Tsunami damage and post-event functionality assessment of road and electricity infrastructure: a collaborative multi-agency approach in Ōtautahi Christchurch, Aotearoa New Zealand.

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Abstract

Coastal infrastructure are critical to the effective operation of society, but are highly susceptible to tsunami impacts. There has been limited research in the tsunami risk assessment discipline on network scale impacts of a tsunami to critical infrastructure. This study proposes and tests a framework for tsunami impact assessment of critical infrastructure. The framework is applied through a collaborative case study approach between researchers and practitioners to co-develop a tsunami impact scenario, which includes road and electricity network component damage, and spatio-temporal service disruption and restoration estimates (roads) in Ōtautahi Christchurch, Aotearoa New Zealand. A series of workshops were conducted throughout the impact assessment process to validate, refine and contribute to inputs, methods and results of this collaborative impact scenario. The results indicate that several coastal suburbs could expect no road access for 3 - 44 days, with 10 – 44 days required for all routes to be reinstated. The results provide inputs for informing mitigation initiatives for asset managers, planners and emergency managers. Results are used to inform recommendations for increasing tsunami resilience, including land-use management, emergency response planning, infrastructure component mitigation and infrastructure network mitigation. This study contributes to the global knowledge of tsunami impacts on built-environments and specifically provides a framework and case study for estimating road and electricity network impacts from tsunamis. The framework and associated methodology presented in this study are applicable to other coastal urban environments exposed to tsunami hazards, for assisting in initiatives that increase tsunami resilience.

Keywords: Disaster risk, resilience, critical infrastructure, natural hazards, service outage, service disruption, restoration time, network components

1. Introduction

Tsunamis damage and disrupt critical infrastructure networks which are crucial to the effective day-to-day operation of society [1–3]. Physical damage caused to network components can have cascading impacts on dependent networks. If impacted services are not quickly recovered, it can result in considerable social (e.g. habitability, liveability) and economic (e.g. regional Gross Domestic Product) consequences within and beyond tsunami affected areas. Service restoration is also critical for implementing effective response and recovery actions immediately after tsunami events [3–5]. There is a need to investigate the consequences of tsunamis on infrastructure network component damage and service disruption for at risk coastal communities.

Direct impacts from tsunamis, such as casualties and damage to the built environment, are caused primarily by hydrodynamic and hydrostatic forces, including flow velocity, scouring, inundation, buoyancy effects and impact by entrained debris [4,6–8]. Inundation extent and amplification effects are influenced primarily by wave height and frequency, local bathymetry, and topography. Analysing relationships between tsunami hazard intensity and levels of network component damage is required for establishing component-specific vulnerability models for use in credible tsunami impact assessments. Vulnerability models are necessary to quantify network component damage levels and service disruption to affected communities, directly or indirectly, by tsunami hazards, as an important part of disaster risk reduction [4,9–11].

Since the 2004 Indian Ocean Tsunami, impacts to critical infrastructure networks and their components have been frequently reported [12–18]. Road network component damage typically observed includes scour of weak base materials and bridge abutments, lifting of surface material and bridge superstructure, removal of signage and barriers, and complete washout of road sections and bridge structures [3]. Debris deposition can also hinder road service [19]. Damage typically observed for electricity network components includes bent/snapped distribution poles, water infiltration causing short circuiting, scoured and compromised buried cables, saltwater contamination and corrosion of electrical components and washout of various components [3]. Indirect impacts to society can be severe and long-lasting, and consist of disruption to lifeline services (including road and electricity networks), community isolation, human displacement, economic loss and psychosocial impacts [5]. Despite these observations, quantitative information on network component damage from tsunamis remains scarce, relative to other built-environment elements (e.g. buildings [8,20]), and data on post-event functionality of infrastructure networks are even more scarce [4].

Given the importance of critical infrastructure to society, a prudent development for tsunami risk assessment is to compile or develop suitable impact assessment tools, specifically infrastructure vulnerability models. These models can be applied to better inform tsunami risk reduction and response planning. The tsunami infrastructure risk and resilience field would ideally strive to replicate the impact assessment capabilities of other, more developed natural hazard disciplines (e.g. earthquake). Extensive post-event earthquake infrastructure impact assessments [21–24] and physical component-level testing [25,26] lend themselves to infrastructure damage, outage, restoration and economic impact quantification that consider infrastructure network interdependencies (e.g. [27–30]). A long-term goal identified for tsunami risk assessment research is the improvement of quantitative infrastructure vulnerability models with attribute- or site-specific tsunami vulnerability information, including material and construction type [11,19,31]. This would provide disaster risk managers with access to relevant data to inform decisions around increasing resilience in coastal communities through the application of local data specifications and globally applicable modelling resources.

Of all the critical infrastructure networks, road and electricity distribution networks are typically rated as the first and second most important for dwelling habitability [5,22,27,32]. Roads provide access to impacted, and potentially isolated, coastal communities and properties following a damaging tsunami event. Road access is typically the first stage of post-disaster infrastructure restoration, with many other infrastructure network operators relying on road access to begin assessing and repairing their respective networks [32,33]. Road transport is the most developed network in terms of available empirical vulnerability models for tsunami hazards (Williams *et al.*, 2020a). Electricity is a key interdependency with most other critical infrastructure networks, and a considerable gap in tsunami fragility and impact assessment literature. Several studies (e.g. [11,19,31,34,35]) highlight the lack of damage and vulnerability models for electricity and road network components, despite their importance for recovery actions and increasing resilience. The importance of road and electricity distribution networks to service recovery efforts heightens the need to investigate physical damage and service disruption at a local-level to determine network service recovery requirements for exposed coastal communities.

This study develops and tests a framework to determine potential tsunami impacts on critical infrastructure networks. We use a deterministic tsunami impact model to quantify direct physical component damage and service disruption to road and electricity networks exposed to a maximum credible tsunami. A contextual background of the case study area (Section 2) precedes an overview of the methodological impact assessment framework development (Section 3) with results then presented for the proof of concept impact assessment of Ōtautahi Christchurch (Christchurch), a tsunami-exposed city in Te Waipounamu the South Island of Aotearoa New Zealand (NZ) (Section 4). A discussion of the impact assessment (Section 5), is then presented, followed by key recommendations for tsunami mitigation, and lessons learned for future investigations of tsunami impacts on critical infrastructure networks.

2. Case Study Background

With a population of 369,000, Christchurch is located on NZ's east coast (Figure 1) and is exposed to local, regional and distal source tsunamis, although the local and regional hazard is considered relatively small [36–42]. The tsunami hazard for Christchurch is estimated to be > 9.5 m and > 12.5 m wave heights at the coast at the 50th and 84th percentiles respectively, for a 1:2,500-year return interval [41]. The most likely tsunami source for both a 1:2,500- and 1:500-year event at the 50th percentile is the Peru subduction zone [41]. Tsunamis, and specifically damaging tsunamis, are broadly considered low probability, but high impact for Christchurch [43]. Although the tsunami hazard has been well researched for Christchurch [3,5,37–41,43], the likely societal impacts have not. Effective risk management is required to reduce potential tsunami impacts on Christchurch's critical infrastructure. Such planning should be underpinned by a credible tsunami impact model for critical infrastructure.

Christchurch experienced major impacts from the 2010–2011 Canterbury Earthquake Sequence (CES) [44,45]. This is contextually important as substantive widespread damage occurred to infrastructure networks, including transport and electricity network components across the coastal suburbs, largely from earthquake-induced liquefaction and attendant ground deformation [46]. The electricity network experienced considerable damage to components, especially buried cables. However, the network remained largely operational, other than localised long-duration outages, and recovered relatively quickly in comparison to the road transport and 3-waters (potable water wastewater and stormwater) networks. This is, in part, due to prior seismic strengthening of new and existing electricity network components, particularly substations, undertaken as a result of past resilience building initiatives [47].

