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Why Groundwater Systems Remember the Past Through Hydrogeological Memory, Legacy Effects, and Delayed Environmental Consequences

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Research Article

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Abstract

Groundwater systems frequently continue responding long after the original disturbance has ceased. Groundwater recovery is therefore often assumed to represent environmental recovery; however, hydraulic recovery, contaminant persistence, groundwater connectivity, and receptor exposure commonly operate on different timescales. As a result, environmental risks may remain active despite apparent groundwater-system recovery. This phenomenon is referred to here as groundwater memory and is expressed through delayed hydrogeological responses, persistent connectivity, contaminant migration, and long-term environmental consequence.

This paper examines the concepts of groundwater memory, hydrogeological lag, and groundwater legacy, and develops a framework for understanding delayed groundwater-system behaviour. The study integrates groundwater recovery, groundwater budgets, groundwater connectivity, travel-time behaviour, contaminant persistence, receptor exposure, and environmental consequence. Practical examples from mine closure, groundwater contamination, and recharge propagation are used to demonstrate how hydrogeological responses can continue for decades or longer after the initiating disturbance has disappeared.

The results show that groundwater recovery should not be interpreted as evidence of environmental recovery. Instead, environmental consequence depends on the interaction between groundwater storage, migration pathways, connectivity, contaminant persistence, and receptor sensitivity. A practical groundwater-memory framework is proposed to improve long-term groundwater assessment, closure planning, environmental risk evaluation, and sustainable groundwater management.

1. Introduction

Groundwater systems are commonly evaluated in relation to active pressures such as groundwater abstraction, mining, contamination, infrastructure development, land-use change, and climate variability. Considerably less attention is given to what happens after these pressures cease. Environmental assessments and management strategies assume that environmental conditions progressively improve once the source of disturbance has been removed. In groundwater systems, however, this assumption is often incorrect.

Groundwater systems possess large storage volumes, complex flow pathways, long travel times, and delayed hydraulic responses. Similar observations have been reported globally where groundwater age distributions and long residence times cause contemporary groundwater conditions to reflect historical recharge and land-use pressures (Jasechko et al., 2017; Befus et al., 2017). Consequently, the influence of a disturbance may persist long after the original source has disappeared. Contaminant plumes may continue migrating after source removal, groundwater levels may continue adjusting following pumping cessation, and groundwater-quality impacts may remain active despite apparent hydrological recovery. Recent studies increasingly highlight the importance of groundwater lag effects, groundwater

connectivity, and delayed hydrogeological responses in understanding long-term environmental behaviour (Taylor et al., 2013; Cuthbert et al., 2020; Kløve et al., 2020; Taylor et al., 2022).

The persistence of groundwater-system response reflects the fact that groundwater systems operate on timescales that frequently exceed management, operational, and regulatory horizons. Changes in recharge, pumping, dewatering, contamination, and land use may propagate through groundwater systems over long periods before environmental consequences become apparent. Modern groundwater-system studies increasingly recognise that present groundwater conditions often reflect both current and historical influences rather than current conditions alone (Hill et al., 2024; Benavides Höglund et al., 2024). This concept is consistent with emerging groundwater-resilience and sustainability studies that emphasise the delayed response of aquifer systems to climate, abstraction and land-use change (Maxwell & Condon, 2016; Bierkens & Wada, 2019).

Examples of delayed groundwater response include:

- contaminant plumes that continue migrating after source removal;
- groundwater recovery following mine dewatering;
- delayed recharge responses following climate change;
- long-term groundwater-quality evolution;
- persistent groundwater–surface water interactions;
- residual seepage following closure and rehabilitation.

Such responses demonstrate that groundwater systems retain information about past disturbances through storage, hydraulic gradients, groundwater pathways, and hydrochemical signatures. This behaviour may be described as **groundwater memory**, whereby historical conditions continue to influence present and future groundwater-system evolution.

Investigations of climate–groundwater interactions have demonstrated that groundwater responses may lag considerably behind changes in climatic conditions because recharge signals require time to propagate through groundwater systems (Cuthbert et al., 2020; Taylor et al., 2022). Similarly, studies of recovering groundwater systems and post-mining landscapes demonstrate that hydrogeological recovery frequently occurs on timescales distinct from environmental recovery, with groundwater quality, connectivity, and ecological response often remaining affected long after hydraulic recovery has begun (McCullough et al., 2020; Nordstrom & Blowes, 2020).

Practical examples also demonstrate that delayed groundwater behaviour is not restricted to mining or contamination. Groundwater recharge systems, groundwater mounding, groundwater-level recovery, and hydrograph response investigations have shown that groundwater systems frequently exhibit delayed reactions to recharge, abstraction, and environmental change because of storage effects and complex groundwater connectivity (Yihdego & Webb, 2011; Yihdego, 2017).

Despite growing recognition of these lag effects, groundwater recovery is still commonly interpreted as evidence of environmental recovery. This interpretation risks underestimating long-term environmental consequences because recovery of groundwater levels does not necessarily imply recovery of groundwater quality, ecosystem condition, receptor exposure, or environmental function.

This paper examines groundwater memory, hydrogeological lag, and groundwater legacy as fundamental characteristics of groundwater systems. By integrating groundwater recovery, groundwater budgets, connectivity, travel times, contaminant persistence, and receptor interaction, the study develops a framework for understanding delayed environmental consequences and long-term groundwater-system behaviour.

1.1 Study Objectives

The objectives of this study are to:

- define the concepts of groundwater memory, hydrogeological lag, and groundwater legacy;
- examine the mechanisms responsible for delayed groundwater responses;
- distinguish groundwater recovery from environmental recovery;
- evaluate the role of groundwater connectivity, storage, and travel times in sustaining legacy effects;
- develop a practical framework for evaluating long-term environmental consequence; and
- improve understanding of delayed groundwater-system behaviour in environmental assessment and groundwater management.

1.2 Novel Contribution

The novelty of this study lies in reframing groundwater legacy as a groundwater-memory problem rather than simply a groundwater-recovery problem. Unlike conventional approaches that focus primarily on groundwater levels and hydraulic recovery, this paper integrates groundwater storage, travel time, connectivity, contaminant persistence, receptor exposure, and environmental consequence within a unified groundwater-memory framework. The study further demonstrates that groundwater recovery, groundwater legacy, and environmental recovery are distinct but overlapping processes that frequently operate on different timescales. This framework provides a practical basis for improving closure planning, long-term environmental risk evaluation, groundwater-management decisions, and sustainability assessment.

