NIWA
Taihoro Nukurangi

Advice on and preparation of evacuation risk and survivability guidelines for New Zealand flood waters

Prepared for Gisborne District Council

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Executive summary

The Gisborne/Tairāwhiti region experienced several flooding episodes in 2023, with the most severe flooding occurring in February during ex-Tropical Cyclone Gabrielle (herein referred to as Cyclone Gabrielle). One key issue that was identified after Cyclone Gabrielle was a limited understanding by Gisborne District Council (GDC) staff of the hazard posed by flowing waters if residents chose to self-evacuate, or if emergency managers issued an evacuation warning. Flood hazard is broadly defined as the combination of flow depth, velocity, and floating debris that pose potential harm to people or property or both. GDC interviews with flood victims after Cyclone Gabrielle indicated that there was substantial uncertainty about the best course of action for evacuation, especially regarding the hazard posed to individuals on foot or driving to flee floodwaters.

NIWA was engaged by GDC through a Ministry of Business, Innovation and Employment (MBIE) Extreme Weather Recovery Advice Fund (EWRAF) grant, to undertake a review of:

- Best practices for quantifying flood hazard posed to individuals and vehicles.
- Undertake a case study of Cyclone Gabrielle-induced flooding in the Te Karaka settlement area to demonstrate the application of the practices identified.

The study was intended to provide guidance to Civil Defence , emergency responders, and community members in the Gisborne/Tairāwhiti region.

This report summarizes the methods and results of the study which bridges gaps between current procedural advice outlined in the GDC flood warning manual, and the flood hazard posed to residents advised or ordered to evacuate during certain flood stage conditions. The NIWA study used a search of grey and primary flood hazard literature, an analysis of modern flood hazard estimation methods with new application to New Zealand residents, and a case study of flood hazard in the Te Karaka village during Cyclone Gabrielle flooding conditions. A flood inundation model generated through a separate MBIE Extreme Weather Recovery project was used here without modification as the flood hazard basis for the Te Karaka case study.

Our review of modern governmental standards for quantifying flood hazard indicate that they rely strongly on having a calibrated 2-dimensional hydrodynamic model simulation of a design flood to generate gridded representations of the flood depth and velocity over a spatial domain of interest and over several time steps representing different conditions of the flood hydrograph. These time steps are used to estimate peak flood hazard (maximum hazard). The flood depth-velocity (hazard) grid is the basis for estimating vulnerability of residents, vehicles, and structures to floodwaters.

The primary methods for converting hazard to vulnerability is using so-called ‘flood vulnerability’ curves. We found that current government flood guidance in the UK, USA, and Australia rely strongly on empirically based vulnerability curves for humans and vehicles, which are based on laboratory experimental studies. However, the scientific and engineering communities are moving toward the use of mechanics-based methods, which use principles of fluid mechanics to estimate force-balance on human bodies and vehicles. All these methods and curves require strong engineering judgement and value choices to be made by emergency managers, and thus have substantial ranges of values that can be applied.

For humans, we compared the empirically-based flood hazard methods with the mechanics-based methods using body types for a range of demographics of NZ residents. We found that the mechanics-based methods had strong overlap with the most widely used empirically-based methods and did not find evidence that the mechanics-based methods were a substantial improvement given the additional uncertainties in the parameters required. We also compared mechanics-based methods for vehicles published in a recent study with widely used empricially-based vulnerability curves. We found that the mechanics-based methods had strong overlap the empirically-based vehicle stability regions and did not find evidence that the mechanics-based methods were a strong improvement given the additional uncertainties in parameters.

We used the RiskScape software engine to generate spatially explicit estimates of flood hazard posed to humans, vehicles, and buildings in the Te Karaka area under the conditions imposed by Cyclone Gabrielle. The flood hydrograph simulated by the regional hydrodynamic model was very similar to the hydrograph observed near Te Karaka. The peak flood hazard in Te Karaka occurred after overtopping of the stopbanks, and estimates indicated that the peak flood hazard was moderate to extreme for adults near town (high to extreme for children) and that 45 percent of roads in the area were unstable for passage by small passenger vehicles. However, model artefacts and geospatial data limitations produced unrealistic results for early portions of the hydrograph, and the spatial scale of the regional model may not have been adequately representing the stop bank elevations near Te Karaka. Nonetheless, the case study provided an example of a modern workflow for emergency flood hazard planning that can be applied anywhere in NZ and highlights key improvements that can be made when using these methods.

Based on our literature review and case study, NIWA has the following primary recommendations for improving estimates of flood hazard posed to residents in the Gisborne/Tairāwhiti region:

1. The current flood hazard guidance adopted by the Australian Disaster Resilience Institute for humans and vehicles have strong overlap with more recently developed mechanics-based methods and appear to be adequate for use in New Zealand flood planning. Mechanics-based methods, while providing more flexibility to choose for human and vehicle types, suggest a level of precision that may not be realistic for everyday use, and should be used with caution.

2. The use of depth and velocity grids from hydrodynamic models to estimate flood hazard requires strict scrutiny of the spatial resolution and modelling artefacts. Although the regional hydrodynamic model was adequate for a general demonstration of a flood hazard workflow for Te Karaka, scrutiny, and potentially additional post-processing of the regional hydrodynamic model results could improve estimates of flood hazard at Te Karaka and elsewhere in the region. If another, more localized hydrodynamic model is available, it could be used with the RiskScape software to cross-check the regional model results and potentially improve hazard estimates. Strict model scrutiny and cross-checking, particularly in populated areas, is advised anywhere these methods are applied in NZ.

3. Flood hazard estimates for bridges and buildings could be improved by attributing the data available from Land Information New Zealand with elevation and other building construction data. When implemented in the RiskScape workflow, elevation information can be used to generate more realistic estimates of hazard to bridges, which are particularly important to connect escape routes when flood waters are rising. Likewise, elevation information for structures such as floor levels and building foundation and wall materials could help improve estimates of where it may be safe to shelter in place under certain circumstances.

4. Although not considered in the case study presented here, estimates of the number and demographics of residents in buildings would be helpful for decision making regarding acceptable levels of hazard. For example, if a town has a large population of elderly adults, or disabled people, this would be a strong consideration when making the value judgement of acceptable levels of flood hazard during evacuation planning. Although these data would be extremely useful, it would need to be considered with great care and caution to protect personal privacy of residents.
5. The GDC flood manual used telemetered observations of stage heights at stream gauges for emergency flood planning and decision making. It is recommended that these stages are revisited on a regular basis and cross-checked with modelling and observations to assure that they are relevant to current conditions. This is particularly important in locations such as Te Karaka where the bed of the Waipaoa River near the local stream gauge at the Kanakanaia bridge has been aggrading for decades and may be shifting the stage-rating curve. As the GDC flood warning manual has had a recent review, revisiting stage-based actions and decisions outlined in that manual would provide additional confidence to emergency managers in the region. Such considerations would apply anywhere in NZ that stages are used for emergency flood decision making.
6. Overall, the methods employed and the findings discussed in this study have direct application to other catchments in Gisborne/Tairāwhiti and across other regions in NZ. The gaps and limitations highlighted in this study, as well as other contextual information at the local scale (e.g., catchment-specific characteristics, population dynamics/distributions), would need to be taken into consideration if applying similar modelling-based approaches to informing the development/updating of evacuation survivability guidelines/procedures.

1 Introduction

The Gisborne/Tairāwhiti region experienced several flooding episodes in 2023, with the most severe flooding occurring in February during ex-Tropical Cyclone Gabrielle (herein referred to as Cyclone Gabrielle). In Cyclone Gabrielle, fatalities and injuries occurred in both Hawkes Bay and Gisborne/Tairāwhiti as well as further injuries and near misses identified in post-event interviews with flood victims. One key issue that was identified after Cyclone Gabrielle was a limited understanding by Gisborne District Council (GDC) staff of the hazard posed by flowing waters if residents chose to self-evacuate, or if emergency managers issued an evacuation warning. While there is international literature into the issue of evacuation risk and pedestrian survivability in flood waters, a limited search of this literature by GDC did not identify any coherent analysis that would provide for the development of evacuation, or stay in place, guidance for New Zealand; especially when considering flood characteristics as exemplified by Cyclone Gabrielle.

Flood hazard is broadly defined as the combination of flow depth, velocity, and floating debris that pose potential harm to people or property or both (Wade et al. 2005). The GDC flood warning manual contains advice and consequences for key areas in Gisborne/Tairāwhiti region that recommend evacuation at certain flood height triggers monitored at stream gauges on the Waipaoa, Te Arai, Waimata/Taruheru, and Uawa/Hikuwai Rivers. For example, "evacuation of Te Karaka" is the advised consequence when the stage at the Kanakanaia stream gauge reaches 7.5 m (GDC 2023). However, beyond these gauged locations there is no indication if this advice is suitable for evacuees of various demographics, or whether stay in place (or other) guidance would be more appropriate under certain conditions. Current advisories do not, for example, consider the flood hazard posed to residents if they are ordered to evacuate, but the experience of Gabrielle is that people evacuating may encounter severe hazards during evacuation.

GDC interviews with flood victims after Cyclone Gabrielle indicated that there was substantial uncertainty about the best course of action for evacuation, especially regarding the hazard posed to individuals on foot or driving to flee floodwaters.

To provide guidance to Civil Defence (CDEM), emergency responders, and community members in the Gisborne/Tairāwhiti region, NIWA was engaged by GDC through a Ministry of Business, Innovation and Employment (MBIE) Extreme Weather Recovery Advice Fund (EWRAF) grant to:

1. Review of best practices for quantifying flood hazard posed to individuals and vehicles.
2. Undertake a case study of Cyclone Gabrielle-induced flooding in the Te Karaka settlement area to demonstrate the application of the practices identified.

Although the flood scenario used in the Te Karaka case study is specific to Cyclone Gabrielle, the application of the hazard quantification practices can be applied to other flood-prone regions in Aotearoa New Zealand.

1.1 Purpose and Scope

This report summarizes the methods and results of a study undertaken to generate guidance which bridges gaps between current procedural advice outlined in the GDC flood warning manual, and the flood hazard posed to residents advised or ordered to evacuate during certain flood stage conditions.

The results and guidance described in this report were built iteratively through engagement with members of GDC and Gisborne/Tairāwhiti community members through an initial inception meeting and final workshop.

