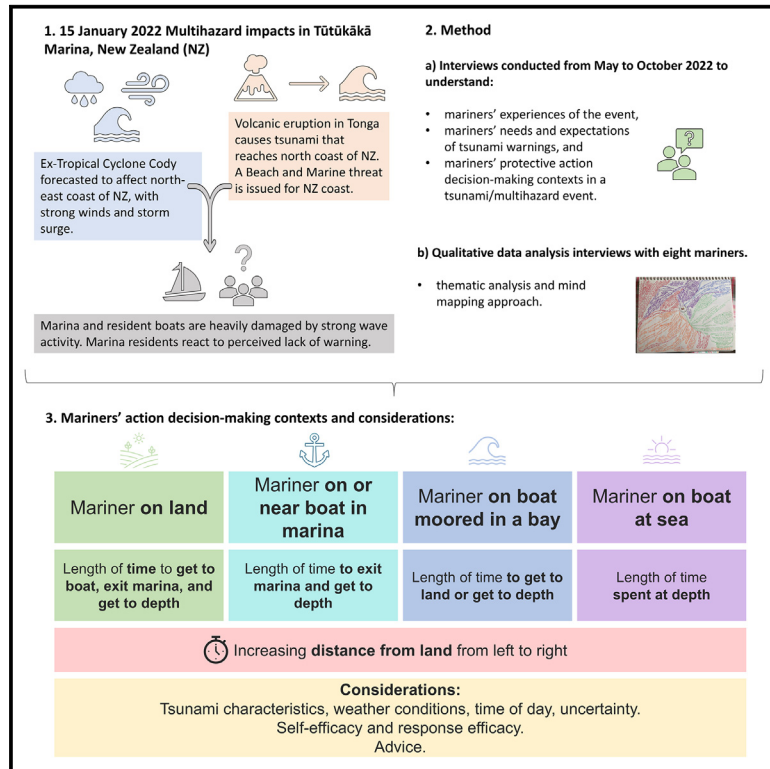


Understanding mariners' tsunami information needs and decision-making contexts: A post-event case study of the 2022 Tonga eruption and tsunami

Graphical abstract



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In brief

Earth sciences; Geology; Geography; Human Geography; Research methodology social sciences

Highlights

- Mariners' decision-making process is complex and clear action advice is desirable
- Warning agencies should coordinate to communicate multihazard risk
- Integrate broad expertise into the warning process for improved consistency
- Co-develop localized response plans for low-magnitude threatening events



Article

Understanding mariners' tsunami information needs and decision-making contexts: A post-event case study of the 2022 Tonga eruption and tsunami

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SUMMARY

The 15 January 2022, Hunga Tonga Hunga Ha'apai volcanic eruption generated a tsunami that spread across the Pacific Ocean and prompted a tsunami advisory in Aotearoa New Zealand (NZ). Concurrently, a severe weather warning was issued for ex-Tropical Cyclone Cody, passing east of NZ and producing heightened swells along the North Island coast. Numerous boats were significantly damaged or sunk in Tūtūkākā Marina, Northland, NZ. Mariners raised concerns over the perceived lack of tsunami warnings. We interviewed mariners in Tūtūkākā to understand their experiences on the night of 15 January 2022 and their needs and expectations of tsunami warnings. The complexity of the multi-hazard event made it difficult to assess and convey the severity of the expected tsunami. We found that mariners require information about expected wave height and arrival time, weather, and sea conditions to inform their anticipatory mitigation actions. This event shows the importance of multi-hazard risk assessments to produce effective warnings and action advice.

INTRODUCTION

Aotearoa New Zealand (NZ), located in the Pacific Ocean, is exposed to meteorological, hydrological, and geological hazards. As such, NZ has warning and alerting systems for monitoring, detecting, and communicating the risks of these hazards. In February 2022, two different coastal hazards co-occurred and posed a risk to coastal communities in parts of the country: an ex-tropical cyclone and a tsunami triggered by a distant, and sudden volcanic eruption. This study provides a case study of the boating community in Tūtūkākā, Northland, who experienced the combined impacts of these two hazards, to understand their needs for both tsunami and multi-hazard warnings. We first provide a high-level overview of the tsunami and severe weather warning systems in NZ, with a particular focus on mariners as a key user-group of these warnings. We then introduce the research problem, followed by an introduction of the multi-hazard case study.

