REVIEW ARTICLE

Digital Twin-Enabled Environmentally Resilient Recovery of Geo-Energy Infrastructure after Disasters

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Abstract

Geo-energy infrastructure—comprising oil and gas systems, CCUS, geothermal installations, and subsurface storage—is critical for energy security and low-carbon transitions. Yet disasters and engineering failures can trigger hazardous leaks and contaminant transport through complex geological media, posing cascading risks to subsurface and surface ecosystems. While urban resilience has been widely studied, environmentally resilient recovery strategies that explicitly integrate leakage risk, contaminant migration, and resource optimization remain underexplored. This review presents a digital twin framework for disaster-driven environmental recovery, unifying real-time monitoring, geological modeling, leakage-risk assessment, contaminant transport analysis, and intelligent resource optimization within a single decision-support architecture. The framework constructs an integrated system linking geo-energy infrastructure, subsurface environment, and surface receptors, enabling dynamic interaction modeling. Representative scenarios—including CH_4, CO_2, H_2S, hydrocarbons, and BTEX—illustrate diverse monitoring, simulation, and decision needs. Emphasis is placed on digital twins for coupling multi-source sensing, subsurface simulation, environmental risk assessment, and adaptive planning. The framework offers a conceptual foundation for embedding digital twins into resilient geo-energy management. It also outlines key challenges and future directions in data integration, geological uncertainty, transport modeling, intelligent decision support, and interdisciplinary collaboration, providing practical guidance for sustainable recovery and long-term resilience of next-generation geo-energy systems.

Keywords: digital twin, Geo-Energy infrastructure, environmentally resilient recovery, leakage risk, contaminant transport, carbon capture, utilization and storage (CCUS), geological environment, resource optimization, decision support.

1 Introduction

Geo-energy infrastructure, including oil and gas production systems, carbon capture, utilization and storage (CCUS) facilities, geothermal energy systems, and subsurface energy storage, is essential for energy security and the global transition toward low-carbon energy systems [1–5]. However, natural disasters such as earthquakes, floods, and landslides, as well as

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operational failures, may compromise infrastructure integrity, resulting in hazardous substance leakage, contaminant migration, and long-term environmental impacts [3, 6–9].

Leakage of methane (CH_4), carbon dioxide (CO_2), hydrogen sulfide (H_2S), petroleum hydrocarbons, and other hazardous compounds may migrate through reservoirs, faults, wellbores, soils, and groundwater systems, creating potential risks for both subsurface and surface environments [6, 10]. In particular, geological storage of CO_2 requires continuous assessment of storage integrity, leakage pathways, and environmental consequences because migration through geological formations may occur over long temporal and spatial scales [1, 11, 12].

Therefore, post-disaster recovery of geo-energy infrastructure should extend beyond conventional engineering restoration and incorporate environmental risk mitigation, contaminant transport evaluation, and sustainable recovery planning. Existing recovery strategies mainly emphasize infrastructure inspection, operational safety, and rapid restoration, whereas the dynamic interactions among engineering structures, geological systems—including geomechanical responses such as caprock deformation, fault reactivation, and leakage-pathway evolution—and environmental receptors remain insufficiently integrated into decision-making processes [3, 6].

Digital Twin (DT) technology provides a promising approach for addressing these challenges by integrating real-time sensing, Internet of Things (IoT), geological modeling, remote sensing, and artificial intelligence into a continuously updated virtual representation of physical systems [13–16]. Through dynamic synchronization between physical assets and their digital counterparts, digital twins enable real-time monitoring, predictive analysis, fault detection, and adaptive decision support throughout the lifecycle of complex engineering systems [13, 17, 18].

Although digital twins have been increasingly applied in oil and gas production, CCUS, geothermal energy, and underground energy-storage systems, current applications mainly focus on operational optimization, asset management, reservoir monitoring, and predictive maintenance [13–18]. Comparatively limited attention has been devoted to developing integrated digital twin frameworks that simultaneously consider leakage risk, contaminant transport, environmental assessment, and adaptive recovery planning after disasters.

To address this research gap, this review proposes a Digital Twin Framework for Environmentally Resilient Recovery of Geo-Energy Infrastructure after Disasters, integrating leakage-risk assessment, contaminant transport analysis, environmental monitoring, and resource optimization within a unified decision-support architecture. The proposed framework establishes an integrated geo-energy infrastructure–subsurface environment–surface environment system to support environmentally resilient recovery and provides future research directions for digital twin applications in complex geo-energy systems.

Despite the growing adoption of digital twin technologies in geo-energy systems, several important challenges remain for environmentally resilient recovery after disasters.

First, existing studies mainly focus on infrastructure monitoring, equipment management, or reservoir operation, whereas post-disaster recovery requires an integrated understanding of engineering facilities, geological media, and environmental systems. Leakage risk, contaminant migration, and environmental impacts are frequently investigated separately rather than within a unified recovery framework [1, 6, 13].

Second, current digital twin applications rarely incorporate dynamic interactions among geo-energy infrastructure, subsurface environments, and surface environmental systems. Although digital twins have demonstrated strong capabilities in industrial monitoring and asset management [13–18], their application in disaster-induced leakage scenarios remains insufficiently explored.

Third, limited attention has been given to coupling environmental risk assessment with intelligent decision support under uncertain disaster conditions. Existing studies indicate that disasters and extreme weather events can critically compromise geo-energy infrastructure integrity and trigger cascading environmental consequences [7–9, 21, 22], yet resilience-oriented recovery concepts have rarely been integrated with geo-energy digital twin architectures.

These limitations highlight the need for an integrated digital twin framework capable of supporting environmentally resilient recovery of geo-energy infrastructure through leakage-risk assessment, contaminant transport analysis, and adaptive decision-making.

This review makes three primary contributions:

First, it proposes an integrated digital twin framework for environmentally resilient recovery of geo-energy infrastructure after disasters. The framework connects geo-energy facilities, subsurface geological environments, and surface environmental systems within a unified decision-support architecture [1, 13].

Second, it incorporates leakage-risk assessment, contaminant transport analysis, and intelligent recovery planning into the digital twin framework, providing a systematic approach for environmental risk management under disaster conditions [6, 10].

Third, it summarizes current challenges and future research directions for digital twin applications in geo-energy systems, including heterogeneous data integration, geological uncertainty, physics-informed modeling, and adaptive decision support [13, 19, 20].

2 Literature Review

2.1 Geo-Energy Infrastructure and Environmental Challenges

Geo-energy infrastructure, including oil and gas production systems, carbon capture, utilization and storage (CCUS) facilities, geothermal energy systems, and subsurface energy-storage facilities, plays an important role in supporting energy security and the transition toward sustainable energy systems [1–5]. These systems involve complex interactions among engineering structures, geological formations, and surrounding environmental media, requiring integrated management strategies to ensure operational reliability and environmental protection.

Unlike conventional surface infrastructure, geo-energy systems operate within complex subsurface environments where engineering activities directly interact with reservoirs, caprocks, wellbores, faults, fractures, soils, and groundwater systems. Geological storage of CO_2, for example, requires long-term evaluation of reservoir behavior, caprock integrity, pressure evolution, and potential leakage pathways to ensure safe and sustainable operation [1, 3, 4].

Natural disasters, including earthquakes, floods, and landslides, together with operational failures, may damage critical components of geo-energy infrastructure and initiate leakage pathways. These failures may result in the release of hazardous substances such as methane (CH_4), carbon dioxide (CO_2), hydrogen sulfide (H_2S), petroleum hydrocarbons, and other chemical compounds into geological and environmental systems [6, 10]. Once released, contaminants—particularly CO_2—may migrate through reservoirs, faults, fractures, and groundwater pathways, altering groundwater geochemistry and isotopic signatures, potentially affecting water resources, ecosystems, and surrounding communities [6, 10].

The increasing deployment of CCUS projects and underground energy-storage systems has further highlighted the importance of leakage prevention and environmental monitoring. Existing research has demonstrated that geological storage security depends strongly on understanding CO_2 migration mechanisms, geological heterogeneity, and the integrity of storage formations [1, 5, 11, 12]. Monitoring experiences from large-scale storage projects, such as the Sleipner CO_2 storage project, have demonstrated the importance of continuous observation and verification for identifying abnormal migration behavior and maintaining storage confidence [11].