2 Methods

This study used a search of grey and primary flood hazard literature, an analysis of modern flood hazard estimation methods with new application to New Zealand residents, and a case study of flood hazard in the Te Karaka village during Cyclone Gabrielle flooding conditions. A flood inundation model generated through a separate MBIE Extreme Weather Recovery project (Lane 2023), was used here without modification as the flood hazard basis for the Te Karaka case study.

2.1 Literature Review of Flood Risk Management

Increasing urbanization and global climate change are exacerbating the frequency and magnitude of flooding threatening communities worldwide. These increasing pressures have accelerated flood risk research and government approaches to flood risk management. We conducted literature searches of government flood risk management documents and scientific research papers to synthesize modern best practices in flood risk management. This effort focused on reviewing analytical methods and vulnerability information requirements for quantifying injury, survivability risk and/or threat to safety when individuals or vehicles are exposed to flood hazard.

2.2 Flood Hazard Analytical Methods Comparison

From our literature review, we identified key methods used in modern flood risk management for quantifying flood hazard to individuals and vehicles seeking to flee rising floodwaters. Many of these methods were developed using experimental studies on individuals in various European countries or Australia (e.g., Cox et al. 2010), and there is little information on their application to the demographics of New Zealand. New Zealand's most recent census indicates that its population was diverse, with 70% of people reporting European ethnicity, 17% Māori ethnicity, and 8% Pacific, 15% Asian and 3% other ethnicities (note that people were free to report multiple ethnicities; https://www.stats.govt.nz/tools/2018-census-place-summaries/new-zealand#ethnicity-culture-and-identity). In the Gisborne district, European ethnicity is 58%, Māori 53%, Pacific 5%, Asian 3% and 1% other ethnicities (https://www.stats.govt.nz/tools/2018-census-place-summaries/gisborne-region#ethnicity-culture-and-identity).

We tested the viability of industry standard empirical flood hazard classifications by applying recently developed mechanics-based (MB) approaches using body types for various demographics of New Zealanders. The MB approaches take inputs of a person's height and weight to calculate the hazard posed to that individual for different combinations of floodwater depths and velocities. We applied the MB method using average heights and weights for male and female adults and children across the four primary ethnic groups in New Zealand: (1) Māori, (2) Pacific Islander, (3) Asian, and (4) European/other. These statistics were extracted from the Ministry of Health's 2022/2023 Annual Data Explorer, which accesses the most recent demographic data from the New Zealand Health Survey (minhealthnz.shinyapps.io/nz-health-survey-2022-23-annual-data-explorer/).

2.3 Case Study – Te Karaka

Te Karaka is a settlement area in the heart of the Waipaoa valley in central Gisborne. Much of the settlement area of Te Karaka is along the banks of the Waipaoa River, with the town itself located on the inside of a large meander loop and protected by stopbanks. The town of Te Karaka lies downstream from the confluence of several major tributaries to the Waipaoa, and sedimentation from these headwater regions has been a persistent problem since at least the mid 1900's. The reach of the Waipaoa River in the Te Karaka area and upstream has been the subject of extensive scientific study, which has indicated that the bed of the Waipaoa has been aggrading (raising in elevation) for decades, with the potential to exacerbate flooding (Gomez et al. 1998).

Some observations of the Cyclone Gabrielle flood hazard and impact characteristics in Te Karaka are:

- Te Karaka was hit particularly hard by floodwaters from Cyclone Gabrielle when the Waipaoa River breached its stopbanks and began flooding residential areas (Funding Approved For Flood Resilience Work In Te Karaka | Scoop News).
- Residents were awakened in the night by emergency services and ordered to evacuate immediately; many residents fled to the nearby hills to escape the rising floodwaters (Cyclone Gabrielle: Te Karaka residents given 20 seconds to escape when flooding hit | Newshub).
- Media reporting indicated that up to 500 residents evacuated up to the hills in their vehicles (Cyclone Gabrielle: Te Karaka locals rushed up hills to safety as usually benign river swamped their town | Stuff).
- As many as 100 homes are being demolished to prevent future flood damage (Funding Approved For Flood Resilience Work In Te Karaka | Scoop News).

The settlement area is also home to three maraes, one of which (Rangatira) was inundated by more than 2m of floodwaters (Figure 2-1).

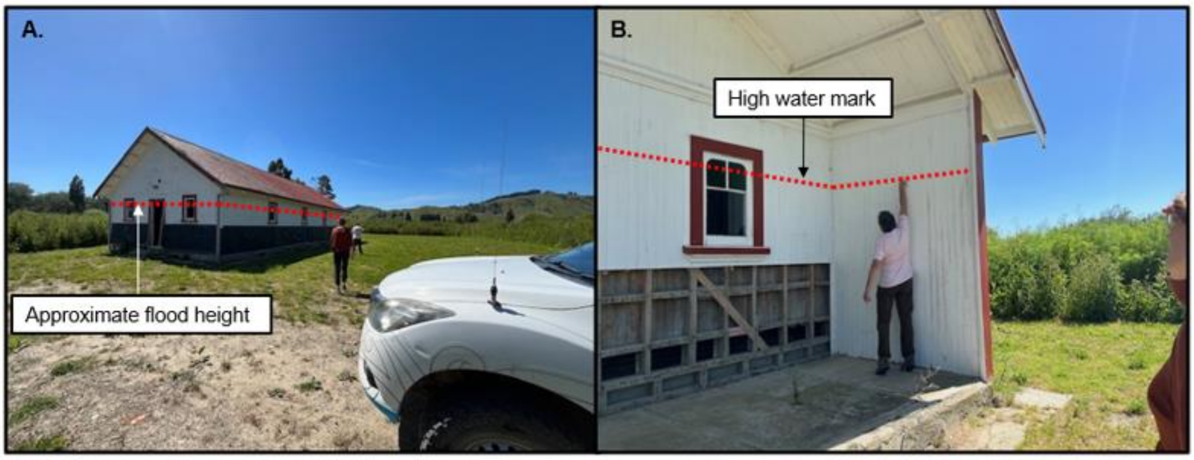

Figure 2-1: Images showing flood inundation levels at the Rangatira marae across the Waipaoa River from the town of Te Karaka. (A) Rangatira marae looking southeast; (B) southern end of Rangatira marae with Murry Cave, Principal Scientist of Gisborne District Council pointing to the high-water mark just overhead.

The extensive damage and emergency evacuation of Te Karaka make it an ideal location for testing and demonstration of state-of-the-art methods for estimating flood risk threat to safety and survivability. We used the multi-hazard risk analysis software RiskScape (Paulik et al. 2022), to generate maps of human safety threats at building locations and on 100 m road segments in the Te Karaka settlement area, as well as threat to vehicle stability on 100 m road segments.

2.3.1 Description of Gisborne area flood model of Cyclone Gabrielle scenario

The basis for flood hazard analysis in the Te Karaka area were time-series of spatially gridded depth and velocity estimates derived from a numerical flood model. The flood model was built as part of a larger, separately funded effort outlined by Lane (2023) to estimate Gabrielle-driven flood magnitudes across the Hawkes Bay and Gisborne Regions. The model in the Gisborne region used a so-called 'rain-on-grid' approach that simulated rainfall and runoff at one-hour time steps across an 8 metre resolution digital elevation model (DEM) of topography. The model calibrated runoff to stages observed at various stream gauges throughout the region. The Te Karaka area has a stream gauge located at the Kanakanaia Bridge over the Waipaoa River, and the flood model accurately reproduced the observed flood hydrograph at that location (Figure 2-2).

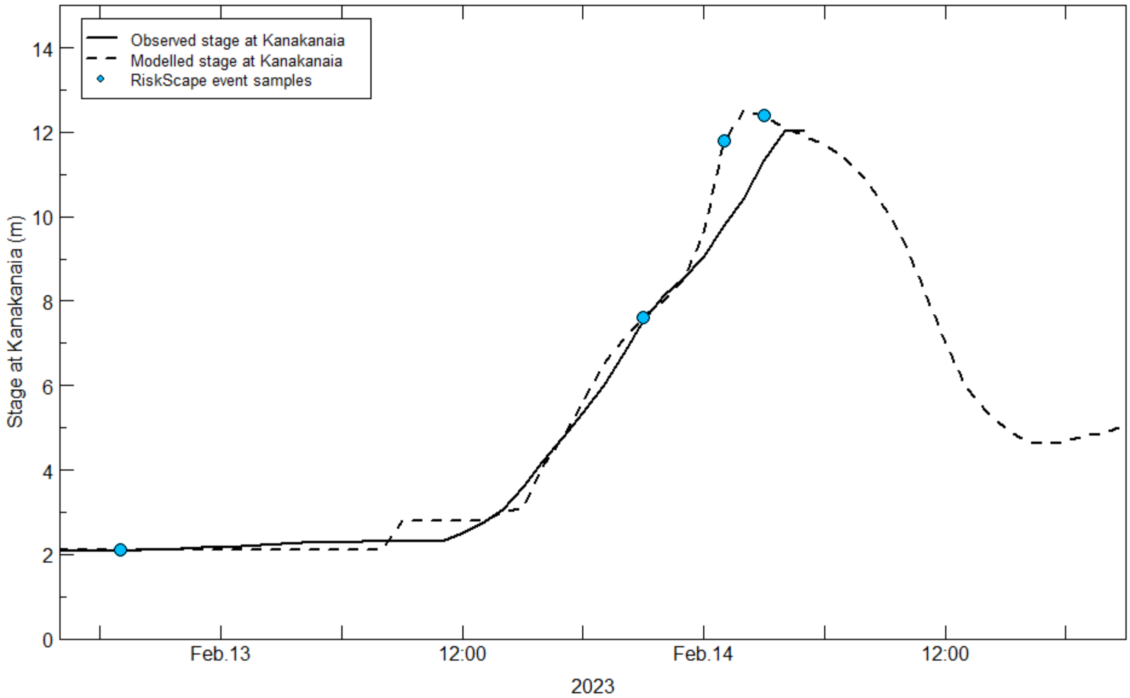

Figure 2-2: Timeseries of observed and modelled stage of the Waipaoa River at the Kanakanaia stream gauge in the settlement of Te Karaka during Cyclone Gabrielle. The blue dots represent the sampling points used to examine changes in flood hazard with rising stage in the RiskScape software.

The approach of Lane (2023) was to start the numerical model by allowing all rain-derived water to runoff the landscape to drainages. Although the model for the Gisborne District accurately reproduced stage hydrographs, the startup approach creates artifacts whereby small depressions in the DEM of the topography (either real or digital artefacts) require filling with water before runoff can occur. Consequently, portions of the landscape can appear to have pools of water when it is possible that none were present during the event (**Error! Reference source not found.**). These a rtefacts may result in unreliable estimates of flood hazard during the model startup stages of the flood event. The effects of these model artefacts are discussed in further detail in sections below.

