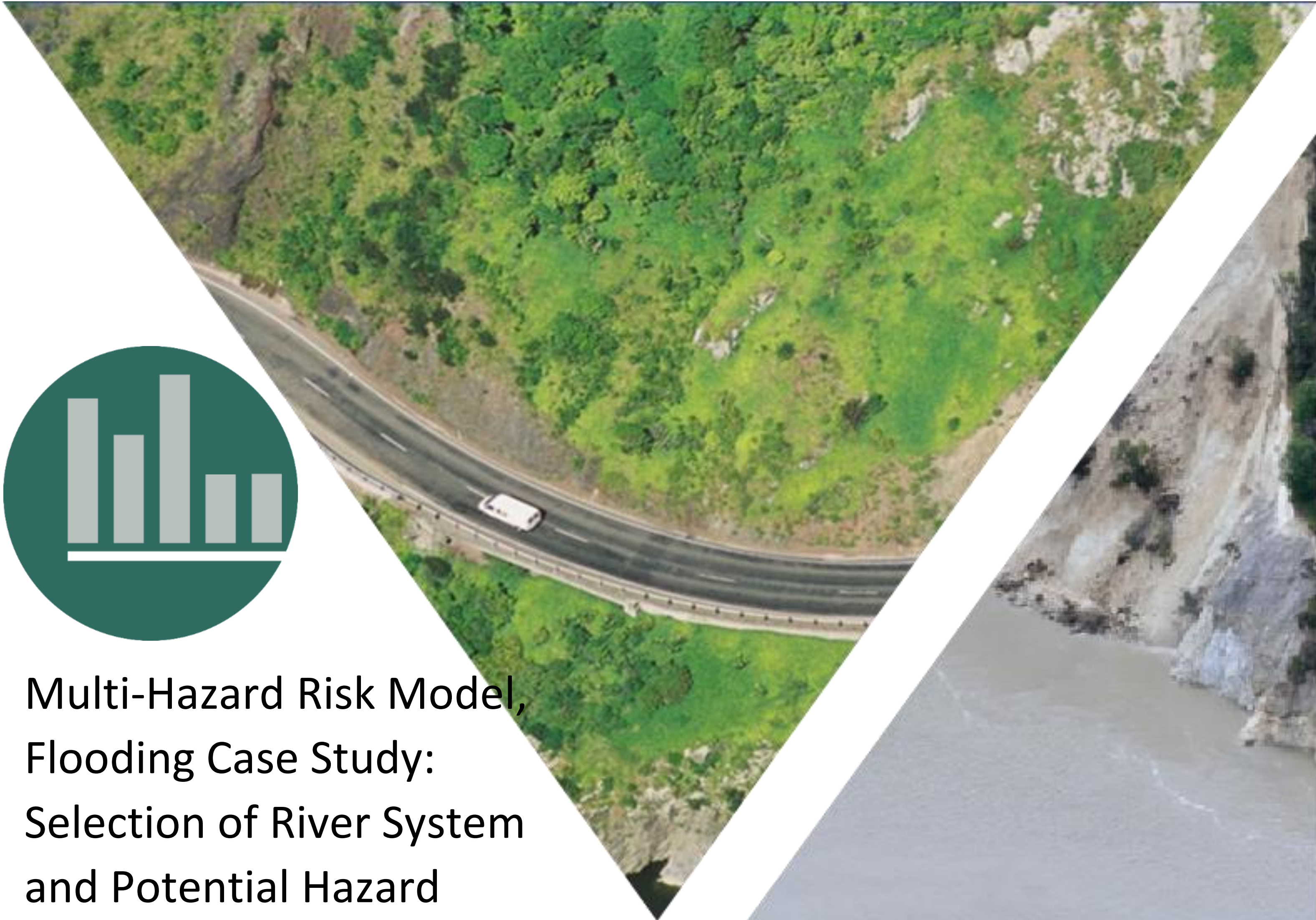

Multi-Hazard Risk Model, Flooding Case Study: Selection of River System and Potential Hazard Cascades.

Davies, T., Mead, S., Bebbington, M., Dunant, A., Harmsworth, G., Harte, D., Harvey, E., Paulik, R., McDonald, G., Smith, N. & Whitehead, M.

Technical Report 2020/1.
MEResearch, Takapuna.

National SCIENCE Challenges

RESILIENCE TO NATURE'S CHALLENGES

Kia manawaroa – Ngā Ākina o Te Ao Tūroa

Resilience to Nature's Challenges 2

Multi-Hazard Risk Model, Flooding Case Study:

Selection of River System and Potential Hazard Cascades

Davies, T.[1], Mead, S.[2], Bebbington, M.[2], Brown, C.[3], Dunant, A.[4], Grimson, D.[5], Harmsworth, G.[6], Harte, D.[7], Harvey, E.[5], Paulik, R.[8], McDonald, G.[5], Smith, N.[5], Whitehead, M.[2]

1. University of Canterbury, 2. Massey University, 3. Resilient Organizations, 4. GNS Science, 5. Market Economics, 6. Landcare Research, 7. Statistics Research Associates, 8. NIWA

EXECUTIVE SUMMARY

The Case Study is designed to develop a forecastable multi-hazard scenario environment with a lifespan/forecast horizon of 10-20 years. The purpose is to provide a testbed for multi-hazard forecasting, impact/operability analysis, economic analysis and decision-making tools. The requirement of decadal-scale hazard requires the scenario to be based on some combination of river aggradation, prolonged volcanic activity, or possibly an intense seismic sequence. The arrived at Case Study will be initiated by a trigger event; in this case a volcanic ash deposition event in the central North Island. This will be followed by a probabilistically-generated eruption sequence, which takes place within a probabilistically-generated weather sequence including intense extra-tropical cyclones. Outburst events from river blockage will also potentially occur. The Case Study will model the impacts of these events on sedimentation in a chosen river system, and their consequential impacts on society and the economy both locally and nationally.

The river systems in the central/southern North Island were investigated systematically to establish their suitability for the Study, using the following (unranked) criteria:

a) methodology developed will be transferable to other North Island river systems
b) potential for realistic multi-hazard cascades
c) potential for substantial social & economic impact, principally rural-based
d) opportunity for internationally publishable science
e) flood-derived impact is not made insignificant by other impacts
f) potential for Māori exposure and linkages
g) information available from prior research
h) existence of realistic management options
i) involvement of river management infrastructure
j) potential links to other (RNC2) programmes.

The Rangitaiki-Tarawera river system was selected as best meeting these criteria.

The primary hazards that can affect the Rangitaiki-Tarawera river system include volcanic eruption and tephra deposition, storm rainfall and earthquake; these can cascade into debris flows, lahars, landslide dams, dambreak floods, river aggradation and flooding, the latter two of which can develop and persist for decades with corresponding impacts on societal functions and commerce.

Table of Contents

1. Introduction

The second phase of the MBIE-funded research programme Resilience to Nature's Challenges (RNC2) began on 1 July 2019 and will run until 30 June 2024. This research will utilise and extend the outcomes of its predecessors RNC1 (2016-2019) and the Natural Hazards Research Platform (2012-2019). RNC2 has an allocation of $40 million for the 5-year period. High-quality outcome-driven science is expected. RNC2 will run under the same governance and advisory structures as RNC1, continuing the vision:

"New Zealand is a nation of people who have transformed their lives, enterprises and communities to anticipate, adapt and thrive in the face of nature's ever-changing challenges."

The mission of RNC2 is stated as:

"With end-users we will co-design and produce research to accelerate New Zealand's journey toward natural hazards resilience.
We will unify underpinning research of geophysical, weather and fire hazard into a multi-hazard risk model.
We will contribute to economic, social and engineering solutions to build inter-generational resilience."

The RNC2 programme comprises ten research themes (Fig. 1): Resilience in Practice, Māori, Urban, Rural, Built; Multi-Hazard Risk, Earthquake & Tsunami, Volcanic, Coastal, Weather.

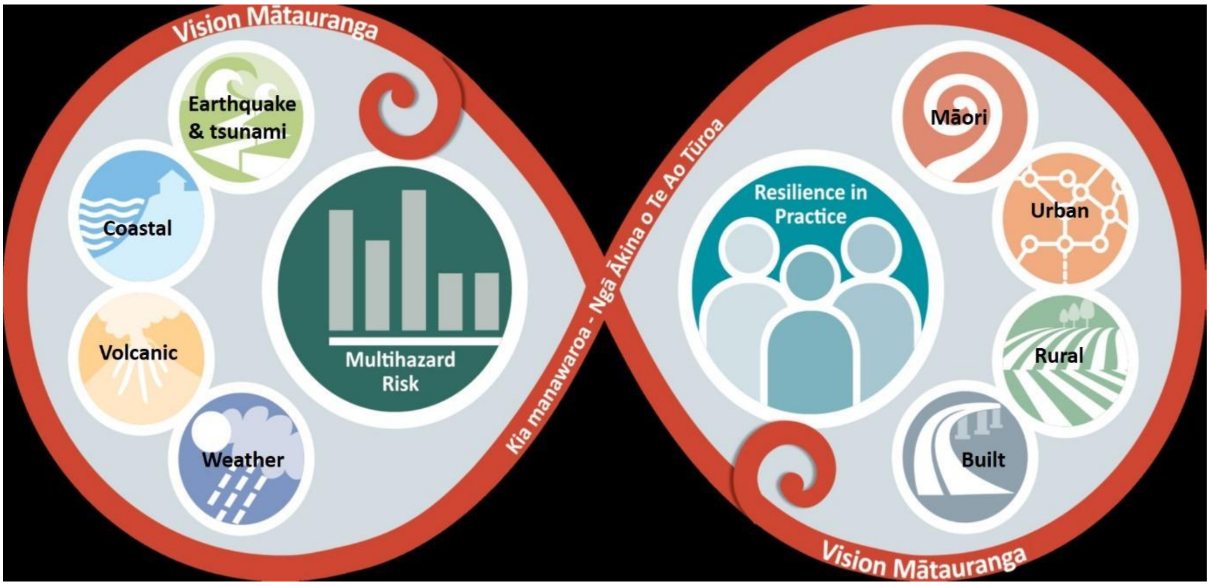

Fig. 1. RNC2 Research programme 2019-2024

2. The Multi-Hazard Risk Model (MRM) theme

This theme (Fig. 2) addresses the issues of modelling coincident and cascading hazards and their impacts, and the estimation of long-term and society-wide social and economic impacts, using realistic scenario frameworks together with improved resilience investment business cases.

