# Modelling Complex Mine Water Closure Challenges using a Coupled FEFLOW-GoldSim™ Model

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**Abstract**

A current limitation in modelling pit lake evolution from active mining through closure to optimise management strategies is the separation between physical process and operational modelling tools. To overcome this limitation, a GoldSim™ water balance model of pit operations is dynamically coupled with a FEFLOW, physically-based, model of groundwater inflow to the pit. This approach can be used as part of mine project planning to provide robust estimates of conditions at closure, including an improved representation of the pit lake system physical response, closure cost analysis, and risk assessment through uncertainty analysis.

**Keywords:** GoldSim™, FEFLOW, dynamic coupling, risk assessment, uncertainty analysis

## Introduction

Mine water management strategies can be complex and composed of multiple facets, which depend on operating, physical site, and climatic conditions. Pit lake water management concerns include operational components like: diversions to and from the lake as part of ore processing and management of water at other site facilities; and, maintenance of target lake levels to provide for storage of excess storm water and to limit pumping head. Physical site concerns include groundwater inflow, near-surface, and surface water runoff. Lake evaporation and direct precipitation are often important meteorological conditions for pit lake management strategies.

One of the current limitations in modelling pit lake evolution from active mining through closure to optimise management strategies is the separation between physical process and operational modelling tools. To overcome this limitation, a GoldSim™ water balance model of pit operations is coupled with a FEFLOW, physically-based, model of groundwater inflow to the pit. The combined modelling approach allows detailed and realistic operations, physical site, and climatic representation.

GoldSim™ is Monte Carlo simulation software for dynamic systems modelling in engineering, science and business. It specialises in simulating future performance and representing uncertainty and risk in complex systems (GoldSim Technology Group 2018). A dynamic simulation model is created in GoldSim™ by manipulating graphical objects representing system components; these graphical objects are called "elements" (GoldSim Technology Group 2017). External elements (i.e. a GoldSim™ logical building block) provide dynamic linkage to external computer programs and require specification of outputs of other elements in the GoldSim™ model that will be passed to the external program as well as specification of what the external program will return to the GoldSim™ model (GoldSim Technology Group 2017).

FEFLOW is a comprehensive program for the simulation of flow, groundwater age, mass- and heat-transport processes in porous media (MIKE by DHI 2018). It uses the finite element analysis to solve saturated and unsaturated groundwater flow equations in two- and three-dimensions. FEFLOW provides an open programming interface controlled by the Interface Manager (IFM) to allow coupled simulations with other software programs (MIKE by DHI 2018).

FEFLOW is used to simulate groundwater – lake interaction including groundwater – pit lake interaction. A FEFLOW - lake interaction plugin, IfmLake (DHI WASY GmbH

2018), is freely available that provides for interaction of groundwater and lakes in a FEFLOW model. Wingle and Sinton (2015) created a pit lake module for FEFLOW and used it in simulations of a mine site in the western USA. GoldSim™ has been used extensively in the mining industry to address mine water management and evaluation of mine closure options (GoldSim Technology Group 2018).

Although FEFLOW, and similar physical process models, are commonly used for modelling pit lake evolution, these models tend to be rudimentary in terms of operations-related process representation. Existing operational models, like GoldSim™ water management models, tend to provide limited physical-process simulation abilities. Dynamic coupling of a FEFLOW groundwater flow model of a pit lake system with a GoldSim™ pit lake management model addresses the limitations of each modelling framework.

## Methods

FEFLOW and GoldSim™ provide facilities for dynamic coupling to external software programs. Coupling requires creation of communication channels combined with logic to transform the information from each program into useable formats for the other program. GoldSim™ models are completely flexible in structure; the user completely determines the model logic and structure, and each GoldSim™ pit water management model will have different computational structures and logic implementation. The flexibility of the GoldSim™ modelling framework means that the overall communication and logic structure presented here provides a general template that requires customization for each implementation.

