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Groundwater Travel Time Does Not Automatically Translate into Environmental Harm

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Research Article

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Abstract

Groundwater travel time is widely used in hydrogeological investigations, contamination assessments, groundwater vulnerability studies, mine closure planning, and environmental impact assessments because it provides a measure of how rapidly groundwater can migrate between sources and receptors. However, travel time alone provides limited insight into environmental significance. Short travel times do not necessarily imply environmental harm, while long travel times do not automatically indicate low risk. Environmental consequences depend on the combined influence of source characteristics, pathway behaviour, groundwater connectivity, attenuation processes, receptor sensitivity, and environmental value.

This paper examines the relationship between groundwater travel time, groundwater connectivity, receptor exposure, and environmental consequence. Drawing upon recent advances in groundwater connectivity, environmental risk assessment, receptor-based evaluation, and decision-support modelling, the study demonstrates why travel time should be interpreted as a pathway characteristic rather than an impact metric. Practical examples from contamination assessment, water-supply protection, mine closure, and groundwater-dependent ecosystems are used to illustrate how identical travel times can produce substantially different environmental outcomes.

A receptor-centred travel-time framework is proposed that integrates source–pathway–receptor principles, travel-time behaviour, connectivity assessment, receptor sensitivity, and environmental consequence. The framework demonstrates that environmental significance emerges from receptor interaction rather than travel time alone. By moving beyond travel-time metrics and towards consequence-based interpretation, the study provides a more robust basis for groundwater assessment, environmental risk evaluation, groundwater management, and regulatory decision-making.

1. Introduction

Groundwater travel time is one of the most widely reported outputs in groundwater modelling, groundwater vulnerability assessment, contamination investigations, wellhead protection studies, mine closure planning, and environmental impact assessment. It provides an estimate of how rapidly groundwater, dissolved constituents, and environmental signals can migrate between a source area and a potential receptor. As a result, travel time is frequently used as an indicator of groundwater risk and environmental significance.

The increasing use of particle tracking, groundwater age dating, groundwater connectivity analysis, and integrated groundwater-flow modelling has significantly improved the ability of hydrogeologists to evaluate migration pathways and receptor interactions. Recent studies increasingly emphasize that groundwater pathways, groundwater connectivity, and travel-time behaviour provide critical information for understanding groundwater-system evolution, environmental exposure, and long-term sustainability (Benavides Höglund et al., 2024; Irvine et al., 2024; Dwivedi et al., 2025; Yang et al., 2025).

Despite its widespread use, groundwater travel time is often misinterpreted as a direct measure of environmental consequence. A common assumption is that short travel times imply high environmental risk whereas long travel times imply low environmental risk. Although intuitively appealing, this interpretation is frequently incorrect. Travel time describes the efficiency and timing of groundwater migration, but environmental significance depends upon a much broader set of factors including contaminant persistence, attenuation mechanisms, groundwater connectivity, receptor sensitivity, environmental value, and exposure potential.

Recent groundwater and environmental-assessment literature increasingly recognize that hydrogeological indicators alone do not determine environmental significance. Groundwater pathways may exist without causing environmental harm, contaminants may attenuate before reaching receptors, and receptors may differ substantially in their sensitivity to groundwater-system change (Delottier et al., 2023; Hill et al., 2024; Winde & Newman-Portela, 2026). Consequently, groundwater movement and environmental consequence should not be considered equivalent.

The distinction becomes particularly important in applied groundwater investigations. In groundwater contamination studies, travel time is often used to estimate exposure potential. In mine closure assessments, travel time is frequently used to evaluate long-term migration pathways. In drinking-water protection studies, travel time helps define source-protection zones. However, identical travel times may produce substantially different environmental outcomes depending on the characteristics of the receiving receptor and the behaviour of contaminants during migration.

Hydrological connectivity studies further demonstrate that groundwater movement occurs within complex and dynamic pathway networks rather than along simple linear connections. Transport pathways may evolve through time as groundwater gradients, recharge conditions, groundwater storage, and groundwater–surface water interactions change (Dwivedi et al., 2025; Yang et al., 2025). Consequently, interpretation of travel time requires an understanding of both pathway behaviour and receptor interaction.

Practical examples from groundwater investigations support this perspective. Evaluations of groundwater influence zones have demonstrated that the spatial extent of groundwater impact does not necessarily correspond to environmental consequence because significance depends on receptor sensitivity and environmental value rather than groundwater movement alone (Yihdego, 2018). Similarly, mine-dewatering investigations have shown that groundwater migration pathways and travel times provide only part of the information required for environmental assessment, because receptor exposure and environmental context ultimately determine consequence (Yihdego & Drury, 2016).

As environmental assessments increasingly focus on risk-based decision-making, there is growing need to move beyond pathway metrics alone and develop approaches that explicitly integrate groundwater movement with receptor sensitivity and environmental consequence. Travel time remains a valuable hydrogeological indicator, but it should be interpreted within a broader framework that considers the complete source–pathway–receptor relationship.

This paper examines the relationship between groundwater travel time, groundwater connectivity, pathway behaviour, receptor sensitivity, and environmental consequence. It argues that travel time should be regarded primarily as a pathway characteristic rather than an impact metric and develops a practical framework for integrating travel-time analysis into environmental assessment and decision-making.

1.1 Study Objectives

The objectives of this study are to:

- evaluate the relationship between groundwater travel time and environmental consequence;
- distinguish between groundwater connectivity and environmental harm;
- examine the influence of attenuation, pathway behaviour, and receptor sensitivity on environmental outcomes;
- investigate the limitations of using travel time as a surrogate measure of environmental risk;
- develop a practical source–pathway–receptor framework for travel-time interpretation; and
- improve the integration of groundwater migration analysis within environmental assessment and decision-making.

1.2 Novel Contribution

The novelty of this study lies in reframing groundwater travel time as a measure of pathway behaviour rather than a measure of environmental significance. While travel time is routinely used as a surrogate for environmental risk, this paper demonstrates that environmental consequence is governed by the combined interaction of source characteristics, pathway behaviour, groundwater connectivity, attenuation potential, receptor sensitivity, and environmental value. A receptor-centred travel-time framework is proposed that explicitly links groundwater migration to environmental consequence, improving groundwater-risk evaluation, consequence classification, and environmental decision-making.

2. Why Travel Time Is Popular

Groundwater travel time has become one of the most frequently applied metrics in hydrogeology because it provides a direct measure of groundwater migration potential and the time required for groundwater to move between a source and a receptor. Travel-time analysis is routinely used in groundwater vulnerability studies, wellhead protection planning, contamination assessment, mine closure investigations, environmental impact assessments, and groundwater-resource management. Modern advances in particle tracking, groundwater connectivity assessment, and integrated groundwater-flow modelling have further increased the use of travel-time information as a decision-support tool (Benavides Höglund et al., 2024; Hill et al., 2024).