A previous study of tsunami impacts on Christchurch's critical infrastructure was conducted by Williams *et al.* [3], which developed and applied a qualitative tsunami damage matrix based on field survey observations and a literature review. This impact assessment included several critical infrastructure components, (e.g. road components), but excluded electricity components. Williams *et al.* [3] qualitatively estimated that, for a large tsunami, many coastal roads in Christchurch had a medium to medium-high damage potential, with the relatively greater damage potentials estimated in the suburbs of Sumner, Moncks Bay/Redcliffs, Southshore, and New Brighton (Figure 1). The only Christchurch tsunami impact assessment to use empirical vulnerability models was for building impacts by Scheele *et al.* [5], to inform a post-event habitability assessment. The assessment incorporated tsunami impacts on infrastructure into a habitability framework, which considered the qualitative infrastructure impact results from Williams *et al.* [3]. Both Williams *et al.* [3] and Scheele *et al.* [5] recommended the development of fragility curves for empirical infrastructure impact assessments, and recommended electricity network components be specifically included in any subsequent impact assessments. Williams *et al.* [3] also goes on to recommend outage and restoration assessments be carried out in future tsunami impact assessment studies. Subsequent studies have developed empirical infrastructure fragility curves [19,31], and the present study develops and tests a framework for such a quantitative infrastructure impact assessment, including for tsunami damage, network outage, disruption and restoration time of road and electricity network components.

The Christchurch City Council (CCC; the local governing body) and Orion Group (Orion; the local electricity distributer) take a proactive approach to risk management and are engaged with the scientific community to understand tsunami hazard and risk. They are supported in this mission by Environment Canterbury (the regional council) and, as per the Civil Defence and Emergency Management Act 2002 [48] (sets post-disaster service requirements for lifeline utilities), by Civil Defence and Emergency Management (CDEM) Groups, (each Group delivers CDEM through its executives, planners and operational staff of the many agencies involved in CDEM) and Lifelines Groups (the CDEM Act 2002 requires individual Lifelines Groups to establish planning and operational relationships with CDEM Groups). Tsunami inundation modelling and risk assessments are used by CCC and Orion to inform infrastructure design and urban planning. This case study is designed to inform these aspects and allow better planning and preparedness measures to be undertaken for critical infrastructure.

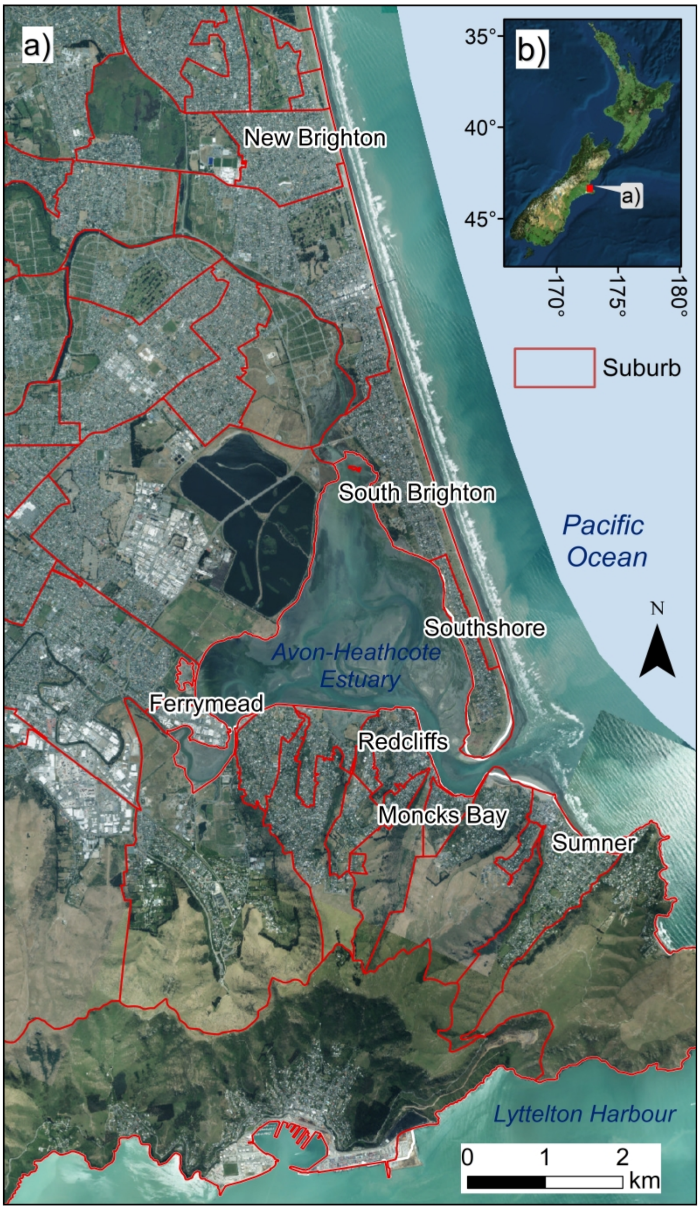

Figure 1: Study area location (a) and relevant locations in Christchurch (b). Base map source: LINZ Data Service (licensed under the Creative Commons Attribution 4.0 NZ).

3. Methods

3.1. Methodological Framework

The methodological framework used in this study (Figure 2) consisted of: defining the hazard, vulnerability and exposure inputs for the impact assessment; a physical damage assessment (Section 3.4) to determine the severity and extent of potential physical damage to exposed network components; and a service disruption assessment (Section 3.5) to quantify the time operating at reduced levels of service (Section 3.6). At each stage of this methodological framework, workshops were held with the relevant utility operators and managers (CCC (roads) and Orion (electricity)) to validate the methodology and results.

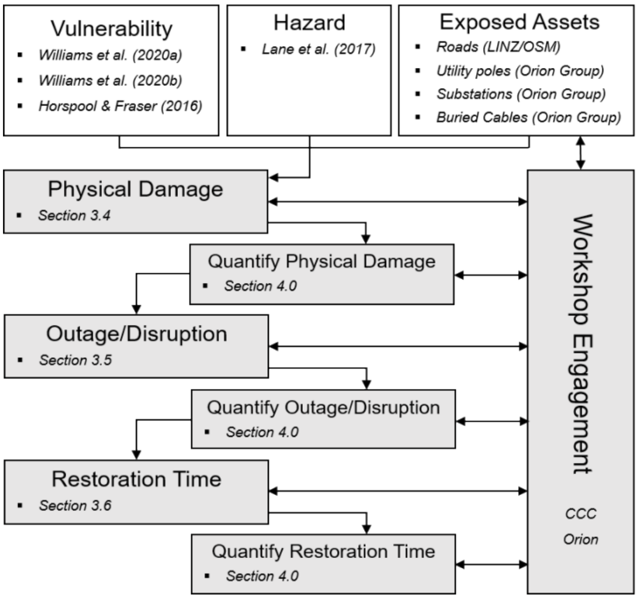

Figure 2: Methodological tsunami impact assessment framework. Shaded boxes indicate direct contributions from the collaborative impact scenario developed.

3.2. Engagement process

An engagement process, centred on a series of workshops with utility collaborators, was used to refine and validate the impact assessment modelling. It was intended to ensure that the approach remained scientifically robust, while also producing useful and useable outputs for lifeline utilities and emergency management planning. Engagement with CCC and Orion was initiated at the study inception and continued throughout (Figure 3). Both CCC and Orion specified a preference for the lead author to conduct impact assessments and present initial results for critique, refinement and/or validation within each engagement cycle (physical damage, outage/disruption and restoration time). Other than method and results validation, the co-developed aspects were the network component data collection/selection (Section 3.3), the impact assessment methodology for buried electricity cables (Section 3.4) and the restoration time modelling for roads (Section 3.6).

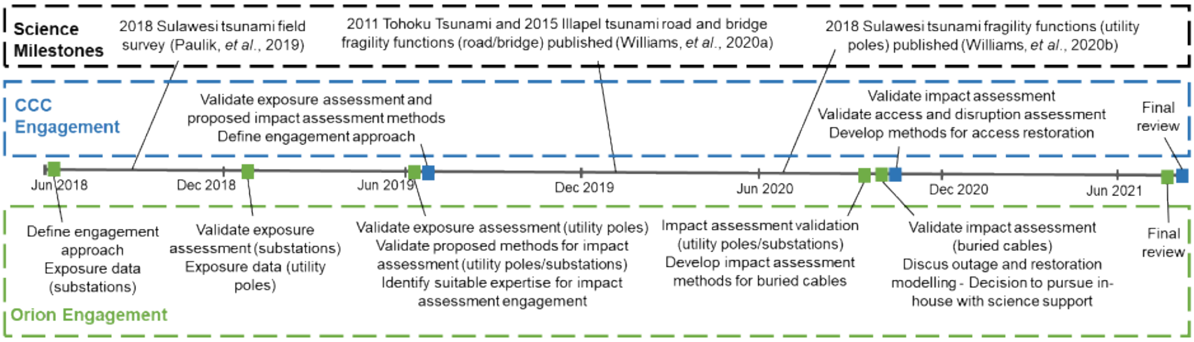

Figure 3: Timeline and key milestones of engagement with CCC and Orion for method development and results validation. Engagement begins June 2018 and continues through to August 2021.

