

Tracing Groundwater Pathways Through Time: Integrating Particle Tracking, Groundwater Recovery, and Receptor Connectivity

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Research Article

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Abstract

Groundwater level recovery is commonly evaluated in long-term groundwater assessments; however, groundwater levels alone provide limited information regarding migration pathways, receptor connectivity, and groundwater travel times. Particle tracking provides a complementary approach by identifying likely groundwater-flow pathways within evolving hydrogeological systems.

This study presents a long-term particle-tracking assessment within a transient groundwater model representing a recovering groundwater system. Forward particle tracking was applied to evaluate groundwater migration pathways, travel times, hydraulic connectivity, and receptor interactions under long-term recovery conditions. Groundwater budgets, groundwater hydrographs, contour maps, and particle-tracking results were integrated to provide a comprehensive interpretation of groundwater movement through time.

Results indicate that groundwater migration follows evolving pathways controlled by hydraulic gradients and regional hydrogeological conditions. Groundwater initially migrates toward local recovery features before progressively reconnecting with regional groundwater-flow systems during long-term recovery. Particle-tracking results reveal that hydraulic connectivity may persist over extended timescales, while groundwater-budget analyses demonstrate that groundwater exchange can occur simultaneously in multiple directions. The study highlights the value of integrating particle tracking, groundwater budgets, and groundwater recovery analyses to improve understanding of long-term groundwater behaviour and receptor connectivity.

1. Introduction

Mine closure assessments increasingly require evaluation of groundwater migration pathways and potential receptor connectivity associated with rehabilitated mine landforms (ICMM, 2019; McCullough et al., 2020). Groundwater-level predictions alone provide limited insight into the pathways followed by groundwater or the time required for groundwater to migrate between source zones and potential receptors (Anderson et al., 2015; Fetter, 2018).

Particle tracking has become a widely applied method for evaluating groundwater migration pathways and travel times within numerical groundwater models (Pollock, 1988; Pollock, 2012). Particle-tracking techniques use simulated groundwater velocity fields to estimate likely groundwater movement through time and can be used to identify potential hydraulic connectivity between mine facilities and environmental receptors.

Closure groundwater systems are particularly complex because groundwater flow patterns evolve throughout the recovery process. Hydraulic gradients associated with mine dewatering progressively diminish following closure, groundwater levels recover and local groundwater-flow systems interact with rehabilitated landforms and residual pit lakes (Younger et al., 2002; ICMM, 2019). Similar post-disturbance groundwater responses have been documented in mine dewatering and recovery

assessments where groundwater movement remained active long after operational changes ceased (Yihdego & Drury, 2016; Yihdego & Paffard, 2016).

This study presents a particle-tracking assessment undertaken within a transient groundwater model to evaluate groundwater migration from a rehabilitated tailings storage facility under long-term closure conditions.

While particle tracking is widely used within groundwater models, it is commonly treated as a visualisation tool rather than a decision-support framework. The novelty of this study lies in integrating particle tracking, groundwater budgets, groundwater recovery analysis, and receptor connectivity into a unified hydrogeological interpretation framework. The paper demonstrates how pathway evolution, travel-time behaviour, and groundwater-system recovery can be assessed together to improve environmental risk evaluation and long-term groundwater management.

1.1 Study Objectives

The objectives of this study are to:

- evaluate long-term groundwater migration pathways within a recovering groundwater system;
- estimate groundwater travel times to key receptors;
- assess groundwater connectivity between source areas and downgradient environments;
- investigate how migration pathways evolve during long-term groundwater recovery; and
- demonstrate the value of integrating particle tracking with groundwater budgets, hydrographs, and contour mapping.

More broadly, the study aims to provide a transferable framework for interpreting groundwater migration and receptor connectivity in long-term groundwater assessments.

2. Conceptual Hydrogeological Framework

The assessment considers a representative groundwater system recovering from historical hydraulic disturbance. The system contains local hydraulic features, regional groundwater-flow pathways, and multiple zones of groundwater interaction.

Groundwater migration occurs within a heterogeneous hydrogeological framework controlled by geological structures, hydraulic gradients, recharge processes, and regional groundwater-flow conditions. Similar pathway complexity has been documented in lake–aquifer systems and structurally controlled groundwater environments where hydraulic connectivity extends beyond local hydrogeological boundaries (Yihdego & Becht, 2013).

The conceptual framework adopted for the assessment is shown in Fig. 1.