Although engineering barriers and monitoring technologies can significantly reduce operational risks, accidental leakage caused by damaged wellbores, geological faults, or caprock failure remains an important challenge for long-term geo-energy management [3, 6]. Environmentally resilient recovery therefore requires not only restoration of damaged infrastructure but also continuous evaluation of contaminant transport, environmental vulnerability, and ecological consequences.

Existing disaster management approaches for geo-energy infrastructure mainly emphasize engineering inspection, emergency response, and operational recovery. However, environmental processes associated with contaminant migration and geological uncertainty are often evaluated separately rather than integrated into recovery decision-making. Historical evidence further demonstrates that natural hazards, including earthquakes, floods, and severe storms, have repeatedly triggered hazardous substance releases from oil and gas infrastructure and industrial facilities, with severe environmental and operational consequences [8, 9, 21]. Resilience-oriented approaches therefore emphasize that complex energy infrastructure systems should possess the capacity to resist disturbances and restore operational functionality, with quantitative performance indices providing a structured basis for evaluating the restoration process following disruption [7, 22]. Therefore, an integrated framework combining engineering resilience, environmental risk management, and intelligent decision support is increasingly necessary for future geo-energy systems.

2.2 Digital Twin Applications in Geo-Energy Systems

Digital Twin (DT) technology has emerged as an effective approach for connecting physical systems with virtual representations through continuous data acquisition, modeling, and intelligent analytics. By integrating sensors, Internet of Things (IoT), artificial intelligence (AI), cloud computing, and physics-based simulation models, digital twins enable real-time monitoring, predictive analysis, and adaptive decision support for complex engineering systems [13–16].

The concept of digital twins has evolved from industrial manufacturing applications toward broader infrastructure and energy systems. Previous studies have identified digital twins as dynamic computational models capable of maintaining continuous synchronization between physical assets and their digital counterparts, thereby supporting lifecycle management and intelligent operation [13–15]. From a modeling perspective, digital twins provide an integrated environment where heterogeneous data, simulation models, and analytical methods can be combined to improve system understanding and decision-making [16].

In the oil and gas industry, digital twins have been widely applied to asset integrity management, well monitoring, pipeline management, reservoir characterization, and predictive maintenance. The integration of operational data with engineering models enables early fault detection, production optimization, and improved reliability of complex energy assets [13, 17]. Recent developments have further expanded digital twin applications toward reservoir management, where dynamic data assimilation supports production forecasting and operational optimization under geological uncertainty.

Digital twins have also attracted increasing attention in carbon capture, utilization and storage (CCUS) systems. Safe geological storage requires continuous monitoring of injection processes, reservoir behavior, pressure evolution, caprock integrity, and potential leakage pathways [1, 11]. By coupling monitoring observations with geological and numerical models, digital twins provide an effective platform for evaluating storage performance and detecting abnormal conditions during long-term operation.

In geothermal energy systems, digital twins have been explored for reservoir monitoring, thermal production optimization, and operational maintenance. Similarly, underground energy-storage systems, including natural gas storage and emerging hydrogen storage facilities, can benefit from digital twin technologies through improved monitoring of pressure evolution, storage integrity, and operational safety.

Despite these advances, existing digital twin applications remain largely focused on routine operation, production optimization, and infrastructure maintenance [13–18]. Comparatively fewer studies have investigated how digital twins can support environmentally resilient recovery after disasters, particularly where infrastructure damage, contaminant migration, and environmental consequences occur simultaneously. Therefore, developing an integrated digital twin framework that combines engineering monitoring, geological modeling, environmental assessment, and adaptive recovery planning remains an important research direction.

2.3 Environmental Risk Assessment and Contaminant Transport

Environmental risk assessment is a fundamental component of disaster recovery for geo-energy infrastructure because failures can introduce hazardous substances into the interconnected geological and environmental systems. Unlike conventional infrastructure failures, leakage events in geo-energy systems involve complex interactions among engineering structures, geological formations, and environmental receptors, resulting in potential long-term impacts [3, 6].

Representative contaminants associated with geo-energy systems include methane (CH_4), carbon dioxide (CO_2), hydrogen sulfide (H_2S), petroleum hydrocarbons, and BTEX compounds. Depending on infrastructure type and failure mechanisms, these substances may escape through damaged wellbores, fractured caprocks, geological faults, pipelines, or storage reservoirs [6, 10]. Field evidence has demonstrated that CO_2 leakage from storage formations can be traced through the chemistry and isotopic signatures of overlying groundwater, providing a basis for monitoring-based leakage verification [10]. Once released, contaminant migration is controlled by geological heterogeneity, hydraulic conditions, reservoir characteristics, and environmental processes.

For CO_2 geological storage, understanding migration pathways and leakage behavior is particularly important because injected CO_2 may move through porous media, fractures, or faults depending on geological conditions [4, 5]. Studies on CO_2 leakage mechanisms have demonstrated that plume evolution and migration behavior are influenced by reservoir properties, pressure distribution, and geological structures [5, 6].

Traditional environmental assessment methods generally rely on periodic sampling, post-event investigations, and localized monitoring. However, these approaches may provide limited understanding of rapidly evolving leakage processes. Continuous monitoring combined with numerical simulation provides improved capability for identifying leakage pathways, predicting contaminant migration, and evaluating environmental exposure under different scenarios [6, 11].

Digital twin technology provides a promising platform for integrating environmental monitoring with contaminant transport modeling. By synchronizing sensor observations, geological models, and engineering information, digital twins enable dynamic assessment of infrastructure conditions, leakage behavior, and environmental risks [13–16]. Such integration supports early warning, scenario simulation, and adaptive recovery planning.

Therefore, combining environmental risk assessment, contaminant transport analysis, and digital twin technologies provides an important foundation for environmentally resilient recovery of geo-energy infrastructure after disasters.

2.4 Limitations of Existing Digital Twin Applications and Research Gaps

Although digital twin technology has demonstrated significant potential in geo-energy systems, existing applications remain primarily focused on operational monitoring, production optimization, and asset management. Limited attention has been devoted to disaster-induced recovery scenarios involving coupled infrastructure damage, contaminant migration, and environmental consequences. Through integration of real-time observations, numerical simulation, and intelligent analytics, digital twins provide continuous insight into system conditions and support adaptive operational decisions [13–18].

In oil and gas production systems, digital twins are commonly applied for monitoring wells, pipelines, and production facilities. Real-time operational data combined with engineering models enable assessment of equipment conditions, fault diagnosis, and predictive maintenance [17]. These applications have improved operational efficiency; however, most existing studies focus on routine production rather than disaster-induced recovery scenarios.

In CCUS systems, digital twins support monitoring of injection performance, reservoir behavior, and storage integrity. Existing approaches typically integrate pressure monitoring, seismic observations, and reservoir simulation models to evaluate CO_2 migration and storage safety [1, 11]. These applications demonstrate the potential of digital twins for long-term environmental management, although disaster-related leakage recovery remains insufficiently explored.

For geothermal and underground energy-storage systems, digital twins have been investigated for reservoir management, thermal optimization, pressure monitoring, and operational safety assessment. These applications demonstrate the flexibility of digital twins across different subsurface energy systems.

However, current digital twin applications remain primarily sector-specific and oriented toward operational optimization. Environmental risk assessment, contaminant transport, and adaptive recovery planning are often treated as independent processes rather than integrated components of a unified framework. Furthermore, interactions among engineering infrastructure, geological environments, and environmental receptors are insufficiently represented.

These limitations indicate the need for a more comprehensive digital twin framework that integrates infrastructure monitoring, geological modeling, contaminant transport analysis, environmental risk assessment, and adaptive recovery planning within a single decision-support architecture.