The popularity of travel-time analysis stems from its intuitive nature. Regulators, environmental managers, groundwater practitioners, and stakeholders often ask a simple question:

How long will it take groundwater to reach a receptor?

Travel-time estimates appear to provide a clear and quantitative answer. Consequently, groundwater assessments frequently use travel time as a proxy for exposure potential, contaminant migration risk, groundwater vulnerability, and environmental consequence.

Recent developments in particle-tracking methods and groundwater connectivity studies have significantly improved the ability to evaluate migration pathways, groundwater travel times, source attribution, and groundwater–surface water interaction across a wide range of hydrogeological settings (Kourakos et al., 2024; Dennedy-Frank et al., 2024). At the same time, modern groundwater assessments increasingly recognise that travel-time information should be interpreted together with groundwater-system behaviour, receptor sensitivity, and pathway characteristics rather than in isolation (Dwivedi et al., 2025; Yang et al., 2025).

2.1 Travel Time Answers an Important but Limited Question

Travel time is valuable because it provides information regarding:

- migration efficiency;
- pathway length;
- groundwater velocity;
- potential exposure timing;
- monitoring horizons;
- attenuation opportunities.

Travel-time estimates are commonly used to support:

- groundwater protection zones;
- receptor screening;
- contamination assessment;
- managed aquifer recharge evaluations;
- groundwater sustainability studies;
- mine closure assessments.

However, travel time answers only one component of a broader environmental question. It describes **how long groundwater migration may require**, but it does not explain:

- what is migrating;
- whether contaminants are present;
- whether attenuation is effective;
- whether receptors are sensitive;
- whether environmental standards are exceeded;
- whether environmental harm will occur.

Consequently, travel time should be regarded as a pathway characteristic rather than a consequence indicator.

2.2 Why Travel Time Is Often Misinterpreted

A common assumption in environmental assessment is:

Short travel time = High environmental risk

and

Long travel time = Low environmental risk

Although attractive in its simplicity, this interpretation is frequently incorrect.

Groundwater travel time provides information regarding migration potential, but environmental consequence depends upon a broader interaction among:

- source characteristics;
- pathway behaviour;
- groundwater connectivity;
- attenuation processes;
- receptor sensitivity;
- environmental value.

A short travel time may pose little concern where contaminants are absent, attenuation is strong, or receptors are insensitive. Conversely, a long travel time may still represent substantial environmental concern where contaminants persist, receptors are highly vulnerable, or cumulative impacts develop over extended periods.

As groundwater assessments increasingly focus on consequence-based evaluation and risk-informed decision-making, travel time alone has become insufficient for evaluating environmental significance (Benavides Höglund et al., 2024; Winde & Newman-Portela, 2026).

2.3 Travel Time and Groundwater Connectivity

Travel time is closely related to groundwater connectivity because movement cannot occur without an effective pathway.

Connectivity determines:

- whether migration is possible;
- how groundwater pathways develop;
- which receptors may be reached;
- how groundwater interacts with environmental systems.

Travel time determines:

- how rapidly migration occurs;
- when receptor exposure might occur;
- how much opportunity exists for attenuation.

Contemporary connectivity research demonstrates that groundwater systems should be viewed as dynamic networks rather than simple flow paths. Groundwater migration may involve multiple pathways, changing hydraulic gradients, evolving groundwater–surface water interactions, and varying travel times (Dwivedi et al., 2025; Yang et al., 2025).

Consequently, travel time should be interpreted as one component of groundwater connectivity rather than a standalone environmental metric.

2.4 Travel Time in Modern Environmental Assessment

Groundwater travel-time analysis remains a powerful tool because it provides information unavailable from groundwater levels alone.

Travel-time assessments can:

- identify receptor vulnerability;
- define monitoring requirements;
- support groundwater protection planning;
- improve understanding of groundwater connectivity;
- assist source attribution;
- support contaminant migration assessment.

However, modern environmental assessments increasingly recognise that groundwater pathways, travel times, receptor characteristics, and environmental values must be evaluated together if environmental significance is to be interpreted correctly (Irvine et al., 2024; Winde & Newman-Portela, 2026).

The conceptual relationship between groundwater travel time, groundwater connectivity, receptor interaction, and environmental consequence is illustrated in Fig. 1.

Figure 1 demonstrates that travel time and connectivity describe pathway behaviour, whereas environmental significance emerges only when pathway characteristics interact with sensitive receptors. Figure 1 shows how groundwater travel time and hydraulic connectivity link a source to a potential receptor through subsurface flow pathways. While travel time describes the movement of groundwater between locations, environmental impact depends on the interaction between pathway characteristics, receptor vulnerability, exposure conditions, and attenuation processes. Thus, travel time informs groundwater behaviour but does not alone determine environmental significance.

2.5 Beyond Travel Time

The discussion above highlights an important distinction:

Travel time explains **how groundwater moves**, but not **why the movement matters**.

This distinction forms the foundation of the remainder of this paper. Subsequent sections demonstrate that groundwater travel time provides valuable information regarding migration efficiency and connectivity, yet environmental significance can only be understood when travel times are interpreted within a broader source–pathway–receptor framework that incorporates attenuation processes, receptor sensitivity, and environmental value.

3. The Travel-Time Misconception

Groundwater travel time is often treated as a practical indicator of environmental risk because it appears to provide a direct measure of how rapidly groundwater can move between a source and a receptor. Consequently, travel-time estimates are frequently used to support vulnerability mapping, groundwater protection planning, contamination investigations, mine closure assessments, and environmental impact studies. While travel time remains an important hydrogeological parameter, its environmental meaning is frequently overstated.

A common assumption encountered in groundwater assessment is:

Short travel time = High environmental risk

Long travel time = Low environmental risk

Although intuitively appealing, this interpretation oversimplifies the relationship between groundwater migration and environmental consequence. Travel time describes the efficiency and timing of groundwater movement, but it does not determine the significance of the environmental outcome.

Recent groundwater and environmental-assessment literature increasingly emphasises that environmental risk depends on a combination of pathway behaviour, groundwater connectivity, receptor

sensitivity, attenuation processes, and environmental value rather than migration rate alone (Benavides Höglund et al., 2024; Delottier et al., 2023; Winde & Newman-Portela, 2026).

3.1 Travel Time Describes Pathway Behaviour

Travel time is fundamentally a pathway characteristic.

It provides information regarding:

- groundwater velocity;
- migration efficiency;
- communication between hydrogeological units;
- pathway length;
- timing of potential receptor interaction.

However, travel time does not directly describe:

- contaminant persistence;
- groundwater quality;
- environmental vulnerability;
- receptor sensitivity;
- ecological consequence.