One communication channel option would be to use files. Files are computationally inefficient because one program would write a file; the other program would read the file, process the information in the file, and write the file with the return information. File manipulation and management is considerably slower than inter-process communications through memory.

A better communication channel option is to use queues. A queue is a First In/First Out (FIFO) data structure in memory (Lee, Hubbard 2015). The complete communication structure between GoldSim™ and FEFLOW is handled with three queues as shown in **Figure 1**. Queues provide for inter-process communications, which is communication between the processes owned by GoldSim™ and the processes owned by FEFLOW.

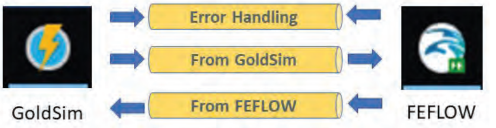


***Figure 1*** *Coupled program structure using queues.*

This queue-centric work pattern that uses queues to pass information among processes, or services, is a common cloud programming pattern (Guthrie, Simms, and others 2014). This type of coupled program structure, requiring consistent and reliable communication between processes or services, would ideally be implemented in a cloud environment as these environments are built specifically for inter-process communication (i.e. communication among services) and provide the communications infrastructure (e.g. queues, distributed cache, and distributed storage). Implementation in a desktop environment is presented here and is achievable with additional communication structure creation and configuration, relative to what would be needed in a cloud environment.

Python programming language modules provide the coupling between GoldSim™ and FEFLOW. Python is used for three reasons: 1) Python DLL for the External element provides integration between GoldSim™ and Python (Martin 2017); 2) Python is integrated with FEFLOW and the FEFLOW IFM (MIKE by DHI 2018); and, the multiprocessing module in the Python Standard Library includes a robust queue implementation (Python Software Foundation 2018).

Coupling of GoldSim™ and FEFLOW for modelling pit lake evolution is implemented using Python modules to link the programs following the procedure provided in **Table 1**. This coupling is dynamic because the programs communicate, or pass information back and forth, for each coupled model time step. Coupling of GoldSim™ and FEFLOW can be extended so that GoldSim™ provides time varying values for recharge, based on a stochastic meteorology model or precipita-

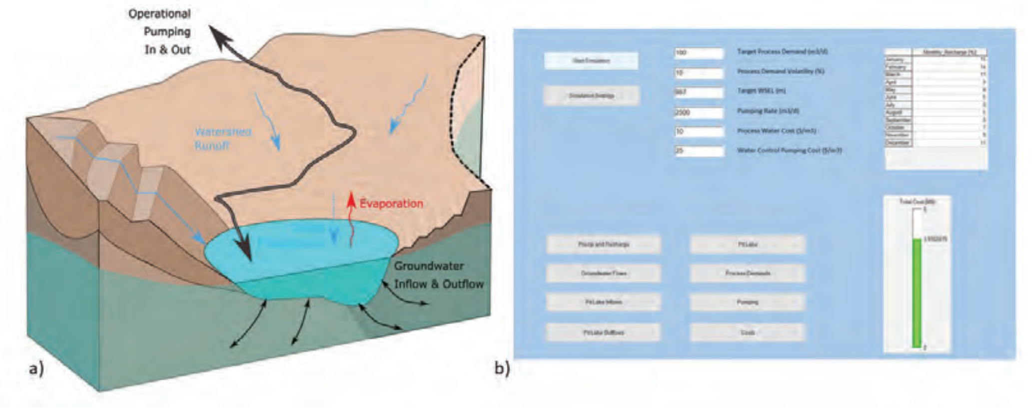


***Figure 2** a) Pit lake water balance schematic and **b)** example application dashboard.*

tion data sets, and elemental Transfer Rates to FEFLOW (Transfer Rates can be set dynamically during a FEFLOW simulation to represent formation of a clogging layer over time (MIKE by DHI 2018)).