3 Conceptual Framework

The preceding review indicates that digital twin technologies have been increasingly adopted in geo-energy applications, particularly for infrastructure monitoring, reservoir management, and operational optimization [13–18]. However, existing implementations are primarily designed for routine operational scenarios, while post-disaster recovery involves more complex interactions among infrastructure damage, subsurface processes, contaminant migration, and environmental consequences.

The geological relevance of this review arises from the close dependence of geo-energy infrastructure on subsurface geological conditions. Reservoir characteristics, geological heterogeneity, faults, fractures, caprocks, and groundwater systems can influence infrastructure integrity, fluid migration, contaminant transport, and environmental exposure following a disaster. Accordingly, post-disaster recovery of geo-energy infrastructure cannot be considered solely as an engineering restoration problem; it also requires consideration of the geological and environmental systems within which infrastructure operates.

Unlike conventional operational management, post-disaster recovery of geo-energy infrastructure requires decision-making under continuously changing conditions. Damage to wells, pipelines, storage facilities, or geological barriers may create new leakage pathways, causing hazardous substances to migrate through geological formations and groundwater systems. Such processes involve coupled interactions between engineered systems and natural environments, where recovery actions may influence subsequent contaminant behavior and environmental exposure [3, 6, 10].

Natural hazards pose significant physical threats to geo-energy facilities and have been shown to trigger hazardous releases and cascading environmental impacts in the oil and gas sector [8, 9, 21]. Existing resilience frameworks further emphasize that complex energy systems should possess the capacity to resist disturbances and restore operational functionality through structured recovery processes, supported by performance indices that quantify post-disaster functional recovery [7, 22]. However, conventional resilience assessments generally evaluate infrastructure performance or system recovery characteristics, while the environmental consequences associated with subsurface contaminant transport remain insufficiently integrated.

To address this limitation, this study develops a conceptual digital twin framework for environmentally resilient recovery of geo-energy infrastructure after disasters. The framework integrates infrastructure monitoring, geological process representation, contaminant transport assessment, environmental risk characterization, and adaptive recovery planning within a unified decision-support architecture. Rather than treating infrastructure restoration and environmental management as independent activities, the proposed framework considers them as interconnected components of a coupled geo-energy infrastructure–subsurface environment–surface environment system.

The framework establishes continuous interactions between physical assets and their virtual representations. Monitoring observations are assimilated into the digital twin to update infrastructure conditions, geological states, and environmental responses, thereby enabling recovery strategies to evolve according to changing system conditions. This approach extends the conventional application of digital twins from operational optimization toward environmentally informed disaster recovery.

3.1 Framework Development

The proposed framework is developed from the premise that environmentally resilient recovery of geo-energy infrastructure requires simultaneous consideration of engineering integrity, geological evolution, and environmental protection. Conventional recovery practices typically prioritize rapid restoration of infrastructure functionality, whereas contaminant migration, groundwater impacts, and ecological consequences are often assessed separately after engineering decisions have been made.

Digital twin technology provides an opportunity to integrate these previously separated processes by establishing a continuously updated virtual representation of the physical system [13–16]. Within the proposed framework, monitoring information is combined with engineering models, geological simulations, and environmental observations to characterize the evolving condition of geo-energy infrastructure and surrounding environments.

Three complementary perspectives constitute the theoretical foundation of the framework.

- The first perspective concerns infrastructure resilience, which focuses on maintaining critical functionality and improving recovery capacity following disruptive events. Natural

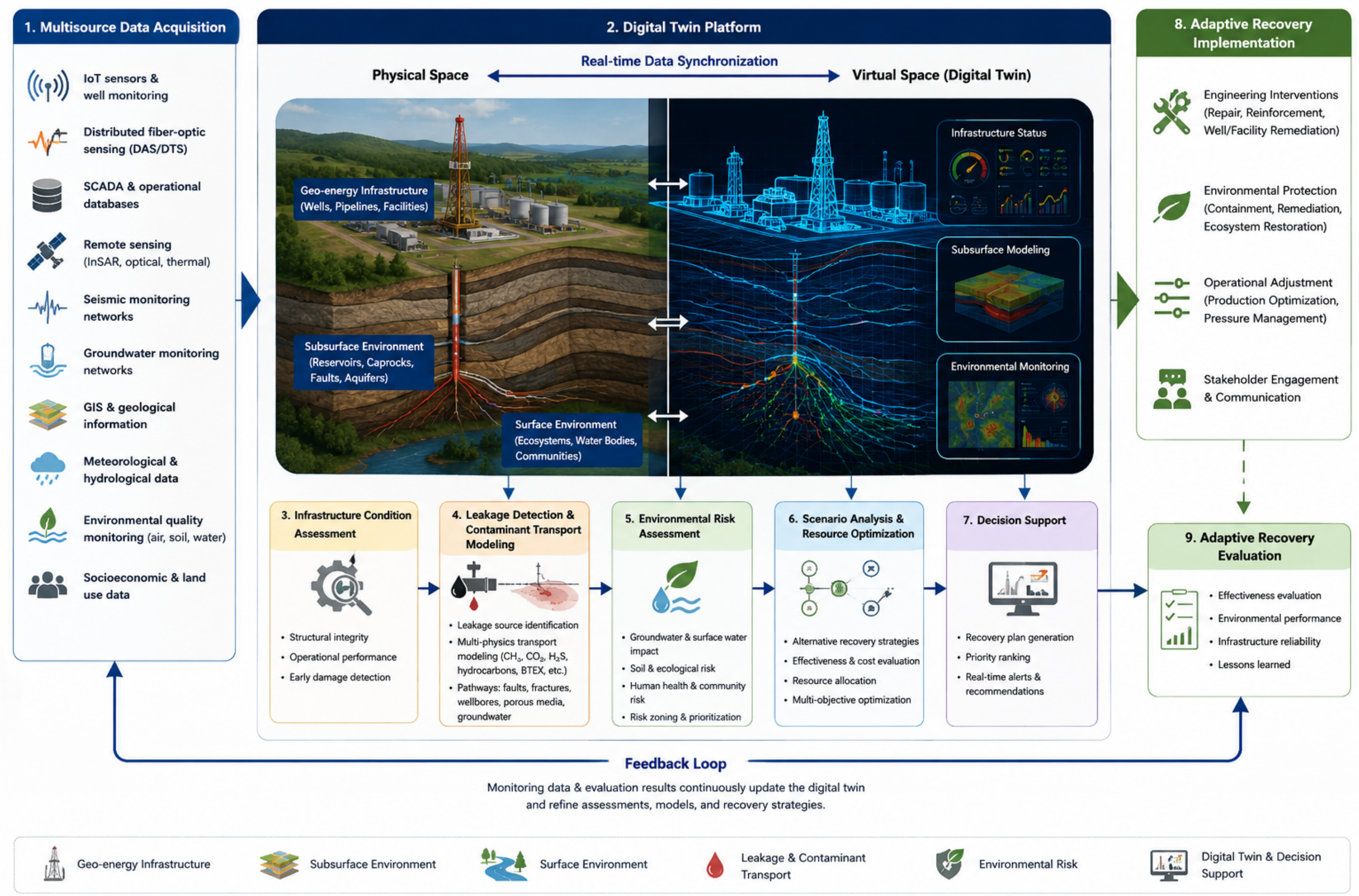

Figure 1. Integrated digital twin architecture for environmentally resilient recovery of geo-energy infrastructure following disasters.

hazards have been shown to cause significant damage to geo-energy infrastructure and trigger cascading environmental consequences [21]. Resilience-based approaches therefore emphasize that recovery should not only restore previous operational conditions but also enhance adaptability to future disturbances [7, 22].

- The second perspective concerns environmental risk assessment, which evaluates potential consequences resulting from hazardous substance release. In geo-energy systems, leakage consequences depend not only on release characteristics but also on transport pathways and receptor vulnerability [6, 10].
- The third perspective concerns subsurface process modeling, which describes the migration and dispersion of contaminants through reservoirs, caprocks, faults, wellbores, and groundwater systems. Geological uncertainty and heterogeneous subsurface structures introduce significant challenges for accurate prediction of contaminant behavior [4, 5].

