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INFRASTRUCTURE FAILURE PROPAGATIONS AND RECOVERY STRATEGIES FROM AN ALPINE FAULT EARTHQUAKE SCENARIO

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ABSTRACT

Recent earthquake events in the South Island of New Zealand (2010-11 Canterbury and 2016 "Kaikōura") have highlighted the need for more hazard-specific preparedness and contingencies planning. New Zealand Civil Defence and Emergency Management (CDEM) are now planning response efforts to specific large-scale hazards, based on risk-informed maximum credible scenarios.

The Alpine Fault (South Island, New Zealand) has been identified as an earthquake hazard capable of producing impacts of national significance, with a high likelihood of occurrence: 30% chance of rupture (M_W 8.0) in the next 50 years. Response planning for such an event requires immediate and ongoing coordination, so *Project AF8* (projectaf8.co.nz) has commenced.

In this paper, utilising the core *Project AF8* **A**lpine **F**ault magnitude **8** earthquake scenario, we detail hazard exposure, impacts, and recovery of interdependent critical infrastructure networks, namely: energy (electricity, petroleum), transportation (road, air, ferry, rail), water & waste (water supply, wastewater, solid waste), and telecommunications sectors (wired, wireless). Asset failures are simulated across each individual network, based on; shaking intensities, exposure to co-seismic hazards (slips, landslides, and major rock falls), and estimated component fragilities, which have been further refined and validated through expert elicitation, via workshops coordinated with regional infrastructure stakeholders. Network disruptions are propagated across an interdependent network framework to quantify and delineate the spatial reach of failures. By incorporating recovery strategies, temporal changes in service levels are quantified to offer insights into expected interdependent network performance and the possible disconnection of communities from the nationally connected networks, otherwise not apparent when studying each infrastructure in isolation.

Keywords: Critical Infrastructure; Recovery; Alpine Fault; Risk reduction; Disaster Preparedness;

1. INTRODUCTION

New Zealand lies at the interface of a complex plate boundary between the Australian and Pacific plates: a westward-dipping subduction zone along the east coast of the North Island terminates northeast of the South Island, where it transitions into mostly strike-slip motion, before transitioning again into eastward-dipping subduction south-west of the South Island. The geological setting means that the country is exposed to a wide range of earthquake hazards, some of which are capable of causing widespread national disasters. Many of these disasters occur due to critical infrastructure failures, which has led to a focus on increasing the resilience of critical infrastructure networks, or "Lifelines" (Brunsdon 2000). This focus is reflected in New Zealand's Thirty Year Infrastructure Plan (NIU 2015) and further

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evidenced by: (i) the frequency of regional scale vulnerability studies (McCahon et al. 2017; ORC 2014; AELG 2014); (ii) New Zealand's increasingly strong Lifelines culture which encourages collaboration between asset owners/operators, across public and private sectors, at regular national and regional forums (New Zealand Lifelines 2007); (iii) annual preparedness exercises at national/regional/local scales (MCDEM 2017); (iv) and the number of centrally funded research initiatives with streams dedicated to researching natural hazard impacts on infrastructure (including *QuakeCoRE* (quakecore.nz), *Resilience to Natures Challenges* (resiliencechallenge.nz), *EoRI* (naturalhazards.org.nz), and *DEVORA* (devora.org.nz), amongst others).

Recent earthquakes in New Zealand (2010-11 Canterbury Earthquake Sequence, 2016 "Kaikōura" Earthquake) have demonstrated the value of pre-event infrastructure resilience efforts (see Davies et al. 2017a; Earthquake Commission 2012; McLean et al. 2012). Given the significant social and economic impacts arising from these events and their consequent infrastructure damage, the Ministry of Civil Defence and Emergency Management (MCDEM) have acknowledged the need for a more focused, scenario-based approach to large scale multi-regional hazards, based on scientific risk-informed maximum credible scenarios (Orchiston et al. 2016). Such scenario-based approaches are highly effective at facilitating communication and integrating knowledge between actors from different backgrounds, serving as a form of translation by allowing discussion in real world terms – as opposed to using more siloed scientific or technical practitioner terminology (Hagendijk and Irwin 2006; Koontz and Bodine 2008; Reed 2008; Reed et al. 2013; Robinson et al. 2014).