2. Groundwater Systems Remember the Past

Groundwater systems do not respond instantaneously to disturbance. Unlike many surface-water systems, groundwater environments store water, hydraulic energy, dissolved constituents, and geochemical signatures over extended periods. As a result, present groundwater conditions frequently

reflect both historical and contemporary influences. This persistence of past conditions is referred to in this study as **groundwater memory**.

Groundwater memory arises because groundwater systems possess storage, connectivity, and travel-time characteristics that can delay system response. Recharge signals, groundwater recovery, contaminant migration, and hydraulic adjustments often continue propagating through groundwater systems long after the initiating disturbance has ceased. Recent studies increasingly highlight these lagged groundwater responses as important controls on water-resource sustainability, environmental resilience, and long-term groundwater behaviour (Cuthbert et al., 2020; Kløve et al., 2020; Taylor et al., 2022; Yihdego, 2016).

Examples of groundwater memory include:

- delayed groundwater recovery following pumping cessation;
- groundwater-quality impacts that persist long after source removal;
- recharge signals that continue propagating through aquifer systems;
- residual hydraulic gradients following dewatering;
- long-term groundwater–surface water interactions reflecting historical conditions.

The conceptual groundwater-memory framework is illustrated in **Fig. 1**.

Figure 1. Conceptual framework of groundwater memory and legacy effects. (a) Three-dimensional conceptual representation showing the evolution of groundwater-system responses following a disturbance, including storage effects, delayed transport, persistent hydrogeological legacies, and delayed environmental consequences. (b) Simplified conceptual groundwater legacy framework illustrating the progression from disturbance through groundwater response and legacy formation to delayed consequences that persist beyond removal of the original stressor.

Figure 1 demonstrates how groundwater systems may continue responding long after the original disturbance has disappeared, creating delayed environmental consequences and persistent hydrogeological effects.

2.1 Storage as the Foundation of Groundwater Memory

Groundwater memory is fundamentally linked to groundwater storage.

Large groundwater systems store substantial volumes of water that may remain within the subsurface environment for extended periods. Consequently, changes introduced into groundwater systems are frequently released gradually rather than instantaneously.

Storage effects influence:

- groundwater recovery;

- contaminant persistence;
- groundwater quality;
- recharge propagation;
- groundwater discharge behaviour.

Systems with large storage volumes often exhibit longer response times than systems with limited storage because hydraulic adjustments occur progressively rather than immediately. Global assessments of groundwater occurrence, storage and water-table distribution indicate that many regional aquifers contain groundwater recharged centuries to millennia ago, further reinforcing the role of storage as a mechanism of hydrogeological memory (Fan et al., 2013; Jasechko et al., 2017).

2.2 Travel Time and Delayed Response

Travel time provides one of the clearest explanations for hydrogeological lag. Age-dating studies have demonstrated that groundwater travel times commonly exceed planning horizons, creating significant delays between disturbance, migration and environmental response (Befus et al., 2017; Jasechko et al., 2017).

Groundwater movement is frequently slow relative to management and regulatory timeframes. Recharge, contaminants, hydrochemical signals, and groundwater disturbances may require years, decades, or longer to move through groundwater systems.

As a result:

- current groundwater conditions may reflect historical recharge;
- environmental receptors may respond long after disturbance occurs;
- groundwater quality may continue evolving after source removal;
- recovery trajectories may persist beyond closure periods.

Travel time therefore links historical disturbance to future environmental consequence.

2.3 Groundwater Connectivity and Legacy Effects

Groundwater connectivity provides the pathways through which memory effects are transmitted.

Connectivity influences:

- recharge propagation;
- contaminant migration;
- groundwater recovery;
- receptor exposure;
- groundwater–surface water interaction.

Highly connected systems may transmit signals rapidly across large areas, whereas poorly connected systems may retain groundwater responses locally for extended periods.

Recent connectivity studies emphasise that groundwater systems should be interpreted as interconnected networks in which historical disturbances can continue influencing groundwater behaviour long after surface evidence of those disturbances has disappeared (Dwivedi et al., 2025; Yang et al., 2025).

2.4 Groundwater Memory Is Not Groundwater Recovery

Groundwater recovery and groundwater memory describe different processes.

Groundwater recovery generally refers to:

- rising groundwater levels;
- replenishment of groundwater storage;
- reduction of hydraulic disturbance.

Groundwater memory refers to:

- persistence of historical influences;
- delayed groundwater-system response;
- continuing propagation of groundwater signals;
- long-term environmental consequence.

A groundwater system may exhibit significant hydraulic recovery while simultaneously retaining strong memory of previous disturbance through groundwater quality, residual connectivity, or receptor exposure.

2.5 Implications for Environmental Assessment

The existence of groundwater memory means that environmental assessments based solely on present conditions may underestimate future consequences.

Groundwater memory affects:

- closure assessments;
- contamination management;
- groundwater-resource planning;
- ecosystem protection;
- sustainability evaluations.

Recognition of groundwater memory is also consistent with broader sustainability frameworks that emphasize cumulative water-system pressures and delayed environmental responses (Gleeson et al.,

2020).

Consequently, evaluation of groundwater systems requires consideration of both current conditions and historical processes if long-term environmental outcomes are to be interpreted reliably. These findings are consistent with recent calls for groundwater sustainability assessments to incorporate delayed aquifer responses and cumulative environmental effects rather than relying solely on current groundwater conditions (Gleeson et al., 2020; Bierkens & Wada, 2019).

3. Groundwater Recovery Does Not Equal Environmental Recovery

Groundwater recovery is often interpreted as evidence that environmental conditions are improving. In many groundwater investigations, rising groundwater levels, reduced drawdown, or restored groundwater storage are regarded as indicators that a disturbed groundwater system is returning to a desirable state. However, hydrogeological recovery and environmental recovery frequently occur on different timescales and may not occur simultaneously.

A groundwater system may appear to recover hydraulically while environmental risks remain active. Groundwater levels can rise, storage can replenish, and groundwater gradients can stabilise even though contaminants continue migrating, receptors remain exposed, or ecological systems continue responding to historic disturbance. Consequently, groundwater recovery should not automatically be interpreted as evidence that environmental risk has diminished.

3.1 Indicators of Groundwater Recovery

Groundwater recovery is commonly evaluated using:

- groundwater levels;
- hydraulic gradients;
- groundwater inflows;
- storage replenishment;
- groundwater-flow stabilisation.

These indicators describe the physical response of the groundwater system to decreasing stress or increasing recharge.

