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REVIEW

Geological Engineering at the Climate Nexus: Innovations in Hazard Assessment, Resource Stability, and Environmental Protection

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ABSTRACT

Geological engineering is changing because of climate change, as it changes the environmental boundary conditions that affect the stability of the ground, its security as a resource and the behavior of contaminants. Geological hazards are becoming more complex due to intensifying rainfall, sea-level rise, drought, permafrost degradation, coastal erosion, groundwater fluctuations, and extreme events, which are affecting the basic design assumptions of historical stationarity. This review explores the field of geological engineering in the context of climate change, with three interrelated themes: hazard identification, resource stability, and environmental protection. It brings together developments in slope-risk assessment, geohazard assessment in the coastal and riverine environment, cold-region instability, compound hazards, remote sensing, field monitoring, predictive modeling, and digital decision-support systems. Additionally, the review assesses the importance of sustainable subsurface engineering for the security of groundwater, critical mineral development, geothermal energy, carbon storage, and containment of my waste. It also covers an analysis of the geoenvironmental risks associated with climate change, adaptive remediation, nature-based and hybrid solutions, resilient infrastructure, land-use planning, and new policy needs. Analysis indicates that, going forward, geological engineering should shift from retrospective, single-hazard models to dynamic, multi-hazard, performance-based models. They need to be technologically innovative, but integration with the understanding of geological processes, uncertainty

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quantification, long-term monitoring, and adaptive governance are essential. Geological engineering can play a vital role in supporting resilient infrastructure, responsible resource development, and sustainable climate adaptation by connecting climate-related hazards, resources, and environmental protection.

Keywords: Geological Engineering; Climate Change; Hazard Assessment; Subsurface Resource Stability; Environmental Protection

1. Introduction

The boundary conditions for defining, assessing, and managing geological engineering problems are changing with climate change. These changes are affecting the stability of slopes, foundations, coastlines, aquifers, underground openings, mine wastes, and contaminated sites [1]. According to the Sixth Assessment Report of the IPCC, climate change is already producing widespread impacts and will lead to further increases in risk with additional warming, especially if exposure, vulnerability, and lack of adaptation are combined. The World Meteorological Organization also said that 2024 was the hottest year in the instrumental record and that the ocean continued to warm, sea level rose, the cryosphere (frozen water) was depleted, and severe weather caused disruption. The changes are not only atmospheric or ecological but are increasingly manifested in the ground and affect geomaterials, pore-water pressures, groundwater flow paths, erosion rates, sediment transport, contaminant mobility, and the serviceability of engineered systems [2,3].

Geological engineering is at a strategic position at this climate nexus as it links processes in the Earth system with the safety of infrastructure, the development of resources, and the protection of the environment [4]. Geological and geotechnical engineering traditionally deals with site characterization, slope stability, foundation design, groundwater control, underground construction, mining and geoenvironmental remediation. But increasingly, the domains are becoming interdependent under climate change. In the same watershed, extreme rainfall can lead to other impacts such as landslides, debris flows, tailing dam instability, and contaminant flushing. Land subsidence, groundwater depletion, and foundation failure may occur during drought. The thawing of permafrost can reduce the capacity of shallow soils, disrupt transport and energy infrastructure, and release pollutants previously bound in permafrost. Homes, aquifers, ecosystems, and strategic infrastructure can all be at risk of coastal erosion and saltwater intrusion. The last decade has seen a growing body of geotechnical literature focusing on the effects of increased rainfall variability, drought, and extreme temperature on deformation and instability hazards in geotechnical infrastructure, and on the inadequacy of traditional design philosophies that rely on stationary hydroclimatic conditions [5].

The climate challenge also shifts geological engineering from a mostly hazard-control science to one that is primarily climate adaptation- and mitigation-focused [6]. Examples of adaptation requirements include assessing nonstationary hazards; designing infrastructure for resilience; managing coastal and riverine retreat; slope stabilization; protecting groundwater; and assisting with land-use planning in high-risk areas, among others. Geological systems such as critical mineral extraction, geothermal energy, underground energy storage and carbon dioxide geological storage are crucial enablers of the energy transition on the mitigation side. As demand for key energy transition minerals, including copper, lithium, nickel, cobalt, graphite, and rare earth elements, continues to increase in all clean energy scenarios, according to the International Energy Agency, new engineering requirements for responsible exploration and extraction, waste management, tailing containment, and water protection are set to emerge. Meanwhile, CCUS requires extensive subsurface characterization, reservoir integrity assessment, leakage risk management, monitoring, and long-term stewardship of geological storage sites [7]. Geological engineering is therefore no longer merely reacting to climate effects but also supporting several technologies needed to decarbonize.

Despite this centrality, the literature on the subject is weak and disjointed. Reviews of climate change-related landslides and coastal erosion, permafrost degradation, groundwater stress, mining sustainability, carbon storage, and geoenvironmental remediation are typically developed within different disciplinary communities. Hazard studies can provide susceptibility mapping and early warning, but little consideration is given to resource security or contaminant pathways [8]. The mining study and critical mineral studies could focus on supply chains and extraction technologies and may neglect geotechnical risks as a secondary concern, while climate change risks are magnified [9]. Geotechnical risks could be of secondary importance when climate change risks are amplified, and the mining study and critical mineral studies could focus on the supply chain and extraction technologies. Reservoir performance and caprock integrity could be the focus of carbon storage studies, but they are not part of a broader environmental risk framework [10]. While remediation and contaminant transport studies might be part of geoenvironmental studies, they may not necessarily include future climate forcing. This fragmentation makes it difficult for researchers and practitioners to gain a holistic sense of cascading risks, to assess trade-offs, and to develop integrated solutions along the hazard–resource–environment continuum.

What makes it unique is the way that geological engineering is presented as an integrative discipline that can play a role in the mutual understanding of hazard of climate change, as well as resource stability and environmental protection. These are not considered separate themes, but rather a problem framework encompassing hazards, resources, and environmental systems within the context of climate change. This view is crucial, as climate impacts can cascade through several pathways: an extreme rain event can cause slope failure, damage transport infrastructure, fail mine-waste facilities, reduce groundwater recharge, and spread contaminants [11]. Likewise, the development of low-carbon infrastructure could lower GHG emissions but also increase demand for minerals, subsurface storage, and land transformation, all of which pose geological and environmental hazards [12]. These dimensions are brought together to emphasize the role of geological engineering as both a risk-reducing measure and part of sustainable pathways for the climate transition. The proposed climate-nexus framework is illustrated in **Figure 1**, which positions geological engineering as an integrative discipline connecting hazard assessment, resource stability, and environmental protection under changing climate drivers.

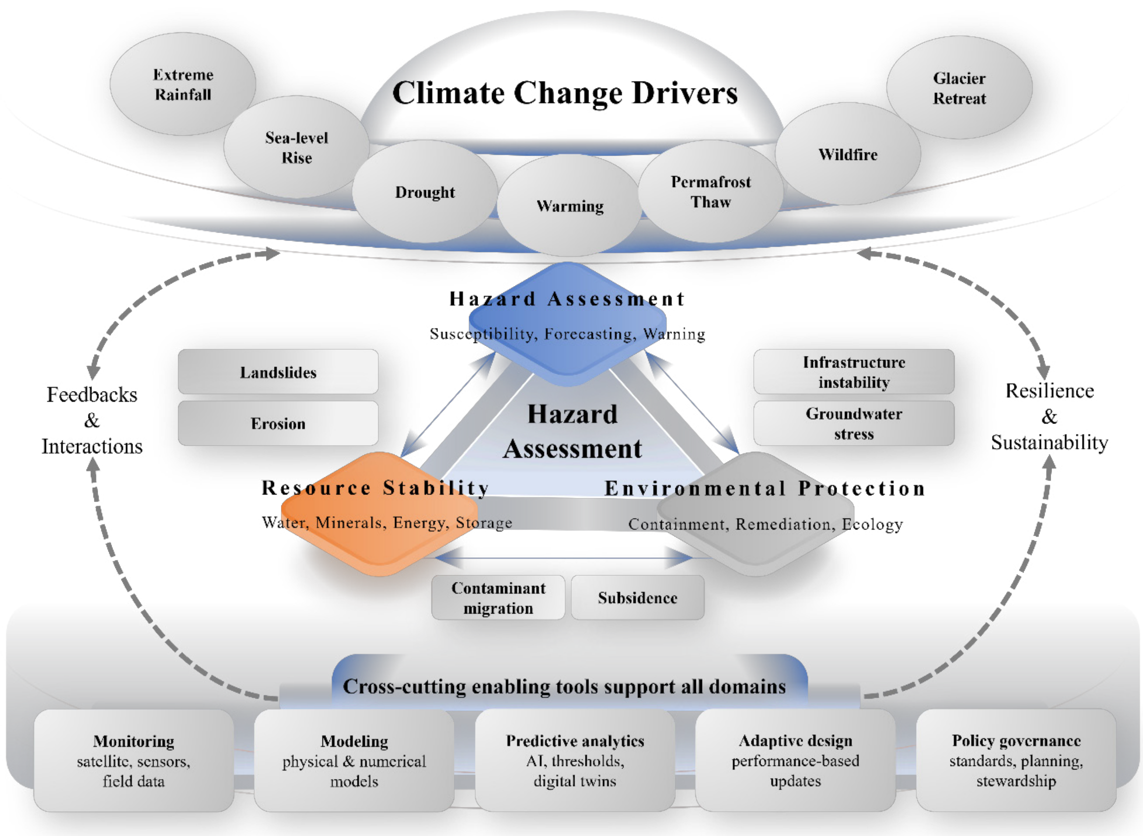

Figure 1. Conceptual framework of geological engineering at the climate nexus.