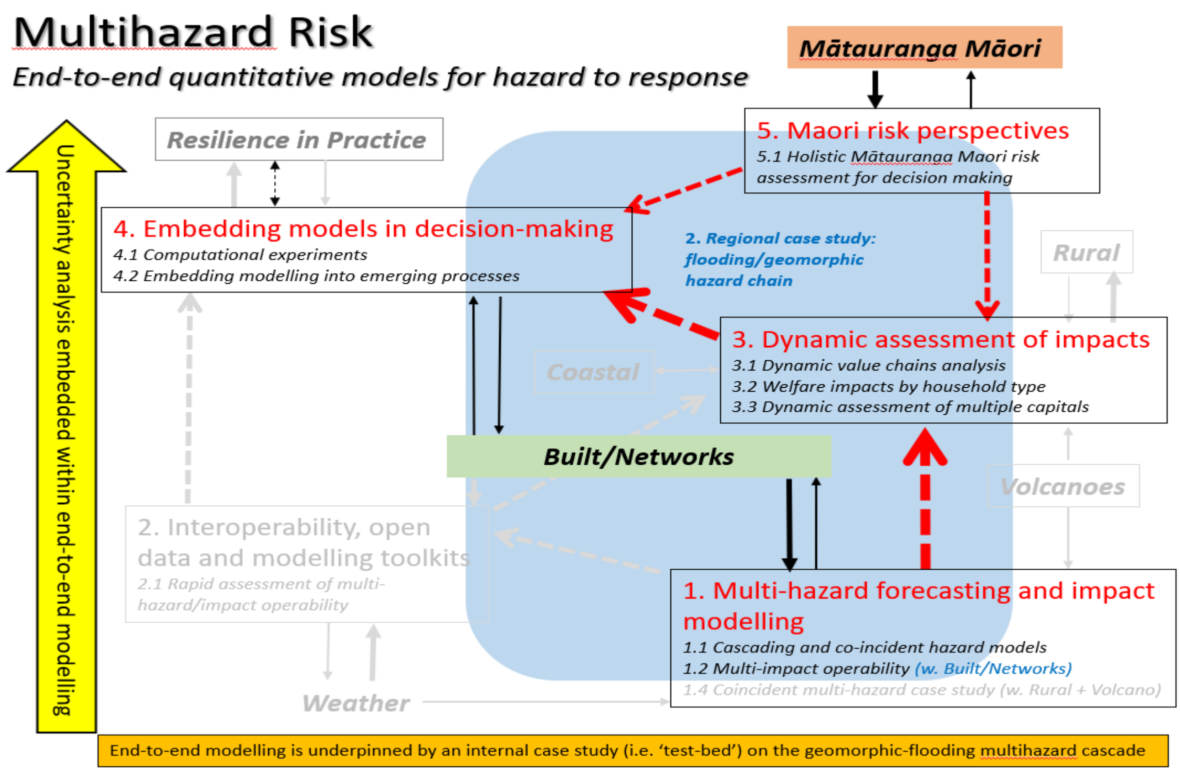

Fig. 2. Multi-Hazard Risk Model Theme of RNC2; centrality of Case Study illustrated by blue area.

The end-to-end Case Study is intended to serve as a vehicle to develop and test the quantitative modelling suite shown in Fig. 3.

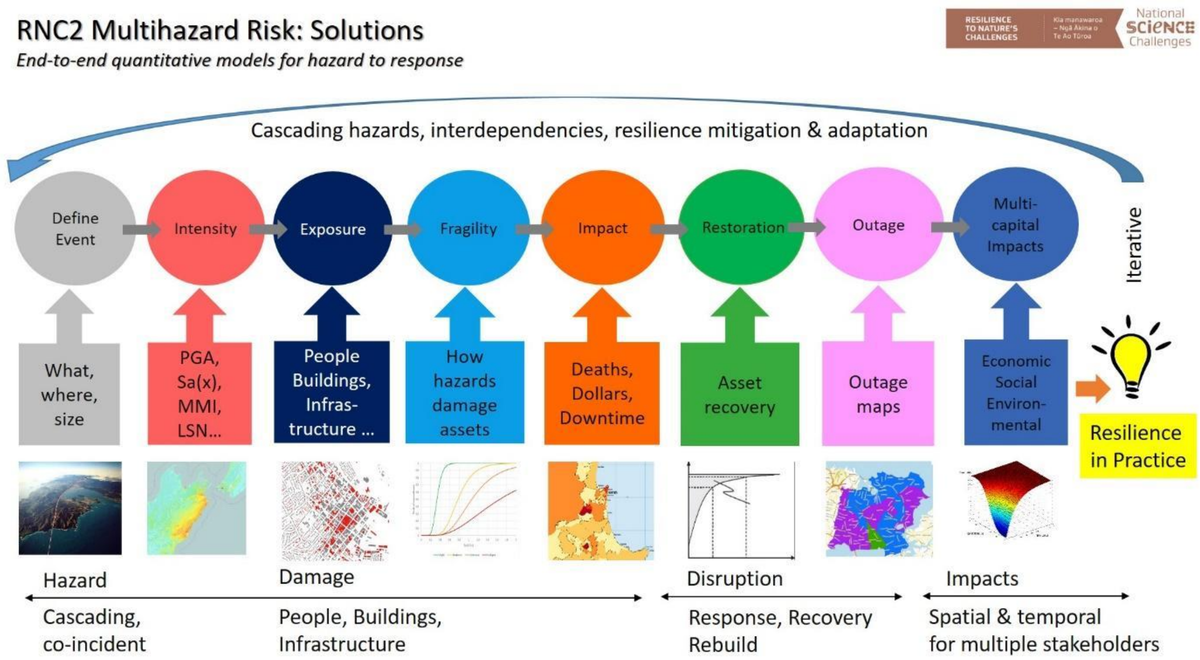

Fig. 3. Example of end-to-end modelling sequence of MRM. Source: GNS Science

The main output of the hazard modelling will be a probabilistic spatio-temporal sequence of river and floodplain aggradation resulting from tephra (volcanic ash) being reworked into rivers by rainstorms. The Case Study deliverables contracted for RNC2 are listed in Table 1; the present report constitutes deliverable 2.1.1.

2.1.1	River system and potential hazard cascades selected for Case Study. *Deliverable*: Report summarizing criteria and reasons for selection of river system and potential hazard cascades.	Tim Davies	Mark Bebbington, Garry McDonald, Stuart Mead, Nicky Smith, Emily Harvey, Charlotte Brown, Garth Harmsworth, Anita Wreford, Ilan Noy, Ryan Paulik, Alex Dunant, David Harte	29 February 2020
2.1.2	Initial quantification of critical triggers and cascades for occurrence of major flooding. *Deliverable*: Report outlining hazard cascades and input data.	Tim Davies	Alex Dunant, Stuart Mead, Postdoctoral Fellow (MU)	30 November 2020
2.1.3	Models developed for sediment transport/deposition and flood depths/extents over time. *Deliverable*: Manuscript submitted on modelling river system response to loading.	Tim Davies	PhD student (UC), Alex Dunant, Stuart Mead, Ryan Paulik	31 August 2022
2.1.4	Physical and socio-economic impacts of major flooding quantified. *Deliverable*: Report on potential physical and socio-economic impacts of Case Study events.	Tim Davies	PhD student (UC), Garry McDonald, Nicky Smith, Ryan Paulik, Stuart Mead, Emily Harvey, Postdoctoral Fellow (MU)	30 November 2023
2.1.5	Role of control structures in flooding assessed through multiple capitals. *Deliverable*: Manuscript submitted on effect of flood control structures on societal impacts of super-design events.	Tim Davies	PhD student (UC), Garry McDonald, Nicky Smith, Ryan Paulik, Stuart Mead, Emily Harvey, Postdoctoral Fellow (MU), Mark Bebbington, Charlotte Brown	30 June 2024

Table 1. MRM Case Study: Deliverables

3. MRM Case Study Scenario Framework

The main purpose of the Case Study is to demonstrate capability for multi-hazard risk modelling and incorporate the modelling of 'decision points' with a particular focus on flooding. While the far-reaching impacts of the volcanic trigger event are not intended as the study focus (e.g. loss of tourism because of fear), we also require realistic scenarios which will be useful to stakeholders. Thus, these aspects should be included as far as possible – but they largely become part of the 'background' that does not change under any decisions.

Conventional flood risk management strategies are based on the increased water levels caused by individual river floods, and modelling of such events is very well developed; by contrast, the longer-term increase in river bed levels caused by a major sediment delivery episode in a river's headwaters will cause increasing flood hazard over a period of decades that may be much more intense and rapid than that caused by normal long-term aggradation caused by landscape evolution. The impacts of this flood hazard will depend on the sequence of storms that occurs during this period. Hence, it was decided at an early stage that the hazard cascade for the Case Study would have increased flood hazard as its central output, in order to provide a suitably lengthy impact stream.

Flooding can be caused by a variety of overlapping or cascading events (rainstorms, aggradation, landslides, volcanic ashfall and their antecedent/consequent hazards where applicable). In the hazard modelling phase of the MRM Case Study, through a mix of computational, graphical, and statistical approaches, we will examine the effects of the spatio-temporal distribution of hazards and the effect of river management structures on flood inundation hazard.

The potential hazard cascades that lead to flooding are depicted in Fig. 4. Coseismic-landslide-driven flooding has been relatively well studied in South Island contexts (e.g. Robinson & Davies, 2013; Robinson et al., 2016, 2018; Briggs et al., 2018), but the aggradation and flooding resulting from severe tephra loading on river catchments has not hitherto been modelled. Nevertheless, considerable empirical experience of this process exists through studies of the 1980 Mt St Helens, 1991 Pinatubo and 2008 Chaiten eruptions, and there are studies of the tephra distributions resulting from the c. 5000 BP Whakatane and c. 1300 AD Kaharoa eruptions from the Okataina volcanic centre in the central North Island that can underpin scenario development for the Case Study. Hence tephra-driven hazard cascades are preferred to seismically-driven ones, particularly because of the opportunity for scientific advance. Nevertheless eruptions commonly involve earthquakes, and we may include an eruption-related river-blocking mass movement as part of the scenario, which could be coseismic.

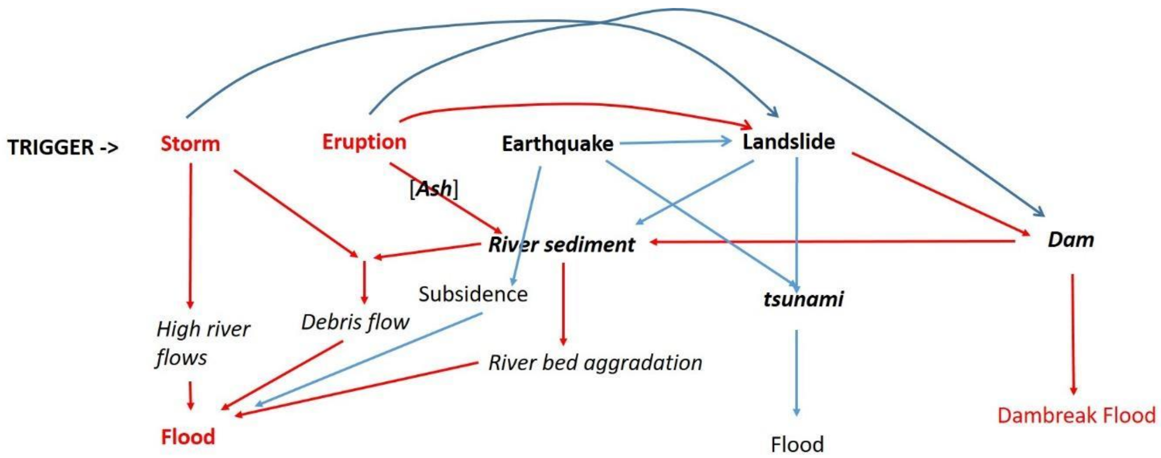

Fig. 4. Potential hazard cascades leading to flooding: red indicates preferred cascades for scenario framework

4. River system selection criteria

The river systems of the central North Island (Fig. 5) were assessed for their potential as Case Study sites on the following criteria

A. methodology developed will be transferable to other North Island river systems
    a. and hence, hopefully, elsewhere
    b. the wider methodology (probabilistic models, economic and social decision analysis etc) constitutes the main resilience advance
B. potential for realistic multi-hazard cascades
    a. scientific advance requires tackling the multi-hazard problem. Hence we require a framework where such cascades are both expected, and of multiple types
C. potential for substantial social & economic impact, principally rural-based
    a. in order to permit decisions to be made
    b. substantial urban impacts (such as Hamilton!) are considered beyond the scope of this project