Hydraulic recovery is often measurable relatively early because groundwater levels respond directly to changes in recharge, abstraction, or dewatering conditions.

3.2 Indicators of Environmental Recovery

Environmental recovery involves different processes and may require:

- reduction in receptor exposure;

- groundwater-quality improvement;
- ecological recovery;
- attenuation of contaminants;
- restoration of environmental function.

These processes often occur more slowly than hydraulic recovery because they depend on transport behaviour, groundwater exchange, contaminant persistence, and receptor sensitivity. Groundwater-dependent ecosystems may require substantially longer recovery periods than groundwater levels due to biological and ecological response lags (Hose et al., 2017).

The distinction between groundwater recovery and environmental recovery is summarised in Table 1.

Table 1
Groundwater recovery indicators versus environmental recovery indicators.

Groundwater Recovery Indicator	Environmental Recovery Indicator
Rising groundwater levels	Reduced contaminant exposure
Reduced hydraulic gradients	Improvement in environmental values
Storage replenishment	Reduced ecosystem stress
Flow-system stabilisation	Reduced consequence
Groundwater equilibrium	Receptor recovery

Table 1 demonstrates that hydrogeological recovery indicators and environmental recovery indicators often represent different processes and may evolve on different timescales.

3.3 Why Recovery and Consequence Diverge

Several mechanisms contribute to divergence between groundwater recovery and environmental recovery.

Groundwater Quality Lag

Contaminants may remain mobile after hydraulic recovery has occurred.

Examples include:

- salinity;
- dissolved metals;
- nutrients;
- hydrocarbons.

Consequently, groundwater quality may remain degraded even when groundwater levels have recovered.

Connectivity Persistence

Groundwater pathways frequently remain active following recovery.

Hydraulic connectivity established during periods of disturbance may continue transporting groundwater and dissolved constituents to receptors long after groundwater levels stabilise.

Travel-Time Effects

Groundwater travel times frequently exceed recovery times.

Receptors may continue receiving groundwater influenced by historical conditions long after local groundwater recovery becomes evident.

3.4 Practical Examples

Hydrogeological recovery preceding environmental recovery has been documented in:

- post-mining groundwater systems;
- pit-lake environments;
- contaminated groundwater systems;
- recharge-driven groundwater systems.

Studies of mine-water environments and pit-lake systems demonstrate that groundwater-level recovery frequently occurs decades before groundwater quality, environmental receptors, or ecological systems fully recover (McCullough et al., 2020; Nordstrom & Blowes, 2020).

Sustainable mine closure frameworks increasingly recognise that post-closure groundwater quality and environmental performance may remain active long after hydraulic recovery has commenced (Adiansyah et al., 2015; Winde & Newman-Portela, 2026.

Similarly, hydrograph-response studies have shown that delayed groundwater-system behaviour may continue propagating after recharge or environmental conditions have changed (Yihdego & Webb, 2011).

3.5 The Importance of Distinguishing Recovery Types

Failure to distinguish groundwater recovery from environmental recovery may lead to:

- underestimation of long-term environmental risk;
- premature closure decisions;
- insufficient monitoring periods;
- inadequate receptor protection.

This distinction is therefore critical for:

- mine closure;
- contamination management;
- groundwater-resource assessment;
- environmental impact assessment;
- sustainability planning.

3.6 Recovery as One Stage of a Longer Process

Groundwater recovery should be viewed as one component of a broader environmental recovery process rather than the final objective.

Hydraulic improvement provides important evidence that groundwater conditions are changing; however, environmental consequence ultimately depends on:

- transport behaviour;
- connectivity;
- receptor exposure;
- groundwater-quality evolution.

Understanding these relationships helps explain why apparent groundwater recovery may coexist with ongoing environmental consequence.

4. Why Legacy Effects Persist

Groundwater legacy effects persist because the processes controlling groundwater movement, storage, transport, and environmental interaction operate over extended timescales. Unlike many surface-water systems, groundwater systems possess large storage volumes, long travel times, and complex connectivity networks capable of transmitting the influence of historical disturbances far into the future.

The persistence of groundwater legacy is therefore not anomalous behaviour. Rather, it is a natural consequence of the way groundwater systems function. Understanding why legacy effects persist is essential for predicting long-term environmental outcomes and evaluating future groundwater risk.

4.1 Groundwater Storage

Groundwater storage is one of the primary mechanisms responsible for hydrogeological lag.

Groundwater systems may contain large volumes of stored water that continue moving and interacting with surrounding environments long after disturbance cessation.

Stored groundwater can:

- sustain residual hydraulic gradients;
- maintain groundwater discharge;
- transmit historical hydrochemical signatures;
- prolong contaminant migration.

The larger the storage system, the greater the potential for delayed response.

4.2 Travel-Time Persistence

Groundwater movement commonly occurs over timeframes much longer than management, monitoring, or operational periods.

Travel-time persistence allows:

- recharge signals to propagate gradually;
- contaminants to migrate slowly;
- groundwater recovery to continue after source removal;
- environmental responses to remain delayed.

As a result, groundwater systems often continue responding to past disturbances even when contemporary conditions have changed substantially.

4.3 Contaminant Persistence

Many groundwater contaminants attenuate slowly and may remain mobile long after source removal. Geochemical reactions, matrix diffusion and slow groundwater transport can prolong contaminant persistence beyond the period of source activity, creating enduring environmental legacies (Bethke & Postma, 2017).

Persistent contaminants may include:

- salinity;
- nitrate;
- dissolved metals;
- hydrocarbons;
- emerging contaminants.

Consequently, contaminant migration may continue after:

- remediation activities;
- source removal;
- closure implementation;
- groundwater-level recovery.

This persistence can sustain environmental risks despite improvements in hydraulic conditions.

4.4 Connectivity Persistence

Groundwater connectivity frequently remains active after disturbance has ended.

Pathways established during:

- pumping;
- dewatering;
- contamination;
- recharge alteration;

may continue transporting groundwater and dissolved constituents for long periods.

The relationship between legacy sources, groundwater connectivity, and receptor exposure is illustrated in Fig. 2.

Figure 2 shows how storage, pathways, and connectivity allow groundwater systems to continue influencing receptors after the original source has disappeared.

4.5 Groundwater Memory as an Environmental Driver

Collectively, storage, travel time, contaminant persistence, and connectivity create groundwater memory.

Groundwater memory allows historical conditions to influence:

- present groundwater behaviour;
- groundwater quality;
- groundwater recovery;
- receptor exposure;
- environmental consequence.

