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Understanding Hydrogeological Connectivity: Linking Groundwater Processes to Environmental Consequences

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Abstract

Hydrogeological connectivity governs the movement of groundwater, hydraulic signals, dissolved constituents, and environmental pressures through subsurface systems. Although connectivity is central to groundwater assessment, it is commonly interpreted only as hydraulic communication between locations. This review synthesises the broader concept of connectivity and distinguishes four interrelated dimensions: structural, hydraulic, transport, and environmental connectivity. A connectivity-based framework is proposed linking sources, pathways, receptors, and environmental consequences across multiple spatial and temporal scales. The review examines the geological, hydraulic, hydrological, and environmental controls that influence connectivity and evaluates methods used for its assessment, including hydrogeological characterisation, tracer studies, groundwater monitoring, modelling, and particle tracking. The analysis shows that hydraulic connectivity alone is insufficient for assessing environmental risk because contaminant migration and environmental consequences depend on transport processes, travel times, and receptor vulnerability. Connectivity is presented as a unifying framework for understanding groundwater flow, recharge, groundwater recovery, groundwater-surface water interaction, contaminant transport, ecosystem response, and environmental management. Incorporating connectivity into groundwater investigations can improve environmental assessments, water-resource management, mine-closure planning, and climate-resilience strategies.

1. Introduction

Groundwater systems function as interconnected networks through which water, dissolved constituents, thermal energy, and environmental stresses are transmitted across a wide range of spatial and temporal scales (Zhang et al., 2021; Wilcox et al., 2022). Understanding the nature and degree of connectivity within these systems is fundamental to hydrogeology because connectivity governs groundwater flow, recharge propagation, contaminant migration, groundwater recovery, ecological dependence, and long-term environmental change. Connectivity therefore provides the physical mechanism linking hydrogeological processes with environmental consequences. Recent global analyses demonstrate that groundwater connectivity is also strongly influenced by groundwater-table architecture and large-scale climate–groundwater interactions (Fan et al., 2013; Cuthbert et al., 2019).

Many of the most important questions in hydrogeology are fundamentally questions about connectivity. Examples include:

- Is a contaminant source connected to a receptor?
- Can groundwater migrate between aquifers?
- Is a river hydraulically connected to groundwater?
- Can groundwater extraction influence a wetland?
- How rapidly can recharge signals propagate through an aquifer system?
- Will groundwater recover following mining, dewatering, or environmental disturbance?

Although these questions appear diverse, they all require an understanding of how groundwater systems are connected and how hydrogeological influences propagate through those systems.

Historically, groundwater investigations have focused on hydraulic gradients, groundwater levels, aquifer properties, recharge estimation, and groundwater budgets. While these remain essential components of hydrogeological assessment, they do not fully explain how stresses, contaminants, recharge signals, or environmental impacts are transmitted through groundwater systems. Connectivity provides a broader framework that links these individual observations and helps explain system behaviour. A groundwater system may exhibit similar hydraulic properties in different locations yet display very different connectivity characteristics due to geological heterogeneity, structural controls, storage behaviour, or transport limitations.

Recent advances in hydrogeology have highlighted the importance of connectivity in groundwater-surface water interaction, river corridor science, lake-aquifer systems, contaminant transport, groundwater-dependent ecosystems, mine-water management, and environmental risk assessment. Studies of river-groundwater systems have demonstrated that hydraulic exchange processes strongly influence groundwater flow paths, travel times, nutrient transport, and ecosystem function (Fleckenstein et al., 2010; Harvey & Gooseff, 2015). Similarly, investigations of hydrogeological controls on groundwater-surface water exchange have shown that connectivity varies considerably through space and time and is strongly influenced by geological and hydrological conditions (Brunner et al., 2009).

Groundwater connectivity has also been examined in lake-aquifer systems where groundwater exchange controls lake levels, salinity evolution, climatic response, and ecological behaviour. Detailed studies at Lake Naivasha in Kenya demonstrated that understanding groundwater-lake connectivity was essential for interpreting system dynamics and water-resource sustainability (Yihdego & Becht, 2013). Subsequent investigations further highlighted the importance of groundwater connectivity in reducing vulnerability to climatic variability and improving resilience of groundwater-dependent lake systems (Yihdego et al., 2017).

Connectivity is equally important in understanding groundwater recovery and system response to environmental change. Groundwater mounding associated with wastewater reuse and recharge systems illustrates how hydraulic responses can propagate through groundwater systems over considerable distances, influencing groundwater levels, flow directions, and potential receptor interactions. Similarly, studies of groundwater-level dynamics have demonstrated that temporal responses observed in monitoring networks can often provide indirect evidence of hydraulic communication and connectivity within aquifer systems (Yihdego et al., 2017).

Despite its importance, hydrogeological connectivity remains inconsistently defined and interpreted. In practice, connectivity is often simplified to the existence of a hydraulic pathway between two locations. However, groundwater connectivity is more complex than simple hydraulic communication. Structural pathways may exist without effective groundwater movement, hydraulic connectivity may occur without significant contaminant transport, and transport connectivity may exist without meaningful

environmental consequences. Consequently, distinctions must be made between different forms of connectivity if groundwater assessments are to support effective environmental decision-making.

Groundwater connectivity may be viewed as a hierarchy of interacting processes that include:

- structural connectivity;
- hydraulic connectivity;
- transport connectivity;
- environmental connectivity; and
- receptor connectivity.

Each component influences different aspects of groundwater-system behaviour and each may operate over different spatial and temporal scales. Failure to distinguish these forms of connectivity may result in misunderstanding of groundwater risk, contaminant migration potential, ecosystem dependence, and long-term environmental outcomes.

The increasing reliance on groundwater modelling, environmental assessment, mine closure planning, groundwater allocation, managed aquifer recharge, and ecosystem protection has heightened the need for more rigorous understanding of connectivity. Groundwater connectivity provides a unifying framework capable of linking groundwater flow processes with environmental consequences and management decisions.

The objectives of this paper are to:

- examine the concept of hydrogeological connectivity;
- distinguish between major forms of groundwater connectivity;
- evaluate the controls governing groundwater connectivity;
- review methods used to assess connectivity;
- examine the role of connectivity in environmental assessment and groundwater management; and
- develop a practical framework linking connectivity, receptors, and environmental consequence.

The central argument of this paper is that hydrogeological connectivity represents one of the most important organising principles in groundwater science because it directly links geological structure, groundwater flow, contaminant transport, environmental receptors, and management outcomes. By placing connectivity at the centre of groundwater interpretation, hydrogeologists can improve understanding of groundwater-system behaviour and develop more transparent, defensible, and environmentally meaningful assessments.

Although connectivity has been widely discussed in groundwater-flow studies, groundwater-surface water interaction, contaminant hydrogeology, and environmental assessment, most investigations examine individual dimensions of connectivity rather than the broader system-wide relationships linking

groundwater processes to environmental outcomes. Existing studies commonly focus on hydraulic connectivity, while less attention is given to the interactions among structural pathways, transport mechanisms, environmental receptors, and consequences.

This review addresses this gap by synthesising current knowledge into a unified conceptual framework that explicitly links structural, hydraulic, transport, and environmental connectivity within a source-pathway-receptor context. The proposed framework extends conventional interpretations of connectivity by demonstrating how environmental consequences emerge only when effective groundwater pathways connect a source to a susceptible receptor. The review further highlights the role of connectivity as an organising principle that integrates groundwater flow, contaminant migration, ecosystem response, groundwater recovery, and environmental risk assessment.

1.2 Literature Review Approach

This study adopts a narrative and conceptual review approach aimed at synthesising current understanding of hydrogeological connectivity and its application in groundwater assessment and environmental management. Relevant literature was identified through searches of major scientific databases including Scopus, Web of Science, Google Scholar, and publisher databases.

Search terms included combinations of:

- hydrogeological connectivity;
- groundwater connectivity;
- hydraulic connectivity;
- transport connectivity;
- groundwater-surface water interaction;
- contaminant transport;
- groundwater recovery;
- environmental risk;
- groundwater-dependent ecosystems; and
- groundwater modelling.

Peer-reviewed journal articles, technical reports, groundwater-modelling studies, and foundational hydrogeological references were reviewed. Priority was given to studies that advanced conceptual understanding, developed assessment methods, or demonstrated practical applications of connectivity in groundwater systems. The selected literature was analysed and synthesised to develop an integrated framework linking sources, pathways, transport processes, receptors, environmental consequences, and management responses.

2. Hydrogeological Connectivity: Concepts and Definitions

Hydrogeological connectivity describes the capacity of groundwater systems to transmit water, hydraulic signals, dissolved constituents, and environmental influences between different parts of the subsurface environment. Although often discussed as a single concept, connectivity is not a single property but rather the combined expression of geological structure, hydraulic behaviour, transport processes, and environmental interactions operating across multiple spatial and temporal scales.

The concept has gained increasing importance as groundwater investigations move beyond simple water-resource assessments towards integrated evaluations of ecosystem protection, contaminant transport, groundwater recovery, climate resilience, and environmental risk. Connectivity provides the framework through which hydrogeologists can understand how changes occurring in one part of a groundwater system may influence other locations, receptors, or environmental processes.

Groundwater systems are rarely homogeneous. Geological heterogeneity, structural discontinuities, variations in aquifer properties, recharge patterns, and boundary conditions create complex connectivity networks that control how groundwater moves through the subsurface. Consequently, two locations may appear hydraulically related while exhibiting substantially different transport behaviour, environmental consequences, or recovery responses.