Integrating these perspectives within a digital twin environment enables recovery decisions to consider both engineering performance and environmental consequences. The digital twin therefore functions not only as a monitoring platform but also as an analytical framework for supporting adaptive recovery under uncertain conditions.

3.2 Conceptual Representation of Recovery and Environmental Risk

The integrated system state is conceptually represented as:

$$DT(t) = I(t) + G(t) + E(t) + M(t) \quad (1)$$

where $I(t)$ denotes the operational state of geo-energy infrastructure, $G(t)$ represents the condition of the subsurface geological system, $E(t)$ describes the environmental state, and $M(t)$ denotes continuously updated monitoring information. Together, these four components provide a conceptual representation of the evolving recovery environment and form the basis for subsequent assessment and decision-making.

Environmental recovery depends not only on infrastructure conditions but also on the interaction between leakage behaviour and environmental vulnerability. Accordingly, the environmental risk associated with post-disaster recovery is conceptually expressed as

$$R = f(L, T, V) \tag{2}$$

where L represents leakage characteristics, including leakage rate and released contaminants, T denotes contaminant transport within geological media, and V represents the vulnerability of surrounding environmental receptors. Rather than serving as a predictive equation, this formulation illustrates the principal factors governing environmental risk within the proposed framework.

The overall objective of recovery is to restore infrastructure functionality while minimizing environmental impacts and improving operational resilience. A conceptual recovery performance index is therefore introduced as

$$RI = w_1 S + w_2 R_e + w_3 O \tag{3}$$

where S denotes structural recovery, R_e represents environmental restoration, and O reflects operational recovery. The weighting coefficients satisfy

$$w_1 + w_2 + w_3 = 1 \tag{4}$$

allowing recovery priorities to be adjusted according to different geo-energy scenarios and management objectives.

These conceptual definitions are not intended to establish a detailed mathematical model but to provide a unified theoretical basis for integrating infrastructure monitoring, contaminant transport, environmental assessment, and adaptive decision-making within the proposed digital twin framework. The corresponding system architecture is presented in the following section.

To improve readability, the principal symbols used throughout the conceptual framework are summarized in Table 1. The corresponding system architecture is presented in Figure 1.

Figure 1 illustrates the overall architecture of the proposed digital twin framework. The framework integrates geo-energy infrastructure, subsurface geological environments, and surface environmental systems into a unified digital environment, allowing monitoring, modeling, environmental assessment, and recovery planning to operate as a continuous process rather than as independent tasks. By maintaining dynamic interactions among physical assets, virtual models, and decision-support modules, the framework enables adaptive recovery under changing post-disaster conditions.

Table 1. Conceptual variables and their physical interpretation.

Variable	Physical interpretation
DT	Integrated state of the digital twin
I	Operational condition of geo-energy infrastructure
G	Geological conditions governing subsurface processes
E	Environmental status of surrounding media
M	Real-time monitoring information
L	Leakage characteristics
T	Contaminant transport
V	Environmental vulnerability
RI	Recovery performance index
W	Weight coefficient assigned to each recovery objective

3.3 Integrated Digital Twin Architecture

The proposed architecture integrates geo-energy infrastructure, geological environments, and surface environmental systems into a unified digital representation. Existing digital twin studies have demonstrated that effective implementation requires integration of heterogeneous data sources, physical models, and analytical methods to maintain consistency between real-world systems and virtual representations [13–16].

The architecture consists of three interconnected layers: the physical layer, the digital twin layer, and the decision layer.

3.3.1 Physical Layer

The physical layer represents geo-energy infrastructure and associated environmental systems. It includes oil and gas facilities, CCUS installations, geothermal systems, underground energy-storage facilities, wells, pipelines, reservoirs, caprocks, faults, groundwater systems, and surrounding ecological environments.

Following disaster events, structural damage may create leakage pathways through which hazardous substances migrate into subsurface and surface environments. Previous studies have demonstrated that geological structures, reservoir properties, and barrier integrity strongly influence leakage behavior

Table 2. Functional components of the proposed digital twin framework.

Layer	Main Components	Representative Data	Primary Functions
Physical Layer	Geo-energy infrastructure, reservoirs, groundwater, surface environment	Sensors, well monitoring, remote sensing, GIS	Real-time monitoring of infrastructure and environmental conditions
Digital Twin Layer	Data integration, geological models, contaminant transport, risk analysis	Monitoring data, engineering models, historical records	Dynamic simulation, leakage prediction, environmental risk assessment
Decision Layer	Scenario analysis, resource optimization, recovery planning	Simulation outputs, risk indicators	Adaptive recovery decision-making and feedback

and environmental impacts, particularly in CO_2 storage systems [1, 3–5].

The physical layer integrates multiple monitoring technologies, including IoT sensors, distributed fiber-optic sensing, wellbore monitoring systems, remote sensing platforms, GIS, groundwater monitoring networks, and seismic observations. These heterogeneous observations provide information regarding infrastructure conditions, geological responses, contaminant concentrations, and environmental changes.

3.3.2 Digital Twin Layer

The digital twin layer converts heterogeneous observations into an integrated virtual representation of the geo-energy system. Monitoring data are synchronized with engineering information, geological models, and historical operational records to maintain an updated representation of system conditions.

Within this virtual environment, infrastructure integrity, contaminant transport, and environmental risks are evaluated simultaneously. Numerical simulations and data-driven methods are combined to characterize leakage pathways, predict contaminant migration, and assess potential environmental exposure.

Physics-informed modeling provides additional opportunities to improve digital twin capabilities by incorporating governing physical laws into data-driven approaches, particularly for complex nonlinear processes such as subsurface transport and multiphysics interactions [19, 20].

The digital twin also supports scenario-based evaluation by comparing alternative recovery strategies under different assumptions regarding infrastructure damage, contaminant behavior, and environmental conditions. The key functional components, representative data, and primary functions of each layer are summarized in Table 2.

3.3.3 Decision Layer

The decision layer translates analytical results into practical recovery strategies. Information generated by the digital twin is combined with environmental risk assessment and engineering priorities to support adaptive decision-making throughout the recovery process.

Recovery decisions consider multiple objectives, including infrastructure restoration, contaminant containment, environmental remediation, and efficient resource allocation. Within the proposed framework, the conceptual environmental risk relationship enables the integrated evaluation of leakage characteristics, contaminant transport, and environmental vulnerability, while the recovery performance index provides a structured basis for comparing alternative recovery strategies under different operational and environmental priorities.

A distinguishing feature of the proposed architecture is its continuous feedback mechanism. Monitoring data acquired after recovery interventions are immediately incorporated into the digital twin, allowing infrastructure conditions, contaminant transport, and environmental risks to be re-evaluated as recovery progresses. This iterative process enables recovery strategies to evolve in response to changing site conditions, improving both operational resilience and environmental protection.

Overall, the proposed architecture extends the role of digital twins beyond infrastructure monitoring by explicitly integrating engineering systems, subsurface environmental processes, contaminant transport, and adaptive recovery planning within a single conceptual framework. This integrated perspective provides a systematic basis for environmentally resilient recovery of geo-energy infrastructure following disasters.

3.4 Adaptive Recovery Workflow

the proposed framework operates through an adaptive recovery workflow that integrates monitoring, modeling, environmental assessment, and decision support within a unified digital twin environment. Unlike conventional post-disaster recovery approaches that typically separate infrastructure restoration from environmental evaluation, the proposed workflow establishes continuous interaction between engineering conditions, contaminant migration processes, and recovery strategies. This enables recovery decisions to be progressively updated according to the evolving state of geo-energy systems.

The workflow begins with the acquisition and integration of multi-source monitoring data from geo-energy infrastructure and surrounding environmental systems. Data collected from wellbore monitoring systems, distributed sensing networks, geological observations, groundwater monitoring stations, remote sensing platforms, and operational databases are continuously assimilated into the digital twin. These heterogeneous data streams provide updated information regarding infrastructure integrity, subsurface conditions, contaminant behavior, and environmental responses, thereby supporting the dynamic reconstruction of the post-disaster system state.

