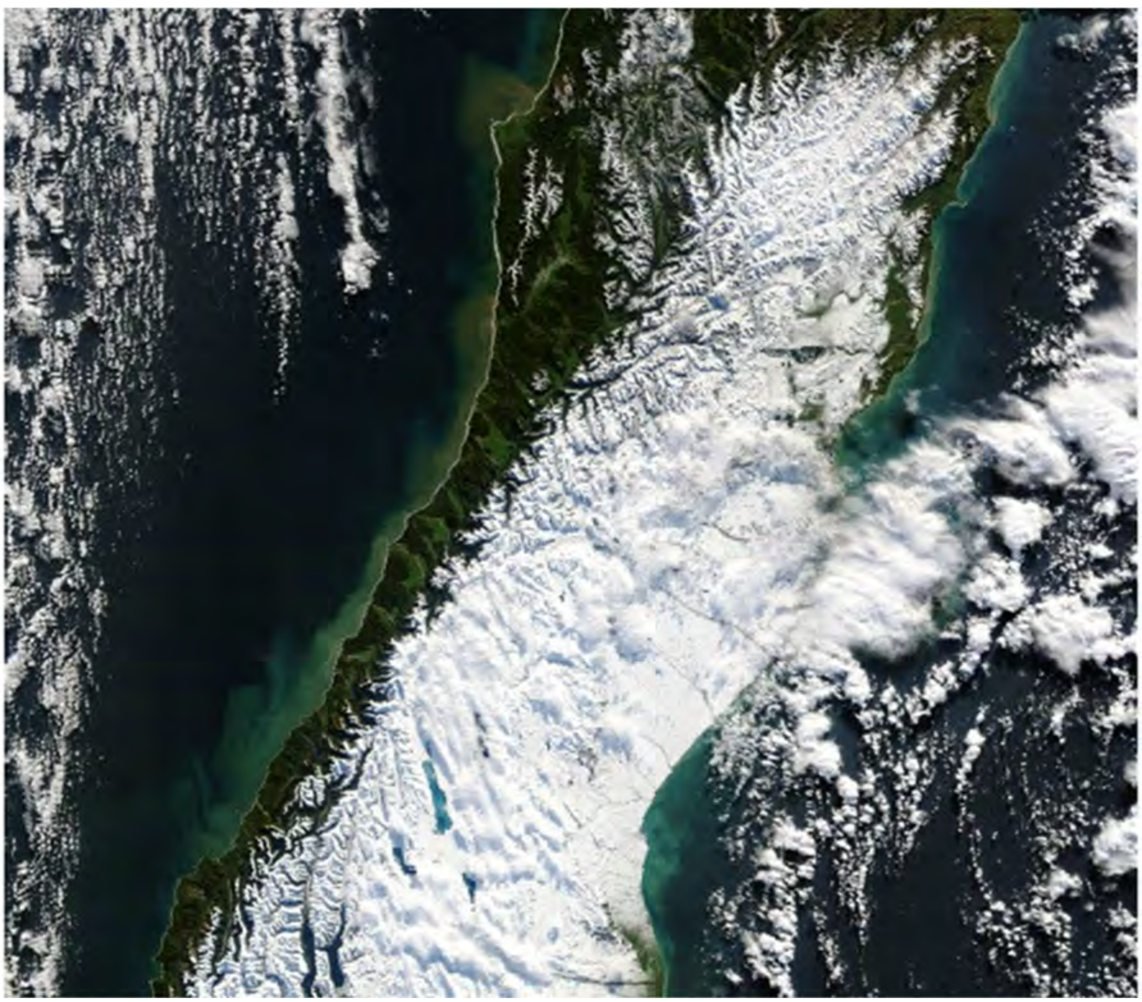
Risks and Resilience

Advancing the Maturity of Infrastructure Vulnerability and Resilience Investment Business Case Assessments

Milestone 5: Vulnerability Modelling and MERIT Analysis Report

Canterbury Civil Defence Emergency Management Group



Quality Information

Document	Risks and Resilience: Advancing the Maturity of Infrastructure Vulnerability and Resilience Investment Business Case Assessments – Milestone 5: Vulnerability Modelling and MERIT Analysis Report
Ref	
Date	June 2023
Prepared by	Mark Gordon
Reviewed by	Martyn Wooster, Tom Logan

Revision History

Rev	Revision Date	Details	Authorised	
			Name/Position	Signature
1	June 2023	Final Report	Mark Gordon	

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1.0 Introduction

1.1 Overview

This project seeks to “connect the dots” in relation to data, tools, resources, knowledge, and practice, with the aim of facilitating informed, up-to-date, and efficient vulnerability and resilience assessments using a lifelines GIS portal. A maturity-based approach has been developed and tested along with a recommended data schema that can be nationally applied.

Engagement has to date largely focussed on the lifelines sector, universities, and research agencies. Drawing on research programmes and tools, an “intermediate” level approach that lies between the current methodology for vulnerability assessments and the more comprehensive “Wellington Regional Lifelines programme business case” approach[1] has been developed.

Using North Canterbury as a pilot "proof-of-concept" demonstration, this “intermediate” approach also adds to Canterbury’s *Risks & Resilience* knowledge base, utilising the GIS portal and supplementing information in earlier more qualitative vulnerability assessments.

This report covers the tasks associated with Milestone 5, i.e., Conduct and report on pilot intermediate level analysis using MERIT. It should be read in conjunction with other project reports for Milestones 1, 2, 3 and 4, in particular *Milestone 4: Data Acquisition and Setup*.

1.2 Milestone 5 Tasks Summary

This report relates to Tasks 14 to 18 as described in the original submission. A summary is also provided in relation to completed activity.

Table 1-1 Task Summary - Milestone 5

Task	Description	Summary
14	Test the use of the GIS portal through workshop with pilot LLUs to assess hazard impact areas for each hazard event, likely damage and disruption effects and outages, interdependencies and cascade effects, affecting stakeholders identified in the scanning stocktake.	A project workshop with North Canterbury lifeline utilities was held in January 2023 – this presented the work to date and provided attendees with hands-on experience in using The GIS Portal and Urban Intelligence (UI) Resilience Explorer. Expected lifelines outage times were agreed for incorporation in the pilot output to MERIT. Feedback from lifeline utilities was positive.
15	Test the use of MERIT and other tools as determined above in assessing the social, cultural and economic impacts of the hazard events. As a worked example, “reverse-analyse” the May 2021 Canterbury flood event.	Following the above workshop, the project team compiled the information needed for the MERIT modelling, the spatial layers and the availability matrix by sector and Statistical Area. MERIT models were configured and run for the North Canterbury pilot area for a 500 year return period flood event – covering economic impacts only. The May 2021 event was not considered.
16	Second workshop with pilot LLUs to identify potential risk reduction mitigation strategies and use the GIS portal to assess the expected reduction in disruptive impacts – e.g., through new infrastructure, increased	This step was included in the workshop above, where a range of potential interventions were identified and discussed. These have not been further developed, and would in practice form part of a scenario based mitigation investment planning process as input to business case development.

[1] Refer to https://www.wremo.nz/assets/Uploads/191111-Wellington-Lifelines-PBC-MAIN-20191009.pdf

Task	Description	Summary
	diversity, strengthen existing, renewal programmes etc.	
17	Rerun the MERIT assessment based on selected mitigation strategies.	Due to time and budget constraints this step was not carried out. Comprehensive flood modelling work would have been required to test the impact on up-stream river protection investments prior to rerunning the vulnerability assessment and MERIT. There were no real additional benefits to the project in doing so.
18	Prepare report on the pilot analysis and recommendations for further development and use of the tools.	This report provides a description of the vulnerability assessment process, MERIT modelling, and recommendations for application and further improvement.

2.0 Previous Phases

2.1 Milestone 1 – Stocktake

In this first phase a review of practices and approaches used by lifelines groups across the country was conducted, to provide a snapshot recognizing the variability across regions. This described the traditional (or “core”) approach to vulnerability assessments.

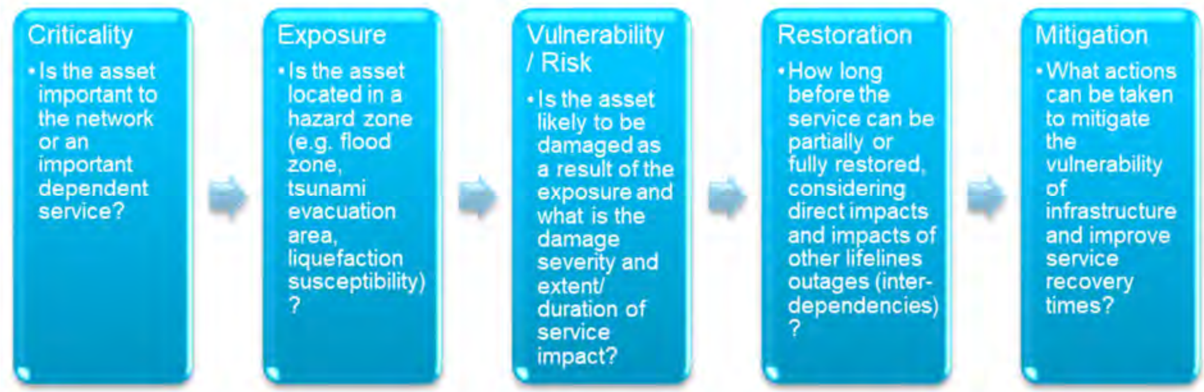


Figure 2-1 Core Lifelines Vulnerability Assessment Process

At a more “advanced” level is the Wellington Resilience Programme Business Case, this work creating the aspiration for a maturity pathway.

The stocktake also explored and documented the work across a wide range of research programmes, completed, in progress, or proposed. This helped the project team in deciding what to focus on in subsequent phases.

Figure 2-2 Research Programmes

Thirdly, the stocktake described a range of stakeholder groups, as summarized below, whose site locations could be important to CDEM and lifelines. An “advanced” vulnerability assessment should consider such sites and the lifelines functions they need in order to remain functional.

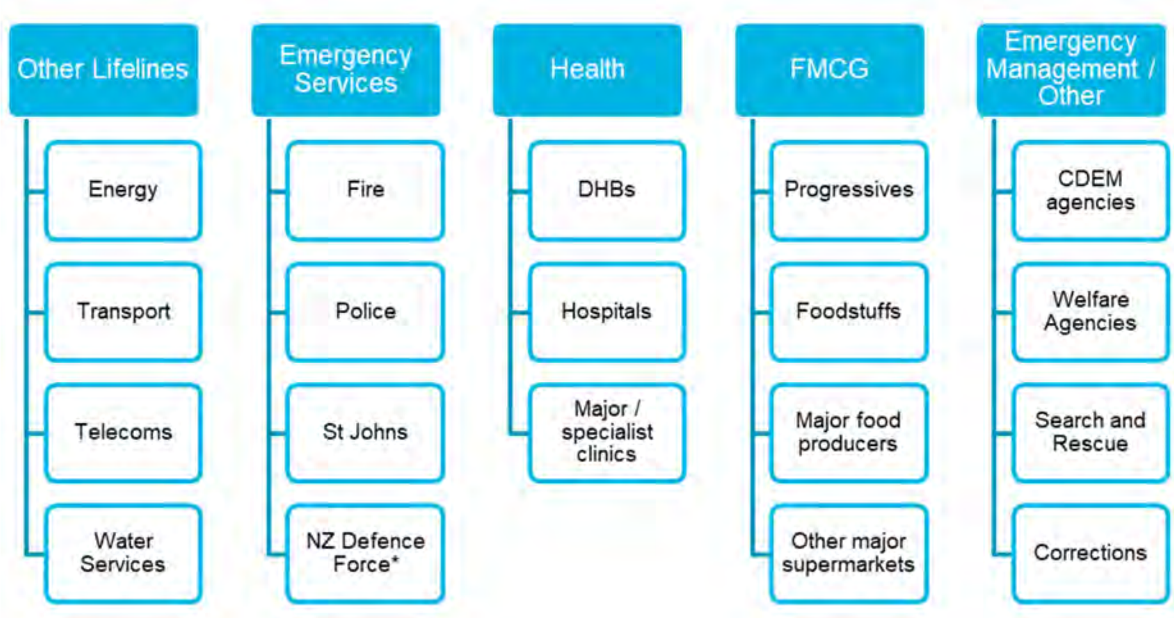


Figure 2-3 Stakeholder Groups

2.2 Milestone 2 – Describe the Integrated Approach

The “maturity pathway” diagram below was developed to show the integration of research, data layers, The GIS Portal, and applications such as the UI Resilience Explorer, RiskScape, and MERIT in moving practice along the spectrum from “core” to “intermediate” to “advanced”.

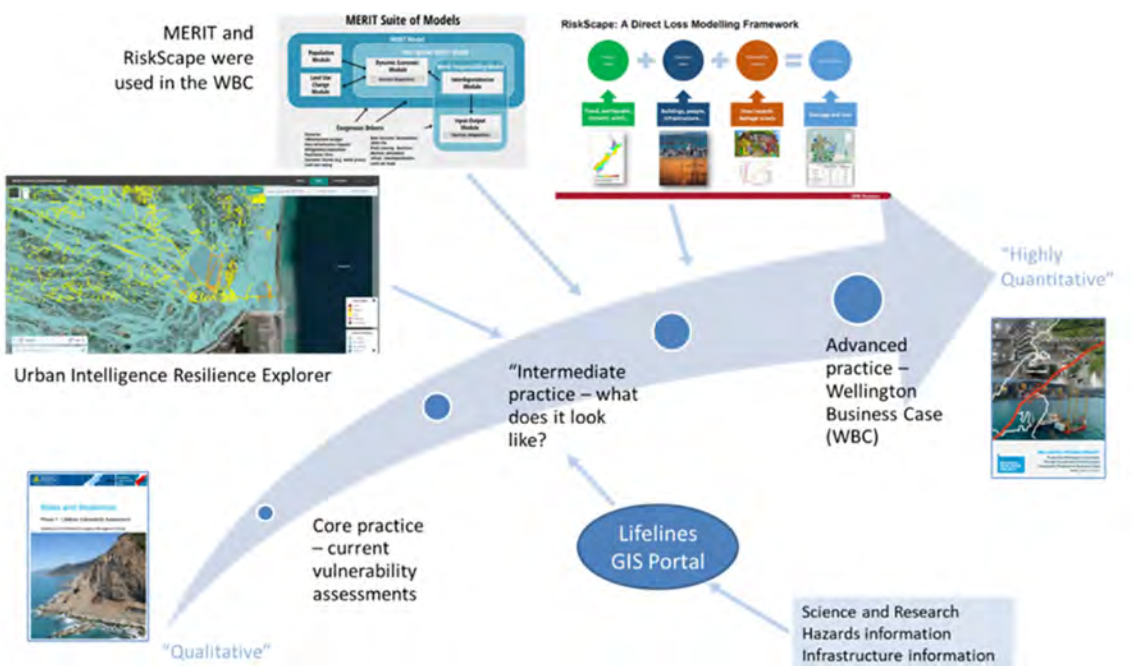


Figure 2-4 Maturity Pathway

Complementing the above, an 11-step process was defined to capture the key elements of an "integrated approach". Most of these steps were implemented as part of the pilot project.

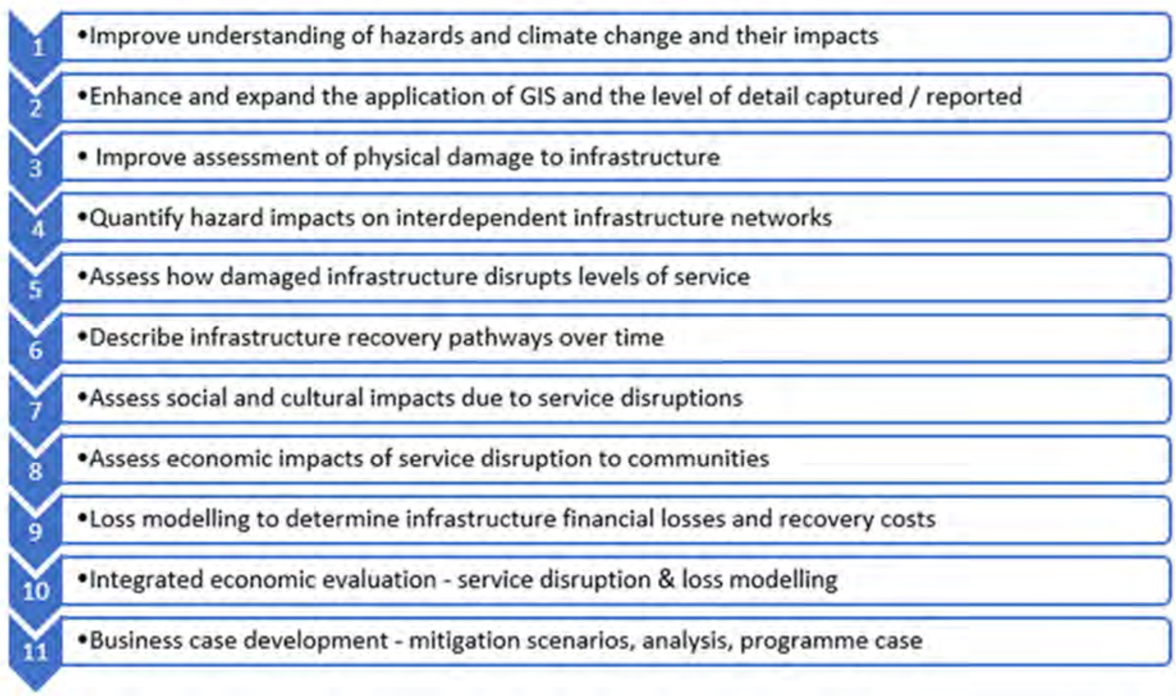


Figure 2-5 Features of the Maturity Pathway

2.3 Milestone 3 – Determine the Pilot Area and Data Needs

The selected pilot area covered North Canterbury and comprised three Territorial Authority areas: Kaikoura, Hurunui, and Waimakariri Districts. In addition, the following lifeline sectors were also invited to participate:

- Electricity
- Telecommunications
- State Highways
- Flood Protection

An asset class library was developed, this involved comparing and harmonising by sector and asset type into a standardised list with common naming conventions. This formed the basis for communicating data needs with lifeline utilities.

The hazards selected for the pilot were:

- Tsunami affecting coastal areas.
- Flooding from river catchments in North Canterbury.

2.4 Milestone 4 – Data Acquisition for Analysis

The North Canterbury Resilience GIS application (The Portal) provides a common platform for overlaying asset and hazard layers, while providing access to underlying information about each.

Each of the lifeline utilities involved in the pilot were individually contacted following the August 2022 workshop and asked to provide data in accordance with the data schema developed in Milestone 3 for each sector. Although there were some gaps, good representation of asset data was received across the five sectors, and these were set up as layers in The Portal. The following data was received from lifeline utilities.

Table 2-1 Asset Data Supplied by Lifeline Utilities

Sector	Lifeline Utility	GIS Layer Name	Attributes (available)
Electricity	MainPower	MainPower HV MV Substations	Site Name; Name
		MainPower MV Cables	Cable type (overhead); Installation Date; Line type; Operating Voltage; Phase; Status (in service)
	TransPower	Transpower Spans	Status (in service)
		Transpower Structures	Status (in service); Construction Type
		Transpower Sites	Status (in service); Description
		Transpower Transmission Lines	Name
Telecoms	Chorus	Chorus Core Sites	Site Name
		Chorus Core Routes	-
	Enable	Enable Ducts	Service Type (distribution)
		Enable Cabinets	Status (in service)
	Vodafone	Vodafone Points	Site Name; Priority
		Vodafone Polylines	Name
Three Waters	Hurunui District Council	HDC Pumpsheds	Type; Subtype; Community; Short_Name; Installation Date
		HDC Pumpstation Service Areas	-
	Waimakariri District Council	WMK Water Supply Assets in Service	-
		WMK Wastewater Assets in Service	-
		WMK Stormwater Assets in Service	-
		WMK DatranSignals	
		WMK DatranSites	Status (in service); Classification (Water/Waste/Storm); Description (eg pump at XXX Road)
Solid Waste	Waimakariri District Council	WMK Solid Waste Sites	Name; Type
Transport	KiwiRail*	KiwiRail Locations	Name; Priority
		KiwiRail Tunnels	Tunnel Name; Line Name
		Kiwirail Bridges	Bridge Name; Line Name
		NZ Railway Network	-
		Kiwirail FibreOptic line	Files relate to third party assets only and are not carried through to UI Resilience Explorer.
		Kiwirail FibreOptic point	
		Kiwirail Colocated services polygons	
		Kiwirail Colocated services points	
		Kiwirail Colocated services lines	
		KiwiRail Locations	
	NZTA	NZTA One Road	Full Road name; ONRC Class; Surface Type; Width

Openly or publicly sourced data sets were also used to offer supplementary asset location data for the telecoms, three waters and transport sectors.

Table 2-2 Supplementary Asset Data – Open Source

Sector	Source	GIS Layer Name	Attributes (available)
Telecoms	Radio Spectrum Management	Mobile Network Towers	Carrier; Height above Sea Level
Three Waters	Canterbury Maps	Community Drinking Water Supply	Well Number; Well Type; Well Supply Name; Depth
	Water NZ	Wastewater Treatment Plants	Name; Treatment Level; Owner; Volume Treated
Transport	Land Information NZ	Bridges	Bridge Use

Environment Canterbury (ECan) provided geospatial hazards data for inclusion in The Portal. This included modelled water depth and flow velocity information for a range of return period events, 100, 200 and 500 years, some of these models included provision for climate change rainfall (e.g., RCP8.5 for 2081-2100).

Data contained in The Portal was subsequently imported directly into the North Canterbury UI Resilience Explorer, which was used for vulnerability assessment, mapping visualisation, and provision of outage data to MERIT.