Recent research in groundwater-surface water interaction, river corridor hydrology, and lake-aquifer systems demonstrates that connectivity is often dynamic rather than static, varying according to hydrological conditions, climatic forcing, and groundwater-system response (Brunner et al., 2009; Fleckenstein et al., 2010; Harvey & Gooseff, 2015). Understanding connectivity therefore requires consideration of both physical pathways and the processes operating along those pathways.

2.1 Structural Connectivity

Structural connectivity refers to the physical arrangement and continuity of geological materials that form potential pathways for groundwater movement.

Structural connectivity is controlled by:

- faults;
- fractures;
- joints;
- bedding structures;
- sedimentary continuity;
- weathered zones;
- karst conduits; and
- palaeochannels.

Structural connectivity determines whether a pathway can exist but does not necessarily indicate that groundwater movement is currently occurring. Highly connected geological structures may remain hydraulically inactive if hydraulic gradients are absent or groundwater recharge is limited.

Conversely, modest structural connectivity may support significant groundwater movement where favourable hydraulic conditions exist.

In fractured-rock and volcanic environments, structural connectivity often exerts a dominant control on groundwater flow behaviour because groundwater movement is concentrated along discrete preferential pathways rather than occurring uniformly through the rock matrix.

2.2 Hydraulic Connectivity

Hydraulic connectivity describes the ability of hydraulic head changes, groundwater pressure variations, and groundwater flow responses to propagate through a groundwater system.

Hydraulic connectivity is influenced by:

- hydraulic conductivity;
- transmissivity;
- storativity;
- groundwater recharge;
- hydraulic gradients;
- aquifer geometry; and
- boundary conditions.

Hydraulic connectivity determines whether groundwater flow is possible and how rapidly hydraulic responses can be transmitted through an aquifer system.

Examples include:

- drawdown propagation during pumping;
- groundwater recovery after dewatering;
- recharge responses following rainfall;
- pressure transmission between aquifers; and
- groundwater-surface water exchange.

Groundwater-level responses observed in monitoring networks are frequently indirect indicators of hydraulic communication within a groundwater system. Studies of groundwater-level dynamics and groundwater recovery demonstrate that hydraulic responses provide valuable evidence of connectivity, particularly where groundwater movement cannot be directly observed (Yihdego et al., 2017).

2.3 Transport Connectivity

Transport connectivity refers to the movement of dissolved constituents, heat, tracers, nutrients, contaminants, and other transported materials through groundwater systems.

Transport connectivity depends on:

- hydraulic connectivity;
- groundwater velocity;
- travel time;
- dispersion;
- diffusion;
- attenuation processes; and
- geochemical reactions.

Importantly, hydraulic connectivity does not automatically imply transport connectivity.

For example:

- hydraulic signals may propagate rapidly through an aquifer;
- contaminants may require decades or centuries to travel the same distance;
- attenuation may prevent contaminant migration despite hydraulic connection;
- geochemical processes may alter transported constituents before receptors are reached.

Consequently, transport connectivity often provides a more realistic representation of environmental impact potential than hydraulic connectivity alone.

Particle tracking, environmental tracers, isotopic techniques, and solute-transport modelling are frequently applied to evaluate transport connectivity and estimate groundwater travel times (Pollock, 1988; Pollock, 2012).

2.4 Groundwater–Surface Water Connectivity

Groundwater and surface-water systems are often interconnected through complex hydraulic exchange processes.

Groundwater-surface water connectivity can occur through:

- river infiltration;
- groundwater discharge to streams;
- lake-aquifer interaction;
- wetland interaction;
- floodplain exchange; and
- hyporheic-zone processes.

These interactions play an important role in controlling:

- streamflow permanence;
- ecological resilience;
- nutrient transport;
- contaminant migration;
- groundwater recharge; and
- drought response.

Research in river-corridor science demonstrates that groundwater-surface water connectivity frequently exhibits strong spatial and temporal variability and is controlled by geological structure, hydraulic gradients, and climatic conditions (Fleckenstein et al., 2010; Harvey & Gooseff, 2015).

Lake-aquifer systems provide particularly valuable examples of groundwater connectivity because groundwater exchange can strongly influence lake levels, salinity, water quality, and long-term system resilience. Detailed investigations at Lake Naivasha demonstrated that groundwater-lake connectivity was fundamental to understanding long-term hydrological behaviour and resource sustainability (Yihdego & Becht, 2013).

2.5 Environmental Connectivity

Environmental connectivity describes the relationship between hydrogeological processes and environmental receptors.

Potential receptors include:

- rivers;
- lakes;
- wetlands;
- springs;
- groundwater-dependent ecosystems;
- water-supply bores;
- infrastructure assets; and
- human communities.

Environmental connectivity determines whether groundwater processes have practical environmental significance.

For example:

- a contaminant source may be hydraulically connected to an aquifer;

- a groundwater pathway may exist;
- transport may occur;

yet environmental consequences will only arise if a sensitive receptor is present and susceptible to impact.

Consequently, environmental connectivity forms the critical link between groundwater science and environmental management.

2.6 Connectivity Across Scales

Connectivity operates across a wide range of scales.

Local Scale

- fractures;
- individual wells;
- contamination sites;
- stream reaches.

Catchment Scale

- aquifer systems;
- river corridors;
- groundwater-dependent ecosystems.

Regional Scale

- groundwater basins;
- recharge zones;
- transboundary groundwater systems.

The scale of investigation strongly influences both observed connectivity and the methods used to evaluate it. A groundwater system that appears highly connected at a local scale may behave very differently when evaluated regionally.

Recognition of scale dependence is therefore essential for effective groundwater assessment and interpretation.

2.7 A Hierarchy of Hydrogeological Connectivity

The preceding discussion suggests that hydrogeological connectivity can be viewed as a hierarchy of progressively increasing environmental significance.

Figure 1 illustrates hydrogeological connectivity as a hierarchical process progressing from geological structure to environmental consequences. Geological controls establish the physical framework for hydraulic connectivity, which enables groundwater movement. Groundwater movement provides the mechanism for constituent transport, while environmental connectivity is achieved only when source-pathway-receptor linkages extend through the entire system. Accordingly, environmental impacts emerge not simply from hydraulic connection, but from the degree to which connectivity is maintained across all hierarchical levels.

The framework demonstrates that structural pathways alone do not guarantee groundwater movement, groundwater movement does not guarantee contaminant transport, and contaminant transport does not necessarily produce environmental consequence. Environmental impacts emerge only when connectivity extends through all levels of the hierarchy.

This distinction is critical because many groundwater assessments implicitly assume that hydraulic connection alone demonstrates environmental risk. In reality, environmental significance depends upon the complete source–pathway–receptor relationship and the degree of connectivity operating throughout the groundwater system.

3. Controls on Hydrogeological Connectivity

Hydrogeological connectivity is governed by a combination of geological, hydraulic, hydrological, transport, and environmental controls that collectively determine how groundwater systems transmit water, dissolved constituents, hydraulic signals, and environmental impacts. Connectivity therefore emerges as a system property resulting from interactions among multiple processes rather than a single measurable parameter.

The hierarchy of connectivity introduced in **Table 1** provides a framework for understanding how physical pathways evolve into hydraulic communication, transport processes, and ultimately environmental consequence. While each form of connectivity can be considered separately, they are strongly interrelated and often operate simultaneously within groundwater systems.

Groundwater systems rarely display uniform connectivity. Geological heterogeneity, structural discontinuities, variable aquifer properties, recharge dynamics, and environmental conditions create complex connectivity networks that may vary substantially through space and time.

3.1 Geological Controls

Geology provides the physical framework within which groundwater connectivity develops. Geological characteristics determine whether pathways exist, how continuous they are, and the extent to which groundwater movement can occur.

Key geological controls include:

- lithology;
- stratigraphic continuity;
- aquifer geometry;
- fault systems;
- fracture networks;
- weathering profiles;
- palaeochannels; and
- karst development.

Structural connectivity is often strongest in fractured-rock and karst environments where interconnected pathways facilitate groundwater movement over considerable distances. Conversely, low-permeability strata, confining units, and discontinuous aquifer systems may substantially restrict groundwater movement even where hydraulic gradients are present.

Geological structure therefore forms the foundation upon which all other forms of connectivity develop.

3.2 Hydraulic Controls

Hydraulic connectivity describes the capacity of groundwater pressure changes and groundwater flow responses to propagate through a groundwater system.

Important controls include:

- hydraulic conductivity;
- transmissivity;
- storativity;
- specific yield;
- hydraulic gradients;
- recharge rates; and
- boundary conditions.

Hydraulic connectivity controls how rapidly aquifer systems respond to pumping, recharge, groundwater recovery, and environmental change. Changes in groundwater levels observed within monitoring networks frequently provide evidence of hydraulic communication and connectivity between different parts of an aquifer system.

Groundwater-level responses have been widely used as indicators of hydraulic connection because they reveal how pressure disturbances propagate within groundwater systems (Yihdego et al., 2017).

3.3 Recharge Controls

Recharge represents one of the principal drivers of groundwater connectivity because it supplies the water required to sustain groundwater movement and hydraulic communication.

Recharge may occur through:

- rainfall infiltration;
- river leakage;
- lake infiltration;
- managed aquifer recharge;
- irrigation return flows; and
- wastewater infiltration.