Consequently, travel-time estimates should be interpreted as descriptors of groundwater movement rather than indicators of environmental impact.

3.2 Short Travel Times Do Not Automatically Imply High Risk

Short travel times are often viewed as undesirable because contaminants or groundwater changes may reach receptors relatively quickly. However, environmental significance remains dependent upon additional factors.

Short travel times may have limited environmental consequence where:

- contaminants are absent;
- groundwater quality is acceptable;
- attenuation processes are effective;
- receptors possess low sensitivity;
- environmental values are limited.

For example, rapid groundwater movement through a highly connected aquifer may present little environmental concern if the transported groundwater remains chemically benign and significant receptors are absent.

This demonstrates that travel time alone cannot determine risk.

3.3 Long Travel Times Do Not Necessarily Imply Low Risk

Conversely, long travel times are often interpreted as evidence of low environmental significance because contaminants may require many years to reach receptors.

However, long travel times may still be associated with substantial environmental consequences when:

- contaminants persist over extended periods;
- attenuation rates are low;
- receptors are highly sensitive;
- groundwater systems remain connected;
- cumulative impacts occur through time.

Groundwater quality degradation may therefore remain environmentally important even when migration occurs slowly.

Recent studies increasingly highlight the importance of considering transport persistence and receptor sensitivity alongside pathway behaviour when evaluating long-term groundwater-system impacts (Irvine et al., 2024; Yang et al., 2025).

3.4 Connectivity Is Not Consequence

Groundwater travel time and groundwater connectivity are closely related but should not be treated as equivalent to environmental consequence.

Connectivity answers the question:

Can groundwater reach the receptor?

Travel time answers the question:

How long will migration require?

Neither question determines:

Does the impact matter environmentally?

Environmental consequence emerges only after consideration of:

- source characteristics;

- transport processes;
- attenuation;
- receptor sensitivity;
- environmental value.

The relationship between groundwater travel time, hydraulic connectivity, receptor interaction, and environmental consequence is illustrated conceptually in Fig. 1.

3.5 Receptor Sensitivity Changes the Meaning of Travel Time

One of the most important reasons that travel time alone is insufficient is that receptor sensitivity varies substantially.

Identical travel times may produce very different consequences when receptors differ.

Examples include:

- a drinking-water supply;
- a groundwater-dependent wetland;
- a culturally significant spring;
- a degraded drainage channel;
- industrial groundwater users.

A travel time of ten years may be considered highly significant for one receptor and relatively insignificant for another.

Consequently, environmental significance is controlled more strongly by receptor characteristics than by pathway timing alone.

3.6 Practical Examples

Example 1

Groundwater Contamination

A contaminant plume may exhibit relatively short travel times, yet environmental risk may remain limited if contaminant concentrations attenuate below relevant thresholds before reaching receptors.

Example 2

Water-Supply Protection

A modest groundwater-quality change affecting a public drinking-water source may warrant a high consequence classification even when travel times are relatively long.

Example 3

Mine Closure

Post-closure groundwater migration pathways may remain active for extended periods. In such systems, receptor location and sensitivity frequently have greater influence on environmental significance than travel time itself.

Example 4

Groundwater-Dependent Ecosystems

Long travel times may still generate substantial environmental concern where groundwater-dependent ecosystems rely on highly sensitive groundwater regimes.

These examples illustrate why travel time should be interpreted within a broader environmental framework rather than used as a standalone risk indicator.

3.7 Beyond Travel Time

The discussion above demonstrates that groundwater travel time is a necessary component of groundwater assessment but not a sufficient indicator of environmental consequence.

Travel time explains:

- how groundwater moves;
- how rapidly migration occurs;
- when receptor interaction may be possible.

Travel time does not explain:

- whether attenuation occurs;
- whether receptors are vulnerable;
- whether environmental values are affected;
- whether environmental harm results.

Consequently, groundwater travel time should be interpreted as a pathway metric rather than an impact metric.

This distinction forms the basis for the source–pathway–receptor framework developed in the following sections, which links groundwater migration behaviour with environmental significance and decision-

making.

4. Travel Time, Connectivity and Groundwater Pathways

Groundwater travel time and groundwater connectivity are closely related concepts, but they describe different characteristics of groundwater systems. Travel time provides an estimate of how rapidly groundwater can migrate through a pathway, whereas connectivity describes whether movement between locations is physically and hydraulically possible. Understanding the distinction between these concepts is critical because environmental significance depends on more than groundwater movement alone.

Modern groundwater investigations increasingly recognise that groundwater pathways, connectivity, travel times, and receptor interactions should be evaluated together rather than as independent metrics. Travel-time analysis therefore provides valuable information regarding pathway behaviour, but environmental consequence can only be assessed through consideration of the complete source–pathway–receptor relationship.

4.1 Travel Time and Hydraulic Connectivity

Hydraulic connectivity describes the existence of groundwater flow pathways between different locations within a groundwater system.

Connectivity may occur through:

- porous aquifer systems;
- fracture networks;
- weathered zones;
- fault-controlled pathways;
- groundwater–surface water interaction zones;
- regional groundwater-flow systems.

Travel time describes the rate at which groundwater moves through those pathways.

Consequently:

- connectivity answers **whether** groundwater can move;
- travel time answers **how quickly** groundwater moves.

A highly connected system may exhibit long travel times, while relatively short travel times may occur along limited but highly transmissive pathways. Therefore, connectivity and travel time are related but not interchangeable concepts.

4.2 Pathways Are Dynamic Rather Than Fixed

Groundwater pathways are frequently interpreted as static features, yet groundwater movement commonly evolves through time.

Pathway behaviour may change due to:

- recharge variation;
- groundwater recovery;
- groundwater abstraction;
- dewatering;
- climate variability;
- groundwater–surface water interaction.

Consequently, groundwater travel times may also change through time as hydraulic gradients and connectivity conditions evolve.

Recent connectivity research demonstrates that groundwater systems are best interpreted as dynamic networks of interacting pathways rather than fixed flow routes.

4.3 Short Travel Time Does Not Necessarily Mean High Consequence

The assumption that short travel times automatically indicate high environmental significance is one of the most common misunderstandings in groundwater assessment.

Short travel times may have limited environmental consequence when:

- contaminants are absent;
- attenuation processes are effective;
- receptors possess low sensitivity;
- environmental values are limited.

For example, groundwater may migrate rapidly through a highly transmissive pathway without creating significant environmental concern if no sensitive receptors are present.

Consequently, travel time alone provides insufficient information for environmental interpretation.

4.4 Long Travel Time Does Not Necessarily Mean Low Consequence

Similarly, long travel times should not automatically be interpreted as indicators of low environmental risk.

