From physical disruption to community impact: Modelling a Wellington Fault earthquake

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Abstract

Modelling the economic impact of an earthquake event provides a means to support decision-making for investment options to improve disaster preparedness. Quantification of economic impact requires a comprehensive understanding of how damage to physical assets such as buildings and infrastructure networks translates into disruption to, and impact on, communities and businesses. This paper describes how a scenario narrative was developed as an essential prerequisite for an ex-ante economic assessment of a Wellington Fault event in Aotearoa New Zealand. The approach begins with the development of a suite of infrastructure asset damage and restoration maps, which account for infrastructure interdependencies. This data is then translated, based on expert elicitation processes, into a range of post-earthquake behaviours including population displacement, business disruption and relocation, and tourism effects. Lastly, these behaviours are set up as inputs for a novel economic model that captures out-of-equilibrium dynamics and behavioural adaptation. This narrative, alongside the economic modelling component, has been used to support decision-making around regional infrastructure resilience investment.

Keywords: *Disaster impact, socio-economic modelling, disaster recovery, Wellington Fault earthquake*

Disaster risk management interventions are often selected based on their ability to reduce economic losses in the event of a disruption. However, evaluation of intervention options is often limited to direct impacts and the links between physical and socio-economic disruption are poorly included (McDonald et al., 2018; Rose, 2004). To effectively evaluate the impact of disaster risk intervention options we need to understand how communities and the economy will respond to varying levels and types of disruption (McDonald et al., 2018). This paper describes how a scenario narrative was developed as an essential prerequisite to an ex-ante economic assessment of a Wellington Fault event to support resilience investment decision-making.

In 2016, the Wellington Lifelines Group (the Group) identified a need to collaboratively plan their infrastructure investment to maximise regional resilience benefits for a credible earthquake scenario. The Group comprises of critical infrastructure providers from across the Wellington New Zealand (NZ) region. The Group includes fuel, road, port, rail, electricity, telecommunications, and water/wastewater utility providers.

Each infrastructure provider identified a suite of potential infrastructure investment options to improve the vulnerable parts of their network and the Group collectively formulated several programmes of work. While the costs and benefits of these programmes of work could be measured in various ways, the Group explicitly decided to use an impact-based measurement associated with reducing the economic impacts of a hypothetical Wellington Fault event. The Group commissioned an economic impact assessment to determine the potential savings (i.e., reduction in economic losses) resulting from the proposed programme of works. Importantly, this included careful consideration of critical infrastructure interdependencies. This work is known as the Wellington Lifelines Resilience Project (WLRP).

In this paper we demonstrate how strong stakeholder engagement and integrated modelling enabled the development of a comprehensive and robust narrative to support decision-making for resilience-building investments in Wellington. First, we outline the modelling process undertaken, namely defining geo-physical disruption and translating these impacts into human behavioural responses. Second, we present the Wellington Fault story developed through the modelling process. Third, we conclude with a discussion reflecting on the modelling process and opportunities to improve how modelling can better support decision-making processes. We do not present the results of our economic modelling here as these will be detailed in a forthcoming paper.

Method

The impact assessment modelling process is described in Figure 1. The process begins with an assessment of the extent and duration of physical infrastructure disruption following a Mw7.5 Wellington Fault earthquake event with associated perils (fault rupture, ground shaking, liquefaction, landslides, lateral spreading, and subsidence). The event was selected as a suitable and credible event to measure the effectiveness of proposed infrastructure investment options as this event has a 10% probability of occurrence in the next 100 years (Rhoades et al., 2010). This assessment of infrastructure disruption is followed by determination of induced population and business behaviours and estimation of the flow-on economic consequences. The analysis is carried out on a comparative basis: first, for earthquake effects on the physical assets with no interventions (base case) then for earthquake effects with proposed interventions. Comparison between the cases allows for the effectiveness of the intervention options to be determined. Importantly, a requirement of our assessment is that it focused on disruption (measuring *flow* impacts; i.e., avoided net losses in economic activity), rather than on physical asset loss (measuring *stock* impacts; i.e., replacement or reinstatement costs). The latter is better measured using other methods (e.g., RiskScape; www.riskscape.org.nz).

The proposed investment packages were determined through a collaborative process between lifelines providers and subject-matter experts. A comprehensive discussion of the process is outside the scope of this paper, but is fully outlined in the Wellington Lifelines Regional Resilience Project Report (2018).