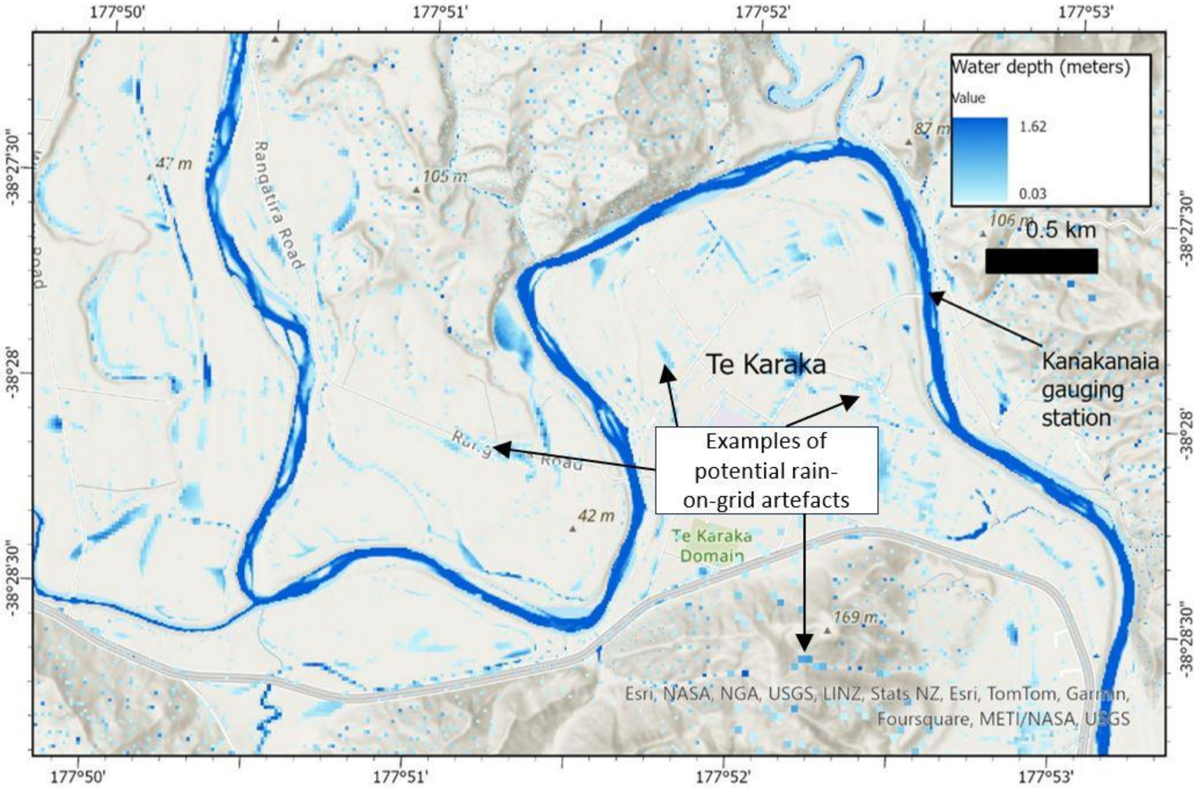

Figure 2-3: Map showing modelled flow depth of the Waipaoa River at Te Karaka and examples of potential rain-on-grid artefacts associated with model . The flow depths shown are for a stage of 2.8 m at the Kanakanaia gauging station, and the arrows point to four of many tens of ponding artefacts identified in the image. Flow direction is top to bottom.

2.3.2 RiskScape analysis of flood scenarios

RiskScape is an open-source software for multi-hazard risk analysis (Paulik et al. 2002). The RiskScape software implements modeller-defined risk rules over defined spatial domains, and applies them to other geospatial elements (roads, building footprints etc.) input to the model. Customised model workflows were developed to analyse human safety threat and vehicle stability in the Te Karaka study area (Figure 2-4).

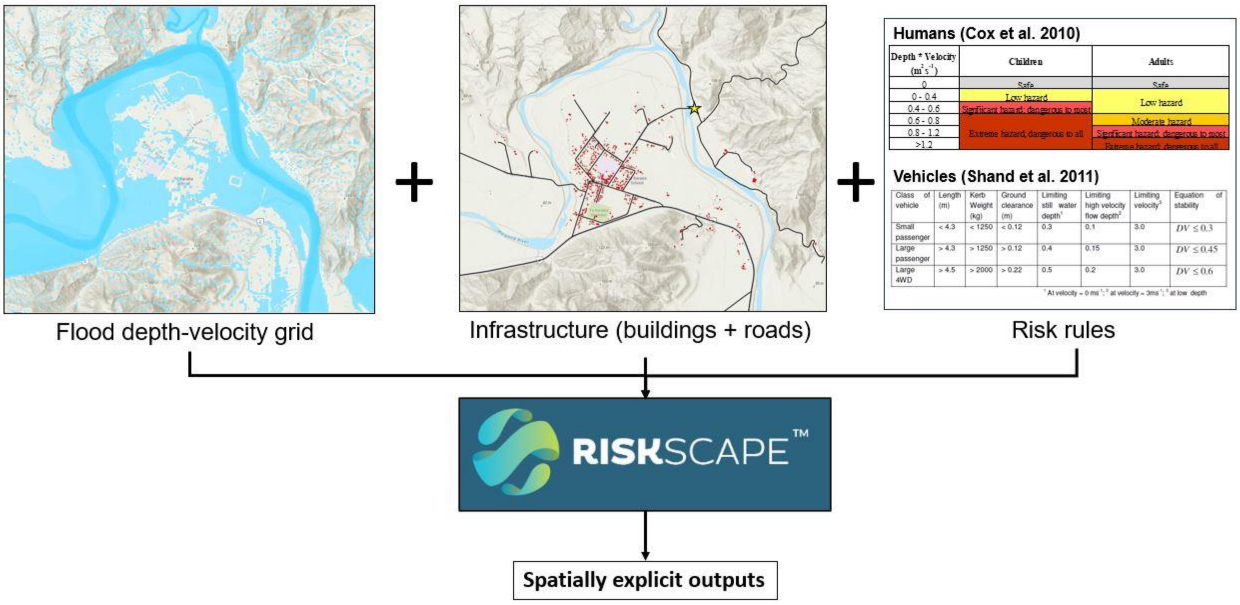

Figure 2-4: Schematic showing RiskScape workflow used to estimate flood hazard for the Te Karaka area.

Model input data to the Te Karaka RiskScape model included:

1. Hazard layers: gridded time series of inundation depth (D), flow velocity (V) and flux (DV, flow rate per m width) from the flood model of the Waipaoa river based on the Cyclone Gabrielle scenario (see Lane 2023 for details of the model). These data were available on an 8 m resolution grid across the Te Karaka landscape for each 1-hour time step (events) over the simulated Cyclone Gabrielle hydrograph (Figure 2-2).

2. Exposure layers: Locations of land, buildings and infrastructure exposed to flood risk. For this case study we focused on roads and buildings because these are associated with evacuation routes and sheltering in place, respectively.

3. Vulnerability models: these are functions that determine human safety threat and vehicle stability at locations exposed to the hazard event. In this case we used the Cox et al. (2010) function for human safety threat when near roads and buildings, and the Shand et al. (2011) safety criteria for vehicles.

Table 2-1 summarises input data for the Te Karaka model. A geoprocessing step was used in the Te Karaka RiskScape model to join information from the hazard input data layers to each exposure layer (buildings and roads). This step identified the hazard intensity present at the location of each building and each 100 m road segment. Details of this geoprocessing step are summarised in Table 2-2.

Table 2-1: Summary of Te Karaka RiskScape model input data.

Data Type	Input Data	Geometry Type	File Format
Hazard Layers	Depth, velocity and flux grids for Event 1, Event 2…Event X (each time-step).	Grid	Geotiff (.tif)
Exposure Layers	Roads (LINZ 2024)	Line	Shapefile (.shp)
	Buildings (LINZ 2024)	Polygon	Shapefile (.shp)
Vulnerability Models	Human (Cox et al. 2010) and vehicle (Shand et al. 2011) safety functions	-	Cpython (.py)

Table 2-2: Te Karaka model geoprocessing and sampling step-functions for input data geometry types.

Input Data Geometry		Geoprocessing Step-Function	Sampling Step-Function
Hazard	Exposure		
Grid	Polygon	Cut by intersection area	Maximum hazard intensity
Grid	Line	Cut by segment	Maximum damage value*

* Calculated during consequence analysis step.

A consequence analysis step was included in the RiskScape model to calculate human safety threat and vehicle stability for each building and road segment exposed to hazard at each analysis time-step. The Te Karaka RiskScape model output data reports human safety threat for flood-exposed buildings and roads, and vehicle stability for flood-exposed roads. For this study, outputs of exposure were generated for every 1-hr time step of flood evolution, enabling an indication of how the hazard exposure changes as the flood event progresses.

2.3.3 Post-processing of flood scenarios

The current GDC flood warning manual uses the stage (water level) of the Waipaoa River as observed at the Kanakanaia stream gauge as the basis for its Waipaoa flood warning procedures (GDC 2023). The Kanakanaia gauge is located adjacent to the town of Te Karaka, so it is a good indicator of flood severity affecting the settlement (**Error! Reference source not found.**). The hydrodynamic model b uilt by NIWA and used to simulate rainfall and runoff from the cyclone Gabrielle event replicated the shape and magnitude of stage change with reasonable accuracy (Figure 2-2), indicating that RiskScape model outputs could be used to accurately examine how flood hazard changes in the Te Karaka settlement area with changing stage at the Kanakanaia stream gauge. However, the flood model of the Gisborne Region was intended to simulate the large-scale flooding over time and space associated with Cyclone Gabrielle, and the 8 m resolution of the DEM used to model the floods of such a large area, was likely not adequate to precisely capture narrow features such as the tops of stopbanks protecting Te Karaka. Thus, some inaccuracy in the timing of stop bank overtopping or drainage would be expected in the model depth and velocity estimates used to estimate flood hazard.