Long travel times may remain environmentally significant when:

- contaminants persist through time;
- receptors are highly sensitive;
- cumulative impacts occur;
- attenuation is limited;
- environmental values are high.

Examples include groundwater-dependent ecosystems, potable water supplies, culturally significant water bodies, and environmentally sensitive groundwater-receptor systems.

In such situations, delayed arrival does not necessarily reduce environmental significance.

4.5 Travel Time and Attenuation

One reason travel time is important is that it influences attenuation potential.

Common attenuation processes include:

- sorption;
- dilution;
- dispersion;
- biodegradation;
- chemical transformation.

Longer travel times may increase opportunities for attenuation and reduce contaminant concentrations reaching receptors. However, attenuation effectiveness depends on contaminant characteristics, groundwater chemistry, geological conditions, and transport pathways.

Consequently, travel time should be evaluated together with attenuation potential rather than interpreted independently.

4.6 Connectivity Without Impact

Groundwater connectivity is often interpreted as evidence that environmental harm will occur. In reality, connectivity establishes the possibility of interaction, not proof of consequence.

Examples include:

- connected groundwater systems with no contaminants present;
- hydraulic pathways that do not intersect receptors;
- migration pathways where attenuation removes contaminants before exposure occurs;
- environmentally resilient receptors capable of tolerating groundwater-system change.

Connectivity therefore represents a necessary condition for impact but is not, by itself, evidence of environmental harm.

4.7 The Importance of Receptor Interaction

Groundwater pathways become environmentally meaningful only when they connect with receptors.

Potential receptors include:

- groundwater-dependent ecosystems;
- rivers and wetlands;
- groundwater supplies;
- drinking-water resources;
- agricultural users;
- culturally significant water bodies;
- engineered infrastructure.

The environmental significance of travel-time information therefore depends substantially on receptor characteristics.

Travel time explains **when** groundwater may arrive at a receptor. Receptor sensitivity explains **why arrival matters**.

4.8 Connectivity, Travel Time and Environmental Consequence

The progressive relationship between connectivity, travel time, receptor exposure, and environmental consequence is summarised in Table 1.

Table 1
Relationship between connectivity, travel time, receptor interaction, and environmental consequence.

Condition	Connectivity	Receptor Exposure	Environmental Consequence
Pathway exists	Yes	No	Negligible
Groundwater reaches receptor	Yes	Possible	Depends on receptor sensitivity
Contaminant reaches receptor	Yes	Yes	Potential consequence
Attenuation prevents exposure	Yes	Limited	Reduced consequence
Sensitive receptor affected	Yes	Yes	Significant consequence
Critical environmental value affected	Yes	Yes	High consequence

Table 1 demonstrates that travel time and connectivity alone do not determine environmental significance. Environmental consequence emerges only when groundwater pathways interact with receptors possessing sufficient sensitivity, vulnerability, or environmental value.

4.9 From Pathway Behaviour to Environmental Significance

The discussion above demonstrates that travel time should be viewed primarily as a pathway metric rather than an impact metric.

Travel-time analysis provides valuable information regarding:

- migration efficiency;
- groundwater connectivity;
- recharge propagation;
- pathway evolution;
- exposure timing.

However, environmental consequence depends upon the combined interaction of:

- source characteristics;
- pathway behaviour;
- groundwater connectivity;
- attenuation processes;
- receptor sensitivity;
- environmental value.

This relationship is summarised conceptually in Fig. 2, which illustrates the progression from groundwater movement to environmental consequence. As shown in Fig. 2, travel time influences the timing of interaction, but environmental significance is ultimately determined by receptor response rather than by migration rate alone.

Groundwater travel time explains how groundwater moves. Receptors determine whether that movement matters environmentally.

5. From Groundwater Behaviour to Environmental Consequence

Groundwater assessments commonly quantify groundwater levels, drawdown, seepage rates, contaminant concentrations, travel times, groundwater budgets, and hydraulic connectivity. These variables describe how groundwater systems behave, but they do not directly determine environmental significance. Environmental consequence emerges only when groundwater-system behaviour interacts with a receptor and influences a valued ecological, cultural, social, water-resource, or engineering asset.

This distinction is critical because hydrogeological change and environmental consequence are not equivalent. A technically significant groundwater impact may produce negligible environmental consequences if receptors are absent or insensitive. Conversely, relatively small hydrogeological changes may generate substantial environmental consequences where sensitive receptors are present. Therefore, environmental significance should not be inferred from groundwater behaviour alone.

5.1 From Source to Consequence

Environmental consequence develops through a sequence of interacting processes.

Source

- groundwater abstraction;
- dewatering;
- contamination release;
- recharge alteration;
- infrastructure development;
- land-use change.

↓

Pathway

- groundwater flow systems;
- fractures;
- faults;
- alluvial pathways;
- groundwater–surface water connections.

↓

Travel Time

- controls migration timing;
- influences attenuation opportunities;
- affects receptor exposure periods.

↓

Connectivity

- determines whether interaction is possible;

- controls migration potential;
- links sources and receptors.

↓

Receptor

- determines environmental sensitivity;
- defines environmental value;
- controls vulnerability.

↓

Environmental Consequence

- ecological impact;
- water-resource impact;
- cultural impact;
- engineering consequence.

This progression demonstrates that environmental significance emerges at the receptor stage rather than at the travel-time or connectivity stage.

5.2 Groundwater Migration Is Not Environmental Harm

Groundwater movement is a natural hydrogeological process and should not be confused with environmental impact.

Groundwater migration may occur without:

- contaminant transport;
- receptor exposure;
- ecological degradation;
- environmental harm.

Similarly, groundwater travel time and groundwater connectivity simply indicate that movement is possible. They do not indicate whether environmental values will be affected.

Recent environmental assessment studies increasingly emphasise that groundwater pathways should be evaluated in conjunction with receptor sensitivity and environmental value rather than interpreted as direct measures of environmental risk.

5.3 Why the Same Travel Time Produces Different Consequences

The same groundwater travel time may result in very different environmental outcomes.

For example:

- a five-year travel time to an unused aquifer may have little environmental significance;
- a five-year travel time to a public water-supply bore may be highly significant;
- a five-year travel time to a groundwater-dependent wetland may require active management;
- a five-year travel time to an engineered receptor may influence infrastructure performance.

This demonstrates that travel time itself does not define environmental significance. Instead, significance depends on the characteristics of the receiving receptor.

5.4 Environmental Value Influences Consequence

Environmental significance is strongly influenced by receptor value.

Environmental values may include:

- ecological importance;
- drinking-water supply value;
- cultural significance;
- heritage importance;
- social dependence;
- economic value.

Consequently, the same hydrogeological change may attract different consequence classifications depending on the value of the receptor involved.

This helps explain why environmental assessments frequently reach different conclusions despite similar hydrogeological observations.