Physical Disruption

A comprehensive risk assessment framework was developed to model physical infrastructure disruption (see Figure 2). Infrastructure modelled included

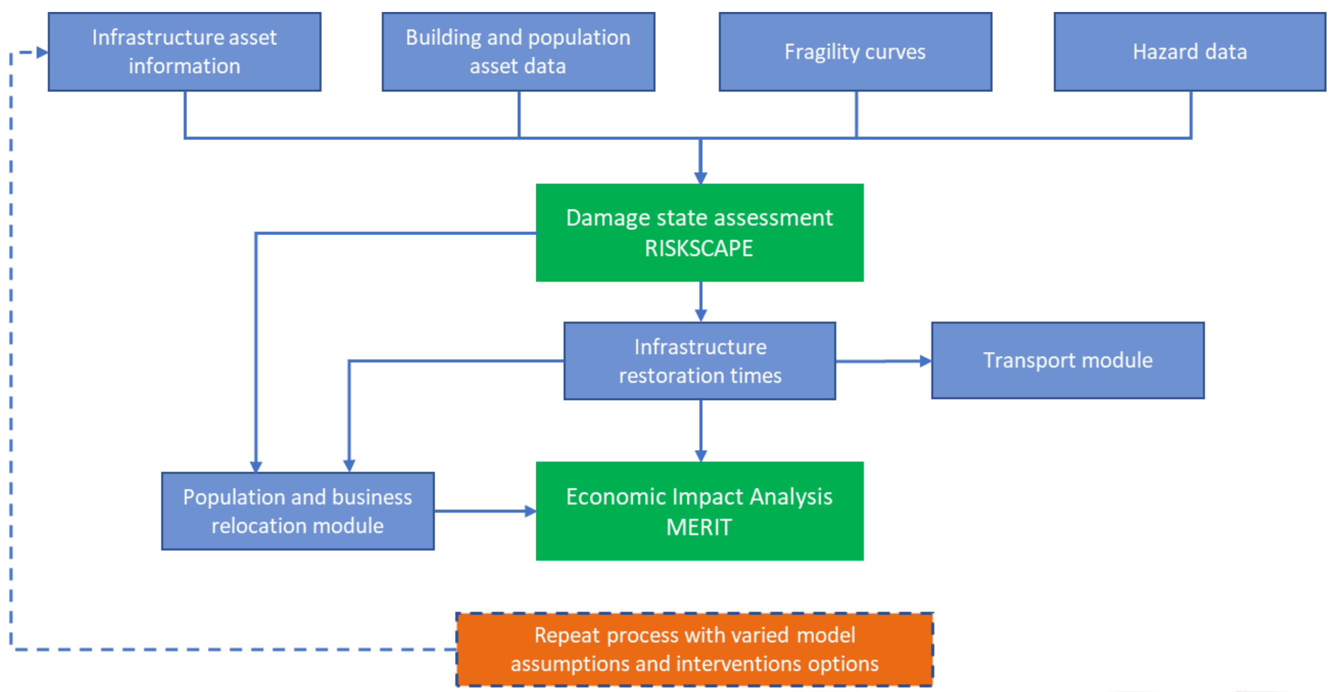

Figure 1. Linkages between the various stages of damage loss assessment and economic impact analysis for the Wellington Resilience Programme Business Case.