The second contribution was the focus on methodological innovation outlined in this review. The use of rapid developments in remote sensing, InSAR, UAV photogrammetry, LiDAR, geophysics, real-time monitoring, machine learning, physics-informed modeling and digital twins is transforming the ways that geological hazards and subsurface systems are observed and predicted [13–15]. For example, the use of satellite-derived information for monitoring ground deformation (InSAR) has become valuable in monitoring volcanoes, landslides, subsidence and deformation of infrastructure under a wide variety of weather and illumination conditions. But, technology is not enough without using it in the design, uncertainty quantification and decision-support systems that are informed by climate change. Hence, in this review, not only individual technologies, but also the potential for combining technologies in adaptive workflows connecting monitoring, modeling, early warning, engineering design and policy response are considered.

The third unique characteristic is that the review focuses on nonstationarity. Rainfall thresholds, flood frequency, groundwater levels, freeze–thaw cycles, erosion rates, and design loads are among the engineering practices that depend on historical records. The idea that past is a good predictor of the future is undermined by climate change. Due to this, the use of climate projections, scenario analysis, probabilistic risk assessment, Bayesian updating, and performance-based design are becoming increasingly important in geological engineering [16]. The problem is not just to raise safety factors, but also to comprehend the response of geomaterials and geological systems to different thermal, hydraulic, chemical and mechanical conditions [17]. This may include unsaturated soil behavior during drying/wetting cycles, foundations of thaw sensitive permafrost, coastal sediments, where sea-level rise is accelerating, and aquifers experiencing changes in recharge and extraction, or containment systems under more severe hydrological events.

Last but not least, this review adds by bringing together the concepts of technical innovation, environmental governance, and sustainability assessment. The field of disaster-risk research has recently gained a greater understanding that risks can cascade across sectors and geographies, and that governance systems need to tackle systemic and compound risks. Therefore, we need to evaluate geological engineering solutions that account for life-cycle impacts, ecosystem effects, social vulnerability, long-term monitoring needs, and compatibility with climate-resilient development. Examples of the many types of solutions are: nature-based solutions, managed aquifer recharge, climate-resilient tailings management, adaptive remediation, and risk-informed land-use planning [18,19].

In the context of this background, the aim of this review is to summarise recent developments in the field of geological engineering at the climate nexus, focusing on new developments in hazard assessment, resource stability, and environmental protection [2]. The article begins with a look at new climate change-related geological risks and risk assessment practices. It then considers developments in monitoring, modeling, and predictive analytics, followed by an evaluation of the stability of groundwater, mining, geothermal, carbon storage, and waste containment resources. The review then assesses approaches to manage the risk of contaminants, remediation, NbS, resilient infrastructure, and policy frameworks to protect the environment. The aim of this article is to suggest a systematic basis for future studies, design, and governance of climate-resilient geological engineering, focusing on the interconnections among climate pressures rather than on engineering subfields.

The proposed climate-nexus framework offers several distinct contributions relative to existing approaches. First, whereas existing multi-hazard frameworks typically focus on hazard interactions without systematically incorporating resource stability or environmental protection, our framework explicitly integrates all three domains, recognizing that climate impacts cascade across these interconnected systems. Second, unlike high-level climate-resilience frameworks (e.g., IPCC risk frameworks) that operate at policy or planning levels, our framework is specifically designed to inform geological engineering practice, including site characterization, design, monitoring, and decision-making. Third, the framework explicitly addresses nonstationarity, providing a structure for incorporating climate projections and scenario analysis into engineering workflows.

This review was conducted following systematic literature review principles. We searched Web of Science, Scopus, Google Scholar, and GeoRef databases using combinations of keywords including 'climate change,' 'geological engineering,' 'hazard assessment,' 'resource stability,' 'environmental protection,' 'slope stability,' 'coastal erosion,' 'permafrost thaw,' 'groundwater security,' 'mining sustainability,' 'carbon storage,' and 'remediation.' The search covered publications from 2015 to 2026, with older references included for foundational concepts. Inclusion criteria required peer-reviewed journal articles, conference proceedings, and authoritative institutional reports directly addressing geological engineering aspects of climate change. Non-English publications and studies without direct geological engineering relevance were excluded. Initial screening of titles and abstracts yielded 342 publications, which were then classified into three thematic domains: hazard assessment (n = 127), resource stability (n = 98), and environmental protection (n = 117). Each domain was further analyzed for methodological approaches, case studies, and emerging innovations.

2. Climate-Driven Geological Hazards and Risk Assessment

Climate change is altering the frequency, magnitude, timing, and spatial distribution of geological hazards [20]. In geological engineering, this shift is especially significant because many design and risk-assessment methods have traditionally relied on the assumption that past environmental conditions provide a reliable basis for future behavior. This assumption is increasingly challenged by nonstationary climate forcing, which modifies hydrological cycles, thermal regimes, sea levels, vegetation patterns, erosion processes, and groundwater dynamics. As a result, hazards that were once treated as site-specific or episodic are now better understood as evolving components of coupled climate–geological systems. Effective risk assessment, therefore, requires not only improved hazard mapping but also a deeper understanding of how geomaterials, landforms, infrastructure, and human exposure respond to changing boundary conditions.

2.1. Slope Instability, Landslides, and Debris Flows

Slope instability is one of the most direct manifestations of climate – ground interactions. The rise in precipitation frequency, intensity, and/or length of wet seasons, combined with rapid snowmelt, loss of vegetation due to wildfires, and repeated wetting/drying cycles, can significantly reduce a slope's stability. These processes affect pore-water pressure, soil suction, shear strength, root reinforcement, and surface erosion. Landslides are increasingly driven in many mountainous and hilly areas not just by static geological susceptibility but also by dynamic interactions between pre-existing terrain susceptibility and variable climate triggers [1].

Rainfall-induced landslides are a good example of this complexity. Historical data are used to create traditional rainfall thresholds, but a threshold may prove ineffective when storm intensity and antecedent moisture conditions fall outside the historical range [21]. Likewise, shallow landslides and debris flows following fire are emerging as increasingly important processes in a future in which hot, dry conditions are more likely to cause vegetation loss and soil hydrophobicity [22]. This resulting gradient can respond very quickly to medium or heavy rainfall, thus allowing a short warning time for hazards. These questions are traditionally addressed by Early Warning Systems based on the duration and intensity of rainfall, but they do not consider land cover recovery, burn intensity, or variations in soil structure.

An important lesson is that landslide risk assessment needs to shift from susceptibility mapping to landslide-dynamics forecasting [23]. Static inventories are still important for identifying hazard-prone areas, but they do not provide much information about the changing risks associated with future climate scenarios. The use of integrated mapping, a hydrological model, satellite deformation monitoring, and machine-learning-based prediction can enhance landslide assessment. But data-based models need to be used with caution. They can detect complex relationships, but their accuracy might decrease if they are used in future climate situations that are not part of their training set. It is therefore more likely that a hybrid approach combining physical mechanisms with data analytics would be more promising for assessing climate-sensitive slope risk.

2.2. Coastal and Riverine Geohazards

The coastline and riverine regions are extremely vulnerable to the effects of climate change as they are influenced by changes in water level, sediment transport, storm surges, coastal erosion and anthropogenic alteration [24]. In many areas, sea-level rise, increased storm surge, altered wave climates and sediment decreased are causing coastal erosion at an increased rate. Meanwhile, river systems are experiencing increased flows during flood events, changing seasonal flow patterns, channel modification due to drought, and changing sediment loads. These processes pose risks to foundations, ports, roads and bridges, pipelines, coastal communities, flood protection and deltaic ecosystems.

Coastal erosion is a special problem because it is a process of retreat and failure. Engineering responses designed only to accommodate past shoreline change may also not be adequate for the increased rate of sea-level rise and storm intensity. Local protection by hard defenses (seawalls and revetments) may lead to transfer of the erosion downstream, decrease in the width of the beach, and degradation of natural buffers. On the other hand, nature-based solutions like dune protection, wetlands and living shorelines can offer adaptive benefits, but their potential effectiveness is dependent on sediment supply, ecological condition and maintenance over time [25]. Sediment budgets, geomorphic feedbacks and ecosystem interactions are therefore important considerations for geological engineering as well as structural stability.

Wild river geohazards are also complex. Bank failure, scour near bridge foundations, levee failure, and channel migration can result from extreme flooding [26]. Droughts can also cause a decline in groundwater, shrinkage of soils and impact on embankment stability. Additionally, in deltas, land subsidence from sediment compaction and groundwater extraction, and diminished sediment supply, can result in significant relative water-level rise when added to the sea-level rise. In this context, the risk assessment involves a joint hydrological, geomorphological and geotechnical analysis. The inability to integrate flood-risk modeling with ground-stability evaluations is a major constraint in many current assessments, but erosion, seepage, piping, and foundation failure can have the most significant impact on the actual performance of flood-protection systems.

2.3. Permafrost Degradation and Cold-Region Instability

An example of the most apparent change in the ground due to climate change is permafrost degradation. The temperature of the ground increases, and ice rich soils weaken, the thaw settlement increases and thermokarst processes alter landscapes. Grounds underlain by concrete structures, such as roads, railways, pipelines, mining works, airstrips and buildings, can suffer from differential settlement, loss of bearing capacity, disruption of drainage and slope instability. Glacier retreat and permafrost thaw in mountainous cold environments can induce instability in rock slopes and lead to the potential for rock falls, rock avalanches, and cascading hazards such as lakes and rivers or settlements [27].