The Alpine Fault (South Island, New Zealand) presents an earthquake source capable of producing impacts of national significance. The Fault forms the onshore plate boundary between the Pacific and Australian tectonic plates, accommodating the majority of plate motion, up to 28 mm/year in areas (Biasi et al. 2015; Barth et al. 2014; Sutherland et al. 2006). Large M_w8+ earthquakes can be expected every 300-500 years (last major rupture occurring 300 years ago in 1717) with an estimated 30% probability of a major rupture in the next 50 years (Barnes et al. 2013; Cochran et al. 2017; De Pascale and Langridge 2012).

Detailed planning for future major earthquakes requires immediate and ongoing coordination, and has commenced in the form of *Project AF8* (projectaf8.co.nz). Focussing on an **A**lpine **F**ault magnitude **8** earthquake scenario, *Project AF8* is a multi-sector, collaborative, multi-year project (commenced in 2016), aiming to improve the response ability of Civil Defence Emergency Management (CDEM) Groups, infrastructure utilities and welfare organisations within New Zealand's South Island. The project is led by CDEM Southland, on behalf of the six regional South Island CDEM groups, and is funded by the Ministry of Civil Defence & Emergency Management (MCDEM), with substantial support from scientific research programmes (*National Science Challenge Resilience to Nature's Challenges*, *QuakeCoRE*, *Natural Hazards Research Platform*) and institutions (Earthquake Commission, central and local government, Crown Research Institutes, non-government organisations).

To maximize leverage from the lessons learned in recent earthquakes, *Project AF8* has used a collaborative approach between scientists, industry and practitioners. A 7-day hazard scenario was compiled in 2016 based on decades of prior research activity (Orchiston et al. 2016). This was exercised in all South Island regions and New Zealand's capital, Wellington. In total, more than 500 representatives from CDEM Groups, partner agencies and organisations participated. Findings and inputs from these regional workshops are being used to develop a 7-day **S**outh Island **A**lpine **F**ault **E**arthquake **R**esponse (SAFER) plan (due for completion in 2018).

This project builds on the initial *Project AF8* scenario, using an extended scenario (out to 10 years) introduced by Davies et al. (2017b), termed the AF8+ scenario. This modified scenario allows a shift in focus from reactive short-term response to analyses of longer-term recovery resilience. Herein, we present findings based on the AF8+ scenario, informed by preliminary findings from ongoing workshops between infrastructure stakeholders (Davies et al. 2017b).

In particular, this paper seeks to apply this gathered knowledge to investigate societal disruptions due to infrastructure damages following the initial AF8+ event and preceding aftershock sequence and resultant landslides. We seek to address: (i) the location(s) most vulnerable to infrastructure losses for extended periods of time, (ii) the magnitude and extent to which disruptions spread spatially and in magnitude due to the interconnected and interdependent nature of the South Islands infrastructure networks, and (iii) temporal changes in infrastructure network functionality during the recovery process.

To address these, we propose an integrated framework for simulating an end-to-end impact assessment of the hazard, cascading network disruption, and resulting recovery processes. The main points of interest lie in the coupling of hazard models (ground shaking, landslides) with expert-elicited recovery priorities and the further simulation of failure, disruption and recovery across national scale interdependent networks. In doing so, the aim is to highlight thematic and systemic vulnerabilities and areas that could be considered in the ongoing preparation of the wider response plan.

Following this introduction, Section 2 outlines our integrated framework for analysis, Section 3 presents the application of the framework to the earthquake scenario and the energy (electricity, petroleum), transportation (road, air, ferry, rail), water & waste (water supply, wastewater, solid waste), and telecommunications sectors (wired and wireless networks). Section 4 provides an overview of results, and Section 5 concludes with a discussion of the results and areas identified for future development.