D. opportunity for publishable science
    a. as in 'scientific impact'. While the end-to-end approach will be novel in its connectivity, we want the individual parts to also be of scientific merit
    b. Modelling of the river system needs to be tractable, i.e. with a catchment scale and complexity, and data availability (e.g. terrain, flow gauges) to allow the application of numerical models.
E. flood-derived impact is not made insignificant by other impacts
    a. thus retaining the multi-hazard focus, rather than a super-hazard
F. potential for Māori exposure and linkages
    a. pursuing the Vision Matauranga objective, in collaboration with the Māori theme
G. information available from prior research
    a. vital, as we don't have the time or resources to create the building blocks
H. existence of realistic management options
    a. for the final stages of the end-to-end solution (Fig. 3)
I. involvement of river management infrastructure
    a. Link to Built Environment theme, with joint project on multiple infrastructure impacts
    b. focus on stopbanks, dams, networks (transportation, power, water)
J. potential links to other (RNC2) programmes.
    a. In particular, Built Environment and Māori

River systems

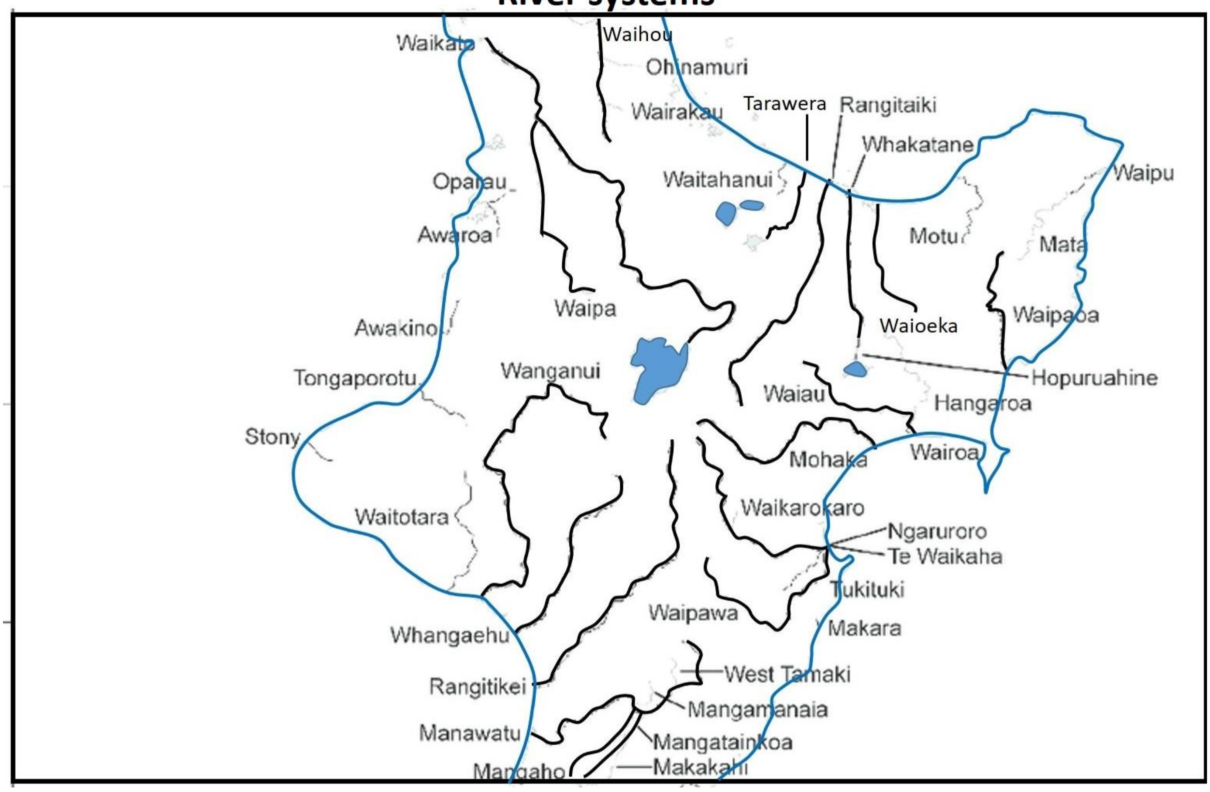

Fig. 5. Central North Island river systems

A spreadsheet (Table 2) was developed and considered at a full-day meeting of the MRM team at Massey University on 15 November 2019. Each river system was considered against the above criteria; some representative comments are listed below.

5. Individual river system comments

A general consideration is that the potential impacts need to exceed the capacity of existing flood management infrastructure, and be significant both locally and regionally, but the trigger event must not be so damaging that flood consequences are less important. National-scale impacts are less desirable, as these will potentially lead to structural changes in socio-economic systems, less amenable to quantitative modelling.

Waikato

The Waikato river travels through many populated areas (e.g. Cambridge, Hamilton, Huntly), dams and rural land, including areas with high Maori populations, marae and high value Maori land. The size of the river provides a great diversity of potential impacts from a multi-hazard sediment cascade. However, the size and complexity of the system limits modelling feasibility, lakes and dams along the river may store and trap much of the sediment cascade, and many unique aspects of the river system limit methodology transfer to other North Island rivers. The large number of hydropower stations on the river implies that an event on this river will be quite unlike that which may occur elsewhere. The potential impacts would almost certainly be national in scope.

Tarawera/Rangitaiki

The Tarawera and Rangitaiki rivers in the Bay of Plenty region both contain sufficient data and are of a scale that may allow for modelling both systems. This presents the opportunity for at least one contrast in output from a common hazard sequence, increasing the scientific value of our study. The catchment contains many valuable assets, Māori communities and values (Bay of Plenty contains 29% of the total New Zealand Māori asset base). Hydrothermal plants contributing c. 6% of the national load, and dams along the Rangitaiki river are significant assets exposed in a hazard cascade scenario along these rivers. There is a good mix of primary land uses within the catchment/study area (native forestry/ plantation forestry/ dairy/ kiwifruit) which affords opportunities to investigate impacts and decision making for a variety of primary sectors. Weather and coastal hazards in this region may also magnify direct and indirect impacts, particularly with the passage of extra-tropical cyclones through the region. The economic impacts could be high, especially if the Port of Tauranga can be impacted by coincident tephra fall and storm hazards.

Waioeka

The Waioeka River in Bay of Plenty is susceptible to eruption and earthquake-triggered hazard cascades, and is of a scale that could be modelled sufficiently well. However, the low exposure of Māori populations and values, and small potential impacts limits the significance of hazard cascades along this system. Economic significance is low.

Potential River Systems for MRM Case Study

	River	Regional Council	River length (km)	Basin area (sq km)	Hazards	Impacts	River management	Theme Links (Built assumed)	Maori interest	Prior Information	Modelling suitability	Initial Assessment
1	**Waikato**	Waikato	425	14456	Flood hazard cascades from eruptions mainly. But storage in lakes will trap much of the sediment generated	Cambridge, Hamilton, downstream of Huntly?	Dams, minor stopbanks	Volcano, Rural?	High		Reasonable data, well gauged river. However too large to simulate without extensive resources/time	No stopbank, impacts probably too large a scale to handle, not much multihazard potential – Not transferable
2	**Tarawera**	BoP	65	984	major flood hazard cascade from eruption/earthquake, ash/mass movement/Lake breakout - e.g. 1315 Kaharoa eruption	Kawerau (Kinleith), Rangitaiki plains, Whakatane.	Stopbanks	Volcano, Rural?Stopbanks	High	Excellent	Small catchment, sufficient measurements, but would prefer more. Good terrain data from BoP (LiDAR)	Possible. Multihazard scope unclear, unless an eruption from Okataina? Kinleith good impact? COMBINE WITH RANGITAIKI?
3	**Rangitaiki**	BoP	155	3005	flood hazard cascade from ashfall, potential landslide dam sites upstream (earthquake)	Rangitaiki plains, Whakatane	Stopbanks	Volcano, Rural, coast	High	Excellent	As above, the role of Matahina dam and its effects on model is unknown	Excellent multihazard. Stopbank failure at Edgecumbe. Coastal progradationDoes it have enough impacts?
4	**Waioeka**	BoP	65	825	Flood hazard cascade from ashfall, landslide dams (earthquake)	Opotiki, SH2	Stopbanks	Volcano	High			Not enough impact?
5	**Waihou/Piako**	Waikato	150/100	1400	Flood hazard cascade from ashfall, storm surge, sea level rise, tsunami	Hauraki plains	Stopbanks	Volcano, Coast, Weather, Rural?	High	Some on Piako	Piako is a good candidate in terms of data, however would need more investigation on control measures and how to model. Upper Waihou is also reasonable.	Good potential with coast/weather – keep in back pocket? Impacts?
6	**Waipaoa**	Gisborne	80	2150	Flood hazard cascade from ashfall, tsunami, earthquake/landslide	Gisborne area, SH2	Stopbanks	Volcano, Coast, Weather	High	OK		Good potential with coast/weather – keep in back pocket? Impacts?
7	**Tutaekuri**	HB		840	Flood hazard cascade from ashfall, earthquake/landslide	Napier area	Stopbanks	Volcano	High	OK		urban impacts, rather than rural
8	**Ngaruroro**	HB		970	Flood hazard cascade from ashfall, earthquake/landslide	Hastings/Havelock North area	Stopbanks	Volcano	High	OK		urban impacts, rather than rural
9	**Tukituki/Waipawa**	HB		955	Flood hazard cascade from ashfall, earthquake/landslide	Waipukurau, Havelock North areas	Stopbanks	Volcano	High	OK	Small volume/flow rivers may be very hard to model given the lack of data.	urban impacts, rather than rural
10	**Waipa**	Waikato	115	3050		Huntly, SH1, Auckland water supply?			High	?	Waipa R. through Ngaruawahia to Huntly may be suitable - reduces the resource load of entire Waikato river system.	Subset of Waikato
11	**Whangaehu**	Horizons	135	1992	Lahars from Ruapehu	SH3, Main trunk line		Volcano	High	Good		Minor impacts
12	**Whanganui**	Horizons	290	7380	Lahars from Tongariro	SH3, Main trunk line, Port of Whanganui		Endeavour on flood sediment	M$30 Contestable Iwi funds	OK	Modelling downstream of 'input' sediment may get more difficult as data is limited.	Urban impacts
13	**Rangitikei**	Horizons	185	3186	Lahars	SH1, Bulls			High	Landslides good	Large size, and detail required makes this difficult.	Urban impacts, rather than rural. Not transferable
14	**Manawatu**	Horizons	180	5898	Earthquake, landslide, liquefaction. No volcanics	SH1, Tararua crossing, Palmerston North, Main trunk line	Major Stopbanks	Rural?	High	Landslide dam	A large amount of data, studies, and previous models make this feasable and suitable.	Not transferable
15	**Hutt**	GWRC	56	655	Earthquake, landslide, liquefaction. No volcanics	Upper/Lower Hutt, SH1, ...	Major Stopbanks	Urban?	Moderate	Landslide dam	As above, large number of previous studies and data make this feasable.	Urban impacts, rather than rural. Not transferable

Table 2. North Island River Characteristics spreadsheet

Waihou/Piako

The Waihou/Piako river system in the Hauraki plains is susceptible to many weather, coastal and earthquake hazards. Several stopbanks and river control systems exist along these rivers and the impact of a hazard cascade could be amplified (to cause national impacts) through isolation of the Coromandel region. The river size and complexity is on a scale that could be simulated. Significant Māori fishery interests (controlled by Hauraki Māori Trust) exist in the Firth of Thames (at the mouth of the Waihou and Piako river systems). However, there appears to be a lack of a credible sediment source as a trigger for a plausible hazard cascade. The RNC Weather and Coastal programmes were considering projects in this area, but the lack of a plausible, ongoing hazard reduces the utility for economic decision making.

Waipaoa

The Waipaoa river in Gisborne is of a reasonable size, with sufficient data for modelling and potential triggers for a sediment cascade hazard. The region also contains significant Māori values, communities and marae. The Poverty Bay Flats are an area of extensive wine and other fruit growing/horticulture. However, the national economic effects from hazards along this river appear relatively minor with limited exposure to nationally important industries and lifelines.