The challenge in engineering is the non-linear and delayed behavior of frozen ground. Permafrost can be stable for a long time until the temperature increases to a point where ice lenses in the permafrost melt, causing excess pore water and collapse of the soil fabric [28]. This can make monitoring and designing challenging, as the surface deformation can follow the thermal change. Additionally, the spatial variability of ground ice can result in very different responses of neighboring structures to the same climatic action. The conventional site investigation techniques are inadequate to pick up this heterogeneity without the use of geophysical surveys, borehole temperature surveys, remote sensing and long term deformation measurements.

A time-dependency of the risk assessment is thus required for permafrost areas. Estimates of the evolution of the frozen or unfrozen state of the ground over the service life of infrastructure are necessary to classify ground. This will need to be coupled with ground-thermal models and mechanical performance assessments [29]. However, there remains considerable uncertainty, especially where there are few monitoring networks. Adaptation measures, such as thermosyphons, insulation layers, adjustable foundations and improved drainage can help to limit risk, but may not be as effective if warming is greater than assumed during design. The overall message is that there is a need to shift cold-region geological engineering from preserving existing frozen ground conditions to adapting to the inevitable thaw at many sites.

2.4. Seismic, Volcanic, and Compound Hazards in a Changing Climate

Tectonic and magmatic processes are the major control on seismic and volcanic hazards, with stress conditions and hazard expression being controlled in certain contexts by processes related to climate [30]. Changes in crustal loading and pore pressure due to glacier retreat, reservoir impoundment, groundwater-level changes, erosion and sediment redistribution, may change crustal loading and pore pressure. These effects are often second order to the tectonic effects, but may be of importance in geologically sensitive regions. Rapid deglaciations, for instance, may cause changes in surface loading, which can impact slope stability, volcanic systems and/or fault stress states. Likewise, reservoir-induced seismicity and fluid-injection-related seismicity demonstrate that there are changes in pore pressure and loading that can trigger or modulate the geological responses.

Geological engineering is not so much worried about the broad effects of climate change on seismic or volcanic activity, but by its ability to exacerbate the effects of these hazards by compounding and cascading through various pathways [31]. Cyclones and earthquakes that follow heavy rainfall can result in greater landslide hazards than the same events occurring in dry weather. Heavy rain can cause volcanic ash that has fallen on steep slopes to become mobilized and form lahars. The GLODs can interact with unstable slopes or volcanic land forms. Coastal earthquakes can amplify the effects of sea-level rise on inundation and/or liquefaction in low-lying areas.

This compound-risk view is critical as infrastructure systems are rarely damaged by a single hazard event. Roads, dams, tunnels, pipelines, and urban slopes can experience multiple seismic, hydrologic, thermal, and geomorphic stresses. Typical hazard assessments tend to break down these risks into individual components, thereby yielding disjointed risk estimates. A climate-nexus approach takes a different approach and focuses on the sequence, interaction and amplification of hazards. It entails multi-hazard scenarios, probabilistic hazard cascading, and stress testing of infrastructure systems under combined events [32]. The challenge is not only technical but also methodological: Risk frameworks need to capture interactions between hazards, not just assume they are independent.

2.5. Advances in Hazard Assessment Technologies

Geological hazard assessment is changing in recent years with the new technologies in monitoring and analysis. Satellite remote sensing, especially interferometric synthetic aperture radar, can be used to sense ground deformation over large areas that occurs due to landslides, subsidence, volcanic inflation, thaw settlement, and infrastructure movement. High resolution topographic data from LiDAR and UAV photogrammetry are used to locate scarps, erosion features, drainage pathways and changes that have occurred after the event. Fiber-optic sensing, geophysical imaging and wireless sensor networks, in addition to ground-based radar, are technologies that allow more continuous monitoring of unstable slopes, embankments, tailing facilities, and subsurface systems [13–15].

These technologies provide significant benefits, but pose new challenges for interpretation. Deformation can be detected by remote sensing but not all deformation signals imminent failure. Sensor networks can generate many false alarms and data gaps that compromise decision-making. While machine learning can enhance pattern recognition, there are still issues of transparency and transferability of models. Thus, geological and technological knowledge must go hand in hand. It is important to note that hazard assessment shouldn't only be a data-driven process without understanding the process [33].

Integrated and adaptive systems will likely be the most effective. Regional deformation hotspots can be identified using remote sensing, field investigations can define geological controls, monitoring systems can be used to monitor temporal change and numerical models can be used to test failure mechanisms for future climate scenarios. Observations can then be translated into actionable information for authorities and communities through digital platforms and early-warning systems. But equitable implementation is a worry. The high income areas may have a robust monitoring network and sophisticated analysis, whereas vulnerable areas with high hazard exposure may have little or no data infrastructure. Therefore, innovative investments in technical solutions, open data, capacity development and locally relevant hazard communication are needed to enhance global hazard resilience [34].

In general, the climate change induced geological hazards require a transition from a retrospective, single hazard analysis to forward-looking, multi-hazard and system-based risk analysis [35]. The major climate drivers, geologic hazard responses, controlling mechanisms, engineering implications and assessment priorities discussed in this section are summarized in **Table 1**. Changing environmental drivers, uncertainty about the future and interactions between ground behaviour, exposure of infrastructure and society must be considered with regard to geological engineering. The shift is a key component of the infrastructure to withstand the impacts of climate change and minimise climate losses in a world where geological risks are increasingly influenced by climate dynamics.

Table 1. Climate-driven geological hazards, controlling mechanisms, and engineering implications.

Climate Driver	Geological Hazard Response	Controlling Mechanisms	Engineering Implications	Assessment Priorities
Intensified rainfall	Landslides, debris flows, slope erosion	Increased pore-water pressure, reduced matric suction, surface runoff, soil saturation	Higher failure probability of slopes, embankments, roads, and cuttings	Rainfall thresholds, real-time pore-pressure monitoring, landslide susceptibility modeling
Sea-level rise	Coastal erosion, saltwater intrusion, delta subsidence	Shoreline retreat, storm surge, groundwater salinization, sediment deficit	Threats to ports, coastal infrastructure, aquifers, and low-lying settlements	Coastal retreat modeling, erosion mapping, groundwater salinity monitoring
Drought and heat extremes	Ground subsidence, soil cracking, reduced slope vegetation	Groundwater depletion, desiccation shrinkage, loss of root reinforcement	Damage to foundations, pipelines, canals, and transport corridors	Groundwater-level monitoring, soil shrink–swell assessment, subsidence mapping
Permafrost thaw	Thaw settlement, thermokarst, rockfall, infrastructure deformation	Ice melting, active-layer deepening, loss of frozen-ground strength	Instability of roads, railways, pipelines, buildings, and mine facilities	Ground-temperature monitoring, geophysical surveys, deformation tracking
Wildfire and vegetation loss	Post-fire debris flows, shallow landslides, erosion	Soil hydrophobicity, reduced interception, loss of root cohesion	Rapid runoff, slope instability, sediment surges affecting downstream assets	Burn-severity mapping, rainfall-trigger forecasting, catchment-scale sediment assessment
Extreme floods	Riverbank collapse, scour, levee failure, contaminant spreading	High flow velocity, seepage, piping, sediment remobilization	Bridge failure, flood-defense instability, pollutant redistribution	Flood–erosion coupling, scour analysis, levee seepage assessment
Glacier retreat	Rock slope failure, glacial lake outburst floods	Debuttressing, thawing joints, lake expansion, sediment instability	Cascading hazards affecting valleys, hydropower systems, and settlements	Remote sensing, lake-volume monitoring, multi-hazard scenario analysis

3. Innovations in Monitoring, Modeling, and Predictive Analytics

Ongoing climate change has led to increasingly complex geological hazards, which have made spatial and temporal monitoring and modeling systems ever more important, and the need to make decisions in an uncertain context greater [36]. In traditional geological engineering practice, much time was spent on field investigations and lab testing, empirical correlations, and deterministic design assumptions. In the face of nonstationary climate forcing, compound hazards, and changing exposure patterns, these approaches remain basic and prove inadequate. Innovations such as monitoring, modeling, and predictive analytics are thus changing a predominantly diagnostic practice to a more anticipatory and adaptive science of the discipline. The key problem that needs to be overcome is not just gathering more data but translating disparate observations into trusted interpretations, actionable forecasts, and sound engineering decisions.

3.1. Integrated Field and Remote Observation Systems

Modern geological engineering increasingly relies on field measurements, remote sensing, and geospatial observations. Field investigations provide first-hand data on lithology and discontinuities, soil properties and conditions, stress history, and geomaterial behavior. But field data can be geographically restricted and may not adequately capture regional deformation trends or temporal changes. The limitations can be mitigated through repeated observations of large, inaccessible areas, using remote sensing technologies such as satellite imagery, interferometric synthetic aperture radar, LiDAR, thermal imaging, and unmanned aerial vehicle (UAV) photogrammetry [13–15].

Integrated observation is especially important for monitoring landslides, assessing coastal erosion, studying permafrost degradation, mapping subsidence, and monitoring tailing facilities. Slow ground deformation can be identified using satellite-based measurements before any visible degradation, and high-resolution terrain models can be generated from UAV surveys following periods of rain, wildfire, or seismic events. Process-level data from ground-based sensors, including inclinometers, piezometers, extensometers, geophones, distributed fiber-optic sensors, and weather stations, can complement data from remote platforms [37]. These systems complement each other and enable engineers to correlate surface deformations with the subsurface mechanisms, hydrological triggers, and structural performance.