Once abnormal conditions or potential leakage events are identified, the digital twin initiates coupled infrastructure and environmental assessments. Infrastructure integrity analysis evaluates damage conditions associated with wells, pipelines, storage facilities, and related engineering components, while contaminant transport modeling estimates the migration behavior of hazardous substances through reservoirs, fractures, faults, caprocks, and groundwater systems. By integrating these analyses, the framework enables the identification of potential leakage pathways and the assessment of their environmental consequences under different geological and operational conditions.

Subsequently, the assessment results are transferred to the decision-support layer to evaluate alternative recovery strategies. Instead of relying on fixed restoration procedures, the framework supports adaptive strategy selection by considering multiple recovery objectives, including infrastructure restoration, contaminant containment, environmental protection, and resource allocation efficiency.

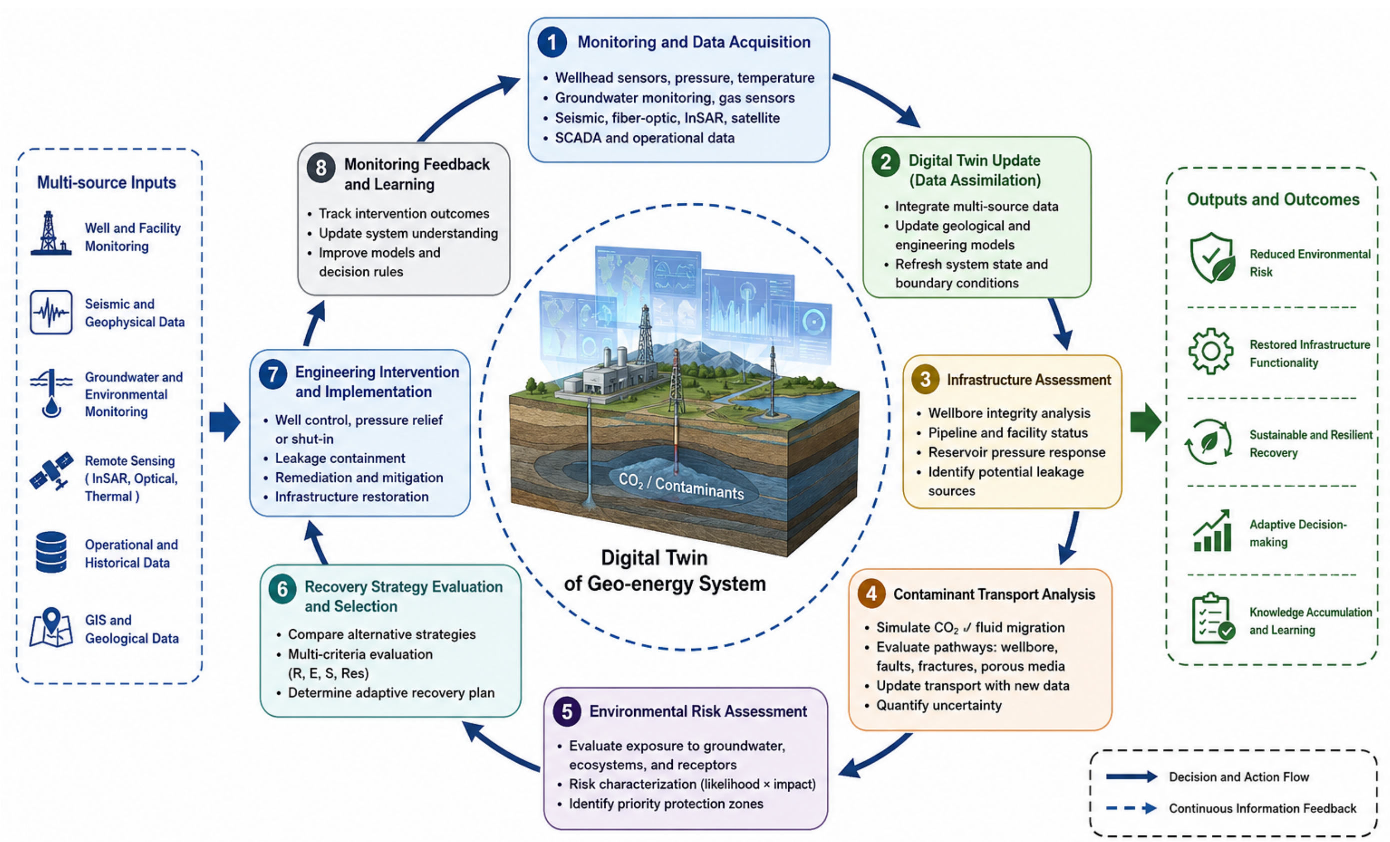

Figure 2. Adaptive recovery decision cycle supported by the digital twin.

Scenario-based analysis allows decision-makers to compare potential interventions under different assumptions regarding infrastructure damage, geological uncertainty, and environmental vulnerability.

A key characteristic of the proposed workflow is the implementation of a continuous feedback mechanism. Monitoring information collected during recovery activities is continuously incorporated into the digital twin, enabling real-time updating of infrastructure conditions, contaminant migration patterns, and environmental risk levels. Accordingly, recovery strategies can be adjusted dynamically as additional evidence becomes available. This iterative process reduces uncertainty and improves the ability of decision-makers to respond to changing post-disaster conditions.

Overall, the adaptive recovery workflow transforms post-disaster management from a sequential restoration process into a dynamic decision-support system. By integrating physical monitoring, digital modeling, environmental risk assessment, and adaptive planning, the proposed approach extends the application scope of digital twin technology from routine geo-energy operation toward environmentally resilient recovery of complex subsurface infrastructure. This iterative decision-making cycle is conceptually illustrated in Figure 2, which highlights the continuous feedback between monitoring, assessment, and recovery actions.

3.5 Framework Characteristics and Potential Applications

The proposed framework differs from conventional digital twin applications by integrating infrastructure monitoring, subsurface environmental processes, contaminant transport, and adaptive recovery planning within a unified conceptual architecture. Rather than focusing on routine operational management, the framework explicitly addresses post-disaster recovery under conditions of environmental uncertainty, where engineering failures and contaminant migration evolve simultaneously.

A key characteristic of the framework is the integration of interconnected geological, infrastructure, and environmental domains. Geo-energy infrastructure, geological formations, groundwater systems, and surface environmental receptors are represented within a common digital environment, enabling infrastructure performance, geological conditions, and environmental consequences to be evaluated simultaneously. This integrated representation supports more comprehensive recovery planning by explicitly considering the interactions between engineering restoration, subsurface geological processes, and environmental assessment.

The framework also introduces contaminant-specific risk characterization into digital twin modeling. By explicitly considering methane (CH_4), carbon dioxide (CO_2), hydrogen sulfide (H_2S), petroleum hydrocarbons, and BTEX compounds together with contaminant transport through reservoirs, caprocks, faults, and groundwater systems, the framework provides a structured basis for environmental risk assessment across different geo-energy scenarios.

Because the framework is conceptual rather than technology-specific, it can be adapted to a wide range of geo-energy applications, including oil and gas production, carbon capture, utilization and storage (CCUS), geothermal energy, and underground energy-storage systems. The modular architecture also facilitates future integration with advanced monitoring technologies, numerical simulation, and artificial intelligence for more intelligent recovery management.

Overall, the proposed framework establishes a systematic connection between monitoring, modeling, environmental risk assessment, and adaptive decision-making. It therefore provides a general conceptual foundation for environmentally resilient recovery of geo-energy infrastructure following disasters.

4 Illustrative Application of the Proposed Framework

4.1 Representative Geo-Energy Disaster Scenario

To demonstrate the applicability of the proposed digital twin framework, a representative disaster scenario involving a carbon capture, utilization and storage (CCUS) facility subjected to seismic disturbance is considered. The scenario is developed as a conceptual case to illustrate the capability of the framework in supporting post-disaster assessment and recovery decision-making, rather than to reproduce the conditions of a specific field site. CCUS facilities are selected because their long-term safety depends on the coupled behavior of engineering structures, geological formations, and environmental systems, where leakage events may lead to complex subsurface migration processes and environmental consequences [1–4].