Changes in recharge can modify groundwater gradients, influence travel times, activate previously insignificant pathways, and alter connectivity behaviour. Recharge signals may propagate through groundwater systems over considerable distances and therefore play a critical role in long-term groundwater-system evolution.

Groundwater mounding associated with artificial recharge and wastewater reuse systems provides a clear demonstration of how recharge can modify groundwater connectivity and influence groundwater-system behaviour.

3.4 Groundwater–Surface Water Connectivity

Connectivity between groundwater and surface-water systems represents one of the most important expressions of hydrogeological connectivity (Banerjee & Ganguly, 2023; Irvine et al., 2024; Ma et al., 2024). Regional-scale assessments increasingly recognise groundwater–surface water interaction as a critical component of integrated water-resource management (Barthel & Banzhaf, 2016).

Examples include:

- river-aquifer interaction;
- lake-aquifer interaction;
- wetland exchange;
- spring discharge;
- floodplain connectivity; and
- hyporheic-zone processes.

These interactions influence:

- streamflow generation;
- recharge distribution;
- ecosystem resilience;

- nutrient transport;
- contaminant migration; and
- drought response.

Research has demonstrated that groundwater–surface water exchange is both spatially and temporally dynamic, varying according to hydraulic gradients, geological conditions, recharge processes, and climatic forcing. Groundwater exchange frequently plays a dominant role in controlling the behaviour of rivers, lakes, wetlands, and groundwater-dependent ecosystems.

Lake–aquifer investigations have demonstrated that understanding connectivity is essential for interpreting long-term groundwater behaviour, water-resource sustainability, and environmental resilience (Yihdego & Becht, 2013; Yihdego et al., 2017).

3.5 Transport and Travel-Time Controls

Hydraulic connectivity alone does not determine environmental significance. Transport processes ultimately control the movement of dissolved constituents through groundwater systems.

Transport connectivity is influenced by:

- groundwater velocity;
- flow-path geometry;
- travel time;
- dispersion;
- diffusion;
- attenuation;
- sorption; and
- geochemical reactions.

Two locations may exhibit strong hydraulic connectivity while demonstrating weak transport connectivity because migration rates are slow or attenuation processes are significant.

Travel time therefore becomes a critical measure of connectivity because it determines the rate at which water, contaminants, and environmental signals move through groundwater systems. Particle tracking, environmental tracers, and groundwater transport modelling are commonly used to evaluate transport connectivity and predict groundwater movement.

3.6 Environmental Receptors

The practical significance of groundwater connectivity is ultimately determined by the presence of receptors and their sensitivity to groundwater-system change.

Potential receptors include:

- rivers;
- lakes;
- wetlands;
- groundwater-dependent ecosystems;
- groundwater supply wells;
- agricultural users;
- infrastructure assets; and
- human communities.

Environmental connectivity exists when hydrogeological pathways provide a mechanism through which groundwater changes can influence receptors. In many cases, groundwater movement may occur without creating measurable environmental impact because receptors are absent or insensitive to the groundwater change.

Consequently, effective groundwater assessments must evaluate connectivity in the context of source–pathway–receptor relationships rather than groundwater movement alone.

3.7 Scale Dependence

Connectivity operates across multiple spatial and temporal scales.

Local Scale

Examples include:

- fractures;
- pumping wells;
- contamination sites;
- stream reaches.

Catchment Scale

Examples include:

- aquifer systems;
- wetlands;
- river corridors;
- groundwater-dependent ecosystems.

Regional Scale

Examples include:

- groundwater basins;
- recharge zones;
- regional flow systems;
- transboundary aquifers.

The scale of investigation strongly influences both the observed degree of connectivity and the methods used to evaluate it. A pathway that appears highly connected at a local scale may have limited significance regionally, while regional connectivity may remain invisible in local investigations.

3.8 Connectivity as a Dynamic Process

Groundwater connectivity is not fixed. Instead, it continuously evolves in response to:

- groundwater abstraction;
- mine dewatering;
- groundwater recovery;
- climate variability;
- recharge fluctuations;
- land-use change; and
- environmental disturbance.

These changes may alter groundwater flow paths, travel times, hydraulic gradients, and environmental interactions. Consequently, connectivity assessments should consider both present-day conditions and potential future changes in groundwater-system behaviour.

The dynamic interactions among structural, hydraulic, transport, and environmental connectivity are summarised in **Table 1**, highlighting the progression from physical pathways to environmental consequence. Understanding how connectivity evolves through time is essential for groundwater management, contamination assessment, environmental protection, ecosystem sustainability, and mine-closure planning.

Table 1
Major forms of groundwater connectivity and the questions they address.

Connectivity Type	Key Question	Assessment Method	Typical Time Scale	Environmental Relevance
Structural	Is a pathway present?	Mapping, geophysics	Static	Potential
Hydraulic	Can flow occur?	Pumping tests	Days-years	Moderate
Transport	Can contaminants move?	Tracers, modelling	Years-decades	High
Environmental	Can receptors be affected?	Risk assessment	Variable	Very High

4. Assessing Hydrogeological Connectivity

Hydrogeological connectivity cannot be observed directly in most groundwater systems and must therefore be inferred from geological, hydraulic, hydrochemical, environmental, and modelling evidence. Because connectivity encompasses multiple interacting processes, no single method can adequately characterize all aspects of groundwater connectivity. Effective assessment generally requires integration of several complementary approaches.

The choice of assessment method depends upon the connectivity question being investigated. Structural connectivity may be evaluated through geological investigations, hydraulic connectivity through groundwater monitoring and hydraulic testing, transport connectivity through tracer studies and particle tracking, and environmental connectivity through receptor-based assessments. Consequently, connectivity assessment should always be aligned with the specific hydrogeological question being addressed.

4.1 Geological and Structural Assessment

Assessment of connectivity normally begins with understanding the geological framework within which groundwater movement occurs.

Geological investigations may include:

- geological mapping;
- core logging;
- borehole interpretation;
- geophysical surveys;
- fracture analysis;
- structural interpretation; and

- hydrostratigraphic characterization.

These methods provide information regarding the existence and continuity of potential groundwater pathways. Geological assessment is particularly important in fractured-rock, karst, volcanic, and structurally complex terrains where groundwater movement is strongly controlled by discontinuities.

Structural investigations can identify potential connections between aquifers, rivers, lakes, wetlands, and contaminant sources. However, the existence of geological pathways alone does not necessarily indicate active groundwater movement. Consequently, structural connectivity assessments should be complemented by hydraulic investigations.

4.2 Hydraulic Assessment

Hydraulic connectivity is commonly evaluated through groundwater-level observations and hydraulic testing.

Typical approaches include:

- groundwater monitoring networks;
- pumping tests;
- recovery tests;
- slug tests;
- seasonal groundwater-level analysis;
- pressure-response monitoring; and
- groundwater hydrograph interpretation.

Evidence of hydraulic connectivity may be observed where groundwater-level changes occurring at one location produce corresponding responses elsewhere within the system.

Hydraulic communication is particularly important when evaluating:

- mine dewatering impacts;
- groundwater recovery;
- aquifer interference;
- groundwater abstraction;
- managed aquifer recharge; and
- groundwater-surface water interaction.

Groundwater-level dynamics often provide valuable evidence of hydraulic connection because aquifer responses can reveal communication pathways that are otherwise difficult to observe directly (Yihdego et al., 2017).

4.3 Hydrochemical and Environmental Tracers

Hydrochemical methods provide a powerful means of investigating groundwater connectivity because groundwater chemistry frequently reflects flow-system behaviour and groundwater origin.

Common techniques include:

- major-ion chemistry;
- environmental isotopes;
- stable isotopes;
- age tracers;
- environmental tracers;
- salinity mapping; and
- temperature-based studies.

Tracer methods are particularly valuable because they provide information regarding:

- groundwater origin;
- groundwater mixing;
- recharge pathways;
- travel times;
- transport processes; and
- groundwater-surface water exchange.

Hydrochemical investigations have been widely applied to evaluate lake-aquifer systems, groundwater recharge processes, contaminant migration pathways, and groundwater-system evolution.

Studies of groundwater-lake interaction demonstrate how groundwater chemistry and flow modelling can be combined to identify connectivity pathways and quantify groundwater exchange processes (Yihdego & Becht, 2013).

4.4 Groundwater Modelling and Particle Tracking

Numerical groundwater models provide important tools for evaluating groundwater connectivity because they allow analysis of groundwater flow pathways, travel times, and groundwater-system response under a range of conditions.

Applications commonly include:

- regional groundwater-flow assessment;
- groundwater recovery forecasting;
- contaminant migration prediction;
- aquifer interference evaluation;

- groundwater-source delineation; and
- environmental impact assessment.

Particle-tracking methods are particularly useful because they provide visual representation of groundwater pathways and travel times.

The development of pathline-based approaches has significantly improved understanding of groundwater connectivity by enabling identification of source areas, migration pathways, and receptor interactions (Pollock, 1988; Pollock, 2012).

Despite their value, groundwater models should not be viewed as direct measurements of connectivity. Model outputs remain dependent on conceptual assumptions, geological interpretation, boundary conditions, and data quality. Consequently, modelling results should be interpreted within the context of broader hydrogeological evidence.

4.5 Groundwater–Surface Water Connectivity Assessment

Understanding groundwater-surface water connectivity is increasingly recognised as a critical component of environmental management and groundwater assessment.

