

INFRASTRUCTURE FAILURE PROPAGATIONS AND RECOVERY STRATEGIES FROM AN ALPINE FAULT EARTHQUAKE SCENARIO: ESTABLISHING FEEDBACK LOOPS BETWEEN INTEGRATED MODELLING AND PARTICIPATORY PROCESSES FOR DISASTER IMPACT REDUCTION

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ABSTRACT

While it is well established that community members should participate in resilience planning, participation with genuine decision-making power remains rare. We detail an end-to-end disaster impact reduction modelling framework for infrastructure networks, embedded within a scenario-based participatory approach. Utilising the AF8+ earthquake scenario, we simulate hazard exposure, asset failure and recovery of interdependent critical infrastructure networks. Quantifying service levels temporally offers insights into possible interdependent network performance and community disconnection from national networks, not apparent when studying each infrastructure in isolation. Sequencing participation enables feedbacks between integrated modelling and participants' impact assessments. Shared ownership of modelling outputs advances stakeholders' understanding of resilience measures, allowing real-time implementation, increasing community resilience. Readily understood by central government, this format may increase support and resourcing, if nationally significant. Finally, this method tested integrated modelling and impacts assessments, identifying and enabling improvements for both.

INTRODUCTION

Communities require essential services, such as electricity, transport, telecommunications (including calls, texts and data), and three waters to be able to function. These essential services are provided by infrastructure networks, such as electricity lines, roads, fibre optic cables and sewerage, which are often highly interdependent. Damage to infrastructure, often caused by natural hazards (such as earthquakes), can result in the partial and sometimes complete loss of a given community's essential services for considerable periods of time. The interdependence of infrastructure networks can compound service loss. Impact on one network is likely to have cascading negative consequences for other networks, reducing the service level provided by other networks, and increasing the time required to restore networks [1]. Accordingly, the modelling of infrastructure networks' asset failure, interdependencies, and recovery are ongoing foci of disaster management research worldwide, however, these models are not often well integrated, which can lead to conflicting results [2,3]. As a result, end-to-end hazard-to-impact-to-recovery modelling for infrastructure networks remains a research gap.

Furthermore, the need for infrastructure resilience is ultimately driven by the need for community disaster resilience [4-6]. It is established that community members should participate in attempts to increase resilience to disasters. Normative reasoning suggests that people have a right to participate in decision-making which affects them, and pragmatic reasoning suggests that participatory processes deliver higher-quality

outputs (than those without participation) [7,8]. However, community participation involves substantial time and effort, when all stakeholders have limited time, resources, and interest, restricting their capacity to participate in or facilitate additional activities [8]. For example, existing commitments such as work and family can limit community members' ability to participate, and limited time and resources can similarly discourage project leaders from facilitating intensive participation [8]. Further, while community members often participate in disaster impact reduction efforts, community participation with genuine decision-making power remains rare and difficult, including in the context of increasing infrastructure resilience [9-11].

Davies [12] introduces a scenario-based participatory approach to enable successful collaboration among community members, researchers, and practitioners, for disaster impact reduction. The benefits of inclusive, participatory approaches have been well established, and include better quality decisions and better identification of vulnerabilities, as well as more empowerment of locals, greater perceptions that decisions are fair, reduced conflict, and increased trust in decision-makers (see Reed [13], for a summary). Davies' approach uses a scenario as a boundary object to enable collaboration between community members, researchers, and practitioners [12]. "Boundary objects" are 'objects which both inhabit several intersecting social worlds and satisfy the informational requirements of each of them. Boundary objects are... a means of translation' (Star and Griesemer [14], p. 393). Numerous studies have shown that boundary objects can enable successful collaboration between

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researchers and practitioners, without compromising either group's identity, integrity or autonomy, when all stakeholder groups perceive the boundary object as credible (scientifically and technically accurate), relevant, and legitimate (fairly reflecting stakeholders' divergent views and interests) [14-17]. Accordingly, within disaster impact reduction projects, natural hazard scenarios have proved to be successful boundary objects, enabling knowledge co-production and establishing ongoing relationships [18-21].

To integrate community members into this established scenario-based approach with genuine decision-making power, Davies [12] combines and sequences participatory methodologies, following Aoki [9]. Sequencing participation allows different stakeholder groups to participate more intensely at different stages during the overall process, focusing on relevant areas. For example, community members gain more influence assessing how a disaster will impact the community but have lower influence over assessing technical infrastructure restoration times (which infrastructure providers gain more influence over). Sequencing participation also helps to overcome barriers to participation by reducing the time commitment required from each stakeholder group, as discussions of most interest to individual stakeholder groups can be held without requiring all participants. This also helps to constrain and ensure credibility, reducing potential confusion which can be caused by non-experts debating and speculating about the needs and outcomes of parameters they know little about. For example, network infrastructure providers may speculate about community post-disaster needs but may have little specific idea. Equally, community members may guess network restoration times but are unlikely to know these. Combining different participation methodologies can further overcome barriers to participation. Methodologies with a range of participation intensities can be used so that participants who can commit more time are encouraged to, but those who cannot commit the same amount of time can still participate, and do not have to be excluded from the process entirely.

Therefore, in this paper, we aim to:

1. Develop an end-to-end disaster impact reduction modelling framework for infrastructure networks which considers direct and indirect impact, cascading network disruption, network interdependence, and resulting recovery processes; and
2. Embed this framework within a scenario-based participatory approach for disaster impact reduction to:
 - i. advance cross-sector understandings of the implications of disruption to, and recovery strategies for, infrastructure networks;
 - ii. increase the effectiveness and shared ownership of disaster impact reduction efforts; and consequently,
 - iii. increase community resilience to future hazard events.

Notably, this approach couples hazard models (ground shaking, landslides) with the modelling of failure, disruption, and recovery, across national-scale interdependent networks. Combining this integrated modelling with community- and practitioner-elicited recovery priorities creates feedback loops. These iteratively highlight vulnerabilities, areas to be revised, and new areas to be considered, in the integrated modelling and in practice. Further, the integration of community members and practitioners allows greater understanding, ownership, and ultimately application of this research, thus increasing community resilience.

Accordingly, we aim to answer the following research questions:

1. What is required to integrate hazard and infrastructure modelling, including direct and indirect impacts, cascading network disruption, network interdependence, and resulting recovery processes, to provide end-to-end impact assessment for infrastructure networks?
2. What value is gained by developing an end-to-end model for infrastructure networks?
3. How might a scenario-based participatory approach incorporate an end-to-end impact assessment model to advance both infrastructure and community resilience in an integrated way?
4. What is required to ensure that such scenario-based participatory approaches incorporate ongoing participant outputs to ensure that disaster impact reduction efforts continue to iteratively build on improvements in shared understanding?