Tsunami warning dissemination is typically designed and implemented at the national scale to reach wide audiences. In New Zealand the National Emergency Management Agency (NEMA) is the official authority responsible for issuing tsunami advisories and warnings. GNS Science is NEMA's primary advisor for tsunami threat analysis, and GNS Science may activate the

Tsunami Expert Panel if further support is required. NEMA also receives tsunami notifications directly from the Pacific Tsunami Warning Center, as one of several considerations to initiate an advisory or warning. Further detail is described in the Tsunami Advisory and Warning Supporting Plan [SP 01/20]¹. However, depending on the proximity of the tsunami source (i.e., local, regional, or distal) it may not be possible for an official tsunami warning to be issued in time. Thus, natural warnings (such as long or strong ground shaking, sudden changes in the water level, or a loud or unusual noise from the sea) are relied upon for local tsunami events, when there is limited time before the tsunami arrival.¹ If an official warning is possible, NEMA will issue one of the warnings or advisories shown in Table 1.

Once NEMA has published a warning or advisory message (when and where possible), secondary agencies pass on the warning or advisory messages to the target audiences. These secondary agencies include the regional Civil Defense and Emergency Management (CDEM) agencies, Maritime New Zealand via the Rescue Coordination Center New Zealand (RCCNZ), harbor masters/post companies.² Upon receiving the warning or advisory, regional CDEM agencies send the message to harbor masters/port companies, who then issue local navigational warnings to vessels inshore, while the RCCNZ sends the message through a coastal navigational warning to offshore vessels.²



Table 1. Tsunami threat levels and additional information used in NZ for regional and distant-source seismically triggered tsunami based on feedback the authors directly received from NEMA representatives

Threat Level	Additional information
National Warning: Land and Marine Threat	Tsunami waves are expected to affect the land. A land and marine threat means that evacuations will be required.
National Advisory: Tsunami Activity (also referred to as a Beach and Marine Threat)	There is a threat to beach and marine areas. The tsunami is likely to cause strong and unusual currents and unpredictable surges at the shore. People should stay off beaches and out of the water.
National Advisory: No tsunami threat to New Zealand	There is no tsunami threat to our coasts.

With regards to ex-tropical cyclones, the New Zealand Meteorological Service Ltd. (herein referred to as the MetService) is responsible for issuing severe weather warnings, including for ex-tropical cyclones.³ The MetService can issue forecasts days in advance and provides tropical cyclone activity updates on their Tropical Cyclone Bulletin.³ In addition to providing forecasts and warnings for hazards that pose threats to New Zealand's land and coastal areas, the MetService provides forecasts and warnings for gales, storms, and cyclones for Metarea XIV and takes over primary warning responsibility for cyclones that pass below 25° South latitude.⁴ The MetService therefore maintains close links with meteorological agencies of various Pacific Island states.

Marinas, harbors, and ports are particularly exposed to coastal hazards (e.g., tsunami and ex-tropical cyclone) and have a history of being impacted by these threats, such as the Santa Cruz Harbor in California following the 2011 Tōhoku earthquake.⁵ Furthermore, tsunami (transliterating to “harbor waves”⁶) hazards that do not present a threat to land can still pose a significant risk to maritime infrastructure and users.⁵ Thus, a key user-group for warnings and advisories for these hazards is maritime users (e.g., boat owners and operators; users and operators of harbors, marinas, and ports; beachgoers; surfers; stand-up paddleboarders; kayakers) who have direct and regular interactions with the sea and weather. These users may have thresholds and requirements for warnings and advice that are different from the more general warning audience due to this high level of exposure. In this study, we focus on advice for boat owners and operators for business and leisure, and marina and harbor managers herein referred to generally as mariners.