The conceptual site consists of a CO_2 injection well, a deep saline aquifer, an impermeable caprock layer, surrounding fault structures, shallow groundwater systems, and surface environmental receptors. A seismic event is assumed to cause potential damage to critical components of the storage system, including wellbore integrity degradation and the reactivation of pre-existing geological discontinuities. Such disturbances may modify fluid migration pathways and increase the possibility of CO_2 leakage through wells, fractures, or fault zones [4, 5]. Therefore, post-disaster recovery requires simultaneous consideration of infrastructure conditions, geological responses, and environmental risks.

Unlike conventional facility restoration processes that mainly focus on repairing damaged components and restoring operational functions, recovery of geo-energy infrastructure requires continuous evaluation of subsurface processes after the initial disaster. Following a leakage event, CO_2 migration behavior is affected by reservoir characteristics, pressure distribution, geological heterogeneity, and groundwater conditions. Consequently, recovery strategies cannot rely solely on initial damage assessments but require continuous updating based on newly acquired monitoring information and model predictions [5, 16].

Within the proposed framework, the digital twin establishes a dynamic representation of the affected CCUS system by integrating multi-source observations with geological and engineering models. Monitoring information obtained from injection wells, pressure observation systems, seismic monitoring networks, distributed sensing technologies, groundwater observation wells, and remote sensing platforms is continuously assimilated into the digital twin. These data streams provide complementary information regarding infrastructure integrity, reservoir responses, leakage characteristics, and environmental changes, enabling the virtual representation to evolve with the physical system.

Based on the updated digital twin, four interconnected assessment tasks are performed during the recovery process. The first task involves infrastructure condition evaluation, where potential damage to wells, pipelines, and surface facilities is identified to determine possible leakage sources. The second task focuses on contaminant transport analysis, in which geological models and monitoring observations are combined to evaluate possible CO_2 migration pathways through reservoirs, caprocks, faults, and groundwater systems. The third task involves environmental risk assessment by linking contaminant migration behavior with the vulnerability of groundwater resources, ecosystems, and nearby receptors. The fourth task supports adaptive recovery planning by comparing alternative interventions according to their expected effectiveness in restoring infrastructure functionality and reducing environmental risks.

Although the illustrative scenario focuses on a CCUS facility, the proposed workflow is applicable to other geo-energy systems, including oil and gas production facilities, geothermal installations, and underground energy-storage systems. These systems share similar challenges associated with infrastructure failure, subsurface fluid migration, and environmental risk management. Therefore, the scenario provides a general demonstration of how digital twin technology can support environmentally resilient recovery across different geo-energy applications.

4.2 Digital Twin-Based Integrated Assessment

Following the occurrence of the seismic event, the primary function of the digital twin is to provide an integrated understanding of infrastructure conditions, subsurface responses, and environmental consequences. Unlike conventional post-disaster assessment approaches that evaluate engineering damage and environmental impacts separately [3, 6, 21], the proposed framework combines heterogeneous monitoring data with geological and engineering models to provide a continuously updated representation of the affected geo-energy system. This integrated approach is consistent with the fundamental characteristics of digital twin technology, which emphasizes dynamic interaction between physical assets and their virtual counterparts through data synchronization, modeling, and intelligent analysis [13–16].

The integrated assessment process begins with the assimilation of multi-source observations into the digital twin environment. Data collected from wellhead monitoring systems, pressure sensors, distributed fiber-optic sensing networks, seismic observations, groundwater monitoring stations, remote sensing platforms, and geographic information systems (GIS) are combined to characterize changes in infrastructure integrity, reservoir behavior, and environmental conditions. The integration of these heterogeneous data sources enables the digital twin to capture the spatial and temporal evolution of post-disaster processes rather than relying on isolated measurements or periodic inspections.

The assessment framework consists of three closely coupled components: infrastructure integrity evaluation, contaminant transport analysis, and environmental risk characterization.

4.2.1 Infrastructure Integrity Evaluation

The first component focuses on identifying damage conditions and potential leakage sources within geo-energy infrastructure. Monitoring indicators, including pressure variations, temperature changes, wellbore integrity parameters, injection performance, and structural deformation measurements, are analysed to determine the operational status of critical components. For CCUS facilities, maintaining wellbore and storage-system integrity is essential because failures in injection wells, sealing structures, or geological barriers may provide pathways for CO_2 migration [1, 4, 16].

4.2.2 Contaminant Transport Analysis

The second component evaluates the migration behavior of leaked substances within subsurface environments. The digital twin integrates geological information, reservoir characteristics, hydraulic conditions, and real-time observations to update contaminant transport predictions. Rather than generating a fixed leakage trajectory, the framework continuously adjusts transport assessments according to new monitoring evidence and evolving geological conditions. Such dynamic integration is particularly important for CO_2 storage systems, where plume migration is controlled by complex interactions among pressure distribution, geological heterogeneity, and fault structures [4–6].

4.2.3 Environmental Risk Characterization

The third component links contaminant migration patterns with environmental vulnerability. Potential impacts on groundwater resources, surface ecosystems, and surrounding receptors are evaluated by combining contaminant distribution information with environmental sensitivity indicators. This enables recovery decisions to consider not only the location and intensity of leakage but also the potential consequences for vulnerable environmental systems.

The outputs of the integrated assessment provide the basis for adaptive recovery planning. Instead of treating infrastructure restoration, leakage control, and environmental remediation as independent activities, the digital twin enables these processes to be evaluated within a unified decision-support environment. As new observations become available, the assessment results are continuously updated, allowing recovery strategies to respond to changes in infrastructure conditions and environmental risks.

Overall, the digital twin-based integrated assessment extends conventional monitoring approaches by establishing a coupled representation of engineering systems, geological processes, and environmental responses. This capability provides a foundation for adaptive recovery management in complex geo-energy systems where uncertainty, subsurface interactions, and long-term environmental impacts must be considered simultaneously. The assessment objectives, representative observations, and corresponding decision-support functions are summarized in Table 3.

4.3 Adaptive Recovery Strategy Evaluation

Following the integrated assessment, the digital twin provides a decision-support environment for evaluating alternative recovery strategies under different post-disaster conditions. In contrast to conventional recovery approaches that rely on predefined restoration procedures, the proposed framework enables recovery strategies to be adjusted according to updated information regarding infrastructure damage, contaminant migration, and environmental risks. The objective is not to identify a universally optimal solution, but to provide a systematic basis for comparing alternative interventions under multiple recovery objectives.

Within the proposed framework, recovery strategies are evaluated by considering three interconnected objectives: restoration of infrastructure functionality, reduction of environmental risks, and maintenance of operational resilience. These objectives reflect the complex trade-offs commonly encountered in geo-energy recovery, where rapid restoration may conflict with environmental protection requirements, while extensive remediation efforts may delay operational recovery.

To illustrate the decision-support capability of the framework, three representative recovery strategies are considered.

4.3.1 Strategy I: Immediate Infrastructure Recovery

This strategy prioritizes the rapid restoration of damaged geo-energy facilities. Typical actions include repairing damaged wellheads, restoring pipeline

Table 3. Integrated assessment components and decision-support functions within the digital twin framework

Assessment objective	Representative observations	Decision support
Infrastructure integrity	Pressure, temperature, wellbore integrity, pipeline condition, structural deformation	Identify damaged components and potential leakage sources
Contaminant transport	CO_2 concentration, groundwater chemistry, geological structures, hydraulic properties	Evaluate contaminant migration pathways and potential environmental exposure
Environmental risk	Groundwater quality, ecological receptors, human receptors, land-use sensitivity	Prioritize environmental protection and remediation measures

Table 4. Illustrative comparison of representative recovery strategies.

Evaluation criterion	Strategy I: Immediate Recovery	Strategy II: Environment-Oriented Recovery	Strategy III: Adaptive Digital Twin Recovery
Infrastructure restoration	High	Medium	High
Environmental protection	Low	High	High
Contaminant control	Medium	High	High
Operational flexibility	Low	Medium	High
Decision adaptability	Low	Medium	High

connections, recovering injection or production operations, and re-establishing basic monitoring capabilities. The primary advantage of this strategy is the rapid recovery of operational functionality. However, if environmental assessment is insufficiently integrated during the early recovery stage, potential contaminant migration pathways and long-term environmental consequences may not be fully characterized.