THE AF8+ SCENARIO

Recent earthquake disasters in Aotearoa New Zealand (2010-11 Canterbury Earthquake Sequence, 2016 Kaikōura Earthquake) have demonstrated the potential fragility and interdependence of infrastructure networks, the extent to which communities depend upon infrastructure networks, and the value of pre-event infrastructure resilience efforts [22-24]. These lessons have informed a strong national drive to increase the resilience of infrastructure networks, which has included the creation of a New Zealand Thirty Year Infrastructure Plan [6]. Under the Civil Defence Emergency Management Act 2002 [26], New Zealand government agencies at local, regional and national levels, infrastructure providers (often termed "lifeline utilities"), and emergency services, all have defined functions and responsibilities for disaster readiness, reduction, response, and recovery. Section 60, for example, requires every lifeline utility to be 'able to function to the fullest possible extent, even though this may be at a reduced level, during and after an emergency' (p. 40). Lifeline utilities must also establish planning and operational relationships with their regional Civil Defence Emergency Management (CDEM) Group under the Act. In most regions, lifeline utilities predominantly fulfil their duties under the act by participating in regional lifelines groups, with national representation and coordination undertaken by the New Zealand Lifelines Council (est. 1999). Regional lifelines groups frequently undertake regional-scale vulnerability studies [27-29], post-event debriefs [24, 30, 31], and other work fostered or contributed to by the Groups, such as annual emergency management exercises at national, regional, and local scales [32], and numerous centrally-funded research initiatives which have streams dedicated to researching natural hazard impacts on infrastructure (including the Resilience to Natures Challenges, resiliencechallenge.nz; QuakeCoRE, quakecore.nz; Economics of Resilient Infrastructure, naturalhazards.org.nz; DEtermining VOlcanic Risk in Auckland, devora.org.nz; and East Coast Life At the Boundary, eastcoastlab.org.nz). This work often develops valuable inter-personal and inter-corporate relationships and has improved resilience [23, 24]. However, there has been growing recognition that greater community involvement in infrastructure resilience planning is required, both from domestic experience and international research [4-6].

The Alpine Fault (Te Waipounamu/South Island, New Zealand) is an earthquake source capable of producing impacts of national significance. The Fault forms the onshore boundary between the Pacific and Australian tectonic plates, accommodating the majority of plate relative motion, up to 28 mm/year [33-35]. The Alpine Fault generates M_w 8+ earthquakes several times per millennium and is late in its current seismic cycle, with an estimated ~30% probability of a major rupture in the next 50 years [36-39].

The Alpine Fault was considered a sufficient potential risk that Project AF8 (projectaf8.co.nz) was commenced in 2016, to undertake detailed planning for future major South Island earthquakes. Focusing on a 7-day Alpine Fault magnitude 8 earthquake scenario, based on decades of prior research activity [40], Project AF8 ran six regional and one national response planning workshops, aiming to integrate regional and national planning. In total, more than 500 participants attended these workshops, including emergency managers, policymakers, lifeline utilities, and community representatives, amongst others [41]. The intended outcome was the South Island Alpine Fault Emergency Response (SAFER) framework [42], focused on identifying likely impacts and addressing these through strategic planning and coordination activities.

This study builds on the initial Project AF8 scenario, using an up-scaled scenario that considers the 10 years following the initial earthquake, introduced by Davies [12], termed the “AF8+ scenario”. The AF8+ scenario allows a shift in focus from reactive short-term response to analyses of longer-term recovery, and was designed as part of a participatory process, according to project goals established by community members in Franz Josef, New Zealand, and subsequent discussions with practitioners [12,43]. In 2015, Franz Inc., Franz Josef’s business collective, invited academics from the University of Canterbury and the University of Auckland to assist them to develop a planning strategy to increase the resilience of the town. Subsequently, a complex participatory disaster impact reduction process has developed. Several participatory groups aiming to increase the resilience of Franz Josef have developed, including the community members’ and Universities’ collaboration, and a process led by the district and regional councils, both including a wide range of stakeholders. Herein, we present findings based on the AF8+ scenario, informed by findings from workshops which enabled engagement between researchers, infrastructure stakeholders, disaster managers, and community members [12].

This paper details expected societal disruptions due to infrastructure damages up to 180 days (6 months) following the initial AF8+ event, including those caused by the aftershock sequence and resultant landslides. We seek to address:

1. the locations most vulnerable to infrastructure losses for extended periods of time;
2. the magnitude and spatial extent to which disruptions spread due to the interconnected and interdependent nature of the South Island infrastructure networks; and

3. temporal changes in infrastructure network functionality during the recovery process, up to 180 days.

METHODOLOGY

Integrated Disaster Impact Reduction Modelling Framework for Infrastructure Networks

Our framework for simulating the cascading network disruption and recovery processes following major hazard-induced damage to interdependent infrastructure networks is presented in the grey boxes in Figure 1. The framework comprises five components: (A) Infrastructure Model, (B) Hazard Scenario, (C) Failure Propagation, (D) Disruption Metrics, and (E) Recovery. Each of these components is briefly outlined below and discussed in more detail by Zorn et al. [44,54].

In the first component, (A) Infrastructure Model, spatial infrastructure asset data are assembled to produce functional and topological geospatial network models, where networks are represented as graphs of nodes and edges represent discrete single point assets (such as water pumping stations or reservoirs) and connections (such as pipelines between these nodes), respectively. Nodes are identified as sources, where resources or services are generated, and sinks, the final points of delivery of the network services. The connectivity of source-sink paths within and between networks creates a functional pathway representation of these networks. User demands are allocated to each individual source and sink node based on “business as usual” statistics adopted from asset owner/operator-provided statistics, publicly available reported statistics, or spatial distribution/collection zones intersected with census data to provide an estimate of populations dependent on assets. These user demands are distributed along the functional pathways to create weighted flow network representations. Using these network models, initial asset failures or disruptions are assumed based on the network assets’ intersection with the modelled hazard extents in (B) Hazard Scenario. Such approaches are established within the literature [2,21,45] and have been used in a range of infrastructure risk and vulnerability studies globally, including studies of interdependent infrastructure vulnerability assessment for New Zealand [44,46].

Components C, D, and E (Figure 1) then follow an iterative process for each modelled timestep, forming a feedback loop. First, (C) Failure Propagation enables the propagation of network failures both within a network and between networks where dependency connections are broken and no redundancy

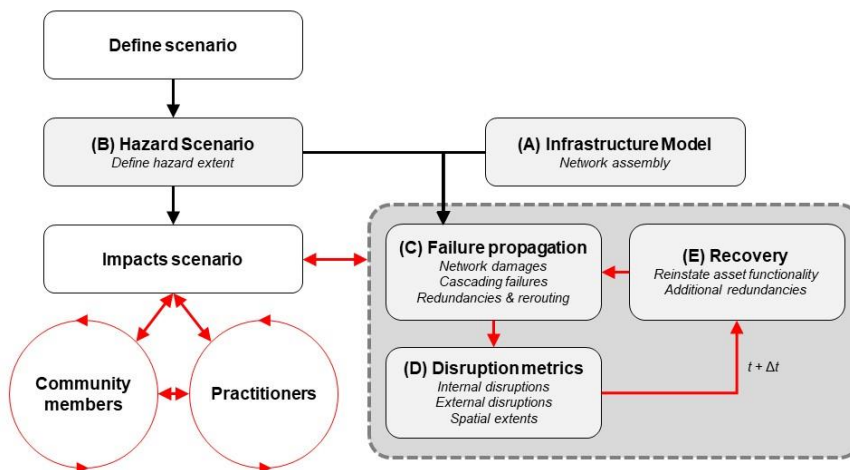


Figure 1: Conceptual diagram of the integrated disaster impact reduction modelling framework for infrastructure networks (indicated by light grey boxes) embedded within the Davies [12] scenario-based participatory approach. The dashed, dark grey box indicates the iterative process incorporating recovery. Feedback loops are highlighted using red arrows.

or rerouting of service flows are possible within our modelled network configuration. (D) Disruption Metrics then computes various consequence metrics. We define Direct Disruptions as the population/number of users adversely affected due to failed assets within the same network, such as a damaged water treatment plant causing a reduction (or removal) of water provision to downstream customers. By contrast, Indirect Disruptions result from failures which are initiated beyond the specific network of interest due to functional dependencies on other networks, such as an undamaged water treatment plant unable to function due to a lack of electricity supply. The spatial outage extent is delineated by the intersection of spatial footprints of failed components and dependent user catchments or distribution/reception zones.

Steps A-D represent the state of the disrupted infrastructure at a snapshot of time (t). For the next timestep ($t + \Delta t$), the final component, (E) Recovery, reinstates asset functionality of previously failed assets (where appropriate). This implies that a restoration process or provision of a permanent redundant supply has occurred to provide pre-event service levels.