***Table 1** GoldSim™ - FEFLOW coupling procedure.*

| Step | Component | Description |
|---|---|---|
| 1.0 | GoldSim | Create pit lake water balance and operations management model for the site. **Figure 2a** displays typical lake/reservoir water balance components. |
| 2.0 | FEFLOW | Create, calibrate and validate a FEFLOW model of the groundwater flow system including the pit. |
| 3.0 | Coupled Model | Couple the models using Python and the three queues so that the FEFLOW model simulates the groundwater inflow and outflow components of the lake water balance shown on **Figure 2a**. |
| 3.1 | Coupled Model - GoldSim | GoldSim™ provides the pit lake water surface elevation to FEFLOW at the beginning of the coupled time step using the "From GoldSim" queue on **Figure 1**. Then, GoldSim™ waits to receive the return information from FEFLOW via the "From FEFLOW" queue in **Figure 1**. |
| 3.2 | Coupled Model - FEFLOW | FEFLOW uses the water surface elevation to set boundary conditions representing the pit lake. |
| 3.2.1 | Coupled Model - FEFLOW | A node selection is identified and stored in FEFLOW that represents the land side of the land – water interface. The IFM is used to go through these nodes and set two types of boundary conditions. |
| 3.2.1.1 | Coupled Model - FEFLOW | Fluid Transfer (Type III) boundary conditions with minimum head constraints (MIKE by DHI 2018) for nodes where the node elevation in the model is less than or equal to the water surface elevation. |
| 3.2.1.2 | Coupled Model - FEFLOW | Seepage Face (Type I with maximum flux constraint of 0.0 m3/d) (MIKE by DHI 2018) boundary conditions for nodes where the node elevation is larger than the water surface elevation. |
| 3.3 | Coupled Model - FEFLOW | FEFLOW simulates forward in time until the end of the coupled time step. The FEFLOW simulation is paused using the IFM and net groundwater inflow to boundary condition nodes is calculated using the IFM. |
| 3.3.1 | Coupled Model - FEFLOW | Net groundwater inflow is the total simulated flux to the boundary condition nodes where inflow to the pit lake is negative and outflow from the pit lake would be positive. |
| 3.4 | Coupled Model - FEFLOW | FEFLOW sends the net groundwater inflow for the pit lake to GoldSim using the "From FEFLOW" queue on Figure 1. Then, FEFLOW waits to receive the next water surface elevation via the "From GoldSim queue on Figure 1. |
| 3.5 | Coupled Model - GoldSim | GoldSim™ uses the net groundwater inflow for the pit lake in its water balance calculation for the coupled time step. The result of this calculation is the water surface elevation for the next coupled time step. |

## Example Application

A hypothetical implementation of a coupled GoldSim™ and FEFLOW, pit water management model is presented to illustrate the coupling process and to highlight the advantages of the coupled model approach. The example application examines the filling of a pit from the start of closure and management of the pit water levels for operational concerns and stormwater control.

A FEFLOW groundwater model of the open pit system is constructed as shown in **Figure 3**. This model is assumed to be calibrated and validated and ready for use in forecasting applications. It is the end of active mining in the pit (i.e. at the start of closure for the pit) and so the initial water table level is just below the bottom of the pit (**Figure 3b**). The model is transient and uses five (5) layers with constant head boundary conditions along the model edges that enforce the hydraulic gradient shown in **Figure 3b**. It is variably saturated and uses the Modified Van Genuchten formulation with spatially uniform parameterization (Unsaturated flow porosity = 0.439; $S_s$ = 1.0; Sr=0.0233, α=0.0314, n=1.1804, m=0.1528, δ=2.2).

A complimentary GoldSim™ pit water management model is also constructed. The GoldSim™ model has the water balance components shown in **Table 1**. It uses a Markov process precipitation simulator (GoldSim Technology Group 2018) to generate daily precipitation depth and a linked stochastic potential evaporation estimator to provide meteorological forcing. A GoldSim™ Dashboard is included in the model (**Figure 2b**) to provide for results visualization and setting of custom operations parameters. **Table 2** provides a description of the operations parameters.