Evaluation methods commonly include:

- streamflow measurements;
- seepage investigations;
- lake-water balances;
- hydrochemical analysis;
- temperature profiling;
- groundwater-surface water modelling; and
- environmental tracer studies.

Groundwater-surface water connectivity influences:

- stream baseflow;
- lake-water levels;
- wetland sustainability;
- groundwater-dependent ecosystems;
- contaminant transport; and
- ecological resilience.

Research within river corridors and groundwater-dependent ecosystems demonstrates that these interactions are often highly dynamic and require integrated assessment approaches (Fleckenstein et al., 2010; Harvey & Gooseff, 2015; Irvine et al., 2024; Ma et al., 2024).

4.6 Connectivity Metrics and Travel Time

Connectivity is frequently evaluated through measures that quantify the degree, strength, or effectiveness of connection between different parts of a groundwater system.

Examples include:

- hydraulic response time;
- groundwater travel time;
- flow-path length;
- connectivity indices;
- tracer recovery rates;
- groundwater age; and
- groundwater-response magnitude.

Travel time is one of the most useful indicators because it provides a direct measure of how rapidly water, contaminants, recharge signals, and environmental disturbances can propagate through a groundwater system.

Groundwater systems with similar hydraulic properties may exhibit significantly different travel times due to variations in pathway geometry, geological heterogeneity, and transport processes.

Consequently, effective connectivity assessment should focus not only on whether groundwater movement is possible but also on the speed and effectiveness of that movement.

4.7 Connectivity and Environmental Risk

Connectivity assessment becomes particularly important when evaluating environmental risk.

A common misconception is that groundwater connectivity automatically implies environmental impact. In reality, connectivity only establishes the possibility of interaction.

Environmental risk depends upon:

- source characteristics;
- pathway effectiveness;
- transport behaviour;
- receptor sensitivity; and
- environmental consequence.

Therefore, groundwater assessments should evaluate connectivity within a source–pathway–receptor framework rather than treating connectivity itself as evidence of environmental harm.

The strongest connectivity assessments combine geological interpretation, hydraulic evidence, transport assessment, and receptor evaluation to determine whether groundwater-system interactions have meaningful environmental significance.

4.8 Integrated Connectivity Assessment Framework

Because no single approach can adequately characterize all dimensions of groundwater connectivity, integrated assessments are generally required.

An effective connectivity assessment should combine:

1. Geological characterization.

2. Hydraulic evaluation.

3. Hydrochemical interpretation.

4. Groundwater modelling.

5. Particle tracking or travel-time analysis.

6. Groundwater-surface water assessment.

7. Receptor evaluation.

The relationship between these assessment components is summarised conceptually in **Fig. 2**.

By integrating multiple lines of evidence, groundwater practitioners can develop a more complete understanding of system behaviour and improve confidence in groundwater-resource management, environmental assessment, contamination studies, groundwater recovery evaluation, and long-term groundwater-system prediction.

5. Connectivity, Groundwater Recovery, and Environmental Consequence

Hydrogeological connectivity exerts a fundamental influence on groundwater-system response to both natural and anthropogenic disturbances. The manner in which groundwater systems recover following abstraction, dewatering, drought, contamination, recharge, or land-use change is strongly controlled by the degree and nature of connectivity operating within the subsurface environment. Consequently, connectivity provides an essential link between groundwater processes and environmental outcomes.

Groundwater systems do not respond uniformly to external stresses. Some systems exhibit rapid hydraulic responses and recovery, whereas others respond gradually over extended periods. These differences are often explained by variations in structural, hydraulic, and transport connectivity rather

than by hydraulic conductivity alone. Understanding connectivity therefore provides important insight into groundwater resilience, recovery potential, and long-term environmental behaviour.

5.1 Connectivity and Groundwater Recovery

Groundwater recovery following disturbance depends largely on hydraulic communication between affected areas and surrounding groundwater systems.

Recovery processes may be influenced by:

• recharge availability;

• aquifer storage;

• hydraulic gradients;

• geological continuity;

• groundwater-surface water interaction; and

• regional groundwater connectivity.

Highly connected systems generally recover more rapidly because recharge and groundwater inflows are able to propagate efficiently through available pathways. In contrast, poorly connected systems often recover slowly because hydraulic communication is restricted and recharge responses are attenuated.

Examples include:

• mine dewatering recovery;

• aquifer recovery following groundwater abstraction;

• groundwater rebound after drought;

• restoration following managed aquifer recharge.

Studies of groundwater-level response demonstrate that recovery behaviour frequently provides indirect evidence of groundwater-system connectivity and hydraulic communication (Yihdego et al., 2017).

5.2 Connectivity and Contaminant Migration

Connectivity is a critical control on contaminant transport because contaminants cannot migrate without effective transport pathways.

However, connectivity alone does not determine contaminant behaviour. Migration depends on interactions among:

• source characteristics;

• hydraulic conditions;

• groundwater velocity;

• travel time;

• attenuation processes;

• geochemistry; and

• receptor sensitivity.

A hydraulically connected groundwater system may exhibit limited contaminant transport where travel times are long or attenuation processes are significant. Conversely, relatively modest hydraulic connectivity may result in substantial environmental impacts when highly mobile contaminants and sensitive receptors are involved.

Consequently, assessment of contaminant migration requires evaluation of transport connectivity rather than hydraulic connectivity alone.

5.3 Connectivity and Groundwater-Surface Water Interaction

Groundwater-surface water interactions represent one of the most important expressions of hydrogeological connectivity.

Connectivity between aquifers, rivers, lakes, wetlands, springs, and riparian environments influences:

• ecological condition;

• water quality;

• recharge processes;

• streamflow persistence;

• nutrient cycling; and

• drought resilience.

River-groundwater and lake-aquifer systems demonstrate that environmental responses are often strongly dependent on the degree of groundwater connectivity operating between groundwater systems and surface-water environments (Brunner et al., 2009; Fleckenstein et al., 2010; Harvey & Gooseff, 2015).

Investigations of Lake Naivasha similarly demonstrated that groundwater-lake interaction represented a dominant control on long-term hydrological behaviour and environmental sustainability (Yihdego & Becht, 2013).

5.4 Connectivity and Groundwater-Dependent Ecosystems

Many ecosystems depend directly or indirectly on groundwater connectivity.

Groundwater-dependent ecosystems include:

• springs;

• wetlands;

• riparian vegetation;

• groundwater-fed lakes;

• hyporheic environments; and

• groundwater-supported river systems.

Environmental impacts may occur when groundwater connectivity is altered through:

• groundwater extraction;

• mine dewatering;

• groundwater contamination;

• climate variability;

• land-use change; or

• hydrological modification.

The ability of groundwater systems to support ecological functions therefore depends not only on groundwater quantity but also on the maintenance of connectivity between groundwater sources and ecological receptors.

5.5 Connectivity and Environmental Risk

One of the most common misunderstandings in groundwater assessment is the assumption that connectivity automatically implies environmental risk.

This assumption is incorrect.

Connectivity establishes the possibility of interaction, but environmental consequence depends on the complete source–pathway–receptor relationship.

Environmental risk depends upon:

• source strength;

• connectivity magnitude;

• transport effectiveness;

• exposure duration;

• receptor sensitivity; and

• consequence severity.

For example:

• a hydraulic pathway may exist without contaminant migration;

• contaminants may migrate without reaching a sensitive receptor;

• receptors may exist without experiencing significant environmental impact.

Consequently, connectivity should be considered a necessary but not sufficient condition for environmental consequence.

5.6 Connectivity and Groundwater Modelling

Groundwater models increasingly play an important role in evaluating connectivity because they provide tools for visualising flow paths, travel times, hydraulic communication, and environmental interactions.

Connectivity-based applications include:

• pathline analysis;

• particle tracking;

• source-area delineation;

• recharge mapping;

• travel-time estimation;

• capture-zone analysis; and

• environmental impact assessment.

Particle-tracking approaches are particularly valuable because they explicitly represent groundwater pathways connecting sources and receptors (Pollock, 1988; Pollock, 2012).

However, connectivity assessments remain dependent on conceptual understanding. Numerical models cannot resolve uncertainty associated with geological structure, recharge processes, or conceptual model assumptions. Consequently, connectivity interpretation should always combine modelling with geological, hydraulic, hydrochemical, and environmental evidence.

5.7 Connectivity and Climate Change

Climate variability and climate change may significantly alter groundwater connectivity over time (Stigter et al., 2023; Fan et al., 2023; Benz et al., 2024; Ndehedehe et al., 2023).

Potential influences include:

• changing recharge patterns;

• altered groundwater gradients;

• modified river-groundwater interactions;

• changes in lake-aquifer behaviour;

• groundwater-level decline;

• ecosystem stress.

These changes may strengthen, weaken, or redirect connectivity pathways depending on local hydrogeological conditions. Climate–groundwater interactions operate across local, regional, and global scales and may substantially alter groundwater connectivity through changing recharge patterns and groundwater-level responses (Cuthbert et al., 2019).

As climate pressures increase, understanding how connectivity evolves through time will become increasingly important for groundwater management, environmental protection, water-resource sustainability, and climate adaptation planning.

5.8 Connectivity as a Unifying Hydrogeological Concept

The examples discussed throughout this section demonstrate that connectivity provides a unifying framework for understanding groundwater-system behaviour.