Integrated Disaster Impact Reduction Modelling Framework for Infrastructure Networks Embedded within a Scenario-Based Participatory Approach

The above integrated disaster impact reduction modelling framework for infrastructure networks was then embedded within the Davies [12] scenario-based participatory approach, as shown in Figure 1. First, all stakeholders collaborate to define the scenario, to ensure that the scenario is perceived to be relevant by all participating groups [8,47-50]. Second, the hazard scenario is developed, as discussed above (Step B in Figure 1). Third, an impacts scenario is co-created through a range of combined and sequenced participatory methodologies [12]. In this way, the impacts scenario acts as a boundary object between participating groups, creating an ongoing feedback loop. As new information about likely damage, disruption and recovery priorities is provided to the impacts scenario by one stakeholder group, other stakeholder groups are able to incorporate this new information and, if necessary, alter their own assessments.

The impacts scenario also functions as a boundary object to embed the integrated disaster impact reduction modelling framework for infrastructure networks into the scenario-based participatory approach. As new damage, disruption and recovery assessments are created by participants in workshops, these can be modelled after workshops to show resulting implications for cascading network disruption, network interdependence, and the effect on recovery. This results in a feedback loop between the integrated modelling and ongoing disaster impact reduction work being undertaken by participants. This feedback loop enables the iterative integration of modelling outputs within the impacts scenario and as a result, this information can be understood and immediately used by community members and practitioners.

APPLICATION

In this section, we briefly summarise the application of the scenario-based participatory approach to the AF8+ scenario, as detailed by Davies [12]. Notably, this method was developed for a context where community members had invited academics to assist them to develop a planning strategy to increase the resilience of their town. We then step through and expand on

the application of each of the modelling framework components (Figure 1) to the AF8+ scenario.

The Scenario-Based Participatory Approach to the AF8+ Scenario

A scenario-based participatory approach was designed by Davies [12], as follows:

1. Identify need:

Work with community members to establish their most pressing collective needs, based on the community's unique social, economic, cultural, and political context. Identify which need is going to be addressed through the process.

2. Design participation:

Select other stakeholder groups associated with the identified need (e.g. council, emergency managers, lifelines, scientists, business groups). Work with each stakeholder group to design a series of participation opportunities, discussing: types of participants; modes of recruitment; modes of communication; and the roles of participants [9].

3. Develop scenario:

In consultation with the participating stakeholder groups, decide on an appropriate scenario, relevant to the identified need. Develop this scenario (Figure 1; B).

4. Co-create scenario:

The series of participation opportunities allows stakeholder groups to further develop the scenario in a sequence. Provide both the previously developed scenario and the co-created outputs from other stakeholder groups' participation as inputs for subsequent stakeholder groups' participation opportunities, so that additions to the scenario continually build on all previous outputs (Figure 2).

Each workshop co-created the impacts scenario. Workshops used the findings of previous workshops to inform the impacts scenario. Recovery estimates were also input into an integrated framework to model infrastructure interdependencies which iteratively informed the impacts scenario and future workshops. Separate workshops were held with Franz Josef community members, Westpower, ground transport operators (the New Zealand Transport Agency and KiwiRail) and road contractors (Fulton Hogan and MBD Construction), and the West Coast lifelines committee. Civil Defence Emergency Management (CDEM) representatives participated in all workshops, followed by a "combined" workshop.

Infrastructure Model (A)

We adopt the spatial infrastructure asset data and functional network models of Zorn et al. [46] across the energy (electricity, petroleum), transportation (road, air, ferry, rail), water & waste (water supply, wastewater, solid waste), and telecommunications sectors (mobile), with the addition of a further wired telecommunications network. In each of these models, major assets are represented. Table 1 provides an outline of the node/edge representations for each of the studied networks across the South Island. Figure 3 presents (a) the mapped faults of the South Island of New Zealand and (b) the spatial distribution of assets for all networks. For visual clarity, we have not represented each infrastructure sector separately.

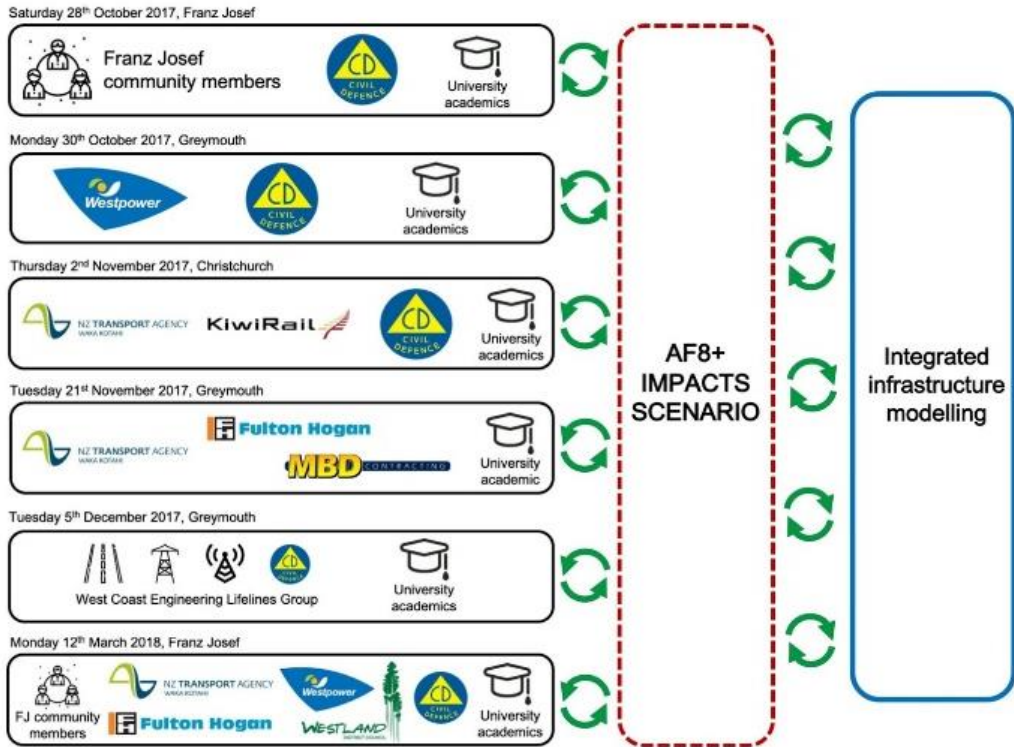


Figure 2: Schematic of the Franz Josef natural hazards scenario-based participatory workshops (each solid box represents a workshop [12]).

Table 1: Network asset representations as nodes and edges with counted values representing the number of exposed assets in this scenario based on the national models of Zorn et al. [44, 46]. Nodes are those assets representing a single asset in space whereas edges represent the spatially continuous linkages between nodes.