We selected key time-steps (events), shown as blue dots on the simulated hydrograph in Figure 2-2, to sample and describe changes in the flood hazard during the Gabrielle flood scenario. These sample events were used to generate maps of human safety threat for infants, children, and adults escaping on foot near buildings and on roads based on the Cox et al. (2010) flood hazard functions. We also simulated vehicle stability threats from floodwaters on roads using the criteria of Shand et al. (2011) for small and large passenger vehicles, large 4WD vehicles, and fire engine-sized vehicles. Finally, we used the RiskScape outputs to generate example time-series visualizations of flood risk for the Te Karaka area as a way of merging spatial-temporal data into a single decision-making graphic.

3 Results

3.1 Literature Review

Our review of literature focused on the most current guidance documents published by emergency management agencies in Australia (Australian Disaster Resilience Guideline 7-3 2014), the United Kingdom (Ramsbottom et al. 2006), and the United States (Federal Emergency Management Agency 2020). We also examined recent scientific literature to determine if current government guidance was out of date relative to new developments. These documents typically focus on three primary steps in the determination of flood vulnerability: (1) development of a depth-velocity grid; (2) application of flood vulnerability curves; (3) integration of flood vulnerability maps into emergency evacuation planning.

The most basic definition of flood hazard is simply:

$$H_f = D * v \tag{1}$$

where H_f is the flood hazard (termed 'flood severity' in the United States) in units of length squared per unit time, D is local water depth in units of length, and v is local water velocity in units of length per time.

Our review of modern governmental standards for quantifying flood hazard indicate that they rely strongly on having a calibrated 2-dimensional hydrodynamic model simulation of a design flood; typically representing a flood magnitude with a certain return frequency or a representative event used for planning. The hydrodynamic model is used to generate gridded representations of the flood depth and velocity over a spatial domain of interest and over several time steps representing different conditions of the flood hydrograph. Herein, 'gridded' specifically refers to a raster representation of a quantity. In plain terms, rasters are images, whereby each image pixel (grid cell) has a value representing a discrete area. For example, a depth raster with 1-metre resolution, may represent the spatial distribution of depth for a given area, with each grid cell holding a value of the average flow depth for its 1 m^2 area (Figure 3-1).

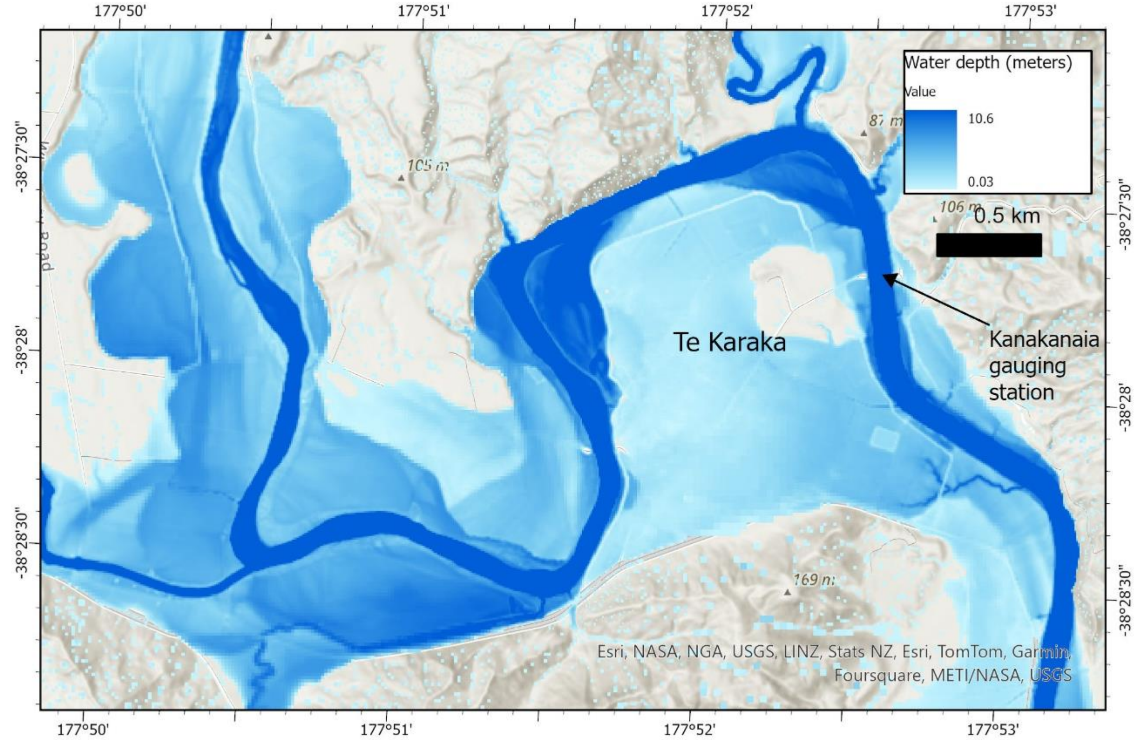

Figure 3-1: Map showing modelled flow depth of the Waipaoa River at Te Karaka. The flow depths shown are for a stage of 12.4 m at the Kanakanaia gauging station after stopbanks had been overtopped. Flow direction is top to bottom.

Peak flood hazard is defined as the maximum combination of depth and velocity over an area of interest, often the area of a single grid cell (Australian Disaster Resilience Guideline 7-3 2014). Because of the complex flow paths of flood waters over local topography and around objects and infrastructure in the landscape, peak flood hazard can occur before or after the actual peak stage of a flood event. It is thus recommended that flood hazard is calculated for each step of the flood hydrograph to identify when flood hazard is maximized (Australian Disaster Resilience Guideline 7-3 2014).

The flood hazard grid is the basis for estimating vulnerability of residents, vehicles, and structures to floodwaters. The primary methods for converting hazard to vulnerability is using so-called 'flood vulnerability' curves. Our review found that government guidance for calculating vulnerability posed to residents evacuating through floodwaters on foot or in vehicles relied mainly on empirically based lookup tables, which were derived and calibrated from a range of laboratory experimental studies conducted over the past four decades. Alternatively, recent scientific literature has been trending toward a focus on use of so-called mechanics-based methods (MB), which incorporate first principles of fluid-mechanics and allow for calibration and input of different body sizes. Below we provide summary of the basis and applicability of each method.

3.1.1 Empirically based flood vulnerability curves for humans

Empirically based flood vulnerability curves are generally drawn from experiments on human subjects. Various experimental studies including Foster and Cox (1973), Abt et al. (1989), Takahashi et al. (1992), RESCDAM (2000), Karvonen et al. (2001), Yee (2003), and Jonkman and Penning-Rowsell

(2008) have exposed human subjects of different body sizes, physical abilities, and footwear to various depths and velocities of water over various surfaces and recorded when these individuals lost stability through either sliding (remaining upright but losing ability to move) or toppling (losing footing and falling into the flow of water). The sample sizes in these experiments range from a single individual stuntman exposed to various conditions (Jonkman and Penning-Rowsell 2008), to as many as 20 adults (Abt et al. 2008).

The UK guidance relies on revised flood vulnerability curves developed by Ramsbottom et al. (2006) and calibrated using the data of Abt et al. (1989) and RESCDAM (2000). Ramsbottom proposed a hazard rating calculated through the following formula:

$$HR = d(v + 0.5) + DF \qquad (2)$$

Where HR is the hazard rating in units of length square per time, and DF is the debris factor. The value of DF is assigned either a 0, 0.5, or 1 depending on the setting (pasture, woodland, or urban), and depth, with DF set to 0 for depths less than 0.25 m. Under these criteria, Ramsbottom et al. (2006) proposed categories of HR with values less than 0.75 being low hazard, between 0.75 and 1.25 being moderate hazard (dangerous for some, i.e., children), between 1.25 and 2.5 being high hazard (dangerous for most), and greater than 2.5 being extreme hazard (dangerous to all).

Guidance published by the Australian Disaster Resilience Institute (Australian Disaster Resilience Guideline 7-3 2014) suggests using a flood hazard rating based on a comprehensive study published by Cox et al. (2010). The Cox et al. (2010) study performed a re-analysis of published experimental data and proposed series of so-called hazard 'regimes' for children, adults, and trained rescue professionals (Table 3-1). Cox et al. (2010) also added absolute boundaries on depth and velocity for children and adults, which made the assumption that even deep stagnant water posed an unacceptable hazard when it reaches a depth requiring a person to swim for safety, or when depths are shallow but velocity is so high a person would be unable to stand.

Table 3-1: Flood hazard regimes for children and adults based on Cox et al. (2010) empirically-based criteria.

<table>
<tr><th>Depth * Velocity (m^2s^{-1})</th><th>Children</th><th>Adults</th></tr>
<tr><td>0</td><td>Safe</td><td>Safe</td></tr>
<tr><td>0 – 0.4</td><td>Low hazard</td><td rowspan="2">Low hazard</td></tr>
<tr><td>0.4 – 0.6</td><td>Significant hazard; dangerous to most</td></tr>
<tr><td>0.6 – 0.8</td><td rowspan="3">Extreme hazard; dangerous to all</td><td>Moderate hazard</td></tr>
<tr><td>0.8 – 1.2</td><td>Significant hazard; dangerous to most</td></tr>
<tr><td>>1.2</td><td>Extreme hazard; dangerous to all</td></tr>
</table>

The US guidance (Federal Emergency Management Agency 2020) presents different curves that have magnitudes like those proposed by Cox et al. (2010), but no reference is provided for those figures in that document. The text of the US guidance does, however, mention USBR ACER Technical Memorandum No. 11. (1988) which itself presents theoretical flood vulnerability curves, although the basis for those curves is also not clearly described in that report. Our interpretation is that the US Federal flood management agencies have not adopted a specific method for recommendation.

3.1.2 Mechanics-based flood vulnerability curves for humans

Recent scientific literature, including Xia et al. (2014a), Kvocka et al. (2016), Chen et al. (2018) and Musolino et al. (2020) have proposed the use of so-called mechanics-based methods in estimating flood hazard posed to humans exposed to floodwaters. These methods incorporate basic principles of fluid mechanics to estimate force-balance on a body submerged in water. These equations include coefficients that can be used to calibrate for shape, size, and mass of a human body.