3. Numerical Groundwater Model

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

The model incorporated:

- Underground mine workings;
- Tailings storage facilities;
- Residual pit-lake systems;
- Recharge and evapotranspiration processes;
- Time-varying hydraulic properties; and
- Closure-specific groundwater recovery processes.

Key model characteristics are summarised in Table 1.

Table 1
Generalised Groundwater Model Characteristics

Item	Description
Model Type	Three-dimensional transient groundwater model
Software	Finite-element groundwater modelling platform
Simulation Duration	Approximately 500 years
Recovery Conditions	Long-term groundwater recovery
Particle Tracking	Forward particle tracking
Primary Objective	Groundwater migration pathways
Secondary Outputs	Hydrographs, budgets, contour maps

4. Particle Tracking Methodology

Particle tracking was undertaken using groundwater velocity fields generated from the transient groundwater model.

Forward particle tracking was selected to identify likely groundwater migration pathways originating from representative source areas within the groundwater system.

The particle-tracking workflow adopted in this study is illustrated in Fig. 2.

5. Results

5.1 Groundwater Migration Pathways

Groundwater migration pathways represent one of the most important outputs of long-term groundwater assessments because they provide information on hydraulic connectivity that cannot be inferred from groundwater levels alone. Particle-tracking analyses indicated that groundwater originating from representative source areas migrated first through intermediate groundwater-interaction zones before progressively reconnecting with the broader regional groundwater-flow system.

The results demonstrate that migration pathways evolve through time as hydraulic gradients diminish and groundwater recovery progresses. During the early recovery period, particle trajectories were strongly influenced by local hydraulic features, while longer-term migration increasingly reflected regional groundwater-flow conditions. Recent large-scale particle-tracking studies demonstrate that groundwater pathways may extend much further than previously assumed and frequently involve regional and inter-basin groundwater connections (Yang et al., 2025).

The conceptual migration framework adopted in this study is illustrated in Fig. 3.

The results indicate that groundwater migration should not be viewed as a static process. Instead, migration pathways evolve continuously as groundwater systems transition from disturbed conditions toward long-term equilibrium.

5.2 Groundwater Travel Times and Connectivity

Groundwater travel times provide an important measure of hydraulic connectivity between source areas and potential receptors.

Particle-tracking analyses suggest that groundwater connectivity develops progressively through time and may occur over multiple timescales. Shorter travel times are generally associated with local groundwater-interaction zones and areas of strong hydraulic connectivity, whereas longer travel times are associated with regional groundwater-flow systems and distant receptors. Emerging groundwater-connectivity research increasingly recognises connectivity as a dynamic property influenced by groundwater pathways, recharge patterns, and hydrogeological architecture rather than distance alone (Dwivedi et al., 2025).

Representative groundwater travel-time categories are summarised in Table 2.

Table 2
Generalised travel-time categories used for interpretation of groundwater migration and receptor connectivity.

Migration Endpoint	Relative Travel Time
Local Recovery Zone	Short
Intermediate Groundwater Interaction Zone	Moderate
Regional Groundwater System	Long
Distant Receptors	Very Long

The results demonstrate that travel times alone do not define environmental significance. Instead, travel times should be interpreted together with groundwater budgets, groundwater-flow directions, hydrogeological conditions, and receptor characteristics.

The particle-tracking assessment further confirms that hydraulic connectivity may persist long after groundwater systems appear to have recovered when evaluated using groundwater-level trends alone. Consequently, groundwater migration and receptor connectivity should form an integral component of long-term groundwater assessments.

5.3 Relationship with Groundwater Recovery

Groundwater migration pathways evolved throughout the recovery period as hydraulic gradients progressively diminished.

During early recovery stages, groundwater movement was strongly influenced by local hydraulic disturbances and recovery features. As groundwater systems stabilised, migration pathways became increasingly controlled by regional hydrogeological conditions.

These observations demonstrate that groundwater recovery and groundwater migration should not be interpreted independently because changes in hydraulic gradients directly influence groundwater travel paths and hydraulic connectivity.

Comparable changes in groundwater movement during recovery have been observed in post-mining groundwater systems where evolving hydraulic gradients altered migration pathways through time (Yihdego & Paffard, 2016).

6. Relationship Between Particle Tracking and Groundwater Budgets

6.1 Groundwater Interaction

Groundwater-budget analyses indicate that groundwater exchange commonly occurs in multiple directions simultaneously.