Infrastructure Sector	Network	Asset representation	
		Node	Edge
Energy	Electricity	63 generation sources, 48 transmission and 289 distribution substations	Transmission and sub-transmission power lines
	Petroleum	5 bulk storage facilities, 431 retail petroleum stations	Connected via state highway Network
Telecommunications	Landline	322 exchanges, 2313 cabinets	Fibre and copper connections
	Mobile	1053 mobile transmitter towers	Connectivity to wired network
Water & Waste	Water supply	585 source, treatment, pumping, or storage nodes	Major transmission or distribution pipelines
	Wastewater collection	354 pump station or treatment assets	Major collection pipelines
	Solid waste	239 collection, transfer, or landfill assets	Routed via state highway network
Transportation	State highways (SH)	855 bridges/tunnels	State highway classified roads
	Rail	16 stations	Rail tracks
	Air	13 Airports	Flight routes (41 domestic, 4 international)
	Ferry	13 Ferry terminals	Ferry routes (10)

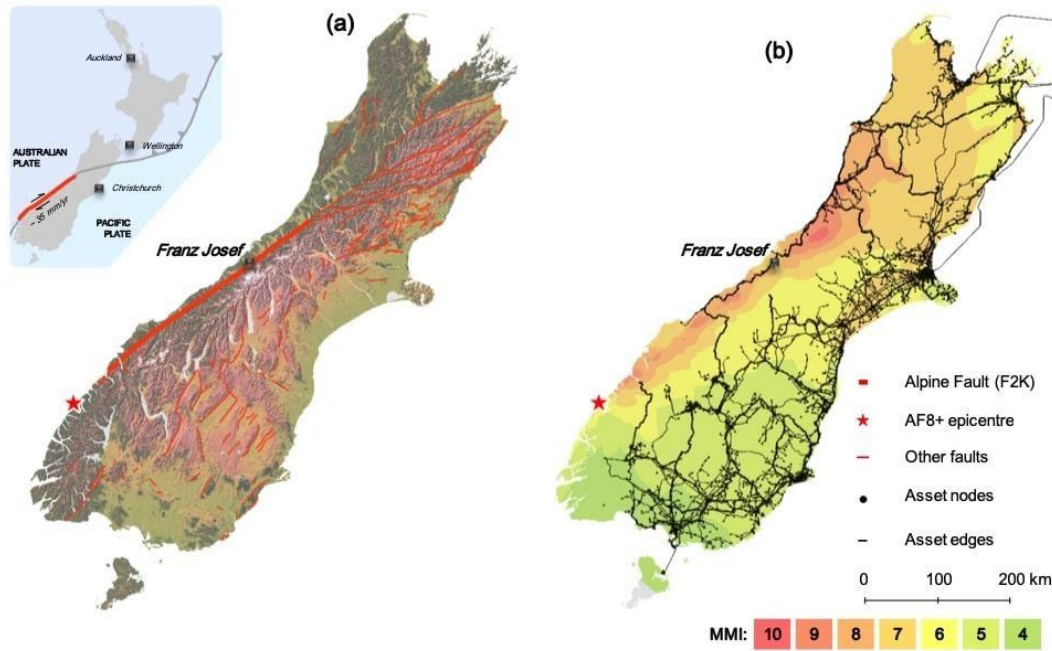


Figure 3: (a) South Island faults, including the Fiordland to Lake Kaniere (F2K) section of the Alpine Fault, and (b) spatial distribution of studied infrastructures with respect to MMI shaking intensities used in the AF8+ scenario, converted from Bradley et al. [51]. Inset map shows plate tectonic context of New Zealand and the Alpine Fault.

User demands are allocated to each of the individual nodes and edges presented in Figure 3 using statistics adopted from asset owner/operator-provided statistics, publicly available reported statistics, or spatial distribution/collection zones, intersected with the smallest publicly available census area unit (~100 permanent residents each). For this paper, we represent direct road transport impacts based on disruptions to passenger transport disruptions to allow for a comparable metric across infrastructures (i.e. population). Further, with island-wide traffic counts only available for state highway classified roads, all dependencies are routed through this network with any assets not directly accessible from a state highway are connected to the state highway via their shortest path. With the majority of shaking occurring on the West Coast (Figure 3b), we consider this a reasonable assumption. Such dependencies represented across the network models are provided in Figure 4 [44]. It should be noted that these are assumed for normal network connectivity and are assumed to be consistent throughout any recovery processes. Where specific connectivity pairs are unknown, edges are assumed to the closest appropriate asset either geographically or through a shortest path connection route.

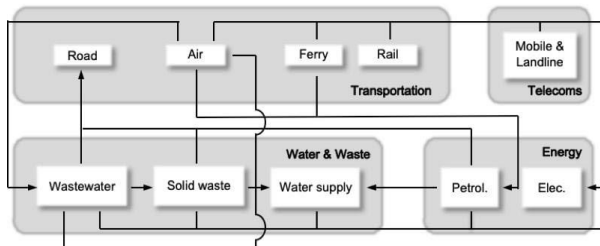


Figure 4: Simplified representation of the directed dependencies modelled from Zorn et al. [44]. An infrastructure i reliance on infrastructure j is represented as $i \rightarrow j$.

Hazard Scenario (B)

To create the AF8+ hazard scenario, Davies [12] extended the AF8 scenario from 7 days to 10 years (herein we focus on the first 180 days). Some hazard severities were reduced for the AF8+ scenario, as these were originally heightened to emphasise the emergency response planning focus within Project AF8 [40, 54] (e.g. removal of a 1-in-100 year rainstorm on Day 3 and large magnitude aftershocks and landslides in each CDEM region).

The AF8+ scenario adopts the AF8 scenario northeast-directed 411 km rupture of the Alpine Fault between Fiordland and Lake Kaniere (F2K) with corresponding ground shaking determined by Bradley et al. [51] (Figure 3). While this aspect of the scenario was considered highly uncertain by the Project AF8 science team, it was adopted given the frequency of reverse-slip earthquakes at the southern end of the Alpine Fault in recent decades [36] progressing from a SW to NE direction [52,53], and because it produces stronger ground shaking in populated areas on the west and east coasts than comparable scenarios [40,41].

A new, 10-year aftershock sequence was created by transferring the aftershock sequence from the 2002 M_w 7.9 earthquake on the Denali Fault, Alaska. Co-seismic landslide exposure was determined through the approach of Robinson et al. [55]; a co-seismic landslide hazard map at 60 m resolution was produced (based on the shaking intensity, slope angle, slope position, and distances to streams and faults), from which exposure estimates for the infrastructure networks were used to determine landslide locations. The rainfall sequence was transferred from the previous ten years of South Island rainfall data. Earthquake rupture, earthquake shaking, rockfall exposure and landslide reactivations were determined through expert judgement. Fault rupture was based on intersection with the location of the Alpine Fault in the NZ Active Faults database. Earthquake shaking damage was based on building construction type. Landslide reactivations were chosen based on increasing risk values (most likely landslides under the co-seismic landslide approach were reactivated). Debris flows were not included as

hazard scenario components due to time constraints, but academics did discuss these with participants.

Failure Propagation (C)

Each individual network asset is assigned one of three initial functionality states as a direct result of the shaking and landslide models described above. These correspond to i) complete disruption, ii) some interim level of functionality, or iii) no disruption (normal pre-event service is provided).

Disruptions were derived from locations where assets intersected the AF8+ scenario modelled fault rupture, shaking intensities (using Modified Mercalli Intensities, MMI, see Figure 3b), and landslide runout footprints, with infrastructure stakeholders providing further input regarding local geology, asset vulnerability, and likely impacts on the assets, based on recent experiences, including responses to storm-induced landslides and the 2016 “Kaikōura” earthquake. Expected recovery times were also derived. In applying these failures, where alternative source-sink connectivity paths do not exist, all dependent nodes/edges are assumed to be disrupted. To reduce data requirements and model complexities, we assume no capacity constraints at network edges and nodes, and we make further assumptions based on expert advice regarding reliabilities of supply (or levels of service) provided by specific networks throughout the AF8+ scenario. For example, electricity supply networks could be expected to provide intermittent service to end-users given the potential for power cuts following an earthquake due to aftershocks and voluntary disconnections for inspection or repair. In such cases, the interim level of functionality is assumed.