Groundwater flow, recharge propagation, contaminant migration, groundwater recovery, ecosystem dependence, and environmental risk can all be interpreted through the lens of connectivity.

Structural connectivity controls whether pathways exist.

Hydraulic connectivity governs groundwater movement.

Transport connectivity determines migration behaviour.

Environmental connectivity links groundwater processes with receptors and consequences.

The interactions among these components establish connectivity as one of the most important organising principles within hydrogeology. By explicitly incorporating connectivity into groundwater investigations, practitioners can improve interpretation of groundwater systems and develop more transparent, defensible, and environmentally meaningful assessments.

The practical implications of hydrogeological connectivity are summarised in Table 2, which links the principal forms of connectivity with groundwater-system behaviour, environmental significance, and management applications. The table demonstrates how connectivity concepts can be applied to groundwater recovery, contaminant transport, groundwater-dependent ecosystems, environmental assessment, and groundwater-resource management.

Table 2
Relationship between connectivity type, groundwater-system behaviour, environmental significance, and typical hydrogeological applications.

Connectivity Condition	Recovery Behaviour
Low Connectivity	Slow recovery
Moderate Connectivity	Moderate recovery
High Connectivity	Faster recovery
Dynamic Connectivity	Variable recovery

As shown in **Table 2**, environmental consequence only develops when connectivity extends beyond geological and hydraulic linkage to include effective transport pathways and susceptible receptors. This distinction is critical when interpreting groundwater risks and environmental impacts.

6. A Connectivity-Based Framework for Groundwater Assessment

Hydrogeological connectivity becomes most valuable when it is incorporated directly into groundwater assessment, environmental interpretation, and decision-making. While hydrogeologists routinely describe groundwater flow, recharge, contaminant migration, and environmental impacts, many investigations evaluate these components separately. A connectivity-based approach provides a unifying framework that links physical groundwater processes with environmental outcomes and management decisions.

The framework proposed in this study is based on the principle that groundwater impacts can only occur when an effective connection exists between a source and a receptor through a viable pathway. Consequently, connectivity should be viewed as the critical mechanism linking groundwater-system behaviour with environmental consequence. The framework is illustrated in **Fig. 3** and provides a practical approach for integrating geological, hydraulic, transport, and environmental information within a single assessment process.

6.1 Source Identification

The first step in connectivity assessment is identification of the source.

Potential sources may include:

• groundwater recharge;

• contaminant releases;

• mine dewatering;

• groundwater abstraction;

• wastewater infiltration;

• managed aquifer recharge systems;

• saline intrusion; or

• naturally occurring groundwater processes.

The nature of the source strongly influences the subsequent assessment because different sources generate different hydraulic responses, transport processes, and environmental consequences.

6.2 Structural Connectivity Assessment

After identifying the source, assessment should determine whether a physical pathway exists within the groundwater system.

This involves evaluation of:

• geological continuity;

• hydrostratigraphy;

• fracture networks;

• faults;

• weathered zones;

• karst features; and

• aquifer geometry.

Structural connectivity establishes whether groundwater movement is physically possible. However, the presence of a geological pathway does not necessarily imply groundwater flow or environmental impact.

6.3 Hydraulic Connectivity Assessment

The next stage involves determining whether hydraulic communication occurs along the available pathways.

Questions include:

• Can groundwater move through the system?

• Can hydraulic responses propagate between locations?

• Are hydraulic gradients sufficient to sustain groundwater flow?

• Does aquifer connectivity permit groundwater exchange?

Groundwater monitoring, hydraulic testing, and groundwater-level analysis provide important evidence for evaluating hydraulic connectivity.

Hydraulic connectivity determines whether groundwater movement is possible, but it does not by itself establish contaminant migration potential or environmental consequence.

6.4 Transport Connectivity Assessment

Transport connectivity evaluates whether dissolved constituents can move through groundwater pathways and reach potential receptors.

Assessment should consider:

• groundwater velocity;

• travel times;

• dispersion processes;

• diffusion;

• attenuation;

• geochemical reactions; and

• contaminant persistence.

Particle tracking, environmental tracers, age dating, and transport modelling are commonly used to assess transport connectivity (Pollock, 1988; Pollock, 2012).

Transport connectivity is often more relevant to environmental assessment than hydraulic connectivity because it determines whether contaminants, nutrients, salinity, or other dissolved constituents are capable of reaching receptors.

6.5 Receptor Connectivity Assessment

The presence of a pathway does not automatically result in environmental consequence. Receptors must also be connected to the groundwater system.

Potential receptors include:

• rivers;

• lakes;

• wetlands;

• springs;

• groundwater-dependent ecosystems;

• water-supply bores;

• irrigation supplies;

• infrastructure assets; and

• human communities.

Assessment should evaluate both receptor sensitivity and the effectiveness of the pathway linking the receptor to the source.

6.6 Environmental Consequence Assessment

Environmental consequence arises when effective connectivity links a source to a susceptible receptor through an active groundwater pathway.

Potential consequences include:

• groundwater contamination;

• ecosystem degradation;

• reduced groundwater availability;

• salinity impacts;

• water-quality deterioration;

• infrastructure impacts; and

• long-term groundwater-resource impairment.

Importantly, connectivity alone does not define environmental consequence. Consequence depends upon the combined influence of source characteristics, transport behaviour, receptor sensitivity, and exposure duration.

6.7 Management Response

The final stage of the framework involves translating hydrogeological understanding into management actions.

Potential responses include:

• groundwater monitoring;

• mitigation measures;

• contaminant containment;

• remediation;

• groundwater-use restrictions;

• environmental management plans;

• mine-closure strategies; and

• adaptive management programs.

The objective is not simply to understand connectivity, but to apply that understanding to improve groundwater management and environmental decision-making.

6.8 The Connectivity Hierarchy

The framework developed in this study may be represented as a hierarchical sequence (Fig. 3).

6.9 Value of the Framework

The framework demonstrates that hydrogeological connectivity is more than a characteristic of groundwater flow. It represents the pathway through which groundwater processes influence environmental outcomes.

By explicitly evaluating each stage of the connectivity hierarchy, groundwater investigations can:

• improve conceptual understanding;

• strengthen environmental assessments;

• enhance groundwater modelling;

• reduce interpretive uncertainty;

• support groundwater-resource management;

• improve contamination assessments; and

• provide more defensible decision-making.

As illustrated in **Fig. 3**, environmental consequences emerge only when effective connectivity links a source to a receptor through viable structural, hydraulic, and transport pathways. Recognition of this progression allows hydrogeologists to move beyond simple descriptions of groundwater flow and develop more comprehensive assessments of groundwater-system behaviour and environmental significance.

7. Applications of Hydrogeological Connectivity in Groundwater Assessment and Management

Hydrogeological connectivity has become a central concept in modern groundwater science because it provides the link between groundwater-system behaviour and environmental consequence. Understanding connectivity enables hydrogeologists to move beyond simple descriptions of groundwater levels and hydraulic gradients towards interpretation of how groundwater systems respond to natural processes, human activities, and environmental change.

The practical importance of connectivity extends across groundwater resource management, contamination studies, environmental assessment, ecosystem protection, mine closure, climate adaptation, and groundwater modelling. In each of these applications, connectivity determines the extent to which groundwater influences can be transmitted through the subsurface environment and ultimately affect receptors.

7.1 Groundwater Resource Assessment

Groundwater resources cannot be evaluated effectively without understanding connectivity.

Questions commonly addressed include:

• Where does recharge enter the system?

• Which aquifers are hydraulically connected?

• How rapidly do groundwater systems respond to recharge?

• What controls groundwater availability?

• Are groundwater resources sustainable?

Connectivity assessment improves understanding of groundwater-flow systems by identifying relationships between recharge areas, storage zones, discharge regions, and groundwater users (Fan et al., 2023; Zhang et al., 2021). Regional groundwater management therefore depends heavily on understanding how connectivity governs groundwater movement and resource replenishment. Groundwater-table configuration and basin-scale groundwater architecture exert a strong influence on regional groundwater connectivity and groundwater-resource behaviour (Fan et al., 2013).

Studies of groundwater-table dynamics and groundwater-system response demonstrate that connectivity strongly influences resource resilience and long-term sustainability (Fan et al., 2013).

7.2 Groundwater Contamination and Remediation

Groundwater contamination investigations fundamentally rely on connectivity analysis.

Key questions include:

• Can contaminants migrate from the source?

• Which pathways are active?

• What receptors are connected?

• How long will migration require?

• What remediation options are effective?

Contaminants cannot reach receptors without effective transport connectivity. Consequently, contaminant risk depends not only on the presence of contamination but also on the strength and effectiveness of the pathways connecting sources and receptors.

Connectivity-based approaches improve remediation planning by identifying:

• dominant transport pathways;

• high-risk receptors;

• travel times;

• attenuation opportunities; and

• monitoring requirements.

Understanding connectivity therefore allows remediation efforts to focus on controlling critical pathways rather than simply addressing contaminant sources.

7.3 Groundwater–Surface Water Interaction

One of the most important applications of connectivity assessment involves groundwater–surface water interaction.

Groundwater connectivity influences:

• streamflow generation;

• lake-water levels;

• wetland sustainability;

• spring discharge;

• nutrient cycling;

• ecological resilience.

Hydrological investigations increasingly recognise that rivers, lakes, wetlands, and aquifers form integrated systems rather than independent hydrological components (Brunner et al., 2009; Fleckenstein et al., 2010).