2. INTEGRATED FRAMEWORK

Figure 1 presents our framework for simulating the cascading network disruption and recovery processes following a major hazard-induced damage to interdependent infrastructure networks. It comprises five components: *A: Model Building*, *B: Hazard Scenario*, *C: Failure Propagation*, *D: Disruption Metrics*, and *E: Damage Recovery*. Each of these components are briefly outlined below with reference to the AF8+ earthquake scenario detailed in Section 3.

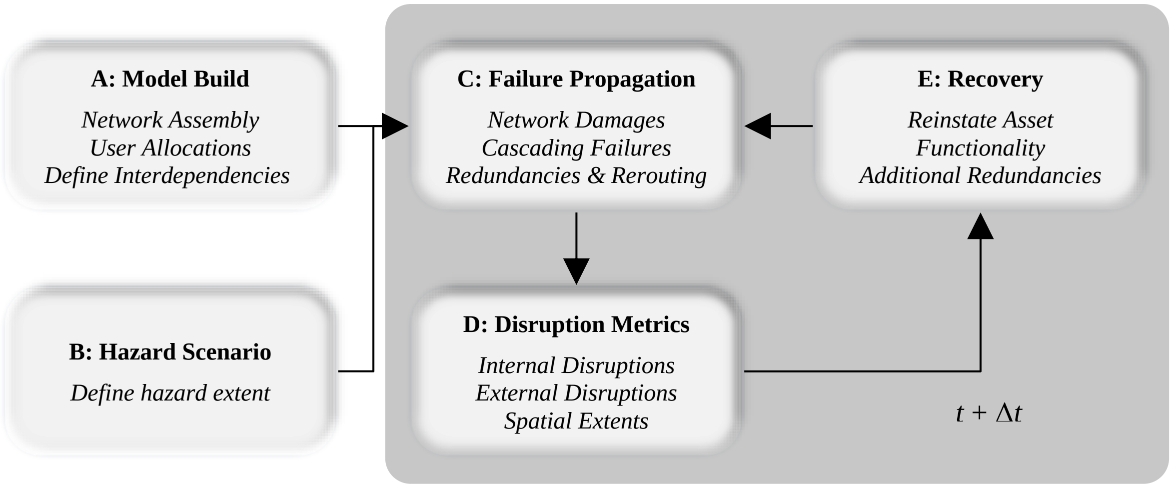

Figure 1. The framework for determining the temporal direct, indirect, and spatial extents of disruptions across interdependent networks. The greyed box indicating the iterative process incorporating recovery.

In the first component, *A: Model Build*, spatial infrastructure asset data is assembled to produce functional and topological geospatial network models where networks are represented as graphs of nodes and edges representing discrete single point assets (such as a water pumping stations or reservoirs) and connections (such as pipelines between these nodes) respectively. The functionalities of the nodes are identified as: (1) sources - where infrastructure resources or services are generated (e.g. power plants, pump stations, airports, etc.); and (2) sinks - which signify the final points of delivery of the infrastructure services typically to the customer (e.g. low voltage electricity substations, airports, etc.). This allows creation of functional pathways, which emerge from the traceability of source-sink connectivity paths both within and between networks that exchange infrastructure resources and services. User demands are allocated to each individual source and sink node based on supplied statistics or through spatial analyses. 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 and have been recently used in a range of infrastructure risk and vulnerability studies globally (Hu et al. 2015; Pant et al. 2017; Thacker et al. 2017), including studies of interdependent infrastructure vulnerability assessment for New Zealand (Zorn et al. 2018a, b).

Components *C*, *D*, and *E* then follow an iterative process for each modelled time step. Firstly, *C: Failure Propagation* enables the propagation of network failures both within a network and between networks where dependency connections are broken and no redundancy or rerouting of service flows are possible. *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 ensuring a reduction (or removal) of water provision to downstream customers. In comparison, *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.

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

3. APPLICATION

In this section, we step through and expand on each of the framework components presented in Figure 1 as they relate to the AF8+ scenario.