It is important to observe the benefits of a common risk assessment platform that is available to all lifeline utilities, balancing the need for data confidentiality with functionality that can contribute to a shared understanding of risk and a collaborative approach to mitigation. There is also a need to continue to better define asset fragility relationships for different hazard events.

Note that the GIS Portal will need to be kept up to date with research outputs as new research is completed and the results translated into a GIS-consumable format. This could include the nature and scale of hazards, the ways in which infrastructural assets can be damaged or affected by such hazards, through to the social and cultural implications to communities. While “community sites” were not systematically captured in The Portal, this is also an obvious improvement plan task.

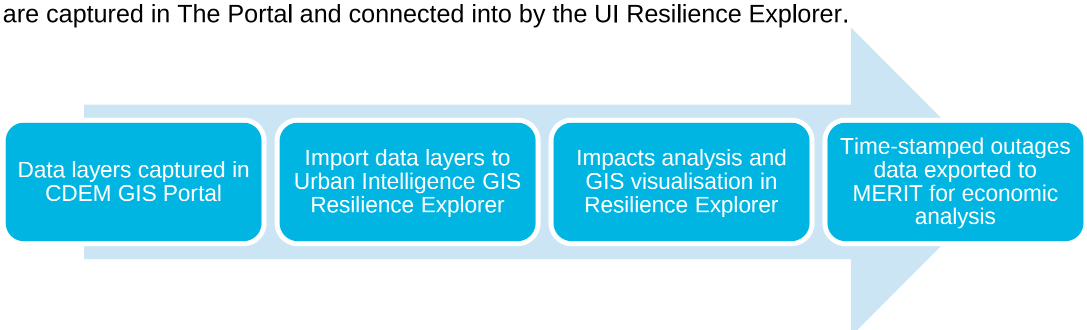
3.0 Hazard Impact Modelling

3.1 Overview

This section summarises the modelling approach adopted by the University of Canterbury and Urban Intelligence teams, including the development and application of the UI Resilience Explorer and production of an export file that is provided to MERIT for economic analysis.

3.2 Modelling Steps

In summary, the modelling process is as illustrated below. All input layers (hazards and infrastructure) are captured in The Portal and connected into by the UI Resilience Explorer.



The UI Resilience Explorer can be found at the following link:
https://projects.urbanintelligence.co.nz/canterbury-resilience

This site is password protected, so please reach out to *info@urbanintelligence.co.nz* for access.

3.3 Hazard Scenarios

3.3.1 Flooding

Three flooding scenarios were obtained from Environment Canterbury for river flooding hazard mapping for 100, 200, and 500 year return period events.

The following maps show 200 or 500 year flood predictions (depending on the District) sourced from the flood modelling app within Canterbury Maps. The data layers are the same as those captured in the Lifelines GIS Portal. As can be seen, the flooding is most widespread in the Waimakariri District. These events do not necessarily occur across all three Districts at the same time as they impact different catchments and rivers.

From these figures it can be seen that:

- **Kaikoura District** (500 year ARI) – exposed to breakouts of the Kahutara and Kowhai Rivers to the south, the latter affecting the Kaikoura Fans area either from The Bluff on the north side where the river flows into the plain or Fernleigh Dip on the south side. Further to the south, the Oaro River poses potential risks to lifelines. Further to the north, the Hapuku, Clarence and Kekerengu Rivers also pose risks to lifelines. Modelling allows for the following climate change impacts – 1m of se level rise and a 25% increase in river flows.
- **Hurunui District** (200 and 500 year ARI depending on locality) – the maps show potential exposure of the Waiau River near Waiau township and exposure of Leithfield and nearby coastal areas to breakout of the Kowai River. Note that there are currently no modelling predictions for other rivers in the District, including the Conway, Hurunui, mid and lower reaches of the Waiau, and Waipara Rivers. These rivers also have the potential to cause disruption to lifelines. Except for Oaro, flood modelling for Hurunui does not allow for climate change effects, although it does assume a 0.4m coastal storm surge.
- **Waimakariri District** (500 year ARI) – the maps exclude the Waimakariri River breakout risk as its level of protection is thought to currently exceed the 500 year ARI period. There is

widespread flooding exposure within the District due to other river systems, including the Ashley, Okuku and Eyre Rivers and their tributaries. Kaiapoi township and rural areas to the north are the most significantly affected. Modelling allows for RCP 8.5 rainfall for the 2081-2100 period.

3.3.1.1 Kaikoura District Flooding Scenario

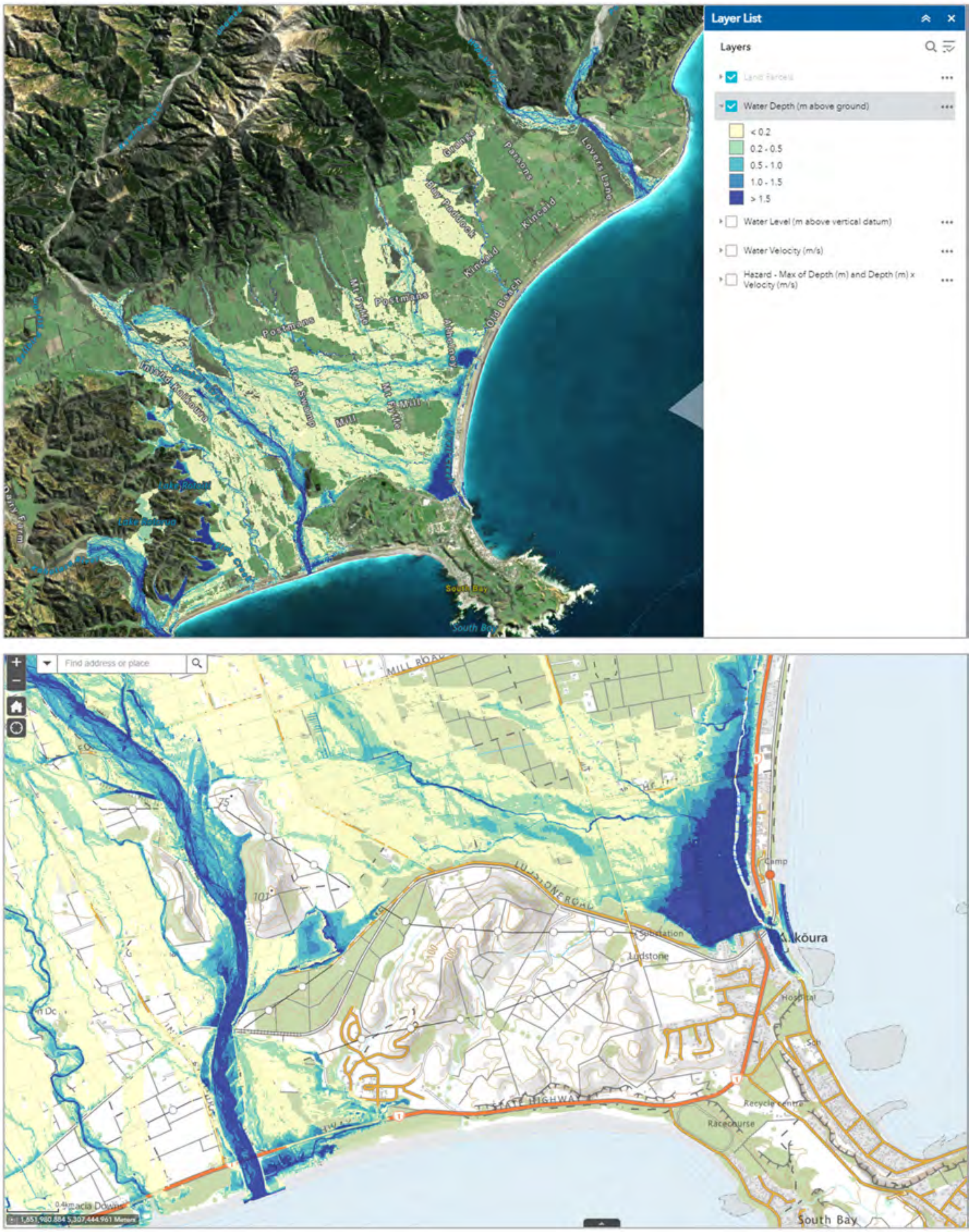


Figure 3-1 Kaikoura area 500 year flooding – Kowai and Hapuku Rivers

3.3.1.2 Hurunui District Flooding Scenario

Figure 3-2 Oaro River 500 year flooding

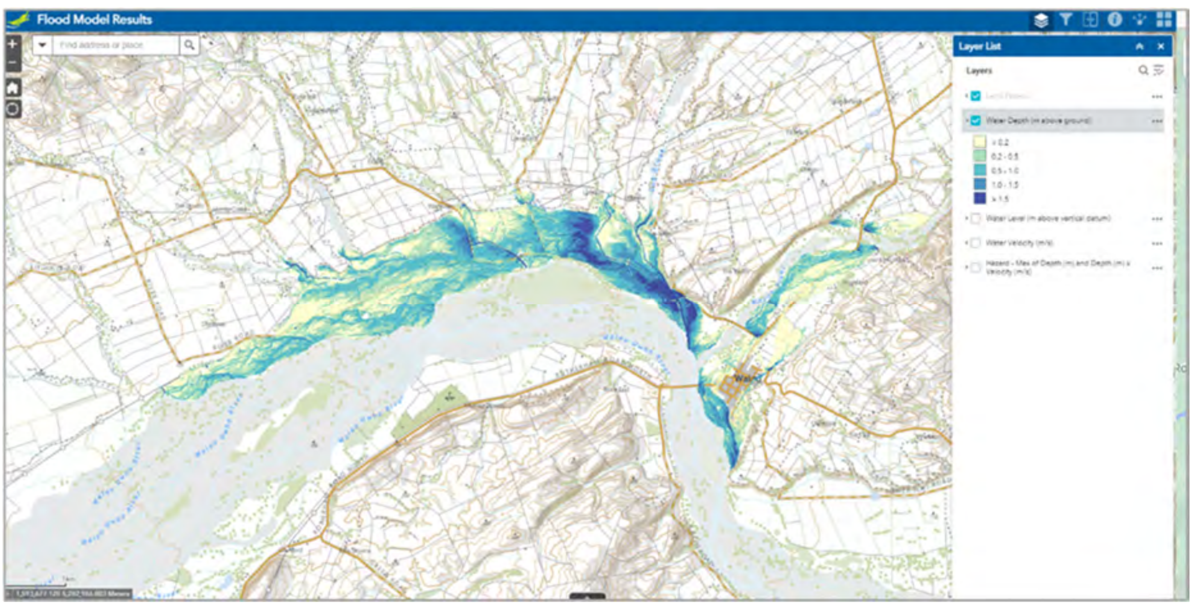


Figure 3-3 Waiau River 500 year flooding

Figure 3-4 South of Amberley – Kowai River 200 year flooding

3.3.1.3 Waimakariri District Flooding Scenario

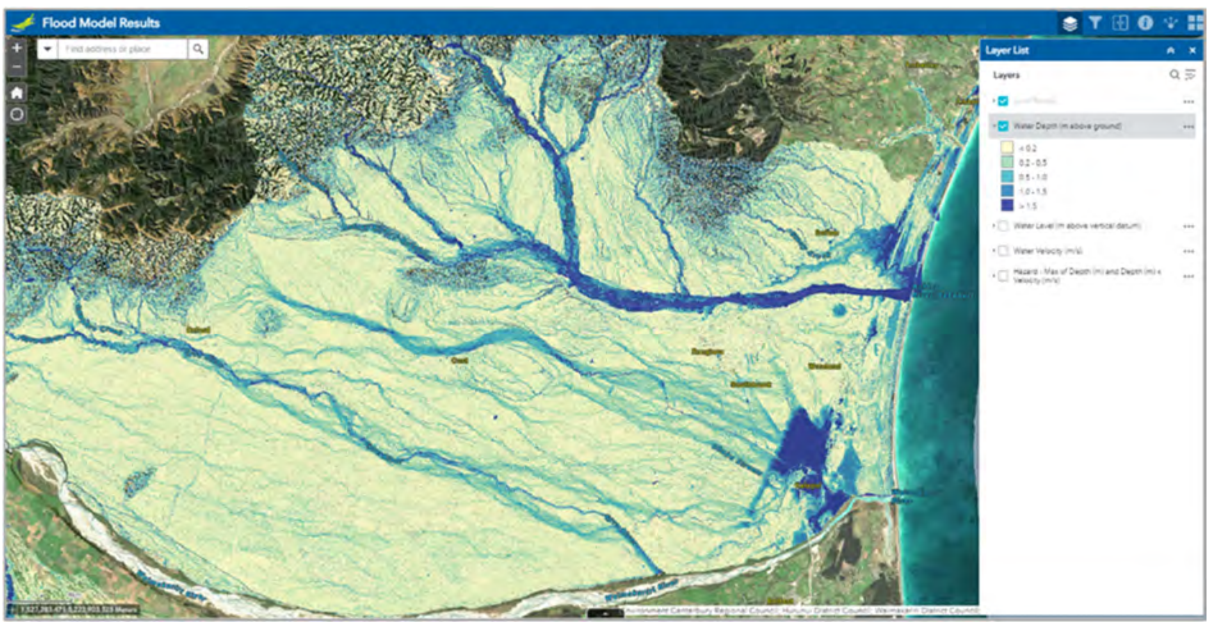


Figure 3-5 Ashley/Okuku/Eyre Rivers and their tributaries – breakouts affecting the Waimakariri District

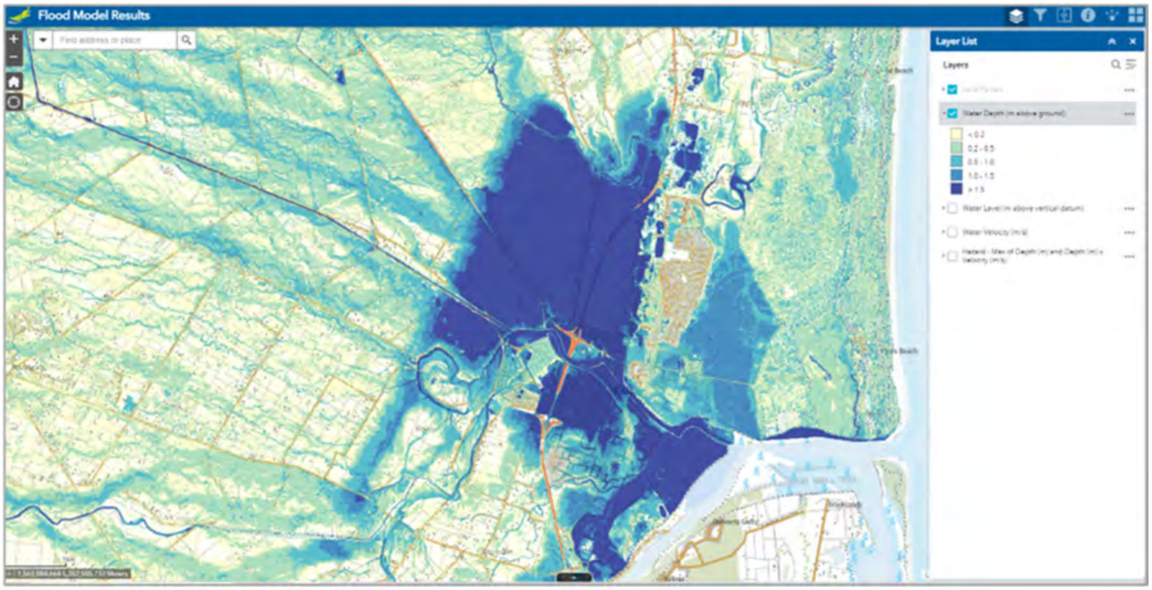


Figure 3-6 Kaiapoi township and environs flooding

3.3.2 Tsunami

A single tsunami scenario was provided by Environment Canterbury, the hazard arising from a major Hikurangi trench earthquake event (M9.0). Mapping was carried out as part of a review of tsunami evacuation zones for the Waimakariri District and the southern portion of the Hurunui District.

Both the earthquake itself and the resulting tsunami would have significant impacts on the east coast of the North Island, with tsunami waves expected to hit the North Canterbury coastline within a short timeframe after the earthquake.

This hazard layer was imported into The Portal along with the current tsunami evacuation zones. The following maps (Figure 3-7) show the evacuation zones and the inundation depths (Figure 3-8, where modelled) for the Hikurangi event.

It can be seen that:

- Kaikoura District – the District was not part of the 2021 evacuation zone review, however there are inundation risks near the mouth of the Clarence River and for the coastal environs of Kaikoura. These zones also indicate the potential for inundation and damage to both State Highway 1 and the railway corridor both to the north and south of Kaikoura.
- Hurunui District – for Amberley Beach and Leithfield Beach, inundation depths of up to 6-8m are possible in low lying estuary areas due to the Hikurangi scenario. Tsunami impacts could affect State Highway 1 from Leithfield south to the boundary with the Waimakariri District as well as local roads near the coast. The township of Amberley is not impacted.
- Waimakariri District – rural areas east of Sefton, the Saltwater Creek area, Waikuku Beach, and the eastern edges of Pegasus and Kaiapoi townships could be impacted, again with water depths up to 6-8m in estuary areas. Saltwater Creek appears to be amongst those areas worst affected. State Highway 1 would also be inundated particularly near Saltwater Creek north to the Hurunui boundary.

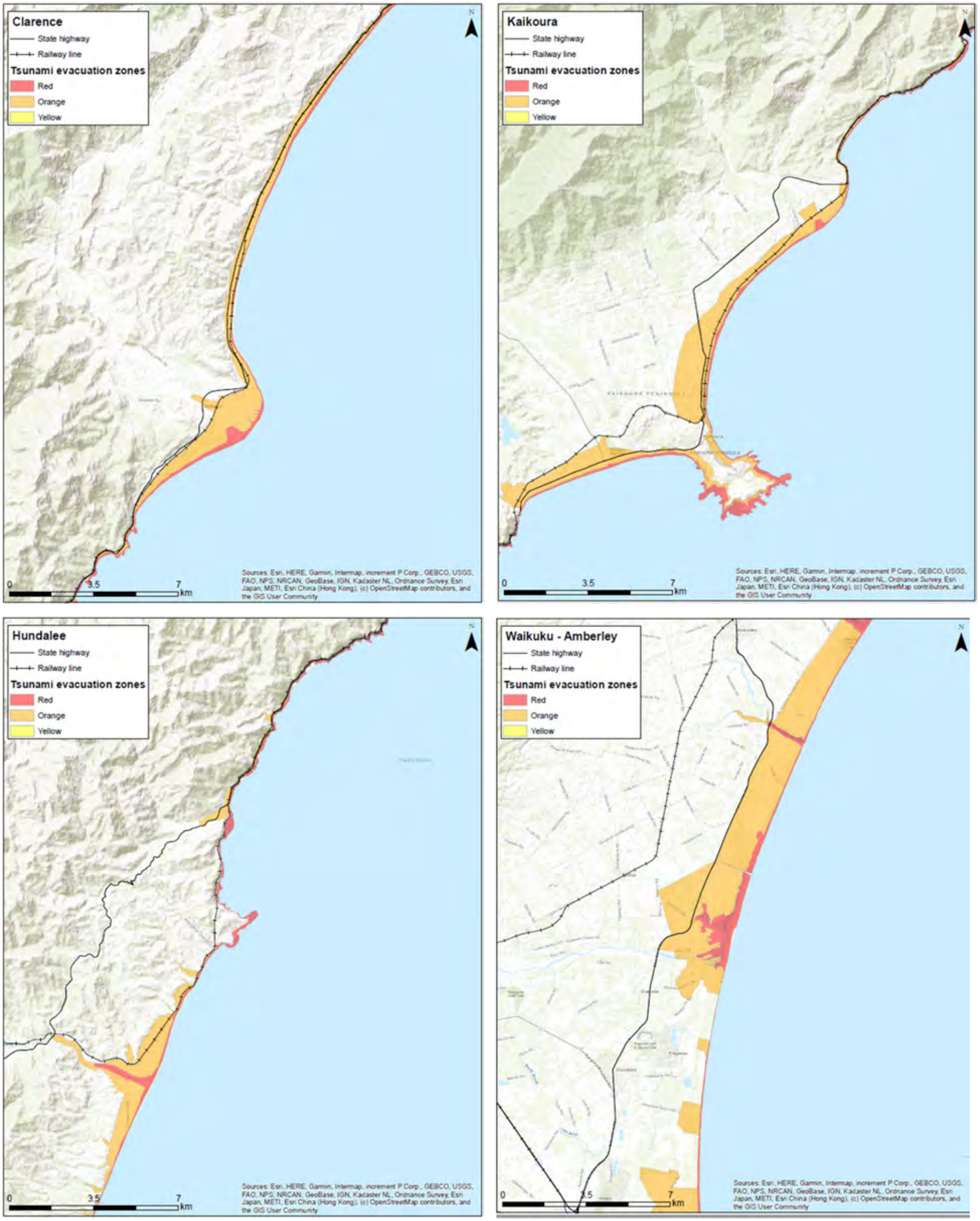
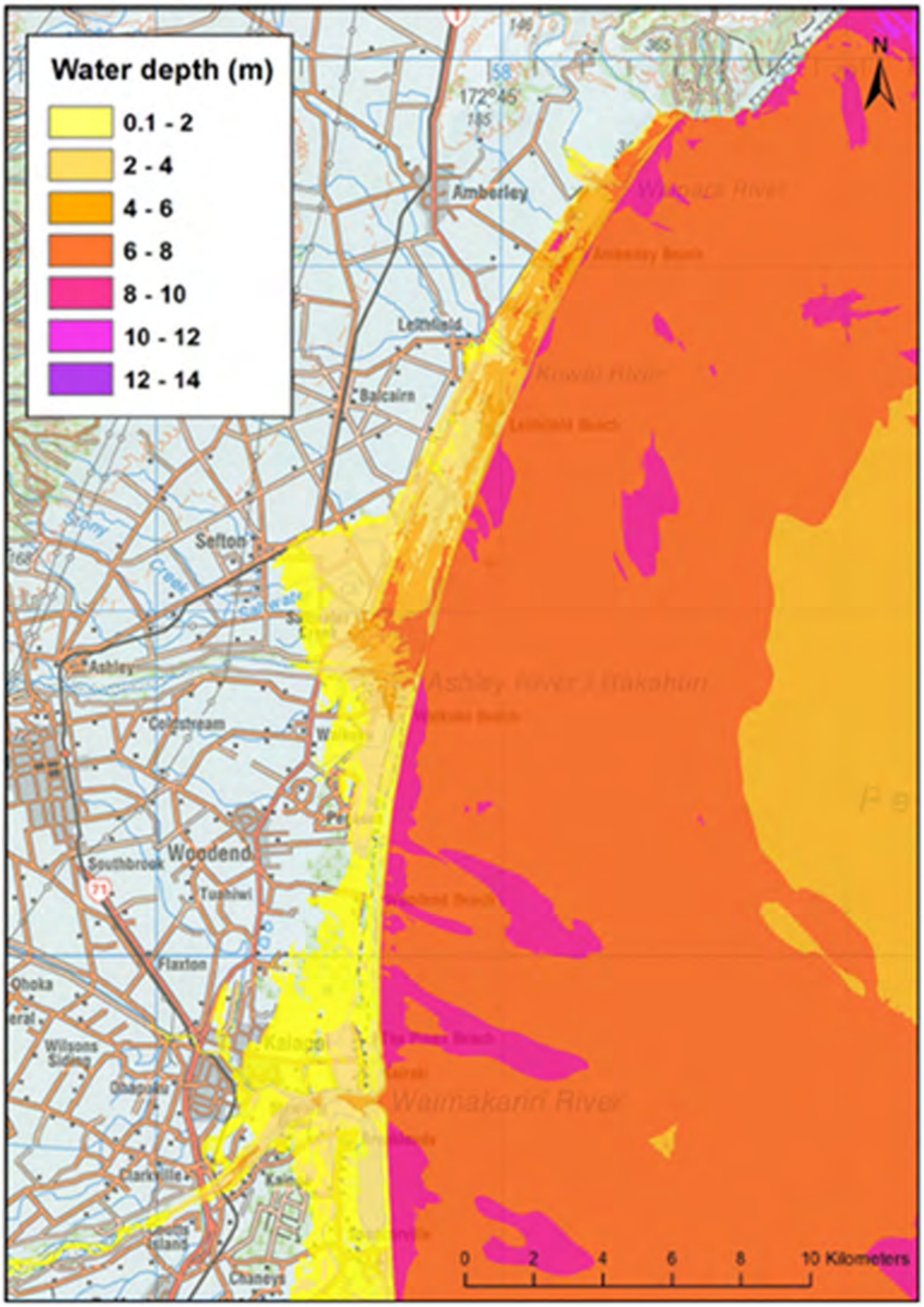


