
Modelling approaches for natural hazard impacts on critical infrastructure networks and dependencies

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ABSTRACT

Critical infrastructure utilities operate as interconnected networks, so exposure and damage estimates are necessary but not always sufficient for holistic decision-making. Network modelling that represents connectivity, redundancy, flow, and operational constraints is needed to translate hazard impacts into service-level outcomes (outage extent, capacity loss, assessable demand, and restoration) within and across dependent lifelines. This paper reviews local modelling approaches across the hazard-impact chain: (i) exposure and asset-functionality screening; (ii) single-network models at increasing sophistication (e.g., road performance metrics and power-system approximations); and (iii) coupled interdependent and system-of-systems models that quantify cascading disruption through physical/functional, geographic, logical/organisational, and (less often) cyber dependencies. It draws on recent collaborations with infrastructure owners/operators and examples spanning local, regional, and national applications, including end-to-end linkage structures for integrated assessment and sector-level abstractions where full operational coupling is impractical. The paper concludes by reflecting on our current research state and setting near-term research goals. New Zealand's modelling efforts are increasingly delivering service-level, interdependent-network insights grounded with strong empirical disaster data, supported by coordinated resilience research. Remaining challenges include limited validation against observed outages and recovery, simplified and non-portable dependency assumptions, and the underrepresentation of the temporal nature of networks, affecting our understanding of restoration logistics and access constraints in recovery.

1 INTRODUCTION

Critical infrastructure comprises the assets and systems that provide essential services, such as electricity, water supply, wastewater, transport, and telecommunications, whose loss can generate widespread societal and economic disruption. Because infrastructure services are delivered through connected networks rather than by isolated components, network modelling (incorporating connectivity, redundancy, and flow as well as operational constraints) is required to translate hazard exposure/damage into service disruptions. In this framing, while asset exposure and damage are necessary inputs, we argue that decision-relevant outputs are primarily at the network level, defined by metrics of connectivity, capacity, accessible demand, and service restoration.

Evidence from recent New Zealand natural hazard events and scenario-based research have reinforced this by quantifying the effect of infrastructure dependencies through their explicit modelling. Accordingly, this paper reviews such selected network modelling approaches (explained in Section 2) that have been used to represent natural hazard impacts related to exposure (Section 3), single networks at multiple levels of complexity (Section 4), and multiple networks using interconnected models to represent dependency effects and cascading disruption (Section 5).

2 FROM HAZARD EXPOSURE TO WIDER SOCIETAL CONSEQUENCES

Firstly, we situate modelling approaches reviewed herein in terms of the objectives they are designed to support across the progression from Hazard Exposure through Asset Functionality, Network State, Service Outcomes, and Wider Societal Consequences (Figure 1).

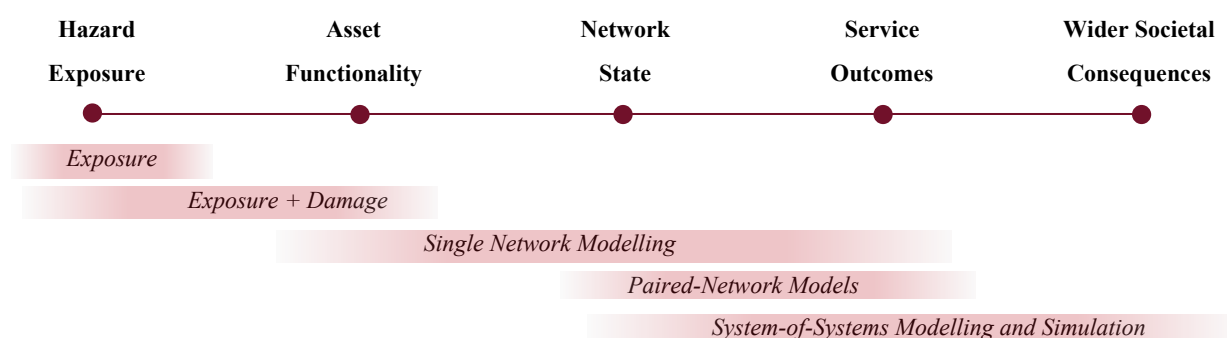


Figure 1: Modelling tiers along the hazard-impact chain. The horizontal axis represents the range of objectives, and vertical bands indicate typical modelling or simulation approaches suitable for each purpose.