3.3. Impact Assessment

This section outlines the collection and preparation of data that is used in the impact assessment scenario modelling. The following paragraphs cover the hazard model, exposure inventory and vulnerability models, summarised in Table 1. Damage level descriptions for each network component are presented in Table 2.

Table 1: Impact assessment input data for Christchurch case study

Hazard Model	Component	Component Geometry	Component Attributes	Vulnerability function
Lane, *et al.* [40], 1:2500 ARI, inundation depth, present day sea level	Bridge	Line converted to point	General	Williams *et al.* [19]
	Road	Line	Capacity class, culvert topographic setting, distance from coastline	
	Culvert	Point	Diameter	N/A
	Utility Pole	Point	Material, height	Williams *et al.* [31]
	Secondary Substation	Polygon converted to point	General	Horspool & Fraser [34]
	Primary Substation	Polygon converted to point	General	
	Buried Cable	Line	Size, road (co-located)	N/A

Table 2: Damage level (DL) descriptions for infrastructure network components [3,12,19]

Network Component	DL0	DL1	DL2	DL3
	No Damage	Partial Damage, Repairable	Partial Damage, Unrepairable	Complete Damage
Road	-	*Minor damage to road surface, all lanes passable with caution*	*Major damage to one lane. One lane impassable*	*Major damage to whole carriageway, all lanes impassable*
Bridge	-	*Minor damage, often from impacts to the superstructure*	*Major damage to superstructure but still in place on piers, superstructure may have been shifted*	*Complete washout of superstructure*
Pathway	-	*Damage to path surface, minor damage to subgrade, passable with caution*	*Damage to path surface and subgrade, not passable*	*Complete damage to subgrade and surface, not passable*
Utility Pole	-	*Scour or minor damage at base, pole in place*	*Buckling of pole, damage to pole base/foundation*	*Pole bent, snapped or sheared from base/foundations*
Buried Cable	-	*Minor scour to weak backfill, cable not exposed, no damage*	*Scour of backfill and partial or full exposure of cables, scrapes and dents to cable insulation, no cable break*	*Full exposure of cable, break in cable, washed away,*
Substation	-	*Minor damage to components, mainly from shallow, low velocity water intrusion. Shorting and loss of service, minor repairs required*	*Moderate damage where components have been inundated. Shorting and loss of service, major repairs or replacement of damaged components*	*Complete damage, components and structure washed away. Loss of service, major rebuild and replacement of components required*

Hazard model: There are a range of available tsunami hazard models for Christchurch [38–40,49–51]. The scenario chosen for this case study represents a maximum credible tsunami from a 1:2,500 annual return interval (ARI) Mw 9.4 Peru subduction zone source (Figure 4). For this, a numerical inundation depth model is selected from Lane, *et al.* [40] (Table 1, Figure 4). This incorporates tsunami flow up rivers, which has resulted in a larger and more credible tsunami hazard when compared to previous model iterations [39]. This model assumes static topography, therefore, in places where dunes are expected to be severely eroded, the model is likely to be underestimating inundation [40,52].

Exposure inventory: As outlined in Section 1, this case study focuses on road and electricity network components. A number of key components are selected to model in each network, with the driving criteria being that they are all critical network components and they have spatial data available. For roads, selected network components include road carriageways and bridges. Road data are publicly available [53,54] and are only refined to suit the spatial distribution of the study area (Figure 4a). Road bridge data are sequestered into a separate dataset and represented as points (Figure 4a). For electricity, selected network components include substations (primary and secondary), utility poles and buried cables (Figure 4b). These data are supplied by Orion directly. Road carriageways and buried electricity cables are split into 20 m and 50 m sections, respectively. For roads, this is to capture the minimum damage length observed in field surveys [19,31], and in the case of electricity this is to capture the minimum jointing distance for older buried cables in the study area. To apply the highest resolution vulnerability modelling available [19] 'steep' and 'flat' topographic classifications are manually assigned to the roads dataset (Figure 5). The presence of culverts (Figure 5) is also considered in the impact assessment, through a damage probability modifier (see Sections 3.4 & 3.5). Culverts are digitised using remote sensing (satellite imagery and "street-view" imagery; [55]) and then refined through a field survey of the study area. Culverts are co-located with each intersecting road section and binary-coded (present = 1, not present = 0).

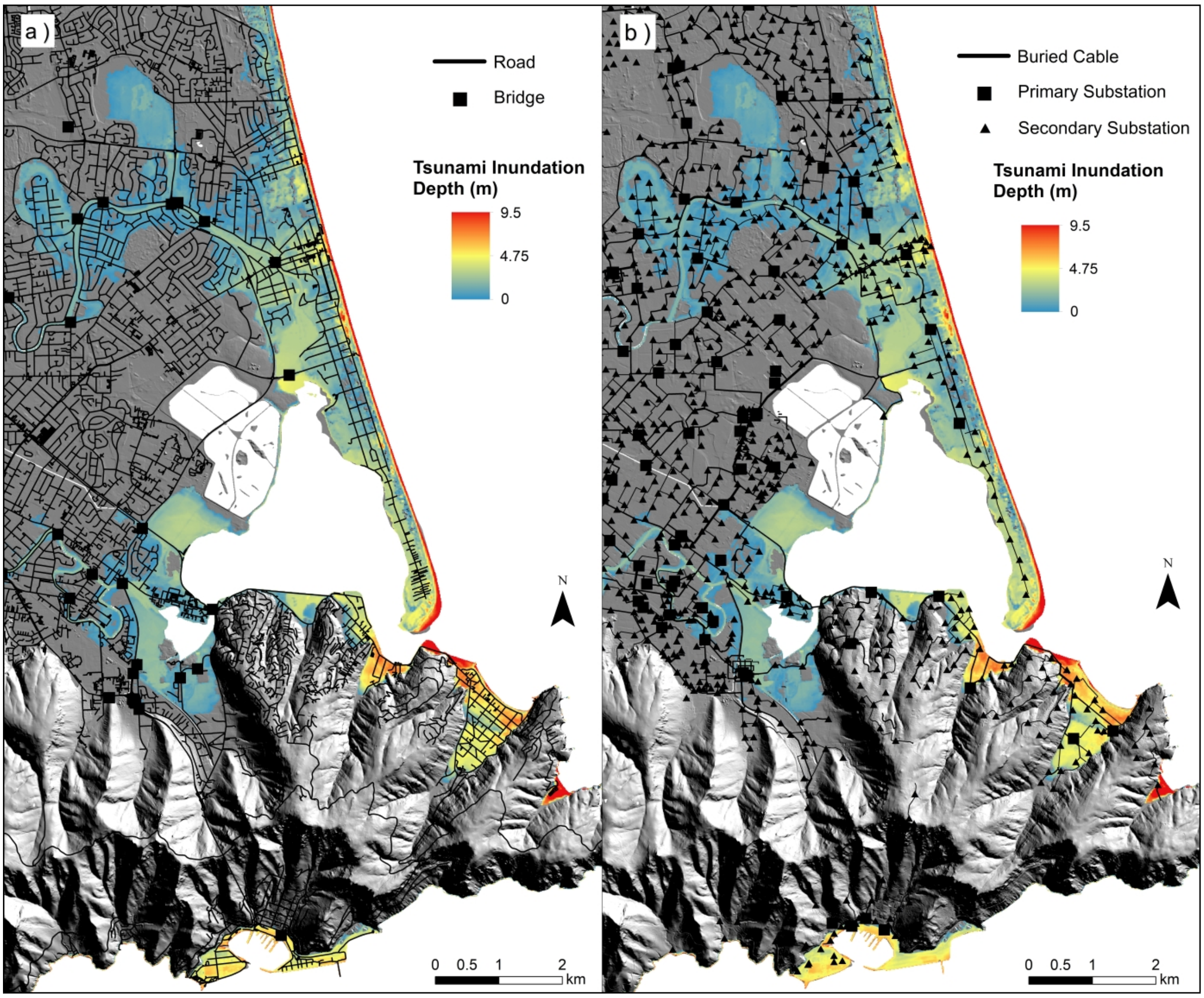

Figure 4: Tsunami hazard model (adapted from Lane *et al.* [40]) and exposure of (a) roads [53,54] and (b) Orion electricity network components.