Figure 3-7 Tsunami Evacuation Zones – Kaikoura and Hurunui Districts



Maximum modelled inundation water depths for thirty M9.0 southern Hikurangi subduction zone earthquake tsunami scenarios (ECan report R21/08)

Figure 3-8 Tsunami risk – Hurunui and Waimakariri Districts

3.4 Impacts to Lifelines

3.4.1 Asset Fragility

Whether an infrastructural asset will be physically damaged or not by a flood or tsunami event depends on a range of factors, including:

- The inundation depth of the water flow.
- The velocity of the water flow.
- Whether the asset is at or above the surface of the ground or buried underground – and in the case of the latter, the ability of the ground itself to withstand damage.
- The physical "robustness" of the asset, i.e., its ability to withstand the combination of flow depth and velocity.
- Whether there is a "debris load" in the flow – such as experienced in the recent Cyclone Gabrielle flood event where debris blocked waterways at bridges. This may result in either the floodwaters flowing around the bridge damaging or overcoming flood protection defences or damaging the bridge or its approaches.
- Whether protection measures have been put in place for vulnerable assets – for example, equipment is raised above ground floor level, specific asset strengthening, or flood protection works.

While there is an international body of knowledge around the relative vulnerability of some physical assets to specific hazard events, this is incomplete in relation to the assets that form part of this study.

3.4.2 Vulnerability Categorisation

Four vulnerability categories are mapped in the UI Resilience Explorer where fragility relationships are available:

- High
- Medium
- Low
- Undefined

Fragility relationships are defined for electricity substations and roads and mapped for demonstration purposes. Where a relationship is "undefined", workshops and expert elicitation are required to estimate what these would be. Such improvements are currently underway with various infrastructure managers. Once modified or new relationships are developed, the UI Resilience Explorer platform is easily updated and this change reflects in the cascading impacts. Categories are linked to the likelihood of failure or damage, defined as follows:

Table 3-1 Defined Fragility Relationships

Asset Type	Low	Medium	High
Electricity Substations	Probability of failure < 10% (Sanchez-Munos 2020), which relates to less than 1.15m depth of flooding.	Probability of failure 10% to 50% (Sanchez-Munos 2020), which relates to flooding depths between 1.15m and 1.55m.	Probability of failure > 50% (Sanchez-Munos 2020), which relates to more than 1.55m of flooding.
Roads	Expected damage < 10% (Espinet et al 2010), which relates to less than 1m depth of flooding.	Expected damage 10% to 50% (Espinet et al 2010), which relates to roads with flood depths greater than 1m. As the fragility method is defined up until 1.5m, any further flood depths are given a 'medium' category.	Expected damage > 50% (Espinet et al 2010)

3.4.3 Flooding Scenario

Flooding events may impact lifelines assets in the following ways, with the level of damage and disruption depending on flow depth, velocity, and debris load. The snapshot view below from the UI Resilience Explorer shows the location, extent and depths of a 500 year flooding hazard scenario.

Table 3-2 Flooding Impacts on Infrastructure

Sector	Asset Type	Possible Damage Impacts
Electricity	Substations / GXPs	Inundation and contamination of electrical equipment
	Overhead lines	Breaks or damage to supporting structures (poles, towers)
	Underground cables	Damage due to land erosion or scour
	Control centres	Inundation of site, loss of access to facility, contamination of equipment
Roading Networks	Bridges	Scour or washout of bridge structure / abutments
	Roads	Flooding, washouts, slips, scour / erosion impacts
Telecommunications	Exchanges	Inundation of buildings, damage to equipment, contamination
	Underground cables / ducts	Damage due to land erosion or scour
	Cabinets	Damage due to inundation and contamination of equipment
	Mobile cellular sites	Contamination and damage to equipment located at or near ground level.
Water / Wastewater	Treatment / Pumping Stations	Inundation, contamination of equipment and water supplies
	Pipe networks	May be damaged if affected by severe scour of the ground

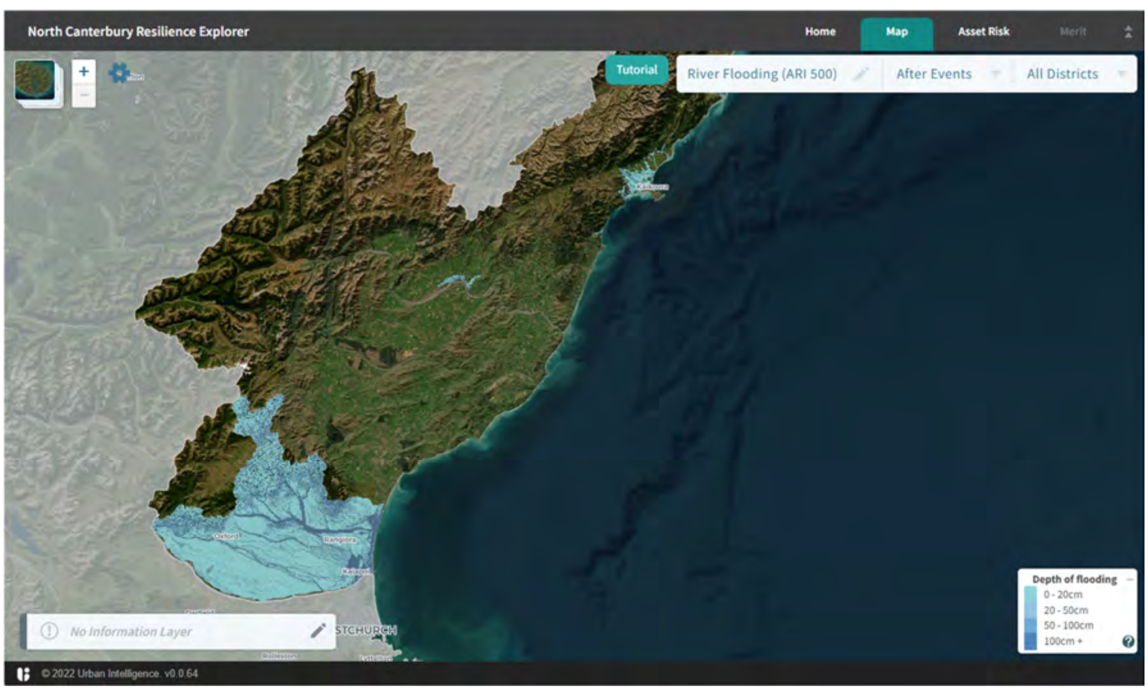


Figure 3-9 Flooding Scenario affecting North Canterbury

The following images provide examples of snapshot views from the UI Resilience Explorer showing the vulnerability of roads to the flooding scenario. These are based on relationships defined in Table 3-1.

- Figure 3-10 shows the Kaikoura area and roads affected by flooding – “Low” and “Medium” vulnerability.
- Figure 3-11 shows the wider Waimakariri District and wide-spread flooding affecting much of the road network, although relatively shallow with predicted depths of a few centimetres for much of the area to the west. Along SH1 the Saltwater Creek area is a known vulnerability.
- Figure 3-12 shows the area to the north of Kaiapoi, with flood levels up to 2.3m above ground level in the vicinity of State Highway 1. While locations are shown, there is currently no fragility relationship in the UI Resilience Explorer for bridges.

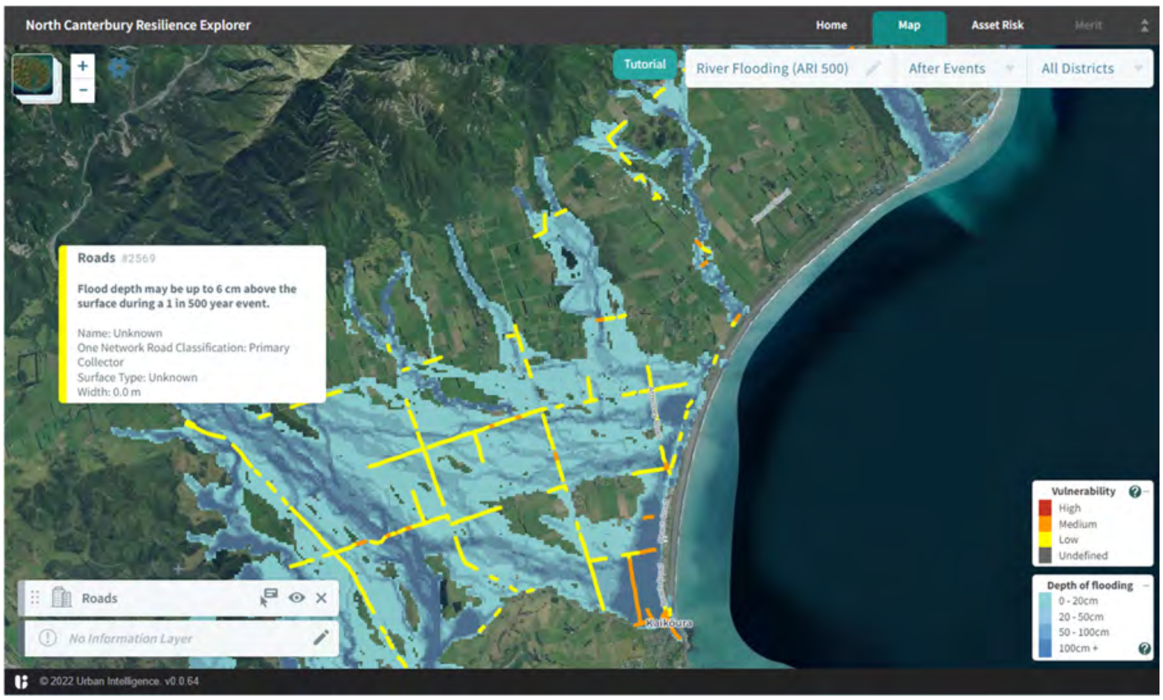


Figure 3-10 **Vulnerability of Road Network to Flooding – Kaikoura and Environs**

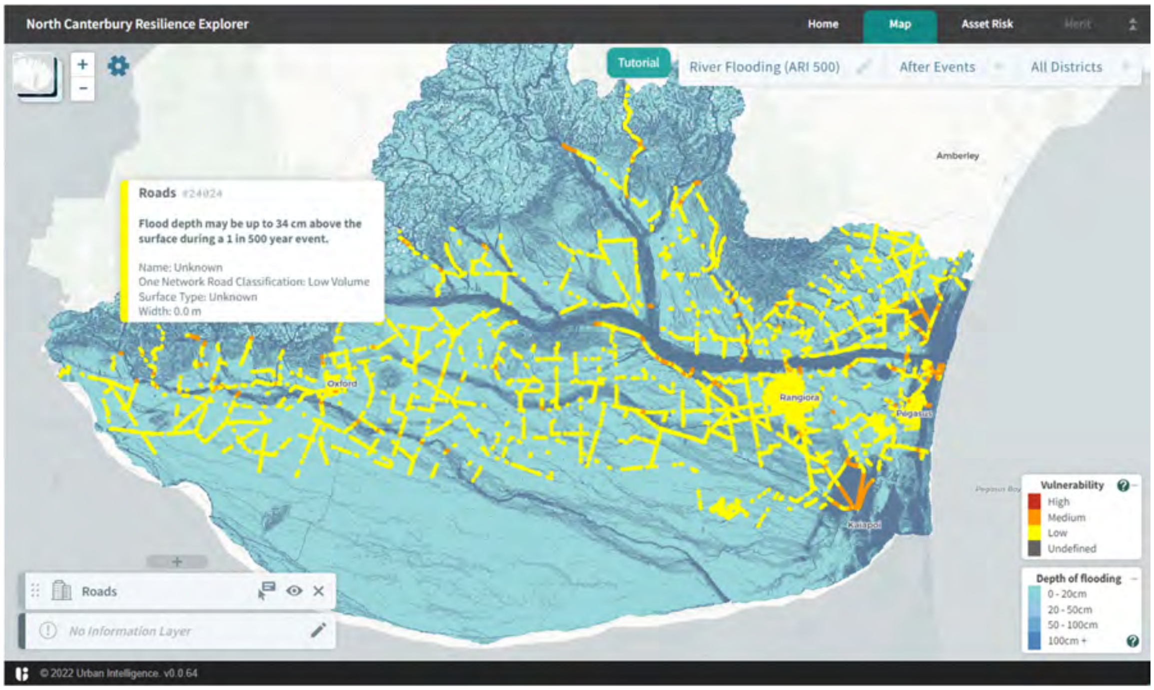


Figure 3-11 **Vulnerability of Road Network to Flooding – Waimakariri District**

Figure 3-12 **Vulnerability of Road Network to Flooding – Kaiapoi and Environs**

For electricity, the following scenarios are mapped below:

- Figure 3-13 shows the location of Transpower's high voltage transmission lines, both DC and AC circuits. These will be surrounded by flooding with some towers in or adjoining riverbeds. MainPower's distribution substations and two GXPs are also shown (Kaiapoi and Rangiora (Southbrook)). Further information is needed to estimate the expected damage or operational state. Once this is available, the UI Resilience Explorer can be updated.
- Figure 3-14 shows a closer view of Kaiapoi and the area immediately to the north. It can be seen that there are "High" and "Medium" vulnerability sites with flood levels up to 2.3m above ground level.

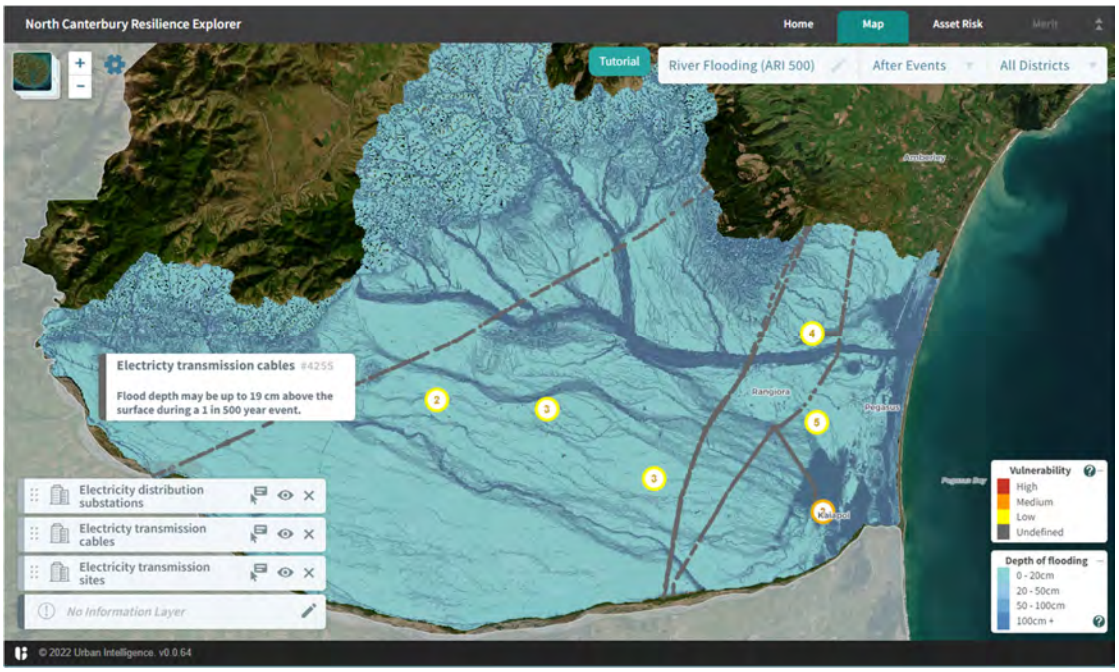


Figure 3-13 Location of Transpower Transmission Lines – Waimakariri District Flooding Scenario

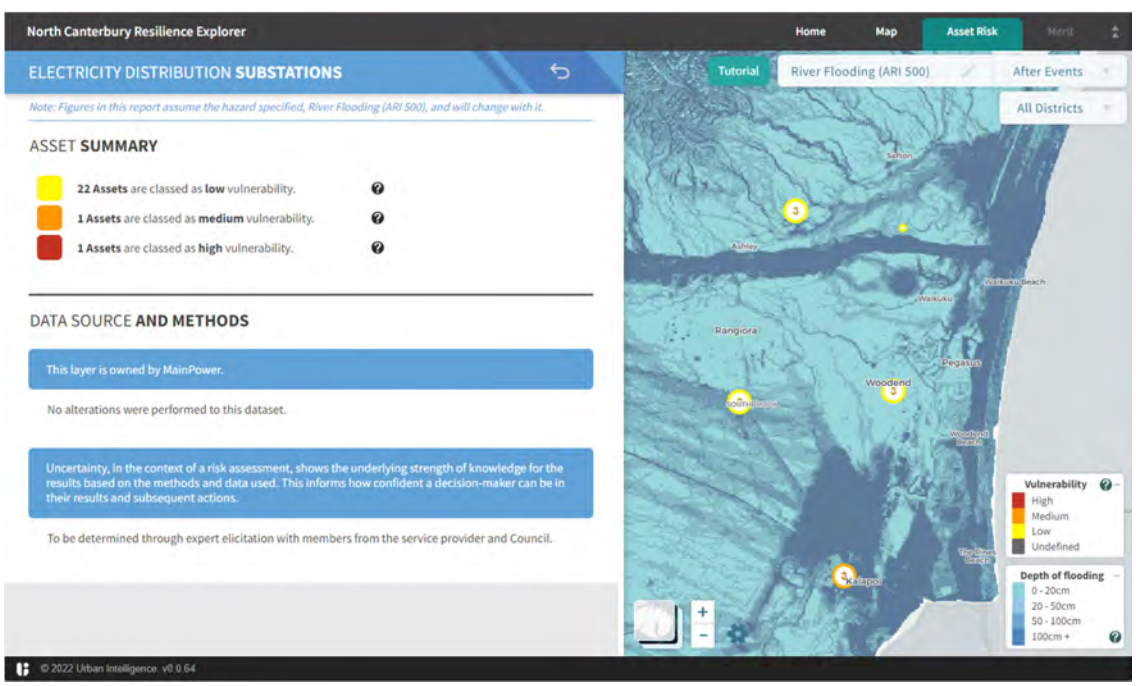


Figure 3-14 Vulnerability of Electricity Substations to Flooding – Kaiapoi and Environs

For telecommunications, the following are mapped below. Further information/workshops are required in order to estimate the damage/operational state.

- Figure 3-15 shows Vodafone, Chorus and Enable assets, primarily the fibre network and mobile cell towers across the district.
- Figure 3-16 provides a closer view of Kaiapoi and the surrounding area, with fibre network cabinets being shown in addition to fibre lines.

Note that fragility relationships are not currently defined for these scenarios.