4.3.2 Strategy II: Environment-Oriented Recovery

This strategy places greater emphasis on controlling contaminant migration and reducing environmental impacts before full operational restoration. Possible measures include temporary shutdown of affected facilities, enhanced groundwater and subsurface monitoring, leakage containment, and targeted environmental remediation. Although this approach provides stronger environmental protection, prolonged operational interruption and increased recovery costs may occur due to the additional assessment and mitigation requirements.

4.3.3 Strategy III: Adaptive Digital Twin-Based Recovery

This strategy integrates infrastructure restoration with continuous environmental assessment through the proposed digital twin framework. Monitoring observations, geological models, contaminant transport analyses, and risk assessments are continuously updated to support dynamic adjustment of recovery actions. Rather than following a fixed sequence of interventions, recovery priorities are modified according to the evolving system state, allowing decision-makers to balance infrastructure restoration, environmental protection, and resource utilization efficiency.

The comparative evaluation of the three strategies is conducted conceptually through the recovery performance index introduced in Section 3.2. The index does not represent a quantitative optimization result but provides a structured approach for organizing multiple recovery objectives. By adjusting the relative importance assigned to infrastructure recovery, environmental restoration, and operational continuity, decision-makers can adapt the evaluation criteria to different geo-energy applications and disaster scenarios.

Table 4 summarizes the conceptual comparison among the three representative strategies. The comparison indicates that immediate recovery may achieve faster restoration but provides limited adaptability to evolving environmental conditions. Environment-oriented recovery improves contaminant control but may involve longer restoration periods. In contrast, the adaptive digital twin-based strategy integrates continuous monitoring and dynamic decision adjustment, providing a balanced approach for managing coupled engineering and environmental challenges.

The proposed strategy evaluation mechanism demonstrates how digital twins can support recovery planning beyond conventional monitoring and maintenance applications. By combining real-time information updating, environmental risk assessment, and multi-objective decision support, the framework enables geo-energy infrastructure recovery to transition from static response planning toward an adaptive and risk-informed management process.

4.4 Framework Implications

The illustrative application demonstrates the potential of the proposed digital twin framework in supporting environmentally resilient recovery of geo-energy infrastructure by integrating engineering assessment, subsurface process analysis, environmental risk evaluation, and adaptive decision support. Rather than representing a site-specific recovery model, the framework provides a general conceptual architecture that can be adapted to different geo-energy systems and disaster conditions.

One important implication of the framework is the integration of infrastructure restoration and environmental management within a unified decision-support process. Conventional recovery practices often prioritize the restoration of physical facilities, while environmental consequences associated with leakage and contaminant migration are evaluated separately. For geo-energy systems, however, engineering failures and environmental responses are closely coupled through subsurface processes. By incorporating geological information, monitoring observations, and environmental indicators into the digital twin, recovery decisions can simultaneously consider operational requirements and environmental protection objectives.

A second implication relates to uncertainty management during post-disaster recovery. Geo-energy systems are characterized by complex geological structures, heterogeneous subsurface conditions, and continuously evolving environmental responses. Under such circumstances, recovery decisions based solely on initial assessments may become inadequate as new information emerges. The proposed framework addresses this limitation by enabling continuous updating of system states through monitoring-data assimilation, allowing recovery strategies to evolve with changing infrastructure and environmental conditions.

A further implication concerns the transferability of the proposed framework across different geo-energy applications. Although the illustrative scenario focuses on earthquake-induced risks in a CCUS facility, the underlying architecture is applicable to other subsurface energy systems, including oil and gas production facilities, geothermal installations, and underground energy-storage systems. The common characteristics among these systems, including infrastructure integrity concerns, subsurface fluid migration, and environmental risk exposure, provide a basis for adopting a unified digital twin-based recovery approach.

From an implementation perspective, the framework also highlights the importance of integrating emerging sensing and modeling technologies into future geo-energy management systems. Advances in distributed sensing, geological modeling, artificial intelligence, and physics-informed simulation provide opportunities to improve the accuracy and responsiveness of digital twin applications. However, practical deployment requires addressing challenges related to data interoperability, model uncertainty, computational efficiency, and integration between engineering and environmental domains.

Overall, the proposed framework expands the application scope of digital twin technology from operational monitoring and asset management toward environmentally responsible recovery of complex geo-energy infrastructure. By establishing connections among physical assets, subsurface processes, environmental systems, and decision mechanisms, the framework provides a conceptual foundation for developing more adaptive and resilient recovery strategies in future geo-energy systems.

5 Discussion

5.1 Contributions to Digital Twin Applications in Geo-Energy Systems

Digital twin technologies have been increasingly adopted in geo-energy engineering for infrastructure monitoring, operational management, and predictive maintenance [13, 17, 18]. Existing applications primarily emphasize equipment performance, production optimization, and asset management, whereas comparatively less attention has been given to post-disaster recovery involving coupled engineering failures and environmental risks.

The framework proposed in this study extends current digital twin applications by integrating geo-energy infrastructure, subsurface geological systems, and environmental processes within a unified conceptual architecture. Rather than considering engineering facilities as isolated assets, the framework explicitly incorporates contaminant migration through geological media, allowing infrastructure recovery and environmental protection to be evaluated simultaneously.

A further contribution lies in the integration of monitoring, modeling, and decision support into a continuous adaptive workflow. Instead of relying on periodic inspections or static recovery plans, the digital twin continuously assimilates monitoring observations to update infrastructure conditions, contaminant transport, and environmental risks. This dynamic representation provides a consistent basis for recovery planning under changing post-disaster conditions.

Unlike conventional digital twin applications that focus primarily on operational efficiency, the proposed framework expands the role of digital twins toward environmentally resilient recovery. This broader perspective aligns with the increasing need to balance engineering performance, environmental protection, and long-term system resilience within modern geo-energy infrastructure.

5.2 Implications for Environmentally Resilient Geo-Energy Recovery

The proposed framework has several implications for the recovery and management of geo-energy infrastructure following natural disasters or accidental failures.

First, recovery planning should not be limited to restoring engineering functionality. Infrastructure damage, subsurface contaminant migration, and environmental degradation frequently occur simultaneously after disasters, particularly in systems involving carbon storage, oil and gas production, or geothermal development. Integrating these interconnected processes within a single digital environment enables recovery decisions to account for both engineering performance and environmental consequences.

Second, continuous monitoring plays a central role in reducing uncertainty during recovery. Because infrastructure conditions and contaminant migration evolve over time, recovery strategies should be updated according to newly acquired observations rather than relying solely on initial damage assessments. Continuous synchronization between physical systems and their digital representations therefore improves situational awareness and supports more adaptive decision-making.

Third, the framework is designed as a technology-neutral conceptual architecture that can be adapted to different geo-energy applications. Although the illustrative scenario presented in this study focuses on a CCUS facility, the same modeling philosophy is applicable to oil and gas production, geothermal energy, underground natural gas storage, and hydrogen storage systems. The proposed framework therefore provides a common conceptual basis for environmentally resilient recovery across diverse geo-energy settings.

5.3 Current Challenges and Future Research Directions

Despite recent advances in digital twin technologies, several challenges remain before their widespread implementation in geo-energy recovery can be achieved.

One major challenge concerns the integration of heterogeneous monitoring data. Geo-energy systems involve engineering measurements, geological observations, environmental monitoring, and geophysical information that differ considerably in temporal resolution, spatial scale, and measurement uncertainty. Efficient integration of these heterogeneous datasets remains an important technical issue.

Another challenge is the representation of complex subsurface processes. Leakage behavior and contaminant migration are strongly influenced by geological heterogeneity, fault connectivity, caprock integrity, and groundwater flow. Reliable digital representations therefore require closer integration between monitoring systems and process-based geological models.