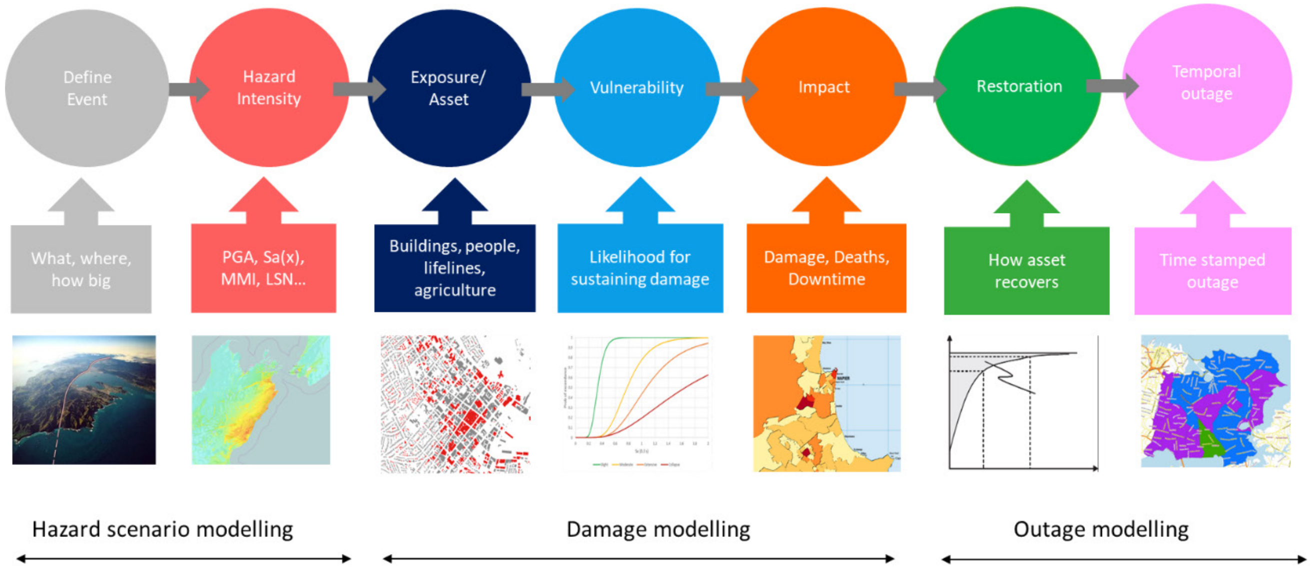

Figure 2. Stages involved in damage and outage modelling framework for a chosen scenario.

road, rail, port, airport, electricity, telecommunications, potable water, wastewater, fuel, and gas networks. Damage to buildings was also modelled to ensure a realistic representation of the benefits of infrastructure investment given the spectrum and multiplicity of experienced disruptions (e.g., a business with a significantly damaged building will be less impacted by loss of water to the site).

The risk assessment framework includes: (a) hazard scenario modelling, to predict the spread of hazard intensities across the region; (b) damage modelling, to predict the likely damage to buildings and infrastructure based on vulnerability characteristics; and (c) outage modelling, to estimate the time required to restore infrastructure services (expressed as a particular level-of-service provisioning). This framework accounts for collective damage to physical assets, interdependencies

Table 1.
Infrastructure damage and restoration estimation process.

Infrastructure	Damage estimation	Restoration
Road	Damage to assets estimated using modelling tool developed by GNS Science for New Zealand Transport Authority (NZTA; Sadashiva, King, & Matcham, 2017)	Expert judgement used to develop a travel matrix between 24 zones, showing additional travel time (above business-as-usual) in response and recovery phases. Reviewed by NZTA and local councils.
Rail	Engineering judgement verified by KiwiRail	Consultation with KiwiRail
Port	Expert workshops	Expert judgement and consultation with port authority
Airport	Meetings with airport authority. Assets divided into runway, hardstand areas, and buildings	Discussion with airport authority
Fuel	Discussion with New Zealand Oil Services LTD (NZOSL) management team	Expert judgment and discussion with NZOSL management team.
Electricity	RiskScape and in-house interdependency modelling tools, with fragility functions refined in consultation with electricity supplier	Discussion with Transpower and Wellington Electricity on repair and restoration strategies. Estimated based on a) modelled asset damage, b) prioritized list of electricity supply zones elicited from the infrastructure provider, and c) location and details of restoration resources available.
Telecommunications	RiskScape	Discussion with telecommunication providers on their preferred restoration strategies
Potable water	RiskScape	Estimated based on a) modelled asset damage, b) prioritized list of water zones elicited from the infrastructure provider, c) number of repair crews available, and d) rate of repair per crew.
Wastewater	RiskScape	As above
Gas	RiskScape	As above

on other networks, and demand for shared recovery resources.

Given the uniqueness of each infrastructure network, the analysis process was modified to suit each infrastructure, as detailed in Table 1. Generally, RiskScape (riskscape.org.nz) was used to carry out the hazard scenario and damage modelling. RiskScape is a multi-hazard risk assessment tool developed by GNS Science and NIWA that estimates damage and direct losses for assets exposed to natural hazards. The modelling software combines spatial information on hazards (e.g., earthquake, tsunami, and flood), assets (e.g., buildings, lifeline infrastructure, and people) and asset vulnerability to quantify the impacts on physical assets, as well as estimating the number of casualties and displaced populations.

