

The Ground Beneath Changes: Representing Time-Varying Hydraulic Properties in Long-Term Groundwater Models

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Research Article

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Abstract

Groundwater conditions within mining environments evolve continuously throughout mine development, operation, rehabilitation and closure. Despite this, many closure groundwater models use static hydraulic-property assumptions that may not adequately represent changing hydrogeological conditions. This study presents a practical framework for implementing time-varying hydraulic conductivity and storage-property schedules within a regional groundwater model to simulate mine development, landform rehabilitation, tailings consolidation and groundwater recovery. The methodology was applied to underground mine workings, residual pit-lake materials and rehabilitated tailings storage facilities within an integrated mine closure groundwater assessment. Results demonstrate that time-varying hydraulic-property representations improve simulation of groundwater recovery, seepage reduction and long-term equilibration processes. The approach provides a practical method for incorporating closure processes into predictive groundwater-flow models and supports improved understanding of post-closure groundwater behaviour.

1. Introduction

Hydraulic properties are among the most influential parameters in groundwater modelling because they govern groundwater flow, storage, recharge response, hydraulic connectivity, and groundwater-system behaviour (Bear, 1979; Anderson et al., 2015).

Conventional groundwater models commonly assume that hydraulic conductivity, specific yield, specific storage, and hydraulic connectivity remain constant throughout the simulation period. While such assumptions may be appropriate for short-term assessments, they become increasingly difficult to justify when simulations extend over decades or centuries (Hill & Tiedeman, 2007; Doherty, 2015).

Many natural and engineered hydrogeological systems evolve continuously through time. Examples include:

- consolidation of deposited materials;
- groundwater recovery following disturbance;
- modification of hydraulic connectivity;
- stabilisation of engineered landforms;
- progressive saturation and desaturation;
- weathering and geochemical alteration;
- changes in fracture behaviour and groundwater storage.

These processes may substantially alter hydraulic conductivity, specific yield, specific storage, porosity, and groundwater connectivity through time (Fetter, 2018; Refsgaard et al., 2007).

Despite this reality, relatively few published studies provide practical methodologies for incorporating evolving hydrogeological conditions into long-term groundwater models. Consequently, many long-term assessments rely on static parameterisation despite acknowledging that hydrogeological conditions will continue to evolve.

This study presents a practical framework for implementing time-varying hydraulic-property schedules within transient groundwater models. The framework links conceptual hydrogeological evolution directly to parameter transitions and provides a transferable methodology for representing changing groundwater systems through time.

1.1 Study Objectives

The objectives of this study are to:

- examine the conceptual basis for representing time-varying hydraulic properties;
- develop a practical framework for implementing hydraulic-property transitions within transient groundwater models;
- evaluate the influence of hydraulic-property evolution on groundwater recovery and seepage behaviour;
- assess the benefits and limitations of time-varying hydraulic-property schedules; and
- provide a transferable methodology for long-term groundwater assessment.

More broadly, the study aims to demonstrate that hydraulic properties should be viewed as evolving hydrogeological states rather than fixed calibration parameters.

2. Conceptual Basis for Time-Varying Hydraulic Properties

Hydrogeological systems rarely remain static over long timescales. Natural processes and engineered disturbances continuously modify groundwater storage, hydraulic conductivity, pore structure, fracture connectivity, and groundwater-flow behaviour.

Examples include:

- development of subsurface voids;
- progressive increase in hydraulic connectivity;
- deposition and consolidation of engineered materials;
- rehabilitation of disturbed landforms;
- groundwater recovery and rebound;
- geotechnical adjustment and settlement;
- weathering and geochemical evolution.

These processes influence:

- hydraulic conductivity (K);
- specific yield (Sy);
- specific storage (Ss);
- effective porosity; and
- hydraulic connectivity.

Importantly, these parameters rarely evolve independently. Changes in hydraulic conductivity are frequently accompanied by changes in groundwater storage and connectivity. Consequently, long-term groundwater simulations require a systems-based perspective in which parameter evolution reflects conceptual hydrogeological change rather than numerical calibration alone.

The conceptual evolution of hydraulic properties through time is illustrated in Fig. 1.