But it is still hard to go technically and interpretatively. Vegetation cover, atmospheric noise, revisit frequency, viewing geometry, or signal decorrelation can affect remote sensing data. Field sensors can be disturbed, drift, become damaged, or may be unrepresentative. Scale mismatch is a key concern: satellite observations might show the regional displacement trend, but engineering decisions might be made at the scale of a slope or foundation or embankment, or structural component. Thus, integrated observation systems should be developed with a clear focus on specific engineering questions, rather than on collecting data. The best monitoring programs integrate regional screening, field validation of a target set of variables, ongoing monitoring of critical variables, and regular refreshment of the hazard model [38].

3.2. Data-Driven and Physics-Informed Modeling

Prediction models play a crucial role in the field of climate-resilient geological engineering, enabling the assessment of geological conditions beyond the historical record [39]. Numerous slope stability, seepage, settlement, erosion, fracture behavior and subsurface storage performance are simulated using conventional numerical models such as finite element, finite difference, limit equilibrium, discrete element, groundwater flow, and coupled hydro-mechanical models. These models are useful since they are physically based and they can explicitly model material properties, boundary conditions and failure mechanisms. But their validity is constrained by the quality of the input data, the constitutive assumptions, the calibration procedures and the representation of uncertainty.

In the assessment of geological hazards, data-driven approaches have grown by leaps and bounds, especially machine learning. They have applications in landslide susceptibility mapping, rainfall threshold prediction, subsidence detection, groundwater forecasting, lithological classification and early-warning systems [40]. The power they have is that they can capture nonlinear relationships between large amounts of data, particularly when there are multiple conditioning factors. But their vulnerabilities are significant as well. Machine-learning models can give good performance with respect to the statistical scope of training data but can be inadequate in novel climate conditions. They can also be subject to biases introduced into incomplete inventories or monitoring records. This is an important issue for climate-related applications, as future climate may be significantly different from past climate.

Physics-informed and hybrid modeling is a promising route to go beyond purely empirical and purely mechanistic modeling. In these models, the data-driven learning is constrained by physical laws, and the observational data are used to improve the model calibration and adaptive prediction [33]. For instance, rainfall-induced slope failure models can be integrated with machine-learning correction factors based on monitoring data. Groundwater models can incorporate remote sensing, pumping information, and recharge estimates while enforcing mass-balance conditions. The heat transfer, phase change and deformation can be coupled in permafrost models, which can be used with observed surface displacement. Such hybrid systems are especially well suited to climate change, maintaining interpretability while keeping up to date with new information.

One important lesson is that, sophisticated models do not necessarily lead to better decisions. The more complex the model, the more it can give a false sense of precision if the uncertainty is not well represented or if the input data are unreliable. On the other hand, simpler models might be more helpful when they are transparent, well calibrated and fit the context of the decisions. The future of geological engineering modeling is not a question of either physical or data driven, but rather about building fit-for-purpose models that are accurate, interpretable, efficient and usable [41].

3.3. Climate-Informed Geotechnical Design

This is an important paradigm change from the past design practice of geotechnical design. Historical rainfall records, groundwater levels, flood frequencies, freeze–thaw cycles or erosion rates have been traditionally used to design many geotechnical systems [3]. This is based on the assumption of stationarity, that is the probability distribution of the environmental loads is relatively stable through time. Climate change calls into question this assumption, as average conditions and extremes change. Consequently, the design parameters employed based on past records may be too conservative in terms of the loading, deformation, degradation or failure probability associated with the future record.

Future rainfall intensity, antecedent moisture state, vegetation alterations and wildfire impacts are all factors that must be considered to design for climate in slope engineering. Coastal and riverine engineering projects require predictions of sea-level rise, storm surge, erosion, sediment supply and scour potential. In cold regions, ground warming, active-layer deepening, thaw settlement and loss of ice-bonded strength must be modeled. In the fields of groundwater and foundation engineering, it involves the evaluation of groundwater recharge variability, shrinkage in certain conditions of drought, subsidence and rising groundwater in some urban or coastal areas. The examples illustrate that climate change can not only impact external loadings, but also the ground properties [5].

The challenge is that the spatial and temporal scales of climate projections are not necessarily directly applicable to geotechnical design [42]. RCMs can give information on precipitation or temperature in a region, but engineers need precipitation and infiltration or pore pressure or shear strength or erosion or settlement at their specific site. The downscaling, bias correction, and scenario translation are thus necessary. But these steps bring new uncertainties and necessitate some communication between climate scientists and geological engineers. Much of this complexity has yet to be integrated in design codes and standards and many practitioners are still not sure how to apply climate projections in their daily engineering practice.

Performance-based design provides a helpful model to tackle this challenge. Performance-based approaches, rather than planning for a single specified event, assess how systems will perform across a variety of credible future events. This enables engineers to pinpoint thresholds, failure modes, residual risks, and a range of adaptation options. The flexibility and adaptability in design are particularly significant when uncertainty is high. This includes incorporating future expansion in drainage systems, designing adjustable foundations, incorporating monitoring in key structures and using a combination of coastal protection and managed retreat or sediment-based adaptation. Climate-informed design, in this way, is not just a technical calculation but a strategy for managing change throughout the entire life cycle of geological engineering systems [38].

3.4. Uncertainty Quantification and Decision Support

Geological engineering is associated with uncertainty due to incomplete observation of subsurface conditions and due to the natural variability of geomaterials [3]. Climate change adds to this uncertainty because of the new environmental conditions it introduces that cannot be known with certainty in the future. Uncertainties come from geology, material properties, the structure of the model, climate projections, hydrological response, growth of exposure, quality of maintenance, and human decision making. However, these uncertainties can result in designs that are over ambitious and risk management that is substandard.

Tools for doing this are available through uncertainty quantification. Probabilistic slope stability analysis, reliability-based design, Monte Carlo simulation, Bayesian updating, ensemble climate modeling and sensitivity analysis can be used to determine which variables are most significant in determining risk [16,43]. Bayesian approaches are especially useful since they can be used to update the knowledge about the situation as monitoring information becomes available. For instance, if deformation increases, pore pressure increases or new rainfall thresholds are exceeded, a slope that had been identified as being moderately hazardous may be reclassified. This dynamic updating is better for climate sensitive systems than one time assessment.

Decision support systems convert technical analysis to operational decisions. For geological engineering, these systems can be used for early warning, evacuation planning, prioritising maintenance, land-use zoning, investment in infrastructure, planning for mine closure or designing remediation. Their usefulness is dependent on their ability to communicate risk with those who may not be specialists. Technically sophisticated models can be of little value if the outputs are incomprehensible, untimely, or fail to relate to obvious action thresholds. Hence, decision support needs to combine hazard probability, consequence analysis, uncertainty, economic aspects, social vulnerability and institutional capacity [44].

One of the big issues is doing a good job of minimizing false alarms while maximizing warnings. The early-warning system for landslide or debris flow or dam instability should be sensitive enough to warn of danger but not so sensitive that it will cause a loss of public confidence through false alarms. This means that it must be on-going, with clear warning levels and lessons learned from previous events. Decision support can also support more deliberative, yet still significant decisions in resource and environmental systems, like expanding groundwater extraction, strengthening a tailings facility, or relocating infrastructure or implementing a NbS. In either case, uncertainty shall not be used as an excuse for not doing anything. Rather, it can be used as a prism for adaptive management, precautionary design, and staged investment [45].

3.5. Digital Transformation in Geological Engineering

Geological engineering information is being collected, stored, analysed and communicated in a new way due to digital transformation [46]. Slopes, tunnels, mines, dams, aquifers, coastal systems and urban infrastructure are just some of the areas where digital twins, cloud-based geospatial platforms, automated monitoring dashboards, artificial intelligence, and real-time data streams are increasingly being applied. The digital twin can be thought of as a constantly updated, dynamic virtual representation of a real geologic or engineering system which can be used to simulate it under various conditions. This is particularly useful in climate-sensitive applications as it enables engineers to assess the evolution of the system instead of making assumptions about the design.

The promise is great. Digital platforms have the potential to combine borehole data, lab data, geophysical data, satellite data of deformation, climate data, hydrological models and infrastructure data. These can help facilitate quick risk visualisation, automated anomaly detection and cross-agency coordination. Digital monitoring can enhance the safety of operations and the planning of tailing disposal closure in the mining industry. For urban geological engineering, subsurface data platforms can help with flood resilience, managing groundwater, and constructing underground utilities, as well as making land use decisions. Digital systems can enhance disaster risk reduction by enhancing early warning and disaster damage assessment [47].

But, digital transformation does come with risks. There are significant issues of data quality, interoperability, cybersecurity, algorithmic bias and long-term maintenance. The reliability of a digital twin heavily depends on the data and assumptions used. Mis-calibrated models can generate outputs that look good but are not. Proprietary platforms may restrict transparency and replicability and inequity in the availability of digital infrastructure can exacerbate disparities between privileged and disadvantaged areas. Additionally, there is a risk that automated outputs will become more important than field expertise and local knowledge, which will be underestimated [48].

In the digital engineering future, the most productive approach for geological engineering is not one in which algorithms replace the professional engineer's judgment, but one in which digital tools enhance the interpretation, communication and adaptive management [49]. It is important that the engineer continues to consider the geological plausibility, the limitations of the models and practical consequences. The purpose of a digital system should be to facilitate traceable decision making rather than to provide a really complicated interface to hide the fact that a decision must be made. Digital transformation, together with good field investigation, clear modelling and open governance, can play a major role in improving geological engineering in the context of climate change.