3.1 Model Build (A)

We adopt the spatial infrastructure asset data and functional network models of Zorn et al. (2018a, b) 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, with Table 1 providing an outline of the node/edge representations for each of the studied networks across the South Island and Figure 2a presenting the combined spatial distribution of assets for all networks with respect to mapped faults. For visual clarity, we have not represented each infrastructure sector separately.

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. (2018a, b).

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	Wired	322 exchanges, 2313 cabinets	Fibre and copper connections
	Wireless	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 Highway (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)

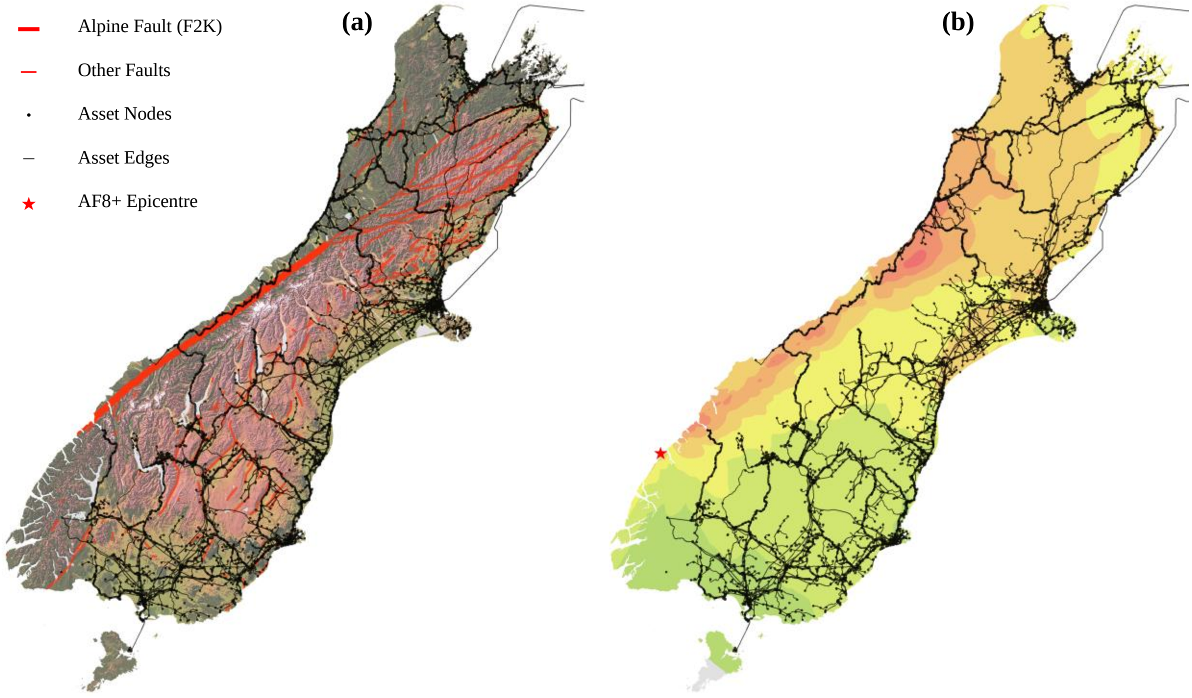

Figure 2. Spatial distribution of studied infrastructures across the South Island of New Zealand and interisland electricity/with respect to (a) the F2K section of the Alpine Fault and other major faults, and (b) MMI shaking intensities used in the AF8+ scenario as simulated and converted from PGV by Bradley et al. (2017).

User demands are allocated to each of the individual nodes and edges presented in Figure 2 using provided statistics/catchments/zones and spatial analyses at the smallest publicly available census areal unit (~100 permanent residents each). For this paper, we consider residential and passenger transportation modes only (i.e. freight, and commercial and industrial customers dependent on these networks are not included). The dependencies represented within the network models are provided in Figure 3 (as per Zorn et al 2018b). It should be noted that these are assumed for normal network connectivity and are assumed 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.