Exposure models support initial screening by identifying where assets intersect hazard footprints. Exposure and damage models estimate the likelihood and severity of asset failure. Single-network models assess how component outages affect connectivity and performance within a single infrastructure sector. Coupled or paired network models capture limited cross-sector dependencies to quantify direct and indirect service impacts, often in much smaller geographies where detailed data are available for physics-based modelling. System-of-systems models extend this to regional or national scales, where multi-network interactions include feedback loops, the potential for widespread cascades, and a wide range of quantitative metrics that require careful comparison for strategic resilience planning, often with competing objectives.

Each are discussed in further detail below.

3 HAZARD EXPOSURE & ASSET FUNCTIONALITY

New Zealand has well-developed national-scale exposure modelling capabilities, due to the widely accessible nature of tools such as GIS, *RiskScape*, *Resilience Explorer*, and *Python/R* libraries for routine tasks such as intersecting assets with hazard footprints, assigning damage or functionality states through vulnerability or fragility functions, and potentially damage/repair costs (Lin et al., 2019; Paulik et al., 2020; Paulik et al., 2026). These models provide essential baselines and summary statistics across assets, supporting broad-scale screening when detailed datasets/models are infeasible, and pinpointing where infrastructure owners/operators may want to further investigate to improve asset robustness (Paulik et al., 2025).

However, exposure and damage alone do not quantify service loss because service depends on network structure, redundancy, and dependency pathways. They are essential inputs to network modelling by identifying where high-resolution service-disruption analysis is likely to be most decision-relevant.

4 SINGLE NETWORK APPROACHES

In the context of this paper, transportation and electricity networks are among the most studied in New Zealand's infrastructure modelling literature, reflecting their central societal role, comparatively strong data availability, and the ability to implement models across multiple levels of sophistication, from topological connectivity to traffic assignment and power-flow approximations.

Transport studies have particularly focused on road networks, given the country's geographically distributed population and the potential for localised failures to produce broad, easily quantifiable impacts. Scenario-based modelling for a range of hazards have quantified disruption through changes in travel times and trip feasibility under staged recovery, demonstrating how network performance metrics provide more decision-relevant information than damaged-asset counts alone (Aghababaei et al., 2020). More recently, Allen et al. (2026) extended this line of research by incorporating hazard probability into consequence modelling via an indirect transport cost prioritisation index for earthquake-induced landslides, quantifying detour-related travel time, cancelled trips, vehicle operating costs, emissions, and maintenance impacts. Related work is also strengthening the linkage between infrastructure disruption, community isolation (Anderson et al., 2022; Anderson et al., 2025), and freight.

Electricity resilience modelling in New Zealand spans methods that incorporate both component vulnerability and network functionality, with infrastructure owners and operators conducting studies internally. From a research perspective, Liu et al. (2021) present a single-network seismic risk framework for distribution systems that integrates network topology with substations' functional vulnerability and uses power flow analysis and Monte Carlo simulation to estimate unserved load and identify critical components for retrofit prioritisation. Extending beyond earthquakes, Mace et al. (2024) evaluate the resilience of the Taranaki electricity distribution system to volcanic hazards, treating the distribution network as a standalone critical infrastructure while incorporating key interfaces with the wider power system to explore resilience enhancement options under volcanic scenarios. At larger scales, Zorn et al. (2025) use a hybrid representation that models electricity transmission using a DC power flow approximation and represents downstream distribution networks topologically to enable computationally tractable simulation of large scenario sets and cross-sector dependency assessments, as explained in the following section.