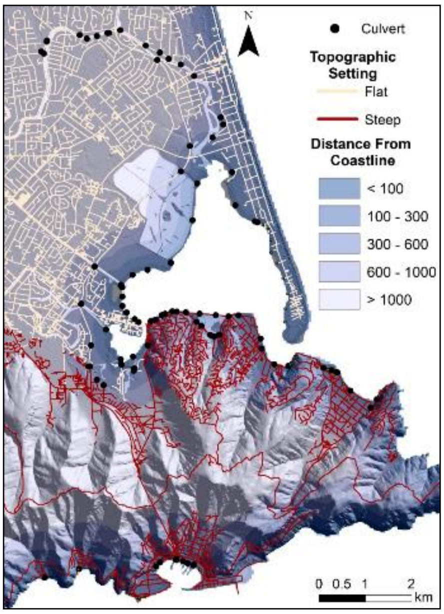

Figure 5: Distance from a coastline and topographic classifications used for Christchurch roads in vulnerability model application and culvert locations used in road damage probability modification.

Vulnerability models: For roads, fragility curves from Williams *et al.* [19] are used for this impact assessment, given their consideration of road capacity classes (as a proxy for construction type) and topographic setting (as an indicator of increased hazard intensity; Table 1; see Section 3.4). Fragility curves from Williams *et al.* [19] are also used for bridges, as they are based on the highest resolution empirical damage dataset available. For utility poles, fragility curves from Williams *et al.* [31] are used, which consider pole height and pole material. Substations do not have empirical fragility curves available, however, Horspool & Fraser [34] have developed fragility curves for substation components through a workshopped expert elicitation process. These consider indoor and outdoor substation components. In this study these are applied by classifying primary substations, which are housed inside buildings, as "indoor" and secondary substations, which are housed at street level, as "outdoor". Buried cables do not have any available vulnerability models so none are used in this study. However, buried cables in Christchurch typically follow existing buried services 'corridors', which themselves typically follow transportation corridors. Therefore, buried cables are co-located with damaged roads, using a 20 m buffer, to infer vulnerability (Figure 3). The buried cables are assigned a 0.5 probability of damage occurring if co-located with a damage level (DL) of DL2 or DL3 road section. This approach was determined with Orion staff, who judged it appropriate in the absence of applicable vulnerability models. Orion also validated a decision to exclude DL1 buried cables (with respect to the co-located road damage method), as this damage level is not conducive with the exposure of buried cables (i.e. no erosion of the backfill surrounding each cable) [3,13].

While tsunami inundation depth is used as the hazard intensity measure (HIM), other hazard intensity indicators that might have a bearing on road vulnerability were also considered. Damage to culverts was not directly calculated in this paper as no fragility curves are available. But they are considered as a vulnerability modifier for roads, along with the distance from the coastline (Figure 5). Inundation speed, the degree of submersion and location and size of the culvert are all factors influencing contraction scour intensity at culverts [56]. Scour can also be exacerbated by enhanced turbulence and vortex formation. Additionally, scour around culverts can be caused by the back flow as the tsunami recedes. Both of these vulnerability modifiers are based on the observations from Williams *et al.* [19]. The damage probability modifiers for the distance from a coastline are based on a linear best-fit model, while the culvert co-location damage probability modifiers are +0.083 (DL1), +0.167 (DL2) and +0.333 (DL3) [19].

3.4. Physical Damage Assessment

The first step of the impact assessment framework (Figure 2) is to calculate the physical damages. First an exposure assessment was conducted to calculate the HIM at the location of each network component, which is presented in Section 4. In the case of linear infrastructure features (e.g. roads), the hazard intensity is sampled from the centroid of each section. The relevant vulnerability models (Table 1; Section 3.3) are then applied to define a probability of reaching or exceeding DL0 – DL3. This vulnerability assessment is conducted using the risk assessment tool 'RiskScape' [57]. A random-weighted distribution method is then adopted to define deterministic damage levels (i.e. one realisation of the random variable) based on the probability of each component reaching or exceeding DL0 - DL3, following the method used by the Wellington Lifelines Group [27]. The results of this initial physical damage assessment were then presented to CCC and Orion, who reviewed and validated the approach and results, with minor refinements. Specifically, CCC requested manual refinements be made to the deterministic damage level for bridges, to reflect recent earthquake strengthening initiatives not directly captured in the exposure inventory and vulnerability models [58].

3.5. Service Outage/Disruption Assessment

The next stage of the methodological framework (Figure 2) is to assess the service outage and disruption as a result of the physical damage results (Section 4). The highly interconnected nature of Orion's electricity network does not lend itself to directly deriving network service disruption and restoration times through expert elicitation (Section 3.6), so none are developed in this study (see Section 5 for commentary on suggested future work). In the case of roads, to define a level of access, routes into and through impacted suburbs are traced using a hierarchy of primary roads; then lower capacity roads until either a route is found that avoids a DL3 (i.e. impassable) road (reduced access) or all routes are exhausted (no access). Although DL1 and DL2 roads would cause a reduction in road capacity and an increase in travel time, they are not considered to directly restrict access. Road 'disruption' (see Section 4), which defines how much access there is within a suburb, is applied using the same approach of tracing routes across each suburb (i.e. secondary access routes and tertiary access routes) and based on whether a vehicle could travel across or around a suburb, rather than simply into a suburb, as with 'access'. This process, and the initial service outage and disruption results, are presented to the CCC road engineers, who agree this approach is logical and that the resulting service levels are credible [58].

3.6. Service Restoration Time Assessment

This approach was co-developed with CCC road engineers (Section 3.2). Based on the physical damage assessment (Section 3.4) and road access levels (Section 3.5), two priority routes through the impacted areas were defined, and a strategy for restoring 'response' level access to all suburbs was developed in conjunction with CCC. 'Response' access is indicative of the response phase of emergency management and would allow emergency-level access for residents, but would primarily serve as access for emergency services and site access for infrastructure repair works. These repair strategies/sequences are explored considering network operation hierarchy, inter- and intra-dependencies of the network components, priority/critical customer needs, availability of repair equipment/machines, replacement materials etc. There are no high-value critical sites (e.g. hospitals) within the inundation zone, however asset managers, including CCC, have access to, and are required to consider, a generic restoration priority list as standard practice for NZ lifelines operators [48].

A number of further assumptions are made when estimating the road outage times. These are:

Restoration timings:

- The response begins on day 2, allowing one day for the hazard to pass, ponded water to drain and for recovery planning to commence.
- Maintenance teams will work on restoring access for two primary routes across the impacted areas (Section 4, Figure 9).
- Maintenance teams will begin at the first accessible point(s) along each primary access route and work in both directions until teams meet (Section 4, Figure 9).
- Debris is considered to be present in all areas, affecting access for maintenance teams. This will be cleared at each section of damage, with debris clearing teams moving ahead of each repair team – therefore no extra days are added for this.
- Access is restored to a response-based level of service (i.e. repairs may be temporary, provide low capacity access, be only for emergency response efforts).
- An estimated 1 day restoration time per DL3 road section. CCC could reinstate 2 - 3 short sections in one day, but longer sections could take 2 - 3 days (1 day on average).

- Culvert size, where available, influences restoration time: assume 2 days for road sections associated with large culverts (>450 mm), 1 day for other culverts (<450 mm) in addition to the 1 day for road repair.
- Culvert depth and loading are also important factors. If near a stream, more caution (and time) is required.