Disruption Metrics (D)

The consequence of asset failure is quantified based on the total user disruptions after allowing for redundancies and rerouting. Under full disruptions, all dependent users are considered disrupted. Under partial disruption, the number of additional users affected is assumed to be half of what would be expected under full disruption: representing the ability of an infrastructure network to provide partial service. Further, for some network functions (namely solid waste movements, wastewater solids disposal to landfills, and petroleum delivery to retail outlets), if rerouting is required, potential user disruptions are assumed to be a function of the increase in travel distance, as per Zorn et al. [44]. Disruptions are defined as being either initiated by direct or indirect causes, with indirect disruptions potentially attributed to multiple sources.

Recovery (E)

For this application, due to current data availability, we have focused on five timesteps: 0-1 days (the initial impacts in the first 24 hours), 3 days, 7 days, 30 days, and 180 days. Individual asset recovery rates were assumed from a range of studies on the Alpine Fault [21, 56] and local vulnerability studies [28]. These were updated using preliminary findings from the scenario-based participatory approach, integrating the modelling as shown in Figure 1.

RESULTS

Franz Josef Community Workshop, Saturday 28th October 2017

Franz Josef community members made detailed estimates of the community’s post-disaster capacity. In summary, the community expected Franz Josef to have:

- 2000 tourists to account for and evacuate;
- 3 satellite phones;

- 5 helicopters;
- 48 hours triage medical supplies;
- 4 days of food for tourists;
- 2 weeks of food for residents;
- 10 days of diesel; and
- 20 days of petrol.

Community members also anticipated:

- Being without road and mains power access for at least 6 months;
- Immediate satellite communications;
- Cell reception restored within a week;
- Evacuating injured as highest priority, all tourists within 7 days (as a goal), and then residents of the town who wish to leave. Evacuations were expected by helicopter, which were expected to back-load essential supplies for residents.

To maximise participation and increase relevance, this workshop was adjusted to focus on emergency response, as community members felt that they had not had enough response practice. This meant that discussion of long-term implications of the scenario (e.g. economic viability) was limited. However, importantly, community members stated that they would wish to remain living in Franz Josef throughout the recovery.

Westpower Workshop, Monday 30th October 2017

West Coast regional electricity outages are shown in Figure 5.

Westpower stakeholders noted that the repair of their electricity network is dependent upon the national supply and road access. As the first infrastructure provider contributing to the AF8+ scenario, both of these dependencies had to be assumed in the workshop. Participants chose to assume that road access would not inhibit the repair of the electricity network, noting that this would be reconsidered in a later workshop. However, it was noted that substations would run out of (back-up) power supply after one week, and that once substations run out of power, they may not be able to be restored. Key findings are detailed as follows:

- Westpower would run out of supplies and gear (poles, cross arms, fuel, etc.) within one week, if these are unable to be replenished from outside the West Coast.
- Within one month, mains power is expected to be restored to Franz Josef, if the Waihapo power plant is still generating.
- Within six months, participants were fairly confident that all power stations between the top of Westpower’s region down to Franz Josef would be restored. Fox Glacier would have an isolated power supply.
- The restoration of the electricity south of Franz Josef would depend on government priorities and road access. This would be a large investment across a large area for a small population.

Ground Transport Workshops, Thursday 2nd November and Tuesday 5th December

Key findings from workshops with ground transport operators and road contractors are detailed below, and South Island State Highway outages are shown in Figure 6. South Island rail network outages were also established but are not shown because it was expected that there would be no rail service on the East-West line, including for the West Coast west of Springfield, for several years.

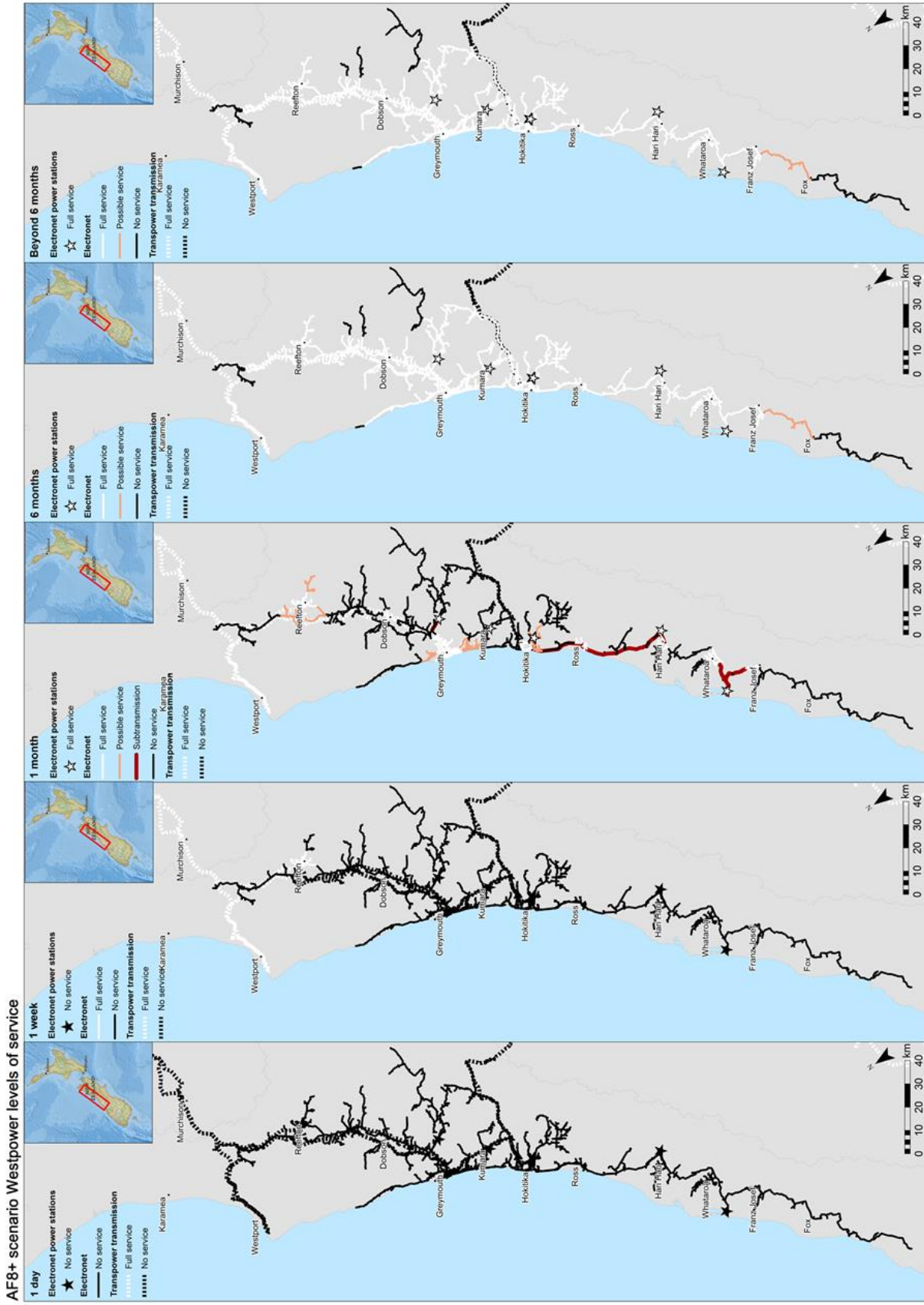


Figure 5: The co-created AF8+ impact scenario for Westpower electricity service levels, from the Westpower workshop.