Tutaekuri/Ngaruroro/Tukituki/Waipawa

Hazard cascades in this collection of small rivers in Hawkes Bay could be triggered from earthquakes in the Ruahine ranges. The wine industry and some urban areas are most exposed along these rivers, but there is minimal exposure to Māori values, communities or marae. The lack of data at a sufficient scale to model these low-flow gravel rivers may also complicate modelling efforts.

Waipa

The Waipa river is a large tributary to the Waikato river and has similar characteristics, including the potential to impact Huntly and State Highway 1. The smaller size makes this system more tractable than the entire Waikato river for modelling, and still contains significant Māori values. However the effects of this system are difficult to isolate from broader impacts along the Waikato River, particularly considering triggering events. This limits the scientific impact of a Waipa (and not Waikato) scenario.

Whangaehu/Whanganui/ Rangitikei

These rivers originate in the Central North Island and have the potential to affect infrastructure networks (State Highways 3 and 1, main trunk line) and hazard cascades triggered from mass movements (lahars for Whangaehu and Whanganui, landslides for Rangitikei) are likely. Māori governance arrangements for the Whanganui River (through Te Pou Tupua) and objectives for joint co-governance of the Rangitikei River by 2022 present promising opportunities for pursuing Vision Matauranga objectives. However, the scale of impacts as a result of sediment cascades compared to the scale of flooding along these basins minimise the importance of hazard cascade and impact modelling. National economic impacts may also be minor, with little significant exposure along these rivers.

Manawatu

Exposure of rural, urban and national lifelines along the Manawatu River indicate there is potential for highly significant, national impacts, including to Māori populations and values. This river is well gauged, and sufficient data exists for modelling. However, credible evidence for sediment inputs, such as large tephra loads or landslides is lacking in the paleo record, which reduces the scientific impact of the work, and suggests that sediment cascade hazards may not be a significant issue in this basin.

Hutt

A sediment hazard cascade in the Hutt river has the potential to create nationally significant impacts, given the proximity of the Wellington reservoirs (Stuart Macaskill Lakes) to the Wellington fault (Cousins, 2013). The river basin contains many stopbanks. The hazard cascade could be triggered from large earthquake-generated landslides in the headwaters. The river system is well-studied, and the availability of this research data increases the modelling feasibility but reduces the scientific impact of a study in this basin. Significant work has already been undertaken in modelling Wellington Fault events and while this programme will focus particularly on flooding, the trigger event will still be an important part of the 'background'.

As a result of these considerations, the workshop participants decided to focus the Case Study on the Tarawera/Rangitaiki system, with the Manawatu or Hutt rivers as backup options. The remainder of the report concentrates on initial thoughts regarding the modelling process(es).

6. Scenario drivers – potential hazard-cascade-initiating events for the Rangitaiki/Tarawera river systems

The Okataina Volcanic Centre (OVC) is coincident with headwaters of the Tarawera river, and has produced 10 large (> 1 km^3 of pyroclastic deposits) eruption episodes over the past 22 ka (Wilson and Cole 2007). Given this history, a credible cascade-initiating event for the Rangitaiki and Tarawera river systems could be triggered by an eruption episode originating from a volcanic complex within the OVC that deposits cubic kilometres of pyroclastics in the headwaters of Tarawera River and the surrounding area. It is important to note that, because the objective of the Case Study is to provide realistic data for model testing, the scenario tephra distribution used for that purpose can differ considerably from recorded distributions such as that in Fig. 6. We consider that it is reasonable to begin the scenario with a selected (provided it is within the bounds of possibility) event. Referring to our selection criteria (in particular, B, E and G), an eruption episode needs to be credibly within the bounds of prior work (to leverage existing knowledge), large enough and with sufficient diversity of impacts to generate multi-hazard impacts (this includes a requirement for the eruption to be ongoing for a sufficient amount of time), but not of a magnitude that may make management decisions and secondary impacts (i.e. not directly caused by eruption) insignificant. The objective of this Case Study is to provide realistic data for model testing with a 'seed' scenario/initial event, after which impacts and hazard effects can be assessed probabilistically. This allows some flexibility, within realistic bounds, in choice of an initial distribution of pyroclastic sediment. For example, a suitable past wind pattern (i.e. that primarily causes impact to Tarawera and Rangitaiki catchments) will be superimposed on the initial explosive phase of the eruption and the deposition modelled by suitable means.

The ca. 1300 AD Kaharoa eruption episode from Tarawera Volcanic Complex was a cascade-initiating event that meets most criteria, with prior research (e.g. Bonadonna et al. 2005, Hodgson and Nairn 2010) demonstrating its suitability as a trigger event with sufficient data to ensure scientific validity and impact. The mapped tephra distribution (cm depths) of the Kaharoa eruption is shown in Fig. 6, overlaid on the spatial extent of the Rangitaiki/Tarawera river system (red). Up to 14 altering units of lapilli and ash (Todde et al. *in press*; Sahetapy-Engel et al., 2014) deposits in separate lobes, oriented from NW to SSE have been identified with an estimated total dense rock volume of greater than 7.3 km^3 for the explosive phase (Sahetapy-Engel et al. 2014). Detailed stratigraphy of the Kaharoa eruption (Todde et al. *in press*) enables some inference into the time-varying characteristics of the eruption episode into its different phases and eruption states. A simplified summary of the interpreted eruption phases and timeline is as follows (over a 4-5 year period; Sahetapy-Engel et al. 2014):

1. Precursory activity, phreatomagmatic-magmatic explosions affecting proximal areas,
2. 5-7 phases of intermittent to continuously explosive eruptions (sub-Plinian), with occasional pyroclastic density currents and Plinian eruption intensities.
3. A phase consisting of mostly pyroclastic density currents (concentrated and dilute) within proximal area (up to 9 km from vent).
4. a further 5-7 phases of intermittent to continuously explosive eruptions (sub-Plinian), with occasional phreatic eruptions, density currents and Plinian eruption intensities.
5. 'Steady' or prolonged ash explosions of lower intensity occurring over a long duration.

A final, topographically controlled unit consisting of medium to coarse ash is also found along the Tarawera river (Todde et al. *in press*), associated with the breach of Lake Tarawera (Hodgson and Nairn 2010). This breach eroded much of the Kaharoa deposits in the upper Tarawera valley, transporting this sediment downstream, eventually reaching the Rangitaiki Plains (Fig. 7).

The multi-lobed nature of the Kaharoa deposit indicates a change in direction of wind during the explosive phases of the episode, although windshear (i.e. vastly different wind directions in troposphere compared to lower altitudes) cannot be ruled out (Sahetapy-Engel et al. 2014). Over long eruption periods, the distribution of wind directions means ash is likely to spread ash across much of the area of interest (see Fig. 6), including Tauranga where ashfall may affect harbour operations (~10% probability of exceeding 1 kg m^{-2} in a Kaharoa-style eruption - Bonadonna et al. 2005).

This eruption sequence, or similar sequences, have the potential to generate complex multi-hazard cascades as demonstrated through the outbreak flood unit. The affect of such a sedimentation event, within the context of current river management, could cause interactions that modify the impact of other hazards. The long term (>20 years) impacts of this event provide ample opportunity for credible extreme weather events (e.g. extra-tropical cyclones, Fig. 9 shows rainfall distributions from Cyclone Lusi in 2014) and other geohazards (e.g. earthquake sequences), that may also occur during this period, to be treated probabilistically. Within the Rangitaiki river system, 30 - 50 cm of tephra may fall directly onto the Matahina and Aniwhenua reservoirs and dams, providing the opportunity to test dam management decisions.

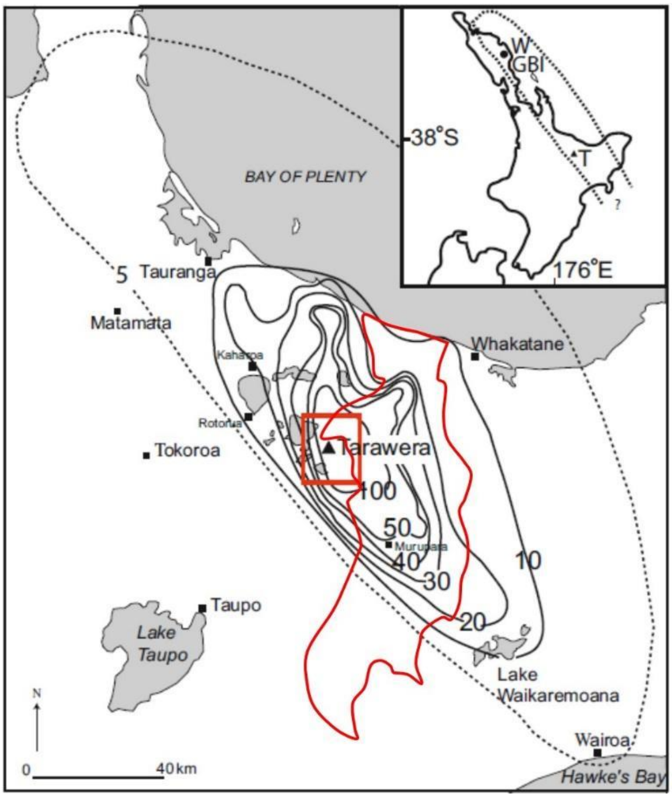

Fig 6. Tephra distribution of Kaharoa eruption after Sahetapy et al., 2014. Tarawera-Rangitaiki catchment outlined in red.

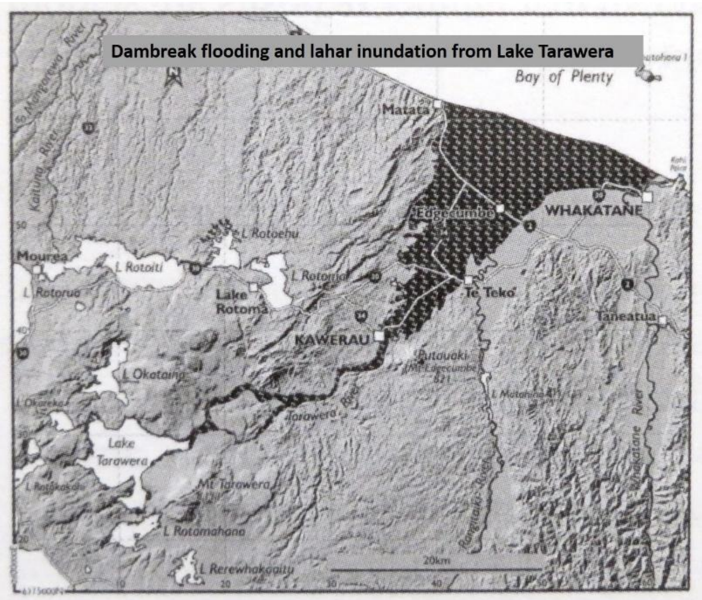

Fig 7. Lahar and dambreak flood inundation from Lake Tarawera in Kaharoa eruption (Hodgson and Nairn, 2005).