In terms of infrastructure, the *damage modelling* predicted the likely damage to the components of the network, accounting for the variation of hazard intensities across the region as derived in the hazard modelling stage. The damaged components were assumed to be fully non-functional and, based on the network connectivity, the areas that are likely to be disrupted were identified. For the *outage modelling*, a participatory approach with infrastructure providers was adopted. The restoration of infrastructure networks is a complex process with many technical and human variables (e.g., availability of skilled labour and materials, individual decision-making, regulatory challenges, and organisational leadership and management). Each infrastructure provider was approached to verify the RiskScape-generated damage model and to describe their likely recovery strategies. Specifically, infrastructure providers were consulted to obtain information related to: (a) network configuration and geographical locations; (b) vulnerability characteristics; (c) functional dependency within the network; (d) restoration strategies; (e) key interdependencies; and (f) level-of-service provisioning under various damage states.

Estimated outage times for a given network were calculated based on the recovery strategies applied to restore the services, including both temporary and permanent solutions. Estimated outage times are heavily influenced by availability of personnel and materials at the time of the hazard event. Restoration of a given network is also affected by the interdependencies on other network services. For example, restoration of water service may require road access, fuel, and electricity. For each infrastructure, a time-stamped outage map was produced to represent the duration of disruption to the service. In some cases, this reflected the level-of-service provided (e.g., potable versus non-potable water). This process was repeated to include all items in the proposed investment packages.

Business and Population Behaviours

Within our economic model, there is an existing module that represents the behaviour of businesses following infrastructure disruption. These behaviours were developed using survey data collected following the Canterbury earthquakes of 2010/11 (Brown et al., 2019; Brown, Seville, Stevenson, Giovinazzi, & Vargo, 2015). In the Canterbury event, businesses and residents generally remained in the region and adapted to the disruption. Early modelling of the Wellington earthquake scenario suggested that physical disruptions may be at a level that tips both residents and businesses into non-adaptive behaviours. In particular, significant expected durations of infrastructure disruptions (notably electricity and water), isolation induced by roading damage, and limited functional building capacity to accommodate displaced businesses and residents within the region may cause people and businesses to leave the region.

As the next step to effectively model the Wellington Fault event, we had to build a realistic set of assumptions around how the population and businesses might respond to the expected levels of disruption both with and without the proposed interventions. An analysis of past events provided insight into the drivers for population and business behaviour.

The San Francisco Bay Area Planning and Urban Research Association (SPUR) have gathered evidence from several disaster events in the United States and surmise that if 5% of housing stock is uninhabitable then significant out-migration can be expected (SPUR, 2012). Other studies provide evidence that suggests population relocation is linked to socio-economic status (LeSage, Kelley Pace, Lam, Campanella, & Liu, 2011; Xiao & Van Zandt, 2012). Post-Hurricane Katrina, Xiao and Van Zandt (2012) found that income negatively correlated with population return; households with higher incomes were less dependent on low waged service industry jobs and were therefore more likely to be professionally and financially mobile. In contrast, low wage householders were more likely to remain in damaged housing, with fewer alternative options available to them. Longer term, low wage households which do not own property are more likely to relocate if living expenses increase or job opportunities reduce (SPUR, 2012). Recent research also indicates that there are other underlying factors that impact individuals' capacity and desire to relocate including social capital (Aldrich, 2012) and existing population growth/decline trajectories (Aldrich, 2011; Matanle, 2011).

Table 2 summarises studies of past events that have caused population relocation, business relocation, and closure. The existing studies are disparate. They report population and business impacts at different timeframes, use different metrics (e.g., there is often no distinction between permanent or temporary business closure), and use different analysis techniques (including different

Table 2.
Business change (closure and relocation), population change, and triggers for business change.

Disaster event	Location	Study timeframe	Business change	Population change	Triggers for business change	References
Hurricane Andrew	South Dade County	A few months after	• 89.9% of businesses closed immediately after the hurricane. • 29.2% temporarily relocated; • 12.5% have been permanently relocated (no data on whether relocated within or outside the region)	17% loss within first year 7% loss over first 2 years	• Transport issues for customers and suppliers • Sector: wholesale/retail most likely to close • More likely to relocate if business premises were rented rather than owned.	(Smith & McCarty, 1996; Wasileski, Rodríguez, & Diaz, 2011)
Hurricane Katrina	Southern Mississippi	8 years after	• A total of 6.9% of businesses verified as closed, and a further 10.3% were likely closed but were unverifiable.	9% loss a year after 2% loss six years after the hurricane	• None given	(Cutter et al., 2014; Schrank, Marshall, Hall-Phillips, Wiatt, & Jones, 2012)
Hurricane Katrina	Village L'Est	2 years after	• 10% loss of businesses	10% loss	• None given	(Aldrich, 2012)
Hurricane Katrina	Mississippi area	8 years after	• Around 10% immediately closed. • 25% business closure after 8 years	9% loss a year after 2% loss six years after the hurricane	• Overall age and health • Loss of utilities, inventory loss, and loss of customers/sales • Service sector less likely to be closed. • Specific geographical location relevant. • Endogenous effects: vulnerability to endogenous shock.	(Cutter et al., 2014; Sydnor, Niehm, Lee, Marshall, & Schrank, 2017)
Hurricane Katrina	New Orleans	0-12 months after	• None given	None given	•Loss of utilities •Low socio-economic status of customers •Neighbouring business failure •Level of impact from event	(LeSage et al., 2011)
Loma Prieta earthquake	Santa Cruz	A few months after	•7 5% of businesses closed immediately after the earthquake. Closure was from a few hours to several months. • 6.7% relocated permanently (no data on whether relocated within or outside the region).	<<1% loss	• Leased business space • Utility interruptions	(Wasileski et al., 2011)
Hurricane Ike	Galveston	3 months after for population estimates 7 months after for business estimates	• 41.4% businesses not operating from pre-disaster location	36% of households unoccupied	• Business return had a positive impact on household return	(Yu Xiao & Nilawar, 2013)