The coupled model is designed for Monte Carlo simulation over a 5-year period. It uses a 1-day time step which means that FEFLOW simulates a day and then passes groundwater inflow information to GoldSim™ and GoldSim™ simulates a day with groundwater inflow rate to update the pit lake water surface elevation for the start of the next day. The stochastic meteorological forcing generates different time series of precipitation and lake evaporation for each realisation.

Each coupled time step, GoldSim™ passes FEFLOW values for pit lake water surface elevation, Inflow and Outflow Transfer Rates for the elements adjacent to the pit lake in FEFLOW, and uniform recharge rate. Recharge rate is calculated using the percentage specification on the dashboard (Figure 2b) and the simulated precipitation rate. A single transfer rate is used for both Inflow and Outflow Transfer Rates, and this transfer rate is sampled from a uniform distribution between 0.01 1/d and 50.0 1/d for each realisation. It is assumed in our hypothetical example that model calibration was not sensitive to Inflow and Outflow Transfer Rates in the 0.01 to 50.0 1/d range; this constrained, but random, se-

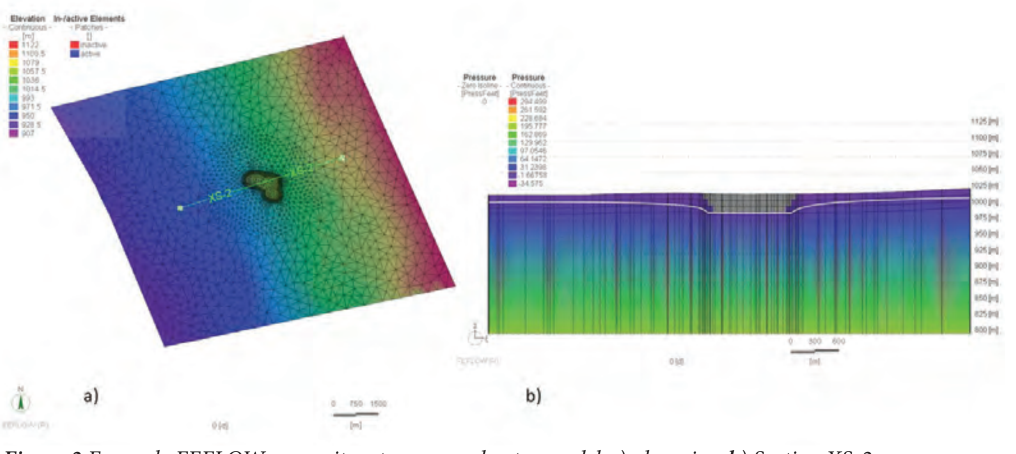


*Figure 3 Example FEFLOW open pit system groundwater model **a)** plan view **b)** Section XS-2.*

*Table 2* GoldSim™ model - pit water balance components.

| Component | Type | Notes |
|---|---|---|
| Direct precipitation | Inflow | Current pit lake surface area ✲ precipitation rate |
| Surface runoff | Inflow | Precipitation rate ✲ runoff coefficient ✲ watershed area |
| Groundwater inflow | Inflow | Calculated by FEFLOW |
| Lake evaporation | Outflow | Calculated with stochastic potential evaporation ✲ pan coefficient ✲ current pit lake surface area |
| Groundwater outflow | Outflow | Calculated by FEFLOW |
| Operations - process demand pumping | Outflow | Operations specified pumping rate to meet process water demands |
| Operations - water level maintenance pumping | Outflow | Pumping to maintain the pit water surface elevation within a target range to provide for stormwater storage |

*Table 3* Operations specifications available on the dashboard.