In general, innovations and advances in monitoring, modeling, and predictive analytics are helping shift from reactive responses to hazards to a more proactive approach to risk management [50]. **Table 2** compares the key tools used in this transition, highlighting their application, strengths, weaknesses, and climate-nexus value. Integrated observations ensure understanding of evolving geological systems; hybrid models aid interpretation and prediction; design for a nonstationary future with climate information; uncertainty analysis ensures robust decision-making; and digital platforms ensure data is linked to action. The takeaway is that technology is not enough. The value depends on whether it enhances understanding, reduces uncertainty, aids timely decision-making, and improves the climate change resilience of engineered and natural systems.

Table 2. Monitoring, modeling, and predictive tools for climate-resilient geological engineering.

Tool or Method	Main Application	Strengths	Limitations	Climate-Nexus Value
InSAR	Ground deformation, landslides, subsidence, permafrost thaw, tailings monitoring	Wide-area coverage, repeated observations, millimeter-scale deformation detection	Vegetation interference, decorrelation, atmospheric noise, limited subsurface interpretation	Enables regional screening of slow-moving and climate-sensitive ground deformation
UAV photogrammetry	Slope failures, erosion, coastal change, post-disaster mapping	High spatial resolution, flexible deployment, rapid surveying	Limited coverage, weather dependence, regulatory constraints	Supports rapid assessment after storms, floods, wildfires, and landslides
LiDAR	Terrain mapping, landslide scarps, river morphology, coastal erosion	Accurate topographic models, vegetation-penetrating capability in some systems	Cost, data processing demand, limited temporal frequency	Improves detection of subtle geomorphic change and hazard-prone terrain
Geophysical surveys	Permafrost, groundwater, voids, weak zones, contamination plumes	Non-invasive subsurface characterization	Ambiguity in interpretation, site-specific calibration needed	Links surface observations with subsurface structure and hydrological change
Sensor networks	Slopes, dams, tunnels, tailings, aquifers	Continuous data on pore pressure, displacement, temperature, vibration, and water level	Installation cost, maintenance, data drift, false alarms	Enables real-time warning and adaptive risk management
Machine learning	Susceptibility mapping, early warning, pattern recognition	Handles large datasets and nonlinear relationships	Limited transferability, dependence on training data, low interpretability	Useful for identifying complex climate–hazard correlations
Physics-informed models	Slope stability, groundwater flow, permafrost thaw, carbon storage	Mechanistic interpretation, scenario testing, improved extrapolation	Requires quality input data and calibration	Supports prediction under future climate conditions beyond historical records
Digital twins	Infrastructure, mines, aquifers, slopes, coastal systems	Dynamic updating, visualization, integrated decision support	Data quality, interoperability, cybersecurity, model uncertainty	Provides adaptive platforms for climate-resilient system management

4. Resource Stability and Sustainable Subsurface Engineering

Climate change has been a major focus of the geological engineering community due to changes in the availability, accessibility, and long-term security of groundwater, minerals, energy resources, and subsurface space for storage [51]. Climate-resilient resource engineering differs from traditional resource engineering, where optimizing extraction efficiency or economic viability is a primary concern, by also accounting for hydrological variability, geomechanical stability, environmental protection, and long-term system performance. The role of the subsurface has become increasingly complex in the context of climate change: as a source of water, minerals for low-carbon technologies, and geothermal energy, and as a storage for CO_2 and a repository for industrial residues and mine wastes. These functions can compete for space, water, energy, and regulatory attention. Hence, sustainable subsurface engineering requires integrated planning that recognizes geological resources as integral to climate adaptation and mitigation.

4.1. Groundwater Security under Climate Stress

Groundwater represents one of the most significant geological assets in relation to climate resilience, especially in drought prone areas or where surface water is unpredictable, as well as in areas where water demand from agriculture, cities and industry is increasing [52]. Groundwater systems are impacted by climate change in a variety of ways, including changes in recharge and more frequent droughts, exposure to more intense storms, changes in evapotranspiration, sea-level rise, and changes in land use. In other parts of the country, there are lower amounts of precipitation and warmer temperatures which decrease recharge and increase reliance on aquifers. In others, heavy rainfall could lead to higher infiltration rates in the short term but also greater runoff, erosion and contaminant transport. These changes make it difficult to manage groundwater, as aquifers are slow to respond, are variable, and have a lag time when responding.

Ground water security is not only a question of ground water quantity but also of ground stability and ground water quality as seen from the geological engineering perspective [53]. Overdraft of groundwater can result in land subsidence, which can affect buildings and infrastructure, as well as aquifer storage capacity and flood susceptibility in lower-lying areas. Groundwater depletion in coastal regions can lead to saltwater intrusion, which can affect the availability of fresh water and the productivity of coastal habitats. Water level reductions in arid and semi-arid areas can lead to soil compaction, ecosystem degradation, and higher pumping expenses. In other urban or coastal environments, however, a rise in groundwater levels may impact on basements, tunnels, foundations, utilities, and even contaminated sites.

Managed aquifer recharge is becoming an important engineering tool for enhancing groundwater resilience [54]. Managed recharge can help reduce seasonal fluctuations and relieve strain on surface reservoirs by intentionally storing stormwater, recycled water and/or desalinated water in appropriate aquifers. But it requires good hydrogeological characterization, clogging control and water-quality management as well as an evaluation of geochemical reactions between recharge water and aquifer materials. Recharge systems that are poorly designed can mobilize contaminants, change the chemistry of the groundwater, or lead to unwanted changes in pressure. Climate-resilient groundwater engineering hence requires a combination of aquifer modeling, monitoring, water-quality assessment, and governance to manage groundwater extraction based on the long-term recharge potential rather than short-term demand.

4.2. Critical Minerals and Climate-Transition Resources

There are key minerals that are integral to energy storage, the power grid, electric vehicles, wind and solar power, and batteries, and they are essential to the transition to low-carbon energy systems [55]. This has led to a greater focus on lithium, cobalt, nickel, copper, graphite, the rare earth elements and other materials of strategic importance. Geological engineering is very important in the location of the deposits, characterisation of ground conditions, safe design of excavations, management of mine water, waste stabilisation and minimisation of environmental impact. But this paradox for the climate transition mineral demand is that, if mined without proper precautions, materials needed for decarbonisation can raise new geological, social and environmental risks.

These risks are exacerbated by climate change because it changes the conditions in which mines operate. Heavy rains can lead to excessive slope failures in open pits, flooding of underground workings, overloading of drainage facilities and failure of tailings facilities. Drought may make process-water less available, increase competition with local communities, and cause increased concentrations of contaminants in mine-impacted water. Heat stress may impact worker safety, equipment performance, and freeze–thaw regimes may impact waste–rock piles and haul roads in cold regions. So, the stability of resources need not only be assessed in terms of the size of the reserve or the availability of the market, but also in terms of their operational stability in the future climate [56].

One of the key concerns is that many of the mineral-rich areas are found in geohazard-prone, socially vulnerable, environment-sensitive, or water-stressed areas. The current extractive paradigm, based on environmental externalities, is becoming increasingly incompatible with climate-resilient development. Geological engineering can help by enabling more selective mining, minimising the volume of waste, stabilising mine slopes, enabling more efficient recycling of water, and promoting less impact mining approaches. Meanwhile, the discipline needs to be more involved in life cycle assessment, circular economy, and land restoration after mining. Technical extraction capacity and minimizing long-term environmental liabilities are therefore critical factors in the stability of climate transition resources [57].

4.3. Geothermal Energy and Subsurface Heat Storage

Importance of geothermal energy and subsurface heat storage as low-carbon, geology dependent energy [58]. While conventional hydrothermal systems use the naturally occurring fluids in the permeable reservoir, enhanced geothermal systems are intended to increase the permeability of the hot rock by stimulation. Shallow geothermal system and underground thermal energy storage can contribute to building heating and cooling, thereby decreasing fossil fuel reliance. The technologies show how the subsurface can not only be used as a resource, but also as a long term energy storage.

One of the primary geological engineering problems is to ensure that the thermal, hydraulic, chemical and mechanical stability is maintained throughout the life of geothermal systems [59]. These assessments of reservoir temperature, permeability, fracture networks, stress state, fluid chemistry, and recharge potential are essential for a successful development. If the characterization is inadequate, then heat recovery may be poor, scaling, corrosion, reservoir cooling, or induced seismicity may result. In particular, enhanced geothermal systems are very sensitive to stimulation-induced alteration of fracture permeability and pore pressure, which can induce seismic events. Many of the earthquakes that are induced are small, but if they are felt, they can have a profound impact on the public's opinion and so risk management is very important.

As climate change may make geothermal systems more relevant in terms of demand for resilient local low-carbon energy. Geothermal engineering, however, should not take the sustainability of the resources in the subsurface for granted. Thermal drawdown, pressure drop, or chemical imbalance can result from overproduction. In urban areas with high population density, more than one shallow geothermal system can thermally interact which can lead to lower efficiencies and conflicts using subsurface space. Groundwater quality impacts and thermal pollution are also a concern in subsurface heat storage. Thus, integrated reservoir simulation, induced-seismicity monitoring in combination with adaptive production control, and regulatory regimes to share the subsurface are all necessary for sustainable development of geothermal resources [60].

4.4. Carbon Capture, Utilization, and Storage

Carbon capture, utilization, and storage is one of the most prominent mitigation pathways involving geological engineering [10]. Geological storage aims to inject carbon dioxide into deep formations such as saline aquifers, depleted oil and gas reservoirs, or unmineable coal seams, where it can be retained through structural, residual, solubility, and mineral trapping mechanisms. The engineering objective is not simply to place carbon dioxide underground, but to ensure containment over timescales far longer than typical infrastructure design lives. This requirement places geological characterization, caprock integrity, fault assessment, pressure management, and monitoring at the center of storage-site evaluation.