5.5 Receptor Vulnerability Governs Exposure

Environmental consequence also depends on receptor vulnerability.

Vulnerability may be influenced by:

- groundwater dependence;
- recovery potential;
- adaptive capacity;
- resilience to disturbance;
- existing environmental condition.

Highly vulnerable receptors typically respond to relatively small groundwater changes, whereas more resilient receptors may tolerate larger disturbances before significant consequences occur.

5.6 Consequence Is More Important Than Pathway Alone

Travel time and connectivity remain valuable because they describe:

- migration efficiency;
- exposure timing;
- groundwater-system behaviour;
- monitoring requirements.

However, environmental management ultimately focuses on consequence rather than groundwater movement itself.

Questions such as:

- Will ecological function be affected?
- Will water quality decline?
- Will environmental values change?
- Will groundwater users be impacted?

cannot be answered by travel time alone.

Consequently, groundwater-pathway assessments should always be integrated with receptor evaluation and consequence assessment.

5.7 Travel Time Becomes Meaningful Through Receptors

Travel time gains environmental relevance only when receptor interaction is considered.

Without receptors:

- travel time remains a hydrogeological metric.

With receptors:

- travel time becomes part of a consequence pathway.

This distinction explains why environmental significance cannot be determined using travel-time analysis alone and why receptor-centred assessment provides a more realistic basis for groundwater-risk evaluation.

The conceptual relationship between groundwater behaviour, travel time, receptor interaction, and environmental consequence is illustrated in Fig. 3.

5.8 A Receptor-Centred Perspective

The discussion above demonstrates that:

- travel time is a pathway characteristic;
- connectivity is a transport condition;
- receptors determine environmental significance.

Accordingly, groundwater assessments should move beyond asking:

How long does groundwater take to arrive?

and instead ask:

What happens when groundwater arrives?

This shift in perspective represents a fundamental transition from pathway-centred assessment toward consequence-centred environmental interpretation and forms the foundation of the receptor-based framework presented in the following section.

6. A Source–Pathway–Receptor Framework for Travel-Time Interpretation

Groundwater travel time becomes meaningful only when interpreted within the broader context of source characteristics, pathway behaviour, groundwater connectivity, receptor sensitivity, and environmental consequence. Although travel time provides valuable information regarding migration efficiency and exposure timing, it does not independently determine environmental significance. Consequently, effective groundwater assessment requires a framework that links hydrogeological movement with environmental outcomes.

The source–pathway–receptor approach has become a fundamental principle of environmental assessment because it recognises that impacts occur only when a source is connected to a receptor through a viable pathway. Recent groundwater assessment literature increasingly emphasises integrated evaluation of pathways, connectivity, receptors, and environmental values rather than reliance on individual hydrogeological metrics alone.

6.1 Source

The first component of the framework is the source.

Potential groundwater sources include:

- contaminant releases;

- mine dewatering systems;
- recharge zones;
- groundwater extraction;
- wastewater infiltration;
- saline intrusion;
- engineered recharge systems.

The source determines:

- what is moving;
- whether contaminants are present;
- whether groundwater quality may change;
- the persistence of the potential impact.

Two pathways exhibiting identical travel times may present very different environmental significance if the source characteristics differ substantially.

6.2 Pathway

The pathway defines how groundwater or dissolved constituents move through the hydrogeological system.

Key pathway characteristics include:

- travel time;
- hydraulic conductivity;
- pathway length;
- geological controls;
- groundwater connectivity;
- attenuation potential.

Travel time is therefore one descriptor of pathway behaviour rather than a consequence measure.

Modern groundwater studies increasingly recognise that pathways are often dynamic and may evolve as recharge, hydraulic gradients, groundwater recovery, or climate conditions change.

6.3 Connectivity

Connectivity determines whether movement from source to receptor is possible.

Connectivity may involve:

- hydraulic connectivity;

- transport connectivity;
- groundwater–surface water connectivity;
- fracture connectivity;
- aquifer connectivity.

Connectivity is a prerequisite for migration but not proof of environmental harm.

A groundwater pathway may be highly connected while producing little environmental consequence because:

- contaminants are absent;
- attenuation is effective;
- receptors are insensitive.

Consequently, connectivity should be viewed as a transport condition rather than a consequence indicator.

6.4 Receptor

Receptors represent the component of the framework that determines environmental relevance.

Examples include:

- groundwater-dependent ecosystems;
- rivers and wetlands;
- drinking-water supplies;
- irrigation users;
- cultural and heritage water bodies;
- engineered structures;
- communities.

The same travel time may have very different implications depending on the receptor involved.

For example:

- a five-year travel time to a degraded drainage feature may have limited consequence;
- a five-year travel time to a public water-supply bore may warrant significant concern.

This distinction illustrates why receptor identification is fundamental to environmental interpretation.

6.5 Receptor Sensitivity

Receptor sensitivity controls how strongly a receptor responds to groundwater-system change.

Factors influencing sensitivity include:

- ecological dependence;
- environmental value;
- cultural significance;
- groundwater reliance;
- resilience to disturbance;
- adaptive capacity.

Because sensitivity varies considerably among receptors, environmental consequence cannot be inferred directly from hydrogeological metrics alone.

The same contaminant concentration, pathway, or travel time may therefore generate different environmental outcomes depending on receptor sensitivity.

6.6 Environmental Consequence

Environmental consequence represents the final outcome of interaction between source, pathway, connectivity, and receptor.

Potential consequences include:

- groundwater-quality degradation;
- ecological change;
- reduced water availability;
- contamination exposure;
- cultural impacts;
- infrastructure impacts.

Consequence therefore reflects environmental significance rather than groundwater behaviour alone.

This distinction helps explain why technically significant hydrogeological impacts may remain environmentally insignificant, while relatively minor hydrogeological changes may generate substantial environmental concern.

6.7 Practical Applications

The source–pathway–receptor framework can be applied across a broad range of groundwater investigations.

Groundwater Contamination

Travel-time analysis helps evaluate:

- migration timing;
- receptor exposure;
- attenuation opportunity.

However, significance depends on receptor vulnerability rather than travel time alone.

Drinking-Water Protection

Travel times assist in defining protection zones, but management priorities ultimately depend on receptor value and water-resource importance.

Mine Closure

Groundwater pathways may remain active long after closure. Travel times help define exposure horizons, but environmental consequence depends on whether receptors remain connected.

Groundwater-Dependent Ecosystems

Long travel times may still be environmentally significant where environmentally sensitive ecosystems depend on groundwater conditions.

6.8 A Receptor-Centred Perspective

The source–pathway–receptor framework demonstrates that travel time gains environmental meaning only when connected to a receptor.

