

Where Does the Water Go? Revealing Long-Term Groundwater Migration Pathways Using Particle Tracking

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Research Article

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Abstract

Groundwater level recovery is commonly assessed in environmental and groundwater management studies; however, water-level behaviour alone provides limited insight into groundwater migration pathways, receptor connectivity, and travel times. Particle tracking has become an important complementary technique because it evaluates groundwater movement directly and identifies potential pathways between source areas and environmental receptors. This study presents a long-term groundwater migration assessment using particle tracking integrated with groundwater-flow modelling, groundwater budgets, and hydraulic-gradient analysis. A generic groundwater system subjected to long-term recovery was simulated over a multi-century period to investigate pathway evolution, travel times, groundwater connectivity, and receptor interactions.

Results demonstrate that groundwater migration pathways evolve through time as hydraulic gradients progressively dissipate. Groundwater initially migrates toward local hydraulic sinks and recovery features before reconnecting with broader regional groundwater-flow systems. Travel times vary substantially depending on hydraulic gradients, geological controls, and hydrogeological connectivity. Groundwater-budget analyses reveal that groundwater exchange may occur simultaneously in multiple directions, explaining why migration pathways can extend beyond intermediate groundwater interaction zones. The study highlights the importance of integrating particle tracking with groundwater budgets, contour interpretation, and hydrograph analysis when evaluating groundwater connectivity and long-term environmental risk.

1. Introduction

Groundwater migration pathways are fundamental to understanding groundwater-system behaviour, environmental risk, contaminant transport, groundwater-resource sustainability, and receptor connectivity ((Dwivedi et al., 2025; Yang et al., 2025).

Groundwater models are commonly used to evaluate groundwater levels, groundwater recovery, recharge processes, and hydraulic gradients. While these outputs provide valuable information regarding groundwater-system behaviour, they do not directly reveal where groundwater travels, how long migration takes, or which receptors may ultimately be affected (Fetter, 2018; Pollock, 2012).

Particle tracking provides a complementary approach by following groundwater movement through simulated velocity fields. The technique allows identification of migration pathways, hydraulic connectivity, travel times, and receptor interactions that may not be evident from groundwater-level information alone (Dennedy-Frank et al., 2024; Kourakos et al., 2024).

Increasingly, environmental assessments require evaluation of:

- groundwater connectivity;
- receptor vulnerability;

- contaminant migration;
- source attribution;
- environmental risk;
- closure performance; and
- long-term groundwater behaviour.

These questions fundamentally concern groundwater movement rather than groundwater levels.

Despite widespread application of groundwater modelling, groundwater migration pathways remain comparatively under-reported relative to groundwater-level results. Consequently, greater integration of particle tracking, groundwater budgets, and conceptual hydrogeological interpretation is needed. Contemporary groundwater research increasingly emphasises groundwater connectivity, pathway evolution, and receptor interaction as critical components of environmental decision-making and sustainability assessment (Benavides Höglund et al., 2024; Dwivedi et al., 2025).

1.1 Study Objectives

The objectives of this study are to:

- evaluate long-term groundwater migration pathways;
- examine groundwater travel times and receptor connectivity;
- investigate how migration pathways evolve during groundwater-system recovery;
- integrate particle tracking with groundwater budgets and hydraulic interpretation; and
- develop a transferable framework for groundwater-pathway assessment.

More broadly, this study demonstrates that understanding where groundwater travels may be as important as understanding groundwater levels themselves.

1.2 Novel Contribution

The novelty of this study lies in demonstrating that groundwater migration pathways, travel times, and receptor connectivity often provide more meaningful information for environmental assessment than groundwater levels alone. While groundwater recovery studies commonly focus on hydraulic response, this paper integrates particle tracking, groundwater budgets, connectivity analysis, and receptor evaluation into a unified framework for interpreting long-term groundwater movement and environmental significance.

2. Conceptual Hydrogeological Framework

Groundwater movement is controlled by hydraulic gradients, hydraulic conductivity, recharge, geological structures, and groundwater connectivity. Recent investigations have shown that groundwater connectivity and hydrological linkages frequently exert greater control on migration behaviour than

groundwater levels alone, particularly where groundwater interacts with rivers, lakes, wetlands, and environmental receptors (Brunner et al., 2009; Barthel & Banzhaf, 2016; Dwivedi et al., 2025).

Groundwater may migrate through:

- regional flow systems;
- fracture networks;
- weathered zones;
- alluvial environments;
- groundwater interaction zones;
- recharge environments; and
- groundwater discharge areas.

