continuously due to excavation, backfilling, and landform modification. As a result, traditional approaches often require multiple sequential simulations with updated geometries, which can introduce inconsistencies in mass balance and reduce computational efficiency.

In addition to limitations in representing evolving landscapes, conventional models often simplify the representation of underground openings such as tunnels, shafts, and repositories. These features are typically approximated using coarse discretization or idealized boundary conditions, such as fixed pressure boundaries. However, such simplifications can lead to significant errors in estimating groundwater inflow, particularly when the scale of underground structures is much smaller than that of the regional model domain. This scale mismatch is a critical issue in applications such as mine dewatering, tunnel design, and safety assessment of subsurface infrastructure.

To address these challenges, this study integrates two methodological advancements within a unified modeling framework. First, a dynamic mesh adaptation scheme is introduced to represent time-dependent changes in surface and subsurface geometry, enabling continuous simulation of evolving topography without the need for model reinitialization. Second, an improved tunnel boundary condition is implemented to more accurately represent groundwater inflow into underground openings by accounting for the relationship between tunnel wall pressure and simulated nodal pressure.

These developments are incorporated into HydroGeoSphere (HGS), a fully coupled surface–subsurface modeling framework, allowing for consistent representation of hydrologic processes across spatial and temporal scales. The proposed approach is evaluated through applications relevant to mining and underground engineering, demonstrating its capability to improve predictive accuracy and provide more reliable support for water management and infrastructure design.

## Methods

### *Integrated surface–subsurface modeling framework*

This study employs HGS (Aquanty Inc., 2023) to simulate water flow dynamics under mining and underground engineering conditions. The model solves variably saturated groundwater flow and depth-integrated surface flow simultaneously,

allowing for dynamic interaction between surface water and subsurface systems through exchange fluxes at the interface.

The governing equations are based on mass conservation principles and incorporate key physical processes, including hydraulic conductivity, pressure head, water saturation, and storage effects. The coupling between domains enables consistent simulation of water redistribution across different hydrologic compartments, which is essential for representing complex responses induced by excavation and subsurface infrastructure.

In the HGS model, areal overland flow is represented by a two-dimensional depth-integrated flow equation which is the diffusion-wave approximation of the Saint Venant equation for surface water flow:

$$\nabla \cdot d_o K_o \cdot \nabla h_o \pm Q_o + \Gamma_o = \frac{\partial h_o}{\partial t} \quad (1)$$

where  $d_o$  is the depth of flow,  $h_o$  is the water surface elevation ( $= d_o + z$ ), and  $K_o$  is the surface conductances that are changed with the friction slopes of the surface and is approximated by the Manning's equation in  $x$ - and  $y$ - directions. The modified form of Richards' equation describing three-dimensional transient subsurface flow under variably-saturated conditions is given by:

$$\nabla \cdot k_r \mathbf{K} \cdot \nabla h \pm Q + \Gamma = \frac{\partial}{\partial t} (\theta_s S_w) \quad (2)$$

where  $k_r$  is the relative permeability of the medium as a function of the water saturation  $S_w$  or the pressure head  $\psi$ ,  $\mathbf{K}$  is the hydraulic conductivity tensor,  $h$  is the total head as  $\psi + z$  where  $z$  is the elevation,  $\theta_s$  is the saturated water content,  $Q$  is an externally applied source or sink of water. The fluid exchange between the surface and subsurface is represented by  $\Gamma$ . For the exchange fluxes, separate surface and subsurface flow models can be combined by explicitly coupling the variably-saturated flow and the surface flow equations. In HGS, it is assumed that the two domains are separated by a thin boundary layer. Thus,  $\Gamma_o$  in the governing flow equation represents a first-order exchange between subsurface and surface domains as follows:

$$\Gamma_o = (k_r)_{exch} K_{exch} (h - h_o) / l_{exch} \quad (3)$$



$$\int_V \Gamma dV = - \int_{A_{\text{interf}}} \Gamma_0 dA_{\text{interf}} \quad (4)$$

where  $(k_p)_{\text{exch}}$  is the relative permeability for fluid exchange,  $K_{\text{exch}}$  is the surface/subsurface conductance, and  $l_{\text{exch}}$  is the thickness of the interface layer between surface and subsurface domains. In the coupling equation, a positive  $\Gamma_0$  indicates movement from the subsurface to the surface domain through the interface ( $A_{\text{interf}}$ ). Note that the HGS model is referred to as a fully-integrated globally-implicit model, opposed to linked or iteratively coupled simulators because the governing equations are solved simultaneously with the above coupling equation.

### Dynamic mesh adaptation for evolving topography

To represent time-dependent changes in land surface and subsurface geometry, a dynamic mesh adaptation scheme is implemented within the modeling framework (Hwang *et al.*, 2025). Unlike conventional approaches that rely on fixed meshes, this method updates nodal elevations and element structures during simulation to reflect excavation and material placement processes (Figure 1).