Because groundwater memory extends the influence of disturbance beyond operational timescales, it must be explicitly considered during long-term environmental assessment.

4.6 Implications for Long-Term Risk

The persistence mechanisms described above demonstrate why groundwater legacy should be evaluated as an active component of environmental risk rather than a historical condition.

Long-term risk assessment therefore requires consideration of:

- groundwater storage;
- pathway persistence;

- connectivity evolution;
- receptor sensitivity;
- travel-time behaviour.

Evaluating these processes provides a more realistic basis for understanding delayed environmental consequences and supports the groundwater-memory framework developed in the following sections. Similar conclusions have emerged from studies of contaminant transport in heterogeneous aquifers where delayed migration processes may continue for decades despite remediation efforts (Tompson et al., 2020).

5. The Concept of Hydrogeological Memory

Hydrogeological memory describes the capacity of groundwater systems to retain and transmit the influence of past disturbances long after the original cause has disappeared. Unlike many surface-water systems that respond relatively rapidly to changes in forcing conditions, groundwater systems often react slowly because groundwater movement, storage exchange, geochemical evolution, and groundwater connectivity operate over extended timescales.

Groundwater memory exists because present groundwater conditions are influenced not only by current processes but also by historical recharge, pumping, contamination, dewatering, land-use change, and climate variability. Consequently, groundwater systems often display delayed responses that continue evolving long after management actions, operational activities, or environmental disturbances have ceased.

Recent studies increasingly recognise hydrogeological memory as a key control on long-term groundwater sustainability, groundwater resilience, and environmental recovery because delayed groundwater responses frequently influence future environmental conditions (Cuthbert et al., 2020; Taylor et al., 2022; Kløve et al., 2020).

5.1 Mechanisms of Hydrogeological Memory

Hydrogeological memory is expressed through several interacting mechanisms.

Groundwater Storage

Groundwater storage allows disturbances to remain within a system long after the initiating event. The strength of groundwater memory is often proportional to residence time, aquifer storage and exchange processes between mobile and less-mobile groundwater domains (Jasechko et al., 2017; Bethke & Postma, 2017).

Examples include:

- delayed groundwater-level response;

- prolonged groundwater recovery;
- persistence of hydraulic gradients;
- continuation of groundwater discharge.

Large storage systems generally exhibit stronger memory effects because groundwater exchange occurs gradually through time.

Delayed Recharge Propagation

Recharge does not instantly influence all parts of a groundwater system.

Depending on aquifer properties, groundwater recharge may:

- require years or decades to propagate;
- continue influencing groundwater systems after climatic conditions change;
- affect receptors long after recharge events occur.

Persistent Connectivity

Groundwater pathways frequently remain active long after disturbance cessation.

Connectivity may continue to transmit:

- hydraulic signals;
- groundwater-quality changes;
- dissolved contaminants;
- groundwater-system responses.

As a result, historical disturbances may continue influencing modern groundwater behaviour through persistent groundwater pathways.

Geochemical Persistence

Groundwater chemistry often evolves more slowly than groundwater levels.

Processes such as:

- contaminant attenuation;
- mineral dissolution;
- salinity redistribution;
- redox evolution;

may continue long after hydraulic recovery is observed.

5.2 Examples of Hydrogeological Memory

Examples of groundwater-memory behaviour include:

- groundwater recovery following long-term abstraction;
- delayed responses to climate variability;
- persistent contaminant plumes after source removal;
- groundwater-quality change following mine closure;
- residual seepage from rehabilitated landforms;
- prolonged groundwater–surface water interaction.

Large-scale climate-groundwater studies have similarly demonstrated substantial delays between climatic forcing and aquifer response, highlighting the importance of historical conditions for understanding contemporary groundwater behaviour (Taylor et al., 2018; Maxwell & Condon, 2016).

Examples of historical influences and their modern expressions are summarised in Table 2.

Table 2
Examples of hydrogeological memory effects.

Historical Influence	Possible Modern Response
Pumping	Delayed recovery
Recharge change	Long-term propagation
Contamination	Persistent groundwater impacts
Dewatering	Recovery lag
Hydraulic modification	Residual connectivity

Table 2 illustrates how groundwater systems frequently continue responding to historical conditions through delayed hydrogeological, hydraulic, and geochemical processes.

5.3 Groundwater Memory and Environmental Consequence

Hydrogeological memory becomes environmentally significant when groundwater-system responses continue influencing receptors after the original disturbance has disappeared.

For example:

- contaminants may continue migrating;
- groundwater-dependent ecosystems may continue responding;
- groundwater quality may remain altered;
- groundwater pathways may continue transporting dissolved constituents.

Consequently, environmental consequence may continue evolving despite apparent groundwater recovery.

This distinction helps explain why groundwater recovery and environmental recovery often occur on different timescales and should not be treated as equivalent processes.

5.4 Groundwater Memory as a Risk Driver

Groundwater memory represents an important source of long-term environmental risk because it extends the influence of historical activities beyond operational periods.

Risk assessments that focus only on present groundwater conditions may therefore underestimate:

- future receptor exposure;
- delayed groundwater impacts;
- long-term contaminant migration;
- residual connectivity effects.

Recognition of hydrogeological memory provides a stronger basis for long-term groundwater-risk evaluation and supports more realistic environmental assessment.

6. Legacy Groundwater and Environmental Risk

Environmental risk is commonly evaluated using current groundwater conditions, present-day groundwater quality, and contemporary hydrogeological behaviour. However, groundwater legacy effects demonstrate that future environmental risk frequently depends as much on historical conditions as on current observations.

Groundwater systems may continue transporting the influence of past activities through stored groundwater, persistent connectivity pathways, delayed transport, and long-term geochemical processes. Consequently, future environmental consequences often remain linked to historical disturbances through groundwater memory.

The conceptual relationship between historical disturbance, groundwater legacy, and environmental consequence is illustrated in Fig. 3.

Figure 3 demonstrates how historical disturbances can continue influencing environmental receptors through groundwater pathways long after the original source has disappeared.

6.1 Legacy Pathways

Groundwater legacy effects commonly persist through:

- groundwater storage;

- hydraulic gradients;
- contaminant pathways;
- groundwater connectivity;
- groundwater–surface water interaction;
- geochemical persistence.

These processes may remain active after:

- source removal;
- cessation of pumping;
- mine closure;
- remediation activities;
- rehabilitation programs.

As a result, environmental risks may continue evolving despite apparent improvement in hydrogeological conditions.