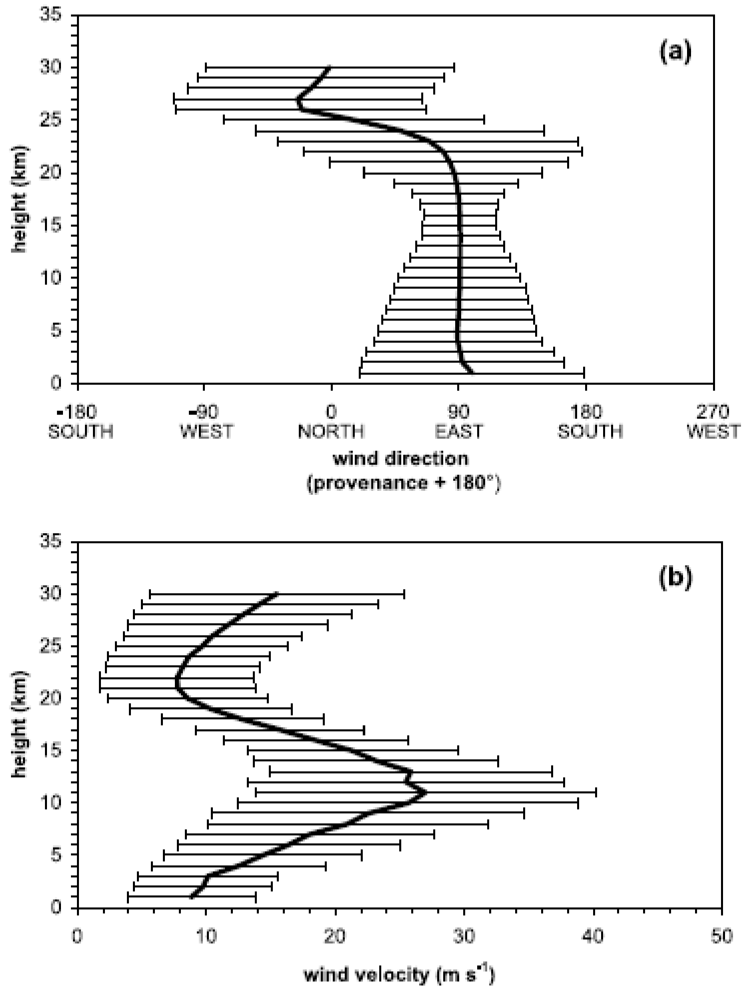

Fig. 8. Wind directions and velocity at Tarawera Volcanic complex, from Bonadonna et al. (2005)

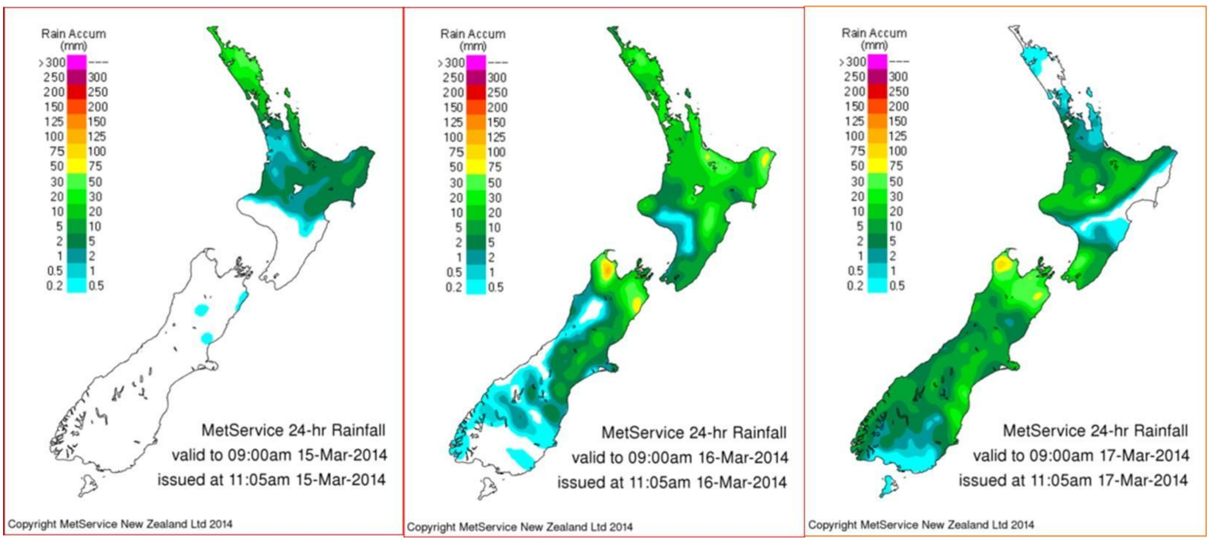

Fig. 9. 3-day rainfall distributions from Cyclone Lusi, 2014, from MetService New Zealand Ltd (2014)

7. Exposed infrastructure, industries and networks for the Rangitaiki/ Tarawera catchments and Bay of Plenty Region

The Rangitaiki and Tarawera catchments are located in the Whakatane, Kawerau and Rotorua district council areas, and within the Bay of Plenty Regional Council area. Both rivers cross State Highway 2 (see Fig. 10) and other major roads in the area. Horizons Energy is the main electricity distributor of the area, with Western Bay of Plenty and Tauranga City supplied by PowerCo. The main grid exit points (GXPs) in the catchments, where energy is transferred from the national transmission network (Transpower), are the Edgecumbe, Kawerau and Matahina GXPs. These are supplied from the transmission network by 110 and 220 kV towers via Ohakuri and Takurenga, near Rotorua. The Ohakuri to Edgecumbe 220 kV line passes in close proximity to Tarawera volcano. These lines may suffer from flashover, an electrical discharge across insulators that can overload and trip the distribution circuit. Crucially, the Ohakuri to Edgecumbe (via Matahina GXP) transmission line appears a single circuit, meaning there is no redundancy in the line (although power may also be supplied via Takurenga).

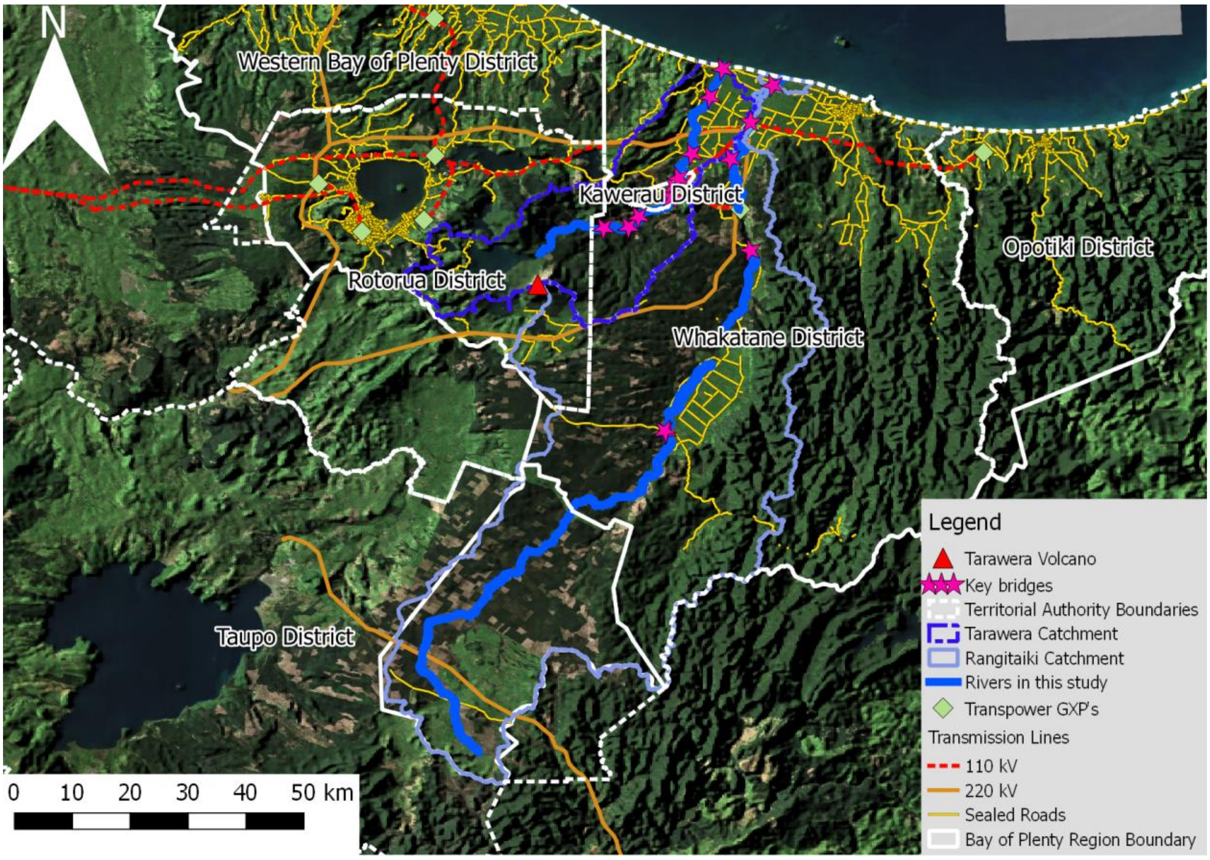

Fig. 10. Map of the Tarawera and Rangitaiki catchments, road and power transmission networks within the Bay of Plenty Region

Electricity load within the Horizons Energy area is dominated by industrial and agricultural load. Electricity load in the Galatea region (Murupara, Minginui, Kaingaroa areas) is dominated by dairy and irrigation, and is mostly supplied from the Aniwhenua Hydro Power station as supply from Edgecumbe GXP is limited by voltage drop due to the long line length. The Kawerau GXP, located approximately 600 m from the Tarawera River, generates ~28 MW through the Te Ahi O Maui Geothermal Plant, with large industrial loads from Asaleo Care (paper & pulp hygiene products), and timber mills (CHH, Sequal). The load from these industries is expected to reduce as industries retrench (Horizon Networks, 2019), however a new dairy factory is proposed in this region that is expected to increase the load. The Edgecumbe GXP is located along the Rangitaiki River (see Fig. 11), with major industrial loads from a Fonterra dairy factory, the Whakatane Mill and Kaingaroa Timberlands Mill. While

Edgecumbe GXP performed satisfactorily in the 2017 breach of flood defences (only shut down at the request of BoP Civil Defence), its proximity to the Rangitaiki River exposes it to increased risk if aggradation and/or weakening of stopbank defences occurs following an eruption of Tarawera. Road bridges crossing the Tarawera and Rangitaiki Rivers near the coastline were surveyed to identify potential exposure and risks from multi-hazard cascades. In this survey, crossings of the Tarawera River at Thornton Road and State Highway 2 appear level with stopbanks. This provides limited clearance under river aggradation, and deck sliding under lahar flows are likely if debris or water levels rise to stopbank elevations around bridges (Daga et al. 2018). Co-located infrastructure (likely communication and water supply) were also observed along many bridge crossings (see Fig. 12). Further summary and comments on infrastructure identified in this initial scoping survey are summarised in Table 3. These observations will be refined and expanded in future objectives (2.1.2-5) to identify critical triggers for hazard cascades, impacts and decision points.

Fig. 11. The Edgecumbe GXP on the Rangitaiki River (top) looking upstream and (bottom) across river.

Fig. 12. (top) State Highway 2 Road Crossing and (bottom) Rail Crossing, with co-located network cables, at Tarawera River.

Name	Type	Comments on potential effects
Edgecumbe GXP	Grid Exit Point	Unaffected in 2017 stopbank breach, although was taken offline. Supply from transmission lines may be exposed to ashfall. Located close to river. 2004 floods breached the eastern stopbank (Fig. 13)
Kawerau GXP	Grid Exit Point	Net input into national network, but with heavy industrial load. Located close to Tarawera River.
Matahina GXP	Grid Exit Point	Supplies Galatea region mostly from Matahina and Aniwhenua hydro plants. Limited alternate supply from Edgecumbe due to voltage drops.
Te Ahi O Maui	Geothermal Plant	Large Geothermal Plant (28MW) into Kawerau GXP
Matahina	Hydro Power Plant/Dam	Would be affected by ashfall. Potential role under high sediment load to be investigated.
Aniwhenua	Hydro Power Plant/Dam	
Tarawera SH2	Bridge and Rail Crossing	Bridges with co-located network infrastructure (power?, communication?) on level of stopbanks.
Tarawera Thornton Rd	Bridge Crossing	Bridge with co-located network infrastructure (water?) on level of stopbanks.

Table 3. Surveyed infrastructure along Rangitaiki and Tarawera Rivers.