The information provided in a warning message is critical for informing mariners' response or evacuation decisions.⁷ Extensive social research has been conducted overseas on hurricane and tropical cyclone warnings,^{8–10} though perhaps not specifically for mariners; while limited research has been conducted on the design, communication, and efficacy of tsunami warning messages,^{7,11} particularly for mariners. However, the theoretical models, such as the protective action decision model (PADM)¹² and results from broader research into designing, communicating, and evaluating warnings can still apply.^{13–19} For example, in addition to the warning messages and channels through which the warning is received, the PADM illustrates that an individual's threat perceptions and response behavior is also influenced by other cues, such as *environmental cues* (e.g., ground shaking, unusual sounds from the sea, a sudden change in sea level), so-

cial cues (e.g., seeing others respond, information or advice from friends/family), and the *individual's characteristics* (e.g., age, gender, primary language, physical abilities, mental models, socio-economic resources).¹²

General recommendations from the literature around designing and communicating effective warnings, as summarized by Sutton and Woods (2016)⁷ with additional literature, include:

- (1) Information about the *hazard*, including the physical characteristics of the threat and severity^{13,20};
- (2) Information about the *impacts* of the hazard on the individuals and infrastructure that are at risk, so that individuals understand the threat^{14,21};
- (3) Clear *advice* on the protective actions that individuals should consider taking to increase their safety, as well as *guidance* on how they can perform those actions^{21,22};
- (4) The *location* of the hazard(s) and impact(s), and the areas at risk so that individuals can determine if they are in the risk area and whether they need to take protective action, such as evacuate²³ and to prevent shadow evacuations [Shadow evacuations occur when people who are not at risk or are not in the official evacuation zone evacuate unnecessarily²³] which may put others at undue risk²⁴;
- (5) The *time*, such as estimated time of arrival and/or impact of the hazard(s), and when individuals should prepare and/or commence their response plans and protective actions^{22,25};
- (6) The *source* of the warning²⁶;
- (7) A *link* to further information, if technically possible.²⁷

Recent events and trends in the literature also suggest the importance of developing integrated multi-hazard early warning systems in which coordination and collaboration occurs across all agencies responsible for monitoring, detecting, and warning for hazards and threats.^{28–30} This facilitates consistency and the consideration of cascading, compounding, and parallel hazards and their impacts in the threat assessment and subsequent communication and warning messages.

Past tsunami events have shown a range of responses and behaviors among mariners during a tsunami and a need for increased education and awareness about tsunami hazards that do not present a land-threat but still pose a threat to the boating sector and communities.⁵ Discussions in online boating forums also suggest that some mariners may not