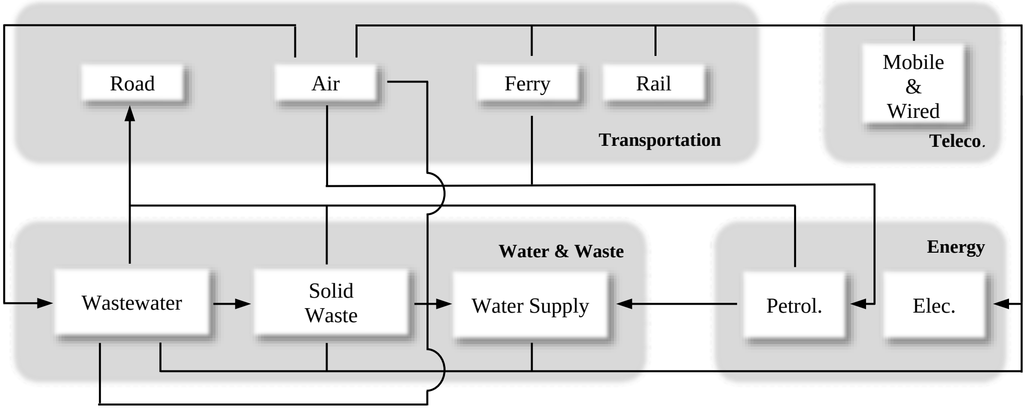

Figure 3. Simplified representation of the directed dependencies modelled from Zorn et al. (2018b). An infrastructure *i* reliance on infrastructure *j* is represented as *i→j*.

3.2 Hazard Scenario (B)

The AF8+ scenario adopts a northeast-directed 411km rupture between Fiordland and Lake Kaniere (F2K) with corresponding ground shaking, as shown in Figure 2b, determined by Bradley et al. (2017). This scenario was agreed upon in *Project AF8*, given the frequency of reverse-slip earthquakes at the southern end of the Alpine Fault in recent decades (Barnes et al. 2013) progressing from a SW to NE direction (McGinty et al. 2001; Downes and Dowrick 2014) and with stronger ground shaking in populated areas on the west and east coasts than comparable scenarios. Davies et al. (2017b) further extended the scenario out to 10 years (here we adopt the first 180 days) and reduced additional hazard severities that were previously heightened to emphasise the emergency response focus (replacement of a 1-in-100 year rainstorm on Day 3 with historic rain gauge data and an updated aftershock sequence).

To determine direct impacts from landslides, we adopt the approach of Robinson et al. (2016). In doing so, a co-seismic landslide hazard map at 60 m resolution is produced based on the shaking intensity, slope angle, slope position, and distances to streams and faults. Exposure estimates for the various infrastructure networks were then used to determine landslide locations. Based upon experiences from the 2015 Nepal and 2016 “Kaikōura” earthquakes (Roback et al. 2016; Dellow et al. 2017), the formation of new landslides after the main shock is only inferred to occur during a large M_w 7.0 aftershock on Day 11. Reactivation of landslides caused by the main shock were included however, using expert judgement.

3.3 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 such that normal pre-event service is provided.

Disruptions were derived from locations where assets intersected the AF8+ scenario modelled fault rupture, shaking intensities (using MMI, see Figure 2b), and landslide runout footprints, with infrastructure stakeholders providing further input regarding local geology, asset fragility, and likely impacts (and expected recovery times) to the assets, based on recent experiences. In applying these failures, where alternative source-sink connectivity paths do not exist, all dependent nodes/edges are assumed further disrupted. While we assume no capacity constraints at network edges and nodes to reduce data requirements and model complexities, we make further assumptions based on expert advice regarding reliabilities of supply (or levels of service) provided by specific networks following an AF8+ style 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.

3.4 Disruption Metrics (D)

The consequence of asset failures are 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, half of the additional affected users are considered disrupted. 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. (2018b).

Disruptions are defined as being either direct or indirect (Section 2). If indirect disruptions are attributable to multiple infrastructures, we make an assumption based on the strength of dependency to determine the initiating infrastructure. For example, a loss in electricity supply to a retail petrol station would have a greater initial impact on customers than a shutdown of a bulk supply node given the storage of petroleum on site.