Fig 13. Edgecumbe, 2004 floods (Whakatane Beacon)

The probabilistic eruptive and weather time-sequences following the initial scenario eruption will be developed as deliverables 1.1.1 and 1.1.2 of the MRM theme, and the tephra inputs to the Rangitaiki-Tarawera river systems, and river flow time-series, will be derived from these as deliverable 2.1.2 (Table 1).

8. MERIT economic modelling

The Dynamic Economic Model (DEM) constitutes a principal component of MERIT and simulates flow-on impact through economy. Within MERIT, the business behaviours model (BBM), and other interfacing models as appropriate, are used to estimate the impact on industries of a natural hazard disruption.

Under the BBM, impacts are simulated through ‘operability’ of which, for example, 0.5 ‘operability’ indicates 50% of its full capacity. The key inputs are the level of service for different lifeline infrastructures (e.g. water/gas/telecommunication/electricity), as well as transport connections and damage to physical premises.

The BBM came out of surveys after the Canterbury earthquakes and has been upgraded to include compatibility with volcanic events (as part of ERI/DEVORA). However, efficiency reduction as a consequence of the presence of low-level ash amounts (cleaning etc.) is not currently included.

Also, the BBM focuses on urban areas. Extensions will be required (modelling/surveys/data) to consider in more depth impacts on rural industries, particularly impacts that arise from natural capital degradation. We will list industry specific questions below, but for now we note that the Taranaki project (MBIE Endeavour Fund) will be looking into similar sorts of questions but this is not scheduled to begin for another 1-2 years.

It is possible that the tourism impacts will be of a different nature/scale to those considered in previous MERIT studies. Previous studies (e.g. Kaikoura earthquake) have been backed-up by data from eftpos/credit card spending. The Rotorua area is potentially more of a ‘key’ destination for tourists and the long-term nature of volcanic events will generate different outcomes from a short-term earthquake event.

All the actions that might be taken will have costs and benefits (changes to monetary flows in the model). We need to make sure that we consider who is paying for mitigation/adaptation measures and how the expenditures are spread over time. E.g. extra infrastructure investment by Regional Councils.

Specific areas/industries to focus on

- *Urban area(s):*
    - Rotorua is the largest urban area close to the proposed vent location (Fig 14). A key question is whether the Case Study scenario will directly affect the Rotorua urban area. If so, this would require modelling of water infrastructure, population disruption, tourism disruption, etc.

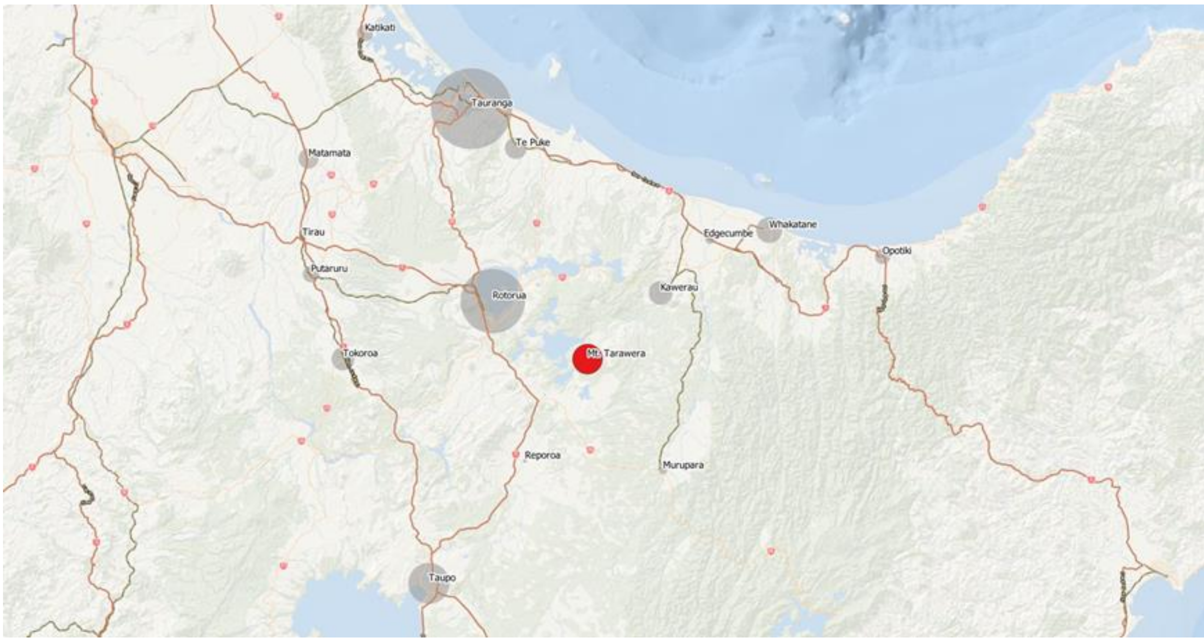

Fig 14. Urban areas in the study area.

- *Māori -Owned Assets (Fig 15):*
    - Significant tracts of commercial forestry exist near to the volcanic vent and much is owned/managed by iwi trusts (Fig 16).
    - Some tourism ventures are owned/run by Māori entities. Although it is expected that most will be located near Rotorua and not impacted by flooding, further investigations are required.
    - Geothermal stations and electric power stations close to flood waters (Kawerau and Aniwhenua stations) would likely face temporary closures.

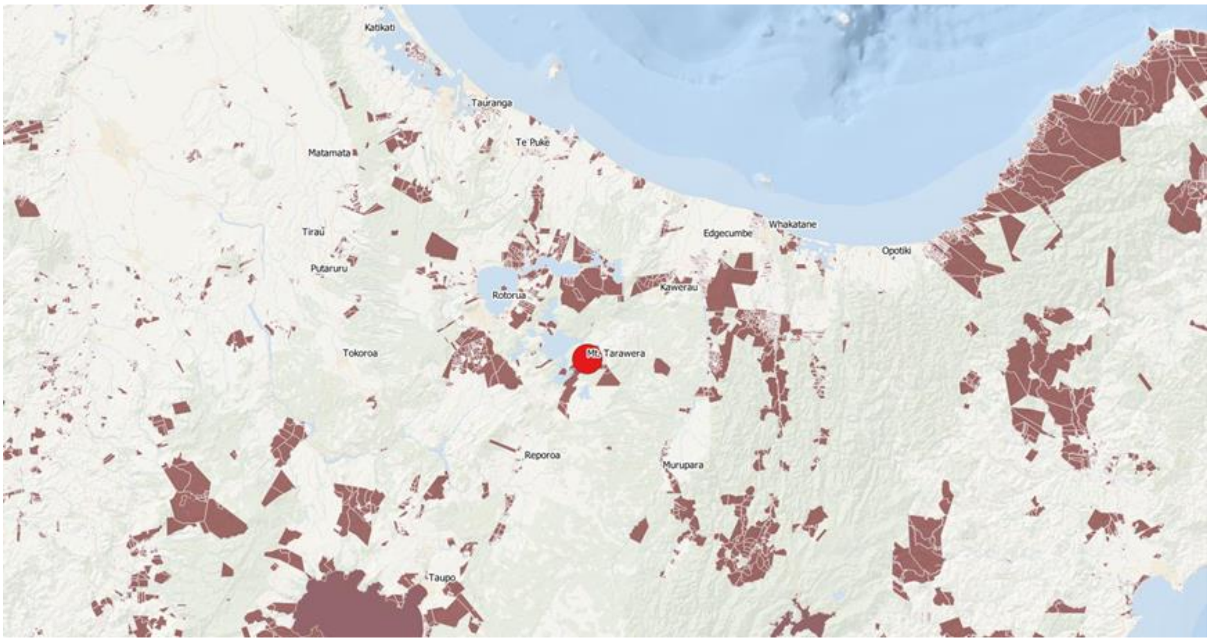

Fig 15. Māori land in the study area.

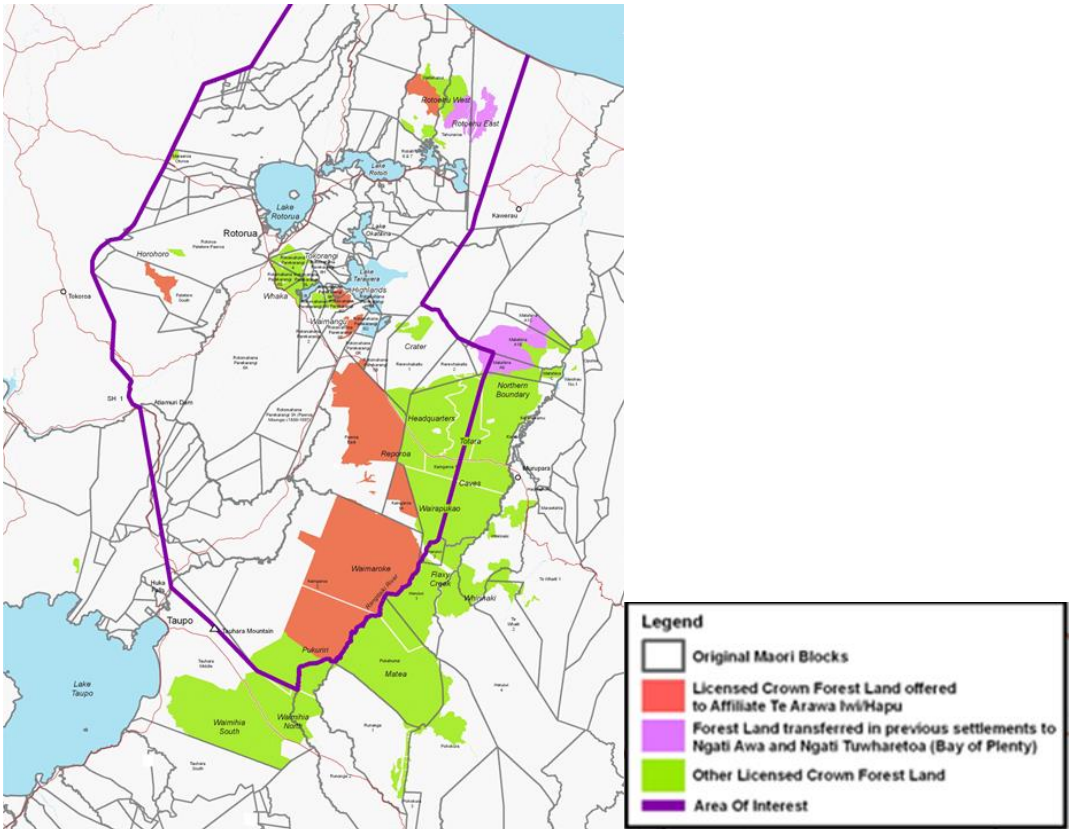

Fig 16. Forestry managed by CNI Iwi Holdings

- *Dairy farming*:
    - Decisions may need to be made on land usage when e.g., the land is covered with various ash depths.
    - Pasture growth will be affected (short and long term) and will depend on the actions farmers take, e.g. turning over all the soil and methods for reseeding.