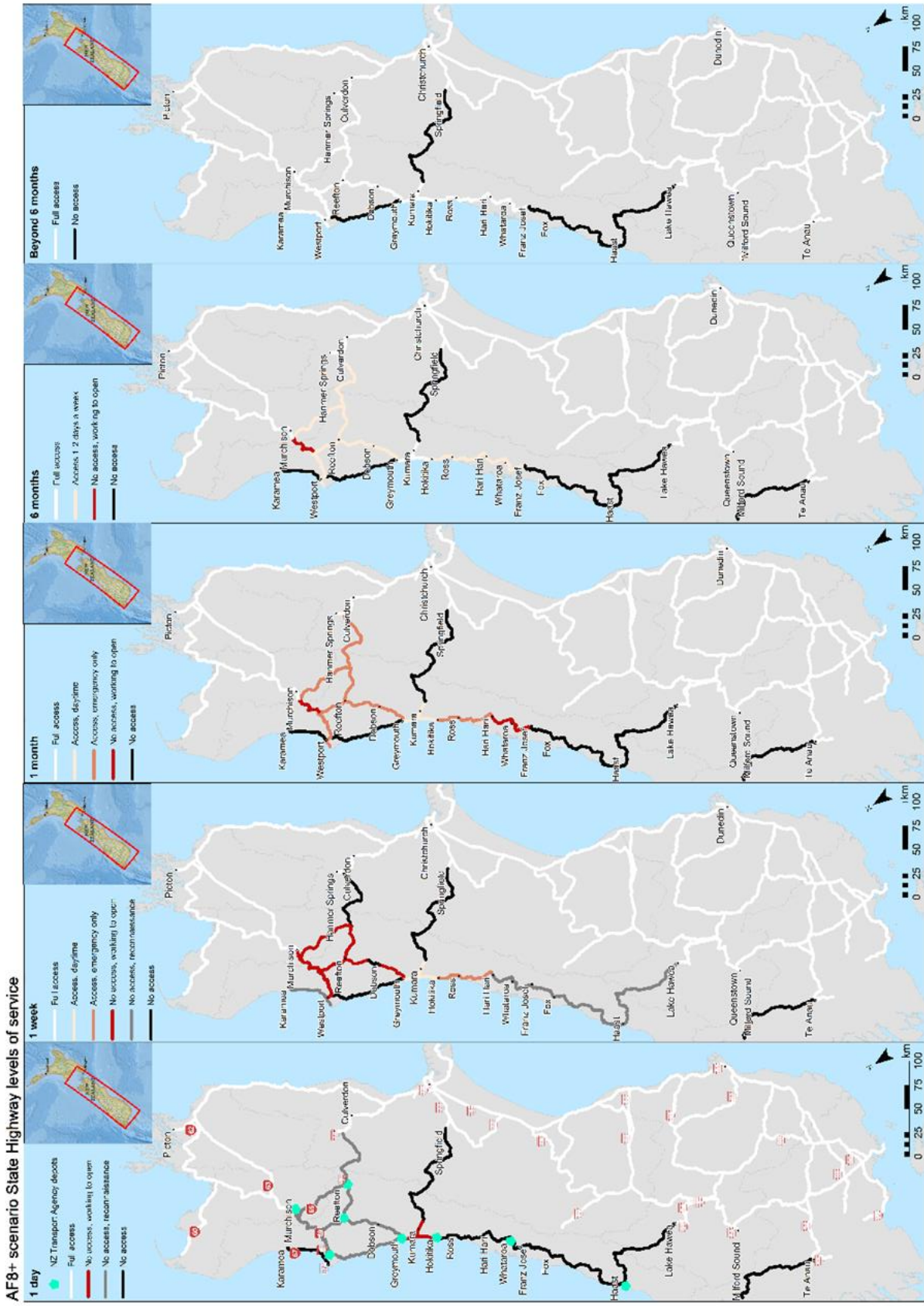


Figure 6: The co-created AF8+ impact maps for South Island state highways' service levels, from the Ground Transport workshops.

- All ground transport access to the West Coast will be closed for weeks.
- Limited public road access to Franz Josef is expected to be restored within six months.
- After restoring access to Franz Josef, NZ Transport Agency would prioritise the repair and improvement of re-opened roads over re-opening other damaged roads, unless the Government made these roads a priority.
- Permanent road closures may occur, including Arthurs Pass, Haast Pass to Franz Josef and the Coast Road between Greymouth and Westport. Restoration of these routes would depend on long-term government priorities.
- Permanent closure of the rail network west of Springfield may occur, depending on government priorities. Without road access through Arthur's Pass, the rail cannot be repaired.
- Closing the road (without any form of public access) for longer will speed road restoration.

West Coast Engineering Lifelines Group, Tuesday 21st November 2017

The focus of this workshop was to discuss interdependencies between the State Highways, rail, and Westpower electricity networks' impact assessments, co-created in previous workshops, and also to discuss the interdependencies between these networks and the other lifeline utilities. Key findings from this workshop were as follows:

- Fuel management will be critical for all lifelines with no or limited road access.
- Rail is critical to the long-term survivability of the milk and mining industry on the West Coast.
- Telecommunications were noted as a key dependency. However, telecommunications providers unfortunately did not attend the workshop, limiting both assessment of telecommunications outages and recovery times.

Integrated Modelling Findings

The modelled spatial extents of infrastructure network outages over time are shown in Figure 7. Shading indicates the number of infrastructure networks providing a complete or interim level of disruption to normal service. Timesteps of 0 and 3 days are combined as interim service levels are expected, i.e. no complete recovery to pre-event levels is simulated.

Recovery (to full pre-disruption service levels) propagates from the north, east, and south-east, after day 7. This is largely due to the more rapid re-instatement of interim/partial levels of service due to available resources (physical and human) located in these areas and less damage to the major assets represented in the models. At the larger timesteps (30 days/ 180 days) the West Coast region still shows substantial infrastructure disruptions: either complete or at some interim reduced level of functionality. Much of these disruptions can be attributed to the requirement for alternative source-sink connectivity paths for petroleum delivery, solid waste movement, and sewage disposal, with any deviation from normal pre-event service levels highlighted in Figure 7. Updating model simulations with new network arrangements (i.e. the definition of normal, interim, and no service) should be a focus in future research.

Many infrastructure recovery trajectories correlate closely to electricity network function (Figure 8a). While electricity providers advise the potential for "islanding" of electricity within the West Coast region within 180 days if the national grid is unable to be reconnected [12], some locations within the

West Coast region may remain without, or with intermittent, electricity supplies. Regardless of location, in this (or any similar) scenario, infrastructures dependent on electricity within the West Coast region should continue to consider potentially widespread use of back-up electricity sources to aid initial recovery.

This dependence on electricity is also reflected in Figure 8b, where the majority of user disruptions, across the presented time frame, can be attributed to indirect failures: predominantly disconnections in electricity supply. At $t = 0$, direct damages (combined across all infrastructures) account for 40% of the cumulative user disruptions with 60% externally initiated. With redundant electricity supplies, the proportion of indirect electricity-initiated disruptions would be expected to decrease (particularly for the mobile and wired telecommunications sectors which represent a combined ~2 million potential user disruptions at peak) and/or be reassigned as indirectly-initiated disruptions, due to reduced road, water supply, or petroleum access, amongst others. Explicitly incorporating redundancies and their attributes/dependencies into the modelling framework (e.g. battery life, generator refuelling requirements, and road access) would be a valuable extension to this research and should be incorporated as data for this become available.

"Combined" Workshop, Monday 12th March 2018

The final workshop in this process brought together representatives from all stakeholder groups that had participated in the previous AF8+ workshops, for the first time in the process. Each stakeholder groups' scenario assessments and integrated modelling findings were presented and discussed. Workshop discussions focused on implications for the Franz Josef community and regional infrastructure by leveraging the detailed national-, regional- and local-scale assessments already completed within the targeted workshops.

The summary of community response and recovery capacity, contrasted against the capacity of Lifelines to respond, highlighted current preparedness shortcomings. The modelling contextualised the stakeholder-assessed impacts on a national scale, and additionally highlighted further dependencies. In particular, practitioners and community members identified dependence on road access and petroleum supplies to be the greatest limiting factor throughout the recovery phase, whereas the modelling highlighted dependence on electricity.