5 COUPLED NETWORKS AND SYSTEMS-OF-SYSTEMS APPROACHES

5.1 Dependencies

A key differentiator in coupled-network and system-of-systems modelling is the representation of dependencies (or interdependencies as they are commonly referred to), defined here as relationships in which the operation or recovery of one asset, service, or network is contingent on another, enabling disruption to propagate beyond the initiating hazard footprint and create indirect service loss. In New Zealand applications, dependencies are commonly treated as physical/functional (service-to-service requirements, such as electricity supply enabling pumping or treatment), geographic (co-location within shared corridors and sites), logical/organisational (policy, institutional, or procedural coupling that shapes restoration sequencing and priorities), and, to a lesser extent, cyber (information and communications technologies and control systems that enable monitoring, dispatch, and remote operations) (Rinaldi et al, 2001).

5.2 National and Regional Scales

National- and regional-scale interdependent infrastructure modelling is used to quantify the magnitude and geographic reach of disruption across sectors, consistently showing that indirect disruption can substantially increase service loss compared with single-network analyses (Zorn et al., 2020; Zorn et al., 2025). These studies typically represent physical/functional dependencies directly, such as electricity enabling water pumping, by simulating disruptions within each network and then propagating impacts into dependent networks to separate direct from indirect service losses, including population-level outcomes where relevant.

Because full operational coupling across all lifelines is rarely feasible at a national scale due to the significant data requirements, studies often adopt abstractions that scale dependency representation. One method uses structured expert judgement to estimate system-level coupling when detailed physics-based models are impractical (Zorn et al., 2021). Another is the sector-level interdependencies approach of Buxton et al. (2016), which characterises interdependency typologies across sectors (including physical/functional, geographic, and organisational linkages) to support scenario analysis where fine-grained, network-to-network flow simulation is not tractable. This complements more detailed coupled models by providing a simplified, transparent way to represent systemwide relationships.

Interdependent network approaches have further expanded into multiphase and multi-hazard settings. In Taranaki, Weir et al. (2024) show how evolving volcanic hazard phases and intervention sequencing shape indirect systemic impacts across networks, demonstrating the relevance of time-varying functional and organisational dependencies when disruptions unfold over extended periods. Zorn et al. (2025) provide a national multi-network example for coastal flooding and sea level rise, modelling electricity, water supply, wastewater, and fuel supply across recurrence intervals. Their results show direct exposure dominating near-term impacts. At the same time, sectors such as fuel supply increasingly depend on the road network and electricity supply, shifting adaptation priorities away from single-network perspectives.

At national and regional scales, interdependencies are necessarily represented through simplified physical, geographic, organisational, and cyber linkages, enabling tractable estimation of indirect disruption. However, many mechanisms that shape real service loss, especially access constraints and on-the-ground dependency pathways, operate at finer resolutions than large-scale models can capture. Local case studies, therefore, provide the essential complement, revealing how these dependencies manifest spatially and how cascading impacts extend beyond the initial hazard footprint at scales local decision makers can act upon.

5.3 Local Scale Modelling

Local case studies illustrate most clearly how explicit dependency modelling alters both the extent and distribution of service loss, including impacts well beyond the initial hazard footprint. In Christchurch,

Brunner et al. (2024) show that cascading effects increase estimated disruption outside directly damaged areas and reshape outage geographies, driven primarily by physical/functional and geographic dependency pathways. In South Dunedin, Lan et al. (2023) identify a sea-level rise tipping point at which disruption to road access and electricity triggers indirect telecommunications losses and constrains wastewater performance, illustrating how multiservice failure emerges nonlinearly once key dependent assets are compromised. Syed et al. (2021) provide a complementary *end-to-end* linkage structure for integrated impact assessment, clarifying how local analyses can connect hazard, asset impacts, network state, and service outcomes across multiple infrastructures in a consistent dependency-aware chain.