- Unfortunately most research seems to focus on impacts on pasture growth – pasture growth is only an intermediate step in the eventual output of farms (i.e raw milk, livestock etc).
    - These decisions may also be increasingly affected by flooding and sediment run-off, especially if timed to coincide with heavy rainfall events.
    - Options and impacts may need to be communicated to the farmers to ensure the best decisions are made.
    - Fonterra may not be willing to take from dairy farms if the farm is not up to a standard. Hence, the farmers lose income.
- *Forest and wood products:*
    - The mills along the river might be affected by flooding, and might be affected by ashfall or ash in the water if they need water to run their processes. Many operations can stockpile goods, so short term transport outages might not be so important.
    - Areas of forest close to the vent will be knocked over by the eruption(s), and others will die if ashfall is above some threshold. It will be important to identify the forestry blocks, their ownership and their age structure, as well as where native forests are located.
    - If native forests are knocked over or killed, a key decision point will be whether they should be harvested.
    - Forest operations may be affected by ashfall onto roads, landings etc.
    - Forest harvesting may contribute to flooding hazard, so whether or not to harvest will be key decision point. It will be important to determine where ash thresholds are for tree survival and rates of ash accumulation. If it is slow accumulation then runoff will help reduce the effect on trees.
    - Forestry expertise will be needed.
- *Kiwifruit:*
    - Kiwifruit is an important industry in the area however the number of farms within the study river catchments are relatively small compared to the numbers further up the coast.
    - Kiwifruit farms would be impacted by the ash, resulting in income losses. But this will depend on seasonality.
    - The base Dynamic Economic Model has all horticulture/fruit growing types aggregated together. In order to get a good idea of the impacts we might need to disaggregate the industry accounts to separate out the kiwifruit/avocado farms that are dominant in the area.
    - Note that even if it was determined in NZ that kiwifruit are safe to be consumed following ash events, the fruit still may not be exportable due to overseas regulations and/or perceptions.
- *Cultural and recreational sites:*
    - Marae are located along/nearby the two rivers in the study area (Māori Maps); the impacts and resilience to these and other sites of cultural importance will be investigated through the project
    - There are many tourist sites in the impacted area; tourism may be impacted due to demand and perception, airports being affected.
    - Hard to model many aspects of tourism.
    - This may call for a decision point: Should tourism areas near Rotorua be promoted or should alternative options be promoted?
    - Tourism should not be a strong focus of the project given that we want to concentrate on and demonstrate more of the flooding aspects of the hazards.
    - There may be linkages with the Rural programme in terms of tourism analysis
- *Ports, airports and hospitals:*

    - Machinery is heavily affected by ash, especially jet engines. It may be important to think about how much ash would end up at ports.
    - A vital decision will be on whether to increase dredging when the ports are affected due to silt. Dredging is difficult to consider due to political reasons.
    - Access to ports may be limited due to flooding in the affected catchments. But this is only a small quantity compared to the overall port volumes *if dredging is carried out*, so would have a local effect on suppliers who are cut off, but not on port operations.
    - There will be periods of road outages, but access to the ports should still be available, just more expensive and time consuming.
    - Barges can be used to transport goods, but it is still usually faster via road. In the economic model, there is currently no coastal shipping model.
    - Tauranga airport has been considered, but unlikely to be affected. Rotorua airport is likely to be affected though, also Whakatane and others at different times.
    - Overall, it seems unlikely (although possible) to have enough ashfall to impact Tauranga harbour, but not also impact on Rotorua city.
- *Aquaculture and fishing :*
    - The economic model has not previously considered impacts (e.g. from fine sediment in coastal waters) on this sector, as mostly it would affect recreational and tāngata whenua customary takes that are not included in the monetary modelling.
    - It would be nice if we could provide physical indicators alongside economic indicators that may be informative of cultural impacts (e.g. depth of sediment on deposited on customary fishing sites). It may be that this is out of the project scope but worth further consideration.

9. Decision modelling

The plan is to simulate a (future) 20-year time-period following the trigger event, subjected to probabilistically-generated weather and volcanism.

In the decision process, every time a decision needs to be made an ensemble of possible outcomes will be simulated. Each decision point will be at different points in the future, i.e., time until the next big storm/rainfall event. Consequently, the number of options/pathways multiply to 1000s very quickly.

The decisions that will be made (in some cases) will depend on the economic situation as well as physical variables. Questions and issues to consider include:

- In the decision process, how can we incorporate and document economic and social changes (e.g. land uses are not likely to be static over 20 years)? Do we have to pick a single future economic trajectory?
- Natural hazards affect economic variables, which then impact the decisions, so we cannot run the economic modelling completely in isolation and then use probabilistic economic outputs for the decision making.
- We need to be cautious about the big picture event impacts (having an eruption and ongoing ashfall) swamping the local and flooding impacts of the natural hazards – which are where the decision points are, and where we can affect outcomes.
- Our main aim is to demonstrate the new methodology. We need to think about the effects of the decisions, who the decision makers are, and make sure we focus on things that can be influenced.

10. Stakeholder engagement

The events and impacts considered in this project will involve and affect a wide range of stakeholders, and the degree to which they are affected will depend significantly on what actions they take, and when, in response to the developing situation.   Broad and ongoing stakeholder engagement with the project will therefore be critical to its success. The project team has extensive contacts with many of the relevant organisations and groups; in particular, engagement with Tangata Whenua is specified as a project objective. Other organisations and groups potentially to be engaged include:

- Regional and District Councils;
- Lifelines and infrastructure providers (transport, power, communications, waters, ...);
- NEMA, CDEM and FENZ;
- MBIE, MPI, ….
- Agriculture and forestry sectors;
- Insurers;
- CRIs (GNS, NIWA, Landcare);
- Port of Tauranga;
- NGOs and civil society organisations

11. Conclusion

On the basis of the vulnerability of its infrastructure, society and economy to long-term tephra-driven flooding impacts, the potential for ground-breaking science and the wider impacts on the nation, the Rangitaiki-Tarawera river system was selected to be the location of the Multi-Hazard Risk Modelling Case Study for RNC2.

Future work towards deliverables 1.1.1/2 and 2.1.2 includes:

- Developing probabilistic eruption time sequences, including consideration of when to switch from ‘scenario’ inputs to probabilistic ongoing eruption phases (as in Bebbington and Jenkins 2019).
    - Potentially just use large plinian eruptions with set wind patterns and let the rest run probabilistically?
    - May only require 1 plinian phase.
- Reviewing effects of post-eruption dam breakouts and remobilisation (e.g. Manville, Hodgson, Nairn 2007) to identify sediment cascade triggers.
- Collate data within the Tarawera and Rangitaiki catchments, including exposure of iwi-owned or managed assets, terrain, control structures and their health.

Acknowledgements

Kaley Crawford-Flett and Ilan Noy attended the first scoping meeting and provided valuable perspectives.

References

Bebbington, M.S. and Jenkins, S.F. 2019. Intra-eruption forecasting. *Bulletin of Volcanology*, 81, 34.

Bonadonna, C., Connor, C. B., Houghton, B. F., Connor, L., Byrne, M., Laing, A., & Hincks, T. K. (2005). Probabilistic modeling of tephra dispersal: Hazard assessment of a multiphase rhyolitic eruption at Tarawera, New Zealand. Journal of Geophysical Research: Solid Earth, 110(B3), 10.1029/2003JB002896

Briggs, J., Robinson, T. and Davies, T., 2018. Investigating the source of the c. AD 1620 West Coast earthquake: implications for seismic hazards. *New Zealand Journal of Geology and Geophysics*, *61*(3), pp.376-388.

Cousins, J. (2013) Wellington Without Water - Impacts of Large Earthquakes. GNS Science Report 2012/30.

Dagá, J., Chamorro, A., Solminihac, H. d., & Echaveguren, T. (2018). Development of fragility curves for road bridges exposed to volcanic lahars. Natural Hazards and Earth System Sciences, 18(8), 2111-2125.

Hodgson, K., & Nairn, I. (2005). The c. AD 1315 syn-eruption and AD 1904 post-eruption breakout floods from Lake Tarawera, Haroharo caldera, North Island, New Zealand. New Zealand Journal of Geology and Geophysics, 48(3), 491-506.

Manville, V., Hodgson, K., & Nairn, I. (2007). A review of break-out floods from volcanogenic lakes in New Zealand. New Zealand Journal of Geology and Geophysics, 50(2), 131-150.

Robinson, T.R. and Davies, T.R.H., 2013. Potential geomorphic consequences of a future great (M w= 8.0+) Alpine Fault earthquake, South Island, New Zealand. *Natural Hazards and Earth System Sciences*, *13*(9), pp.2279-2299.

Robinson, T.R., Davies, T.R.H., Wilson, T.M. and Orchiston, C., 2016. Coseismic landsliding estimates for an Alpine Fault earthquake and the consequences for erosion of the Southern Alps, New Zealand. *Geomorphology*, *263*, pp.71-86.

Robinson, T.R., Rosser, N.J., Davies, T.R., Wilson, T.M. and Orchiston, C., 2018. Near-Real-Time Modeling of Landslide Impacts to Inform Rapid Response: An Example from the 2016 Kaikōura, New Zealand, Earthquake. *Bulletin of the Seismological Society of America*, *108*(3B), pp.1665-1682.

Sahetapy-Engel, S., Self, S., Carey, R. J., & Nairn, I. A. (2014). Deposition and generation of multiple widespread fall units from the c. AD 1314 Kaharoa rhyolitic eruption, Tarawera, New Zealand. Bulletin of Volcanology, 76(8), 836.

Todde, A., Kereszturi, G. K., Procter, J. et al. (in press). Stratigraphy and deposit characteristics of the AD 1314 Kaharoa eruption at Tarawera, New Zealand - Insights into multiphase rhyolitic eruptions.

Wilson, T. M., & Cole, J. W. (2007). Potential impact of ash eruptions on dairy farms from a study of the effects on a farm in eastern Bay of Plenty, New Zealand; implications for hazard mitigation. Natural Hazards, 43(1), 103-128. 10.1007/s11069-007-9111-8

Appendix: Rangitaiki-Tarawera Catchment Economic Summary

Background

Within the Multi-Hazard Risk Model programme of the National Science Challenge: Resilience to Natures Challenge, a Case Study will be undertaken to test and demonstrate end-to-end modelling of multi-hazard cascades, incorporating the potential implications of socio-economic decision making. The selected case study will involve an initial volcanic triggering event within the Okataina volcanic centre with resulting implications for the Tarawera and Rangitaiki river systems. This Appendix provides a preliminary economic profile of the geographic area likely to be subject to direct impacts from the multi-hazard events. As the specific location and scale of physical impacts is still to be determined as part of the future research, for this report the Case Study Area has been defined simply according to local council boundaries and is comprised of three territorial authorities: Rotorua District, Whakatane District, and Kawerau District (Fig A1).

Geographic Area and Transport

The Case Study Area makes up a sizeable fraction of the Bay of Plenty region. Key urban areas within the catchment include Rotorua, New Zealand's twelfth largest city by population, Whakatane, and Kawerau. These urban areas make up the bulk of employment in the catchment. Of the Statistical Area Units[1][1] within the Bay of Plenty Region, Rotorua Central, Mangakakahi Central (a suburb of Rotorua), and Whakatane Central alone make up almost 40% of employment.[2]

The Case Study Area is serviced by airports in Rotorua and Whakatane. However, road transport makes up the majority of transport in the region due to proximity to Auckland and Tauranga, two cities with major seaports and airports. State Highways 2, 5, 30, 33, and 36 run through the region, providing adequate transportation links between the major settlements in the Case Study Area as well providing access to neighbouring settlements and regions such as Waikato, the rest of the Bay of Plenty, and Gisborne.

Rail transport in the Case Study Area is underdeveloped, as shown by a simple location quotient (SLQ)[3] of 0.56 for rail transport employment. Meaning rail transport employment in the Case Study Area is scarce relative to New Zealand's rail transport employment. Air and space transport in the case study area follows a similar trend, a SLQ of 0.17 indicates there is very little employment in this sector compared to New Zealand as a whole. An SLQ of 1.15 for road transport employment in the Case Study Area further indicates that road transport is the preferred methods of transportation.

Key Economic Aggregates

According to Market Economics' Business Directory employment database, the Case Study Area makes up around 2% of the country's employment. Over the 10-year period from 2008 to 2018, the

[1] Endnotes appear at the end of the Appendix

Figure A1 - Case Study Area

Case Study Area recorded a growth rate in employment of 4.3%, significantly lower than the New Zealand growth rate in employment over the same period of 13.3%. According to Market Economics' Input-Output Table calculations, the Case Study Area accounts for approximately 2.4% of New Zealand's total exports and approximately 1.7% of New Zealand's total imports.[4]

Primary and manufacturing industries make up a significant proportion of the region's export revenue, with key industries such as dairy product manufacturing, horticulture and fruit growing, forestry and logging, wood product manufacturing, and pulp, paper, and converted paper product manufacturing making up approximately 40% of the Case Study Area's export revenue.