Future research should also strengthen the incorporation of uncertainty into digital twin applications. Rather than producing deterministic recovery plans, future frameworks should quantify uncertainties associated with monitoring observations, geological parameters, and contaminant transport, thereby supporting more robust risk-informed decision-making.

In addition, emerging technologies such as distributed fiber-optic sensing, autonomous monitoring platforms, artificial intelligence, and physics-informed modeling provide opportunities to improve the predictive capability of digital twins. Integrating these

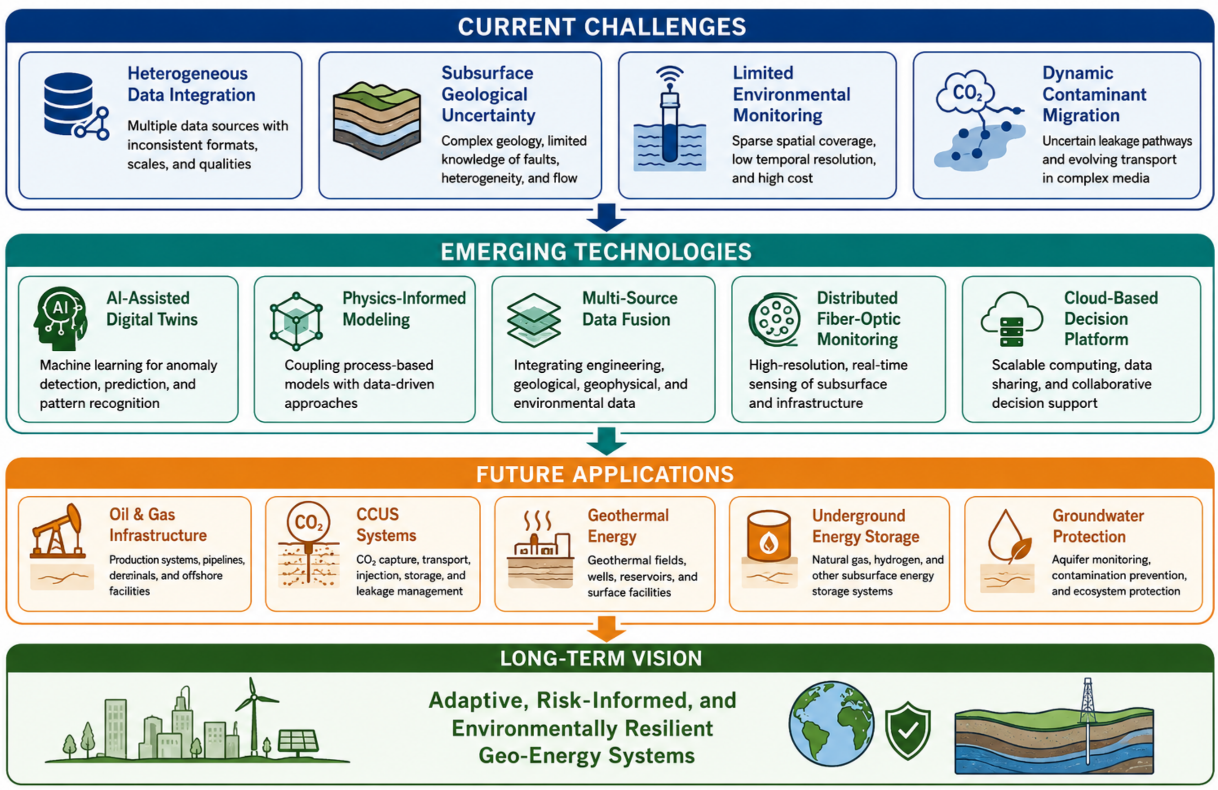

Figure 3. Future research roadmap for digital twin-enabled environmentally resilient geo-energy systems.

technologies within a unified digital environment is expected to enhance adaptive recovery planning and environmental risk management for future geo-energy systems. A structured roadmap for advancing these capabilities is presented in Figure 3, which outlines priority research directions and their anticipated contributions to environmentally resilient geo-energy systems.

5.4 Comparison with Existing Digital Twin Frameworks

Compared with existing digital twin applications, the proposed framework places greater emphasis on the interaction between engineering recovery and environmental protection. Rather than focusing exclusively on operational monitoring or infrastructure maintenance, the framework explicitly incorporates contaminant transport, environmental risk assessment, and adaptive recovery planning into a unified decision-support process.

A distinguishing feature of the framework is its representation of coupled engineering–geological–environmental interactions. Infrastructure integrity, geological structures, contaminant migration, and environmental receptors are evaluated as interconnected components rather than independent systems. This integrated perspective provides a broader analytical basis for post-disaster recovery than conventional infrastructure-oriented digital twin applications.

Another important difference lies in the adaptive nature of the framework. Continuous updating of monitoring observations enables recovery priorities to evolve as infrastructure conditions and environmental risks change, allowing recovery planning to remain responsive throughout the recovery process. Such adaptive capability is particularly valuable for geo-energy systems, where subsurface processes may continue to evolve long after the initial disaster event.

A comparison between conventional digital twin applications and the proposed framework is summarized in Table 5.

6 Conclusions

The increasing complexity of geo-energy systems and the growing frequency of natural hazards highlight the need for recovery strategies that integrate engineering restoration with environmental protection. Conventional post-disaster recovery often prioritizes the restoration of infrastructure functionality, whereas the evolution of subsurface processes and associated environmental risks may receive comparatively less attention. This gap is particularly important for oil

Table 5. Comparison between conventional digital twin applications and the proposed geo-energy recovery framework.

Aspect	Conventional Digital Twin Applications	Proposed Framework
Primary objective	Infrastructure monitoring and operational management	Environmentally resilient post-disaster recovery
System representation	Engineering facilities	Integrated geo-energy infrastructure, geological media, and environmental systems
Geological processes	Limited consideration	Explicit representation of reservoirs, caprocks, faults, and groundwater
Environmental assessment	Operational monitoring	Contaminant transport and environmental risk assessment
Monitoring strategy	Equipment condition monitoring	Integrated engineering, geological, and environmental monitoring
Decision support	Maintenance and operation	Adaptive recovery planning and environmental management
Typical applications	Manufacturing, smart infrastructure, routine facility management	Oil and gas, CCUS, geothermal energy, underground energy storage

and gas production, carbon capture, utilization and storage (CCUS), geothermal energy, and underground energy-storage systems, where infrastructure failures may trigger long-term contaminant migration through geological media.

This study proposes a digital twin framework for environmentally resilient recovery of geo-energy infrastructure. The framework integrates infrastructure monitoring, geological modeling, contaminant transport assessment, environmental risk characterization, and adaptive decision support within a unified conceptual architecture. Rather than treating engineering recovery and environmental management as separate activities, the proposed framework establishes continuous interactions between physical systems and their digital representations, enabling recovery strategies to evolve as monitoring information becomes available.

Compared with existing digital twin applications that primarily emphasize operational monitoring and maintenance, the proposed framework extends digital twins toward post-disaster recovery planning. By explicitly incorporating geological structures, leakage pathways, contaminant transport, and environmental receptors, the framework provides a more comprehensive representation of coupled engineering–geological–environmental processes. This integrated perspective supports more adaptive and environmentally informed recovery decisions under uncertain post-disaster conditions.

Although the framework is presented as a conceptual review and synthesis rather than a validated engineering system, it provides a systematic foundation for future research on digital twin-enabled geo-energy recovery. Future studies should validate the framework through representative field applications, integrate process-based numerical simulations with real-time monitoring, and incorporate uncertainty quantification into adaptive decision-making. Further development of physics-informed artificial intelligence, distributed sensing technologies, and high-resolution geological modeling is expected to strengthen the practical implementation of digital twins for environmentally resilient geo-energy systems.

Overall, the proposed framework demonstrates how digital twin technologies can move beyond conventional infrastructure management to support integrated post-disaster recovery of geo-energy systems. By connecting engineering restoration, environmental assessment, and adaptive decision support within a unified analytical environment, the framework provides a forward-looking reference for the sustainable management of future geo-energy infrastructure.

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