Particle tracking evaluates these pathways directly by following water movement through simulated velocity fields. Modern particle-tracking frameworks have increasingly been applied to evaluate travel times, source attribution, groundwater–surface water interaction, and long-term pathway evolution across a wide range of groundwater settings (Dennedy-Frank et al., 2024; Kourakos et al., 2024).

The conceptual groundwater migration framework adopted in this study is illustrated in Fig. 1.

3. Groundwater Modelling and Particle Tracking

A transient three-dimensional groundwater model was used to represent long-term groundwater-system behaviour.

The assessment integrated:

- groundwater-flow simulation;
- groundwater-level recovery;
- groundwater budgets;
- contour interpretation; and
- particle tracking.

Forward particle tracking was selected because it provides direct information regarding groundwater migration from source areas toward environmental receptors. Particle tracking is increasingly recognised as one of the most effective approaches for evaluating groundwater connectivity, transport pathways, capture zones, and receptor interaction because it directly represents groundwater movement rather than groundwater-level response alone (Pollock, 2012; Dennedy-Frank et al., 2024).

The principal characteristics of the modelling framework are summarised in Table 1.

Table 1
Generalised groundwater-model characteristics adopted for groundwater migration and connectivity assessment.

Item	Description
Model Type	Three-dimensional transient groundwater model
Assessment Period	Long-term recovery period
Particle Tracking	Forward tracking
Recovery Representation	Fully transient
Outputs	Hydrographs, groundwater budgets, contours, pathways
Assessment Objective	Migration pathways and receptor connectivity

As shown in Table 1, the assessment combines multiple complementary outputs rather than relying on a single modelling metric. This allows groundwater migration, recovery behaviour, connectivity, and receptor interactions to be evaluated simultaneously.

4. Particle Tracking Methodology

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

The workflow included:

1. Development of groundwater-flow simulation.
2. Generation of groundwater velocity fields.
3. Definition of source areas.
4. Particle release.
5. Pathline simulation.
6. Travel-time evaluation. Travel-time assessment has become an increasingly important component of environmental decision-making because travel time often provides more useful information regarding risk and receptor interaction than groundwater levels alone (Harvey & Gooseff, 2015; Dwivedi et al., 2025).
7. Assessment of receptor connectivity.

The methodology is summarised in Fig. 2.

5. Results

5.1 Groundwater Migration Pathways

Particle tracking identified groundwater pathways connecting source areas with regional groundwater-flow systems.

Migration pathways evolved through time as groundwater recovery reduced hydraulic gradients and modified groundwater connectivity. Similar behaviour has been reported in lake–aquifer systems where evolving hydraulic gradients altered groundwater connectivity and long-term migration pathways (Yihdego & Becht, 2013; Yihdego et al., 2017).

Initially, pathways were strongly influenced by local hydraulic conditions. With time, migration increasingly reflected regional hydrogeological controls.

The results demonstrate that migration pathways are dynamic and should not be interpreted as fixed features.

5.2 Groundwater Travel Times

Groundwater travel times varied substantially between migration pathways. Recent particle-tracking investigations demonstrate that groundwater travel times may vary significantly even within the same groundwater system because pathway geometry, connectivity, and storage conditions strongly influence migration behaviour (Dennedy-Frank et al., 2024; Kourakos et al., 2024).

Shorter travel times were associated with:

- strong hydraulic gradients;
- highly conductive pathways;
- direct hydraulic connectivity.

Longer travel times were associated with:

- diffuse groundwater movement;
- weaker gradients;
- complex groundwater interactions.

Representative travel-time categories are summarised in Table 2.

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

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

As shown in Table 2, travel time is strongly dependent on the position of the receptor within the groundwater-flow system and the connectivity of migration pathways. These categories provide a practical framework for screening receptor interactions and interpreting groundwater migration behaviour.

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.

The changing travel-time relationships summarised in Table 2 demonstrate that pathway evolution influences not only groundwater migration patterns but also potential receptor exposure and environmental response.

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

6. Relationship Between Particle Tracking and Groundwater Budgets

6.1 Groundwater Interaction

Groundwater-budget analysis indicated that groundwater exchange occurred simultaneously in multiple directions. This observation is consistent with contemporary studies showing that groundwater exchange frequently occurs through multiple interconnected pathways operating across different spatial scales (Brunner et al., 2009; Barthel & Banzhaf, 2016).

Groundwater inflows, groundwater outflows, recharge, and storage adjustment collectively influenced migration behaviour.

Particle tracking therefore provides connectivity information, while groundwater budgets explain the hydraulic processes sustaining migration pathways.

6.2 Why Some Pathways Terminate

Not all particle pathways continued throughout the simulation period.

Possible explanations include:

- groundwater discharge;
- evapotranspiration losses;
- stagnant groundwater zones;
- low groundwater velocities;
- geological heterogeneity;
- hydraulic barriers.