independent variables). These factors and the inherent challenges in making cross-contextual comparisons makes it difficult to definitively identify the factors that drive economic and community response to disruption.

Consequently, a series of workshops were held to augment the existing literature and develop some contextually relevant assumptions around population and business behaviours following a Wellington Fault event. Workshop participants represented the government sector, business sector, and key community functions and services (e.g., insurance, fast moving consumer goods, emergency management, and housing). Participants were asked to consider three different post-disaster "worlds":

a) The adaptive world: population and economy are disrupted but largely continues as normal;
b) The hostile world: significant but largely temporary relocation of individuals and closure of businesses; and
c) The apocalyptic world: large scale movement of people and businesses out of the region and Wellington's economy and community changes dramatically and permanently.

For each "world", participants were asked what types of disruption would tip the region into this situation. Participants were encouraged to consider:

a) Habitability: short-term basic survival needs (water, shelter, electricity, livelihoods etc.);
b) Liveability: medium-term quality of life factors (schooling, health care, community, transport etc.); and
c) Business viability – short to long-term feasibility of economic activity (demand changes, business confidence, insurance etc.).

Based on the above, a set of assumptions around population and business relocation and operability were determined (refer to Smith et al., 2017, for more details).

Economic Modelling

The physical disruption data and the assumed behavioural responses, discussed above, are designed to link into our economic model. The Measuring the Economic Resilience of Infrastructure Tool (MERIT) is a fully dynamic multi-sectoral economic model that captures the indirect consequences of infrastructure disruption events through time and across space for multiple stakeholders (Kim, Smith, & McDonald, 2016; McDonald, Cronin, et al., 2017; McDonald, Smith, Ayers, Kim, & Cardwell, 2016; McDonald, Smith, Ayres, Kim, & Harvey, 2017; McDonald, Smith, Kim, Cronin, & Proctor, 2017; Smith, McDonald, & Harvey, 2016; Smith, McDonald, Harvey, & Kim, 2017). MERIT is designed to imitate the core features of a Computable General Equilibrium (CGE) model. Among the advantages of these types of models is the whole-of-economy coverage which captures indirect and induced impacts. MERIT differs from a standard dynamic CGE model in that it is formulated in a systems dynamics framework using finite difference equations, which enables impacts over time to be simulated and inclusion of abnormal behaviour and adaptation, as exhibited during times of disruption, by economic agents (e.g., households, industries, and government).

Figure 3 shows how the physical disruption and resulting population and business behavioural responses connect to the MERIT model. The physical disruption modelling links through to:

- Population relocation module to estimate level of out-migration and corresponding household expenditure changes and labour availability changes;
- Business behaviours module to estimate level of out-migration and business operability over time;
- Cordon analysis to identify residents and businesses that will need to relocate due to building damage;
- Transport analysis to identify need for, and cost of, freight re-routing and identification of areas that are inaccessible and cannot trade; and
- Tourism analysis to identify likely loss of tourism demand over time.