3. Study Site and Groundwater Model

The study was undertaken for a large integrated mining operation comprising:

- Underground mine workings;
- Tailings storage facilities;
- Waste-rock landforms;
- Water-management infrastructure; and
- A residual pit lake.

A transient groundwater model was developed using FEFLOW (Diersch, 2014; Trefry & Muffels, 2007).

Principal model characteristics are summarised in Table 1.

Table 1
Generalised Model Characteristics

Category	Description
Model Type	Three-dimensional transient groundwater model
Simulation Horizon	Long-term
Property Representation	Time-varying
Assessment Purpose	Groundwater recovery and system evolution
Major Processes	Recovery, consolidation, connectivity change
Output Metrics	Hydrographs, budgets, gradients, migration pathways

The assessment incorporated progressive hydraulic-property changes throughout operations, rehabilitation and closure.

4. Methodology

4.1 Time-Varying Property Framework

Time-varying hydraulic-property schedules were developed to represent anticipated changes in hydrogeological conditions through time.

The framework assumes that hydraulic-property evolution is controlled by identifiable physical processes rather than arbitrary numerical adjustment. Property schedules were therefore linked directly to conceptual hydrogeological changes expected during system development, disturbance, rehabilitation, recovery, and long-term stabilisation.

Property transitions may include:

- increasing hydraulic connectivity;
- evolving groundwater storage;
- consolidation of deposited materials;
- reduction of seepage processes;
- groundwater-system recovery;
- stabilisation of disturbed hydrogeological environments.

The implementation workflow adopted in this study is presented in Fig. 2.

4.1.1 Linking Parameter Evolution to Physical Processes

A distinguishing feature of the methodology is that parameter evolution is explicitly linked to conceptual hydrogeological processes.

Rather than treating hydraulic conductivity and storage parameters as static calibration values, hydraulic-property schedules are used to represent expected physical changes occurring throughout system evolution. This approach improves consistency between conceptual understanding and numerical representation while maintaining transparency regarding future assumptions.

4.2 Underground Mine Workings

Underground mine domains were represented using time-varying hydraulic conductivity and storage-property schedules.

During mine development:

- Hydraulic conductivity increased;
- Hydraulic connectivity increased;
- Effective groundwater storage increased.

Following closure:

- Hydraulic connectivity decreased;
- Hydraulic gradients diminished;
- Groundwater storage stabilised.

Representative property assumptions are summarised in Table 2.

Table 2
Example Hydraulic Property Schedule

Simulation Stage	Relative Hydraulic Conductivity	Relative Storage
Initial State	Low	Low
Development	Increasing	Increasing
Transitional Phase	Moderate	Moderate
Recovery	Stabilising	Stabilising
Equilibrium	Stable	Stable

4.3 Time-Varying Tailings Properties

Tailings storage facilities were assigned property schedules representing:

- Tailings deposition;
- Increasing saturation;
- Consolidation;
- Rehabilitation;
- Long-term closure conditions.

Hydraulic conductivity and storage properties were progressively reduced to represent continued consolidation and rehabilitation of deposited materials.

4.4 Residual Pit-Lake Materials

The residual pit lake was represented using separate property schedules for:

- Pit-water body;
- Pit infill materials; and
- Surrounding geological units.

Progressive reductions in storage properties were adopted to represent stabilisation and consolidation of pit infill materials.

Representative assumptions are summarised in Table 3.

Table 3 Example Time-Varying Storage Schedule	
Relative Time	Relative Specific Yield
Initial Condition	High
Transitional Phase	Moderate
Recovery Phase	Reduced
Equilibrium Phase	Stable

5. Results

Comparison between static-property and time-varying-property representations demonstrated that groundwater-system response was sensitive not only to assigned parameter values but also to the timing of parameter transitions. The influence of property evolution became increasingly important as recovery proceeded and hydraulic gradients diminished.

Application of time-varying hydraulic-property schedules produced system responses that differed substantially from equivalent simulations employing static hydraulic-property assumptions.

The greatest differences occurred during periods of rapid hydrogeological adjustment when hydraulic gradients, groundwater storage, and hydraulic connectivity evolved simultaneously. These results indicate that long-term groundwater behaviour may be strongly influenced not only by hydraulic-property values themselves but also by the timing and magnitude of parameter transitions.

Representative model behaviour is summarised conceptually in Fig. 3.