6.2 Delayed Receptor Exposure

One of the most important consequences of groundwater legacy is delayed receptor exposure. The vulnerability of modern water supplies to contamination from relatively young groundwater further illustrates the importance of travel-time behaviour in determining future risk exposure (Jasechko et al., 2017).

Because groundwater travel times are often long, receptors may not experience impacts until long after the original disturbance has occurred.

Examples include:

- delayed contaminant migration;
- long-term groundwater-quality deterioration;
- groundwater-dependent ecosystem response;
- extended pit-lake interactions;
- persistent groundwater discharge.

This delayed response means that management success cannot always be evaluated using short monitoring periods.

6.3 Practical Examples of Groundwater Legacy

Example 1

Mine Dewatering Recovery

Groundwater levels may recover relatively rapidly following cessation of dewatering, while groundwater-quality impacts and hydraulic pathways continue evolving for substantially longer periods. Post-closure mine-water investigations have repeatedly demonstrated that hydrogeological recovery may precede environmental recovery by decades (McCullough et al., 2020; Nordstrom & Blowes, 2020).

Example 2

Groundwater Contamination

Contaminants may continue migrating after source removal because groundwater travel times, storage effects, and attenuation processes operate over extended timescales. Consequently, environmental risks may remain active despite remediation of the original source.

Example 3

Climate and Recharge Signals

Recharge signals generated under historical climatic conditions may continue propagating through groundwater systems long after climatic conditions have changed. Groundwater responses therefore frequently lag climate response by years or decades (Cuthbert et al., 2020; Taylor et al., 2022).

6.4 Implications for Monitoring and Management

Integrated groundwater-management frameworks increasingly recommend monitoring designs that explicitly incorporate aquifer lag effects, legacy contaminants and future climate pressures (Wöhling et al., 2021; Scanlon et al., 2018). Recognition of groundwater legacy has important implications for:

- monitoring programs;
- mine closure planning;
- contamination management;
- environmental-risk assessment;
- sustainability evaluation.

Groundwater pollution risk frameworks similarly recognise the importance of understanding delayed contaminant migration, legacy contamination, and long-term receptor exposure when designing monitoring and management programs (Foster & Chilton, 2018).

Groundwater assessments should therefore consider:

- delayed responses;
- travel-time behaviour;
- storage effects;
- connectivity persistence;

- receptor exposure.

Failure to consider these processes may underestimate long-term environmental consequences and create false confidence regarding environmental recovery.

6.5 Beyond Current Conditions

The findings demonstrate that environmental significance cannot be evaluated solely from present groundwater behaviour.

Groundwater legacy requires consideration of:

- historical activities;
- current groundwater condition;
- future groundwater evolution.

This broader perspective provides a more realistic basis for evaluating environmental risk and long-term sustainability.

7. A Groundwater Memory Framework for Long-Term Assessment

The concepts of groundwater memory, hydrogeological lag, groundwater recovery, environmental recovery, and groundwater legacy can be integrated into a practical assessment framework that supports long-term groundwater management and environmental decision-making.

The framework recognises that groundwater systems retain information from past disturbances and that environmental consequences may develop over timescales much longer than operational, regulatory, or planning horizons. Consequently, groundwater assessments must extend beyond current conditions and explicitly evaluate the persistence of historical influences.

The proposed framework is illustrated conceptually in Fig. 4.

7.1 Framework Components

The groundwater-memory framework consists of six interconnected components:

Historical Disturbance

Examples include:

- groundwater abstraction;
- mine dewatering;
- contamination releases;
- recharge alteration;

- land-use change;
- climate variability.

These activities initiate groundwater-system change.

Groundwater Storage

Storage determines how long groundwater-system responses persist.

Storage controls:

- recovery rates;
- response delays;
- transport persistence;
- groundwater-memory strength.

Connectivity and Pathways

Groundwater pathways determine how disturbances propagate through groundwater systems.

Examples include:

- aquifer connections;
- fracture systems;
- groundwater–surface water interaction;
- regional flow systems.

Travel Time

Travel time controls:

- migration rates;
- receptor exposure timing;
- contaminant persistence;
- groundwater-system response.

Receptor Interaction

Environmental significance emerges when groundwater-system responses interact with receptors.

Potential receptors include:

- groundwater-dependent ecosystems;

- water supplies;
- streams and wetlands;
- cultural assets;
- engineered infrastructure.

Environmental Consequence

Environmental consequence represents the final expression of groundwater memory.

Examples include:

- delayed contaminant exposure;
- ecological response;
- groundwater-quality change;
- long-term groundwater risk.

7.2 Framework Application

The framework may be applied to:

- mine closure;
- groundwater contamination;
- recharge assessment;
- environmental impact assessment;
- groundwater-resource management;
- climate adaptation planning.

The framework may also support groundwater assessments in data-scarce regions where uncertainty, limited monitoring data, and conceptual-model limitations complicate long-term prediction and sustainable groundwater management (Borzì, 2025).

By integrating historical influences with current groundwater behaviour and future environmental outcomes, the framework improves understanding of delayed groundwater responses and long-term environmental risk.

Recent advances in integrated hydrological modelling provide opportunities to quantitatively evaluate groundwater memory, delayed system response and long-term sustainability under changing environmental conditions (Wöhling et al., 2021; Condon et al., 2020).

7.3 Why Groundwater Legacy Matters

Traditional groundwater assessments often focus on:

- groundwater levels;
- recharge;
- groundwater quality;
- current groundwater behaviour.

While important, these observations alone may not explain:

- delayed environmental outcomes;
- persistent groundwater impacts;
- receptor exposure;
- future risk.

Groundwater sustainability assessments increasingly recognise that long-term environmental outcomes depend on interactions between storage depletion, recharge dynamics and groundwater-dependent systems (Bierkens & Wada, 2019; Scanlon et al., 2018).

The groundwater-memory framework therefore provides a structured approach for interpreting long-term groundwater behaviour in a way that explicitly links historical disturbance with future consequence.

7.4 A New Perspective on Recovery

A key outcome of this study is the recognition that:

Groundwater recovery, environmental recovery, and environmental consequence represent different processes operating on different timescales.

Consequently, recovery should be viewed as one stage within a broader groundwater-memory system rather than the end point of hydrogeological assessment.

7.5 Supporting Long-Term Environmental Decision-Making

The framework provides a practical basis for:

- improving closure planning;
- extending monitoring horizons;
- evaluating delayed consequences;
- strengthening groundwater-risk assessments;
- supporting sustainable groundwater management.