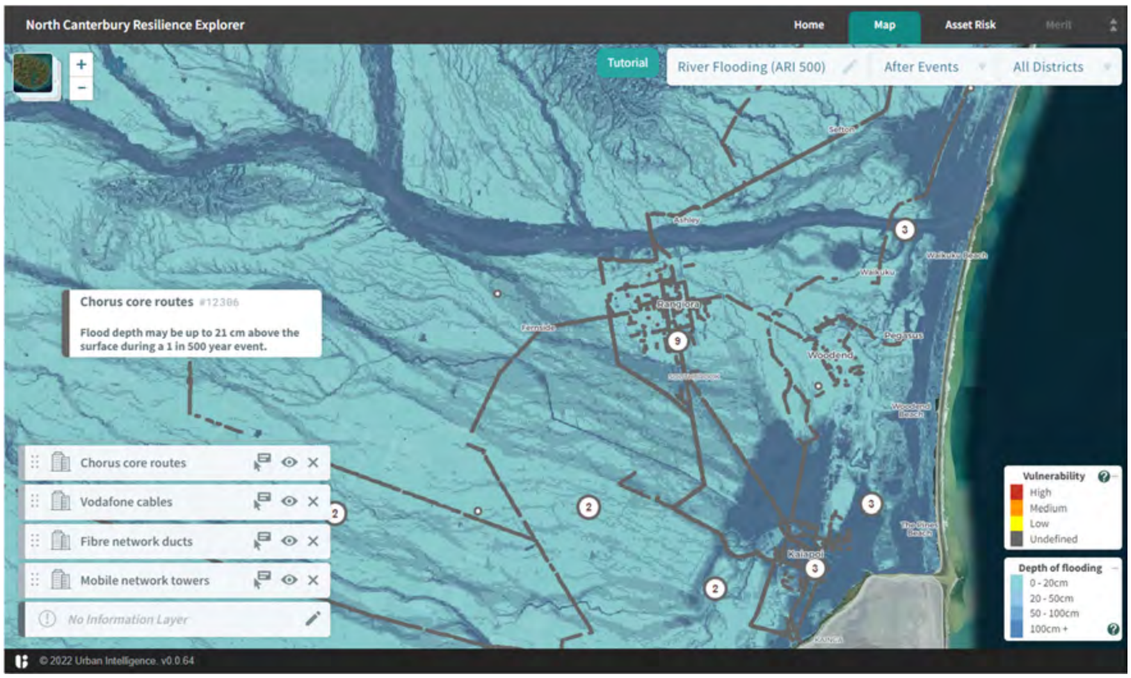


Figure 3-15 Location of Telecommunications Assets - Waimakariri District Flooding Scenario

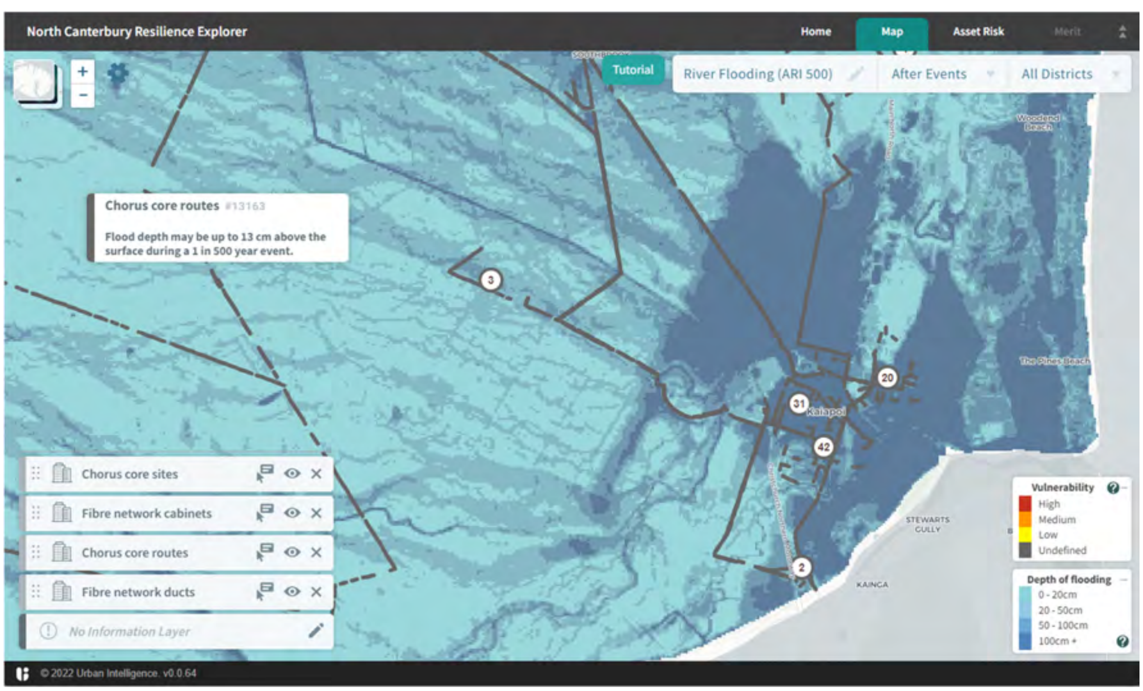


Figure 3-16 Location of Telecommunications Assets – Kaiapoi Area Flooding Scenario

For water, wastewater and stormwater facilities, pumping stations are shown in Figure 3-17. Again, fragility relationships are not defined.

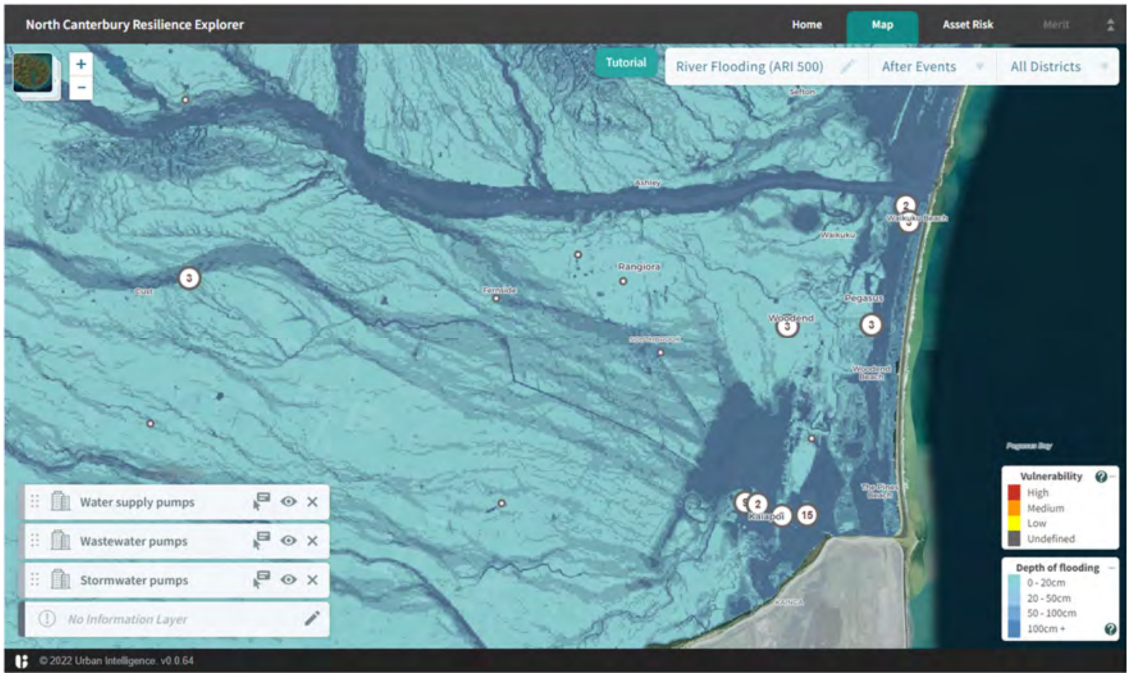


Figure 3-17 Location of Three-Waters Pumping Stations – Waimakariri District

3.4.4 Hikurangi Tsunami Scenario

Tsunami events may impact lifeline assets in a number of ways, summarised below.

Table 3-3 Tsunami Impacts on Infrastructure

Sector	Asset Type	Possible Damage Impacts
Electricity	Substations / GXPs	Inundation of substations or transformers, damage due to debris flows, contamination of equipment
	Overhead lines	Broken / collapsed poles and overhead lines
	Underground cables	May be damaged if affected by severe scour, e.g., at bridge approaches
	Control centres	Inundation of buildings, damage to equipment, contamination
Roading Networks	Bridges	Approaches washed away, debris damage to bridge structures, loss of bridge
	Roads	Inundation, debris damage, material left on roads, scouring of roads
Telecommunications	Exchanges	Inundation of buildings, damage to equipment, contamination
	Underground cables / ducts	May be damaged if affected by scour, e.g., at bridge approaches
	Cabinets	Damage due to debris flows, contamination of equipment
	Mobile cellular sites	Foundations or structural support may be damaged due to debris flow. Contamination and damage to equipment located at or near ground level.
Water / Wastewater	Treatment / Pumping Stations	Inundation, damage due to debris flows, contamination of equipment and water supplies
	Pipe networks	May be damaged if affected by severe scour of the ground

The following images provide examples of snapshot views from the UI Resilience Explorer showing the extent of the tsunami hazard and the vulnerability of roads to the tsunami scenario. These are based on relationships defined in Table 3-1.

- Figure 3-18 shows the extent of the tsunami hazard area including depths.
- Figure 3-19 shows the overlay of roads within the hazard area at three vulnerability levels, plus “undefined”.
- Figure 3-20 shows further detail for the road network in the vicinity of the lower reaches of the Ashley River. State Highway 1 north of the river is particularly affected with vulnerability levels “low” and “medium”.

In the case of medium voltage (MV) electricity cables, fragility relationships were not available, and the UI Resilience Explorer simply highlights the assets within the hazard area – noting that the vulnerability is “undefined”, this can be updated at a later date. There are no MainPower Distribution substations nor Transpower assets within the hazard area.

- Figure 3-21 shows the overlay of MV electricity cables (MainPower assets) within the hazard area.
- Figure 3-22 shows further detail in the vicinity of the lower reaches of the Ashley River.

Vulnerability is further explained in Section 3.5 in relation to vulnerability definitions, outage and recovery timeframes. The asset types are consistent with the data schema for those assets where data was able to be provided.

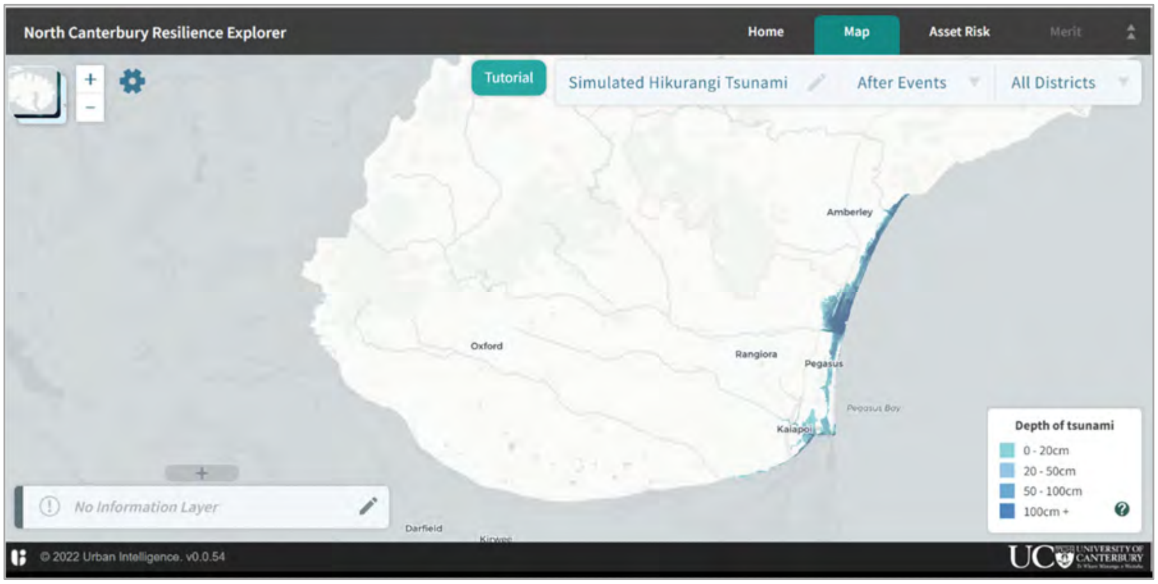


Figure 3-18 **Hikurangi Tsunami affecting Waimakariri and Southern Hurunui District Coastline**

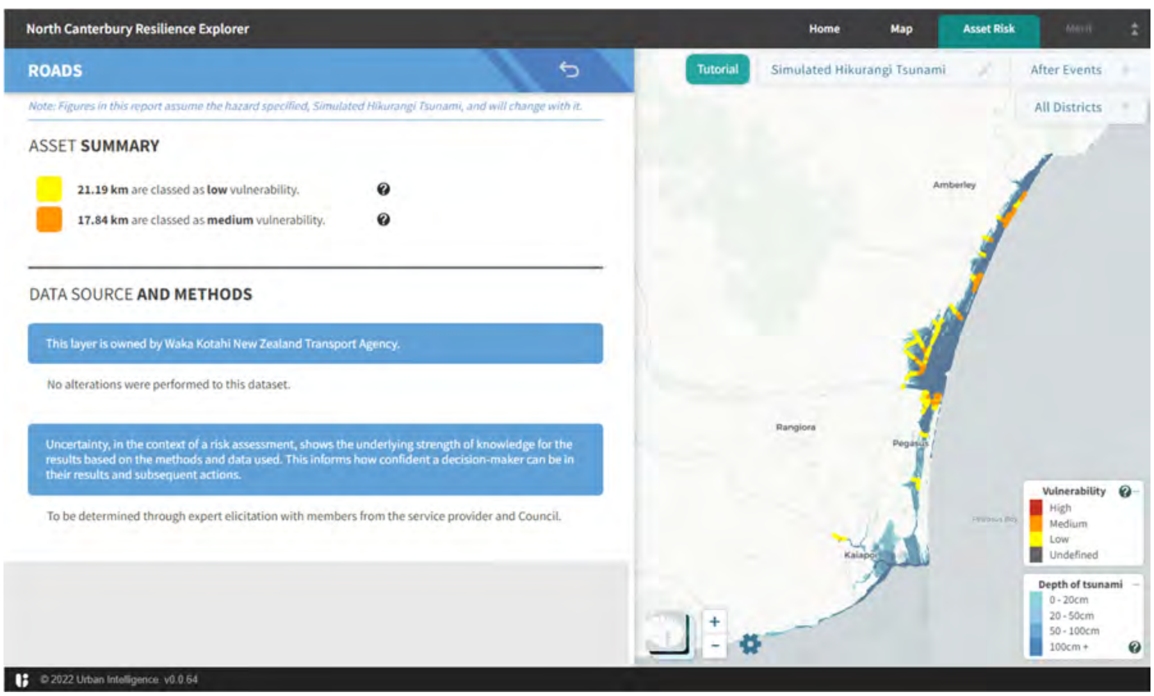


Figure 3-19 **Vulnerability of Road Network near Coastline to Tsunami Scenario**

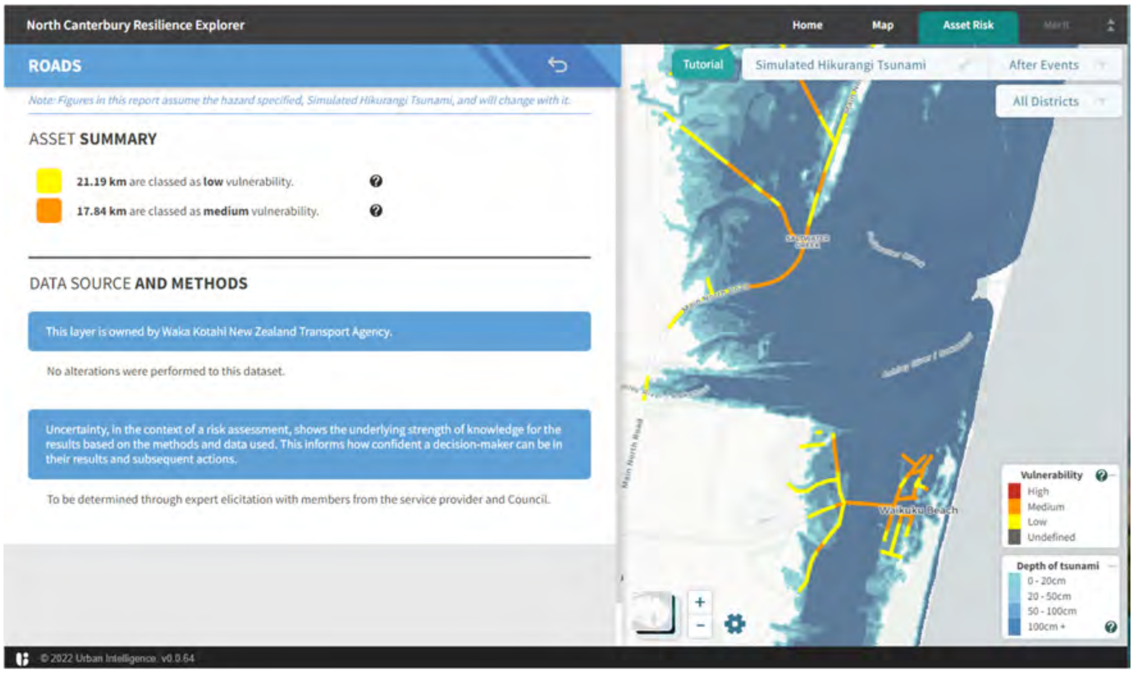


Figure 3-20 Vulnerability of Road Network around Waikuku Beach and Coastal Environs to Tsunami

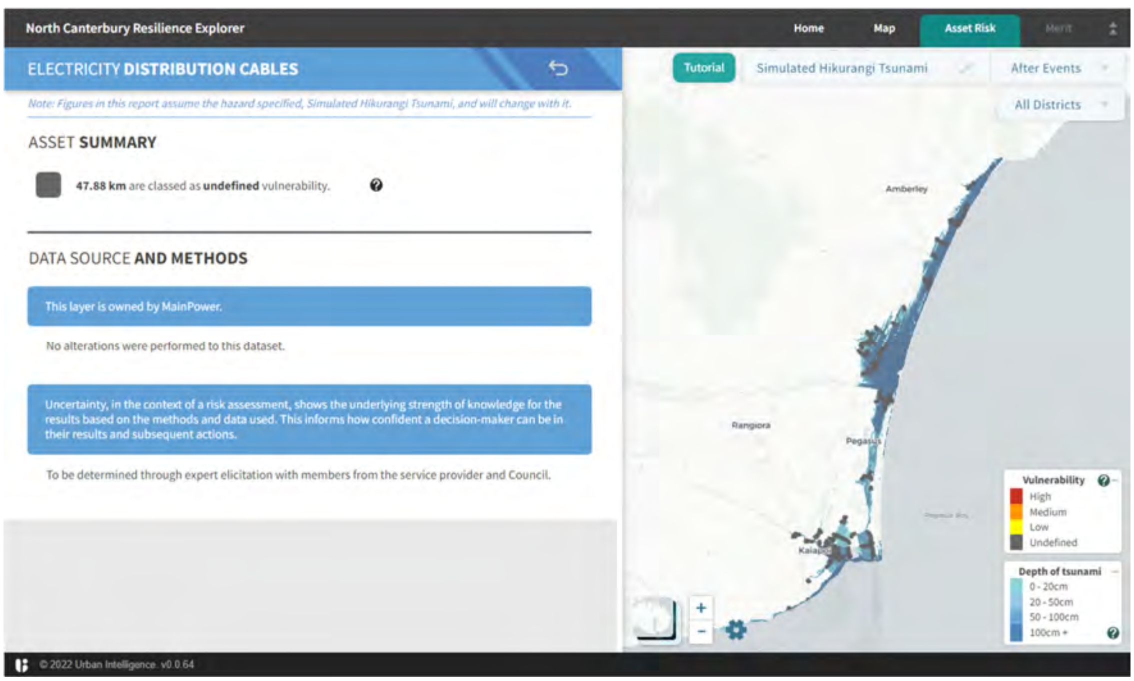


Figure 3-21 Location of Electricity MV Distribution Cables near Coastline with Tsunami Scenario

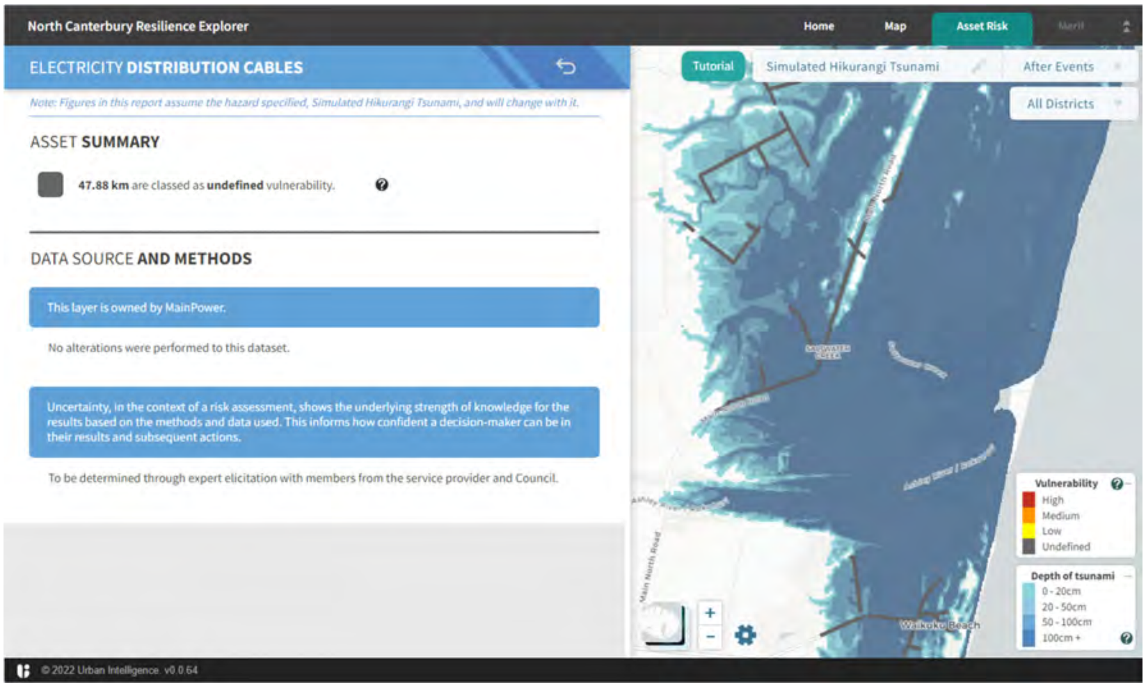


Figure 3-22 Location of Electricity MV Distribution Cables around Waikuku Beach and Coastal Environs with Tsunami Scenario

3.5 Disruption due to Lifeline Outages

Vulnerabilities were assessed in the UI Resilience Explorer using the fragility relationships defined in Section 3.4 above. Note that fragility curves relate to damage state rather than operational status.