Resources:

- There are enough resources for maintenance teams to begin at each starting point and work simultaneously.
- DL3 roads would likely be filled with gravel/aggregate to achieve short- to medium-term access for emergency operations. There is a large easily accessible supply <20 km from affected areas.
- CCC are likely to engage 4 - 5 major contracting companies. Tsunami damage in multiple regions could affect contractor availability. CCC will have no major issue with resourcing, but could have issues with fitting resources into an area and access to that area and will be reliant on how quickly local quarries can supply materials.
- Restoration planning assumes enough resources are available to restore access from both directions of isolated communities (e.g. Ferrymead – Sumner and Sumner - Ferrymead) simultaneously.
- Large culvert replacements (>450 mm) may need to be ordered in.
- CCC are likely to adopt a collaborative model (as used during the 2010/11 CES) where contractors share a resource pool, while being distributed/relocated to different damaged suburbs around the city.

Bridges:

- CCC requested that all but one of the bridges assessed to be in DL3 for the impact scenario are manually adjusted to DL1, reflecting a perceived over-estimation of damage with respect to recent seismic and tsunami bridge strengthening works in Christchurch.
- Restoring bridge access with bailey bridges would require 2 - 4 weeks. This is not considered in the service restoration assessment as it has no change the restoration time results in this impact scenario.

3.7. Limitations

Inherent uncertainties associated with assumptions and limitations within each stage of the impact assessment framework are summarised in Table 3, in addition to the likely implications for under- or over-estimating tsunami impacts for the given case study.

Table 3: Limitations and assumptions made in the methods used and their implications for the impact scenario in terms of underestimation or overestimation.

	Assumption/Limitation	Implications for impact scenario *	
		Under-estimation	Over-estimation
Hazard	Inundation depth is the only hazard intensity directly considered for assessing component vulnerability (Figure 4).	■	
	The hazard model used (Figure 4) is based off a 15 m resolution grid, so may not capture the true effects of building and land features on form-drag [40,52].	■	▨
	The hazard model used (Figure 4) does not consider sediment transport, erosion or aggradation. This likely underestimates inundation where dunes are damaged [40,43,52].	■	
	Cascading hazards are not directly considered, including debris, ponding, rainfall, slope stability, topography changes (aggradation/erosion), scour and pre-existing conditions associated with seasonal changes in the water table and precipitation. There is high uncertainty around many of these factors.	■	
	Inundation flow speed and energy are only indirectly, and broadly, considered through topographic classifications and distance from coastline. Although this increases the model resolution, it is based on conservative expert judgement and likely under-estimates damage further from the coast and overestimates it closer to the coast.	▨	▨

Exposure		There may be critical infrastructure components not included in each network's (road and electricity) dataset.	░	░
		Culverts are not visible in-field, but remotely sensed through aerial, satellite and 'street view' imagery. This means for the most part their attributes are unknown.		▒
Vulnerability		Most vulnerability models do not directly consider a component's attributes (with respect to tsunami vulnerability).		▒
		The vulnerability models used, which are based on international network component standards, and local source earthquakes, are based on events with high levels of seismicity (other than Illapel) compared to the distal source Christchurch case study.	░	▒
		Vulnerability models based on inundation depth resulted in some anomalous damage being modelled, particularly evident near the extent of in-land inundation. These were infrequent, and easily removed, which has very slightly reduced the reported damage overall.	░	
		The culvert damage probability modifiers (Section 3) are based on one international event with a considerably smaller tsunami than the case study tsunami scenario. As a result, these damage probability modifiers likely underestimate damage at the coast and overestimate it further inland.	▒	
		The vulnerability models used for substations are based on expert elicitation rather than empirical field data.	░	░
Impacts	Physical damage	The impact modelling represents one realisation of the random variable (Figure 6 and Figure 7). Subsequent representation of the random variable will see a change in the damage distribution represented and therefore a modification of the subsequent outage and restoration modelling.	░	░
		Cascading impacts are not directly considered. For example, considerations of the post-event cascading storm water impacts (blockages and changes in flow paths) could create considerable drainage issues and flooding.	▒	
	Service disruption and restoration time	Various references (Section 1) highlight the need for interdependencies to be considered in infrastructure service outage and disruption modelling (Section 3), which is only indirectly considered through stakeholder engagement workshops in the present case study.	▓	
		Many political and social factors are not directly considered in the case study, including human welfare, crowd management, exclusion zones, post-event land-use changes or restrictions, post-event public pressure for recovery, time of year, the welfare of road maintenance crews, road engineers and traffic management personnel.	▓	░

**darker colours represent relatively major implications than lighter colours, which reflect relatively minor implications. No colour means none or negligible implications.*

4. Results

This section presents the results of the tsunami exposure and impact assessment. Table 4 displays the results of the exposure assessment outlined in Section 3.4. More than 87.7 km of roads, 2318 utility poles and 62.9 km of buried cables are exposed to >1 m inundation depth. Notably, there are 65.6 km of infrastructure network linear components (roads and cables) and 945 component points (bridges, substations and poles) exposed to >2 m of tsunami inundation in this scenario. Approximately 32 km (16%) of tsunami exposed roads and 1 bridge are damaged beyond repair (≥ DL2). For electricity, 10 km (6%) of buried cable, 1254 (27%) utility poles, 79 (29%) secondary substations and 5 (24%) primary substations exposed are damaged beyond repair (≥DL2). The highest concentrations of physical damage are expected, occurring in areas with either higher inundation depths and/or higher concentrations of network components.

Table 4: Tsunami exposure and damage levels for Christchurch road and electricity network components

Infrastructure component	Total Exposed	Exposure			Damage Level			
		< 1 m depth	1 – 2 m depth	> 2 m depth	DL0	DL1	DL2	DL3
Bridge	24	22	2	0	13	10	0	1
Road (km)	200	112.5	45.1	42.6	151	17.5	17.4	14.3
Utility Pole	4652	2333	1422	896	2197	1259	371	874

Secondary Substation	270	170	53	47	143	48	42	37
Primary Substation	21	13	6	2	13	3	4	1
Buried Cable (km)	155.0	91.6	39.9	23	145		7.8	1.9

The results for the road network access and disruption (Section 3.5) are presented in Figure 8. There are three areas of complete isolation in Southshore/South New Brighton, Ferrymead and Moncks Bay (Figure 8). In the case of South New Brighton and Southshore, this is due to the physical damage (Figure 6) and a lack of alternative routes down the coastline, which restricts access to these suburbs even during business as usual. In Ferrymead there are multiple routes into the area, but, in this scenario, they are all cut off (Section 3.6; Figure 6). Moncks Bay is accessed by a coastal route, pre-event, but unlike neighbouring suburbs, there is no access from the roads above (see Figure 9 for alternate access routes). In terms of disruption (i.e. the ability to travel across a suburb), these completely isolated communities (Figure 8b) all experience major disruption, as well as New Brighton, Sumner and Redcliffs, with the latter two experiencing some of the highest tsunami exposure in the city (Figure 4).