By explicitly accounting for hydrogeological lag, groundwater memory, connectivity persistence, and receptor exposure, the framework offers a more defensible basis for managing groundwater systems over long timescales and improves the interpretation of environmental risk long after disturbances have ceased. Recent advances in uncertainty quantification and integrated hydrological modelling further

support the need to account for multiple future groundwater trajectories when evaluating long-term environmental risk (Delottier et al., 2023).

8. Discussion

The findings presented in this study demonstrate that groundwater systems frequently continue responding to disturbances long after the initiating activity has ceased. While environmental assessments often focus on current groundwater conditions, hydrogeological evidence increasingly shows that groundwater behaviour is strongly influenced by historical stresses, delayed recharge propagation, groundwater storage, persistent connectivity, and long travel times. Consequently, groundwater recovery should not be interpreted as evidence that environmental risk has disappeared.

A central implication of the groundwater-memory concept is that hydrogeological recovery and environmental recovery are fundamentally different processes. Groundwater levels may recover, hydraulic gradients may stabilise, and groundwater storage may replenish, yet contaminant migration, receptor exposure, groundwater-quality impacts, and ecological responses may continue for prolonged periods. Similar observations have been documented in post-mining groundwater systems where hydraulic recovery occurred substantially earlier than geochemical and environmental recovery (McCullough et al., 2020; Nordstrom & Blowes, 2020).

The study further highlights the importance of groundwater connectivity as a mechanism through which legacy effects persist. Stored groundwater, residual hydraulic gradients, and established migration pathways allow historical disturbances to continue influencing environmental receptors despite source removal. Groundwater pathways may therefore remain environmentally significant long after visible evidence of disturbance has disappeared. Recent investigations of hydrological connectivity and groundwater–surface water exchange similarly demonstrate that connectivity often controls the timing, magnitude, and persistence of groundwater-system response (Dwivedi et al., 2025; Irvine et al., 2024; Yang et al., 2025).

Continental-scale analyses further reveal that groundwater-stream connectivity can sustain delayed hydrological responses across large regions, even where causative disturbances have long ceased (Fan et al., 2018; Maxwell & Condon, 2016).

Travel time represents another fundamental control on delayed environmental consequence. Groundwater movement frequently occurs over timescales that exceed operational, management, and even regulatory horizons. As a result, environmental receptors may respond many years after the original disturbance occurred. This behaviour explains why assessments based solely on current conditions may underestimate future groundwater risks and highlights the importance of adopting longer-term assessment horizons.

Similar lagged responses have been documented under future climate-change scenarios where groundwater depletion and recharge recovery occur over significantly longer periods than atmospheric

forcing (Condon et al., 2020; Scanlon et al., 2018).

The groundwater-memory framework proposed in Fig. 4 provides a practical approach for integrating groundwater storage, connectivity, travel-time behaviour, receptor exposure, and environmental consequence into a single interpretive structure. This requirement becomes increasingly important where geological uncertainty influences groundwater-flow pathways and long-term prediction of environmental outcomes (Ntigkakis et al., 2026). Unlike conventional recovery assessments that focus primarily on groundwater levels, the framework explicitly links historical disturbance with future environmental outcomes. This broader perspective improves understanding of delayed responses and supports more realistic environmental-risk evaluation.

From a management perspective, the study suggests that long-term monitoring, adaptive management, and extended assessment horizons are particularly important where:

- groundwater storage is large;
- travel times are long;
- groundwater connectivity remains active;
- contaminants are persistent;
- receptors are sensitive.

Under such conditions, groundwater systems may continue evolving long after operational activities have ceased.

Ultimately, the concept of groundwater memory provides a useful framework for understanding why environmental consequences frequently persist beyond apparent hydrogeological recovery. Recognising the distinction between groundwater recovery and environmental recovery improves risk assessment, supports better management decisions, and encourages greater consideration of long-term hydrogeological behaviour within groundwater-resource management, contamination assessment, mine closure, and environmental planning.

9. Conclusions

Groundwater systems frequently retain the effects of disturbance long after the original cause has disappeared. This study demonstrates that delayed hydrogeological responses, groundwater connectivity, travel-time behaviour, and groundwater storage collectively contribute to a phenomenon referred to as **groundwater memory**.

Several key conclusions emerge:

- Groundwater recovery does not necessarily imply environmental recovery.
- Groundwater systems frequently continue responding to historical disturbances through delayed hydraulic, geochemical, and environmental processes.

- Groundwater storage and travel times are major controls on hydrogeological lag.
- Groundwater connectivity allows historical influences to continue propagating through groundwater systems after operational activities have ceased.
- Environmental consequence depends on receptor exposure and sensitivity rather than groundwater recovery alone.
- Short assessment horizons may underestimate long-term environmental risks associated with groundwater systems.
- Long-term monitoring and adaptive management are essential where groundwater-memory effects are significant.

The principal contribution of this paper is the development of a groundwater-memory framework that explicitly links historical disturbance, groundwater storage, connectivity, travel-time behaviour, receptor exposure, and environmental consequence. The framework demonstrates that groundwater recovery, groundwater legacy, and environmental recovery should be considered related but distinct processes operating on different timescales.

Long-term prediction of groundwater-system evolution is also affected by conceptual, geological and parameter uncertainty, requiring adaptive monitoring and model updating throughout the post-disturbance period (Konikow & Bredehoeft, 2020).

Emerging groundwater-sustainability research increasingly demonstrates that understanding aquifer memory, legacy behaviour and delayed environmental consequences is essential for effective long-term water-resource management under future environmental change (Gleeson et al., 2020; Bierkens & Wada, 2019; Taylor et al., 2018).

By recognising groundwater memory as a fundamental hydrogeological characteristic, groundwater practitioners can improve environmental assessments, strengthen closure planning, enhance long-term groundwater-risk evaluation, and support more sustainable groundwater management. Understanding what happened in the past remains essential for understanding what groundwater systems may do in the future.

Declarations

Competing Interests

The author declares no competing interests.

Ethics Approval

Not applicable.

Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

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Author Contribution

Y.Y. conceptualized the study, developed the methodology, conducted the analysis, interpreted the results, prepared figures and tables, wrote and revised the manuscript, and approved the final version.

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Data Availability

All data generated or analysed during this study are included in this published article. No new datasets were generated during the current study.