The MB approaches began with Xia et al. (2014a), who presented two MB equations for sliding and toppling instability and tested them against the experimental data of Abt et al. (1989), and Karvonen et al. (2001). Although both methods are valid, the toppling stability equation appears to be the most widely adopted:

$$U_c = \alpha \left(\frac{h_f}{h_p}\right)^{\beta} \sqrt{\frac{m_p}{h_f^2 \rho_f}(cos\theta + \gamma sin\theta) - \left(\frac{a_1}{h_p^2} + \frac{b_1}{h_f h_p}\right)(a_2 m_p + b_2)} \quad (3)$$

Where:

U_c = incipient (critical) velocity causing toppling (m/s)

h_f = water depth (m)

h_p = height of a person (m)

m_p = weight of a person (kg)

ρ_f = density of water (kg/m^3)

α = empirical coefficient

β = empirical coefficient

a_1, b_1, a_2, b_2 = coefficients that vary with characteristics of the human body

θ = angle of the sloping ground

γ = correction constant

When the tilting angle is assumed to be at or near 90° (person standing straight up), the angle term is excluded, and the equation reduces to:

$$U_c = \alpha \left(\frac{h_f}{h_p}\right)^{\beta} \sqrt{\frac{m_p}{h_f^2 \rho_f} - \left(\frac{a_1}{h_p^2} + \frac{b_1}{h_f h_p}\right)(a_2 m_p + b_2)} \quad (4)$$

With the flood hazard risk being evaluated as the minimum of 1 or the ratio of local velocity to U_c:

$$FHR = MIN\left(1, \frac{U}{U_c}\right)$$

These equations have been applied in a variety of studies including Musolino et al. (2020) who compared the MB methods against the empirically based methods and asserted that the MB methods were more conservative and, thus, a potentially better representation of threats to safety. Despite this conclusion, we did not find government guidance documents from the UK, Australia, or US recommending adoption of MB approaches.

3.1.3 Vehicle stability curves

Flood vulnerability of vehicles follows the same general concepts as for humans whereby some combination of flow depth and velocity will either destabilize or immobilize a vehicle attempting to traverse floodwaters. Like humans, the methods used to estimate vehicle stability in floodwaters have included both experimental as well as theoretical approaches. Guidance from the UK relies on the methods of Keller and Mitsch (1993), while guidance in the US cites methods outlined in USBR ACER Technical Memorandum No. 11. (1988).

Shand et al. (2011) examined published experimental data from many sources and proposed interim criteria for vehicle stability using the product of depth and velocity whereby 0.3, 0.45, and 0.6 are the proposed limits for small passenger, large passenger, and large 4WD vehicles, respectively (Table 3-2). Although considered interim at the time of publication, the criteria of Shand et al. (2011) were adopted by the Australian Disaster Resilience Institute (Australian Disaster Resilience Guideline 7-3 2014).

Table 3-2: Vehicle stability criteria proposed by Shand et al. (2011).

Vehicle class	Length (m)	Kerb weight (kg)	Ground clearance (m)	Limiting still water depth (m)[1]	Limiting high velocity flow depth (m)[2]	Limiting velocity (m/s)[3]	Equation of stability
Small passenger	< 4.3	< 1250	< 0.12	0.3	0.1	3.0	DV ≤ 0.3
Large passenger	> 4.3	> 1250	> 0.12	0.4	0.15	3.0	DV ≤ 0.45
Large 4WD	> 4.5	> 2000	> 0.22	0.5	0.2	3.0	DV ≤ 0.6

[1] At velocity 1 m/s

[2] At velocity 3 m/s

[3] At low depth

As with flood vulnerability curves for humans, the science and engineering community have further explored vehicle stability in floodwaters using new experiments and MB methods. The experimental methods have included full-scale experiments on select vehicles (Smith et al. 2019), as well as experiments on smaller scale-model vehicles to calibrate MB parameters (Xia et al. 2014b). Recent reviews have indicated that the methods of Shand et al. (2011) underestimate stability for most vehicles relative to experimental data and that the limiting high velocities and depths may be unrealistically low (Martinez-Gomariz et al. 2018; Bocanegra et al. 2020). However, our comparison (Figure 3-2) of a recently published MBM vehicle stability calculation by Bocanegra and Frances (2021), which used an MB method published by Arrighi et al. (2015), indicates that, except for the limiting velocities, that MB method produced more conservative thresholds than those published by Shand et al. (2011). There is thus some disagreement between methods recommended by governments, empirical data, and limits estimated with MBM approaches.

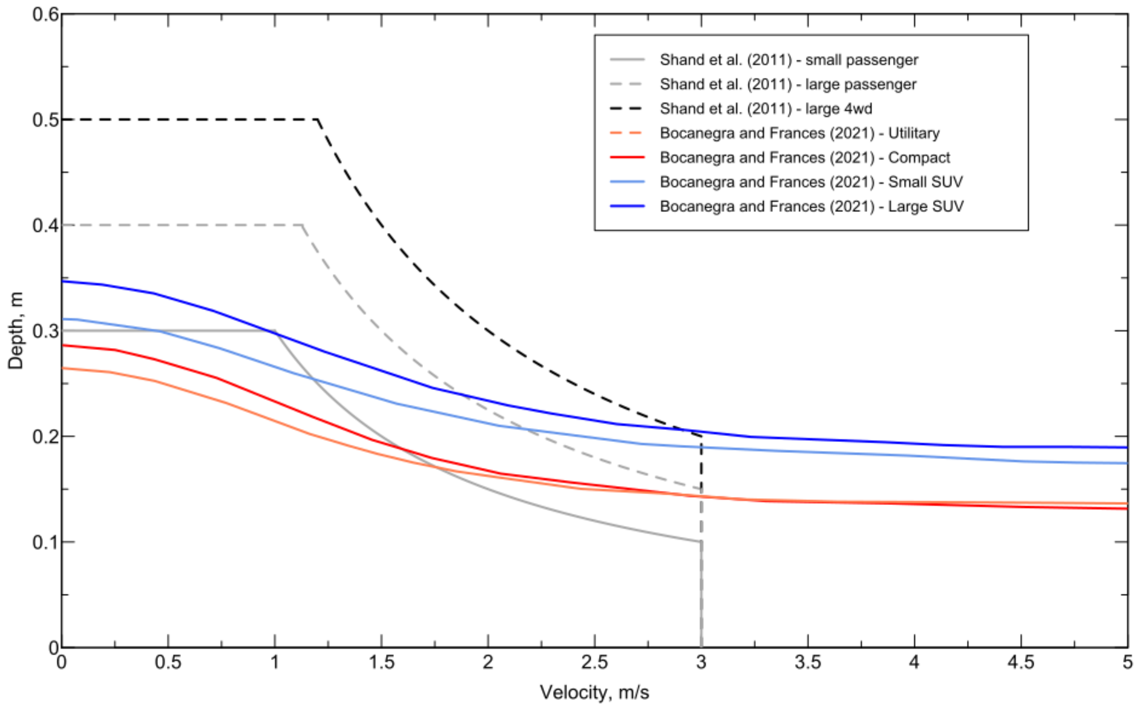

Figure 3-2: Stability curves for vehicles in floodwater. Lines represent thresholds above which vehicles of the types shown are estimated to be unstable.

3.2 Flood vulnerability methods comparison

We compared MB methods with the most current and comprehensive empirically based guidance of Cox et al. (2010). The MB method of Xia et al. (2014) was used to calculate U_c over a range of depths using a range of combinations of body heights and weights (4). For adults and children, female Asians and male Pacific ethnic groups represented the range of average body sizes for residents of Aotearoa (Table 3-3).

Table 3-3: Statistics of average height and weight of various ethnic groups of New Zealand (based on 2018 census data available from New Zealand Ministry of Health).

Ethnic Group	Female Adults		Male Adults		Female Children		Male Children	
	Height (cm)	Weight (kg)	Height (cm)	Weight (kg)	Height (cm)	Weight (kg)	Height (cm)	Weight (kg)
Māori	164	82	177	96	132	41	135	40
Pacific	**166**	**93**	**177**	**107**	**133**	**47**	**139**	**47**
Asian	**158**	**62**	**172**	**76**	**127**	**33**	**130**	**33**
European/Other	164	75	177	89	132	36	134	35

A variety of calibration values were available in the literature for toppling threat (Table 3-4), and there was no one set of values that we found were recommended. As a consequence, we extracted all of these values from the literature, and used median values for α and β, and majority values for a_1, b_1, a_2, b_2 (Table 2-1).

Table 3-4: Coefficients reported for mechanics-based flood hazard equations reported in literature. Values are shown for toppling threat only and are based on the equations outlined by Xia et al. (2014). Median values for alpha and beta, and majority values for a1, a2, b1, and b2 were used for the analysis comparing empirical functions and mechanics-based methods.

Source	Variable/coefficient					
	alpha	beta	a_1	a_2	b_1	b_2
Xia et al. (2014)[1]	3.47	0.19	0.737	0.001	0.263	-0.005
Xia et al. (2014)[2]	7.87	0.46	0.737	0.001	0.263	-0.005
Kvocka et al. (2016)[3]	8.86	0.47	0.633	0.001	0.367	-0.005
Kvocka et al. (2016)[2]	4.83	0.16	0.633	0.001	0.367	-0.005
Chen et al. (2018)[3]	3.67	0.27	0.735	0.001	0.265	-0.005
Chen et al. (2018)[2]	2.47	0.20	0.735	0.001	0.265	-0.005
Chen et al. (2018)[4]	3.06	0.30	0.735	0.001	0.265	-0.005
Musolino et al. (2020)	1.71	0.20	0.735	0.001	0.265	-0.005

[1] calibrated with plastic human-shaped figurines.
[2] calibrated for human subjects based on data in Karvonen et al. (2000).
[3] calibrated for human subjects based on data in Abt et al. (1989).
[4] 'unified', average values.

Comparison of the MB and empirically based methods showed that the methods had strong overlap, with the minimal criteria for both adults and children from the MB method plotting very near the minimum stability criteria in the Cox et al. (2010) stability fields (Figure 3-3). The MB method tended to show greater stability than Cox et al. (2010) regimes for children at the lower depth velocity combinations, and less stability in the higher velocity regions. For adults, the MB method tended to have near perfect overlap with Cox et al. (2010) for deep and moderately fast water but tended to show less stability in the higher velocity regions (Figure 3-3).