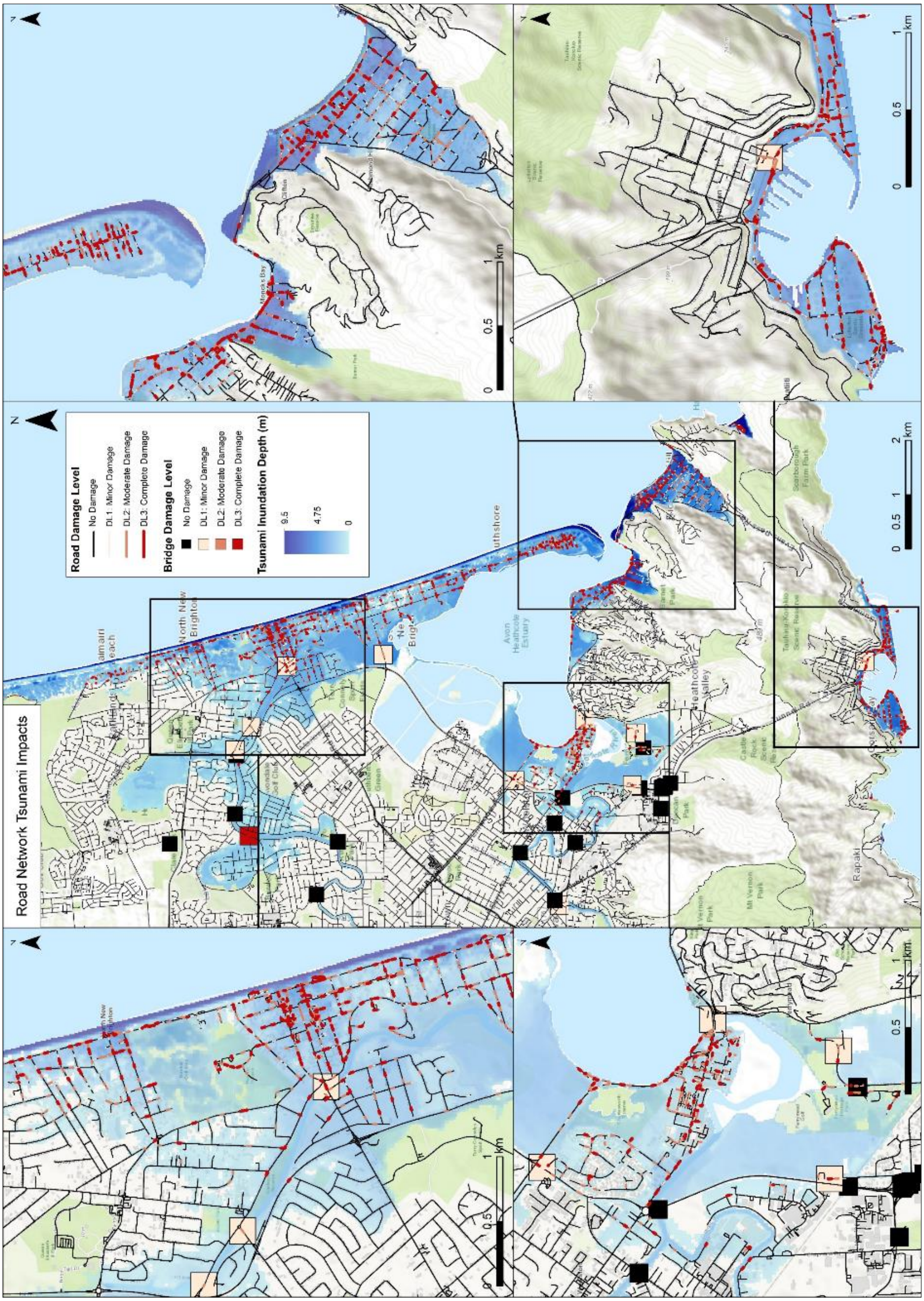

Figure 6: One realisation of the modelled road component damage levels for a maximum credible tsunami inundation scenario in Christchurch, NZ.

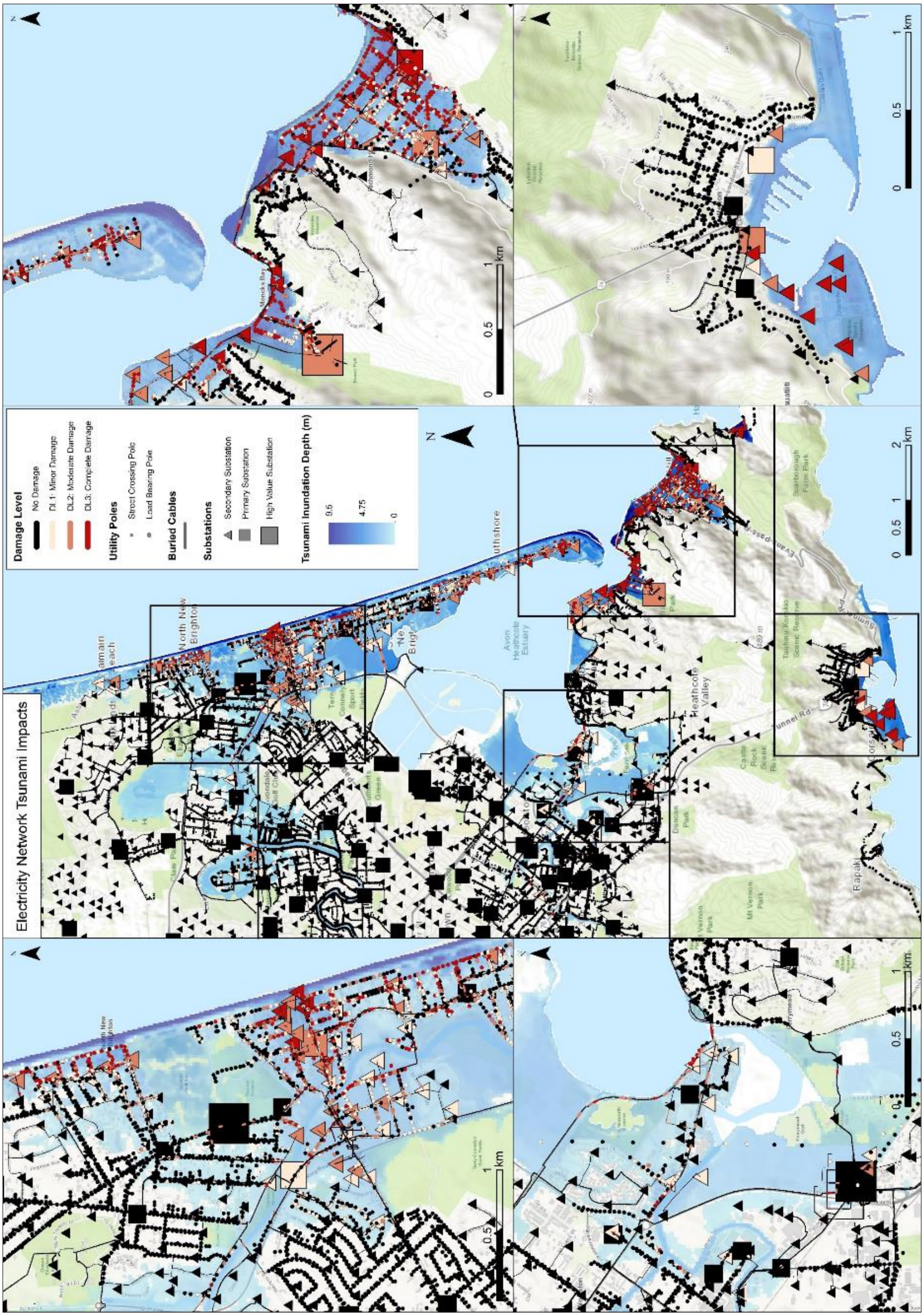

Figure 7: One realisation of the modelled electricity component damage levels for a maximum credible tsunami inundation scenario in Christchurch, NZ