The progression may be summarised as:

Source

↓

Pathway

↓

Travel Time

↓

Connectivity

↓

Receptor

↓

Environmental Consequence

This conceptual relationship is illustrated in Fig. 3.

As shown in Fig. 3, travel time controls the timing of potential exposure, while receptors determine environmental significance. Consequently, groundwater travel time should be interpreted as a pathway metric that supports environmental assessment, rather than as a standalone measure of environmental harm.

The framework therefore shifts attention from a simple question:

How long does groundwater take to arrive?

to the more important environmental question:

What happens when groundwater arrives?

This transition from pathway-centred interpretation to consequence-centred assessment provides a more robust basis for groundwater-risk evaluation, environmental management, and groundwater decision-making.

7. Practical Applications of Travel-Time Assessment

The preceding sections demonstrate that groundwater travel time should not be interpreted as a direct measure of environmental impact. However, travel-time analysis remains one of the most valuable tools available to hydrogeologists because it provides insight into groundwater movement, pathway behaviour, receptor exposure, and long-term system evolution. The key challenge is ensuring that travel-time information is interpreted within a broader environmental context rather than being used as a standalone indicator of risk.

Recent groundwater-management and environmental-assessment studies increasingly emphasise integrated approaches that combine pathway analysis, groundwater connectivity, receptor evaluation, uncertainty assessment, and consequence-based interpretation (Benavides Höglund et al., 2024; Delottier et al., 2023; Winde & Newman-Portela, 2026).

7.1 Groundwater Contamination Assessment

Travel-time analysis is widely used in contamination studies because it provides information regarding:

- migration rates;
- potential exposure timing;
- monitoring requirements;
- attenuation opportunity;

- contaminant persistence.

However, contamination assessments should not assume that short travel times automatically imply high environmental consequence.

Environmental significance depends on:

- contaminant characteristics;
- attenuation processes;
- groundwater chemistry;
- receptor sensitivity;
- environmental value.

Consequently, travel-time information should be interpreted together with source strength, groundwater quality, connectivity, and receptor exposure.

7.2 Drinking-Water Source Protection

Travel-time assessments are commonly used to delineate groundwater protection zones around drinking-water supplies.

Typical applications include:

- capture-zone definition;
- wellhead protection planning;
- contaminant vulnerability assessment;
- monitoring design.

Although short travel times often indicate increased exposure potential, management priorities ultimately depend on:

- water-resource value;
- population dependence;
- contaminant characteristics;
- resilience of the supply system.

Travel time therefore provides a useful screening tool but does not independently determine risk.

7.3 Mine Closure and Post-Closure Assessment

Mine closure assessments frequently utilise travel-time analysis to evaluate:

- groundwater recovery;
- contaminant migration;

- seepage pathways;
- pit-lake interaction;
- receptor exposure.

Travel-time estimates help identify how groundwater pathways may evolve after operations cease. However, closure significance depends on whether receptors remain connected to migrating groundwater and whether groundwater quality conditions are likely to affect environmental values.

Investigations of mine dewatering and post-closure groundwater response demonstrate that relatively long groundwater travel times may still require active management when sensitive receptors remain connected to legacy pathways (Yihdego & Drury, 2016; McCullough et al., 2020).

7.4 Groundwater-Dependent Ecosystems

Groundwater-dependent ecosystems are often highly sensitive receptors because ecological function may depend upon specific groundwater levels, groundwater quality conditions, or groundwater discharge regimes.

Examples include:

- wetlands;
- springs;
- riparian vegetation;
- groundwater-fed lakes;
- groundwater-supported streams.

Travel-time information assists in understanding:

- ecological response delays;
- groundwater recharge pathways;
- groundwater discharge timing;
- ecosystem vulnerability.

However, ecological significance depends primarily on receptor sensitivity rather than migration rate alone. Long travel times may still generate substantial environmental concern where ecological dependence is strong.

7.5 Managed Aquifer Recharge and Water Reuse

Travel-time analysis is increasingly important for managed aquifer recharge and groundwater-reuse projects.

Applications include:

- recharge verification;
- groundwater mounding assessment;
- recharge-pathway evaluation;
- water-quality protection;
- compliance monitoring.

Groundwater travel time helps explain how recharge propagates through aquifer systems and how groundwater exchange develops through time. Nevertheless, project performance ultimately depends on groundwater quality, aquifer response, and receptor protection rather than travel time alone.

7.6 Environmental Impact Assessment

Environmental impact assessments commonly incorporate:

- groundwater modelling;
- particle tracking;
- travel-time evaluation;
- pathway analysis;
- receptor assessment.

Travel-time estimates contribute valuable information regarding migration timing and potential exposure periods. However, consequence classification requires integration of:

- source characteristics;
- pathway behaviour;
- connectivity;
- attenuation;
- receptor sensitivity.

Consequently, environmental impact assessment should move beyond the question:

How fast does groundwater move?

toward the more important question:

What environmental consequence may occur when groundwater arrives?

7.7 A Practical Interpretation Framework

The discussion above demonstrates that travel-time analysis is most effective when integrated within a broader source–pathway–receptor framework.

The practical interpretation process may be summarised as:

Source

↓

Groundwater Pathway

↓

Travel Time

↓

Connectivity

↓

Receptor Sensitivity

↓

Environmental Consequence

↓

Management Response

This framework links hydrogeological pathway behaviour to environmental significance and provides a more defensible basis for environmental-risk evaluation than travel-time analysis alone.

7.8 Key Management Message

The practical examples presented above reinforce a central message of this paper:

Groundwater travel time explains when interaction may occur, but receptor sensitivity determines whether that interaction becomes environmentally significant.

Accordingly, the most effective groundwater assessments are not those that simply quantify travel times, but those that integrate travel-time information with connectivity analysis, receptor vulnerability, environmental value, and consequence assessment to support informed environmental decision-making.

8. Discussion

The analyses presented in Figs. 1–3 and Tables 1 demonstrate that groundwater travel time is among the most widely reported yet frequently misunderstood outputs of hydrogeological investigations. Travel times provide valuable information regarding groundwater migration efficiency, pathway behaviour,

hydraulic connectivity, receptor exposure timing, and monitoring requirements. However, travel time alone provides limited insight into environmental significance because environmental consequence depends on the interaction between groundwater pathways, attenuation processes, receptor sensitivity, and environmental value rather than migration rate alone.

A central finding of this study is that groundwater travel time should be interpreted as a **pathway metric rather than an impact metric**. Traditional groundwater assessments often assume that shorter travel times imply higher environmental risk and longer travel times imply lower risk. While this assumption may occasionally hold, it frequently oversimplifies environmental reality. Numerous groundwater systems demonstrate that travel time alone cannot determine whether environmental harm will occur because environmental significance depends on factors operating beyond the pathway itself.