The Wellington Fault Event Narrative

The geography of Wellington means that the region will be extremely isolated following a Wellington Fault event. Our infrastructure disruption modelling, undertaken in consultation with infrastructure providers, indicates that the Wellington region will divide into 23 road islands and will be isolated from the rest of NZ. It is estimated to be 28 days before a connection out of the region is restored and over 120 days before the last two road islands are connected to the rest of the roading network (R. Mowll (Wellington Region Emergency Management Office), personal communication, September 18, 2017*).* We estimate that the port will also be out of action for one to three months, creating challenges getting fuel into affected areas. Depending on location, our modelling shows that electricity will be disrupted for three to six months and water will be disrupted for between one to

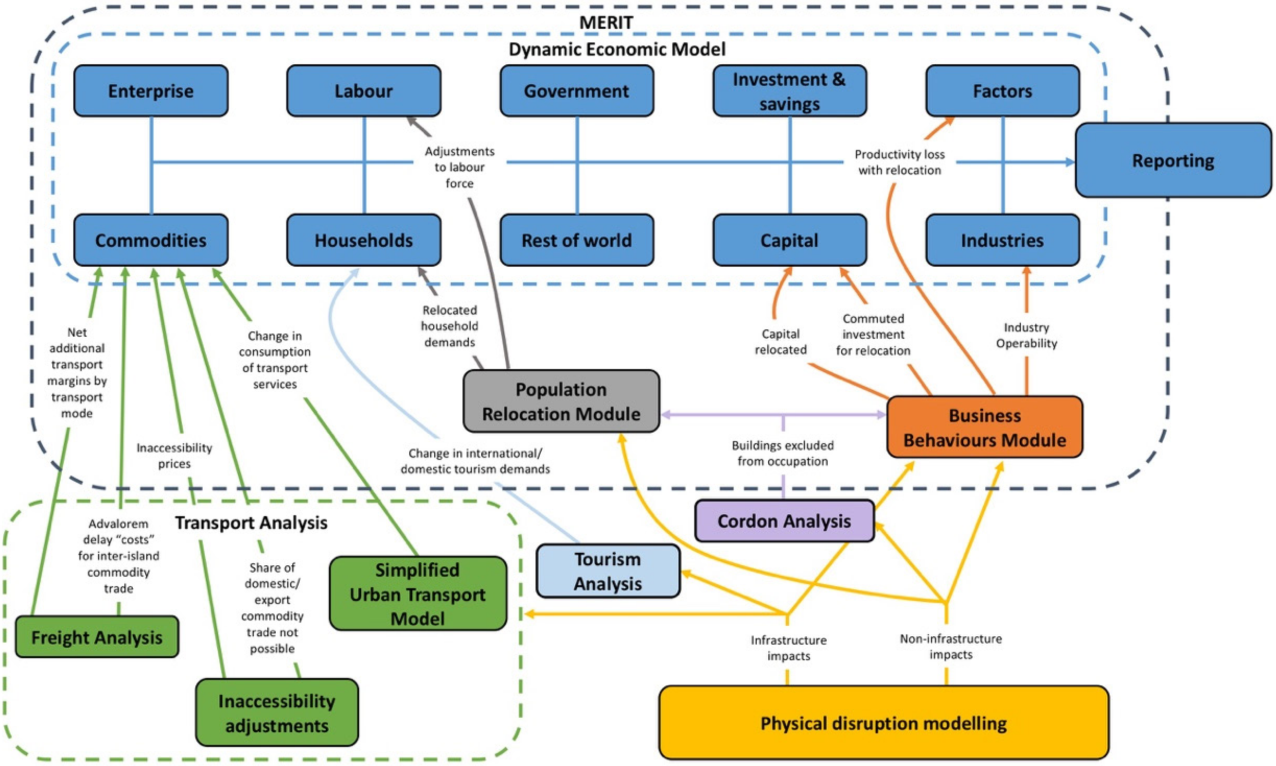

Figure 3. Overview of economic modelling process, including link to physical and behavioural modelling.

12 months for non-potable water reticulation and three to 12 months for potable water reticulation. Water restoration time frames are highly dependent on road, fuel, and electricity restoration.

The combined effect of all infrastructure and building disruptions is an estimated temporary population relocation of approximately 19% of the region and a further 6% of population permanently relocating (Table 3). We anticipate there would be an initial emergency evacuation of vulnerable persons (and their supports) via air and sea. Largely based on the Ministry of Civil Defence and Emergency Management (MCDEM) Mass Evacuation Guidelines (MCDEM, 2008), this would include aged, infirm, people with disabilities, people in prisons, and tourists. The estimates also include fatalities and serious injuries.

Table 3.
Estimated population relocation estimates for a Wellington Fault event.