The quantities of lifeline assets categorised using these relationships are summarised in the following tables.

Table 3-4 500 Year Flood Vulnerabilities

Asset Type	Low	Medium	High
Electricity Substations	22 sites*	1 site**	1 site***
Roads	702.9km	63.6km	0km

* Low includes Kaiapoi and Southbrook GXP sites, inundation depth up to 1.1m. Research suggests a probability of around 6% that this would result in an outage.
** Medium vulnerability site is in Kaiapoi, inundation depth up to 1.28m
*** High vulnerability site is in Kaiapoi, inundation depth up to 2.3m

Table 3-5 Tsunami Vulnerabilities

Asset Type	Low	Medium	High
Electricity Substations	0 sites	0 sites	0 sites
Roads	21.2km	17.8km	0km

While some asset types were not able to be categorised using expected damage/operational state in this way in the pilot due to fragility relationship gaps, the assets exposed to the hazard are mapped in the UI Resilience Explorer and the depth of floodwater or tsunami can be determined simply by hovering over the asset in the GIS application. This means that infrastructure managers can estimate the likely damage/operational status based on the exposure. Additionally, the UI Resilience Explorer is easily updated once this information becomes available and workshops are ongoing to establish these relationships for NZ contexts.

3.6 Outage Modelling

3.6.1 Assumptions

For the pilot, a number of simplifying assumptions have been made in order to develop and test the "proof of concept" process through to economic analysis, allowing for the application of vulnerability above together with an elicited view of lifelines damage or functionality and timeframe to restoration. Elicitation in relation to the flooding scenario was discussed at the January 2023 workshop with lifeline agencies. Only the 500 year flooding event has been considered for MERIT.

There are interdependencies within the analysis, including:

- All affected sites, power, telecommunications, water, etc., require road access to be restored before the repair process can begin.
- Telecommunications sites require electricity before service can be restored. Sites with battery or generator back-up can provide service – 12-24 hours for batteries, generators subject to daily supply of fuel.

Table 3-6 Assumed Lifelines Damage and Outages due to Flooding Scenario

Sector	Asset Type	Flooding Damage and Outage Assumption
Road Network	Bridges	Ashley River SH1 bridge structurally damaged – restoration period 3 weeks. Other bridges have no significant structural damage with restoration of service, for example due to washout of approaches, occurring shortly after the event.
	Roads	Scour of road surfaces at "Medium" or "High" level – restoration timeframe 3 days. For example, SH1 and Lineside Road (SH71) both cut off due to flooding. Temporary flooding of roads at "Low" level – restoration follows shortly after floodwaters recede. Detour route planning and implementation required across the network.
Electricity	Substations / GXPs	Two MainPower substations at Kaiapoi ("Medium" and "High") inundated and out of service for 5 days – assuming that spare parts are available. The nearby Transpower GXP is assumed to be similarly affected. The whole of Kaiapoi is affected. Other MainPower substations ("Low") have little or minor impacts only with no or minimal loss of service. Transpower GXP at Southbrook assumed to be "Low" as per nearby MainPower substations.
	Transmission Lines and Towers	While widely exposed to surface flooding, for the purposes of the pilot no significant damage, with no or minimal loss of service. Towers in riverbeds – no outage assumed. Note that telecommunications are important in monitoring network status.
Telecommunications	Exchanges	Exchange in Kaiapoi mechanical and electrical equipment damaged requiring replacement – 1 week to restore once access provided.

Sector	Asset Type	Flooding Damage and Outage Assumption
	Underground cables / ducts	No damage assumed.
	Cabinets	Assumed to be out of service until power is restored. All cabinets flooded by more than 300mm non-operational for 4 days.
Water / Wastewater / Stormwater	Treatment / pumping stations	Assumed to incur flood damage if flood level rises more than 300mm above ground level. Outage period – 4 days.
	Underground pipes	No or minimal direct damage assumed, minimal outage periods.

3.6.2 MERIT Information Needs

Essentially, the information needed for economic analysis using MERIT includes:

- The spatial basis of the analysis, this being "Statistical Area 1" (SA1) – there are 483 such areas in North Canterbury, the base year being 2018 (see Figure 3-23 below).
- Whether each asset is operable or not, given the above assumptions, immediately after the event in each SA – this involves assigning a value of "0" or "1" in the model. This has been applied for Electricity, Roads, Telecommunications, and Water Supply in the pilot.
- The time over which each asset is operable or not in the days following the event, the input template providing capacity for up to 2 years if desired.

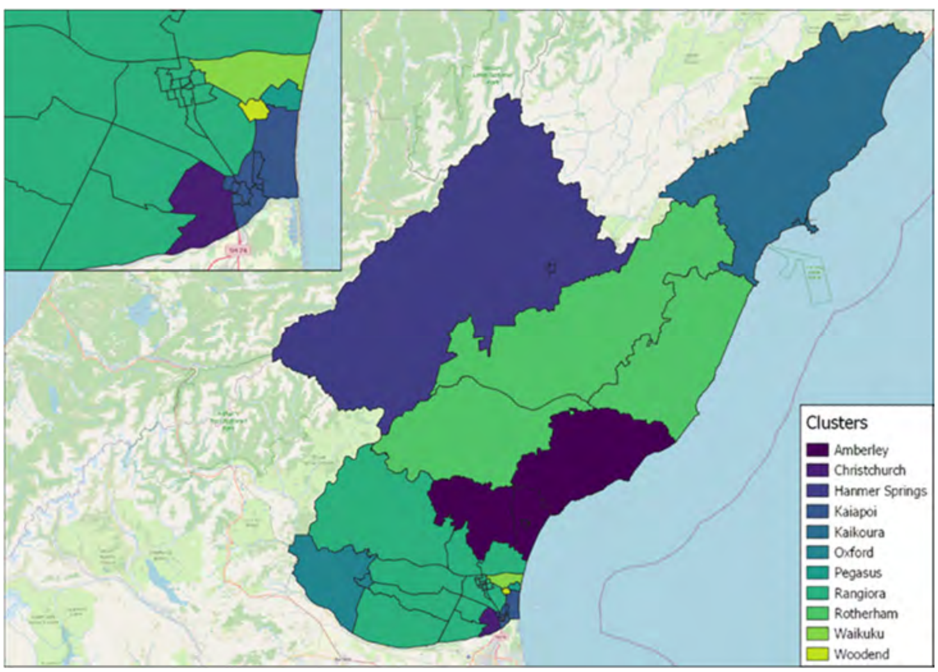


Figure 3-23 Statistical Area Clusters

It is also necessary to understand the interdependencies between sectors in modelling outages, such as the reliance of telecommunications exchanges or water and wastewater treatment and pumping facilities on electricity. Loss of electricity supply will result in an immediate loss of service functionality and capacity unless alternative generation facilities are available. These impacts also affect economic outcomes.

3.7 Potential Mitigations

The two project workshops with lifeline utilities highlighted a range of potential mitigations that could reduce the impacts of flooding or tsunami impacts, including:

- Enhanced flood protection schemes, especially the Ashley River, such as stopbanks, groynes, plantings, controlled overflow points, etc.
- Increasing the height above ground of critical infrastructure – such as transformers, electrical equipment, etc. In some locations where deep flooding is expected, relocation or duplication to add diversity would be preferable.
- Building up low-lying roadways over time.
- Armouring bridge approaches to reduce scour and erosion risk – this can affect both the roadway and underground services that cross the bridge (e.g., water supply pipes, fibre optic cables, etc.).
- Strengthening, relocating, or protecting vulnerable infrastructure. Such works could be carried out in association with BAU asset renewal programmes.
- Add diversity or back-up to networks – particularly telecommunications.

3.8 Outputs for MERIT

The primary output from the vulnerability modelling process above is an availability matrix. Screenshots from this are provided below:

Infrastructure:	**Description:**	**Data format:**
1. Electricity	electricity outage	SA1 x Day (0=no service, 1=service)
2. Water	water outage	SA1 x Day (0=no service, 1=service)
3. Telecom data cell	data-cell outage	SA1 x Day (0=no service, 1=service)
4. Telecom data landline	data-landline outage	SA1 x Day (0=no service, 1=service)
5. Telecom voice cell	voice-cell outage	SA1 x Day (0=no service, 1=service)
6. Telecom voice landline	voice-landline outage	SA1 x Day (0=no service, 1=service)
7. Road	road accessibility	Road segment x Day (0=no accessibility, 1=accessible)

Information:
For the following infrastructures: electricity (Tab.1), water (Tab.2), telecoms (Tab. 3-6):
Each tab contains the locations (SA1), time (Day) and on/off infrastructure (electricity, water, telecom).
The 2018 statistical area 1 code (SA1) for the Canterbury Region are listed in column A.
On the first row, from column C onwards, the days. Days start from day 0 to day 729. This is a two year period. Day 0 is the first day of the hazard.

For road accessibility, Tab. 7 contains the list of road segments (based on method A or B) in column A.
On the first row, from column C onwards, the days. Days start from day 0 to day 729. This is a two year period. Day 0 is the first day of the hazard.
There are two methods to obtain road segments (please choose one):
a) Method 1: Integrate speed info into LINZ centreline data — See tab 7 - table A, for a small example of this method output
b) Method 2: Use Open Street Map data — See tab 7 - table B, for a small example of this method output

Instruction:
For each tab, please delete the dummy data and enter your data in the format (0=no service,1=service) in the highlighted cells (yellow).
Example: Cell B8 will take the value 1 if the SA1 7023547 will have electricity at day 0, otherwise 0 if there is an electricity outage in that SA1.
Please note that for road accessibility, we don't need the road segments in both formats. Please choose one of the two methods in Tab7 to obtain the road segments.
Then, please populate Table7 with a list of road segments and enter the data in the format (0=road segment inaccessible, 1=road segment accessible).

Contents | 1. Electricity | 2. Water | 4. Telecom data landline | 7. Road | +

Figure 3-24 North Canterbury Pilot – Outages Data Template

Table 1

Electricity outage data for the Canterbury Region
By SA1, day

SA1 (2018)	X0	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17
7024206	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024216	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024217	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024192	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024193	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024195	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024218	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024219	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024262	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024264	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024273	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024178	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024179	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024180	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024181	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024182	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024183	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024184	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024185	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024186	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024187	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024188	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024189	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024190	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024191	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024194	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024196	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024197	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
7024198	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	

Contents | 1. Electricity | 2. Water | 4. Telecom data landline | 7. Road

Figure 3-25 **Electricity 5 day Outages by Statistical Area**

The risk and vulnerability assessment is overlaid on the Statistical Area 1 areas with individual outages aggregated to the SA1 level, such that any outage in an SA1 area results in MERIT modelling the entire SA1 as having a loss of service for the given utility.

MERIT requires input information indicating binary (0 or 1) operational status information at the statistical area 1 (SA1 meshblock) level. This information is an automated output of the UI Resilience Explorer for any spatial unit. In this case, individual outages are aggregated to the SA1 level, such that any outage in an SA1 area results in MERIT modelling the entire SA1 as having a loss of service for the given utility. Further work could assess and report partial service within SA1 areas, where a proportion of the SA1 may have service while some may not.

This information can be provided for different time horizons following a disruption, based on recovery scenarios.

4.0 MERIT Economic Analysis

4.1 Overview

The MERT modelling conducted for the North Canterbury pilot is described in a separate report[2], included as an Appendix. Only the flooding scenario has been considered in order to demonstrate the end-to-end process.

MERIT itself is a “modelling pipeline” with a range of components shown below. Not all of these were implemented for the North Canterbury pilot, with those shown in yellow utilised.

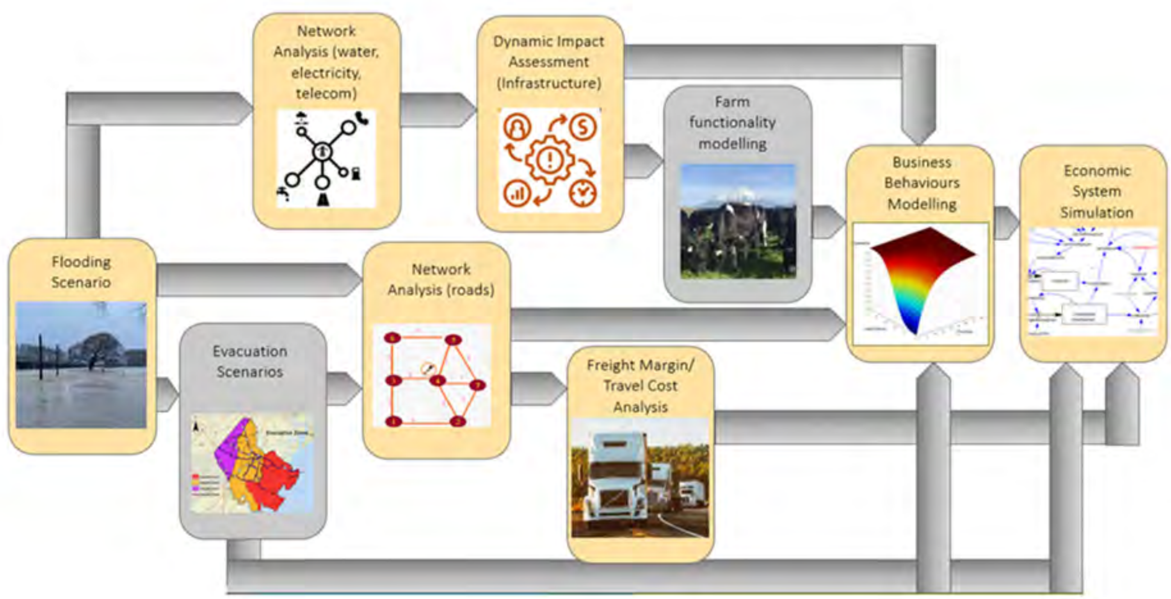


Figure 4-1 MERIT Modelling Pipeline

MERIT simulates the dynamics of a shock event and estimates the economic consequences of the specific disruption event across time at both regional and national scales. It can model complex events with multiple infrastructure outages, and how those events impact different stakeholders, such as households and industries, within North Canterbury and across New Zealand.

4.2 Modelling Approach

MERIT modelling was carried out in two phases:

- Calculation of initial direct economic impacts using the Business Behaviours Module (BBM) – this estimates the ability of industries to continue operating from initial disruption back to full production. Transport accessibility has also been considered using the Direct Transport Cost Analyser, this feeding into the BBM.
- Assessment of wider flow-on impacts in the Dynamic Economic Model (DEM) – this combines all the inputs and simulates how the economy responds over time, providing a dynamic picture of the disrupted economy.

Operability curves are shown for the manufacturing sector in Figure 4-2. Similar sets of curves were produced for other sectors, including farming, services, accommodation, etc.

[2] Market Economics, Preliminary MERIT Study: North Canterbury Flooding, May 2023

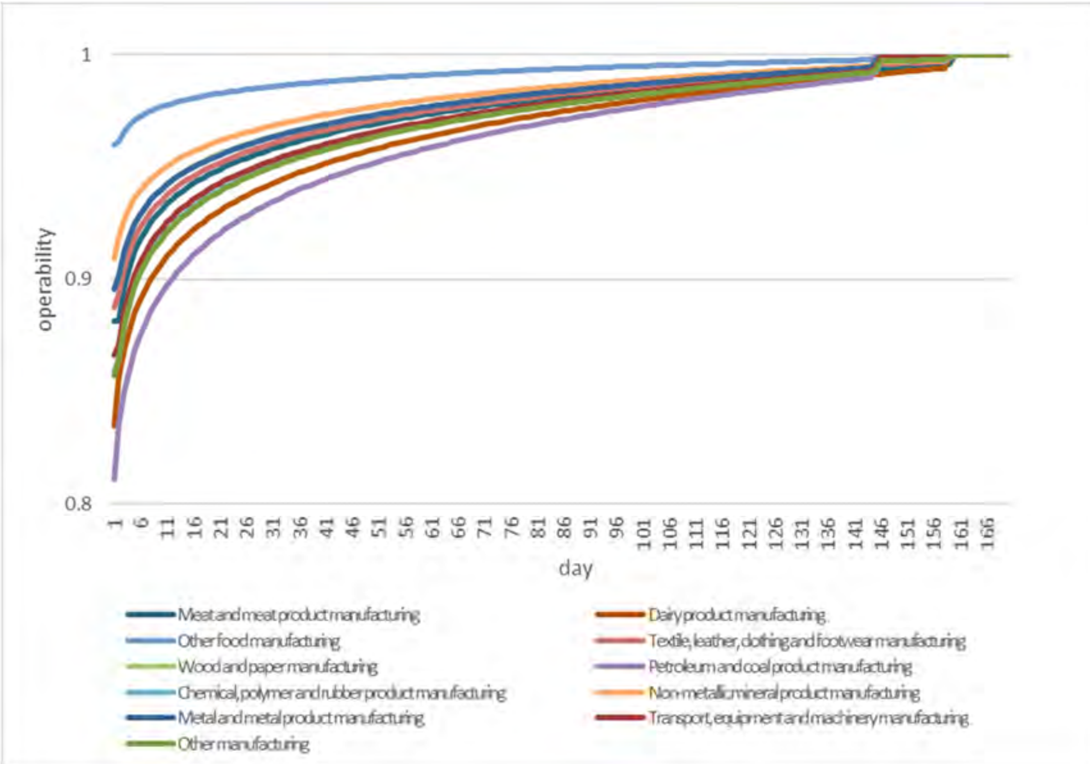


Figure 4-2 Operability Curves for Manufacturing Industries

MERIT also produces a range of graphs reporting the loss of economic activity: Real GDP, Real GRP, and Value Added. The flooding event results in reported losses or reductions in each of these measures. GDP impacts are illustrated in Figure 4-3**Error! Reference source not found.**, showing the “dip” at both national and regional levels.

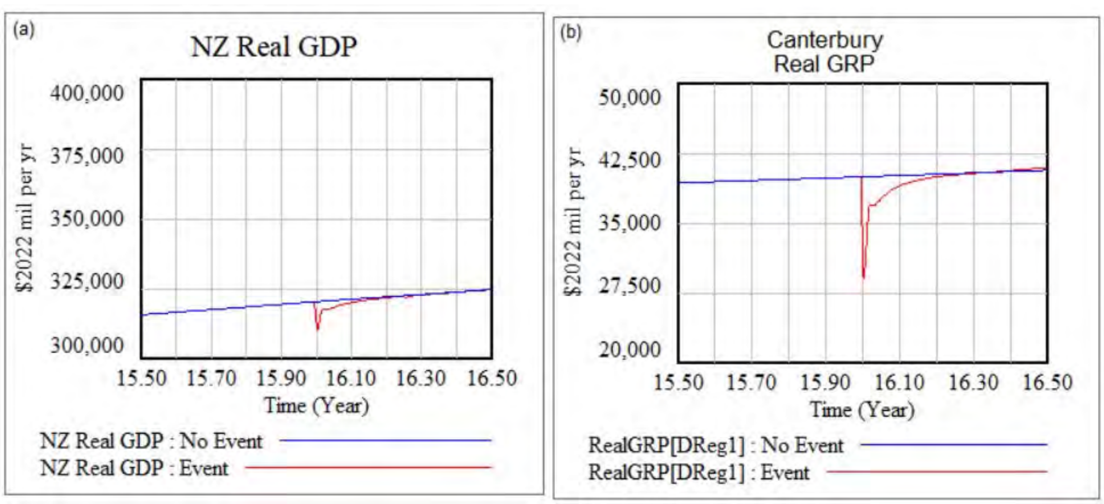


Figure 4-3 GDP Impacts – MERIT Dynamic Economic Model

More details can be found in the MERIT modelling report appended.

4.3 Whole of Economy Impacts

Ultimately, the cumulative loss of value added across all industries over the first six months of the event is estimated to be ~NZ$_{2022}$\$390m as summarised by industry in the figure below. Note that this is the modelled impact of a 500 year event, with an approximate probability of occurrence of 0.2% in any given year – yielding an annualised risk exposure for this event only of \$390m x 0.2% = \$780,000.