During excavation, surface nodes and corresponding subsurface layers are adjusted to represent reductions in elevation and modifications in geological structure. To maintain numerical stability, minimum element thickness is preserved to avoid degeneracy in the mesh. During material placement, additional layers or adjusted nodal positions are used to represent backfilling and restoration processes.

This approach enables continuous simulation of evolving landscapes without the need for restarting the model between

different stages of engineering operations. As a result, temporal continuity is preserved, and inconsistencies associated with sequential simulations are avoided. The method is particularly suitable for representing open-pit mining, land reclamation, and other engineered landscape transformations.

### Tunnel boundary condition for groundwater inflow

Groundwater inflow into underground openings is represented using an advanced head-dependent boundary condition. Conventional approaches often apply fixed pressure (Dirichlet) boundary conditions along tunnel nodes, which can lead to overestimation of inflow when tunnels are represented in coarse regional models (Figure 2).

To improve accuracy, a Cauchy-type boundary condition is introduced, which relates the tunnel wall pressure to the simulated nodal pressure through a physically based formulation derived from radial flow theory. This approach accounts for the difference between the actual tunnel wall pressure and the numerically computed pressure at model nodes, thereby reducing discretization-induced errors (Park *et al.*, 2020).

The formulation can be extended to incorporate additional engineering features, including excavation damaged zones (EDZ) and grouted zones (GZ), by modifying effective hydraulic properties around the tunnel. This allows for more realistic representation of tunnel-groundwater interactions under varying hydrogeological conditions.

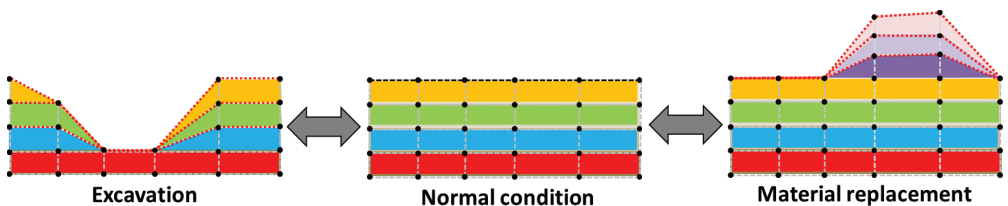


Figure 1 Conceptual illustration of dynamic mesh adaptation for evolving topography: excavation (left), initial condition (center), and material placement (right).

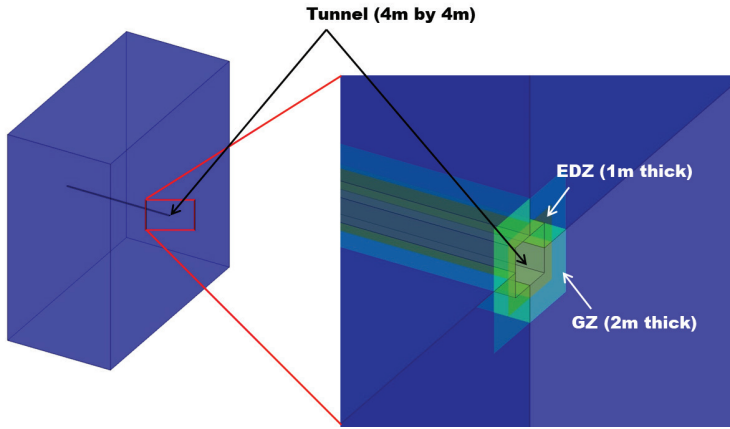


Figure 2 Conceptual representation of a tunnel with excavation damaged zone (EDZ) and grouted zone (GZ) (adapted from Park et al., 2020).

## Results

### Hydrologic response to mining-induced landscape evolution

The integrated modeling framework was applied to synthetic mining scenarios involving excavation and material placement processes over a multi-year period. The results show that excavation induces substantial hydrologic disturbances, including increased surface water accumulation within mining areas and significant groundwater drawdown near excavation zones (Figure 3).

During excavation, surface water tends to accumulate due to localized depressions in topography, while groundwater levels decline as a result of enhanced drainage toward the excavation site. Following the material placement phase, surface water conditions recover relatively quickly; however, the groundwater system exhibits delayed recovery, reflecting the cumulative effects of hydrologic disturbance.