3.5 Recovery (E)

For this application, due to current data availability, we have focused on five time steps: 0-1 days (the initial impacts in the first 24 hours), 3 days, 7 days, 30 days, and 180 days. Individual asset recovery rates have been assumed from a range of Alpine Fault studies (Robinson et al. 2014, 2015), local vulnerability studies (McCahon et al. 2017), and preliminary findings from expert-elicitation workshops (Davies et al. 2017b). In the near future, with further workshops and analysis, recovery strategies will be further defined.

4. RESULTS

Figure 4 presents the spatial extents of infrastructure network outages over time. Shading indicates the number of infrastructure networks that are providing a complete or interim level of disruption to normal service. Time steps of 0 and 3 days are combined as some interim level of service are expected to remain over these times, i.e. no complete recovery to pre-event levels is simulated.

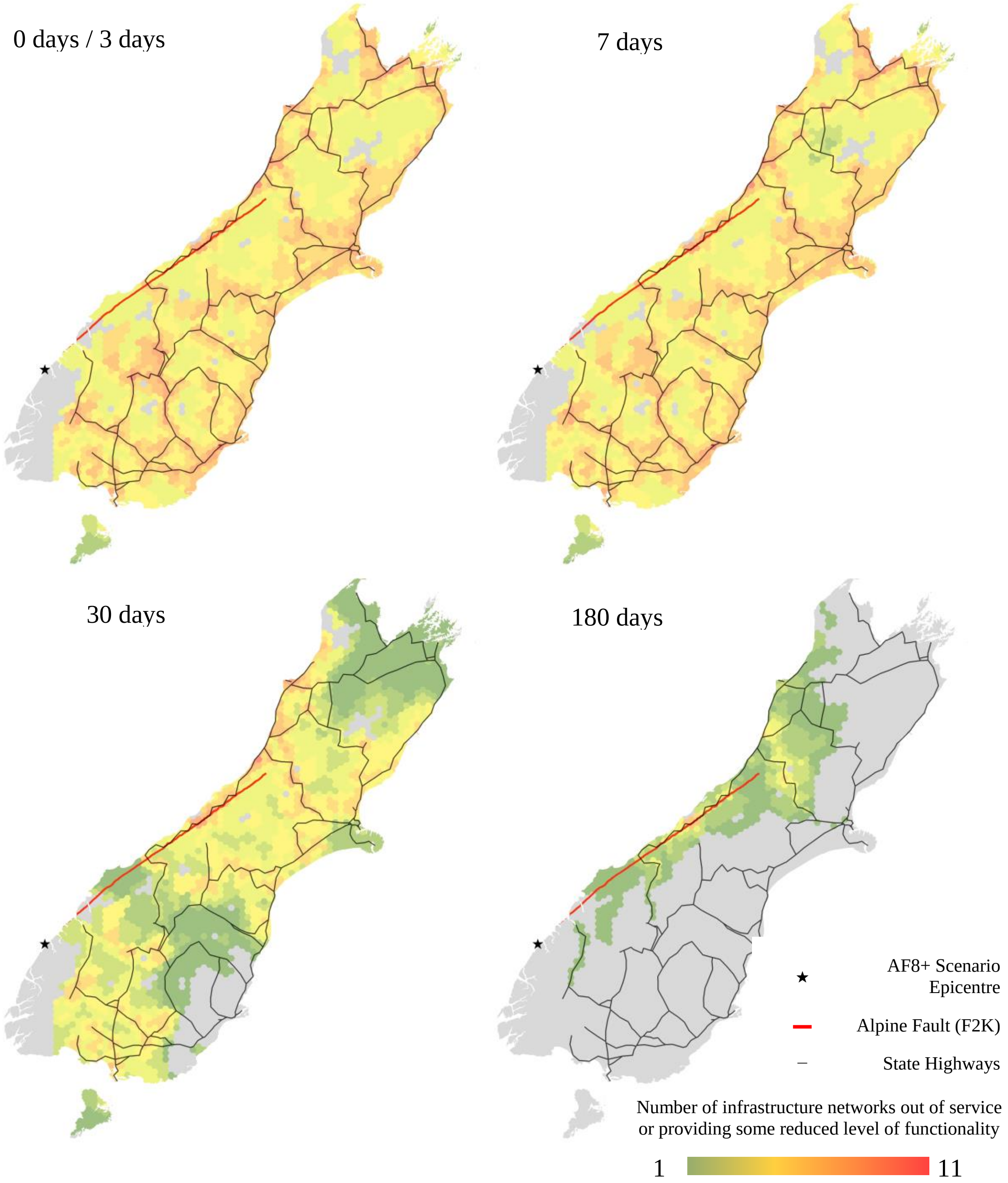

Figure 4: Spatial extents and frequency of infrastructure disruptions across the South Island. Darker (red) cells indicate a higher proportion of disrupted infrastructure services (either full disruption, or some reduced level of functionality/reliability compared to pre-event services) with greyed out cells representing normal pre-event functionality (or areas without any permanent residents and hence losses in infrastructure service).

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 time steps (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 can be attributed to the requirement for alternative source-sink connectivity paths for petroleum delivery, solid waste movement, and wastewater solids disposal, with any deviation from normal pre-event service levels highlighted in Figure 4. Updating model simulations with new network arrangements (i.e. the definition of normal, interim, and no service) should be a focus in future developments.

Many infrastructure recovery trajectories correlate closely to electricity network function (Figure 5a). 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 (Davies et al. 2017b), some locations within the West Coast region may remain without, or with intermittent, electricity supplies. Regardless of location, in this scenario (or any similar), 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.