	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6
1 Horticulture and fruit growing	-1	0	0	0	0	0
2 Sheep, beef cattle and grain farming	-1	0	0	0	0	0
3 Dairy cattle farming	-6	-2	-2	-1	-1	0
4 Poultry, deer and other livestock farming	-1	0	0	0	0	0
5 Forestry and logging	-1	0	0	0	0	0
6 Fishing and aquaculture	-2	-1	0	0	0	0
7 Agriculture, forestry and fishing support services	0	0	0	0	0	0
8 Mining, quarrying, exploration and other mining support services	0	0	0	0	0	0
9 Oil and gas extraction	0	0	0	0	0	0
10 Meat and meat product manufacturing	-17	-5	-2	-1	0	1
11 Dairy product manufacturing	-39	-7	1	4	4	5
12 Other food manufacturing	-2	0	0	0	0	0
13 Textile, leather, clothing and footwear manufacturing	-2	0	0	0	0	0
14 Wood and paper manufacturing	-3	-1	-1	0	0	0
15 Petroleum and coal product manufacturing	0	0	0	0	0	0
16 Chemical, polymer and rubber product manufacturing	-3	-1	0	0	0	0
17 Non-metallic mineral product manufacturing	-2	-1	0	0	0	0
18 Metal and metal product manufacturing	-4	-1	-1	0	0	0
19 Transport, equipment and machinery manufacturing	-17	-6	-4	-2	-1	1
20 Other manufacturing	-2	-1	-1	0	0	0
21 Electricity generation and supply	-6	0	0	0	0	0
22 Gas supply	0	0	0	0	0	0
23 Water, sewerage, drainage and waste services	-4	0	0	0	0	0
24 Construction	-32	-7	-2	0	0	1
25 Wholesale trade	-13	-3	-1	-1	0	0
26 Retail Trade	-26	-2	1	1	1	2
27 Accommodation and food services	-9	-1	0	0	0	0
28 Road transport	-1	0	0	0	0	0
29 Other transport, postal, courier, transport support and warehousing services.	-4	-1	-1	-1	0	0
30 Air and space transport	1	0	1	1	1	1
31 Information media and telecommunications	-3	-1	0	0	0	0
32 Finance and insurance	-3	-1	0	0	0	0
33 Rental, hiring and real estate services	-15	-3	-1	0	0	0
34 Ownership of owner-occupied dwellings	-47	-5	0	1	2	3
35 Professional, scientific, technical, administrative and support services	-8	-2	-1	-1	0	0
36 Central government administration, defence and public safety	-4	-2	-1	-1	0	0
37 Local government administration	-1	0	0	0	0	0
38 Education and training	-14	-5	-3	-2	-1	0
39 Health care and social assistance	-17	-3	-1	0	1	1
40 Arts and recreation services	-7	-1	-1	-1	-1	0
41 Personal and other services	-4	-1	0	0	0	0
TOTAL	-319	-65	-21	-6	5	16

Figure 4-4 Value Added Economic Impacts by Industry for the Canterbury Region Economy

It is important to note that this assessment has a number of exclusions, discussed in Section 4.5. The real impact could be substantially larger.

4.4 Economic Analysis of Investment Options

While this project did not go so far as identifying and assessing the effectiveness of potential mitigation options, this is the natural next step in developing cross-sector investment scenarios that consider:

- The benefit of mitigation in terms of reducing the impacts of the hazard, in turn leading to less disruption and less impact on the "whole of economy impacts" above.
- To do this would require the hazard to be remodelled following intervention – for example, flood protection schemes change the spatial extent of flood breakouts from rivers, as well as channelling floodwaters downstream[3].
- Flood hazards of different return periods (both longer and shorter) could be modelled in order to develop an annualised flood exposure risk on an "area under the curve" monetised basis.
- This could be extended to a multi-hazard approach, incorporating other risks such as tsunami or storm surge. Furthermore, the effects of climate change on sea -level rise and rainfall intensity leading to increased flooding risk need to be modelled.

The results of "before and after" vulnerability assessment and impacts analysis inform business case development, asset management planning, and investment strategies. The benefits of intervention and the associated costs can be used in assessing the cost:benefit ratio and/or net present value (NPV) of mitigation scenarios comprising packages of options across sectors.

The application of interdependency analysis in the decision-making process also helps support cross-sectoral optimisation of investment to maximise the realisation of resilience benefits to communities.

4.5 Future Opportunities for MERIT

It is important to note that the analysis excludes:

- "Loss of capital assets" – e.g., damage to infrastructure, buildings and property, this being the "Financial Loss Modelling" step in the Maturity Pathway. Various approaches can be used for modelling these losses, an existing tool being RiskScape 2.0 – refer Section 5.2 below.
- "Loss of farm production" – direct losses by farmers are not currently modelled in MERIT, although new functionality is being developed.
- "Impacts on natural capital affecting economics service benefit delivery" – work is also currently underway in this area.

These are areas where a more complete understanding of economic, financial, and environmental impacts could be sought in further work.

Other areas where improvements could be made include:

- Evacuation of people and red zones/cordon areas.
- Customise thresholds for the enablers to recovery for different business industries.
- Inclusion of other types of infrastructure outages in the analysis (e.g., wastewater, rail).

These are further discussed in the MERIT modelling report.

[3] Note that this could in some instances increase downstream risk, therefore a holistic approach to river and waterway management needs to be taken that is cognizant of all potential impacts.

5.0 Application in Other Regions

5.1 Overall Approach

The approach and methodology developed in the course of this project are transferable to other regions – noting the following features:

- The Maturity Pathway, describing the step-by-step approach towards economic analysis and cross-sector business case development. These steps can be addressed one at a time.
- The GIS Portal including data feeds from publicly available sources, regional council hazard layers or other sources of hazard data (such as the science and academic communities), as well as asset-specific data provided by lifeline utilities under the terms of data confidentiality agreements where applicable. Similar portals can and have been established elsewhere, or, as The Portal captures some national data it would be possible to utilise it directly in conjunction with Environment Canterbury. The "architecture" is freely available.
- Furthermore, additional spatial data layers can be included in The Portal covering community and stakeholder sites to also check their vulnerability by overlay – such as emergency services sites, hospitals, marae, supermarkets, etc.
- The layers in The Portal are then imported to suitable vulnerability assessment software, such as the UI Resilience Explorer which can be configured for any region or area in New Zealand. What is important at this stage is the ability to apply fragility models to assets or sites that are exposed to the particular hazard, generate interdependency relationships, export the output in a form suitable for consumption by MERIT, and present the information in map form. Other applications, such as RiskScape 2.0, can also be utilised here for analysis.
- Import the modelling output in terms of outage and duration by statistical area by sector (or at a finer level of granularity if available) to MERIT in order to conduct economic analysis. As described above, there are other functionality options than those used in the pilot that could be adopted to provide a wider picture of the impacts – and these are evolving.
- The output from MERIT can be utilised in combined financial loss modelling and economic analysis in considering mitigation investment scenarios. A business case approach would explore alternative mitigation scenarios across lifelines sectors, testing the feasibility, viability, interdependence, and likely benefits in terms of investment in risk reduction. Simplistically, what level of investment could be justified in addressing the $390 million+ impact calculated in the pilot, bearing in mind the return period of the event was 500 years with different smaller or larger events also resulting in impacts?
- A probabilistic approach is recommended that assesses the annualised risk exposure ("likelihood x consequence") of various hazard events and the reduction in risk exposure that mitigation investment could deliver. Note that various approaches are currently used by lifeline utilities, for example Waka Kotahi NZTA recently published the latest version of its *Monetised Benefits and Costs Manual (April 2023)* and its *National Resilience Programme Business Case (June 2020)* also describes a risk-based methodology.

5.2 Financial Loss Modelling

As noted above direct financial losses associated with damage to infrastructure, buildings and properties have not been assessed in the pilot. Broadly, such a process would involve the following steps:

- In addition to the GIS infrastructure layer, add layers with buildings and property data, including type and value (typically, replacement cost insurance could be used for buildings and land value for property).
- Include infrastructure valuation data within infrastructure layers – typically, this would be on a link and node basis assigned to the level at which the vulnerability assessment is carried out.

- Assess vulnerability in terms of the scale of damage across infrastructure, buildings and property, and thus the loss of financial value, using an appropriate software application (e.g., RiskScape2.0)[4].
- Incorporate direct financial losses into the economic impacts analysis using the same probabilistic approach in determining annualised risk as for MERIT above.

As more modules become available in MERIT, as summarised above, wider aspects of economic, social and environmental analysis could also be incorporated.

6.0 Recommendations and Future Opportunities

The outputs of this pilot proof-of-concept project are to be disseminated in the following manner:

- Milestone reports to be published on NEMA's CDEM Resilience Fund website.
- Development of a slide pack and "poster" version for communication purposes.
- Presentation to National Lifelines Forum later in 2023. An initial presentation was provided to the 2022 Forum.
- Provision of links to demonstration tools (subject to current data confidentiality agreements relating to the project).

The project has already been discussed in various forums across the lifelines community, and there is interest in making further improvements to enhance vulnerability assessments. In particular, it would be desirable to:

- Expand coverage to the wider Canterbury region and beyond, and encompass additional lifelines sectors, in particular Ports, Airports, Fuel, and Fast Moving Consumer Goods.
- Improve the capture of infrastructure data and other data such as community sites – seek ways to create a common GIS platform that all regions can readily access. In addition, introduce "criticality" considerations to help inform prioritisation.
- Leverage off research and gradually improve the quality and currency of hazards data and our understanding of the fragility of different asset types to hazard events.
- Enhance the modelling approach to improve interdependency and cascade failure impacts analysis across multiple well-beings, the use of fragility curves, outage estimation, recovery capacity, etc.
- Broaden the impacts analysis to include financial loss analysis, as well as social, cultural and environmental impacts, thus implementing more of the maturity pathway. This could involve both MERIT and other tools such as RiskScape 2.0 and the UI Resilience Explorer. Note that these applications are commercial in nature.
- Work with the CDEM community across response and recovery functions to identify ways in which these approaches and tools could be better understood and further developed for the benefit of all stakeholders.

[4] Note that a case study example based in Queenstown was provided in the Milestone 1 Report Scanning Stocktake Report

Appendix A – MERIT Economic Analysis

<insert MERIT report>

Preliminary MERIT Study

North Canterbury Flooding

6 May 2023

m.e research

Prepared for

Canterbury Lifelines

Document reference: RES008.21/Report/Canterbury Lifelines Report.docs

Date of this version: 6 May 2023

Report author(s): Dr Stefania Mattea, Dr Garry McDonald, Dr Nicola McDonald

Director approval: Dr Garry McDonald (6 May 2023)

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Contents

Figures

1 Introduction

This document describes a pilot MERIT study that has been undertaken by Market Economics Research for Canterbury Lifelines. The document summaries the steps taken to model the economic outputs of a natural hazard event in North Canterbury. The aim is to show the feasibility of a full study, rather than focusing on specific details, highlighting potential criticalities and modelling assumptions.

The case study is a 500-year flooding event affecting North Canterbury. This comprises the Kaikoura District, the Hurunui District and the Waimakariri District, with a total of 483 Statistical Areas (SA1s) considered (Figure 1). In terms of impacted infrastructures, we concentrate on electricity, water, telecommunication data-landline outages and road closures. The outages last for 6 to 23 days. Outage data have been provided by Urban Intelligence Ltd. This pilot study is a first step in the pathway towards capturing the full economic and other wellbeing consequences of future flooding in North Canterbury.

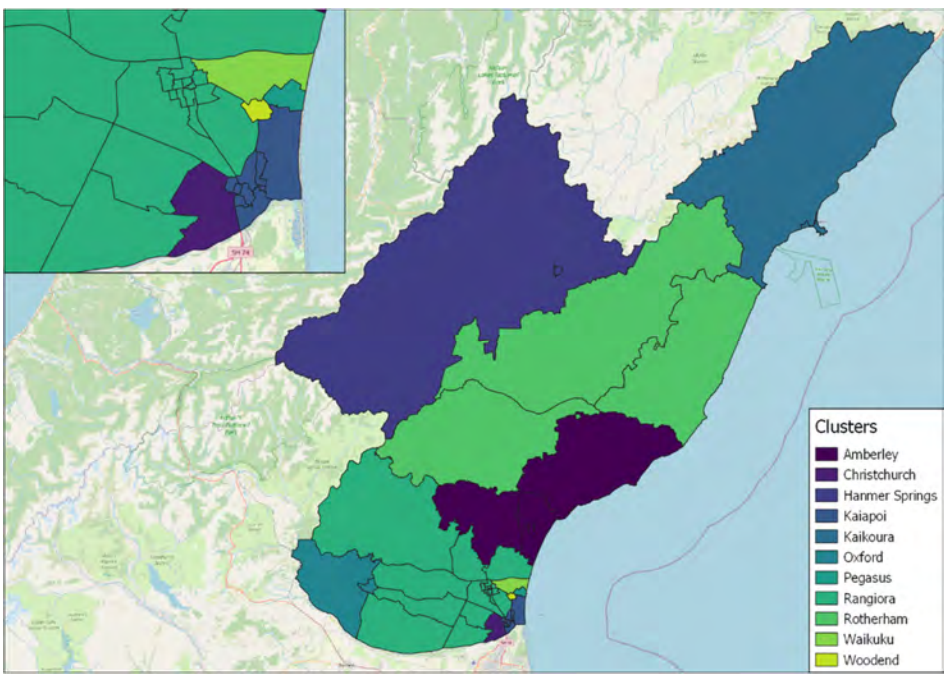

Figure 1. North Canterbury Case Study Area

2 Methodology

As depicted in Figure 2, the modelling pipeline shows all the different modelling components that were or could be undertaken and how they feed into each other. It commences with the flooding hazard and consequential infrastructure damage, follows through to the interconnected and cascading infrastructure outages, and then traces the flow on impacts to the local and national economies through complex economic interconnections. To understand the economic consequences of disruptions, it is important to know not only what is damaged and the flow on effects, but also how long loss of service occurs (i.e., add recovery/rebuild within the modelling of infrastructure).

The yellow blocks in the pipeline are the actual steps that were conducted; while the grey blocks (i.e., evacuation, farm functionality) are steps that were not included in the case study due for additional modelling inputs through RiskScape, and human decisions around evacuation, cordoning and the need to develop dynamic impact and recovery models for agriculture that include implications of damages to natural capital from hazard events.[1]

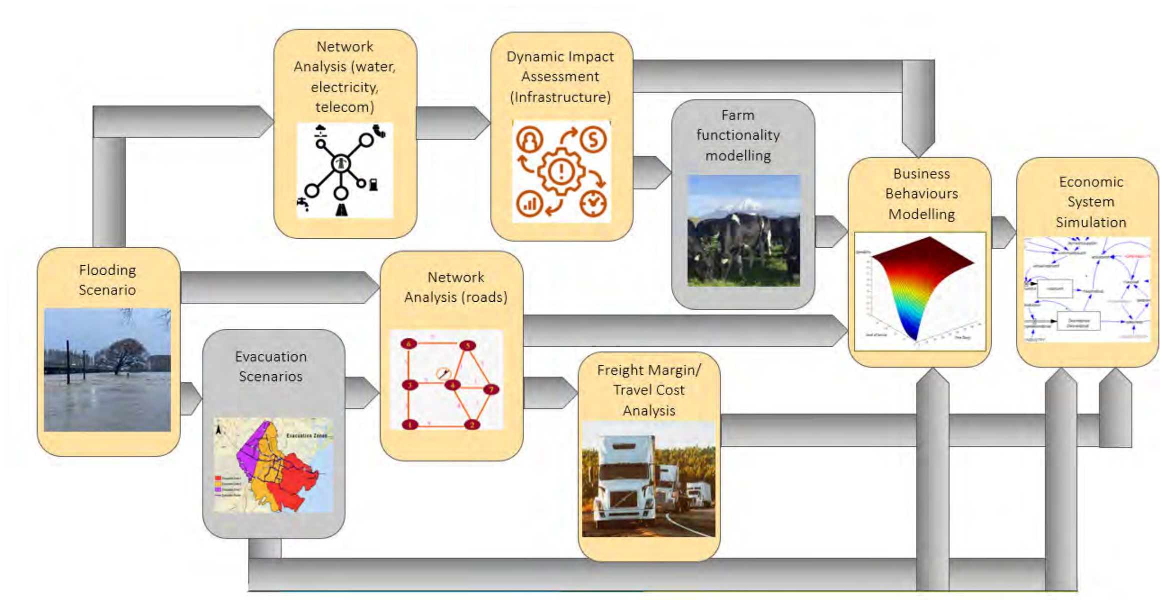

Figure 2. MERIT Modelling Pipeline

2.1 MERIT

MERIT (Modelling the Economics of Resilient Infrastructure Tool) is a decision support system developed by Market Economics, Resilient Organisations and GNS. MERIT simulates the dynamics of a shock event

[1] The modelling of farm losses in production following a natural hazard event requires consideration of not only the consequences of infrastructure outages, but also losses in the ability of the farm to produces due to direct impacts on crops, pastures and stock, and the interactions between these and infrastructure. Work is underway within the Transitioning Taranaki to a Volcanic Event and the Future Coasts Aotearoa Endeavour Programmes as well as the Resilience to Nature's Challenges Science Challenge to deliver this functionality including dynamic risk models for farming. Work is required to collate and integrate within the MERIT pipeline.

and estimates the economic consequences associated with the specific disruption event across time at both regional and national scales. It can model complex events with multiple infrastructure outages, and how those events impact different stakeholders, such as households and industries, within North Canterbury and the rest of New Zealand.

MERIT model is a set of inter-related modules, with the Dynamic Economic Model (DEM) at its core (Figure 3). The disruption data is used in the Business Behaviours Module (BBM) of MERIT to estimate the ability of industries to continue operating from initial disruption back to full production. Other disruption effects, like business relocation, population relocation and transportation system responses, are also accounted for. Then, in the DEM, MERIT combines all those inputs and simulates how the economy responds over time, including indirect effects between industries and the implications of changes in income (induced effects), providing a dynamic picture of the disruptive economy. It generates different economic measures such as income, value added, GDP at industry or household level for regional and national economy. The DEM can be used to evaluate a wide range of potential scenarios and policy questions. The model results can be used to assess not only the economic consequences of events, but also the benefits of different recovery options and to identify the main drivers of economic impacts for most effective intervention options. See Smith *et al*. (2017) for more information.

In brief, the key modelling phases are:

1) calculation of the initial direct economic impacts resulting from: reductions in business operability (i.e., functionality), people and business relocation, transport accessibility, and tourism demands (as derived through the Business Behaviours Module (BBM)),
2) then, the wider flow-on impacts are assessed in the Dynamic Economic Model (DEM). Those impacts are felt through changes in labour, capital, income, price and substitution dynamics across all industries and households' economies. As outputs, the model then reports on the key economic indicators identified above.

Figure 3 shows the inter-related modules that has been used within and without MERIT. The grey boxes in the diagram below (building impacts, cordon analysis, and population relocation) have not been modelled for the specific case study.

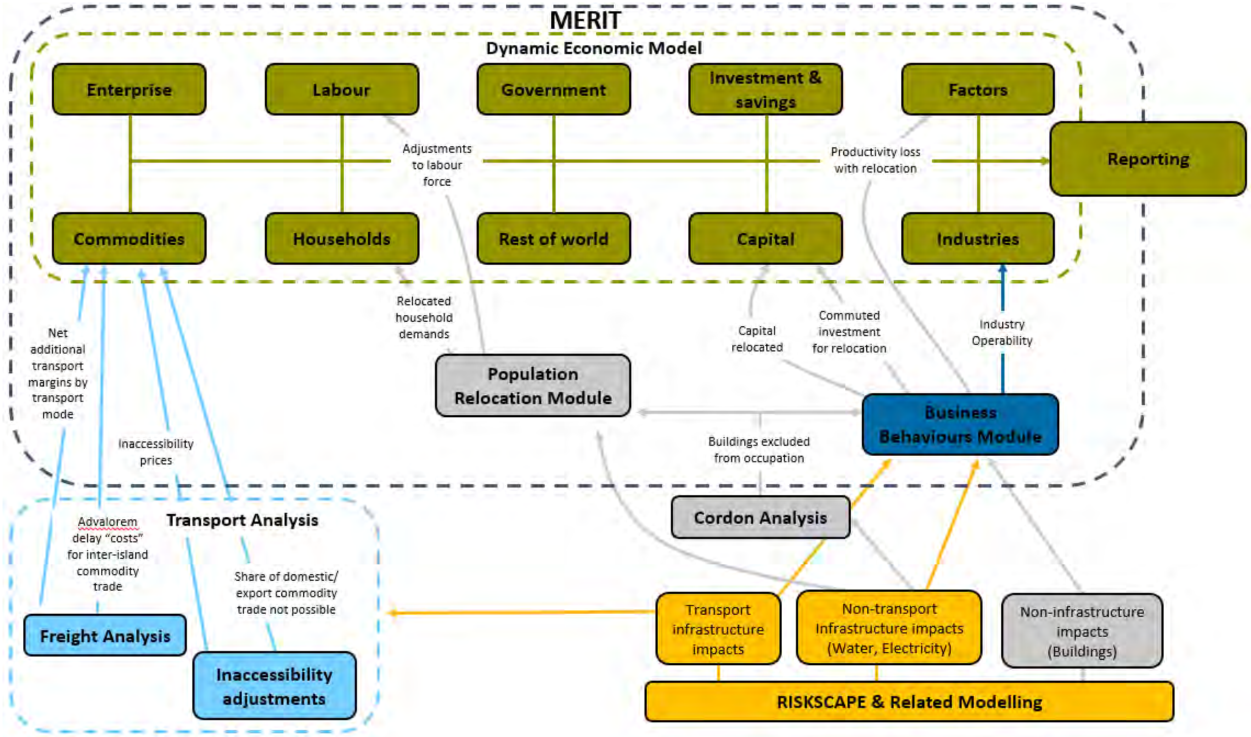

Figure 3. MERIT Modules

The key inputs to the DEM come from:

- the BBM, and
- the Direct Transport Cost Analyser.

Therefore, we focus on the description of those two modules (sections 2.1.1 and 2.1.2) and their outputs (sections 3.1, 3.2, and 3.3). Finally, we demonstrate the simulation of economy wide impacts (section 4.0).

2.1.1 Business Behaviours Module

The BBM module has been developed using empirical data gathered following the 2010/2011 Canterbury Earthquakes (Brown *et al*., 2015). A major purpose of the BBM module is to identify, in a dynamic way, the loss in operability of businesses who face infrastructure and other types of disruptions. This information then feeds into a whole-of-system economic model (i.e., MERIT's DEM) and the flow on impacts through the North Canterbury and rest of New Zealand economies is simulated over time.