Lake-aquifer systems provide particularly valuable examples because groundwater exchange frequently controls water balance, salinity evolution, and ecosystem function. Detailed investigation of Lake Naivasha demonstrated that groundwater connectivity was a dominant control on long-term hydrological behaviour and environmental sustainability (Yihdego & Becht, 2013).

7.4 Groundwater-Dependent Ecosystems

Many ecosystems rely upon connectivity with groundwater systems.

Examples include:

• wetlands;

• riparian vegetation;

• springs;

• groundwater-fed lakes;

• hyporheic habitats;

• groundwater-supported river systems.

Changes in connectivity resulting from groundwater abstraction, dewatering, recharge reduction, or climatic change may alter groundwater supply to these ecosystems.

Environmental assessments therefore increasingly focus on identifying:

• groundwater pathways;

• ecological receptors;

• groundwater dependence;

• connectivity strength; and

• vulnerability to groundwater-system change.

Connectivity assessment provides the framework for understanding whether groundwater alterations can propagate sufficiently to affect ecological health and environmental values.

7.5 Mine Water Management and Closure

Mining activities often modify groundwater connectivity through:

• dewatering;

• depressurisation;

• pit excavation;

• waste-rock storage;

• tailings facilities; and

• pit-lake development.

As a result, understanding connectivity is essential for evaluating:

• dewatering impacts;

• groundwater recovery;

• pit-lake evolution;

• contaminant migration;

• closure performance.

Groundwater recovery following mining frequently depends upon the degree of hydraulic communication between disturbed areas and surrounding groundwater systems. Similarly, closure predictions require understanding how connectivity may evolve through time as groundwater systems recover.

Studies of mine-water systems have demonstrated that groundwater inflow behaviour, recovery trajectories, and long-term environmental performance are strongly influenced by groundwater connectivity (Yihdego & Paffard, 2016).

7.6 Climate Change and Groundwater Connectivity

Climate variability and climate change can modify groundwater connectivity through changes in recharge, groundwater levels, hydraulic gradients, and groundwater-surface water interaction.

Potential impacts include:

• altered recharge pathways;

• shifting groundwater gradients;

• modified groundwater recovery patterns;

• changing surface-water connectivity;

• reduced ecological resilience.

These effects may strengthen, weaken, or redirect connectivity pathways depending upon hydrogeological conditions.

Long-term assessments increasingly require evaluation of how groundwater connectivity may evolve under changing climatic conditions. Investigations of groundwater-connected systems demonstrate that climatic variability can significantly influence groundwater behaviour and environmental outcomes through changes in connectivity relationships (Yihdego & Webb, 2011).

7.7 Connectivity in Groundwater Modelling

Groundwater modelling provides one of the most powerful tools for investigating connectivity because it allows visualisation of groundwater pathways and quantification of groundwater-system behaviour.

Connectivity-related applications include:

• particle tracking;

• capture-zone analysis;

• travel-time estimation;

• contaminant transport prediction;

• source delineation;

• groundwater recovery assessment.

Particle tracking has become particularly important because it explicitly represents groundwater pathways linking sources and receptors (Pollock, 1988; Pollock, 2012).

However, connectivity modelling remains dependent on conceptual understanding of groundwater systems. Numerical methods complement rather than replace hydrogeological interpretation.

7.8 Connectivity as a Basis for Environmental Decision-Making

Ultimately, connectivity provides a bridge between groundwater science and environmental decision-making.

Groundwater managers, regulators, environmental practitioners, and engineers increasingly require answers to questions such as:

• Will groundwater changes affect receptors?

• Is environmental harm possible?

• Are groundwater resources sustainable?

• What pathways require protection?

• What mitigation measures are necessary?

Each of these questions depends upon understanding connectivity.

The practical applications discussed throughout this section demonstrate that connectivity is not simply a hydrogeological characteristic but a decision-support concept that links groundwater movement, transport processes, environmental receptors, and management outcomes.

The major applications of hydrogeological connectivity across groundwater-resource assessment, contamination studies, groundwater-surface water interaction, groundwater-dependent ecosystems, mine closure, climate adaptation, and groundwater modelling are summarised in Table 3. The table highlights how different forms of connectivity contribute to hydrogeological interpretation, environmental assessment, risk evaluation, and groundwater management.

Table 3
Applications of hydrogeological connectivity in groundwater science, environmental assessment, and groundwater management.

Component	Assessment Objective
Source	What enters the system?
Connectivity	Can groundwater move?
Pathway	How does groundwater move?
Receptor	What may be affected?
Consequence	Why does it matter?

As shown in **Table 3**, environmental consequence develops only when connectivity extends beyond geological and hydraulic linkage to include effective transport pathways and susceptible receptors. This distinction is fundamental to understanding groundwater behaviour, evaluating environmental risk, and supporting defensible groundwater-management decisions.

8. Discussion

Hydrogeological connectivity represents one of the most important yet frequently underappreciated concepts in groundwater science. While groundwater investigations traditionally focus on hydraulic gradients, recharge estimates, groundwater levels, aquifer properties, and groundwater budgets, connectivity provides the overarching framework through which these individual observations can be interpreted and linked. Connectivity explains not only how groundwater moves through subsurface environments, but also how groundwater influences, contaminants, recharge signals, environmental stresses, and ecological responses propagate through groundwater systems.

The review demonstrates that connectivity should not be interpreted as a single hydrogeological property. Rather, it represents a hierarchy of interacting processes that includes structural, hydraulic, transport, and environmental connectivity. These components operate at different spatial and temporal scales and may vary considerably within the same hydrogeological system. Recognition of these distinctions is important because groundwater assessments frequently assume that hydraulic connectivity automatically implies contaminant migration or environmental consequence. In practice, transport processes, travel times, attenuation mechanisms, and receptor vulnerability may substantially modify the environmental significance of a connected groundwater pathway.

Recent research increasingly recognises connectivity as a fundamental control on groundwater-system behaviour, influencing groundwater flow, groundwater-surface water interactions, ecosystem functioning, contaminant transport, and climate resilience across multiple spatial and temporal scales (Zhang et al., 2021; Wilcox et al., 2022; Banerjee and Ganguly, 2023; Ndehedehe et al., 2023; Irvine et al., 2024; Dwivedi et al., 2025).

A major implication of this review is that groundwater connectivity provides a unifying framework for interpreting groundwater-system behaviour. Groundwater recharge, groundwater recovery, contaminant migration, groundwater-surface water interaction, ecosystem dependence, and environmental risk can all be understood through connectivity relationships. Rather than treating these processes as independent phenomena, connectivity links them within a coherent hydrogeological framework that improves understanding of system response and environmental consequence.

The review also highlights the dynamic nature of connectivity. Hydrogeological connectivity is not fixed and may change through time in response to groundwater abstraction, groundwater recovery, mine dewatering, recharge variability, climatic change, land-use modification, and environmental disturbance. Consequently, groundwater assessments should recognize that connectivity relationships observed today may not remain unchanged in the future. Long-term groundwater management therefore requires not only understanding current connectivity but also evaluating how connectivity may evolve under future hydrogeological and climatic conditions.

Groundwater–surface water interaction provides one of the clearest demonstrations of the importance of connectivity. Rivers, lakes, wetlands, and groundwater-dependent ecosystems frequently rely upon groundwater exchange processes that vary through time and space. Investigations of river corridors, lake-aquifer systems, and groundwater-supported ecosystems consistently demonstrate that accurate understanding of connectivity is essential for environmental protection, water-resource management, ecosystem resilience, and climate adaptation. Similar conclusions have emerged from studies of lake-aquifer connectivity, where groundwater exchange exerts a dominant influence on hydrological behaviour, salinity evolution, and long-term environmental sustainability (Yihdego & Becht, 2013; Yihdego et al., 2017).

The increasing use of groundwater models, particle tracking, environmental tracers, and integrated hydrogeological assessments has also strengthened connectivity-based approaches. These methods have improved the ability of hydrogeologists to identify groundwater pathways, quantify travel times, evaluate receptor interactions, and assess environmental risk. Nevertheless, the review reinforces the importance of conceptual understanding. Connectivity assessments remain dependent on realistic representation of geological structure, groundwater flow systems, recharge processes, and receptor relationships. Numerical sophistication cannot compensate for deficiencies in conceptualisation.

An important finding of this review is that connectivity should be incorporated explicitly into environmental decision-making. Many groundwater-management questions can ultimately be reduced to questions of connectivity. Examples include whether contaminants can reach receptors, whether groundwater extraction will influence ecosystems, whether groundwater recovery is likely, whether recharge can sustain abstraction, and whether environmental impacts are possible. Connectivity therefore serves as the mechanism that links groundwater science with practical management decisions.

The connectivity-based framework proposed in Fig. 3 provides a structured approach for evaluating these issues. By progressing systematically from source identification through structural, hydraulic, transport, and receptor connectivity to environmental consequence and management response, the framework offers a transparent process for assessing groundwater-system behaviour and environmental significance. Such an approach has applications across groundwater-resource management, contamination assessment, ecosystem protection, mine closure, environmental impact assessment, and climate-resilience planning.

Ultimately, hydrogeological connectivity provides a bridge between physical groundwater processes and environmental outcomes. Understanding connectivity improves interpretation of groundwater flow systems, strengthens assessment of groundwater risk, enhances groundwater modelling, and supports more informed and defensible groundwater-management decisions. As pressures on groundwater resources continue to increase globally, connectivity-based approaches will become increasingly important for achieving sustainable groundwater management and environmental protection.

