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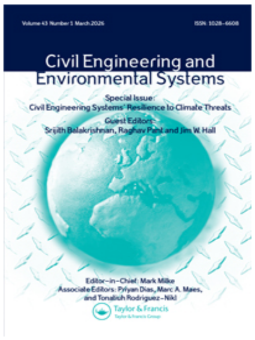

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EDITORIAL

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Advancing a systems approach to climate resilience in civil engineering

1. Climate resilience and the limits of asset-centric resilience thinking

Climate change is no longer a distant or abstract concern for civil engineering systems. Across transportation, water, energy, and urban infrastructure, climate-related hazards, ranging from extreme heat and flooding to sea-level rise and compound events, are already disrupting services, accelerating deterioration, and exposing systemic fragilities. The defining challenge for civil engineering in the coming decades is therefore not only to design assets that are more resistant to extreme loads, but to adapt entire infrastructure systems that continue to provide essential services under deep uncertainty, evolving risks, and societal change.

While the research community has made substantial progress in understanding climate hazards and their impacts on individual assets and networks, adaptation practice remains largely dominated by asset-level or single-system interventions. Bridges are strengthened, drainage capacity is increased, substations are elevated, and protective standards are revised, often in isolation or without sufficiently accounting for future climate change driven hazards. Such measures are necessary but are becoming increasingly insufficient as existing asset protection measures are coming undone in the face of increasing climate extreme. Moreover, climate impacts do not respect asset boundaries, sectoral mandates, or administrative jurisdictions. The failure of one component can propagate rapidly across interconnected systems, triggering cascading disruptions whose social and economic consequences far exceed the initial physical damage. For example, during the February 2021 Texas power crisis, millions of residents experienced prolonged power outages and widespread water-system disruptions, and official health data attribute around 246 deaths to conditions created by the event, demonstrating how localised infrastructure failures can escalate into system-wide societal disruption when critical interdependencies are stressed (Leslie 2021).

A growing body of research has therefore converged on the conclusion that resilience to climate threats is not a static attribute of individual assets, but an emergent property of interconnected systems (Thacker, Pant, and Hall 2017). This perspective challenges traditional engineering approaches that treat infrastructure components as largely independent objects of design and management. Instead, it calls for a system-of-systems (SoS) approach, in which infrastructures are understood as interdependent networks embedded within social, institutional, and environmental contexts.

2. Why a systems-of-systems perspective matters for climate resilience?

From a systems perspective, climate resilience is not merely about reducing the probability of failure, but about preserving functionality, connectivity, and recovery capacity under a wide range of plausible futures. Physical, societal, and organisational layers of infrastructure systems are deeply interwoven: transport depends on energy and communications; water systems rely on power and institutional coordination; emergency response depends on mobility, information, and organisational preparedness. Ongoing technological transitions, such as decarbonisation through clean energy, digitalisation, and the growing integration of artificial intelligence in operations, are further reshaping infrastructure interdependencies over time, often in ways that are not yet fully understood. Climate hazards frequently exploit weaknesses in these interdependencies, amplifying impacts through feedback loops and cascading failures (Lawrence, Blackett, and Cradock-Henry 2020).

A SoS framing offers several critical advantages for adaptation planning. First, it allows decision-makers to identify critical assets and interfaces whose failure disproportionately affects overall system performance (Balakrishnan and Zhang 2020). Second, it highlights the role of redundancy, resourcefulness, and adaptive capacity across systems, rather than focusing narrowly on hardening individual components. Third, it makes explicit the importance of institutional decision-making, governance structures, and socio-technical interactions, which shape how systems respond before, during, and after climate extremes.

Importantly, SoS approaches also align with the need to manage deep uncertainty. Climate projections, socio-economic pathways, and technological change introduce uncertainties that cannot be resolved through probabilistic refinement alone. Systems-oriented methods, such as exploratory modelling, stress testing, and scenario discovery, support robust decision-making by examining how infrastructure systems behave across a wide range of conditions, rather than optimising for a single expected future.

Despite strong theoretical and methodological maturity and consensus, the translation of these insights into practice has been slow and uneven. The persistence of asset-centric adaptation reflects not a lack of analytical capability but a deeper misalignment between the systemic nature of climate-related risks and the fragmented structures through which infrastructure systems are governed, financed, and managed, as well as a failure of infrastructure decision processes to engage with risk, uncertainty, and interdependencies at the system level.