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Figures

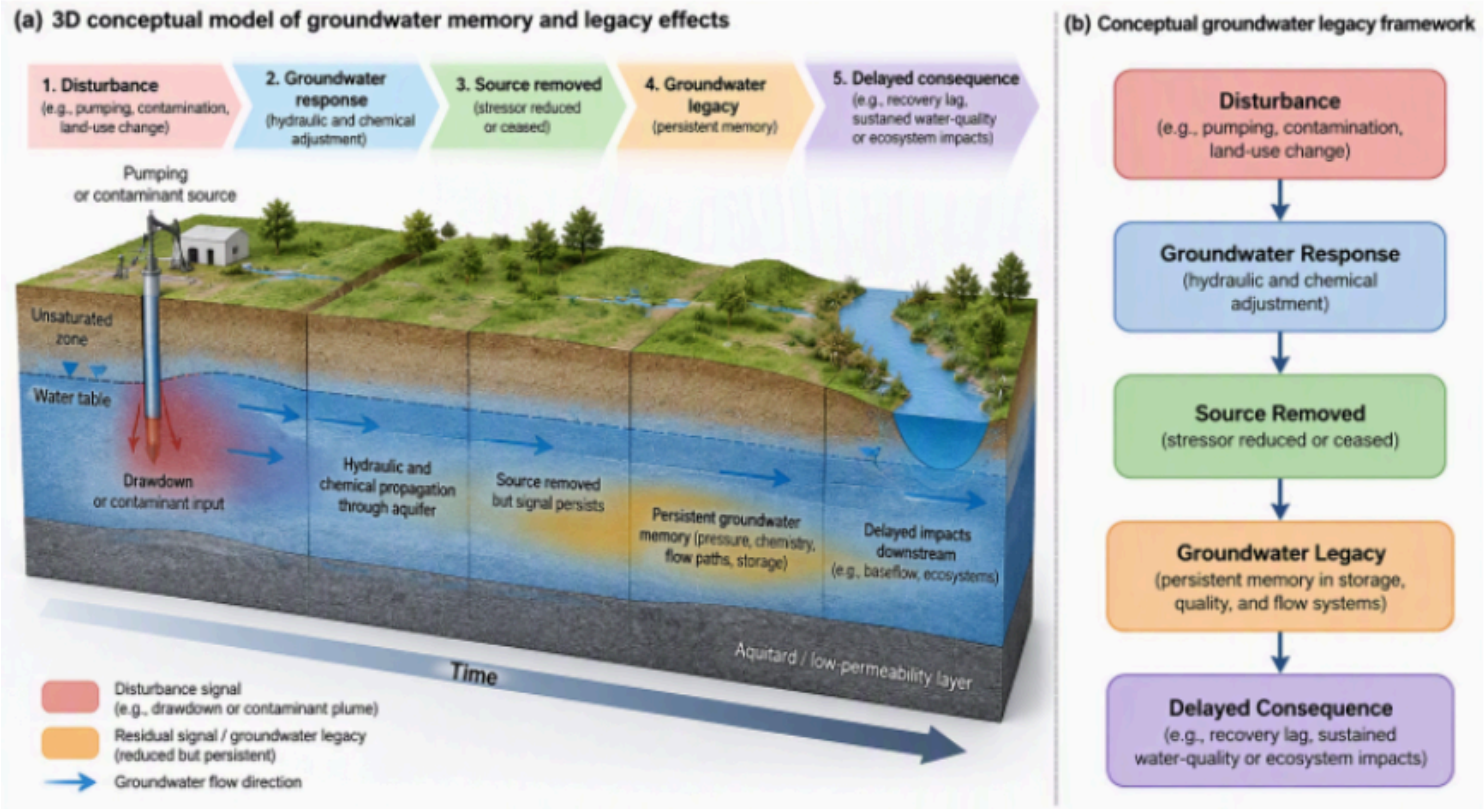


Figure 1

Figure 1. Conceptual framework of groundwater memory and legacy effects. (a) Three-dimensional conceptual representation showing the evolution of groundwater-system responses following a disturbance, including storage effects, delayed transport, persistent hydrogeological legacies, and delayed environmental consequences. (b) Simplified conceptual groundwater legacy framework illustrating the progression from disturbance through groundwater response and legacy formation to delayed consequences that persist beyond removal of the original stressor.

Figure 1 demonstrates how groundwater systems may continue responding long after the original disturbance has disappeared, creating delayed environmental consequences and persistent hydrogeological effects.

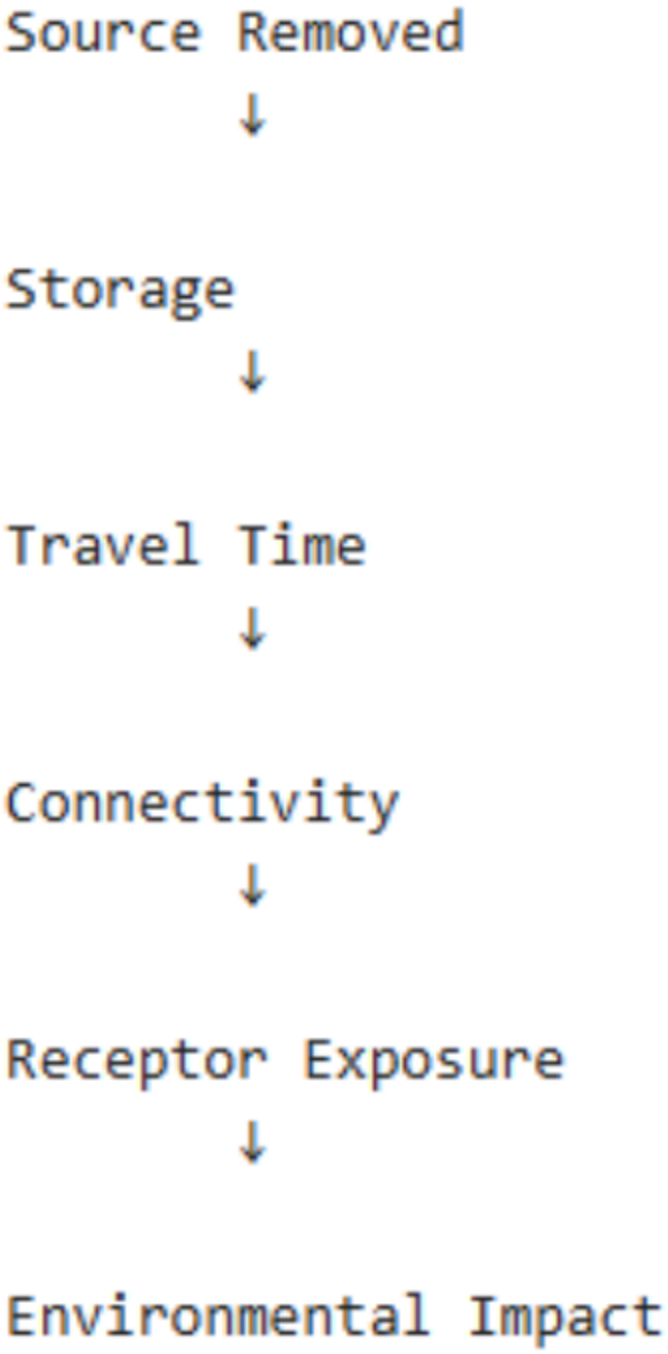


Figure 2

Figure 2. Mechanisms through which groundwater legacies continue to influence environmental receptors after source removal.