Consequently, apparent pathway termination does not necessarily imply 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. Connectivity assessments increasingly emphasise the distinction between physical groundwater pathways and environmental consequence because receptor exposure, travel times, and transport processes ultimately determine environmental significance (Dwivedi et al., 2025; Yang et al., 2025). Travel-time information, such as the categories presented in Table 2, helps explain how groundwater may move between source areas and receptors, but additional groundwater-budget analysis, transport modelling, and water-quality assessment are often required to evaluate environmental significance.

Consequently, particle tracking should be considered one component of a broader groundwater-assessment framework rather than a standalone impact-assessment tool.

7. Discussion

The study demonstrates that integration of groundwater budgets, particle tracking, groundwater connectivity analysis, hydraulic interpretation, and receptor assessment provides a more complete understanding of groundwater-system behaviour than groundwater levels alone. Recent groundwater research increasingly recognises that migration pathways, travel times, and groundwater connectivity are

critical components of environmental assessment because they provide direct information regarding groundwater movement and receptor interaction (Harvey & Gooseff, 2015; Benavides Höglund et al., 2024).

The groundwater-model framework summarised in Table 1 provides the physical basis for migration assessment, while the travel-time categories presented in Table 2 support interpretation of connectivity and receptor interaction.

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. Geological uncertainty continues to influence pathway prediction and groundwater connectivity assessment, reinforcing the importance of combining particle tracking with strong conceptual hydrogeological understanding (Ntigkakis et al., 2026; Delottier et al., 2023).

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

8. Conclusions

This study demonstrates that understanding groundwater levels alone is insufficient for assessing groundwater migration, receptor connectivity, and environmental risk.

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 modelling framework summarised in Table 1 and the travel-time categories presented in Table 2 demonstrate how groundwater migration can be interpreted in a structured and transferable manner across a range of groundwater environments.

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.

The findings further demonstrate that migration pathways, groundwater connectivity, and travel times frequently provide more meaningful information for environmental assessment than groundwater levels alone because they directly explain how groundwater interacts with receptors through time.

The methodology provides a transferable framework for groundwater-pathway assessment applicable to groundwater management, environmental impact assessment, closure planning, groundwater sustainability, and environmental risk evaluation.

Declarations

Author Contributions

Y.Y. conceived the study, developed the conceptual framework, conducted the analysis and literature synthesis, prepared the figures and tables, interpreted the findings, wrote the manuscript, revised the manuscript, and approved the final version.

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Competing Interests

The author declares no competing interests.

Data Availability

No new datasets were generated or analysed during this study. All information supporting the findings and conclusions is contained within the published literature cited in the manuscript.

Ethics Approval

Not applicable.

Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

Conflict of Interest

The author declares that there are no competing interests, financial interests, or personal relationships that could have influenced the work reported in this manuscript.

Clinical Trial Registration

Not applicable. This study does not involve human participants, patient data, animals, clinical trials, or clinical interventions.