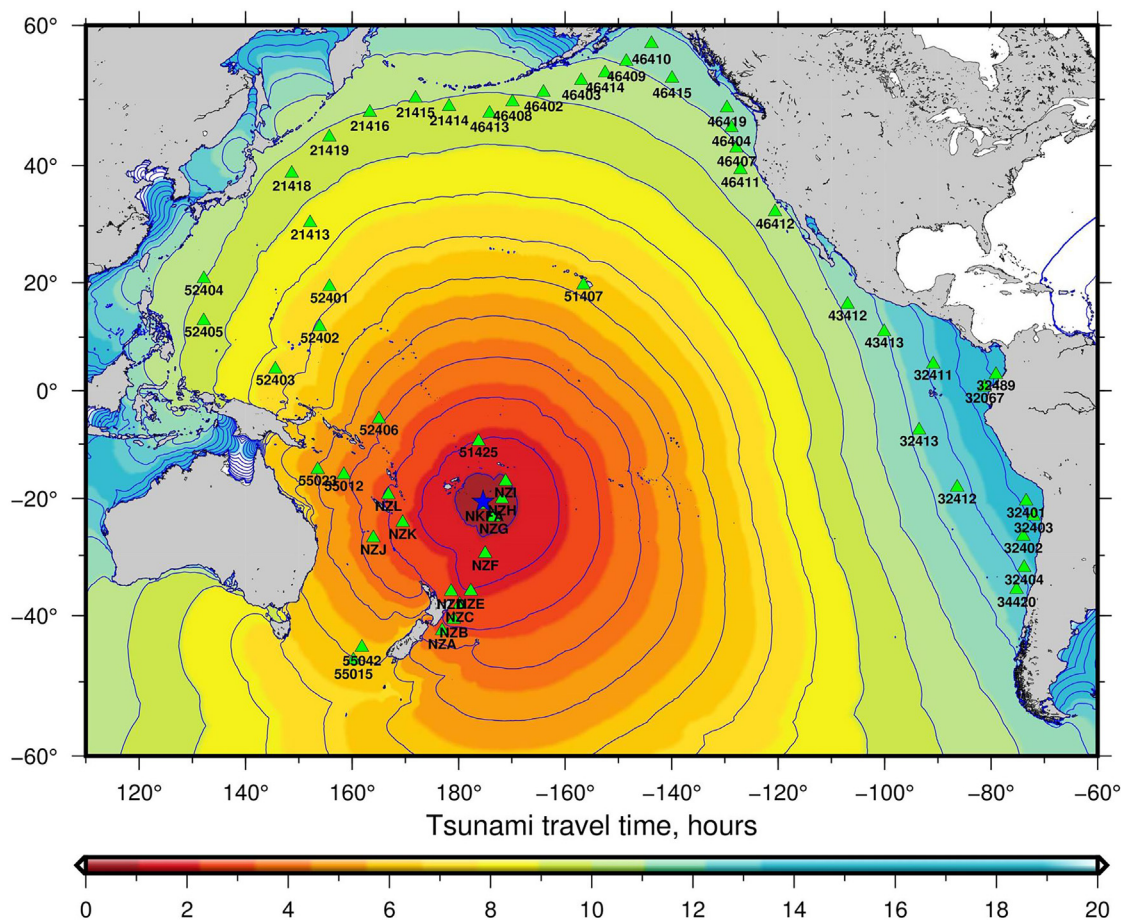


Figure 1. Theoretical tsunami (long wave) travel time in hours from Hunga Tonga-Hunga Ha'apai (blue start)

The green triangles represent locations of Deep-ocean Assessment and Reporting of Tsunamis (DART) stations. Image source: Gusman & Roger,^{91,92} re-used with permission.

be sure of what to do when faced with a tsunami threat in relation to their boat.³¹ These discussions indicate that, depending on the tsunami source (distal, regional, and local) and the amount of time until tsunami arrival, mariners may have a choice between evacuating their boat out to sea, or evacuating to higher ground/further inland with or without their boat. Thus, the decision-making process for mariners may differ from non-mariners in response to a tsunami and/or multi-hazard coastal threat.

This study investigates the information needs and decision-making contexts of mariners when faced with a tsunami and multi-hazard threat through a post-event case study analysis of the impacts of the 2022 Hunga Tonga-Hunga Ha'apai (HTHH) volcanic eruption-induced tsunami on the Tūtūkākā Marina in NZ. While the initial focus of the cases study and data collection was on understanding mariners' needs for tsunami warnings in particular, the multi-hazard complexity of the event which occurred at the same time as ex-Tropical Cyclone Cody, provides an additional dimension to this case worthy of consideration in the context of multi-hazard warning systems.

Case study

Approximately 2,000 km from Aotearoa New Zealand (NZ), the HTHH volcano erupted at about 17:15 NZDT (04:15 UTC) on 15 January 2022.³² The eruption generated tsunami waves across the Pacific Ocean³³ (Figure 1). In NZ, after receiving the tsunami assessment from GNS Science, the Tsunami Expert Panel, and the Pacific Tsunami Warning Center (PTWC) the National Emergency Management Agency (NEMA) released a National Advisory for Tsunami Activity from 20:14 Saturday 15 January to 19:06 Sunday 16 January NZDT, advising of "strong and unusual, currents and unpredictable surges at the shore", also referred to as a "beach and marine threat".³⁴ The message contained information provided in Table 2.

Around the time of the eruption and expected time of arrival for the tsunami activity, ex-Tropical Cyclone (ex-TC) Cody was expected to pass east of NZ, producing heightened swells along the east coast of the North Island (Figure 2). From the 14 to 15 January 2022, the MetService forecast large swells and waves to affect much of the eastern coastline of the North Island including Northland, which already saw increasing wave heights

Table 2. Press release for a National Advisory: Tsunami Activity from the National Emergency Management Agency issued at 20:14 NZDT on 15 January 2022³⁴

Message No: 1

Issued 20:14 15 January 2022

This message is current and replaces all/any previous messages for this event.