The BBM calculates the operability of different industries (up to 75 industries that comprehensively cover the economy), across time (on a 2-day time step, reporting annual values), and for a combination of infrastructure or other types of disruption. Here, operability is defined as the proportion of demand for products and services that the organisation can meet at a given point in time. The industry's operability parameters are the outputs of the BBM and one of the inputs into the DEM. The operability parameters adjust the levels of productivity within each economic industry. Figure 4 also shows how the operability framework integrates with other modules within MERIT.

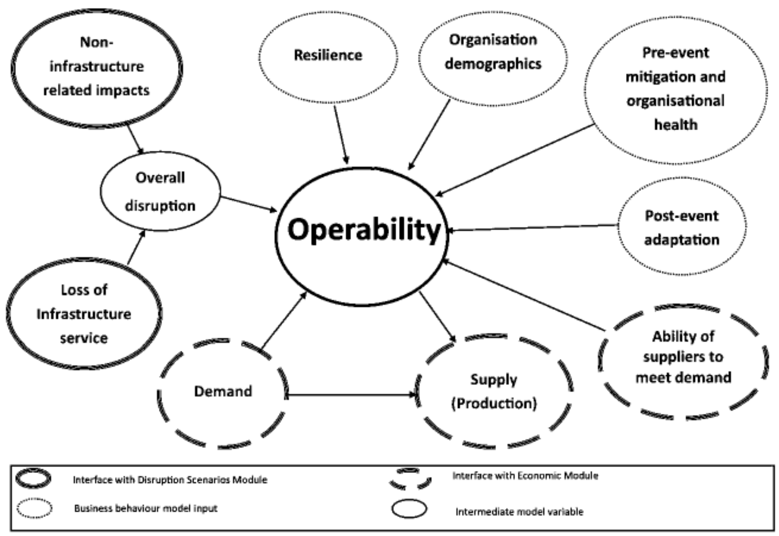

Figure 4. BBM module framework (from Brown et al., 2015)

2.1.2 Direct Transport Cost Analyser

Another important component of the modelling pipeline is the road transport analysis, which produced inputs for the BBM and DEM. In fact, the BBM needs information about which spatial areas in the North Canterbury region would effectively become isolated, and over what time. Additionally, the DEM needs inputs on how freight transport margins would change, and how costs for travel to work would change, due to disruption to the road network and re-routing. All of this is handled by the Direct Transport Cost Analyser.

The outputs of the Direct Transport Cost Analyser are:

- the tables of isolated SA1s,
- the additional freight margins, and
- the additional household travel cost.

The direct transport cost analyser is an interface between a transport model, where time and distance changes due to road outage are calculated, and the DEM, where overall economy wide impacts are calculated. It is based on the estimated loss of functionality of road segments provided by the flood modelling undertaken by Urban Intelligence Ltd. The modelling Steps are described in Figure 5 below.

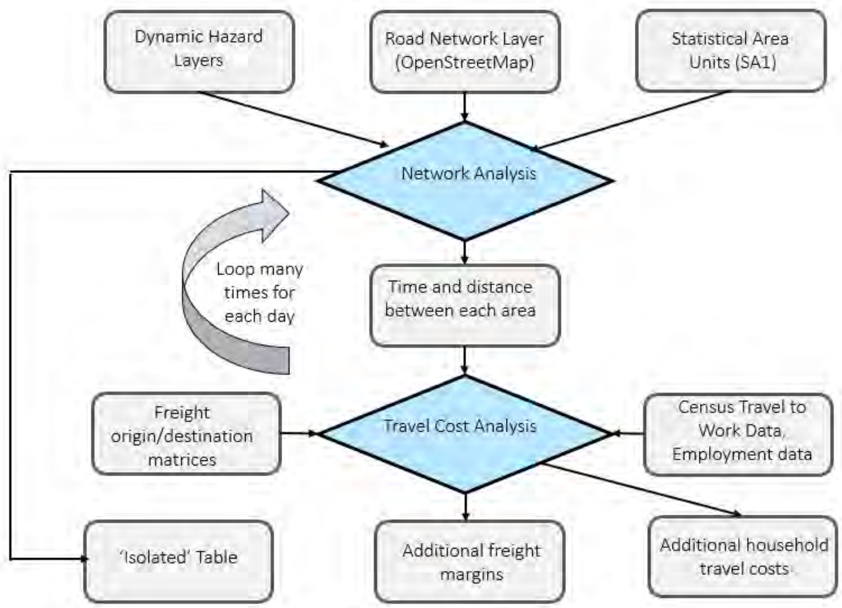

Figure 5. Direct Transport Cost Analyser

3 Analysis of Direct Impacts

This section presents the results of the most important scenario settings:

- the BBM,
- the additional freight margins, and
- the additional household travel cost.

3.1 Business Operability

The operability function is the primary way the BBM links with the full MERIT model. The operability is a function of the overall disruption, which is specific for each industry and SA1. As said before, the operability function translates the disruption scenarios impact information into a level of operability over time that can be applied, as an adjustment factor, to the DEM.

The graph in Figure 6 shows the operability curves over time obtained for the 41 BBM-industries. The operability curves have a similar pattern, except for two industries (i.e., the water, sewage, drainage and waste services, and the electricity generation and supply). This is because water and electricity are infrastructures directly impacted by the flooding event. In these cases, the shape of the operability curve is driven by the electricity and water outage data. Among the most affected industries are manufacturing and transport. Instead, central government and some office-based services (e.g., finance and insurance) are the least impacted with operability close to 1 (i.e., 100% operational). For local government administration and ownership of owner-occupied dwellings industries, the flooding event has not impacted their operability. The plot also shows that all industries regain full operability over time (approx. 6 months).

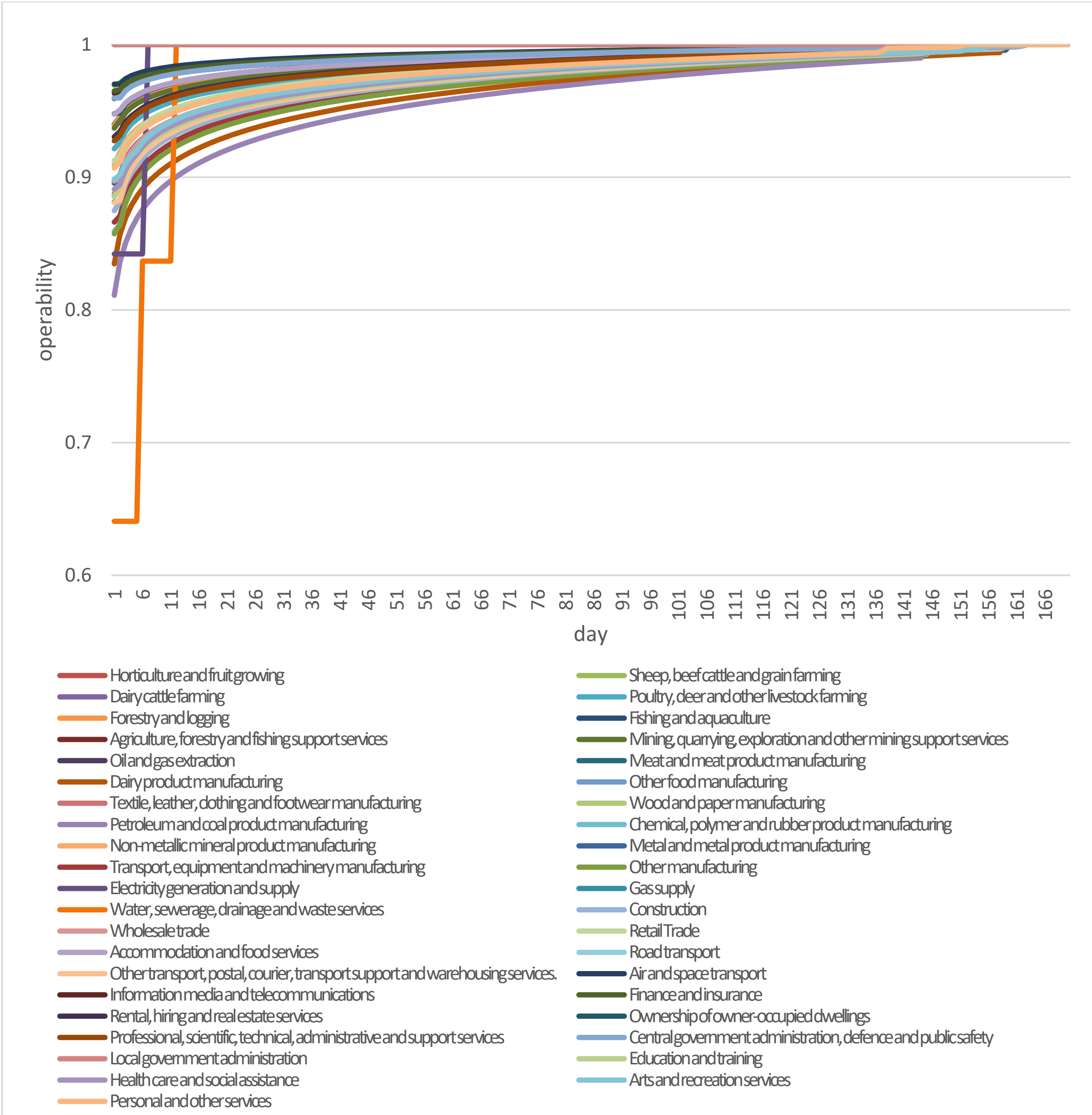

Figure 6. Operability curves for North Canterbury industries

The operability curves for the manufacturing industries are provided below (Figure 7). The manufacturing sector is one of the key areas of employment in North Canterbury. The graph shows that the sector is affected by the flooding, but initial operability at day 1 stays high (over 84%). The full operability across all industries is restored within 163 days.

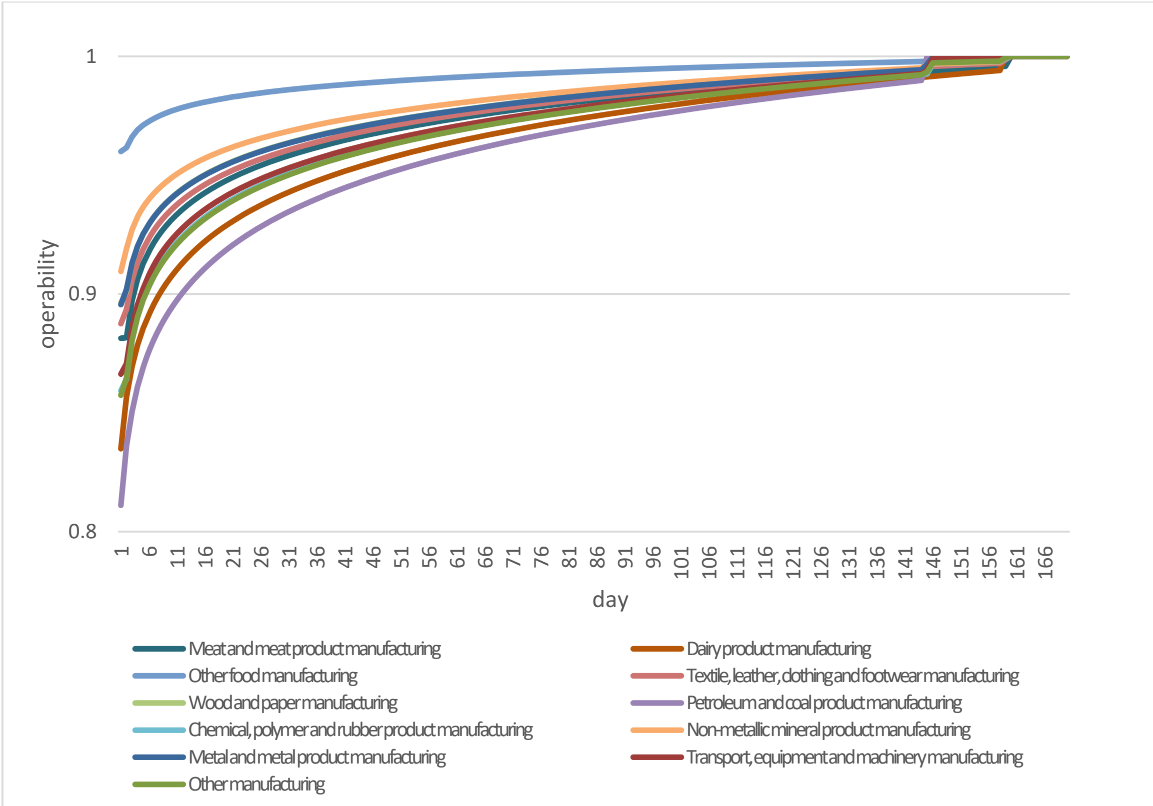

Figure 7. Operability curves for the manufacturing industries

3.2 Additional Freight Margins

One of the outputs of the transport analysis are the margin shock coefficients. They represent the net additional road transport margins per unit of commodity under the road outage scenario. They assess the additional transport costs on commodity freight (NZ_{2022}\$m transport cost/NZ_{2022}\$m commodity) as direct transport outage impacts.

The domestic margin shock coefficients are the net addition to the margins on domestically produced and consumed commodities. Similarly, the export and import margin shock coefficients are respectively the net addition to the margins on export commodities and on import commodities.

In the figures below, we refer to:

- DReg1 - Demand region: North Canterbury
- DReg2 - Demand region: Rest of New Zealand
- SReg1 - Supply region: North Canterbury
- SReg2 - Supply region: Rest of New Zealand

As examples, the three types of margin shock coefficients have been plotted below. Please note that the time dimension is not displayed; the coefficients have been plotted only for a specific day (Day 1). However, the margins are the same from Day 1 to Day 4 and after that they return to zero.

Figure 8 illustrates the domestic margins, which are the quantity of additional road transport margins charged per unit of domestically produced and consumed commodity under the specific road outage scenario. The highest margins are displayed by wood and non-wood forest products demanded by North Canterbury and supplied by the Rest of New Zealand (0.007). Raw milk has the second highest margin coefficient (0.002), followed by sheep and cattle, horticulture and fruit, oil and gas products, and wood and paper products (0.001).

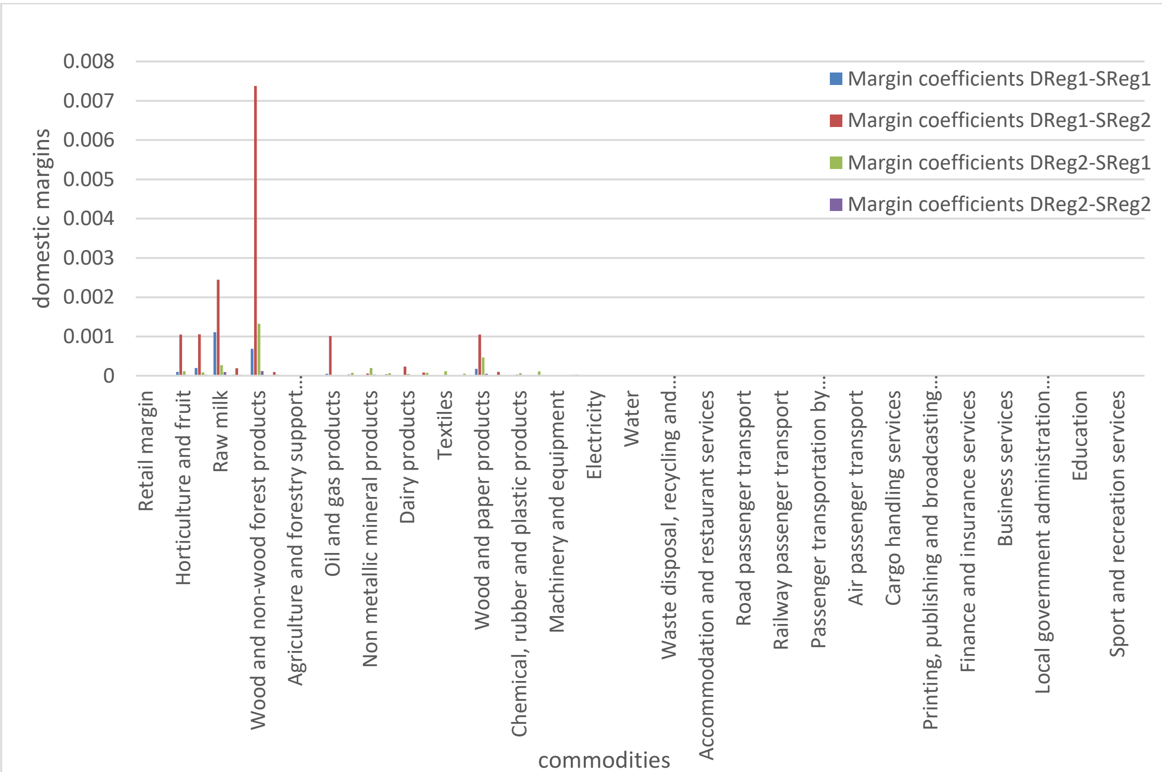

Figure 8. Domestic margins – DReg1-SReg1, DReg1-SReg2, DReg2-SReg1, and DReg2-SReg2

The price experienced by foreign purchases for NZ commodities can vary from the price received by NZ producers for the same commodities due to the imposition of net additional transportation margins. Figure 9 shows export margins just below 0.004 for raw milk, and for wood and non-wood forest products.

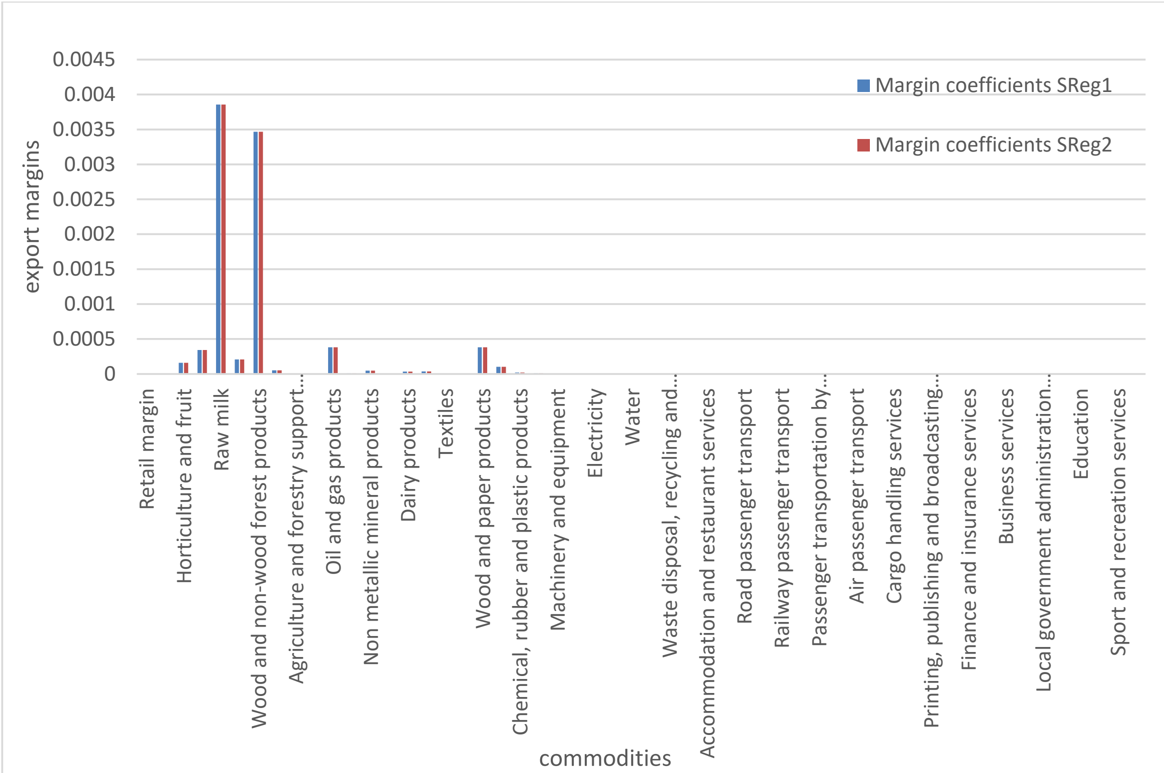

Figure 9. Export margins – SReg1 and SReg2

The import margin coefficients are intended to capture short term additions of net margins charged on imports under the road outage scenario that is causing more costly transportation. The import margins graph in Figure 10 displays the highest coefficient for importing wood and non-wood forest products to the Rest of New Zealand (0.0014).