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Figures

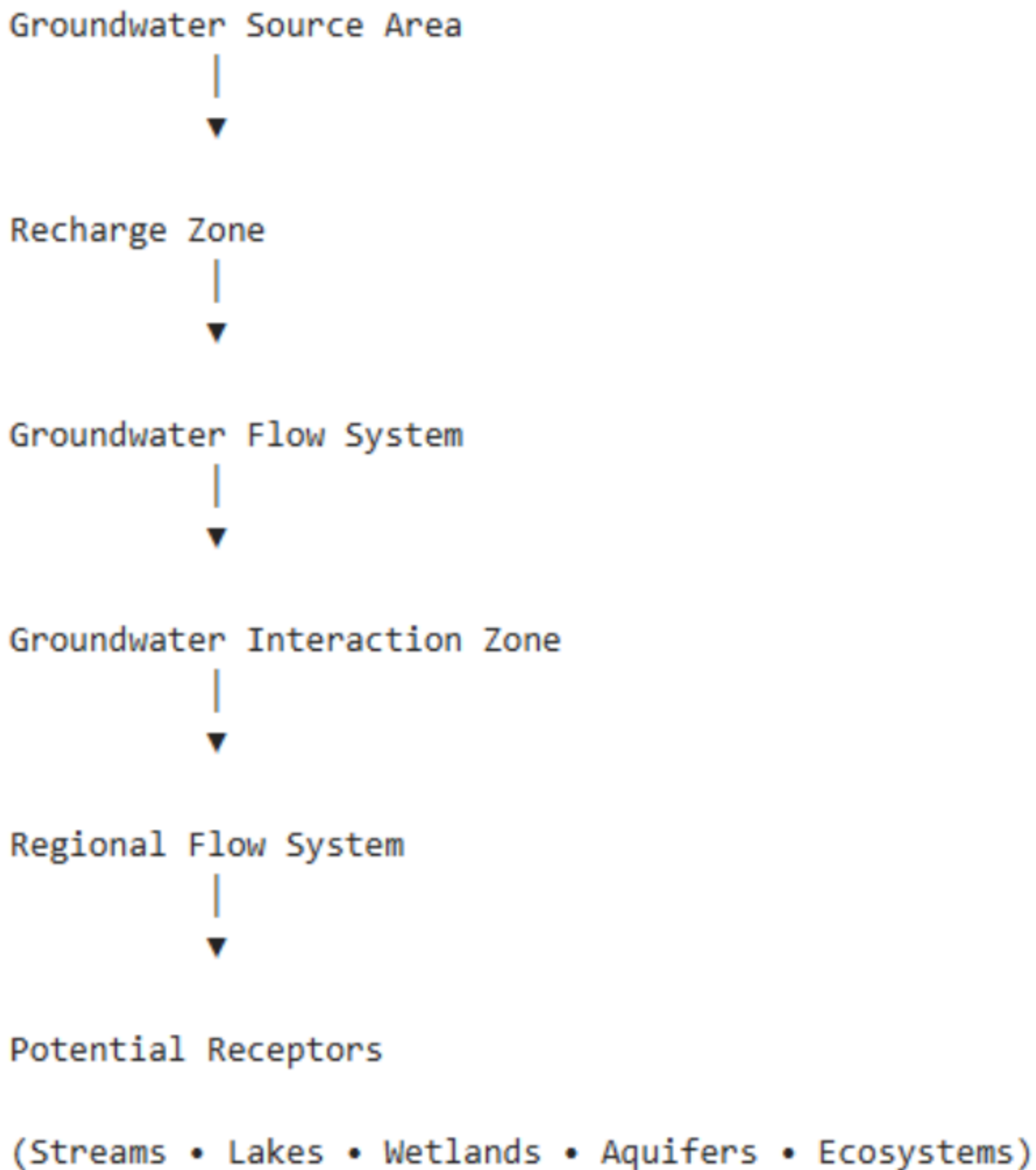


Figure 1

Conceptual groundwater migration framework showing groundwater movement from source areas through groundwater interaction zones and regional groundwater systems toward potential environmental receptors.

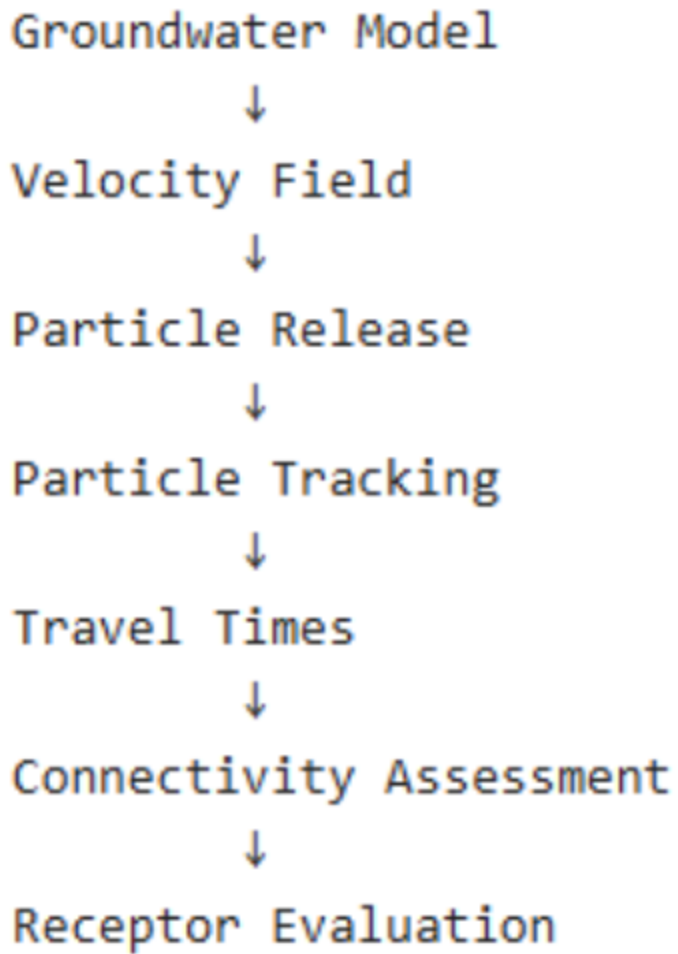


Figure 2

Workflow used to evaluate groundwater migration pathways, travel times, hydraulic connectivity, and receptor interactions.