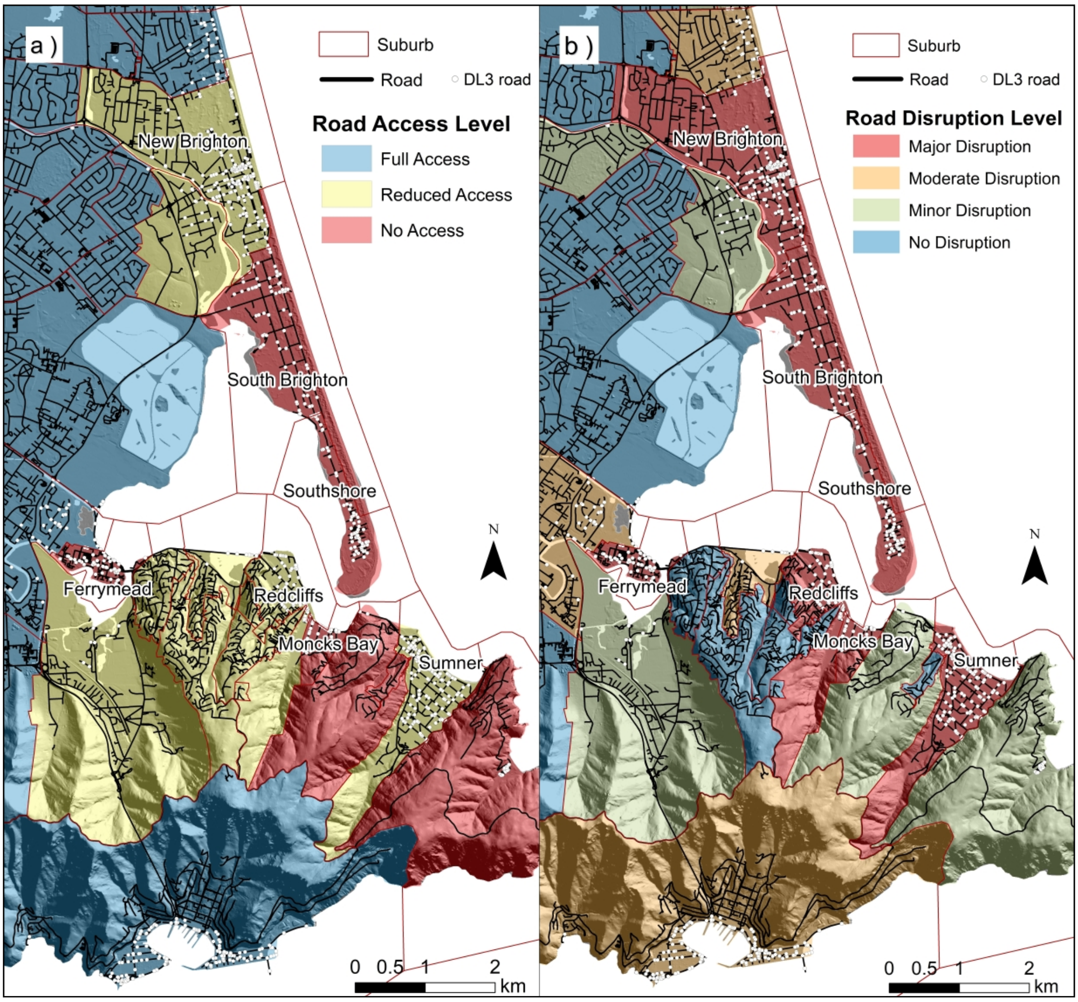

Figure 8: Road access (a) and disruption (b) levels estimated for Christchurch, NZ, immediately following the case study tsunami scenario.

The times to restore a response-based level of road service are presented in Figure 9. Shown are the times required to restore one primary access route ("no access" to "reduced access"), at least two primary access routes, and all primary access routes ("reduced access" to "full access"), respectively. The highest number of days, post-event, required to restore response-based access (Figure 9a) is in Southshore (44), followed by South Brighton (20), Moncks Bay (17) and Ferrymead (3). Note that Southshore only ever has one access route. In terms of gaining access to more than one route, the coastal suburbs are disproportionately affected relative to the rest of the city (Figure 9b & c). This is a result of physical damage and comparatively low pre-event route redundancy. Most southern coastal suburbs do not receive access to a second primary access route until Day 17 (Figure 9), which is a result of the coastal route restoration providing access from west to east on Day 17 (Figure 9). The road service disruption (Figure 8) and access restoration times (Figure 9) are consistent with assumptions, used in Scheele *et al.* [5], around access in Christchurch following a large tsunami. These results (Figure 8 and Figure 9) are also consistent with the transport recovery work undertaken by CCC and their contractors, who repaired and replaced 1,300,000 m^2 of roads and 144 bridges following the CES [59] and, more recently, the road response and recovery work following the 2016 Kaikōura earthquake [21,22,32].

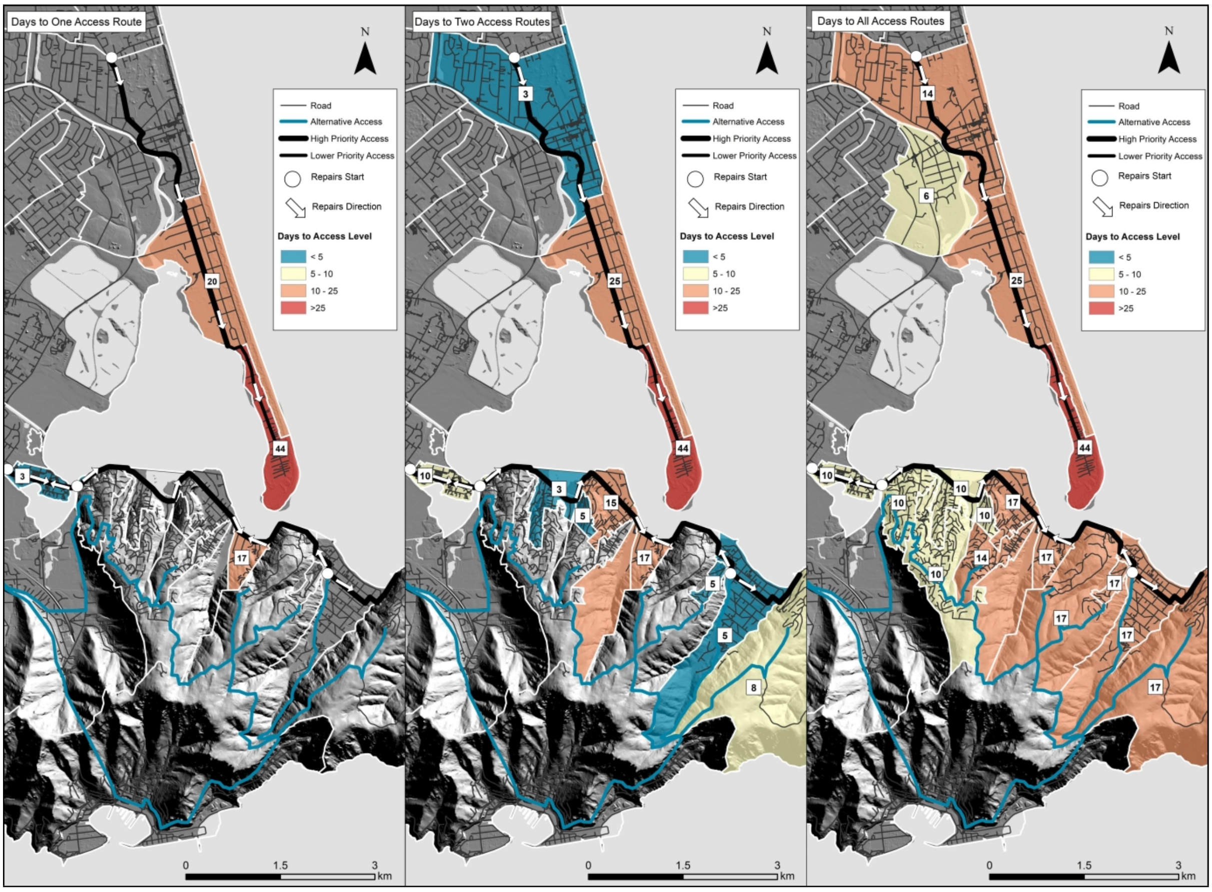

Figure 9: Time to restore response-based access routes for a) one primary route, b) at least two primary routes, and c) all primary routes.

The service outage, disruption and restoration assessment (Figure 8 and Figure 9) is not included for electricity, as Orion preferred to model these internally.

5. Discussion

This study represents an important step for tsunami impact assessment for critical infrastructure using empirical models. It is the first time road transportation outage, disruption and restoration time have been modelled for a hypothetical tsunami event. The tsunami impact assessment framework presented in this study can produce results reported as damage level likelihoods and deterministic component damage levels (e.g. Figure 6, Figure 7, Figure 8 and Figure 9). This study demonstrates a collaborative interdisciplinary approach to impact model methods can considerably improve the realism and credibility of a tsunami impact scenario. Honing an impact assessment towards the requirements of relevant practitioners is likely to increase involvement and uptake in the research outputs, ultimately increasing the usefulness and usability of the research.

The following sections provide further discussion on the effectiveness of the engagement approach, model limitations, case study mitigation recommendations and recommendations for future research.

5.1. Effectiveness of engagement approach

The effectiveness of the engagement approach used throughout this study included:

For physical damage assessment (roads and electricity):

- A guided approach to the selection of appropriate vulnerability models.
- An informed implementation of the hazard scenario(s).