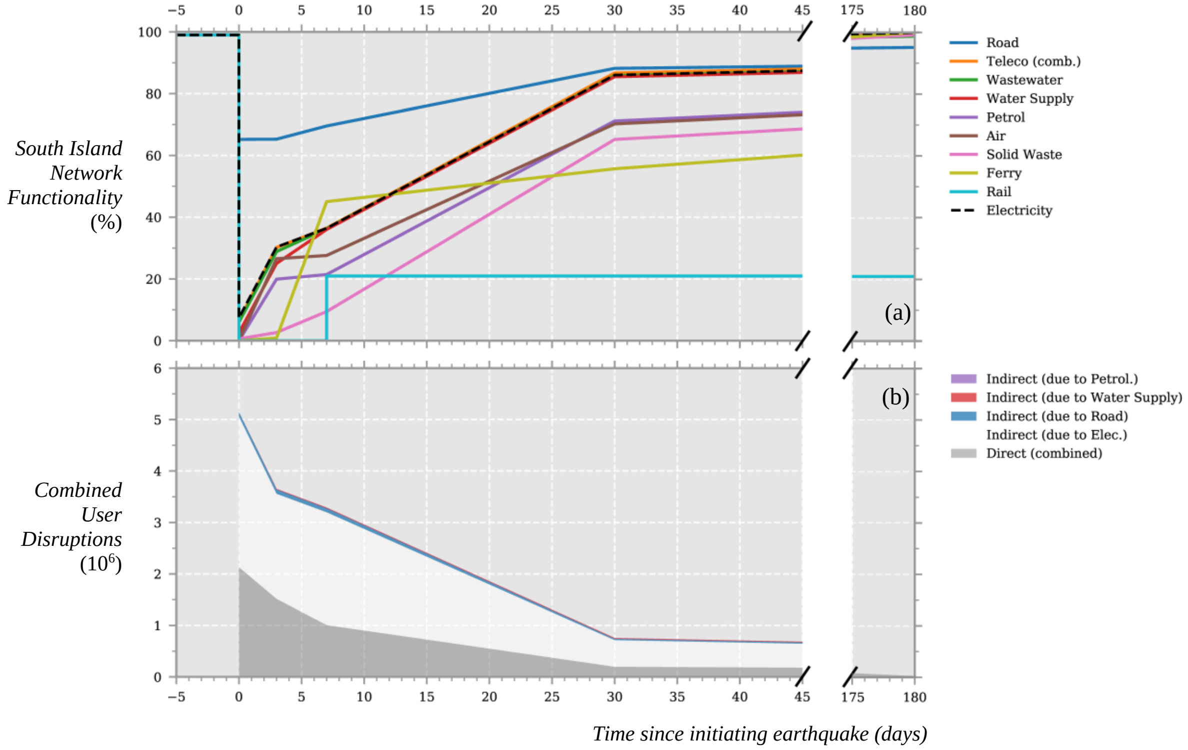

Figure 5: (a) Infrastructure network functionality for the South Island of New Zealand in terms of users disrupted (or passenger-kilometres restored for State Highways) and (b) the attribution of disruptions to direct or indirect causes (via interdependencies) combined across networks. A selection of Wellington (ferry/air) and South Island bound transport passengers (air) are also included.

This dependence on electricity is also reflected in Figure 5b, 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) accounts 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 (battery life/generator refuelling requirements/road access/supervision etc.) would be a valuable extension to work and should be incorporated as data for this becomes available.

5. CONCLUDING REMARKS

In this paper, we have presented an application of an end-to-end assessment framework for earthquake shaking and landslide hazards coupled with interdependent critical infrastructure network models and the corresponding recovery processes. Whilst this work is preliminary in nature, a number of immediate discussion points are highlighted for those charged with forming a response to a similar major earthquake event. 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 geographic setting, increasing connectivity (and therefore redundancy) across the State Highway network is largely unfeasible. Therefore, improving/maintaining asset robustness should be a priority. For electricity, ongoing work to introduce embedded generation and backup supplies in critical areas within the West Coast region should prove to significantly benefit the local resident populations while aiding timely recovery for dependent infrastructures.

In addition to the highlighted reliance on electricity, upon validation, infrastructure owner/operators further suggest that road access (along with petroleum supplies) is often a major limiting factor throughout the recovery phase (Davies et al. 2017b, McCahon et al. 2017). Such observations are not entirely represented in the curves of Figure 5a/b, 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. Similarly, the potential indirect disruptions due to petroleum shortages across the West Coast region during the recovery process is not immediately visible. This is due to the modelling approach which 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 impact the curves presented in Figure 5a with the potential for cascading setbacks across multiple networks.