NATIONAL ADVISORY: TSUNAMI ACTIVITY – EXPECT STRONG AND UNUSUAL CURRENTS AND UNPREDICTABLE SURGES AT THE SHORE

We expect New Zealand coastal areas on the north and east coast of the North Island and the Chatham Islands to experience strong and unusual currents and unpredictable surges at the shore following a large volcanic eruption at Hunga-Tonga-Hunga-Ha’pai in Tonga.

Strong currents and surges can injure and drown people. There is a danger to swimmers, surfers, people fishing, small boats and anyone in or near the water close to shore.

People in or near the sea should move out of the water, off beaches and shore areas and away from harbors, rivers and estuaries until at least 04:00a.m. NZDT Sunday 16 January 2022.

STAY OFF THE BEACHES AND SHORE AREAS

There is no need to evacuate other areas unless directly advised by local civil defense authorities. Coastal inundation (flooding of land areas near the shore) is not expected as a result of this event. We are advising people to:

- Move out of the water, off beaches and shore areas and away from harbors, rivers and estuaries.
- Do not go to the coast to watch the unusual wave activity as there may be dangerous and unpredictable surges.
- Listen to local civil defense authorities and follow any instructions.
- Share this information with family, neighbors and friends.

Strong and unusual currents and unpredictable surges will continue for several hours and the threat must be regarded as real until this Advisory is canceled.

This National Advisory has been issued following advice from GNS Science. This is the largest eruption from Hunga-Tonga-Hunga-Ha’pai Volcano so far, and the eruption is ongoing. The situation may change as new information becomes available. Listen to the radio or TV for updates, or check www.civildefence.govt.nz.

on the morning of 15 January 2022. The MetService further indicated that waves at 3.5 m were expected, gradually rising to 7 m by the early evening of Monday 17 January 2022.³⁵ A timeline of events for both the HTHH eruption and ex-Tropical Cyclone Cody is provided in [Table 3](#).

The current advice for tsunami threats in NZ, as shown previously in [Table 1](#), is largely based on seismic triggers and modeling, rather than volcanic triggers. At the time of the HTHH eruption in 2022, the Pacific Tsunami Warning System was not able to deal with a tsunami generated by a volcanic eruption.³⁶ Since this event, global efforts have progressed the development of procedures and products to aid responses to future volcano-generated tsunami threats.^{37,38} Consequently, there was a dearth of modeled scenarios available for the HTHH volcanic eruption-induced tsunami. Within an hour of the eruption, the tsunami threat to NZ was assessed as no threat and monitoring continued. Approximately 2 h later, and just over 1 h before reports of heightened wave activity and damage in Tūtūkākā Marina were received, this was upgraded to a National Advisory for Tsunami Activity (i.e., a Beach and Marine Threat; [Tables 2](#) and [3](#)) due to observations on the deep-ocean assessment and reporting of tsunamis (DART) network.

The advisory in [Table 2](#) provides information about the volcanic source of the tsunami, but it does not contain information about the estimated arrival time of the strong and unusual currents and unpredictable surges at the shore, nor of the duration of the activity; only that people should stay away from the shore, harbors, rivers, and estuaries until 04:00 NZDT Sunday 16 January 2022. Thus, it appears that the content in the advisory for the unexpected HTHH eruption-induced did not differ significantly from the information in [Table 1](#) nor in the Tsunami Advi-

sory and Warning Supporting Plan [SP 01/20]¹ for the more common seismically triggered tsunami threats.

Unusual wave activity (due to either the tsunami, ex-TC Cody, or both) was observed at various points along the NZ coastline.^{33,39} The most damaging impacts appear to have been in the Tūtūkākā Marina, Northland (approximately 190 km north of Auckland), where several boats were damaged or sunk.^{33,40} No injuries were reported and the individuals who were aboard their boats were able to evacuate to higher ground; one individual did however fall into the water during the evacuation and was fortunately rescued without injury.³⁴ The boating community raised concerns over the perceived lack of tsunami warnings for this event.⁴⁰ This suggests a possible misalignment in expectations of the purpose and design of tsunami warning systems between key groups, such as boat owners and operators, and the designers and issuers of the warnings. We thus conducted interviews with mariners who were associated with Tūtūkākā Marina at the time of the heightened wave activity on the night of 15 January 2022. More details about our data collection and analysis method are available in the [STAR Methods](#) section.