6. Discussion

6.1 Importance of Time-Varying Hydraulic Property Representation

The principal advantage of time-varying hydraulic-property representation lies in its ability to preserve consistency between conceptual hydrogeological understanding and numerical implementation.

Static-property models implicitly assume that hydrogeological conditions remain unchanged throughout the assessment period. In contrast, long-term groundwater systems frequently evolve through physical, hydraulic, geotechnical, and environmental processes.

Incorporating hydraulic-property evolution therefore allows groundwater models to respond dynamically to changing hydrogeological conditions and improves simulation of:

- groundwater recovery;
- seepage behaviour;
- storage response;
- hydraulic connectivity; and
- long-term equilibration.

Representation of changing hydrogeological conditions reduces the conceptual disconnect that frequently occurs when static parameters are used to represent systems known to evolve through time.

Similar observations have been reported in studies examining long-term mine closure behaviour (Younger, 2002; ICMM, 2019).

6.2 Benefits of Time-Varying Property Representation

Several benefits were identified through application of the methodology:

- improved conceptual realism;
- more realistic representation of groundwater recovery;
- improved simulation of seepage reduction and stabilisation;
- stronger linkage between rehabilitation assumptions and groundwater response;
- greater transparency of conceptual-model assumptions;
- improved communication of long-term hydrogeological behaviour.

An additional benefit is that time-varying approaches provide a transparent mechanism for linking closure assumptions directly to model behaviour. Rather than embedding closure processes implicitly within calibrated parameter values, the modeller can explicitly represent hydrogeological evolution and communicate the underlying assumptions more effectively to regulators, reviewers, and stakeholders.

The methodology provides a practical mechanism for translating conceptual hydrogeological evolution into transient numerical simulations.

Importantly, the approach enables model assumptions regarding recovery, rehabilitation, and long-term adjustment to be represented explicitly rather than being embedded implicitly within calibrated parameter values.

Several practical benefits were identified through application of the methodology. The principal benefits and limitations are summarised in Table 4. Time-varying hydraulic-property schedules improve conceptual realism, strengthen linkage between conceptual understanding and numerical

implementation, and provide a more transparent representation of hydrogeological evolution through time.

Table 4

Principal benefits and limitations associated with implementation of time-varying hydraulic-property schedules in long-term groundwater simulations.

Benefit	Implication
Improved conceptual realism	Better representation of hydrogeological evolution
Improved recovery simulation	More realistic groundwater-response trajectories
Improved seepage representation	Better simulation of changing hydraulic conditions
Explicit linkage to physical processes	Greater transparency of modelling assumptions
Improved long-term prediction capability	Better support for environmental assessment and planning
Limitation	Implication
<i>Increased parameter uncertainty</i>	<i>Requires sensitivity analysis and justification</i>
<i>Additional calibration complexity</i>	<i>More supporting data may be required</i>
<i>Greater implementation effort</i>	<i>Increased model setup and management time</i>
<i>Dependence on conceptual assumptions</i>	<i>Requires defensible hydrogeological interpretation</i>

6.3 Implications for Long-Term Groundwater Assessment

The results indicate that long-term groundwater predictions may be highly sensitive to assumptions regarding the timing, direction, and magnitude of hydraulic-property evolution.

Consequently, uncertainty assessment should extend beyond absolute parameter values and incorporate alternative trajectories of parameter change through time.

This finding has broader implications because many long-term groundwater assessments acknowledge hydrogeological evolution conceptually while continuing to implement static parameterisation numerically.

The results demonstrate that representation of hydrogeological change may be as important as representation of initial hydrogeological conditions when predicting future groundwater behaviour.

Future applications would benefit from:

- ensemble hydraulic-property schedules;
- scenario-based parameter transitions;
- uncertainty analysis of property evolution trajectories; and

- explicit representation of hydrogeological change mechanisms.

7. Conclusions

Hydrogeological systems evolve continuously through time, yet long-term groundwater simulations frequently assume static hydraulic properties.

This study demonstrates that time-varying hydraulic-property schedules provide a practical framework for representing changing hydraulic conductivity, groundwater storage, and hydraulic connectivity within transient groundwater models.