A major challenge in carbon storage is uncertainty in subsurface heterogeneity [61]. Reservoir permeability, caprock continuity, fault transmissivity, abandoned wells, and geochemical reactions can strongly influence plume migration and leakage risk. Even when storage formations appear favorable, injection can alter pore pressures and stress states, potentially reactivating faults or creating new pathways if not properly managed. Therefore, site selection must go beyond volumetric storage capacity and include coupled hydro-mechanical and geochemical analysis. Monitoring technologies such as seismic surveys, pressure sensors, geochemical sampling, gravity measurements, and satellite deformation analysis can help verify storage performance, but monitoring design must be tailored to site-specific leakage scenarios.

The climate value of carbon storage depends on public trust, regulatory oversight, and long-term stewardship. Communities may be concerned about leakage, induced seismicity, groundwater contamination, or weak accountability after project closure. Geological engineering can address these concerns through transparent risk assessment, conservative site selection, baseline monitoring, adaptive injection strategies, and clear closure criteria. However, carbon storage should not be framed as a substitute for emissions reduction. Rather, it is a geological engineering contribution to mitigation where emissions are difficult to avoid, provided that storage integrity and environmental protection are demonstrably maintained [62].

4.5. Mining, Tailings, and Waste-Storage Stability

The most climate-sensitive activities in resource engineering are mining and waste storage systems [9]. Tailings dams, waste-rock piles, heap-leach pads, slag deposits, ash ponds, and land repositories are engineered to store massive amounts of material for extended periods of time. These systems are threatened by climate change, which increases the likelihood of extreme rainfall, flooding, erosion, drought cracking, freeze–thaw degradation, wildfire effects, and faster snowmelt. Stability of waste storage is a geotechnical and environmental protection concern due to the potential for failures that could release contaminated solids and water over large areas.

Particular attention needs to be paid to the tailings facilities, as their stability critically depends on the tailings dam geometry, the dam's foundation conditions, the facility's construction method, drainage capacity, pore pressure, susceptibility to liquefaction, and the governance of operations [19]. Rising water levels, narrowing beaches, seepage, and spillway blowouts are all possible impacts of rising water levels driven by climate-driven increases in rainfall intensity. Drought may lead to desiccation cracking, dust formation, and changes in tailings fabric. In the event of a seismic loading, coupled with high saturation and loose tailings structure, catastrophic flow failure may result. These interacting hazards illustrate the need to consider tailings hazards in a multifactorial stability analysis.

The long-term challenges are also the waste-rock piles and mine residues. The influx of oxygen and water can help to speed up the formation of AMD and the leaching of metals. During heavy rain, contaminants may run off into surface water and into groundwater, and fine particles may be eroded and spread. In cold regions, thawing of permafrost could alter hydrological pathways and destabilize the foundations of waste storage. Historic climate closure designs can be less effective when future precipitation, evaporation, vegetation, or freeze–thaw cycles differ from those experienced in the past. Hence, the closure of mines needs to be considered a dynamic engineering problem requiring climate-adapted cover systems, drainage designs, seepage control, and post-closure monitoring [63].

One important input is that resource stability is inextricable from environmental responsibility. Geological engineering that minimizes the likelihood of long-term damage will be socially and politically acceptable for securing access to minerals, energy, and subsurface storage. This means transitioning from a compliance-based to a performance-based, risk-informed approach to design. Monitoring should not end at the end of active operation, and design criteria should account for all possible future climate scenarios, not only the minimum requirements set by regulation. However, in this context, sustainable subsurface engineering is not simply focused on the efficient extraction or storage of subsurface resources, but also on the stability, integrity, and environmental compatibility of geological systems over time scales of decades to centuries [4].

In general, a more comprehensive view of the concept of geological engineering performance for resource stability at the climate nexus is required [2]. The key climate stability issues at stake for groundwater, critical minerals, geothermal systems, carbon storage, tailings, mine waste, and underground repositories are summarised in **Table 3**, along with sustainable engineering responses. A groundwater system should be operated with resilience rather than for short-term production. Critical minerals should be developed without taking on new climate and environmental liabilities. Geothermal and subsurface heat recovery systems must account for reservoir stability in conjunction with energy recovery. Carbon storage needs to be publicly accountable and securely contained. Mining and waste-storage systems need to be safe under nonstationary climatic conditions. These priorities collectively demonstrate that the subsurface is emerging as a critical space for climate action, while also highlighting the need for careful engineering, adaptable governance, and long-term environmental management.

Table 3. Resource-stability challenges and sustainable subsurface-engineering responses.

Resource or Subsurface System	Climate-Related Stability Challenge	Geological Engineering Concern	Sustainable Engineering Response	Long-Term Research Need
Groundwater aquifers	Recharge variability, drought, salinization, land subsidence	Declining water tables, reduced storage, saltwater intrusion, infrastructure settlement	Managed aquifer recharge, extraction regulation, groundwater modeling, salinity barriers	Coupled climate–groundwater models and adaptive allocation strategies
Critical minerals	Extreme rainfall, water scarcity, slope instability, waste generation	Open-pit instability, mine flooding, tailings risk, community water conflict	Selective mining, water recycling, slope monitoring, low-impact extraction	Climate-resilient mine planning and life-cycle assessment of mineral supply
Geothermal reservoirs	Pressure change, induced seismicity, reservoir cooling	Fracture stimulation risk, permeability decline, chemical scaling	Reservoir simulation, seismic monitoring, adaptive injection and production control	Improved forecasting of induced seismicity and long-term thermal recovery
Underground thermal energy storage	Thermal interference, groundwater-quality alteration	Subsurface space conflict, heat plume migration, aquifer disturbance	Thermal zoning, monitoring wells, regulatory control of subsurface heat use	Urban-scale thermal resource governance and cumulative impact assessment

Table 3. *Cont.*

Resource or Subsurface System	Climate-Related Stability Challenge	Geological Engineering Concern	Sustainable Engineering Response	Long-Term Research Need
Carbon storage reservoirs	Leakage risk, pressure buildup, caprock integrity, fault reactivation	Plume migration, wellbore leakage, induced seismicity, long-term containment	Site screening, pressure management, caprock assessment, monitoring networks	Integrated hydro-mechanical-chemical models for storage security
Tailings and mine waste	Extreme rainfall, drought cracking, erosion, thaw settlement	Dam instability, liquefaction, acid mine drainage, contaminant release	Filtered tailings, improved drainage, climate-adjusted covers, long-term monitoring	Performance-based closure criteria under future climate scenarios
Underground repositories	Groundwater fluctuation, thermal and geochemical change	Barrier degradation, contaminant migration, long-term isolation	Multi-barrier systems, geochemical modeling, monitoring and stewardship	Century-scale assessment of engineered and geological barrier performance

5. Environmental Protection and Climate-Resilient Engineering Solutions

With the changing nature of climate change, environmental protection is increasingly a relevant aspect of geological engineering because contaminant pathways, ecosystem stability, infrastructure performance and engineered containment are all impacted and change [64]. Traditionally, geoenvironmental practice has been directed towards identification of the sources of contamination, control of pollutant migration, stabilization of waste materials and the design of remediation systems on the basis of fairly stable assumptions about the hydrogeology. But, climate change is altering conditions that influence contaminant mobility, erosion, groundwater fluctuations, soil chemistry, and protective barrier durability. Hence, protecting the environment is no longer considered as an independent downstream issue, once hazard assessment and resource development are done. It needs to be taken into account for the design, operation, adaptation, and closure of geological engineering systems.

5.1. Geoenvironmental Risk under Climate Change

Climate change can increase geoenvironmental risk by modifying physical and chemical conditions that govern contaminant release and transport [65]. Flooding may cause contaminated soils to be washed out, mine material to be remobilized, landfills to be flooded, and industrial chemicals to be distributed on the floodplain. Drought may cause groundwater levels to decline, leading to increased concentrations of dissolved substances; it may also oxidize sulfide-rich substances and cause the soil to crack, allowing dissolved substances to flow more readily during the next rainfall. Heavy rains can accelerate leaching from waste-rock piles, tailings, landfills, and contaminated soils, and sea-level rise can increase salinity and alter groundwater gradients in coastal aquifers. A thaw in permafrost could also release contaminants previously frozen in the ground, including those associated with mining, military operations, fuel storage, and industrial development.

These processes indicate that the risk of contamination is not permanent. A site that was stable at historical hydrological conditions can become vulnerable if it is subjected to increased frequency or duration of flooding, or an increased groundwater level. This is especially relevant with legacy contaminated sites and waste repositories, which were sited or left behind before the full impacts of climate change were taken into account. Some of these facilities have short monitoring records, poor documentation, or aging containment systems. These vulnerabilities may manifest as changes in climate conditions that create stresses beyond those originally designed for, or through degradation of the covers and liners, increased seepage, or other geochemical changes [3].

One of the key constraints in existing evaluations is that geoenvironmental risk is still assessed independently of geohazard risk. For instance, landslide susceptibility maps can show the potential for landslides, but not if the landslide material is toxic. Flood-risk assessments can estimate inundation depth but not contaminant remobilization. Although both are controlled by hydrology, erosion, and material weathering, mine-closure plans sometimes separate the analysis of slope stability from that of water quality. There is a need for an integrated assessment of contaminant sources, exposure pathways, geotechnical stability, hydrogeological connectivity, and future climate scenarios to develop a climate-resilient approach [66]. This broader view is crucial for avoiding irreversible and/or costly environmental damage.