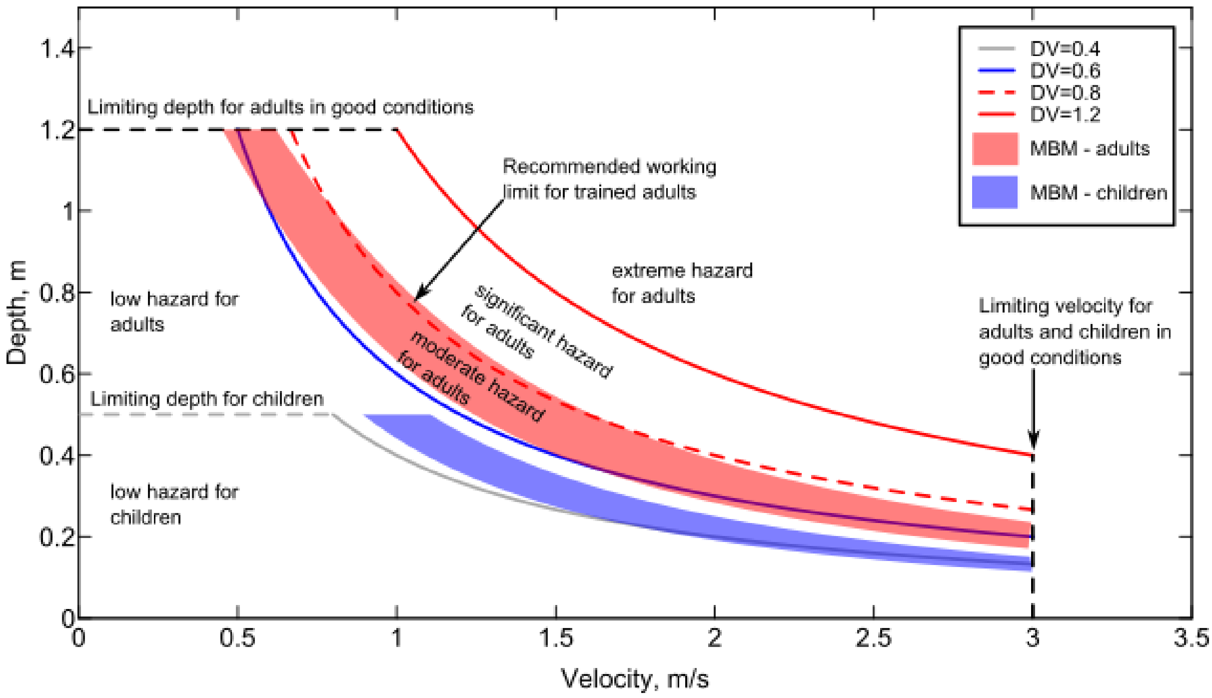

Figure 3-3: Overlay of critical velocity regions calculated using the mechanics-based method (MBM) of Xia et al. (2014) with the empirically based flood hazard regions of Cox et al. (2010). The MBM regions were calculated using ranges of average weight and height data for male and female adults and children from different ethnic groups in New Zealand.

Although we observed differences between the MB and Cox et al. (2010) methods, the uncertainties in the constants and calibration values of the MB method are high enough that we consider these differences to be within the uncertainties of the methods and suggest that the Cox et al. (2010) methods are adequate for estimating threat in the Te Karaka case study.

3.3 Case Study -Te Karaka

The model of Lane (2023), which was generated to simulate the floodwater conditions on the Waipaoa River imposed by Cyclone Gabrielle, was used to output hazard grids (flow depth and velocity) for the Te Karaka area. The Lane (2023) model covered a large region, and a local grid was extracted using the boundary obtained from the 'suburbs and localities' feature dataset available from the NZ LINZ Data Service (https://data.linz.govt.nz/layer/113764-nz-suburbs-and-localities/ accessed February 24, 2024). The hazard grid, roads network, and building representations from LINZ 2024) were ingested into the RiskScape software (Paulik et al. 2022), and the flood vulnerability rules of Cox et al. (2010) and Shand et al. (2011) for humans and vehicles, respectively were used to generate spatial representations of hazard levels at the location of all roads and buildings. Hazard levels were calculated for four selected times during the flood hydrograph (blue dots in Figure 3-5) and are available as interactive online maps (see Appendix A for details).

An example of the time representation of hazard posed to human evacuees escaping on foot via the road network is shown in Figure 3-4. Note that the flood hazard observed at bridges over the Waipaoa River in Figure 3-4B increases to 'significant' (depicted in red) while most of the roads are still in the 'low' safety threat category (depicted as yellow). This depiction is a consequence of the elevation of the road networks being tied to the elevation of the DEM. For much of the road network the elevation of the ground in the DEM is likely adequate, however, the elevation of the DEM at the bridge is the riverbed itself. This causes the bridge to falsely appear to be overtopping when nearby roads are either not inundated or have a low threat to safety categorization. To fix this error across the entire road network would require obtaining and attributing the elevations of bridge features (girder, deck, kerb etc.). This exercise was out of the scope of the Te Karaka case study but is recommended if GDC would like to obtain the best estimates of flood hazard posed to bridges in the area.

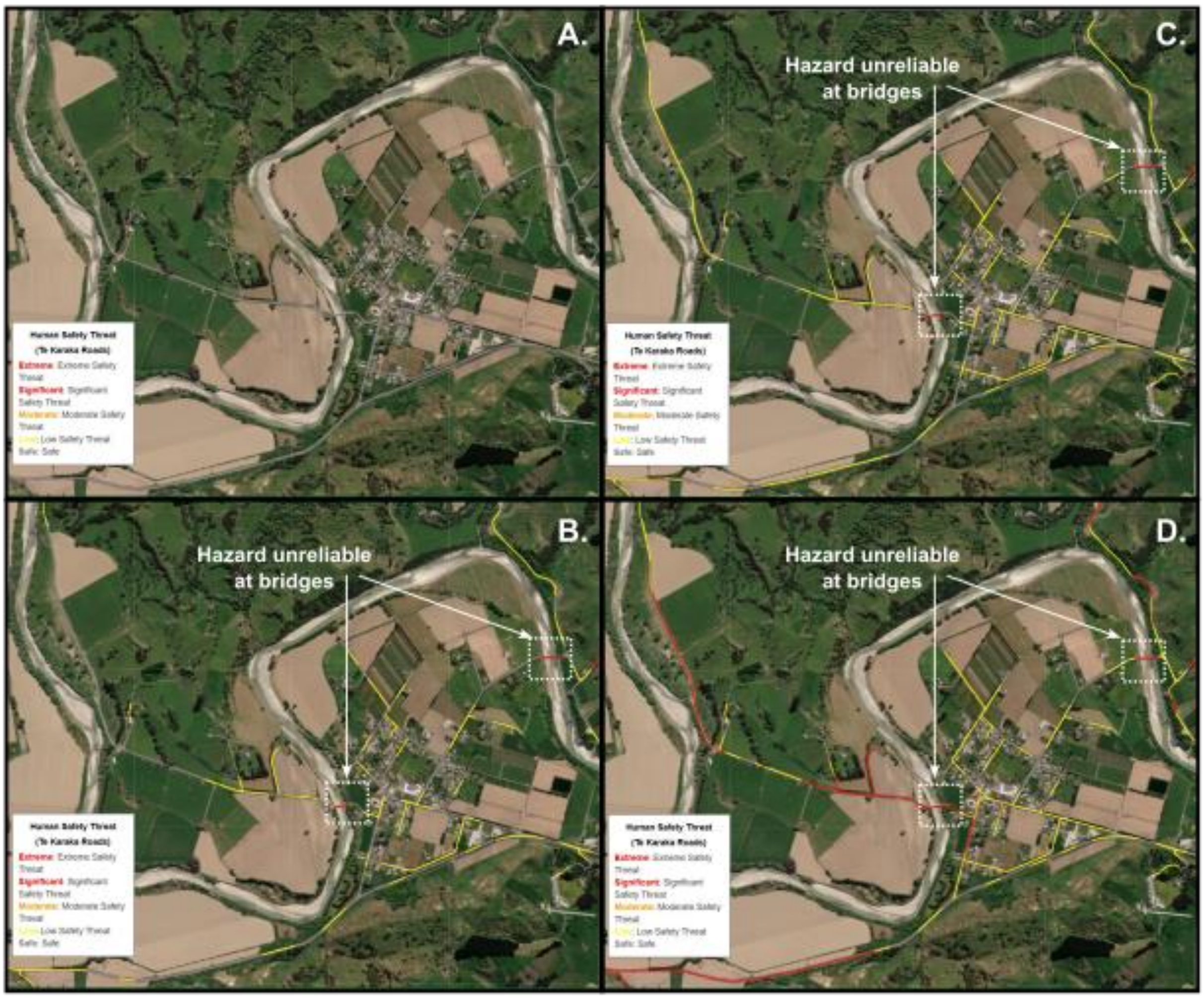

Figure 3-4: Maps showing RiskScape estimates of safety threat of flowing waters to adults attempting to escape on foot via road in the vicinity of Te Karaka. Maps A-D sequentially correspond to the six 'RiskScape event samples' shown on time series figures above and below for the modelled stages of the Waipaoa River at the Kanakanaia stream gauge.

We also generated time-series to summarize the flood hazard conditions for the Te Karaka area relative to each hourly output time-step saved in the model of Lane (2023). These time steps were tied to the stages of the Waipaoa River observed at the Kanakanaia stream gauge in the town of Te Karaka. Figure 3-5 shows the spatially averaged flood hazard category for adults in the town of Te Karaka, with the error bars depicting a single standard deviation value. Although the single standard deviation value is taken on integers (hazard categories), it reasonably depicts the range of hazards for each time step.