Groundwater inflow, groundwater outflow, recharge, and storage change collectively influence migration pathways and groundwater connectivity. Consequently, interpretation of migration pathways requires understanding of groundwater budgets as well as particle-tracking results.

Groundwater-budget and pathway analyses therefore provide complementary perspectives on groundwater-system behaviour. Similar integration of hydraulic response and groundwater migration has proven valuable in dewatering and recovery studies (Yihdego & Drury, 2016).

6.2 Why Some Pathways Terminate

Not all particle pathways continue throughout the entire simulation period.

Potential explanations include:

- groundwater discharge;
- evapotranspiration losses;
- low groundwater velocities;
- groundwater stagnation zones;
- geological heterogeneity;
- local hydraulic controls.

Consequently, apparent pathway termination should not automatically be interpreted as cessation of groundwater movement.

6.3 The Difference Between Connectivity and Impact

Particle tracking provides information regarding pathway connectivity and travel times but does not quantify seepage volumes, contaminant concentrations, or mass transport.

This distinction is important because hydraulic connectivity alone does not imply environmental impact. Additional groundwater-budget analysis, transport modelling, and water-quality assessment are often required to evaluate risk.

Additional transport modelling would be required to address these questions (Anderson et al., 2015).

7. Discussion

The study demonstrates that integration of groundwater budgets, groundwater recovery assessments, contour mapping, and particle tracking provides a stronger understanding of groundwater migration than any individual technique alone.

Particle tracking identifies likely migration pathways and travel times, while groundwater budgets explain the hydraulic processes that sustain those pathways. When interpreted together, these approaches improve confidence in groundwater-system conceptualisation and receptor assessment.

The methodology highlights the importance of evaluating groundwater migration in the context of evolving groundwater systems rather than assuming static flow conditions.

Similar conclusions have been reported in groundwater recovery and dewatering assessments where groundwater pathways, recharge dynamics, and recovery processes could only be fully understood through integration of groundwater budgets and migration analysis (Yihdego & Drury, 2016; Yihdego & Paffard, 2016).

The integrated pathway framework aligns with recent recommendations for science-informed groundwater decision-making that combine groundwater modelling, connectivity assessment, and regulatory interpretation (Curran et al., 2023).

8. Conclusions

A long-term particle-tracking assessment was undertaken to evaluate groundwater migration pathways within a recovering groundwater system.

The results demonstrate that:

- groundwater migration pathways evolve through time;
- groundwater connectivity may persist for extended periods;
- migration pathways respond to changing hydraulic gradients;
- groundwater budgets provide essential context for interpreting particle-tracking results;
- hydraulic connectivity does not necessarily imply environmental impact; and
- integration of multiple groundwater assessment techniques improves interpretation of groundwater behaviour.

The principal contribution of this study is demonstrating how particle tracking, groundwater budgets, contour mapping, and groundwater recovery analyses can be interpreted together to provide a more complete understanding of groundwater migration and receptor connectivity.

Declarations

Competing Interests

The author declares no competing interests.

Ethics Approval and Consent to Participate

Not applicable.

Consent for publication

Not applicable.

Clinical Trial Number

Not applicable.

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Author Contribution

Y.Y. conceptualized the study, developed the groundwater migration and particle-tracking methodology, designed the conceptual hydrogeological framework, conducted the groundwater-flow and particle-tracking analyses, interpreted the hydrogeological results, prepared all figures and tables, performed the literature review, wrote the original manuscript, revised the manuscript, and approved the final version for submission.

Data Availability

All relevant information supporting the findings of this study is contained within the manuscript.

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Figures

Source Area



Groundwater Recovery Zone



Groundwater Interaction Zone



Regional Groundwater System



Potential Receptors

Figure 1

Conceptual framework illustrating groundwater migration from local source areas through intermediate groundwater interaction zones toward regional groundwater-flow systems and potential receptors.