- The provision and continual updating of relevant network component data.
- An interpretation of network component data and explanation of network connectivity.
- Some critique of results in direct conflict with previously approved methodology.
- Extensive discussion on network pinch points/nodes (bridges/substations) over links (roads/cables) (a potentially unintentional consequence of visual representation in impact maps).
- A perceived over-estimation of network component damage associated with the use of peer-reviewed fragility curves.
- Manually refinement of damage levels (e.g. bridges), which are within the bounds of the underlying probabilistic assessment.

For service outage and disruption assessment:

- A validation of methods used by research team, where the utility operators/managers experts considered them logical and credible with no changes.
- An indication by road operators/managers of the presence of service roads (unknown to research team), which considerably refined the access results.

For service restoration (roads):

- This assessment was entirely reliant on the CCC experts' input and enthusiasm to develop a credible repair strategy within the bounds of this impact scenario.
- Considerable debate amongst CCC experts on restoration timings led to the adoption of an average (1 day) repair time, which was successful for establishing a modelling assumption to be across the study area.
- These discussions highlighted potential continued collaborative projects.

5.2. Recommendations for tsunami mitigation in Christchurch:

The impact assessment case study provides a demonstrative application of the framework and provides a specific resource for local lifeline utility and emergency management planning (Section 1). To this affect, the tsunami impact assessment engagement with CCC and Orion collaborators, both during and following the impact assessment process, has identified a suite of recommendations for tsunami risk reduction in Christchurch:

Identified areas for infrastructure mitigation

- Strengthen infrastructure where practical (at the coast) on primary access routes to reduce impacts and therefore reduce disruption and repair time post-event. Site specific assessments should be considered.
- Increased redundancy, or strengthening of redundant infrastructure, would allow for more ground transport capacity post-event. A key finding of this study is the lack of access into an out of Moncks Bay if the coastal route is damaged (Figure 1 & Figure 8).
- Allow for potential access easements over private land (if not already in place) to improve post-event access capacity.

Component specific recommendations

- Conduct site specific bridge performance assessments to determine the tsunami vulnerability of exposed bridges in Christchurch (Figure 4 & Figure 6). This is particularly important in Christchurch given recent earthquake strengthening works on a number of tsunami exposed bridges, which did not directly consider tsunami loadings.
- Where practical, replace jointed electricity cables in areas of high tsunami damage potential (Figure 7) or lay new cables on alternate routes to improve network redundancy.
- Lay new horizontal network components along routes that bypass coastal vulnerabilities (e.g. electricity cables currently bypass the McCormack's Bay causeway with an inland route (Figure 1 & Figure 8)).

- Use buried electricity distribution in coastal areas exposed to tsunamis (Figure 4b) since utility poles (i.e. overhead cables) are particularly vulnerable in high hazard areas. It is assumed this would increase response and recovery times (which were not directly modelled in this study for electricity). Additionally, stockpiles of replacement and/or temporary utility poles should be considered, if not already in place, to increase response times for service restoration post-event.

Land use planning:

- Consider tsunami exposure and potential impacts in future developments (buildings and infrastructure). This could include exclusion zones and re-zoning of existing land.
- Build key future infrastructure network components conservatively outside of maximum credible tsunami inundation zones where possible (Figure 4).
- Assess and communicate any potential post-event residential exclusion zone planning and management to critical infrastructure operators pre-event. If there is no population returning to an impacted area then infrastructure rebuild prioritisation will likely vary from that shown in the present case study. There is a clear need for policy makers and infrastructure operators to discuss this point along with community engagement to investigate uptake.

Emergency response planning:

- Develop traffic management and contingency planning for alternative access routes (Figure 9), and subsequent temporary primary access routes, identified in this study. There is a need for emergency managers to be clear on what the actual purpose of restoring access would be e.g. retrieving valuables from damaged property.
- Hold community engagement workshops around tsunami damage, service disruptions, post-event response/recovery and public expectations around levels of infrastructure services post-event. These have been identified as priorities for improving community resilience post-tsunami.
- Consider the wider effects of infrastructure service disruption beyond the areas directly impacted by tsunami inundation (Figure 6 & Figure 7) and the implications for emergency management, high-value critical sites and welfare facilities. Electricity outage, although not considered in this case study, could be restricted or lost for large areas not directly exposed to the tsunami if primary substations are damaged (Figure 4b & Figure 7).

5.3. Recommendations for future work:

The framework adopted in the present case study should be applied and tested for other case studies, nationally and globally. A national infrastructure damage and outage model could feasibly be conducted depending on uptake and data availability. This would reduce the uncertainty identified around resource availability post-event, as it would be clear what the national impacts, and therefore restoration priorities, are and where resources will go. Further interdependencies should also be considered in subsequent tsunami impact assessments, with 3-waters (stormwater, wastewater and potable water networks) being identified as a priority for future work [58]. This would involve a damage assessment of each network, then the same engagement and modelling approach for service outage, disruption and restoration as in the present study. With each network included, the interdependencies of all networks will become increasingly more robust compared with the present case study. This is a widely adopted approach for other natural hazard impact assessments (e.g. Sadashiva *et al.* [27]).

Subsequent recovery assessments (i.e. Figure 9) should also consider network components beyond just primary access routes (e.g. secondary and tertiary routes) to begin quantifying full recovery/rebuild timeframes and service outage for all businesses and residences of a given study area. Additional future research should also consider an economic loss assessment, which is often the next step in an impact assessment [61]. This would help further inform mitigation prioritisation for loss reduction and funding allocations. It is strongly recommended any subsequent work in this field continues with expert collaborator engagement.

Based on the discussion of the effectiveness of the engagement approach (Section 5.1) within this study, some wide recommendations for engagement are:

- Define roles early on the engagement process.
- Involve a liaising neutral/semi-neutral party.

- Ensure the relevant expertise (from all organisations involved) attend the applicable engagement workshops.
- Provide plenty of relevant risk context for expert collaborators and request/enable the provision of expert knowledge/review.
- Conduct evaluation (formally or informally) of expert collaborator's perception of ongoing engagement effectiveness.
- Continually steer discussion back to objectives (while allowing room for wider discussion).
- Allow plenty of time for individual workshops and ensure participants are aware of timings.
- Allow plenty of time in project for sufficient workshops beyond those initially scoped.

The present impact assessment would have been enhanced by vulnerability models that consider HIMs beyond depth. Existing post-event impact datasets could be extended to develop fragility curves which consider additional HIMs, if numerical hazard models were applied in the absence of empirical hazard observations. This work would be possible with additional analysis for the likes of the 2011 Tōhoku, 2015 Illapel and 2018 Sulawesi tsunami infrastructure impact and numerical hazard model datasets (e.g. [13,19,31,62]) and future post event field survey datasets.

6. Conclusions

This study provided and tested a framework for tsunami impact assessment of critical infrastructure. The framework was applied through a collaborative case study approach between researchers and practitioners to co-develop a tsunami impact scenario including road and electricity network component damage, service disruption and restoration time in Ōtautahi Christchurch, Aotearoa New Zealand. A series of workshops were conducted throughout the impact assessment process to validate, refine and contribute to inputs, methods and results of this collaborative impact scenario. The resulting impact scenario estimated that for the road network, 16% (32 km) of the exposed roads and 5% (1) of the exposed bridges could potentially be damaged beyond repair for a large tsunami. For the electricity network, 6 % (10 km) of the exposed buried cables, 27% (1254) of the exposed utility poles, 29% (79) of the exposed secondary substations and 24% (5) of the exposed primary substations could potentially be damaged beyond repair. These workshops also elicited network service outages and disruptions, representing response and recovery phases respectively (for road transport). This highlighted that several coastal suburbs could expect no road access for 3 - 44 days with 10 – 44 days required to reinstate all routes. This paper discusses these results in the context of the impact scenario case study and provides recommendations for increasing tsunami resilience, including land-use management, emergency response planning, infrastructure component mitigation and infrastructure network mitigations. The tsunami impact framework and scenario also provide potential input for subsequent planning and impact modelling (economic and habitability). This study has contributed to global knowledge of tsunami impacts on built-environments and specifically provides a framework and case study for estimating road and electricity impacts from tsunamis. The tsunami impact assessment framework presented in this study is intended to be widely applicable, and it is recommended that it be applied to other case study locations, and at local to global scopes, to quantify infrastructure impacts and inform initiatives for ultimately improving tsunami resilience.

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Data availability: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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