Through collaborative discussions in the workshop, disaster impact reduction strategies were then co-created. For example, Franz Josef community members identified that they would be severely impacted locally, have limited resources and a large population to support, and would be isolated. Practitioners were able to confirm that the community would be inaccessible via ground transportation (i.e. State Highways) for months (Figure 6). Further, road operators identified that, due to the magnitude of damage, attempting to open the State Highways would require a structured, centrally-led and resourced response, meaning that in the immediate response, their locally-based roading contractor staff could be of more use to communities by helping to repair local infrastructure, as opposed to attempting to re-open the State Highways.

Additionally, given the modelled criticality of restoring the electricity network, practitioners discussed prioritising the repair of local roads to enable critical power supplies to be restored. Subsequently, the community identified that this infrastructure prioritisation, alongside self-rationing to ensure critical supplies would last, could enable Franz Josef to remain habitable to community members who wished to remain (as they planned to).

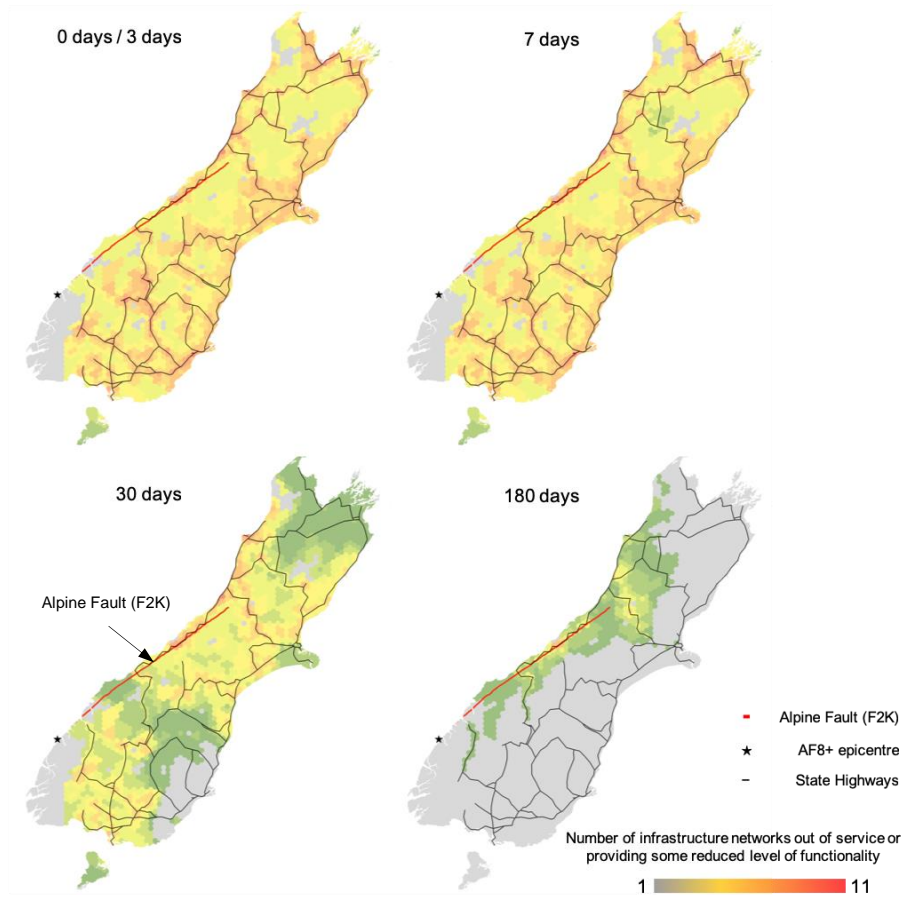


Figure 7: Spatial extents and number of infrastructure disruptions across the South Island. Darker red cells indicate a higher proportion of disrupted infrastructure services (either full disruption, or some reduced level of functionality/reliability compared to pre-event services) where the green end of the spectrum may indicate just a single infrastructure is not offering full functionality. Greyed out cells representing normal pre-event functionality (or areas without any permanent residents).

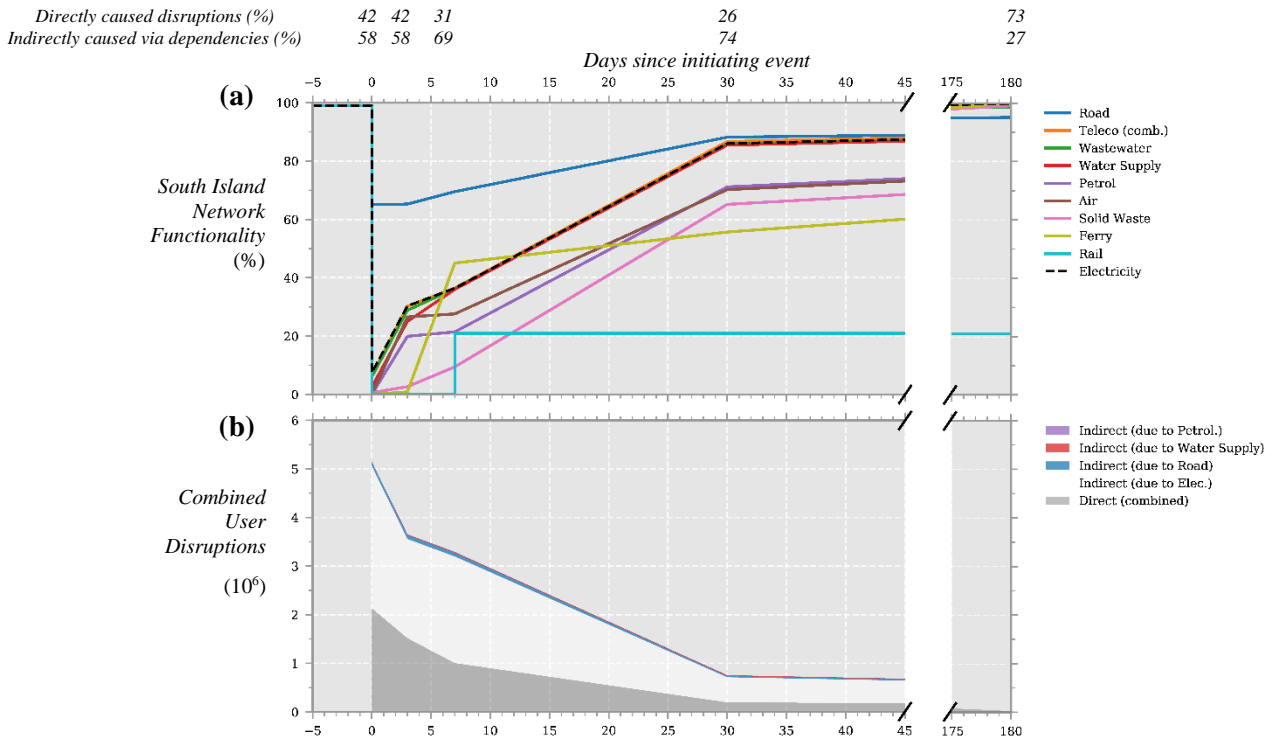


Figure 8: (a) Infrastructure network functionality for the South Island of New Zealand in terms of users disrupted (or passenger-kilometres restored for state highways) and (b) the attribution of disruptions to direct or indirect causes (via interdependencies) combined across networks. A selection of Wellington (ferry/air) and South Island bound transport passengers (air) is also included.