8.1 Connectivity and Environmental Management

The significance of hydrogeological connectivity extends beyond groundwater science and directly supports environmental-management objectives. Environmental impact assessments, strategic environmental planning, water-resource allocation, ecosystem conservation, mine-closure planning, and climate-adaptation strategies all depend on understanding the pathways through which groundwater influences are transmitted.

Connectivity-based assessment can improve decision-making by:

• identifying environmentally sensitive receptors;

• prioritising monitoring and mitigation efforts;

• supporting risk-based environmental management;

• improving ecosystem protection strategies;

• guiding sustainable groundwater development;

• strengthening mine-closure and rehabilitation planning; and

• enhancing climate-resilience assessments.

The framework developed in this paper aligns with broader sustainability objectives by supporting integrated management of groundwater resources, surface-water systems, and groundwater-dependent ecosystems. Through improved understanding of source-pathway-receptor relationships, connectivity provides a practical basis for reducing environmental risk and promoting sustainable management of groundwater resources.

Emerging evidence further demonstrates that effective groundwater management requires explicit consideration of connectivity under changing climatic conditions, as groundwater responses are increasingly influenced by climate variability, groundwater-surface water interactions, ecosystem dependencies, and adaptation requirements (Stigter et al., 2023; Fan et al., 2023; Benz et al., 2024; Ndehedehe et al., 2023; Lapworth et al., 2023; Irvine et al., 2024).

While the scientific understanding of hydrogeological connectivity continues to evolve, its greatest value may lie in its application to environmental management and decision-making. Connectivity provides the mechanism through which groundwater processes influence environmental receptors and ultimately determine environmental outcomes. Accordingly, connectivity-based assessments can support more effective planning, monitoring, risk management, and resource protection.

8.2 Critical Knowledge Gaps and Future Research Needs

Critical Knowledge Gaps

Despite substantial advances in understanding hydrogeological connectivity, several important scientific and practical gaps remain.

1. Lack of Quantitative Definitions

Although connectivity is widely used in hydrogeology, there remains no universally accepted quantitative definition. Different studies use the term to describe geological continuity, hydraulic communication, transport pathways, groundwater-surface water interaction, or ecological dependence. This lack of standardisation makes comparison between studies difficult and often creates ambiguity in environmental assessments.

2. Disconnect Between Hydraulic and Transport Connectivity

Many investigations infer environmental risk from hydraulic connectivity alone. However, strong hydraulic communication does not necessarily imply effective contaminant transport. Travel times, attenuation, sorption, and biogeochemical processes are often poorly constrained, creating substantial uncertainty when translating hydraulic observations into environmental consequences.

3. Limited Understanding of Connectivity Dynamics

Most connectivity assessments are based on static conceptual models. In reality, connectivity changes through time due to groundwater abstraction, mine dewatering, recharge variability, climate change, land-use modification, and groundwater recovery. Methods for quantifying temporal changes in connectivity remain poorly developed.

4. Scale Dependence Remains Poorly Resolved

Connectivity observed at borehole or site scales may differ substantially from connectivity observed at catchment or basin scales. The mechanisms responsible for scaling groundwater connectivity remain insufficiently understood, creating challenges when transferring local observations into regional groundwater management decisions.

5. Uncertainty in Fractured and Heterogeneous Systems

Connectivity assessment remains particularly difficult in fractured-rock, karst, and structurally complex environments. Subsurface pathways are often poorly characterised and may dominate groundwater movement while remaining largely undetected by conventional investigation methods.

6. Limited Integration of Ecological Receptors

Most groundwater studies focus on hydraulic and transport processes, while ecological connectivity receives comparatively little attention. Quantitative relationships between groundwater connectivity and ecosystem response remain insufficiently understood, particularly for groundwater-dependent ecosystems.

7. Model-Based Connectivity Uncertainty

Groundwater models and particle tracking are increasingly used to infer connectivity. However, connectivity predictions remain highly sensitive to conceptual model assumptions, boundary conditions, recharge estimates, and geological interpretations. Formal approaches for quantifying connectivity uncertainty are still underdeveloped.

Future Research Priorities

Future investigations should focus on:

• Development of standardised metrics for quantifying connectivity.

• Improved methods for linking hydraulic connectivity with transport and ecological outcomes.

• Long-term monitoring programs capable of evaluating temporal variability in connectivity.

• Integration of environmental tracers, remote sensing, machine learning, and high-resolution numerical models.

• Better representation of uncertainty in connectivity assessments.

• Development of receptor-based connectivity frameworks that explicitly incorporate environmental consequence.

• Assessment of climate change impacts on groundwater connectivity pathways and recovery processes.

Implications for Groundwater Management

Addressing these gaps would significantly improve environmental-risk assessment, groundwater-resource management, mine-closure planning, ecosystem protection, contaminant management, and climate-resilience strategies. Future groundwater investigations should move beyond simply demonstrating connectivity and instead focus on quantifying the strength, timing, uncertainty, and environmental significance of groundwater connections.

8.3 Limitations

This paper presents a conceptual synthesis and does not generate new field data, laboratory investigations, or numerical simulations. Consequently, the proposed framework should be considered a guiding approach rather than a predictive model. The interpretation of connectivity remains influenced by uncertainties associated with geological heterogeneity, groundwater recharge, transport processes, and conceptual model assumptions.

Furthermore, groundwater systems are highly site-specific, and the relative importance of different forms of connectivity may vary considerably between sedimentary, fractured-rock, karst, and volcanic environments. Future research should focus on validating and refining the framework through field investigations, quantitative connectivity metrics, and integrated monitoring and modelling studies.

8.4 Emerging Technologies for Connectivity Assessment

Recent technological developments are creating new opportunities for understanding groundwater connectivity across a range of spatial and temporal scales. Advances in remote sensing, environmental monitoring, geospatial analytics, and artificial intelligence are improving the ability to identify groundwater pathways and assess environmental responses.

Emerging approaches include:

• distributed temperature sensing (DTS) for identifying groundwater-surface water exchange zones;

• environmental DNA (eDNA) for tracing groundwater-supported ecosystems;

• machine-learning techniques for pattern recognition and connectivity classification;

• remote-sensing methods for recharge and groundwater-dependent ecosystem assessment;

• high-frequency groundwater-monitoring networks;

• autonomous sensor technologies; and

• digital-twin frameworks integrating monitoring and predictive modelling.

These technologies have the potential to improve detection of dynamic connectivity processes, reduce uncertainty in groundwater assessments, and support adaptive groundwater management. Future integration of conventional hydrogeological techniques with emerging digital technologies is likely to significantly advance connectivity science and environmental decision-making.

9. Conclusions

Hydrogeological connectivity is a fundamental property of groundwater systems that governs the movement of water, hydraulic signals, dissolved constituents, and environmental influences throughout the subsurface environment. Although connectivity is frequently discussed in groundwater investigations, it is often simplified to the existence of a hydraulic pathway between two locations. This review demonstrates that connectivity is considerably more complex and should be understood as a hierarchy of interrelated structural, hydraulic, transport, and environmental processes.

The review highlights that groundwater connectivity provides a unifying framework for interpreting groundwater-system behaviour. Groundwater flow, recharge propagation, contaminant migration, groundwater recovery, groundwater–surface water interaction, ecosystem dependence, and environmental risk can all be viewed as expressions of connectivity operating at different spatial and temporal scales. Understanding these relationships improves interpretation of groundwater processes and strengthens the link between hydrogeological science and environmental management.

Several important conclusions emerge from this review:

1. **Connectivity is multidimensional.** Structural, hydraulic, transport, and environmental connectivity represent distinct but interconnected components of groundwater-system behaviour.

2. **Hydraulic connectivity does not necessarily imply transport connectivity.** Groundwater movement may occur without significant contaminant transport due to attenuation, dispersion, travel-time constraints, or geochemical processes.

3. **Transport connectivity does not necessarily imply environmental consequence.** Environmental impacts occur only when effective pathways connect a source to a sensitive receptor.

4. **Connectivity is scale dependent.** Connectivity observed at local scales may differ substantially from behaviour observed at catchment or regional scales.

5. **Connectivity is dynamic rather than static.** Groundwater abstraction, recharge variability, climatic change, mine dewatering, groundwater recovery, and land-use change may alter connectivity through time.

6. **Groundwater–surface water interactions represent a critical expression of connectivity.** Rivers, lakes, wetlands, and groundwater-dependent ecosystems frequently depend upon groundwater exchange processes.

7. **Connectivity assessment requires multiple lines of evidence.** Effective evaluation commonly combines geological interpretation, hydraulic assessment, hydrochemistry, environmental tracers, groundwater modelling, particle tracking, and receptor analysis.

The connectivity-based framework proposed in this paper provides a structured approach for linking groundwater sources, pathways, transport mechanisms, receptors, environmental consequences, and management responses. By explicitly evaluating each stage of this hierarchy, groundwater investigations can become more transparent, environmentally meaningful, and decision focused.

The review also demonstrates that many questions encountered in groundwater resource management, contamination assessment, environmental protection, ecosystem resilience, mine closure, and climate adaptation are fundamentally questions of connectivity. Consequently, connectivity should be treated not simply as a hydrogeological characteristic but as a central organising principle of groundwater science.