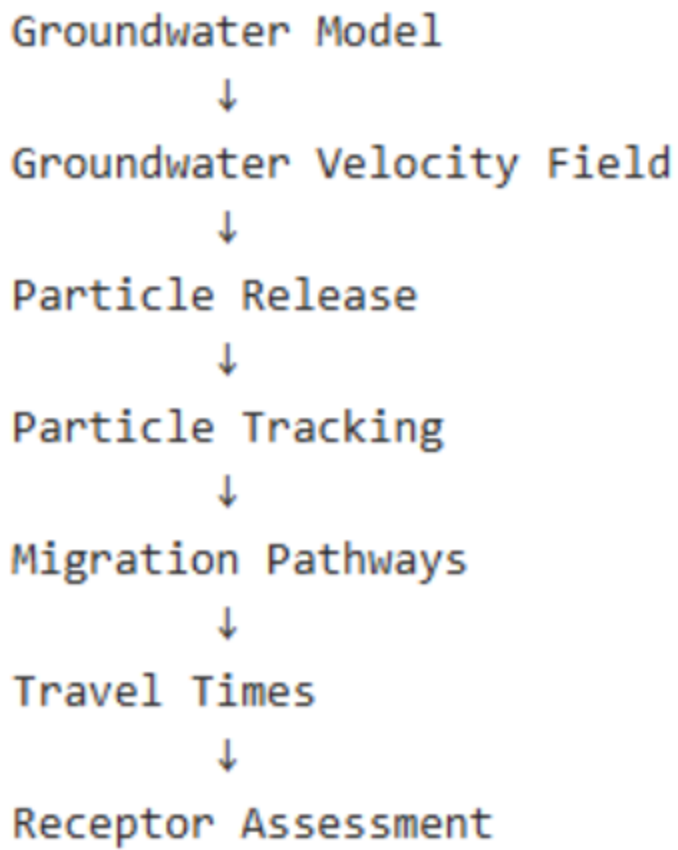


Figure 2

Workflow used to evaluate groundwater migration pathways, travel times, hydraulic connectivity, and receptor interactions within a transient groundwater-flow model.

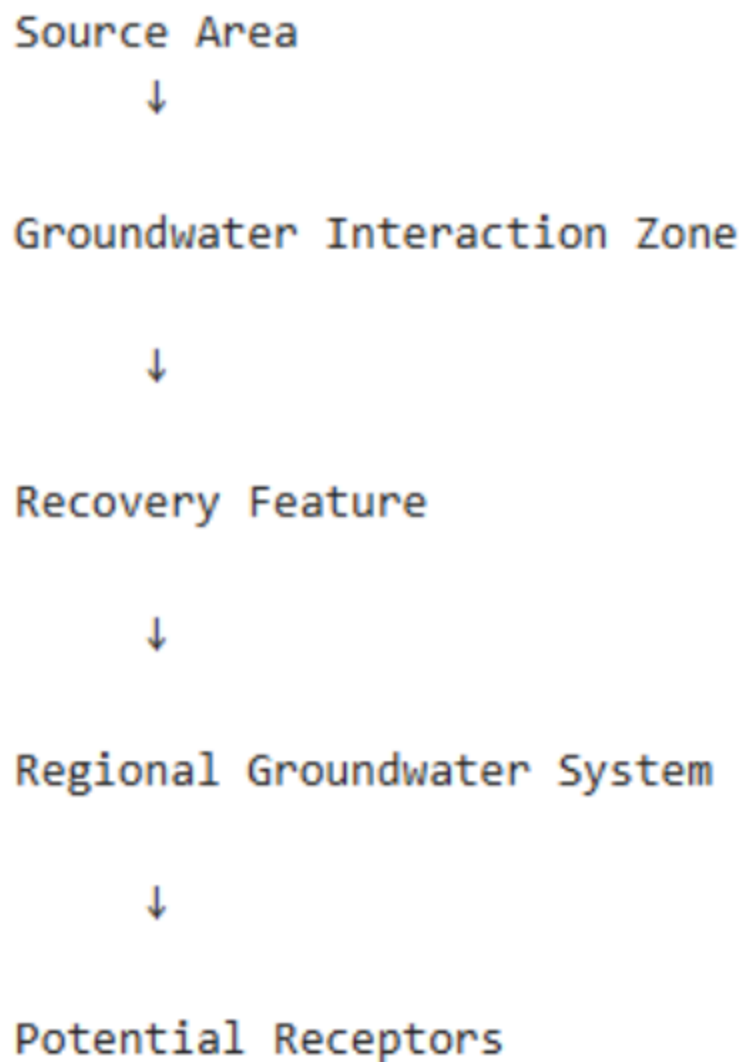


Figure 3

Conceptual groundwater migration pathways illustrating movement from representative source areas through local groundwater-interaction zones and towards regional groundwater-flow systems. Pathway evolution reflects progressive adjustment of hydraulic gradients during groundwater recovery.