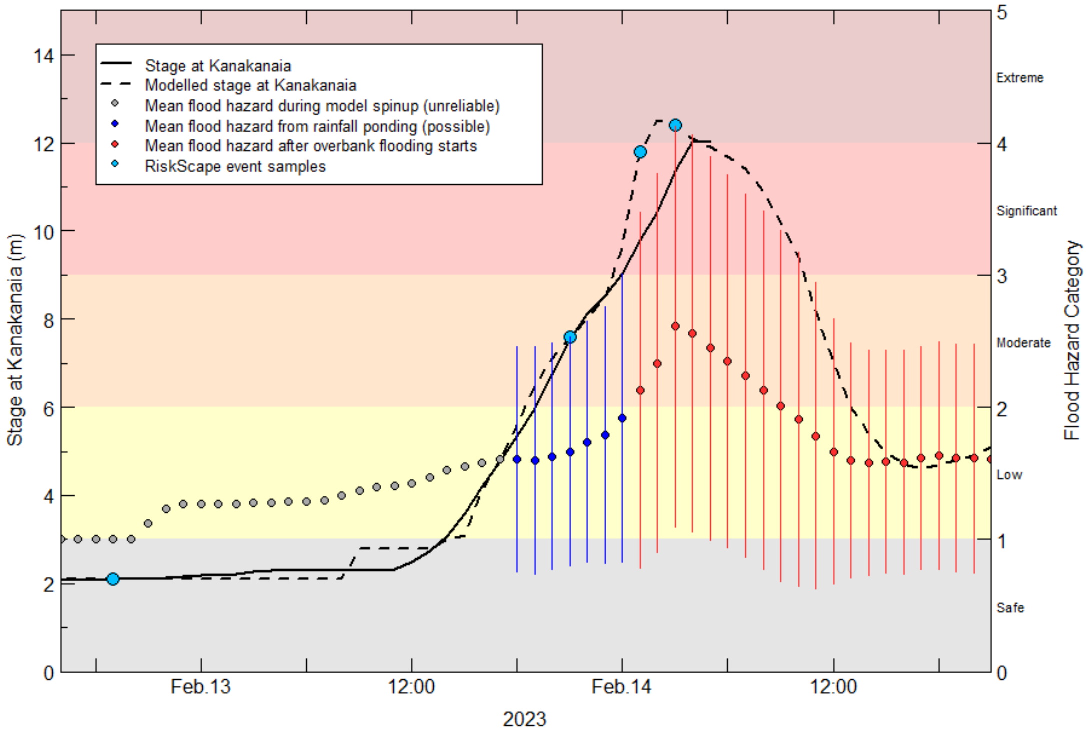

Figure 3-5: Time series showing road evacuation flood hazard (on foot) for adults relative to observed stage as the Cyclone Gabrielle flood on the Waipaoa River. The errors bars represent single standard deviations from the mean.

Note that the modelled mean flood hazard shown in Figure 3-5 increases to the 'low' category when the stage (modelled and observed) has not increased at all on late February 12 and early February 13 (Figure 3-5). This increase is an artefact of the ponding that occurs during model startup (**Error! R eference source not found.**), and the actual hazard is unknown but assumed to be lower. As depicted in Figure 3-5, we considered the hazard estimates for stages below about 5 m to be unreliable based on examination of flow depth maps. Above 5 m, note that the flood hazard decreases slightly, then begins to gradually increase. We interpret the slight decrease in hazard as the onset of true pluvial (rainfall-induced) runoff (as opposed to ponding) and suggest values after that mark are more reliable.

The recommended stage of the Waipaoa River at Kanakanaia for beginning evacuation of Te Karaka is 7.5 m (GDC, 2024). Our analysis shows that mean flood hazard for the Te Karaka area at a stage of 7.6 m (closet modelled stage) is still in the low hazard regime, but a single standard deviation is well into the moderate hazard category (Figure 3-5). Our analysis also shows that mean flood hazard to adults reaches moderate (extreme for children or vulnerable adults) when the stage at the Kanakanaia gauge jumps from 9.6 to 11.8 m, which occurred over a single hour in the simulated hydrograph. This jump occurred 3 hours after the stage of 7.6 m, indicating further evacuation on foot was unlikely to be possible on most roadways within four hours of the recommended evacuation stage.

We summarized the time evolution of hazard categories near buildings for the Te Karaka area over the flood hydrograph (Figure 3-6). These data can be interpreted as the hazard that would be experienced by residents attempting to escape from their homes or residences over the progression of the flood wave. As before, we interpret flood hazard estimates for stages less than about 5 m to be unreliable. As shown on Figure 3-6, the onset of rapid increases in flood hazard occurs after a stage of 11.8m, just before levee overtopping. After levees overtop, but flood stage remains near its peak (last blue dot on Figure 3-6, stage of 12.4 m), the flood hazard in Te Karaka is maximized, with at least 60 percent of all structures in the low hazard category, and as many as 37 percent of buildings in the moderate hazard category (high hazard for children and vulnerable adults; Figure 3-6).

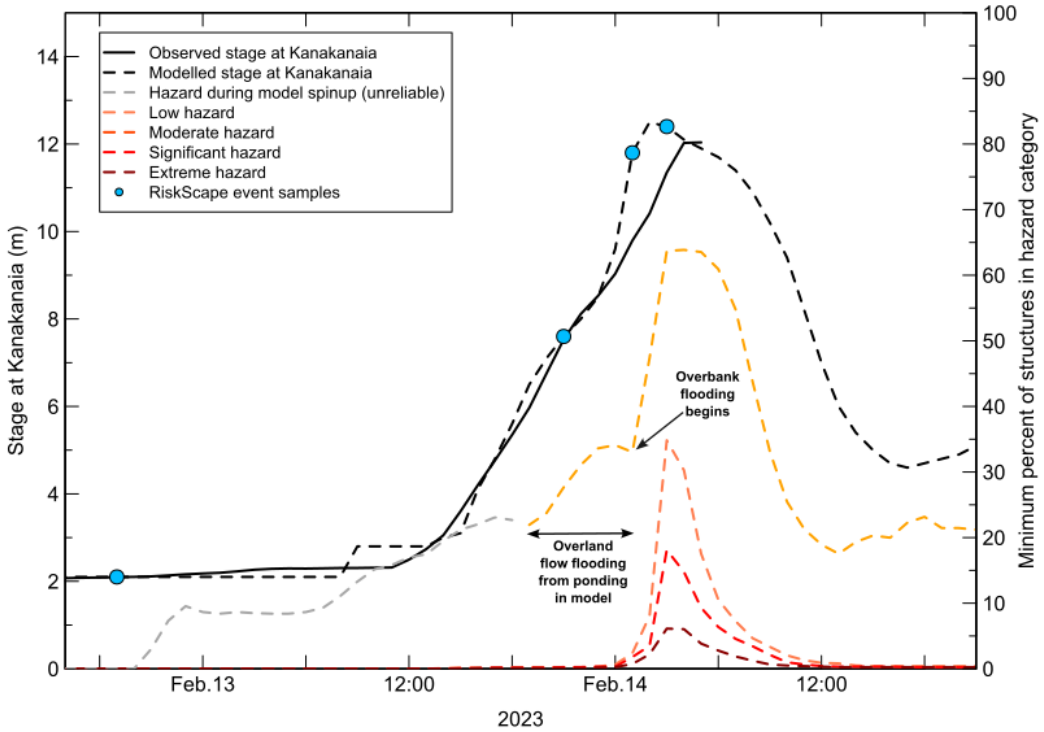

Figure 3-6: Time series showing flood hazard posed to adults at/near buildings with stage rise observed at the Kanakanaia gauge over the Cyclone Gabrielle induced flood on the Waipaoa River.

Finally, we summarized the time evolution of flood hazard posed to vehicles estimated by RiskScape (Figure 3-7). As before we considered flood hazard for stages less than 5 m to be unreliable. Vehicle stability on roads in the Te Karaka area begins to decrease rapidly for stages beyond about 8.0 m. At the maximum hazard of 12.4 m (0.1 m less than maximum stage), 45 percent of roads in the area register as unstable for small passenger vehicles, and 32 percent of roads are unstable for the largest vehicles (fire engines). The time between the stage of 8.0 m and 12.5 m (levee overtopping), was 4 hours, and the rate of rise in vehicle instability was steep over that period, indicating rapidly changing road conditions during the time when evacuations were likely occurring (Figure 3-7).

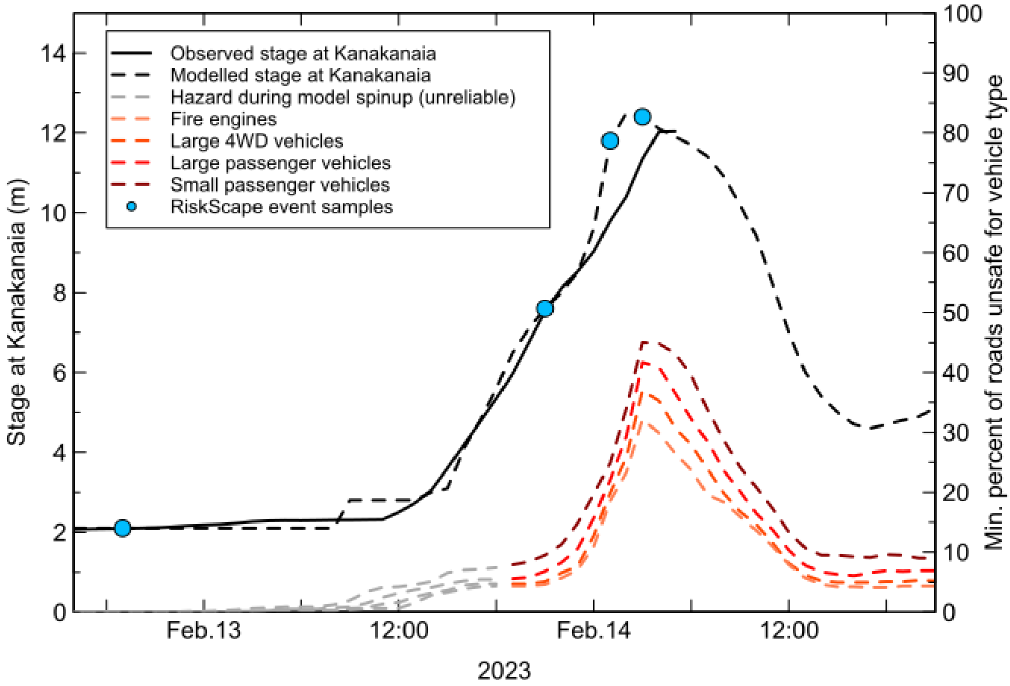

Figure 3-7: Time series showing percent of roads in the Te Karaka area estimated to be unstable (not passable) to different vehicle types. The estimates were created using the RiskScape software and the vehicle stability curves of Shand et al. (2011).

3.4 Limitations and other considerations

A key consideration in analysis of flood hazard for residents attempting to evacuate is that the acceptable level of hazard is a value choice. That is, emergency managers must consider the relative vulnerabilities of the communities they are planning to protect to decide on acceptable levels of flood hazard exposure. Our analysis showed that the criteria of Cox et al. (2010) were generally acceptable for the body types of peoples of Aotearoa, but using the demographic information also showed that there was a range of vulnerability depending on body size and mass. That range demonstrates that, for a given set of conditions, the most vulnerable people in a community, small children, may be unable to escape conditions that larger children and smaller adults could escape. Likewise, none of the methods we examined made attempts to estimate hazard for elderly or disabled community members, which means emergency managers must use careful judgement when using flood hazard exposure levels generated from this study.