DISCUSSION

We have presented an application of an end-to-end modelling framework for earthquake shaking and landslide hazards coupled with interdependent critical infrastructure network models and the corresponding recovery processes. This integrated modelling immediately highlighted several discussion points for those concerned with reducing the impacts of major South Island disasters. The vulnerability of the West Coast region of the South Island is clear, as are the expected extended recovery times for many dependent infrastructures due to major disconnection from the transportation (predominantly state highway) and electricity networks. Given the mountainous setting and (resulting) financial cost, increasing connectivity (and therefore redundancy) across the state highway network is unlikely to occur. Therefore, improving and/or maintaining asset robustness should be a priority. For electricity, ongoing work by network owner/operators to introduce embedded generation (local generation sources connected to the distribution network reducing the reliance on the national grid), and backup supplies in critical areas within the West Coast region, should substantially benefit the local resident populations while aiding timely recovery for dependent infrastructures.

Embedding the end-to-end modelling framework within the scenario-based participatory approach had three obvious benefits for disaster impact reduction. First, simulation of failure, disruption, and recovery across national-scale interdependent networks allowed community members and practitioners to use the modelled impacts to advance their assessments of likely disruption and recovery strategies. Second, it helped to translate the relative importance of the spatial extents and number of infrastructure network outages (Figure 7) in relation to communities', and particularly Franz Josef's, post-disaster capacities, and so their ability to recover. Third, this method allowed testing of integrated modelling and impacts assessments, as community members and practitioners identified vulnerabilities, enabling appropriate adjustments to modelling and relevant disaster impact reduction measures implemented by community members and practitioners. In short, the modelling highlighted areas requiring increased focus in practice, while practitioners and community members highlighted necessary improvements for models. Road access and petroleum dependence were not accurately represented in the curves of Figure 8, as the dependencies represented in our model highlight the connectivity required for normal operation, as opposed to any new or changing dependencies arising to enable recovery. Additionally, the potential indirect disruptions due to petroleum shortages across the West Coast region during the recovery process are not immediately visible in Figure 8b. This is due to the modelling approach that defines user demands based on private car refuelling as opposed to petroleum demands for recovery works. Further supply shortages, for those restoring various infrastructure network functionalities, could substantially change the curves presented in Figure 8a, with the potential for cascading delays across multiple networks.

Moreover, coupling the integrated infrastructure modelling and the scenario-based participatory approach created a valuable feedback loop (Figure 1), which was enabled by sequencing participation. As new damage, disruption, and recovery assessments were identified by workshop participants, they were incorporated into the modelling to show resulting implications for cascading network disruption, network interdependence, and effects on recovery. Community members noted that this feedback loop, enabled by sequenced participation, critically added credibility to their impact assessment by extrapolating the national level implications of the integrated community assessment of local damage, and so translating their assessment into a format which is readily

understood by government at a national level. In turn, this increased the likelihood of central support and resourcing for relevant national-level disaster impact reduction efforts for the community. Embedding modelling within the scenario-based participatory approach also increased the shared ownership of the modelling and allowed both community members and practitioners to (in some cases immediately) implement disaster impact reduction measures at the local and regional levels in response to the implications of the modelling [12]. For example, a Franz Josef business owner noted that "from a business point of view, knowing likely outage times, as shown on the maps used in the workshop [Figure 5; Figure 6], is very useful for crisis management."

Notably, willingness to participate was critical to the success of this process, both in terms of being able to use stakeholder impact assessments to model infrastructure impacts, and in terms of collaboration to increase disaster preparedness. While lifeline utilities are legislated to improve disaster readiness, reduction, response, and recovery [26], the additional leadership and willingness to participate in this process shown by the West Coast Engineering Lifelines Group, and in particular the New Zealand Transport Agency and Westpower, greatly aided this process. Moreover, the drive shown by community members to start the process, and the unwavering commitment of community members to increase the resilience of Franz Josef, cannot be understated as essential to the process. This may have been partly enabled by the tight-knit and remote character of this community, as it has been established that place attachment and strong connections between community members (including government employees) can enable compromises for the good of the community [9,57,58]. This is not to say that participation was easy. The scenario lacked some credibility insofar as national telecommunications and electricity providers/distributors did not engage with the process. This increased the influence of other stakeholders, particularly academics, on the scenario, as best judgement was used as a substitute for participation. Further, while complete participation is a near impossibility for any project of this scale, when key personnel were unable to attend, this affected, and in some instances limited, discussions. While part of the project's success was due to the close collaboration between researchers and the West Coast Engineering Lifelines Group, closer collaboration could have encouraged more participation. Utilising a wider range of participation methodologies beyond exclusively organising workshops could have increased participation in the process. Moreover, making the project a formal West Coast Engineering Lifelines Group project may have encouraged participation from telecommunications providers. Legislation is also an option which has been successful in New Zealand at effectively mandating collaboration between infrastructure companies and emergency managers [26]. Clarifying and, if necessary, strengthening this mandate could greatly increase necessary collaboration between community members and lifelines organisations.

Several extensions to this work are required both to i) assess the generalised recovery strategies and priorities across a wider range of potential hazard event scenarios that are both in progress and proposed, particularly building on the need to focus on recovery, and not just on the initial response; and ii) to improve the application of the integrated framework in future projects.

This paper has outlined an approach to enable the integration of knowledge between community members, researchers, and practitioners, and has highlighted the benefits of end-to-end disaster modelling and of using a scenario-based participatory approach to integrate this modelling with preparedness assessment. Further, this paper has proved that using a scenario as a boundary object and sequencing participation also enables the integration of autonomous participant initiatives within the

scenario-based participatory approach introduced by Davies [12]. This suggests that different autonomous initiatives (in addition to integrated infrastructure modelling) could be integrated by any participating group. Overall, the collaborative linking of scientific, technical, and community knowledge offers great potential to increase resilience of socio-technical systems in preparing for future events such as the anticipated Alpine Fault rupture.

CONCLUSIONS

This paper has addressed its research questions as follows:

1. An end-to-end disaster impact reduction modelling framework for infrastructure networks has been outlined. This integrated direct and indirect impacts, cascading network disruption, network interdependence, and resulting recovery processes.
2. When applied to the AF8+ Alpine Fault earthquake scenario, this integrated modelling immediately highlighted several discussion points for those concerned with reducing the impacts of major South Island disasters, particularly around extended recovery times for many dependent infrastructures due to major impacts to electricity and transportation (predominantly state highway) networks. Improving and/or maintaining asset robustness should be a priority, as should ongoing work to introduce embedded generation and backup supplies in critical areas within the West Coast region.
3. The end-to-end modelling framework was embedded within a scenario-based participatory approach [12] by using a scenario as a boundary object and sequencing and combining participatory methodologies [9,15]. This created a feedback loop. As community members and practitioners outlined their assessments of likely damage, disruption, and recovery priorities, these were used to advance the modelling, and modelled outputs were then fed back into the participatory approach. This highlighted vulnerabilities within integrated modelling and impact assessments by community members and practitioners, improving both.
4. Critically, the feedback loop increased the shared ownership of the modelling, consequently allowing both community members and practitioners to (in some cases immediately) implement disaster impact reduction measures due to the implications of the modelling, increasing community resilience to future hazard events. Further, the modelling also translated the integrated community assessment of local damage to national implications, allowing the community assessment to be communicated more clearly to national government, increasing the likelihood of relevant national-level disaster impact reduction policies for the community.

This application particularly highlighted the criticality of sequencing participation to the scenario-based participatory approach. Beyond the genuine two-way communication required to ensure that boundary objects are perceived by all participants to be relevant, credible, and legitimate [15], the participatory approach [12] benefits from sequencing that enables feedback loops to occur, as assessments iteratively build on the current best shared understanding.

Overall, this approach has been very well-received by community members and practitioners, having addressed two key needs: integrated modelling and genuine community participation. The willingness of community members and practitioners to participate was essential to this success. The process would benefit from further validation, evaluation, and numerous improvements (many identified herein), but clearly, future research in this area is likely to be both highly valuable and highly valued.

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