3. Fragmented management and the persistence of siloed climate adaptation

One of the central barriers to system-level climate adaptation lies not in analytical capability, but in governance and institutional fragmentation (Lah 2025). Infrastructure systems are typically planned, financed, regulated, and operated by separate governmental agencies and private sectors with distinct mandates, organisational goals and values, performance metrics, and time horizons. While risks are shared across society, responsibility for adaptation is often narrowly defined and sector-specific.

This fragmentation encourages incremental, localised interventions that may improve the resilience of individual assets while leaving system-wide vulnerabilities unresolved, or even exacerbated. Protecting one infrastructure system or component without considering its dependencies can shift risks elsewhere, create new bottlenecks, or lock-in maladaptive pathways. For instance, in suburban and peripheral municipalities of Santiago de Compostela, Spain, the absence of formal climate adaptation plans means that routine infrastructure extensions and upgrades proceed as *de facto* adaptation measures, shaped by localised development pressures and sectoral logic rather than coordinated, system-level assessments of climate risks (Cerrada Morato 2024). Similar patterns are observed in other contexts, where unclear leadership and fragmented responsibility for climate adaptation result in incremental, asset-level responses and governance vacuums, in which no actor is positioned to address cross-sector dependencies or system-wide risk, ultimately constraining effective adaptation (Becker and Kretsch 2019; Fried, Hamilton, and Berardo 2022). In this sense, siloed adaptation is not merely inefficient; it can be counterproductive and prove to be costly with significant socio-economic and political consequences when disruptions occur.

Moreover, prevailing appraisal and investment frameworks tend to undervalue cross-sectoral benefits, long-term resilience dividends, and avoided cascading losses. Integrated adaptation options that require coordination across agencies or sectors struggle to compete with projects that deliver immediate, asset-specific returns. This misalignment between the systemic nature of climate risk and the structures through which the decisions are made remains one of the most persistent challenges for enabling climate-resilient infrastructure systems.

Breaking these siloes requires more than improved models and more granular data. It demands a shift in how civil engineering systems are conceptualised, governed, and appraised, such that systems thinking moves from the margins of research into the core of engineering practice and policy.

4. Toward integrated socio-technical climate resilience efforts

Climate adaptation for civil engineering systems is fundamentally a socio-technical challenge in which technical measures, such as design modifications, protective grey infrastructure, and digital monitoring, interact with social and institutional dimensions, including governance arrangements, equity in access to services, public trust, and organisational learning. While engineering interventions are necessary, their effectiveness depends on their integration within regulatory frameworks and decision-making processes, as well as their alignment with user behaviours that shape risk perception, prioritisation, and recovery. Resilience emerges through learning, coordination, anticipation, and adaptation across these dimensions.

In practice, however, these socio-technical dimensions of resilience are rarely addressed in an integrated manner. Social consequences, such as loss of access to essential services, business disruptions, social burden, inequitable recovery, or erosion of public trust, often fall outside formal accountability assessments. This institutional context, in which social consequences are routinely treated as externalities rather than core performance criteria, helps explain why advances in systems-of-systems resilience research have struggled to translate into routine engineering practice, despite growing analytical maturity.

Despite these challenges, several ongoing system-of-systems approaches in practice are advancing integrated climate adaptation for civil engineering infrastructure, at least at regional and national levels. New Zealand's Lifelines programme (New Zealand Lifelines Council 2020), for instance, fosters cross-sector collaboration among utilities and agencies to analyse interdependencies and prioritise resilience investments against hazards including climate impacts, as demonstrated in post-earthquake Christchurch retrofits. In the Netherlands, the Delta Programme exemplifies a holistic, multi-stakeholder framework combining grey and green infrastructure, such as dike upgrades and nature-based solutions like salt marshes, to enhance flood resilience and adapt to accelerating sea-level rise across interconnected water, transport, and urban systems, guided by adaptive delta management principles and the ongoing Sea Level Rise Knowledge Programme (Delta Commissioner & Ministry of Infrastructure and Water Management 2023). In the United States, New York City's Climate Change Adaptation Task Force, embedded within PlaNYC, OneNYC, and related resilience initiatives, brings together numerous city agencies and infrastructure stakeholders to examine interdependencies and cascading risks across energy, transportation, and water systems (Zimmerman et al. 2019). These initiatives highlight emerging efforts to bridge socio-technical gaps through coordinated, learning-oriented governance.