Key Industries and Employers

Industries such as food and beverage services, school education, and construction services are some of the largest sectors, with each employing roughly 5% of the workforce in the region. With the majority of this employment located largely in the key urban areas such as Rotorua and Whakatane. While these industries are large employers within the Case Study Area, they are fairly consistent with national employment averages.

Of significance, the Case Study Area provides a relatively high level of employment to workers in the forestry and logging sector. The forestry and logging sector in the Case Study Area has an SLQ of 4.65, indicating the specialisation and comparative advantage this Case Study Area has in forestry and logging. New Zealand's largest plantation forest, the Kaingaroa Forest, is located partly within the Case Study Area. As a result, both wood product manufacturing and pulp, paper and converted paper product manufacturing are significant components of the Case Study Area's economy. Notably, the

Tasman Mill and Whakatane Mill are key businesses within the pulp, paper, and converted paper product manufacturing sector, with the Tasman Mill employing 826 full-time equivalents (MECs)[5] and the Whakatane Mill employing 204 MECs. Making these mills two of the single largest employers in the region. In total, the Case Study Area provides almost 20% of the country's employment in pulp, paper and converted paper product manufacturing sector.

Other large singular employers in the Case Study Area include Rotorua Hospital, which employed 1197 MECs in 2018 and Whakatane Hospital, at 577 MECs. These two hospitals make up 96% of all hospital employment. Toi Ohomai Institute of Technology, with campuses inside the Case Study Area in Tihiotonga, Whakarewarewa, and Whakatane, as well as bordering the region in Taupo, Tauranga, and Tokoroa is also a significant employer.

Wood product manufacturing, which accounts for approximately 2.2% of the country's total exports, is also highly concentrated in the Case Study Area with roughly 10% of New Zealand's wood product manufacturing employment located here. Key businesses are spread around the region, including the Kawerau Sawmill, Red Stag Timber, and Claymark Industries. Although not directly located within the Case Study Area as defined above, the Port of Tauranga provides a great benefit to the export potential of the forestry and forestry-related sectors of the Case Study Area. Approximately 9% of all New Zealand's forestry and logging exports come from the Case Study Area, whilst the region also accounts for approximately 11.1% of New Zealand's wood product exports and approximately 22.5% of New Zealand's pulp, paper, and converted paper product exports. Thus, indicating the importance the Case Study Area has to New Zealand's forestry and related sectors. Additionally, SLQs for wood product manufacturing and pulp, paper, and converted paper product manufacturing of 4.29 and 8.59, respectively, further highlight the dominance these sectors have on the employment within the Case Study Area.

Dairy cattle farming is also fairly prominent in the Case Study Area, particularly south of Rotorua, Galatea, and around Edgecumbe. In total, the dairy cattle farming sector in the Case Study Area makes up just over 5% of New Zealand's dairy cattle farming employment and has an SLQ of 2.32, indicating the comparative advantage the region has in dairy cattle farming. Dairy product manufacturing in the region is driven by the Fonterra plant located in Edgecumbe, which employs around 300 MECs and helps contribute to New Zealand's employment in the dairy product manufacturing sector, which makes up 2.3% of the country's employment. In terms of exports, dairy products rank as the biggest export from the region contributing roughly almost 3% to New Zealand's dairy product exports. Having employed almost 500 MECs in 2009, the decline of employment in the Fonterra Edgecumbe plant has driven the decline in the dairy product manufacturing sector in the Case Study Area as a whole.

While dairy products are the largest export found in the Case Study Area, accounting for almost 1 quarter of all Case Study Area exports and roughly 3% of New Zealand's dairy product exports, an SLQ of 1.06 indicates that the area is not particularly dominated by dairy product manufacturing. This indicates that a proportion of dairy cattle farming production is likely manufactured into dairy products in the neighbouring Waikato region and beyond.

Combined, the forestry and forestry-related industries and dairy products make up approximately 60% of all exports out of the Case Study Area. Another large export earner for the Case Study Area is the horticulture and fruit growing industry, earning approximately 10% of all exports.

Rotorua is a well-known tourist hub, due to its cultural significance, thermal activity, and proximity to major cities such as Auckland and Tauranga, making it an attractive place for many to visit, for both domestic and international travellers. The Port of Tauranga acts as an attractive destination for many cruise ships visiting NZ. Over the 2018/19 season, the port hosted 116 cruise ships. In addition, New Zealand's major international airport is located in Auckland. As a result, accommodation ranks fairly high on the list of the Case Study Area's international exports and contributes 3.4% to the Case Study Area's total exports and 25.7% to New Zealand's accommodation exports, indicating tourism is a strong component of the region’s economy. As a whole, the accommodation sector in the Case Study Area has an SLQ of 2.36, indicating the accommodation is concentrated in the region relative to New Zealand. Many global hotel chains such as Millenium & Copthorne, Pullman, Holiday Inn, Ibis, and Novotel can all be found in Rotorua.

Both the heritage and artistic activities and sport and recreation activities sectors dominate the tourist areas. The Statistical Areas Tihiotonga-Whakarewarewa, home to Te Puia as well as various mountain biking tracks, has SLQs of 3.13 and 8.76 in heritage and artistic activities and sport and recreational activities, respectively. Ngongotaha, home to Skyline Rotorua, ZORB, and Rainbow Springs Nature Park, has SLQs of 16.09 and 2.53 in heritage and artistic activities and sport and recreational activities, respectively. Collectively, the Case Study Area has SLQs of 1.98 and 1.50 in the heritage and artistic activities and sport and recreation activities sectors.

Areas near Rotorua’s main attractions are heavily dominated by food and beverage and accommodation services. For example, Fenton Park, which borders Tihiotonga-Whakarewarewa, has an SLQ of 14.22 in accommodation, indicating the concentration of accommodation services in this area. The Case Study Area’s beachside areas are also dominated by food and accommodation services. Ohope, for example, has an SLQ of 2.80, due to its popularity as a vacation spot. Fenton Park and Rotorua Central employ the largest number of MECs in the accommodation sector at 329 and 764 MECs, respectively.

Underrepresented Industries

Interestingly, the Case Study Area is below the national average for employment in the horticultural and fruit growing sector despite its proximity to the main Kiwifruit growing region of New Zealand. The Case Study Area’s horticulture and fruit growing SLQ of 0.72 indicates that horticulture and fruit growing is scarce in the region relative to the rest of the country. This is likely because only a relatively small component of the Case Study Area is suited to horticultural production, with most of this being in the Thornton-Awakeri and Coastland regions, near Whakatane. Despite being a small contributor to New Zealand’s horticultural and fruit growing sector, employing only 1.6% of the countries employment in this sector, it is estimated that the Case Study Area contributes approximately 2.6% to New Zealand’s horticultural exports.

Notably, professional services such as scientific, architectural and engineering services, banking and financing, and advertising, market research and management services are underrepresented in the Case Study Area. While collectively being a large employer in the region, these sectors are well below the national average. SLQs for scientific, architectural and engineering services, banking and financing, and advertising, market research and management services of 0.69, 0.53, and 0.42, respectively, indicate the Case Study Area holds a comparative disadvantage in the professional sectors. Together, Rotorua Central and Tihiotonga-Whakarewarewa make up almost 50% of the regions scientific, architectural and engineering services, with a key industry in these two areas being Scion, a Crown Research Institute headquartered in Rotorua, which specialises in development in the forestry, wood product, and wood-derived and other biomaterial sectors. The comparative advantage the Case Study Area has in forestry and logging, wood product manufacturing, and pulp, paper, and converted paper product manufacturing enables the region to act as a strategic location for a crown research institute of this specialisation.

Many food product manufacturing sectors are also underrepresented in the Case Study Area. Sectors such as fruit, oil, cereal and other food product manufacturing, meat and meat product manufacturing, and beverage and tobacco product manufacturing in the Case Study Area are all below national levels of employment. SLQs of 0.60, 0.16, and 0.32 for these sectors respectively, indicate that food product manufacturing in the Case Study Area is relatively sparse.

Growth Industries

Growth and decline in the food product manufacturing sectors have been rather mixed over the 10-year period from 2008 – 2018. Sectors such as dairy product manufacturing and meat and meat product manufacturing have both decreased in employment considerably, decreasing 53.4% and 38.0% from 2008 through to 2018. While growth in employment has been experienced in beverage and tobacco product manufacturing and seafood processing. Although these growing sectors are still small and may be considered in their infancy, these trends signal a shift in production to more niche food products.

Professional services have shown similar mixed trends with advertising, market research and management services, and insurances services increasing in employment over the 10-year period, while declines in employment have been felt in the banking and financing and real estate services sectors over the same time period. However, the trends in these sectors match the directions of the trends at the national level.

In terms of the Case Study Area's important industries, employment in the forestry and logging sector has been constant. Despite this, a contraction in employment has been experienced in both the wood product manufacturing and pulp, paper and converted paper products manufacturing sectors. However, the growth of employment in both sectors was experienced towards the end of the 10-year period analysed, particularly in the wood product manufacturing sector, which experienced a 32.6% increase in employment from 2015 to 2018. This was largely driven by an increase in employment in Kawerau which increased employment in the wood product manufacturing sector by 141% from 2014 through to 2018.

Overall, the largest increases in employment have been felt in the medical and other health care services, the agriculture, forestry and fishing support services, and the public order, safety and regulatory services sectors. Whilst the largest decreases in employment have been experienced in the dairy product manufacturing, the banking and financing, and the dairy cattle farming sectors.

Growth in Settlements

Growth in employment from 2008 to 2018 has been particularly prominent in the eastern suburbs of Rotorua as well as a 7.7% increase in the level of employment in Central Whakatane. Holdens Bay-Rotokawa, Owhata, and Lynmore, all in eastern Rotorua, have all grown strongly over the 10-year period with growth in employment at rates of 58.0%, 37.9%, and 62.2% respectively. This follows a decline in employment in other Rotorua suburbs such as Fenton Park and Hillcrest, which contracted 35.7% and 19.5% respectively. Declines in employment over the 10-year period were also seen in Murupara and Matata-Otakiri, two rural towns, indicating some potential level of rural to urban migration.

---

[1] Statistics New Zealand reports business demography data according to an area unit classification. The classification is updated regularly with Statistical Area 2 (SA2) being the current classification system.
[2] Employment data referenced onwards in the report comes from Market Economics' employment database taking data directly from Stats NZ.
[3] A simple location quotient (SLQ) is a method of quantifying how concentrated a specific industry is in a region relative to a larger region. This approach can be used to identify industries that a region may have a comparative advantage in. An SLQ is reported as a ratio and is calculated by dividing the proportion of employment in an industry in one region by the proportion of employment in the same industry in the larger region. An SLQ of

above 1 indicates the industry is concentrated in the area relative to the larger region, less than 1 indicates the industry is relatively sparse in the area. For example, to calculate the concentration of dairy farming in the study area relative to the level of dairy farming in New Zealand, the proportion of dairy farming employment in the study area is divided by the proportion of dairy farming employment in New Zealand.

[4] Export, Import, and other data referenced to later in the report is approximated through an Input-Output Table developed by Market Economics. An Input-Output table describes the sale and purchase relationships between producers and consumers within an economy, representing the interdependencies between different sectors of different regional economies. Flows of final and intermediate goods and services defined according to industry outputs are quantified, allowing the analysis of production in the economy.

[5] Modified Employment Counts or MECs are a measure of employment based on Statistics New Zealand's Employment Count (EC) metric. Unlike ECs, the MEC measure includes estimates of working proprietors – i.e. persons who own and work in a business but do not record their income through payments of wages/salaries.