Recent groundwater-assessment literature increasingly emphasises process-based interpretation, groundwater connectivity, receptor vulnerability, and environmental consequence rather than hydrogeological metrics alone (Benavides Höglund et al., 2024; Delottier et al., 2023; Winde & Newman-Portela, 2026). This shift reflects growing recognition that environmental impact is governed not simply by groundwater movement but by what groundwater carries, where it moves, which receptors are affected, and how those receptors respond.

The discussion also highlights an important distinction between groundwater connectivity and environmental consequence. Connectivity establishes the possibility of interaction but does not independently define environmental harm. Groundwater pathways may remain active for decades without producing measurable environmental impacts if contaminant sources are absent, attenuation is effective, or receptors are insensitive. Conversely, relatively modest groundwater movement may have significant environmental implications when pathways intersect vulnerable receptors of high environmental, cultural, ecological, or economic value.

The practical examples presented in Section 7 reinforce this conclusion. Groundwater contamination, drinking-water protection, mine closure, groundwater-dependent ecosystems, and managed aquifer recharge all illustrate situations in which travel-time interpretation requires broader contextual understanding. In each case, travel time contributes important information regarding pathway behaviour, but receptor sensitivity ultimately determines environmental importance.

Another important implication involves environmental risk assessment. Groundwater travel time is commonly used to support risk evaluations because it provides quantitative estimates of migration timing. However, effective risk assessment requires integration of:

- source characteristics;
- pathway effectiveness;
- transport processes;
- attenuation potential;

- receptor sensitivity;
- environmental value.

Travel time addresses only one component of this sequence. Consequently, risk assessments based solely on travel-time metrics may either underestimate or overestimate environmental significance depending on local hydrogeological and environmental conditions.

The source–pathway–receptor framework presented in Fig. 3 provides a practical mechanism for addressing this limitation. By explicitly linking groundwater movement with receptor exposure and environmental consequence, the framework improves transparency and consistency in groundwater-impact interpretation. It also helps explain why hydrogeological assessments and environmental assessments sometimes reach different conclusions when evaluating the same groundwater system. Hydrogeologists often focus on groundwater behaviour, whereas environmental significance depends on receptor interaction.

This observation leads directly to the broader contribution of the paper. Groundwater investigations should evolve from asking:

How fast does groundwater move?

to asking:

What environmental consequence may occur when groundwater arrives?

This shift places travel time within its proper role as a pathway descriptor and emphasises consequence-based interpretation rather than pathway-based interpretation alone.

Ultimately, groundwater travel time remains a valuable hydrogeological tool, but its environmental significance depends on factors extending beyond migration timing. Effective groundwater assessment requires integration of travel time, connectivity, attenuation, receptor sensitivity, and environmental consequence within a unified framework. By doing so, groundwater practitioners can produce more realistic assessments, improve environmental decision-making, and develop interpretations that are both hydrogeologically sound and environmentally meaningful.

9. Conclusions

Groundwater travel time is one of the most widely applied metrics in hydrogeological investigations, groundwater protection studies, environmental assessments, contamination evaluations, and mine-closure planning. While travel time provides valuable information regarding migration efficiency, connectivity, and potential exposure timing, it is not a direct measure of environmental significance.

This study demonstrates that groundwater travel time should be interpreted as a **pathway characteristic rather than an impact metric**. The environmental significance of groundwater movement depends on a

broader interaction among source characteristics, pathway behaviour, groundwater connectivity, attenuation potential, receptor sensitivity, and environmental value. Consequently, identical travel times may produce substantially different environmental outcomes depending on the receptors involved.

Several key conclusions emerge from this study:

- Groundwater travel time describes migration behaviour but does not independently determine environmental consequence.
- Hydraulic connectivity is necessary for impact to occur but does not, by itself, demonstrate environmental harm.
- Short travel times do not automatically imply high environmental risk, and long travel times do not necessarily indicate low environmental significance.
- Receptor sensitivity, environmental value, and vulnerability frequently exert greater influence on consequence than migration time alone.
- Effective environmental assessment requires integration of source characteristics, pathways, connectivity, attenuation processes, and receptor exposure.
- Travel-time interpretation is most effective when applied within a source–pathway–receptor framework.
- Environmental significance should be evaluated through consequence-based assessment rather than pathway-based assessment alone.

The receptor-centred framework proposed in Fig. 3 provides a practical methodology for linking groundwater travel time with environmental consequence and management decision-making. By integrating travel-time behaviour, groundwater connectivity, receptor sensitivity, and environmental value, the framework improves transparency, strengthens environmental-risk evaluation, and supports more defensible groundwater assessments.

The novelty of this study lies in demonstrating that environmental significance is controlled primarily by receptor interaction rather than by travel time itself. While groundwater models and particle-tracking analyses remain essential for understanding groundwater movement, they can identify only the potential for interaction. Receptors determine whether that interaction becomes environmentally meaningful.

Ultimately, groundwater travel time helps explain **when** groundwater may arrive, but receptor sensitivity determines **why its arrival matters**. Future groundwater assessments should therefore move beyond travel-time metrics alone and adopt consequence-based approaches that integrate hydrogeological understanding with receptor vulnerability, environmental value, and environmental outcome.

Declarations

Author Contributions

Y.Y. conceived the study, developed the conceptual framework, conducted the analysis and literature synthesis, prepared the figures and table, 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