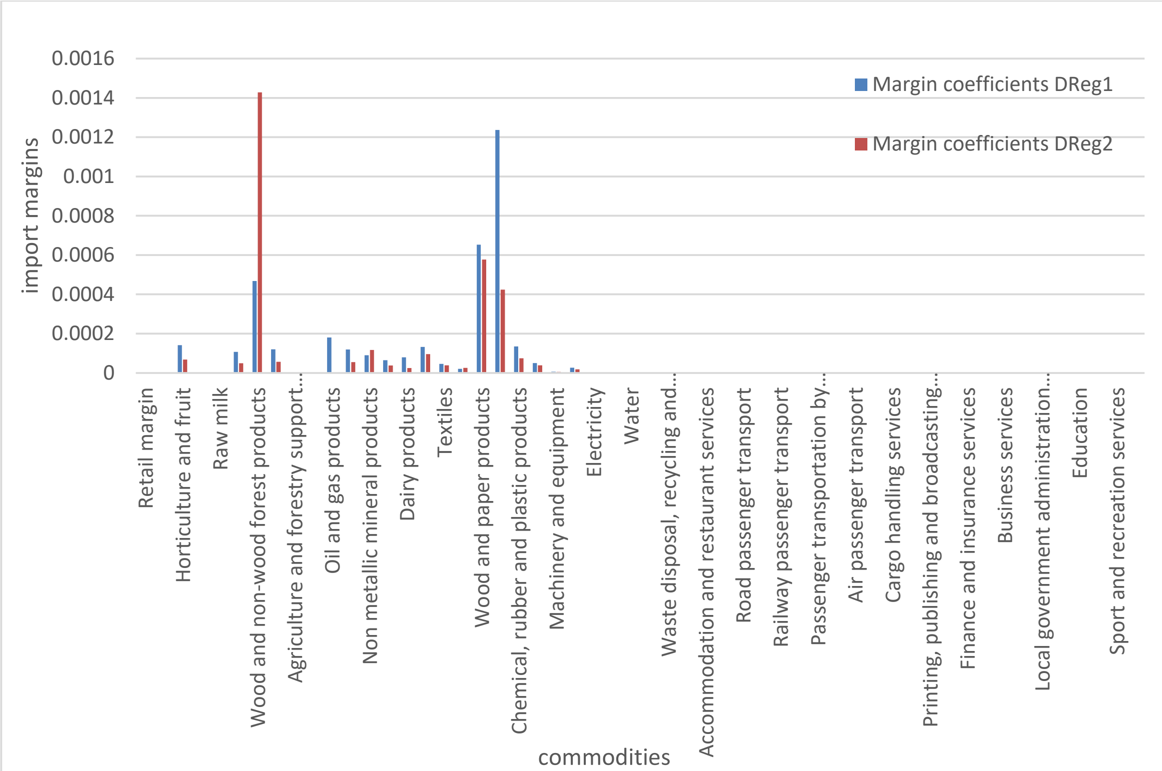

Figure 10. Road import margins – DReg1 and DReg2

3.3 Additional Households Travel

In case of road disruption, there are costs to households for additional travel. The additional household travel cost (NZ_{2022}\$m) is the net increase in consumption of transportation related commodities (e.g., petroleum, and vehicle maintenance services) incurred by households in travelling to work under the disruption. In Figure 11, petroleum products (NZ_{2022}\$398m), personal and community services (NZ_{2022}\$96m), and chemical, rubber and plastic products (NZ_{2022}\$84m) are the main transport-related commodities that add additional travel costs to the households.

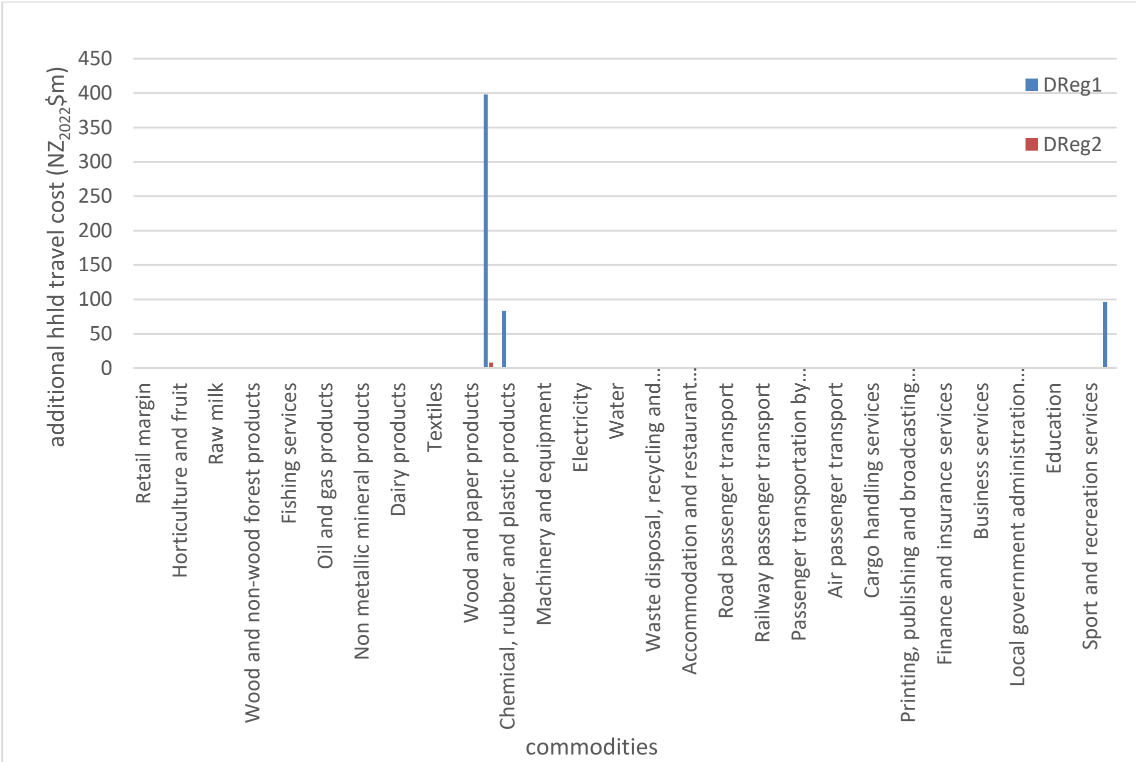

Figure 11. Additional household travel cost

4 Whole of Economy Impacts

In this Section we demonstrate that the outputs developed across the modelling pipeline (i.e., as described in Section 3) can be utilised as inputs into the MERIT Dynamic Economic Model, thereby generating the economy-wide implications. Please note that the results are only indicative as the focus of our work is on achieving an automated end-to-end integration linking the hazard and risk assessment of Urban Intelligence, with the MERIT BBM and DEM modules. Importantly, this enables a rapid assessment of the socio-economic implications of a hazard (or multi-hazard) event – in this case for a North Canterbury region flood event.

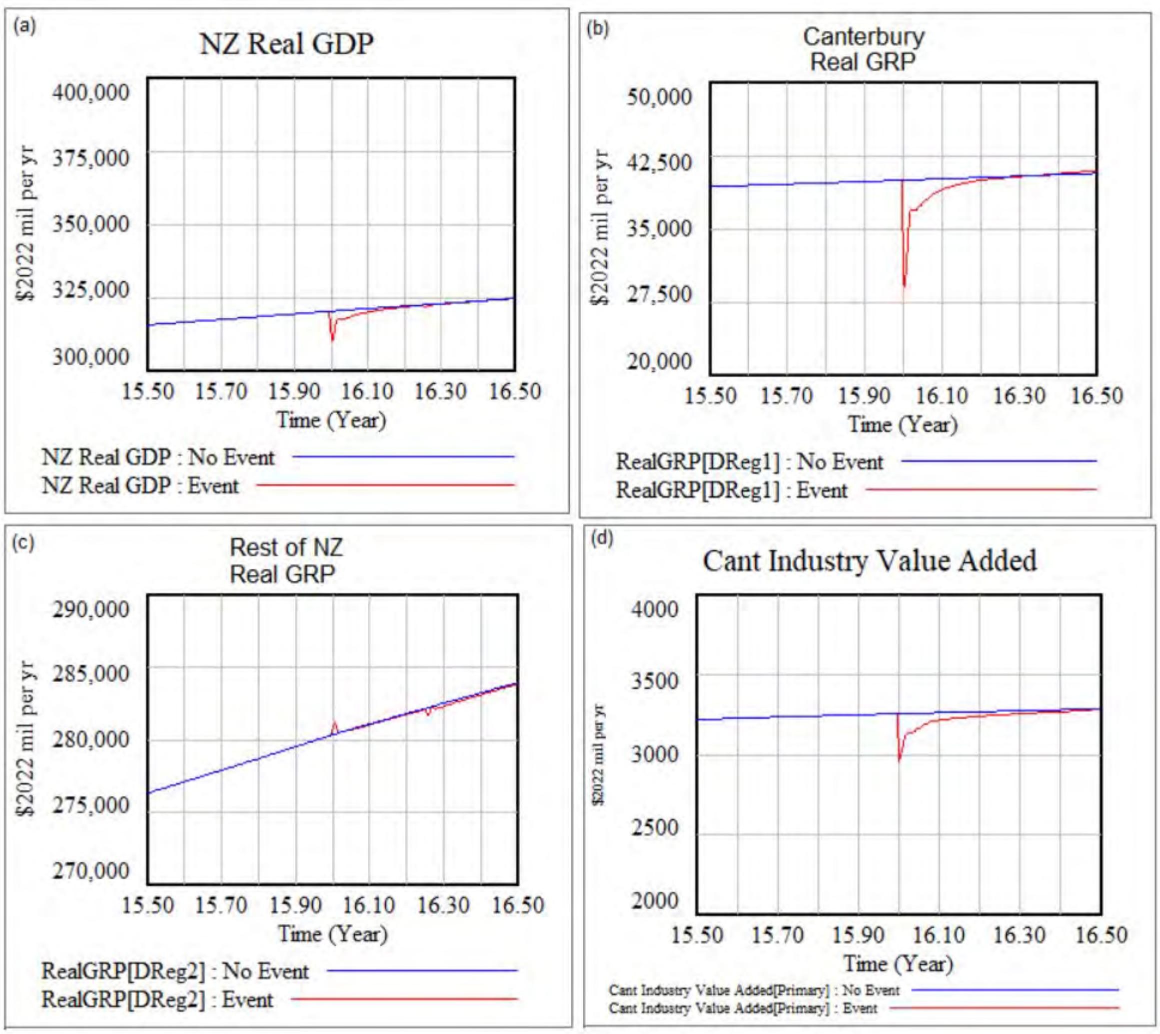

Figure 12: Examples of Outputs from the MERIT Dynamic Economic Model

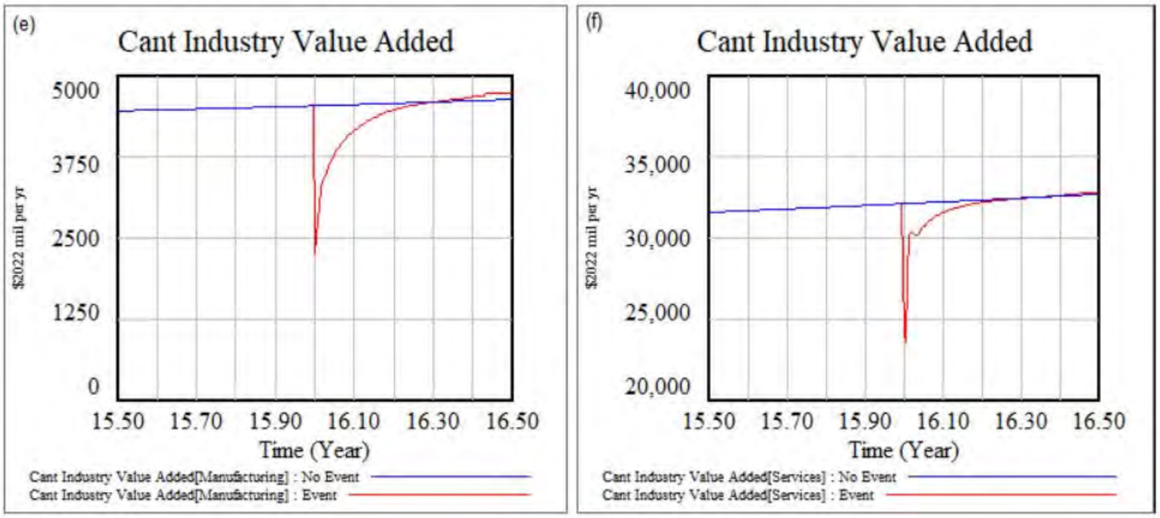

Figure 12 (continued): Examples of Outputs from the MERIT Dynamic Economic Model.

The top-level economic impacts are recorded in Figure 12. For each of the panels shown in Figure 12, two simulations are described – one is the baseline simulation or 'No Event' simulation (in blue) which is the results for the model when no natural hazard or other shock event is included. The second simulation, i.e., 'Event' (in green) is the simulation that incorporates the North Canterbury flood event. Note that the flooding event is set to occur in the model at time = 16, which corresponds to the financial year starting 1 April 2021).

Figure 12a shows annual NZ GDP (NZ$_{2022}$\$m) over time, with a slight blimp in GDP experienced over the first 6 months of the event. The second (12b) and third (12c) panels show that the losses in GDP are experienced primarily in the Canterbury Region; with the rest of NZ experiencing small temporary gains following the event – due to gains associated with recovery processes, changes in supply chain dynamics, and displacement of spend. Note that panels 12b and 12c are a breakdown of 12a. The final three panels (12d, 12e and 12f) respectively show the changes in annual value added over time for three separate sectors in Canterbury, i.e., primary[2] (12d), manufacturing[3] (12e) and services[4] (12f). Note that value added is roughly equivalent to the Gross Regional Product (with value added varying between ~90-95% of GRP) generated by individual sectors or industries. The cumulative loss of value added across all industries across over the first six months of the event is estimated to be ~NZ$_{2022}$\$390m.

[2] This includes horticulture and fruit growing; sheep, beef cattle and grain farming; dairy cattle farming; poultry, deer and other livestock farming; forestry and logging; fishing and aquaculture; agriculture, forestry and fishing support services' mining, quarrying, exploration and other mining support services.

[3] This includes manufacturing of meat and meat products; dairy products; other food; textile, leather, clothing and footwear; wood and paper; petroleum and coal product; chemical, polymer and rubber; non-metallic mineral product; metal and metal product; transport, equipment and machinery; and other commodities. It also includes electricity generation and supply, gas supply, water, sewerage, drainage and waste services.

[4] This includes wholesale and retail trade; accommodation and food services; transport (road, rail, postal courier); information media and telecommunications; finance and insurance; rental, hiring and real estate; ownership of owner-occupied dwellings; professional, scientific, technical, administrative and support services; central government administration, defence and public safety; local and central government services; education; health; arts and recreation; and personal and other services.

Other metrics could also be produced from the MERIT Dynamic Economic Model, for example, gross national income, gross output of industries, household income, government revenue, exports/imports and changes in jobs.

Table 1 below shows detailed results for the estimated economic impacts of the flooding event in North Canterbury, across different industries of the economy. Each column represents the cumulative economic impact for each month over a six-month period, while the rows show cover the industries that make up the Canterbury economy. The negative figures represent losses, while positive figures represent gains.

At one month, the total economic impact is estimated to be a loss of NZ_{2022}\$319m. This is a significant loss for the region and shows the severity of the flooding event. As time progresses, the monthly economic impact lessens, with losses reducing to NZ_{2022}\$65m at two months and NZ_{2022}\$21m at three months. By five months, the region has started to recover, with an estimated gain of NZ_{2022}\$5m.

The impacts on the different industries are also significant. The agriculture industry is one of the most affected, with dairy cattle farming, experiencing losses of NZ_{2022}\$6m after one month, NZ_{2022}\$2m for the second month, and a further NZ_{2022}\$2m in the third month. Meat and meat product manufacturing and dairy product manufacturing also experience significant losses, with respectively estimated losses of NZ_{2022}\$17m and NZ_{2022}\$39m over the first month. These losses are likely due to infrastructure outages impacting transport, and in turn, supply chain operation.

Construction and ownership of owner-occupied dwellings are also severely impacted, with respectively losses of NZ_{2022}\$32m and NZ_{2022}\$47m over the first month. This is likely due to damage to infrastructure that prevents construction and improvements to homes by home-owners from occurring. Retail trade and wholesale trade also experience significant losses, with respectively estimated losses of NZ_{2022}\$26m and NZ_{2022}\$13m over the first month. These losses are likely due to the disruption of supply chains and temporary closure or reduction in output of businesses.

Other industries that experience significant losses include transport, equipment, and machinery manufacturing, which experience losses of NZ_{2022}\$17m at one month, and rental, hiring, and real estate services, which experience losses of NZ_{2022}\$15m at one month. The impacts on these industries are likely due to damage to infrastructure, along with a reduction in demand for their services.

Industries that experience minimal impacts include horticulture and fruit growing, sheep, beef cattle and grain farming, poultry, deer and other livestock farming, forestry and logging, fishing and aquaculture, and mining, quarrying, exploration, and other mining support services. These industries are likely less affected because they are less reliant on infrastructure and have lower direct impacts.

Overall, the flooding event in North Canterbury, had significant economic impacts across direct industries, with losses totalling NZ_{2022}\$411m over the first four months. The impacts lessen as time progresses, with the region starting to recovery after five months. The agriculture industry, meat and dairy product manufacturing, construction, ownership of owner-occupied dwellings, and retail and wholesale trade were the most severely impacted industries. Other industries, such as horticulture and fruit growing, sheep and beef farming, and forestry and logging, experienced minimal impacts.

Table 1: Value Added Economic Impacts by Industry for the Canterbury Region Economy, Monthly Totals (NZ_{2022}\$)

	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6
1 Horticulture and fruit growing	-1	0	0	0	0	0
2 Sheep, beef cattle and grain farming	-1	0	0	0	0	0
3 Dairy cattle farming	-6	-2	-2	-1	-1	0
4 Poultry, deer and other livestock farming	-1	0	0	0	0	0
5 Forestry and logging	-1	0	0	0	0	0
6 Fishing and aquaculture	-2	-1	0	0	0	0
7 Agriculture, forestry and fishing support services	0	0	0	0	0	0
8 Mining, quarrying, exploration and other mining support services	0	0	0	0	0	0
9 Oil and gas extraction	0	0	0	0	0	0
10 Meat and meat product manufacturing	-17	-5	-2	-1	0	1
11 Dairy product manufacturing	-39	-7	1	4	4	5
12 Other food manufacturing	-2	0	0	0	0	0
13 Textile, leather, clothing and footwear manufacturing	-2	0	0	0	0	0
14 Wood and paper manufacturing	-3	-1	-1	0	0	0
15 Petroleum and coal product manufacturing	0	0	0	0	0	0
16 Chemical, polymer and rubber product manufacturing	-3	-1	0	0	0	0
17 Non-metallic mineral product manufacturing	-2	-1	0	0	0	0
18 Metal and metal product manufacturing	-4	-1	-1	0	0	0
19 Transport, equipment and machinery manufacturing	-17	-6	-4	-2	-1	1
20 Other manufacturing	-2	-1	-1	0	0	0
21 Electricity generation and supply	-6	0	0	0	0	0
22 Gas supply	0	0	0	0	0	0
23 Water, sewerage, drainage and waste services	-4	0	0	0	0	0
24 Construction	-32	-7	-2	0	0	1
25 Wholesale trade	-13	-3	-1	-1	0	0
26 Retail Trade	-26	-2	1	1	1	2
27 Accommodation and food services	-9	-1	0	0	0	0
28 Road transport	-1	0	0	0	0	0
29 Other transport, postal, courier, transport support and warehousing services.	-4	-1	-1	-1	0	0
30 Air and space transport	1	0	1	1	1	1
31 Information media and telecommunications	-3	-1	0	0	0	0
32 Finance and insurance	-3	-1	0	0	0	0
33 Rental, hiring and real estate services	-15	-3	-1	0	0	0
34 Ownership of owner-occupied dwellings	-47	-5	0	1	2	3
35 Professional, scientific, technical, administrative and support services	-8	-2	-1	-1	0	0
36 Central government administration, defence and public safety	-4	-2	-1	-1	0	0
37 Local government administration	-1	0	0	0	0	0
38 Education and training	-14	-5	-3	-2	-1	0
39 Health care and social assistance	-17	-3	-1	0	1	1
40 Arts and recreation services	-7	-1	-1	-1	-1	0
41 Personal and other services	-4	-1	0	0	0	0
TOTAL	-319	-65	-21	-6	5	16

5 Final Considerations

As final considerations, it is important to stress the fact that this is a simplified case study that is focused on demonstrating how the hazard, risk and socio-economic impacts of an event can be generated through an automated toolkit. It is important to note that the study has several limitations that the impacts experience represent only a partial set of the full set of impacts associated with a North Canterbury flooding event. The focus of the case study is on the infrastructure impacts and their flow-on business disruption effects through the Canterbury and rest of New Zealand economies. The estimates given in Section 4 above are likely to be underestimates of the actual impacts experience – as only a subset of the full set of impacts have been estimates. Key omissions include:-

- *Loss of capital assets*. These impacts are best estimated by tools such as Riskscape 2.0, where reinstatement or renewal costs are available. Capitals asset losses are typically covered by insurance. Riskscape 2.0 is a good tool for evaluating these impacts.
- *Loss of farm production*. While impacts associated with infrastructure losses on farm systems are included, the direct losses felt by farmers are not. The development of algorithms to assess these impacts is underway in the MERIT pipeline through the Resilience National Science Challenge, Transitioning Taranaki to a Volcanic Future (He Mounga Puia), and Future Coast Aotearoa Endeavour programmes.
- *Impacts on natural capital effecting economics service benefit delivery*. Again, these are not included, but workstreams in the Our Land and Water, Biological Heritage and Deep South National Science Challenges and Future Coast Aotearoa Endeavour programme are indirectly addressing this challenge.

Also, this case study has no RiskScape modelling done about evacuation areas and damages to buildings. These modelling inputs can significantly change the final outcomes along with causing additional disruption. Lastly, given that the modelled infrastructure outages last for only few days, the reduction in operability is not as significant as if the outage duration is several weeks or months. To obtain more precise estimates and information, future works could focus on addressing the following points:

- *Evacuation of people and red zones/cordon areas*. The decision-making around zoning and cordoning depends on many factors which cannot be predicted but play out in an event and can only really be captured post-event or through an elicitation process in a simulation. Perhaps the key factor is safety risk from further possible damage to infrastructure or property associated with a hazard (e.g., flooding) or secondary hazard (e.g., landslides).
- *Customise thresholds for the enablers to recovery for different business industries*. Business flight is a major risk following a major natural hazard event (e.g., a large seismic sequence such as that experience in Canterbury in 2010/11). Again, this cannot be predicted by a model, but can be captured post-event or through an elicitation process in a simulation.
- *Inclusion of other types of infrastructure outages (e.g., wastewater, rail)*. This initial scoping study is more of a proof-of-concept regarding creating an automated end-to-end process

for assessing hazard, risk and socio-economic impacts. For this reason, not all infrastructure types are included.

References

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