5.2. Nature-Based and Hybrid Engineering Solutions

NbS and hybrid engineering solutions are becoming more relevant in response to the increasing climate-amplified geological and environmental risks [18]. Nature-based systems differ from hard-engineered solutions, as they rely on restoring or harnessing natural processes to mitigate hazards, stabilize landforms, filter pollutants, and increase ecological resilience. These include wetlands in upland areas to attenuate flooding and remove contaminants; dunes and mangroves for coastal protection; vegetated slopes for erosion control; riparian buffers for riverbank stabilization; and restored floodplains for sediment and water control. Hybrid systems integrate natural features with traditional engineering techniques such as retaining structures, drainage systems, geotextiles, revetments, and/or controlled spillways.

The beauty of NbS is that they are multifunctional. An improved wetland can lower flood peaks, capture sediments, enhance water quality, help biodiversity, and sequester carbon. A vegetated slope can be used to minimize erosion, enhance shallow slope stability by root reinforcement, control soil moisture, and enhance the beauty of a landscape. Coastal marshes and dunes will dissipate wave energy and will gradually change in response to waves and sediment availability. For climate adaptation, where engineering solutions are often needed to tackle multiple risks, these co-benefits are particularly salient [67].

But it is important not to romanticize NbS solutions as one-size-fits-all or as having no maintenance needs. Site characteristics, ecological maturity, sediment availability, hydrological regime, plant health, and disturbance frequency influence them. During extreme events, natural systems can be impacted or temporarily overloaded. However, for deep-seated failures or long periods of saturation, vegetation-based slope stabilization might not be effective enough. Contaminants that exceed the ecological tolerance of wetlands may reduce their ability to treat. However, mangroves and marshes might not be able to "catch up" with sea-level rise rates if sediment inputs are insufficient or landward migration is hindered. Geological engineering is therefore a crucial element in assessing the potential for NbS, in designing them, and in determining when hybrid reinforcement is needed [68].

Performance-based hybrid design is the most promising approach. Instead of picking a natural or a structural solution, engineers can opt for both ecological adaptability and geotechnical reliability. This involves long-term monitoring and clearly defined performance standards such as stability, hydraulic function, contaminant retention, ecological condition, and ecological recovery following disturbance [69]. In this context, NbS will be considered a living engineering system, not a static replacement for traditional systems.

5.3. Soil and Groundwater Remediation Innovations

Remediation technologies also need to be adjusted to adapt to climate change. Traditional remediation designs are based on relatively stable conditions in groundwater gradients, contaminant plumes, redox conditions, and infiltration patterns. The climate change challenge is to those assumptions, changing recharge, groundwater levels, temperature, salinity, and geochemical environments. Systems that are working well under current conditions may not perform as well if contaminant plumes shift, if reactive media are short-circuited during periods of extreme recharge, or if drought and rewetting cycles alter contaminant speciation [19].

Each of the following climate-sensitive tools has limitations: Permeable reactive barriers, Bioremediation, Phytoremediation, Electrokinetic remediation, Soil washing, Stabilization–solidification, and monitored natural attenuation [70]. The effectiveness of a reactive barrier hinges on the groundwater flow path and residence time—high rainfall or changes in the hydraulic gradient can diminish the interaction between contaminants and the reactive barrier. The elements of bioremediation—microbial activity, available nutrients, oxygen, moisture, pH, and temperature—are all regulated by climate variability. Phytoremediation can be a low-impact method for contaminant uptake and soil stabilization if the plants survive drought, heat, flooding, or salinity stress. The long time scale of the predictable natural processes involved in monitored natural attenuation makes this process especially sensitive to climate uncertainty.

Thus, more adaptive and resilient designs are needed to promote innovation in remediation. Incorporating remediation with real-time or periodic monitoring is an important direction, enabling evaluation of system performance under varying conditions. Plume migration, barrier bypass, change in soil moisture, and/or vegetation stress may be detectable using sensor networks, geophysical surveying, groundwater sampling, and/or remote sensing. One approach is to implement treatment trains with several technologies, thereby reducing reliance on any single technology. For instance, a contaminated groundwater plume can be managed by source stabilization, hydrologic control, reactive treatment, and monitored attenuation [71]. These are layered strategies and are more robust under uncertainty.

Sustainability is also a concern in climate-resilient remediation. Energy-intensive systems that pump and treat may minimize contamination but result in long pump-and-treat schedules and high carbon emissions. Passive/low-energy systems, however, may be more sustainable, but they must be carefully designed to be reliable. A balance among contaminant reduction, climate adaptation, life-cycle impacts, and long-term stewardship is the future of remediation. That is, the success of remediation should be judged not only by concentration goals but also by hydrological extremes, GHGs, ecological recovery, and the persistence of risk reduction [19].

5.4. Resilient Infrastructure and Land-Use Planning

Resilience of infrastructure and environmental protection are closely connected, since damaged infrastructure can be a source of and/or a conduit for environmental damage [5]. Climate-induced ground movement, flooding, erosion, subsidence, thaw settlement, and slope instability are increasingly threatening roads, railways, dams, tunnels, pipelines, ports, foundations, drainage, and underground utilities. The breakdown of these systems can lead to the discharge of pollutants, disruptions to water supply, harm to ecosystems, and greater losses during disasters. Thus, geological engineering helps protect the environment by enhancing the built environment's capacity to withstand natural disasters.

Incorporating climate-resilient infrastructure design is more than just making infrastructure more resilient. It requires knowledge of the interactions among infrastructure, landforms, groundwater, soils, and future climate processes. Drainage management, erosion control, retaining systems, vegetation restoration, and monitoring, for example, may be necessary for a road constructed across an unstable slope [68]. A tunnel in a coastal city might need protection against groundwater rise, salinity, corrosion, and flooding. Thermal stabilization, flexible joints, realignment options, and monitoring for long-term deformation may be necessary in permafrost terrain for a pipeline crossing. The examples illustrate that the resilience of infrastructure is not only an engineering issue but also a geological one.

Land-use planning equally plays a crucial role. Many losses are due to settlements, industrial facilities, and infrastructure in landslide- and flood-prone areas, as well as in areas prone to erosion, liquefaction, subsidence, or coastal retreat [72]. With climate change comes the pressing need for risk-sensitive zoning, managed retreat, zoning restrictions, and natural buffer protection. Geological hazard maps should therefore be updated to include future climate scenarios and translated in a way that informs planning decisions. But implementation can be lacking due to economic pressures, land ownership, political opposition, and social equity issues. Poorly-resourced communities might be in more vulnerable places and less able to move elsewhere or adapt.

An important lesson is that resilience is not just about withstanding failure, it is about adapting, recovering, and not displacing risk. Hard defenses may protect one site but cause more erosion downstream. Drainage systems can help decrease flooding in an area, but can also increase the flow of contaminants. Moving may help to limit exposure, but can lead to social problems. Geological engineering should therefore engage with planners, ecologists, policymakers, and communities to consider the trade-offs. Best practices in land-use planning integrate technical hazard assessment, participatory planning, environmental justice, and long-term climate adaptation [73].

5.5. Policy, Standards, and Sustainability Assessment

Supportive policy, up-to-date standards, and sustainability-based assessment frameworks are necessary to ensure the gradual shift towards climate-resilient geological engineering [66]. Existing design codes and environmental regulations are based on historical climate assumptions and may be inadequate to deal with nonstationary hazards, compound events, or long-term environmental change. This leaves practitioners, regulators, and project owners with uncertainty. In the absence of direction, adaptation might take unpredictable forms: some projects might begin using more sophisticated scenario analysis, while others may still rely on past design baselines.

New standards should promote the use of climate projections, risk-based design, adaptive management, and long-term monitoring. But standards have to be flexible, too, since climate science and engineering techniques are still developing. A more flexible approach might be appropriate, whereby practitioners demonstrate how they have accounted for future climate conditions, uncertainty, and residual risk. Regulatory requirements should incorporate periodic reassessment, in light of the availability of new data, for critical infrastructure, tailings facilities, carbon storage sites, contaminated lands, and coastal developments. This would change the practice of geological engineering from one-time approval to life-cycle stewardship [38].

The need for sustainability assessment is also growing. Life cycle assessment can inform decision-making by considering the environmental impacts of the various engineering options available, such as embodied carbon, energy, materials, land disturbance, and solution maintenance [74]. Environmental impact assessment can be broadened to incorporate climate vulnerability and adaptation performance. The Resilience indicators will assess whether a system can function under stress, recover from stress, and avoid unacceptable environmental impacts. In the resource and infrastructure sectors, environmental, social, and governance principles are becoming more widely applied and should be backed by tangible technical measures, not general statements.

One of the policy challenges is reconciling short-term project economics with long-term environmental protection. The costs of climate-resilient design, monitoring, and adaptive management can be higher than those of traditional design, construction, and management, and benefits can take decades to materialize, particularly in terms of failure avoidance, remediation cost reduction, and improved public safety. Thus, long-term risk reduction should be recognized as a value by regulatory systems and financial mechanisms. Carbon-storage liability laws, public procurement rules, insurance, infrastructure funding, and mine-closure bonds can all shape whether climate-resilient geological engineering becomes the norm [75]. **Figure 2** frames environmental protection as an adaptive engineering cycle in which risk identification, climate-scenario assessment, design, monitoring, performance evaluation, and redesign are continuously linked.