This paper has highlighted the benefits of end-to-end disaster preparedness assessment, using a scenario-based approach. Detailed within this paper are a number of extensions to the work to assess the generalised recovery strategies and priorities across a wider range of potential Alpine Fault scenarios that are both in progress and proposed, particularly building on the need to focus on recovery, and not just the initial response. Firstly, the formal linking of hazard models, such as ground motion (Bradley et al. 2017), landslides (Robinson et al. 2016) and liquefaction (Motha et al. 2017), can provide a range of realistic inputs and allow model updates to be easily included when available. Improvements are further envisaged across each of the infrastructure sector models. In addition to increasing asset data (quality and quantity) and formalising attributes (such as whether assets are buried/overhead and if redundant electricity supplies are present), process based sector models (i.e. power flow) would be desirable for more accurately modelling user disruptions over our topological focused functionality metrics (LaRocca et al. 2015). Building these at a South Island scale proves difficult given the extensive data requirements and inherent computation costs – depending on the desired resolutions. Despite this, a number of these wider infrastructure network process models are in development through the research initiatives discussed in Section 1 (Liu 2017; Wotherspoon 2017). Similarly, there is further opportunity to provide a more robust assessment of damage and recovery at local/neighbourhood scales by incorporating the highly detailed water supply network fragility and recovery models of Bellagamba et al. (2018), without the need for extensive hydraulic modelling. Further, population movements (and therefore demands), transportation network behaviours (i.e. origin-destination pairings), and dynamic changing dependencies will in reality adjust our definitions of ‘normal’ service levels. Taking these into account will allow a more accurate representation of the true user disruption as opposed to pre-event comparisons which are more suitable to lower intensity events. The temporal resolution of any model updates should also be carefully considered.

Overall, this paper has explored the benefits of the scenario-based approach to integrate knowledge between infrastructure stakeholders and communities (Davies et al. 2017b). 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 discussed Alpine Fault rupture.

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