5. Integration

An integrated engineering approach to climate adaptation therefore calls for a shift from asset- and sector-centric climate adaptation decision-making to an integrated socio-technical approach grounded in system-of-systems principles, with the following core directions:

- **Cross-sectoral and cross-scale analysis**, capturing interactions between assets, civil engineering systems, businesses, and communities;
- **Decision-support tools** that prioritise interventions based on system-wide performance and societal outcomes, rather than asset condition or sector-specific priorities alone;
- **Multi-level, multi-stakeholder governance mechanisms** that enable coordination, shared accountability, and adaptive planning under deep uncertainty;
- **Long-term and adaptive perspectives**, treating resilience as an iterative process that evolves alongside climate conditions, technologies, governance structures and societal expectations.
- **Integrating resilience into routine civil engineering life-cycle decisions**, including planning, design, operation, and management, such that resilience also emerges as a co-benefit and is made visible through metrics and appraisal frameworks that capture system-wide performance and avoided cascading losses.

6. Contributions of this special issue

This special issue is motivated by the recognition that advancing climate resilience requires precisely such systems-oriented approaches. The contributions collected here demonstrate how network science, socio-technical modelling, uncertainty analysis, and decision-support frameworks can reveal vulnerabilities and opportunities that remain invisible under conventional asset-level analyses.

Across diverse infrastructure contexts, the papers share a common theme: climate resilience is not an attribute of individual components, but an emergent property of interacting technical, organisational, and economic systems. Each contribution addresses a different phase of the resilience cycle: degradation, recovery, and adaptation, while collectively reinforcing the need to move beyond siloed analysis and decision-making.

The study by Gao et al. (2025), '*Understanding the vulnerability of multimodal public transportation networks*', focuses on the vulnerability of urban public transportation systems under climate-related disruptions, explicitly challenging the dominant tendency to analyse transport modes independently. By representing subway and tram systems as a multi-layer, geospatially embedded network, the authors show how intermodal transfer links fundamentally alter system behaviour under stress. Their use of percolation analysis moves vulnerability assessment away from single-event or worst-case thinking toward a more systemic understanding of how connectivity degrades as disruptions escalate. A key insight from their study is that neglecting intermodal interdependencies leads to a systematic overestimation of vulnerability, while overlooking the role of redundancy and substitution in sustaining mobility. This contribution demonstrates how network-based approaches combined with real world data can support more informed prioritisation of resilience interventions in complex urban systems.

While vulnerability assessment is a necessary starting point, resilience ultimately depends on how systems recover following disruption. Addressing this dimension, Pan and Boyles (2025), in their paper titled '*Optimising repair sequences for interdependent infrastructure resilience: A simulation model of power and transportation networks*,' examine post-disaster recovery in interdependent road and power networks, highlighting how restoration outcomes are shaped by two-way interactions between infrastructure systems. Their simulation-based optimisation framework reveals that repair strategies developed in isolation, reflecting current institutional practice, are inherently suboptimal when interdependencies are ignored. By contrast, interdependency-aware repair sequencing substantially accelerates recovery and improves overall system performance. Importantly, the study makes explicit that these gains are not purely technical: they depend on coordination across infrastructure operators whose objectives, responsibilities, and operational constraints are typically fragmented. In this sense, the paper reinforces a central theme of this Special Issue: resilience failures are often governance failures as much as engineering ones.

Extending the systems boundary further, the contribution by Johnson, Wehbe, and Baroud (2025) '*How flood-resilient port infrastructure can reduce economic impacts of climate change: a case study of the US inland waterways*' analyses infrastructure resilience from the standpoint of broader economic and supply-chain systems under future climate scenarios. Focusing on flood disruptions along the US inland waterways, the authors integrate climate projections, agent-based logistics modelling, and economic input–output analysis to quantify cascading economic impacts across regions and sectors. Crucially, the paper moves beyond impact assessment to evaluate the adaptive value of a flood-resilient port investment. The results demonstrate that strategically located, system-level interventions can deliver substantial resilience dividends by enabling rerouting and flexibility across the network, even under deep climate uncertainty. This work illustrates how adaptation decisions assessed solely at the asset level may fail to capture their true system-wide and societal value, a recurring limitation in current appraisal practices.

The papers in this special issue illustrate how systems thinking can be translated into practical methods for analysing and enhancing climate resilience in civil engineering systems. Collectively, they show that vulnerability, recovery, and adaptation cannot be meaningfully addressed without accounting for interdependencies across infrastructure modes, sectors, institutions, and wider socio-economic systems. In doing so, they highlight a key aspect in climate adaptation: while the consequences of infrastructure failure are shared across society, adaptation efforts continue to be shaped by fragmented, asset-centric approaches that are increasingly misaligned with the systemic nature of climate risk. Addressing climate threats effectively therefore requires breaking soloes, not only analytically, but also in planning, governance, and investment processes, and embedding integrated systems thinking more firmly within civil engineering practice.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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