In general, we need to move from reactive remediation to more preventative, adaptive, and integrated approaches to risk management in the context of environmental protection at the climate nexus [19]. A changing climate is changing contamination behaviors, undermining assumptions in legacy designs, and growing the impacts of infrastructure failure. **Table 4** summarizes the major environmental challenges, climate-sensitive processes, potential consequences, engineering solutions, and management requirements. Meanwhile, emerging solutions include NbE, adaptive remediation, resilient infrastructure design, and sustainability-focused governance. A pivotal role in decision-making can be played by coupling ground behavior, environmental processes, and human decision-making through the tools of geological engineering. Its future contribution will not only lie in technical innovation but also in its capacity to be integrated into all aspects of planning, design, operation, closure, and long-term stewardship.

Table 4. Environmental protection strategies for climate-resilient geological engineering.

Environmental Challenge	Climate-Sensitive Process	Potential Consequence	Engineering Solution	Policy or Management Requirement
Contaminated floodplains	Flooding, erosion, sediment remobilization	Redistribution of polluted soils and sediments	Flood-compatible containment, sediment control, risk-based land management	Integration of contamination maps with flood-risk zoning
Landfills and waste repositories	Rising groundwater, extreme rainfall, and liner degradation	Leachate escape and groundwater contamination	Improved covers, drainage systems, leachate collection, and monitoring wells	Climate-adjusted design standards and periodic reassessment
Mine-impacted waters	Drought, intense rainfall, oxidation–reduction changes	Acid mine drainage and metal mobilization	Source control, reactive barriers, water treatment, cover systems	Long-term closure bonding and post-closure monitoring

Table 4. *Cont.*

Environmental Challenge	Climate-Sensitive Process	Potential Consequence	Engineering Solution	Policy or Management Requirement
Coastal aquifers	Sea-level rise and over-pumping	Saltwater intrusion and loss of freshwater supply	Managed recharge, pumping control, subsurface barriers	Coastal groundwater governance and demand management
Permafrost-contaminated sites	Thaw settlement and active-layer deepening	Release of stored pollutants and fuel residues	Site stabilization, excavation, thermal control, containment	Inventory and monitoring of vulnerable cold-region legacy sites
Urban infrastructure corridors	Subsidence, flooding, soil shrinkage and swelling, groundwater rise	Damage to roads, tunnels, pipelines, and utilities	Climate-informed foundation design, drainage, flexible joints, and monitoring	Risk-sensitive urban planning and infrastructure prioritization
Slopes and degraded catchments	Vegetation loss, wildfire, and rainfall extremes	Erosion, debris flow, sediment pulses	Bioengineering, reforestation, check dams, and hybrid stabilization	Catchment-scale restoration and maintenance planning
Coastal protection zones	Wave attack, storm surge, sediment deficit	Shoreline retreat and habitat loss	Dune restoration, wetlands, living shorelines, and hybrid revetments	Managed retreat, sediment management, ecosystem-based adaptation

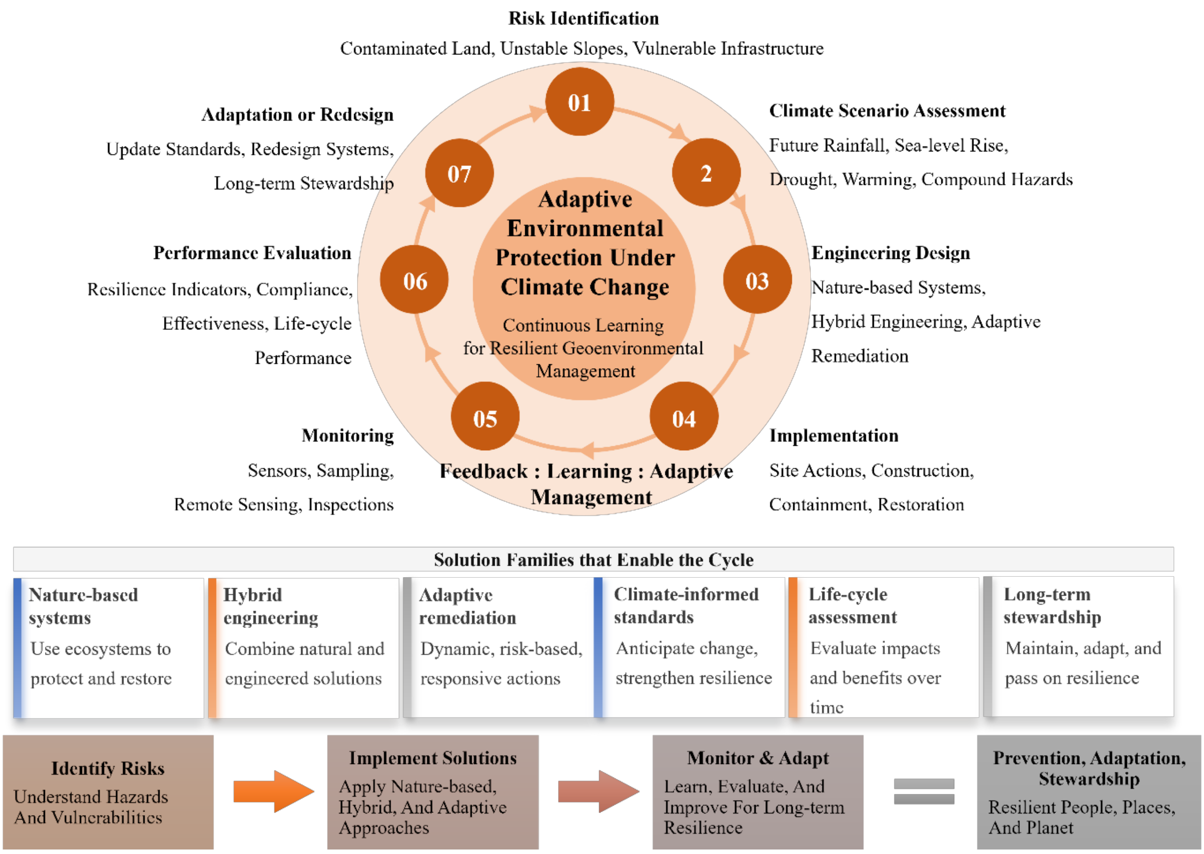

Figure 2. Climate-resilient environmental protection and adaptive engineering cycle.

6. Conclusion

Geological engineering is steadily gaining importance for climate adaptation, resource security, and environmental protection. Ground conditions supporting infrastructure and ecosystems are not stationary. Still, they are changing with climate change, which affects them through shifts in rainfall patterns, sea level, groundwater conditions, temperature patterns, erosion processes, and cryospheric stability. This review has demonstrated that geologic hazards are dynamic, interrelated processes that respond to a changing climate and cannot be viewed as isolated events. Landslides, debris flows, coastal erosion, river instability, permafrost degradation, subsidence, tailings failures, and contaminant remobilization can occur and interact through shared hydrological, thermal, geomorphological, and geomechanical pathways. Therefore, geological engineering should go beyond retrospective hazard assessment and towards a forward-looking, multi-hazard, systems-based approach to risk analysis.

One of the key findings is that innovation in monitoring, modeling, and predictive analytics is reshaping this field. New observations and modeling methods are increasing the ability to observe and predict geological changes, including remote sensing, InSAR, UAV photogrammetry, LiDAR, geophysical imaging, sensor networks, machine learning, physics-informed modeling, and digital twins. But technological sophistication is not enough. These tools will need to be grounded in process understanding, uncertainty quantification, field validation, and actionable decision support. Beyond accuracy, there is a need for climate-resilient geological engineering models that are interpretable, adaptive, and useful to infrastructure managers, regulators, planners, and communities.

The review also focuses on the increasing need for resource stability and sustainable subsurface engineering. Climate variability and long-term environmental change have the potential to significantly affect groundwater security, critical mineral development, geothermal energy, and carbon storage, as well as the containment of mine waste. These are important resources for adaptation and mitigation. Still, if not developed in a geomechanically stable manner that protects water, limits induced seismicity and containment-integrity breaches, and includes post-closure stewardship, they can create new risks. Thus, the broader performance sphere, including extraction, storage, environmental responsibility, and long-term sustainability and resilience, needs to be integrated in sustainable resource engineering.

Another turning point is in environmental protection. Climate change can mobilize contamination, compromise containment, alter groundwater flow, and unmask legacy contamination. NbS, hybrid engineering solutions, adaptive remediation, resilient infrastructure design, and climate-sensitive land-use planning provide important avenues for reducing risk. However, they are effective only under certain geologic conditions at a site, and require long-term monitoring and realistic performance assessment. Nonstationary climate, compound hazards, life-cycle assessment, and adaptive management should be included in future standards and policies.

There are a number of knowledge gaps. In many high-risk areas, particularly where vulnerability and exposure are highest, long-term datasets remain limited. The site-specific geotechnical design parameters are not yet well known for climate projections. The interplay among the various geological hazards, infrastructure systems, ecological processes, and social vulnerability remains insufficiently integrated. High-priority research areas include the development of coupled climate-hydro-geo-mechanical models, scalable early-warning systems, climate-informed design codes, digital platforms that transparently treat uncertainty, and equitable access to monitoring technologies.

Overall, geological engineering at the climate nexus needs to shift from a reactive approach focused on stabilization and hazard control to a proactive approach to resilience design. In the future, it will be shaped by its ability to predict change, manage uncertainty, preserve environmental systems, and facilitate the sustainable exploitation of the subsurface. Geological engineering can be a core discipline for safe infrastructure, the climate transition resources, and community protection in a warming world by combining hazard risk assessment, resource stability, and environmental protection.

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