Local studies also emphasise that dependency is not only a matter of physical flows. Hughes et al. (2020) operationalise multiple dependency classes: geographic dependencies through corridor-based colocation scoring to identify critical hotspots; logical/organisational dependencies through restoration sequencing and access constraints; and conceptual recognition of cyber dependencies (communications and control). In practice, this often manifests as a decisive coupling between transport access and the restoration of other lifelines, reinforcing findings from Davies et al. (2021) that access-mediated organisational dependencies frequently determine restoration viability. based colocation scoring to identify critical hotspots; logical/organisational dependencies through restoration sequencing and access constraints; and conceptual recognition of cyber dependencies (communications and control).

Although cyber dependencies are widely acknowledged, they remain comparatively under modelled in New Zealand's natural hazard simulations relative to physical, geographic, and access-mediated mechanisms.

6 SYNTHESIS AND PRIORITIES GOING FORWARD

Recent research shows momentum shifting from asset exposure toward wider, system-relevant decision-making outputs through service disruption and cascading impact simulation. Through comparatively generous data sharing and interest by infrastructure owners/operators, we have a broad local evidence base demonstrating that indirect (cascading) impacts can substantially exceed direct impacts when end-user service loss is measured across multiple networks (Brunner et al., 2024; Lan et al., 2023; Weir et al.; Zorn et al., 2020, 2025). Such outputs should translate directly into lifeline planning and resilience investment decisions, so ongoing work needs to tie closely with the respective decision-makers.

Similarly, we have strong empirical grounding from disaster experience that can and should anchor modelling assumptions, especially around restoration and operational behaviour. The Christchurch earthquake sequence remains a rich reference globally for how distributed lifelines respond and recover, including the operational factors that support rapid reinstatement (Giovinazzi et al., 2011) and business disruption and recovery (Brown et al., 2019). There is a wealth of information similarly collectable following severe weather events that should be utilised further. This grounding in empirical data is a comparative advantage: it supports models that are not only plausible but defensible when used for real planning.

Despite progress, three limitations are evident across local practice and provide development opportunities:

1. Validation against observed service outages and restoration is still uneven. Many studies produce plausible outage maps, but fewer systematically benchmark outage extent and restoration trajectories against observed events such as earthquakes and high-impact weather. The empirical record exists, and methods also exist to infer and test dependency structure from restoration data (Zorn & Shamseldin, 2016). However, these are not yet used routinely as calibration and validation baselines.
2. Dependency mechanisms are often simplified and not easily portable, as rule-based assumptions (e.g. *pump fails when power fails*) depend heavily on local backup, reconfiguration, and operational practices that vary widely across regions. A practical way forward is to scale dependency modelling using tractable, uncertainty-aware methods, such as pairwise dependency metrics informed by expert

judgement (Zorn et al., 2021), sector-level interdependency models (Buxton et al., 2016), and probabilistic methods, providing defensible, transparent representations without requiring fully integrated co-simulation of all lifelines. Likewise, a more detailed appreciation of local or asset-scale interdependencies will enable a better understanding of smaller, more frequent cascades between networks.

3. Restoration constraints and logistics are underrepresented relative to their real-world importance. Christchurch experience shows restoration is shaped by access, workforce, and response operations (Giovinazzi et al., 2011). However, many models still approximate restoration as exogenous time steps rather than an outcome constrained by access and resources, precisely where cross-network coupling (e.g., transport enabling restoration) becomes critical (Hughes et al., 2020; Brabhaharan, 2021; Brunner et al., 2026).

Finally, in conjunction with these priorities, the continued empirical development of fragility and repair models remains central (e.g., Bellagamba et al., 2019; Lin et al., 2026; Moratalla & Sadashiva, 2022; Paulik et al., 2022; Williams et al., 2025), alongside open and disciplined use of nationally consistent hazard products to reduce avoidable uncertainty from hazard-damage-decision mismatches. Together, these will ultimately improve the credibility of end-to-end service disruption modelling in New Zealand and significantly improve our resilience to natural hazards.

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