The key findings indicate that:

- hydrogeological systems rarely behave as static environments over long timescales;
- representation of evolving hydraulic properties improves conceptual realism;
- groundwater recovery and seepage behaviour are sensitive to hydraulic-property transitions;
- explicit representation of hydrogeological evolution improves consistency between conceptual understanding and model behaviour; and
- time-varying hydraulic-property schedules provide a transferable framework applicable to a broad range of groundwater-management and environmental-assessment challenges.

The principal contribution of this study is the recognition that hydraulic properties should be considered evolving hydrogeological states rather than fixed calibration parameters. By linking parameter transitions directly to physical hydrogeological processes, the methodology improves long-term prediction capability and provides a more defensible basis for representing changing groundwater systems through time.

Declarations

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Consent for Publication: Not applicable.

Author Contribution

Y.Y. conceptualized the study, developed the research framework and methodology, conducted the literature review, designed the time-varying hydraulic-property approach, performed the groundwater modelling analysis, interpreted the hydrogeological results, prepared all figures and tables, wrote the original manuscript, revised the manuscript, and approved the final version of the manuscript.

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Figures

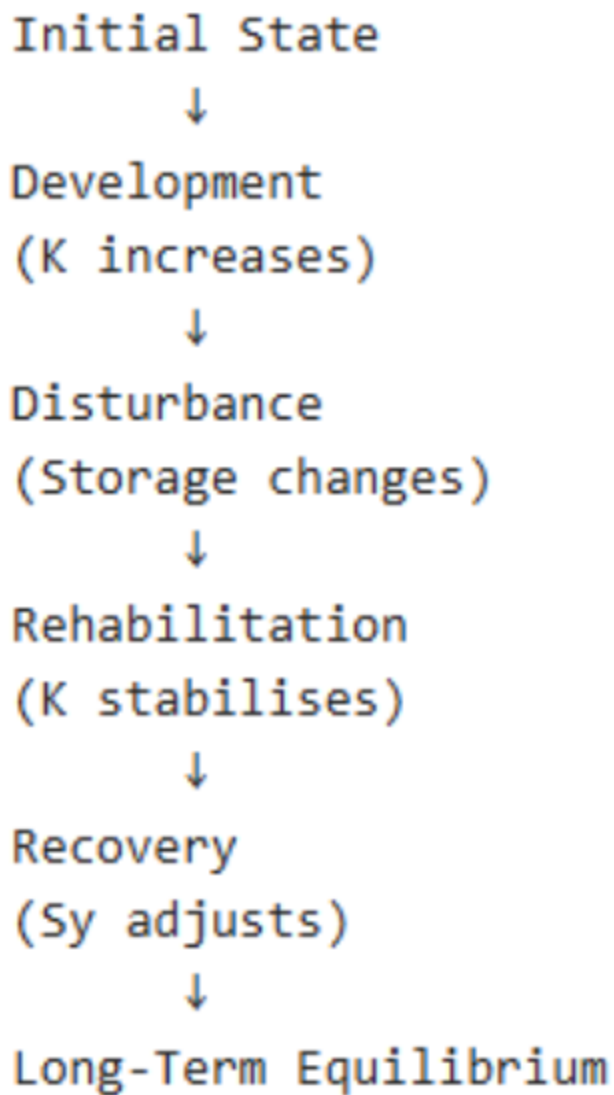


Figure 1

Conceptual representation of hydrogeological evolution showing changing hydraulic conductivity (K), specific yield (Sy), and hydraulic connectivity throughout system development, rehabilitation, recovery, and long-term equilibrium.