Not applicable. 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

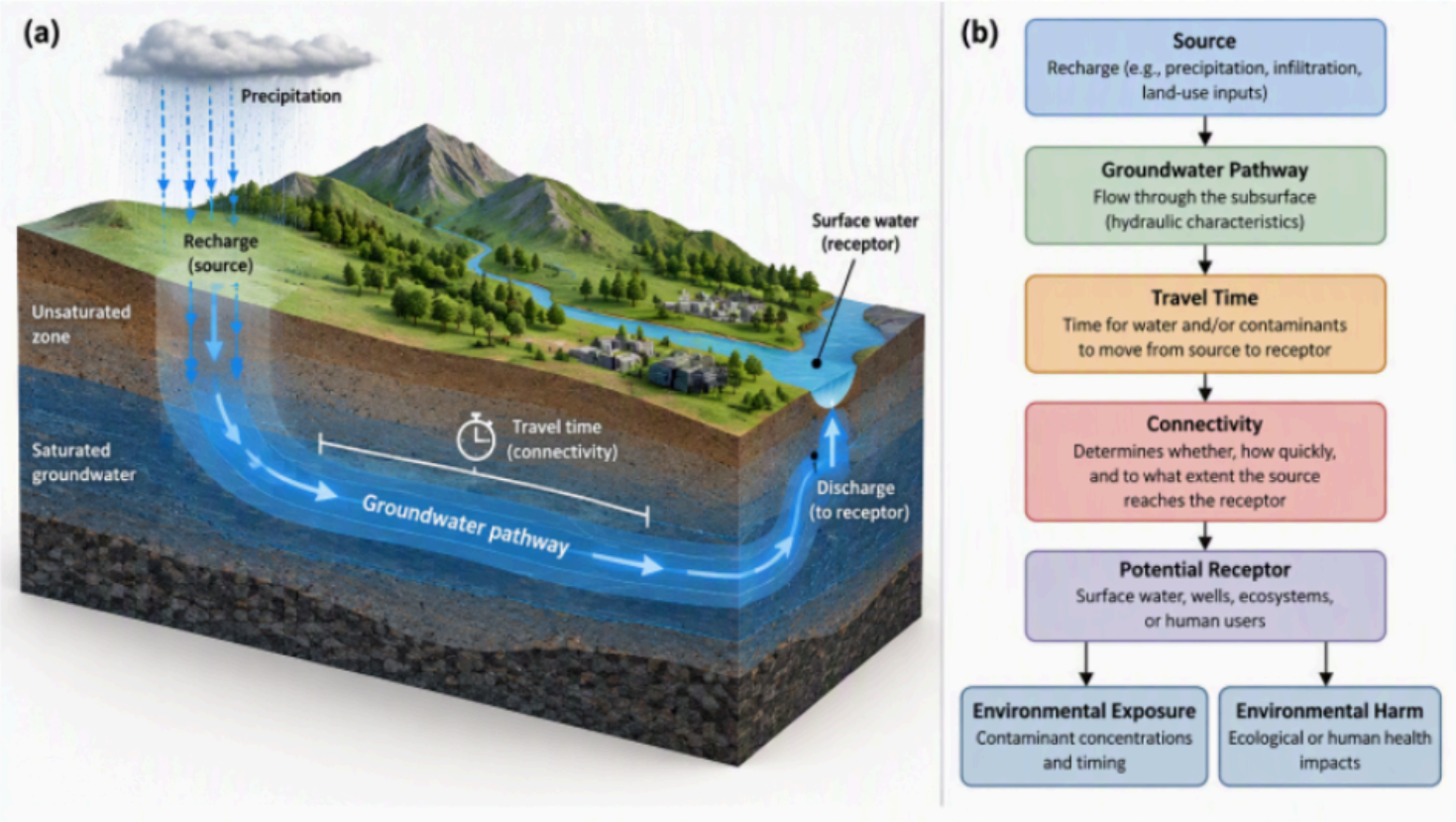


Figure 1

Groundwater travel time, connectivity, receptor interaction, and environmental impact: (a) conceptual 3D groundwater system; (b) source-pathway-receptor framework showing exposure and environmental harm.

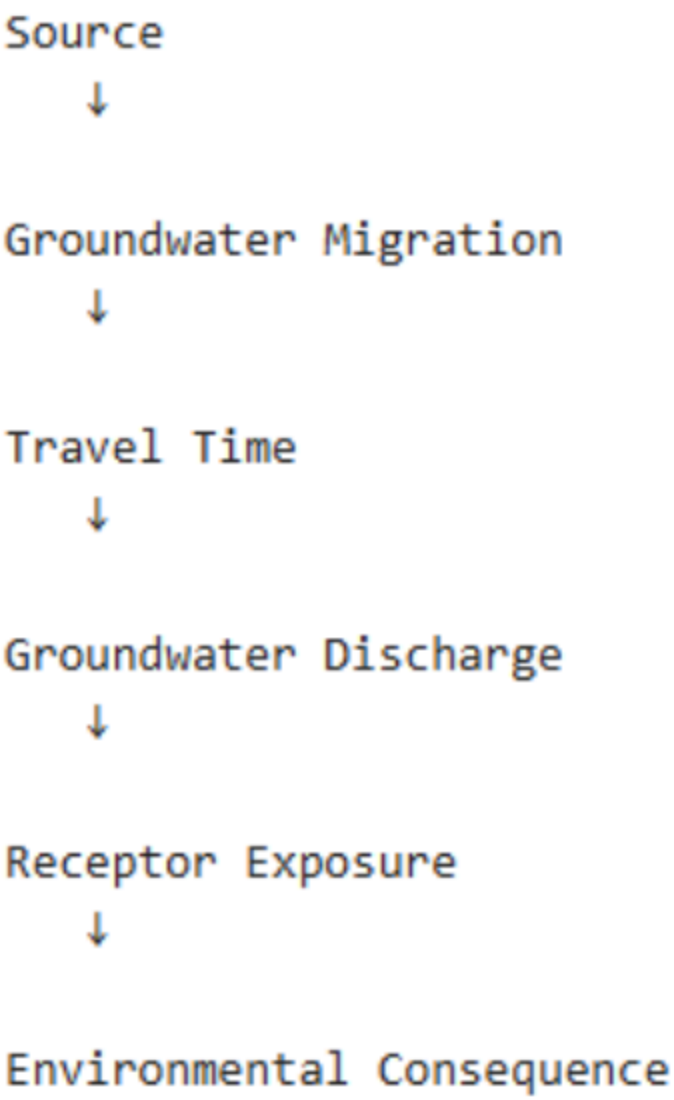


Figure 2

Groundwater travel time influences connectivity, but environmental harm depends on discharge conditions, attenuation, receptor sensitivity, and environmental values.

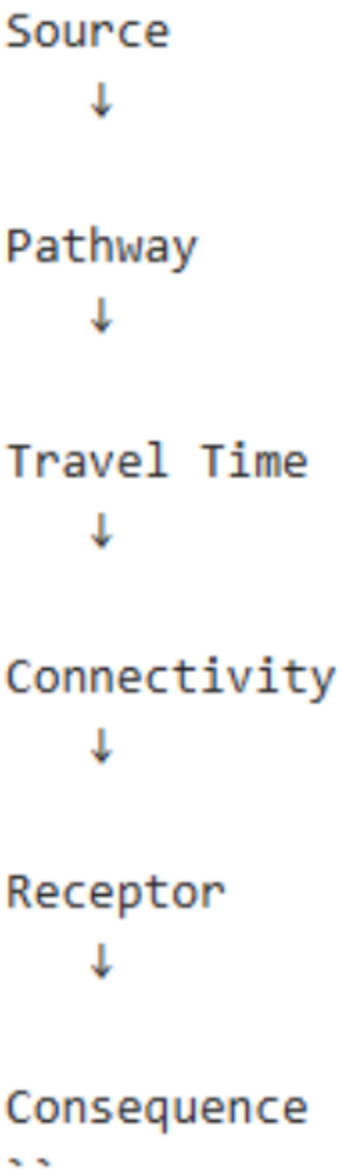


Figure 3

Source–pathway–receptor framework linking groundwater travel time to environmental consequence.