The mechanics based (MB) methods we examined for people and vehicles, while allowing for more granularity in estimates of stability, should be used with caution. In the case of human stability, our purpose in comparing the MB methods with the empirical studies of Cox et al. (2010) was simply to understand if major differences were apparent when accounting for general New Zealand body types (Figure 3-3). These methods cannot account for a person's physical and mental capacity for navigating floodwaters. Two people of the same general body type may have very different levels of confidence for entering and moving through floodwaters, especially if physical disabilities are considered. Likewise, our comparison of MB and empirical methods for vehicles indicated strong overlap in estimates (Figure 3-2), and any attempt to account for specific vehicle types may give an operator a false sense of precision for localized conditions where road surface roughness, slope, debris and other factors may not be known with certainty. In short, the MB methods, while being explored in the scientific and academic community, are helpful for cross-checking against empirically based methods but require a much larger burden of judgement regarding parameters and local conditions potentially making them less useful for everyday applications.

Our analysis for Te Karaka also did not consider the effects of floating or jamming debris transported in the Waipaoa River, a process that was widely documented in the region (Interpine Innovation, 2023). However, as is demonstrated by the Ramsbottom et al. (2006) hazard rating equation (2), even if a smaller quantity of debris is present (debris factor = 0.5), then the hazard increases substantially. For example, if the depth velocity combination results in the left side of equation (2) to be 0.5, a rating of 'low hazard', is pushed to 'dangerous for some'. Further, any value near the low hazard boundary of 0.75, will be pushed near the boundary of 'high hazard' (dangerous for most) if debris is present (DF ≥ 0.5). Thus, it can be assumed that if debris is present, conditions otherwise deemed to be in low to moderate hazard rating for adults are probably unacceptable for children and vulnerable adults.

Although estimation of depths and velocities required to transport large in-channel wood vary, a rule of thumb for the depth needed to mobilize (float) wood is approximated as half the trunk diameter (Kramer and Wohl 2017). In the Waipaoa Basin, the wood transported during the Cyclone Gabrielle flooding was generally observed to be from slash piles generated from agricultural forestry, which is widespread in the region. These slash piles are thus likely to be composed of 26 to 30-year old *Pinus radiata* (Monterey Pine), which are known to have mean diameters of about 0.5 m at harvest (New Zealand Farm Forestry Association 2024). Thus, floodwaters with depths of at least 0.25 m would potentially be deep enough to transport wood from these slash piles. This is in agreement with the Ramsbottom et al. (2006) criteria whereby a depth of 0.25 m is considered minimum for the debris factor to exceed 0.

Our analysis of flood hazard on the Waipaoa River during Cyclone Gabrielle was tied to stages at the Kanakanaia stream gauge because that stream gauge is used by regional emergency managers for decision-making when flood waters are rising or expected to rise in the Te Karaka area (GDC 2023). While our analysis showed general agreement with some of the action stages outlined in the GDC flood manual (i.e., flood hazard increased substantially after a stage of 7.5 m), the bed of the Waipaoa River in the Te Karaka area has been aggrading for decades (Gomez et al. 1998), and the accuracy of the consequences associated with each stage listed in the flood manual are unknown. A key consideration would be for emergency managers to use the gridded depth and velocity data from Lane (2023), as well as the HTML interactive maps from RiskScape generated for this study to cross-check and update the consequences associated with stages at the Kanakanaia gauge.

As stated before, our case study analysis contained some results that we considered to be unreliable due to limitations of the datasets used. The model of Lane (2023), while useful for quantifying inundation hazard at the regional scale, may not be the most appropriate model for estimating depths and velocities at the more local scale, like the Te Karaka area. A hydrodynamic model built specifically for the Waipaoa basin, with a spatial resolution that can more accurately capture the geometries of stopbanks in and around Te Karaka, as well as local drainage infrastructure, would likely provide a more realistic depiction of the time-evolution of depths and velocities in the area. When combined with robust estimates of elevation of bridges and other structural elements (i.e., floor levels of homes etc.), the RiskScape software could be used to provide a more detailed and accurate depiction of flood hazard over the Te Karaka area under the conditions of Cyclone Gabrielle than was presented here.

This study demonstrated the rise in flood hazard conditions for the conditions of Cyclone Gabrielle on the Waipaoa River at Te Karaka. The HTML maps generated from this study can be used to examine locations where roads become impassable for a given stage observed at the Kanakanaia gauge. Emergency managers must consider that these conditions are only valid within the region around Te Karaka, and that the flood hazard on roads outside of the Te Karaka area are likely to be different than those in our case study area. In short, emergency managers should be cautious in making decisions about road or escape conditions beyond Te Karaka given the data generated for this study.

4 Summary and recommendations

The primary flood hazard estimation methods recommended in government guidance documents for Australia, the United Kingdom (UK), and the United States (US) relied mainly on empirically based approaches derived from experimental data. Over the past decade, the scientific literature has been trending toward use of mechanics-based (MB) methods, which use a force-balance approach to quantifying crucial depths and velocities and have the advantage of being able to incorporate information for specific body types (demographics) and specific vehicle types.

While the guidance from Australia, UK, and the US has not been updated to incorporate MB methods, we compared the empirical and MB methods using information for body types of the peoples of Aotearoa and found strong agreement between the two methods. This analysis indicated that the empirical methods were adequate to represent vulnerability of residents in the Te Karaka area to floodwaters. Likewise, the MB methods for vehicle hazard had strong overlap with the empirical methods, which themselves are known to overestimate hazard relative to experimental data. The empirical methods have the potential to incorporate effects of floating debris, however, under the conditions where floating debris may be present, its' presence would increase hazard beyond the low or moderate levels that would be considered reasonable planning targets for evacuation. That is, if managers assume that floating debris will be present for a given evacuation condition, then the hazard posed to evacuees wading or driving through floodwaters should be considered high or extreme.

A case study of the Te Karaka suburb during the flood conditions caused by Cyclone Gabrielle in February 2023 indicated that the flood hazard on roads and near buildings increased rapidly over the rising limb of the hydrograph and maximized just after stopbank overtopping. Because of the spatial resolution of the flood model used, depth and velocity estimates for stages at the Kanakanaia stream gauge below about 5 m were considered unreliable, and the accuracy of stopbank representation was potentially poor. Likewise, road networks available from LINZ, did not contain bridge elevations, and estimates of flood hazard at bridges were also considered unreliable. Nevertheless, the case study provides a clear demonstration of the potential for combining geospatial data to generate spatially explicit estimates of flood hazard that can provide emergency managers with valuable information tools for planning evacuation and rescue operations.

Based on our literature review and case study, the following primary recommendations for improving estimates of flood hazard posed to residents in the Gisborne/Tairāwhiti region include, but are not necessarily limited to:

1. The current flood hazard guidance adopted by the Australian Disaster Resilience Institute for humans (Cox et al. 2010) and vehicles (Shand et al. 2011) have strong overlap with more recently developed mechanics-based methods and appear to be adequate for use in New Zealand flood planning. Mechanics-based methods, while providing more flexibility to choose for human and vehicle types, suggest a level of precision that may not be realistic for everyday use, and should be used with caution.

2. The use of depth and velocity grids from hydrodynamic models to estimate flood hazard requires strict scrutiny of the spatial resolution and modelling artefacts. Although the regional model of Lane (2023) was adequate for a general demonstration of a flood hazard workflow for Te Karaka, scrutiny and potentially additional post-processing of the Lane (2023) model results could improve estimates of flood hazard at Te Karaka and elsewhere in

the region. An improved hydrodynamic model which sufficiently resolves stopbanks, for example, could be used with the RiskScape software to cross-check the model results of Lane (2023) and potentially improve hazard and subsequent threat estimates at key locations of interest. Strict model scrutiny and cross-checking, particularly in populated areas, is advised anywhere that these methods are applied in NZ.

3. Flood hazard estimates for bridges and buildings could be improved substantially by attributing the data available from LINZ with elevation and other building construction data. When implemented in the RiskScape workflow, elevation information can be used to generate more realistic estimates of hazard to bridges, which are particularly important for escape when flood waters are rising. Likewise, elevation information for structures such as floor levels and building foundation and wall materials could help improve estimates of where it may be safe to shelter in place under certain circumstances.

4. Although not considered in the case study presented here, estimates of the demographic distribution of residents in buildings would be helpful for decision making regarding acceptable levels of hazard. For example, if a town has a large population of elderly adults, or disabled people, this would be a strong consideration when making the value judgement of acceptable levels of flood hazard during evacuation planning. Although this data would be extremely useful, it would need to be considered with great care and caution to protection of personal privacy.

5. The GDC flood manual used stages observed at stream gauges for emergency flood planning and decision making. It is recommended that these stages are revisited on a regular basis and cross-checked with modelling and observations to assure that they are relevant to current conditions. This is particularly important in locations such as Te Karaka where the bed of the Waipaoa River near the local stream gauge at the Kanakanaia bridge has been aggrading for decades and may be shifting the stage rating curve. As the GDC flood warning manual has had a recent review (Wilkinson 2024), revisiting stage-based actions and decisions outlined in that manual would provide additional confidence to emergency managers in the region. Such considerations would apply anywhere in NZ that stages are used for emergency flood decision making.

6. Overall, the methods employed and the findings discussed in this study have direct application to other catchments in Gisborne/Tairāwhiti and across other regions in NZ. The gaps and limitations highlighted in this study as well as other contextual information at the local scale (e.g., catchment-specific characteristics, population dynamics/distributions), would need to be taken into consideration if applying similar modelling-based approaches to informing the development/updating of evacuation survivability guidelines/procedures.

5 Acknowledgements

The authors would like to thank Murry Cave, Bridget Bosworth, Nick Gordon, and Divesh Mistry of GDC for their advice and knowledge of flood processes on the Waipaoa River during Cyclone Gabrielle and ongoing bed and channel adjustments near Te Karaka. Richard Measures provided technical review of this report and his comments greatly improved the clarity and technical interpretations of the manuscript.

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7 Glossary of abbreviations and terms

GDC	Gisborne District Council
MBIE	Ministry of Business, Innovation and Employment
NIWA	National Institute of Water and Atmospheric Research
TEMO	Tairāwhiti Emergency Management Office
EWRAF	Weather Recovery Advice Fund

Appendix A Selected snapshots of threat to safety and vehicle stability

Interactive maps enabling the visualization of threat to safety and vehicle stability results are accessible via the 'html' links listed below (copy and paste into your web-browser if the links do not work when you click on them):

- Human Safety Threat - Te Karaka Buildings.html
- Human Safety Threat - Te Karaka Roads.html
- Vehicle Stability Threat - Te Karaka Roads.html