	Left	Returned	Difference
Emergency Evacuations	38,100	37,900	200
Strategic Evacuations	4,800	0	4,800
Shelter Relocation	6,200	6,200	0
Voluntary Flight	75,100	49,700	25,400
Total	124,200	93,800	30,500
% of region	25%	19%	6%

Similarly, we anticipate a certain level of strategic evacuation of government officials and key business personnel (and their families) who feel they cannot operate effectively in the disrupted environment. The relocation of key government services will also likely pull supporting professional services away from the region. Evacuation will also come from those that cannot find shelter within the region. It is anticipated that persons that cannot shelter in place will either move in with neighbours, family and friends within the region (particularly in low-socio-economic groups), use temporary shelters, or will move out of region. In time, we anticipate that voluntary population flight will be driven by a low level of liveability which includes:

- Duration of disruption to one or more of water, electricity, and communications (including data) at household level;
- % of uninhabitable houses (causing community disaggregation); and
- Lack of connectivity to a) local CBD, b) Wellington CBD, and c) rest of NZ, affecting access to work, school, and services.

- The level of out-migration will also be influenced by the socio-economic status of households, with highest and lowest income groups being most mobile.

Our research indicates that business relocation will be driven by:

- Industry sector (nature of service, infrastructure needs, customer base, connection to place, and ease of relocation);
- Extent of commercial/industrial property damage in region;
- Duration of disruption to one or more of water, electricity, and communications (including data) at business premises; and
- Lack of connectivity to a) local CBD, b) Wellington Region CBD, and c) rest of NZ, affecting staff and customer access and transportation of goods.

Wellington is a knowledge economy (Norman & Oakden, 2014) and, as such, is relatively mobile. Without reliable electricity and communications infrastructure, these businesses can easily relocate and still maintain their staff and client base. This, in turn, may draw population away from the region. Our modelling shows that for those businesses which remain in the region, the combined effect of the infrastructure and building disruptions will suppress industry production levels until basic services are restored, at which point a recovery process will commence. Businesses will also experience challenges in finding and retaining staff.

We anticipate that the event will cause some initial loss of international tourism nationally, but that international tourists will quickly return across the rest of NZ. Domestic tourism numbers in the Wellington region will notably decline due to loss of hotels and other tourism infrastructure but will largely redistribute across NZ. The relocation of residents and businesses, the absence of tourists, disruption to roads, and the perception of disruption to Wellington businesses will heavily reduce the demand for services in the region.

The proposed infrastructure investment packages explored in this project were designed to significantly reduce the expected duration of infrastructure disruption following a Wellington Fault event. The economic modelling showed the difference in economic loss with and without the investment packages. The most beneficial investment packages were those that targeted infrastructure which enables restoration of other services (such as fuel, transport, and electricity) as well as those that best reduced population and business relocation (road access or water, electricity, and communications service restoration). The reduction in economic losses as well as the event narrative are key inputs into the investment decision-making process.

Discussion and Conclusion

The WLRP represents the most comprehensive investigation into the economic implications of any natural hazard event carried out within NZ. There are three key strengths of the study: 1) the robust stakeholder engagement process undertaken to deliver the study, 2) the all-of-infrastructure or system-of-systems view of infrastructure adopted, and 3) the use of a novel *impact-based investment approach* to support resilience-building within the region.

Strong governance and leadership facilitated the committed engagement of key stakeholders, including politicians as key project sponsor and advocate, infrastructure chief executives and members of senior leadership teams, experienced emergency management individuals, and leading professional experts. Without this sort of end-to-end engagement, a complete narrative of the Wellington Fault event would not have been possible.

The all-of-infrastructure approach treated the Wellington Fault event through a systems lens with infrastructure seen as a system of critically-interdependent sub-systems; that is, disruption in any sub-system may have repercussive consequences in other systems and, in turn, other sub-systems and so on. This so-called *infinite regress* may result in unforeseen failure in any sub-system indirectly, independent of whether it is affected directly. Specifically, the WLRP focused not only on horizontal infrastructures but on how these systems interacted with building damage, resident populations, and businesses.

Fundamental to understanding these interdependencies were stakeholder engagement and expert elicitation processes. While noted as a key strength, this engagement process has inherent limitations. The project team faced significant challenges in collating and analysing data from 10 different regional infrastructure networks. Each infrastructure network provider or authority used disparate storage mechanisms and attribute sets for their network data. Further issues and delays were encountered gaining access to the data, which had to be sourced from separate authorities, each of which had its own data access agreements. For example, the road network included road assets owned and managed by New Zealand Transport Agency (for State Highways) and the five local councils.