Figure 2 shows how storage, pathways, and connectivity allow groundwater systems to continue influencing receptors after the original source has disappeared.

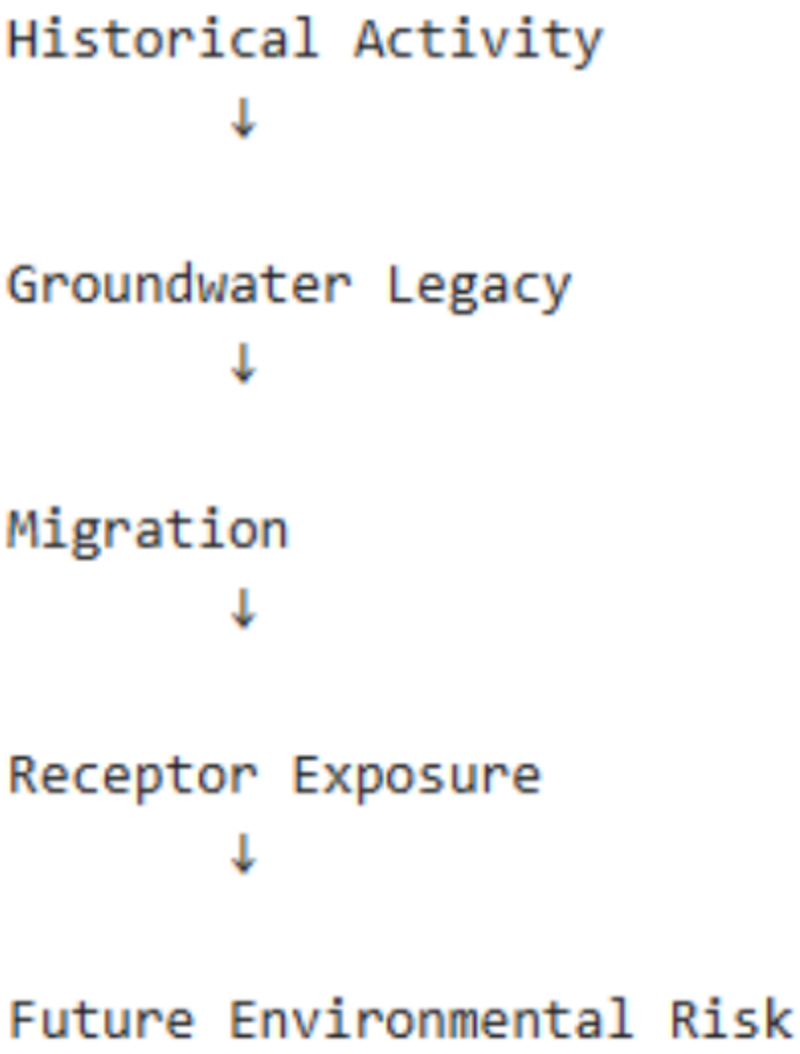


Figure 3

Figure 3. Relationship between historical disturbances, groundwater legacy effects, and future environmental risk.

Figure 3 demonstrates how historical disturbances can continue influencing environmental receptors through groundwater pathways long after the original source has disappeared.

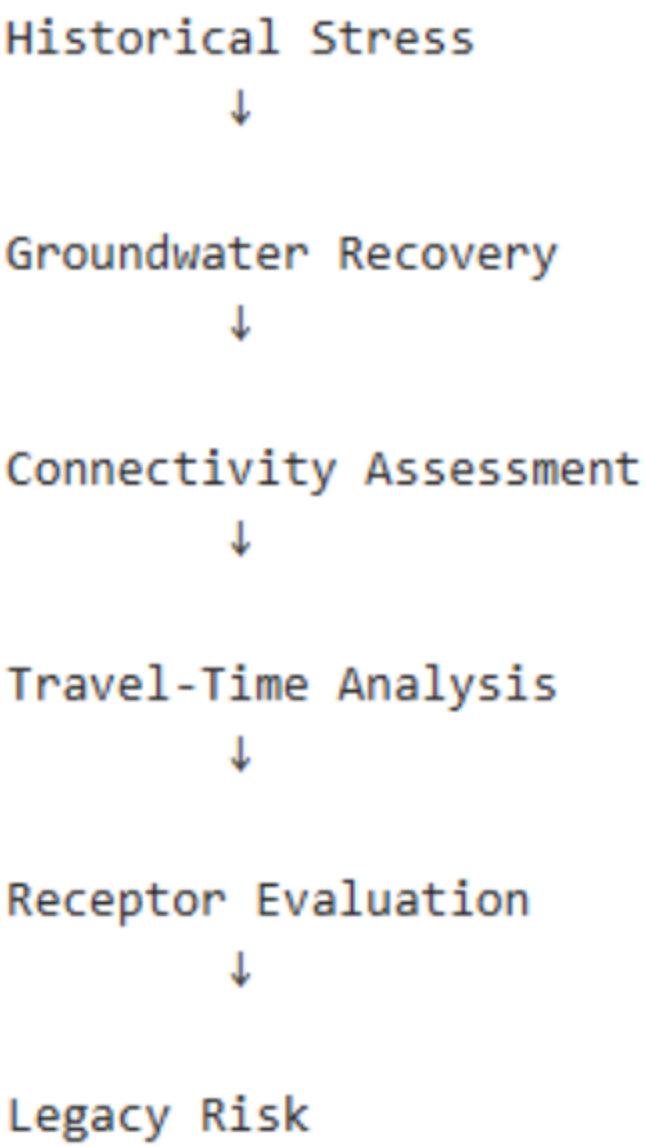


Figure 4

Figure 4. Framework for evaluating long-term groundwater legacy effects and environmental consequences.