Sensitivity analysis of excavation and backfilling schedules indicates that shorter excavation periods produce more

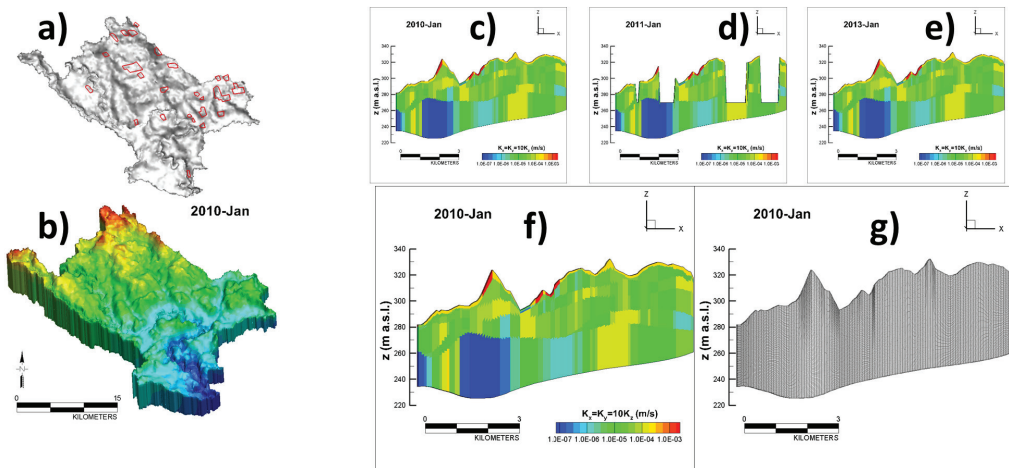


Figure 3 Model domain (a–b) and cross-sectional views showing the spatial distribution of topography and hydraulic conductivity. Temporal snapshots illustrate the evolution of the system at selected simulation times (2010–2013) (c–g).



pronounced transient responses, whereas longer material placement durations lead to more gradual recovery of groundwater levels. These results highlight the importance of operational timing in controlling hydrologic impacts in mining environments.

### Evaluation of tunnel boundary condition

The improved tunnel boundary condition was evaluated by comparing simulated groundwater inflow with analytical and high-resolution numerical solutions. The results indicate that conventional fixed-head boundary conditions tend to overestimate inflow, particularly when tunnels are represented within coarse discretization (Figure 4).

Additional simulations incorporating excavation damaged zones and grouted zones demonstrate that the formulation can effectively represent engineering controls on groundwater inflow. The inclusion of these features allows for realistic evaluation of inflow reduction strategies and tunnel-groundwater interactions.

### Conclusions

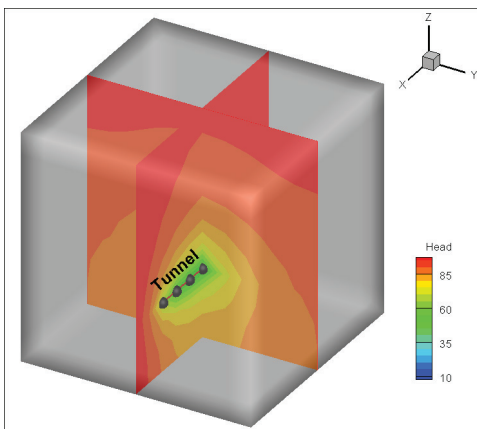
This study presents an integrated modeling framework that combines dynamic mesh adaptation and an advanced tunnel boundary condition to improve the simulation

of hydrologic processes in mining and underground engineering environments. The results demonstrate that both methodological developments address key limitations of conventional numerical models related to static geometry representation and simplified boundary conditions.

The dynamic mesh adaptation scheme enables continuous representation of evolving topography associated with excavation and material placement processes. By updating nodal elevations and mesh structures during simulation, the approach eliminates the need for sequential model restarts and ensures consistency in mass balance. Model verification under both surface flow and groundwater flow conditions confirms that the method accurately captures transient hydrologic responses to time-varying terrain. Applications to mining scenarios show that excavation can induce localized surface water accumulation and groundwater drawdown, while post-reclamation recovery of the groundwater system may be delayed relative to surface conditions.

The improved tunnel boundary condition enhances the accuracy of groundwater inflow estimation into underground openings, particularly in regional-scale models with coarse discretization. By incorporating a physically based relationship between tunnel wall pressure and nodal pressure, the formulation reduces errors associated with conventional fixed-head boundary conditions. The approach is also flexible in representing additional engineering features such as excavation damaged zones and grouted zones, enabling more realistic assessment of tunnel-groundwater interactions.

When combined within a fully coupled surface-subsurface modeling framework, these two advancements provide a robust and scalable approach for simulating complex hydrologic systems influenced by mining and underground infrastructure. The integrated methodology improves predictive capability for key processes such as groundwater drawdown, surface water redistribution, and tunnel inflow, which are critical for mine water management, infrastructure safety, and environmental protection.



*Figure 4 Simulated groundwater head distribution around a tunnel, illustrating drawdown and flow convergence toward the tunnel.*



Overall, this work demonstrates that incorporating dynamic system evolution and physically consistent boundary conditions is essential for advancing next-generation hydrologic modeling. Future research should focus on extending the framework to include coupled hydro-mechanical processes, land-use dynamics, and climate-driven variability to further enhance its applicability to real-world engineering and water resource management challenges.

### Acknowledgements

This work was partially supported through collaborative research efforts with industry partners, including Suncor Energy Inc., whose contributions to project development and technical discussions are sincerely appreciated.

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