RESULTS

The first resulting category presented and discussed in this paper is on the interviewees’ experiences of the event on 15 January 2022, with themes around their awareness and risk perceptions of the tsunami threat, environmental and social cues, any warnings or advisories they did or did not receive, and their resulting behaviors and actions. The second category discussed is around the interviewees’ evacuation decision-making information needs,

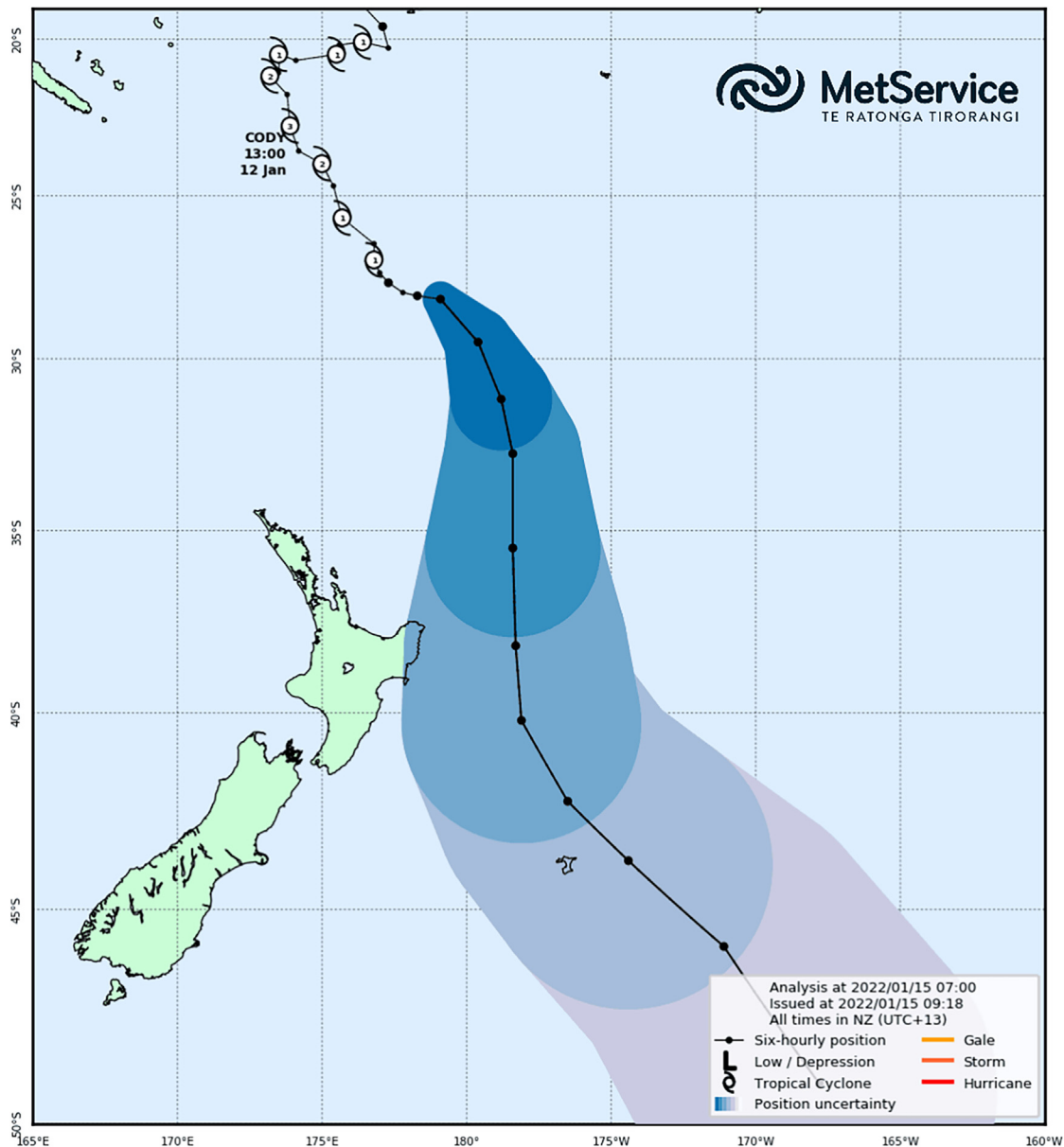


Figure 2. The forecast track of Cyclone Cody issued by MetService at 09:18 NZDT on 15 January 2022

Image source: NZ MetService, re-used with permission.

with themes around life safety, advice, tsunami specifics, boating and marina specifics, and other considerations.