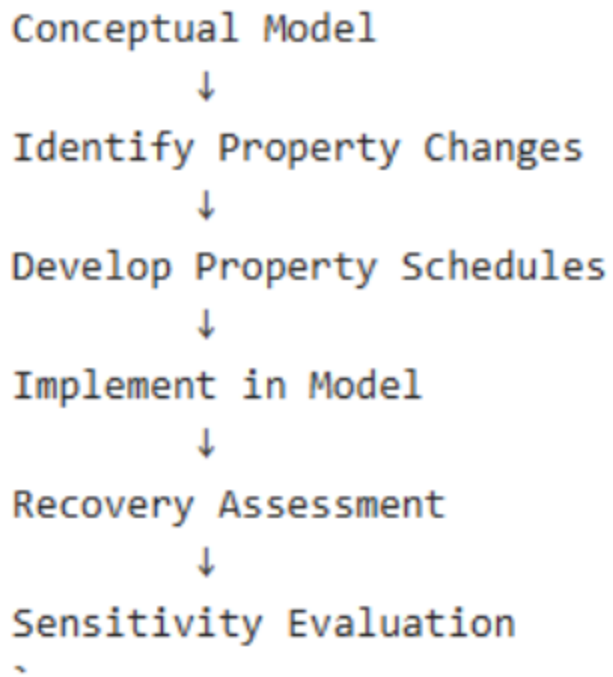


Figure 2

Generalised workflow for implementation of hydraulic-property schedules in long-term groundwater models.

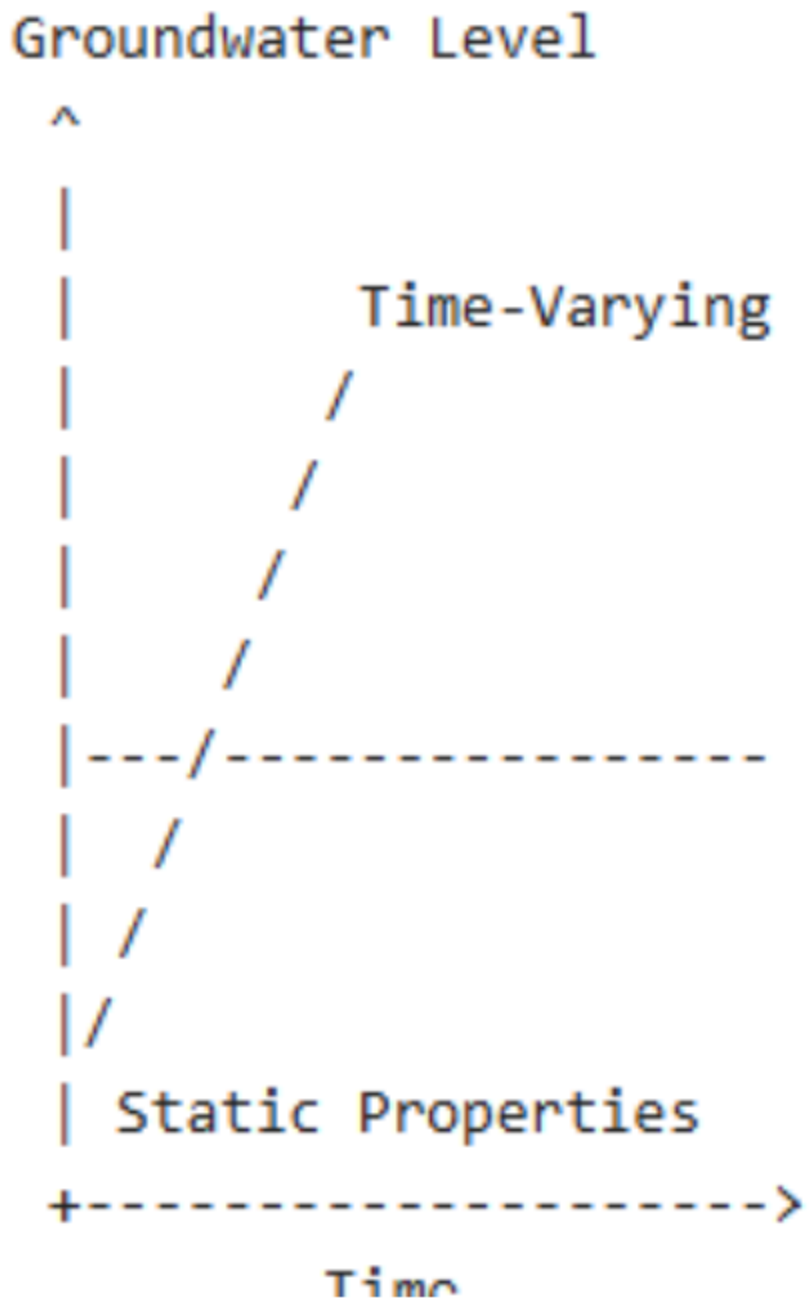


Figure 3

Comparison of groundwater-recovery behaviour under static-property assumptions and time-varying-property assumptions.