As pressures on groundwater resources continue to increase due to population growth, resource development, environmental change, and climate variability, improved understanding of hydrogeological connectivity will become increasingly important. Future groundwater investigations should therefore place greater emphasis on connectivity-based assessment frameworks that integrate geological structure, groundwater flow, transport behaviour, environmental receptors, and environmental consequence. Such approaches will improve groundwater-system understanding, strengthen environmental assessments, and support more sustainable groundwater-management decisions.

Declarations

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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Figures

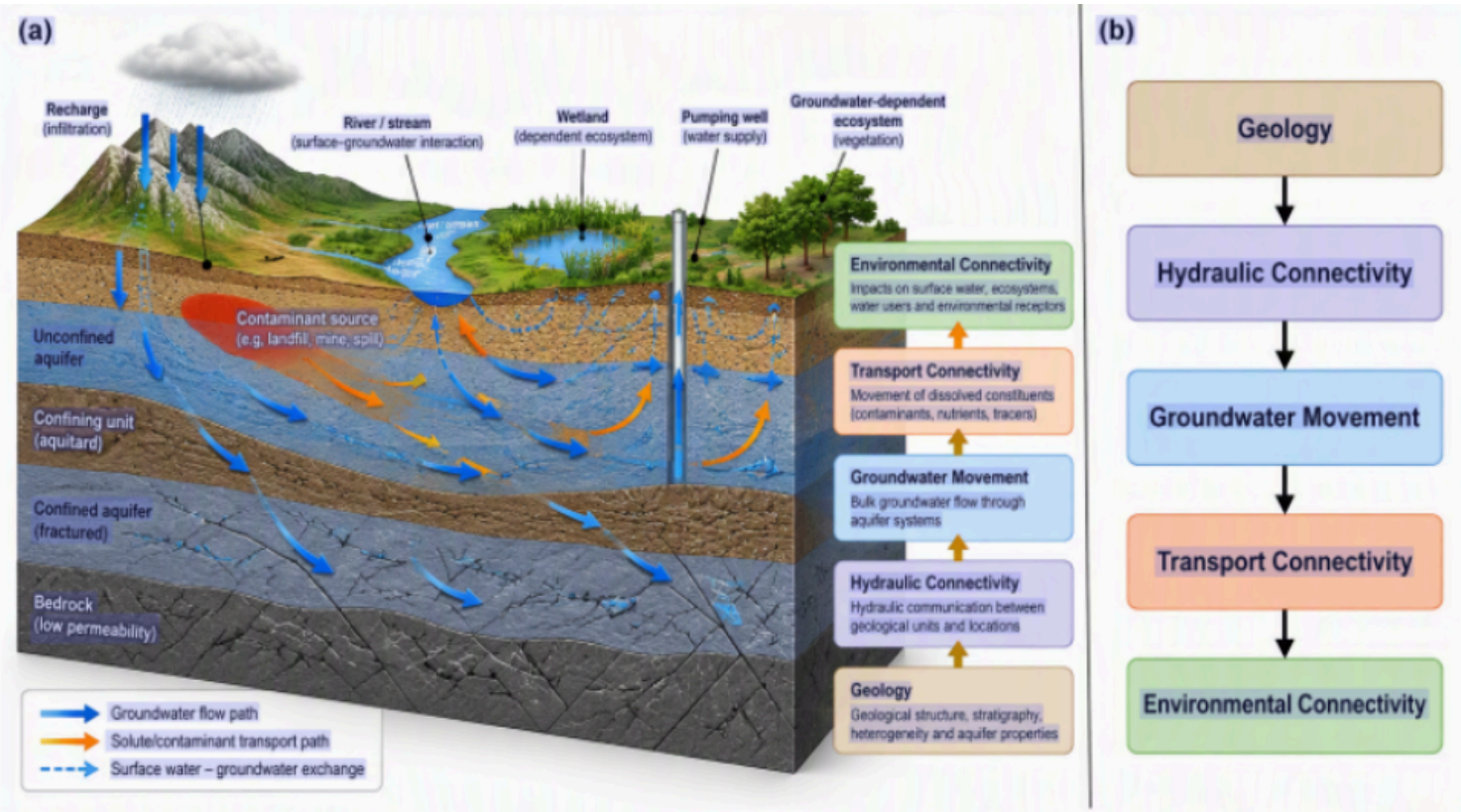


Figure 1

Hydrogeological connectivity hierarchy and conceptual framework. *(a)* Three-dimensional conceptual representation of hydrogeological connectivity linking geological structure, groundwater flow, solute transport, and environmental receptors. *(b)*Simplified hierarchy of connectivity from geology to environmental connectivity.

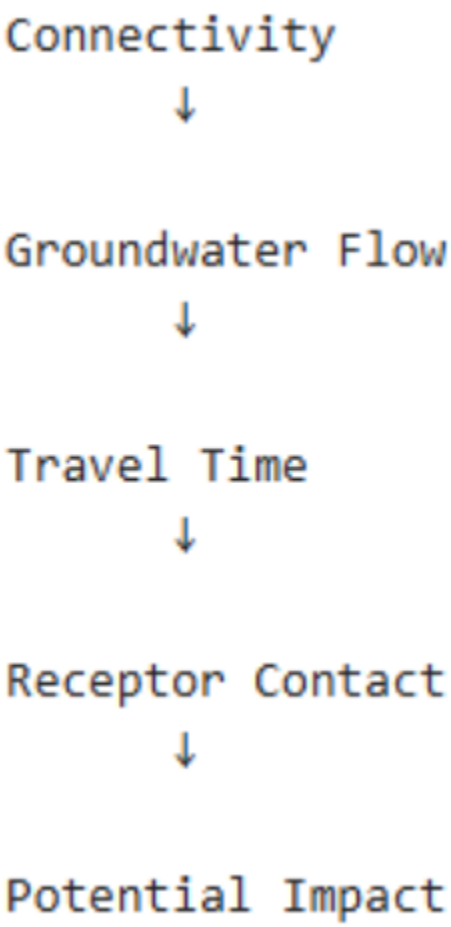


Figure 2

Connectivity forms a prerequisite for groundwater movement but does not independently determine environmental impact.

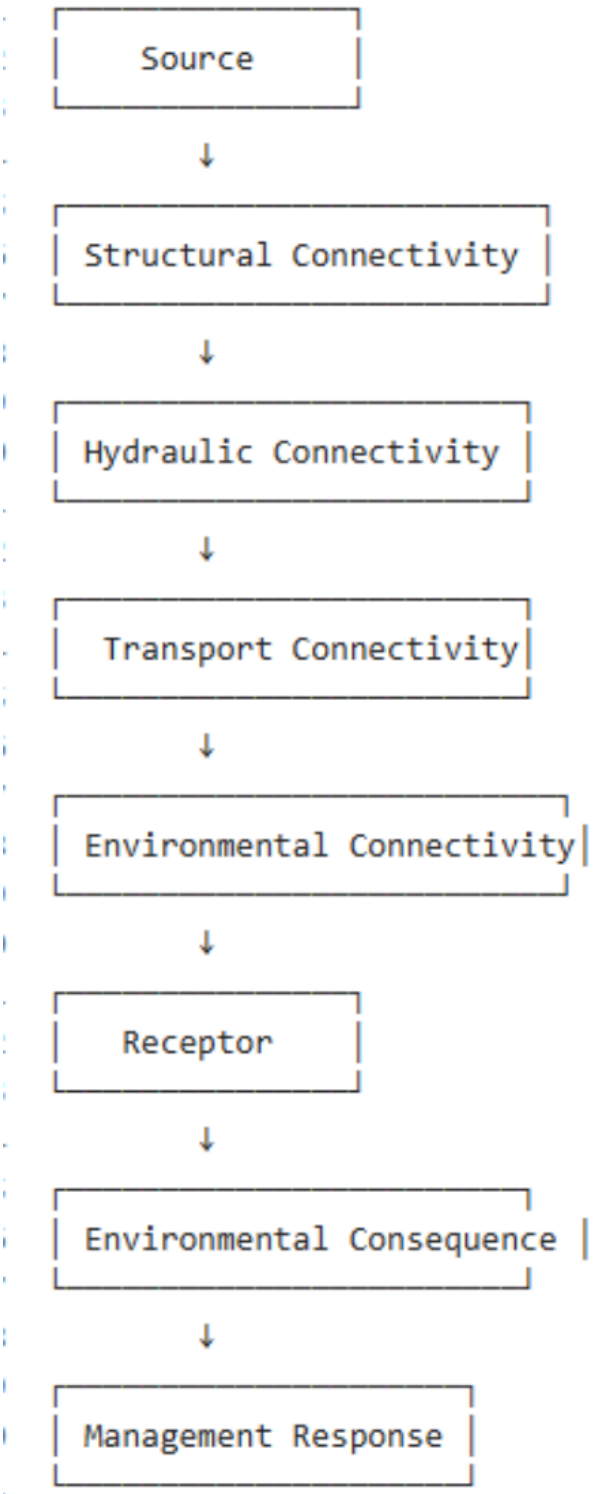


Figure 3

Connectivity-based groundwater assessment framework illustrating the progression from source identification through structural, hydraulic, transport, and environmental connectivity to receptor interaction, environmental consequence, and management response. The framework demonstrates how groundwater connectivity provides the mechanism linking hydrogeological processes with environmental outcomes and decision-making.