Experiences on 15 January 2022

Of the eight mariners that were interviewed for this study, five were aboard their boats or otherwise at the marina on the night of 15 January 2022 and experienced the effects of the tsunami/ex-TC activity. The experiences of these interviewees are summarized in Table 4 and described next.

Awareness and risk perceptions

All interviewees aboard their boats were aware of and had prepared for the effects of ex-TC Cody, including strong winds

and storm surge, as they had heard about it from the MetService and the news. Mariner G – On board felt concerned about the cyclone, while the others stated that they prepared for it (Mariner A – On board), with one saying that the ex-TC “wasn’t too bad” (Mariner F – On board). In terms of the HTHH eruption and tsunami, four of the ‘on-board’ interviewees said that they heard of the eruption (Mariner G – On board, Mariner F – On board, Mariner E – On board, Mariner A – On board). Of the four that were aware of the eruption, two did their own research (Mariner E – On board, Mariner A – On board), one of whom came across the tsunami advisory (Mariner E – On board), which “said to keep away from the water, which they usually say.”

Table 3. Timeline of events for Cyclone Cody⁸⁸ and the HTHH eruption⁸⁹ and tsunami^{34,90}

Date	Time and events
Sun 2 Jan	Time not available <ul style="list-style-type: none"> Minor volcanic activity is observed in satellite imagery of Hunga Tonga-Hunga Ha'apai (HTHH).
Tues 4 - Thurs 13 Jan	Time not available <ul style="list-style-type: none"> A low-pressure system is detected by the Fiji Meteorological Service (FMS) which is designated as Tropical Disturbance 03F on 5 January. From 8 to 10 January TD 03F is upgraded to a Category 2 Cyclone and is named Cody. The FMS issues several heavy rain and severe flood alerts and warnings throughout Fiji from 4 to 8 January. The storm results in 1 death and 4,500 evacuees in Fiji. From 10 to 13 January the NZ MetService forecasts Cody to pass near the Northeast coast of the North Island, causing higher wind and wave activity for much of the North Island, including eastern Northland toward the weekend. High levels of uncertainty in the forecast track. On 13 January Cody weakens to a Category 1 and enters the NZ area of responsibility. NZ MetService updates the forecast track with higher confidence and advises "dangerous coastal conditions" to be felt along the eastern coast of the North Island with 6-8m waves, coastal flooding and damaging wind. The NZ Coastguard publishes advice for mariners to prepare for Cody.
Fri 14 Jan	04:20 NZDT <ul style="list-style-type: none"> A subaerial eruption begins at HTHH and generates a mushroom-shaped eruption plume. Tsunami warnings are issued for Tonga. Fluctuating tsunami waves are recorded off the coast of Tongatapu throughout the day. 07:00 NZDT <ul style="list-style-type: none"> The NZ MetService issues a Heavy Rain Watch for Gisborne and Wairoa District and expresses a high confidence of large easterly swells affecting eastern coastlines with potential for hazardous waves and rip currents from Saturday onwards.
Sat 15 Jan	00:43-06:04 NZDT <ul style="list-style-type: none"> An intermittent eruption at HTHH in Tonga occurs. 07:00 NZDT <ul style="list-style-type: none"> The NZ MetService publishes a new forecast track for Cody with higher confidence. The track shows an eastward shift resulting in reduced impacts from winds and rain. However, impacts on the sea conditions along the eastern coastline of the North Island remain. Wave heights are increasing along the coastline of Northland, NZ ahead of Cody's transit east of the country. High easterly swells are expected to spread east throughout the day and over the weekend. The NZ MetService advises that these large waves are likely to be significant with potentially hazardous surf and swell conditions for coastal residents and recreational activities. This includes the possibility of hazardous rip currents closer to shore, and significant sea surges and coastal inundation. Things are expected to gradually ease Tuesday into Wednesday from the north. 07:20 NZDT <ul style="list-style-type: none"> An ash plume rising to 14km altitude is detected over HTHH in Tonga due to an eruption that lasts 10–15 min. 10:00 NZDT <ul style="list-style-type: none"> The tsunami warning in Tonga for Tongatapu, Ha'apai, and southern Tonga due to the Nuku'alofa is canceled. 17:14 NZDT <ul style="list-style-type: none"> A larger submarine eruption at HTHH in Tonga begins from vents just below the surface of the ocean, generating a large ash plume. The eruptive activity lasts 8 min and the plume rises to 15.2km. Tsunami waves ranging from 1 to 15m high and 200m inland reach Nuku'alofa, Mango Island, Tongatapu, 'Eua, and Ha'apai Islands in Tonga. Coastal roads and properties are damaged by the tsunami, all homes on Mango Island are destroyed. 4 deaths are caused by the tsunami in Tonga. A communications blackout occurs in Tonga due to the eruption damaging a submarine fiber-optic cable and satellite terminants. Ash fall is widespread. 18:00 NZDT <ul style="list-style-type: none"> Ashfall measuring several centimeters thick begins and lasts for approximately 10 h in Tonga. This contaminates water tanks and causes breathing problems for residents due to ash in the air. 18:08 NZDT <ul style="list-style-type: none"> The initial tsunami threat for NZ was assessed by NEMA to be no threat, with monitoring continuing. 20:14 NZDT <ul style="list-style-type: none"> NEMA upgrades the threat assessment for NZ to a Beach and Marine Advisory based on observations on the DART Buoy network. NEMA issues a NATIONAL ADVISORY: TSUNAMI ACTIVITY – EXPECT STRONG AND UNUSUAL CURRENTS AND UNPREDICTABLE SURGES AT THE SHORE (Table 2). The message applies to coastal areas on the north and east coast of the North Island and the Chatham Islands. 21:29 NZDT <ul style="list-style-type: none"> Northland Regional Council in NZ receives reports of a precautionary evacuation of a campground in the Far North after elevated sea levels/wave heights are observed.