| Dashboard Item | Descriptions |
|---|---|
| Target Process Demand | History Generator element used to generate process demands. This item provides the target value for the generator. |
| Process Demand Volatility | Volatility specification for the History Generator element |
| Target WSEL | Target pit lake water surface elevation which is used to control pumping to maintain stormwater storage. |
| Pumping Rate | Pumping rate to use when pumping for maintaining target water surface elevation |
| Process Water Cost | Cost allocation for process water demand |
| Water Control Pumping Cost | Cost allocation for pumping to maintain target water surface elevation |
| Operations - water level maintenance pumping | Pumping to maintain the pit water surface elevation within a target range to provide for stormwater storage |

lection of Transfer Rates provides one avenue to incorporating FEFLOW model uncertainty into the coupled model representation. Each coupled time step, FEFLOW returns the net flux to the boundary condition nodes that represent the pit lake.

Figure 4 displays select results for 25 realisations. Figure 4a shows the simulated, probabilistic time history of pit lake water surface elevation. Water surface results provide the integrated solution for all lake water balance components shown on Figure 2a and described in Table 2, including groundwater inflow and outflow. Figure 4b provides the simulated cumulative distribution function (CDF) of total operations cost which provides an estimate of the risk, in terms of possible cost range, provided by the uncertainty in coupled model results.

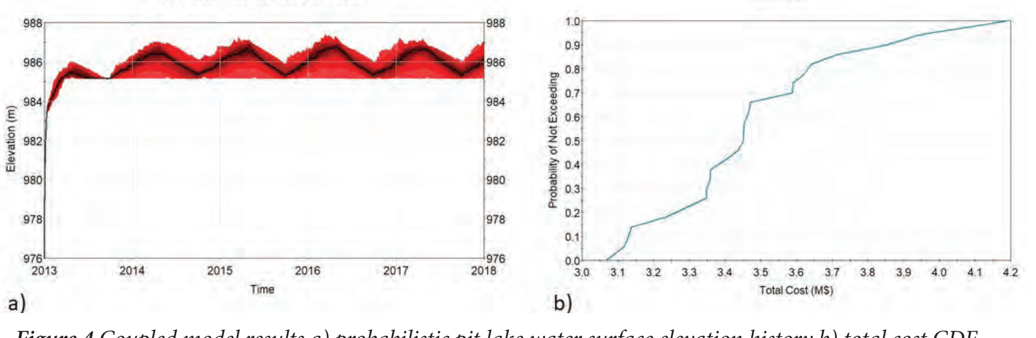


*Figure 4* Coupled model results a) probabilistic pit lake water surface elevation history b) total cost CDF.

## Conclusions

The dynamically-coupled FEFLOW and GoldSim™ pit lake water management model provides a combined operational and physically-based model. This combination allows prediction and examination of the impacts of different operational practices and protocols on the underlying physical site. This approach can be used as part of mine project planning to provide robust estimates of conditions at closure and an improved representation of the pit lake system, physical response, post-closure. The combined pit lake management modelling tool provides for risk assessment via uncertainty analysis, using the built-in uncertainty analysis features of both GoldSim™ and FEFLOW, and for detailed operational cost analysis and comparison, via the built-in financial tools in GoldSim™. Advanced FEFLOW uncertainty analysis could be included in this approach by using a different, calibrated Null Space Monte Carlo distributed parameter representation of system hydrostratigraphy (MIKE by DHI 2018) for each realisation in a coupled model analysis.

The primary drawbacks of the dynamically-coupled FEFLOW and GoldSim™ pit lake water management model approach are complexity and the technical knowledge and skill required to implement the coupling. Dynamic-coupling of computational models is always complicated; in this case the main impediment to a functioning coupled model is impacts of dynamic internal forcing, especially extreme scenario forcing, on FEFLOW model stability during simulations. Technical requirements of coupled model implementation are significant. The need to create custom communication structures for dynamic coupling can be partially alleviated using cloud environments.

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