Where infrastructure providers could not supply information for modelling, engineering judgements were applied, particularly for estimation of restoration times. Each infrastructure type was treated slightly differently due to the varying nature of the infrastructure assets and services (e.g., distributed electricity network versus an airport with centralised assets; see Table 1) and the complexity of restoration. Inherent in these expert judgements were assumptions around expected level of organisational capacity, access to key resources and personnel, and dependence on other infrastructure services. Similarly, in development of the population and business behavioural assumptions, we asked professionals to speculate on a hypothetical event involving complex human behaviours. The assumed behaviours are shaped by the experiences and cognitive biases of the expert participants. Consequently, the narrative and behaviours described in this paper should be considered as a starting point for understanding and modelling a response to a large-scale disruption event in Wellington. The uncertainty in these "predicted" behaviours needs to be accounted for and continually evolved as knowledge and experience is gained through future disaster events.

Development of integrated, comprehensive narratives is of growing importance in modelling processes as we increasingly see a need to: a) move towards impact-based decision-making, b) use models as an input into development of plausible scenarios, and c) embed modelling in deliberative decision-making processes. There is increasingly a movement towards impact-based resilience investment decision-making (Morgan Stanley, 2018 ; The Rockefeller Foundation, 2012). This approach represents a movement away from basing decisions purely on conventional evaluation frameworks such as Benefit-Cost Analysis (BCA) and Multi-Criteria Analysis (MCA) which tend to focus on direct costs and benefits of investment. This impact lens requires widening to capture a fuller range of direct and indirect impacts (i.e., social, economic, and environmental) and to better acknowledge and communicate uncertainty. This project was based on a single highly-significant and credible event scenario. While advances in data science, probabilistic modelling, and prediction may help us better understand uncertainty around such a scenario they cannot fully account for that uncertainty. Emergent behaviours, tipping points and "unknown unknowns" exist, the occurrence, and particularly dynamics, of which cannot be easily predicted but need to be explored through the modelling and decision-making process.

A key reason supporting the movement towards impact-based investment decision-making is that increasingly decision-makers are faced with complex and deeply uncertain decisions and are having to balance competing objectives and stakeholder needs. In this project for example, infrastructure has long existence timeframes (typically anything between 30 to 100 or more years) and it is necessary to balance immediate needs (often driven by economic efficiency and effectiveness) with resilience-building that may or may not be tested. Thus, part of the movement to impact-based investment decision making is the imperative of decision-makers to provide integrated robust and cohesive storylines to support the case for resilience-building. Under this approach, modelling should be more an input into the development of plausible scenarios than taking a set of inputs and assessing resilience scenarios. The distinction here may be subtle, but it is important. If modelling is to be useful then it must be applied iteratively within a decision-making process to create evidence-based plausible and defendable storylines that remain robust under many different conditions. Development of the storylines is as important, if not more so, than the outcome modelling work itself. Modelling provides an integrating glue that ensures the storylines are plausible, coherent, and internally consistent, and can also help decision-makers to identify tipping and leverage points around which intervention options can and should be designed.

Modelling must sit within a deliberative process. In the end, and as noted above, decision-makers often face a plethora of complex considerations for which often no simple or perfect decision exists. The role of supporting evidence, where modellers often sit, is to provide enough evidence to aid in the decision-making process, and modelling narratives play a key role in this. To effectively support disaster mitigation intervention decision-making, models and modellers need to create a comprehensive narrative of disruption events, from physical disruption through to community and economic responses. The method described in this paper could be readily adapted to other geographic and hazard contexts. The infrastructure outage modelling process is an important step in extending traditional measures of infrastructure disruption modelling from asset disruption to network service level disruption. Work is currently underway to automate the estimation of network restoration times within RiskScape (incorporating infrastructure system interdependencies and resource sharing limitations) to improve our ability to determine indirect impacts across a range of events. Further, the method used to generate business and population behaviour model assumptions is transferable not only to other contexts but also to decisions relating to other disaster risk management initiatives. It is likely that the factors that impact business and population relocation identified in this project (accessibility/road connectivity, infrastructure service disruption, property disruption, and industry sector) will be common across other communities facing major disruption and will affect other risk management interventions such as building standards, urban planning, and emergency response planning. However, further ex and post ante research in other contexts would be needed to validate this.

This research demonstrates the critical and systemic links between physical, social, and economic disruption. Quality narratives will help decision-makers to understand the causal effects of complex decisions and will enable the holistic benefits of proposed interventions to be effectively valued. Development of these narratives must be collaboratively built with key stakeholders.

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