(Continued on next page)

Table 3. Continued

Date	Time and events
	21:34 NZDT <ul style="list-style-type: none"> ● Wave activity in Tūtūkākā Marina, Northland, NZ escalates.
	21:49 NZDT <ul style="list-style-type: none"> ● Northland CDEM receives reports of damage in Tūtūkākā Marina, Northland, NZ including damage to marina infrastructure and boats. People in the marina (on land and on their boats) evacuate to higher ground.
	23:00 NZDT <ul style="list-style-type: none"> ● Approximate end of damaging surges in Tūtūkākā Marina, Northland, NZ. No injuries or deaths reported in NZ.
Sun 16 Jan	07:33 NZDT <ul style="list-style-type: none"> ● NEMA issues an update to the ongoing National Advisory for Tsunami Activity that tsunami activity continues to be observed.
	09:40 NZDT <ul style="list-style-type: none"> ● NEMA issues another update to the ongoing National Advisory for Tsunami Activity, extending the advisory area to include the west coast of the South Island.
	19:06 NZDT <ul style="list-style-type: none"> ● NEMA cancels the national tsunami advisory stating that based on ocean observations the Beach and Marine threat has passed for all areas. People are advised to remain vigilant and take extra precautions with regards to beach and ocean activities due to the continuation of strong and unusual currents and unpredictable surges for up to 24 h in some locations around the country.

Mariner E – On board further said “[the message] doesn’t really click ... that’s my home ... they don’t say ‘leave your home. Evacuate.’ You don’t really associate it.” Mariner E – On board then added that “I should know better because this place has had it before.” Business Owner A – In marina said they received one alert, but it was a message “that didn’t indicate anything ... it didn’t cause us to go holy moly.”

The remaining three interviewees did not come across the tsunami advisory. Mariner F – On board indicated that when they heard about the eruption on the news, “at that point it was terribly underestimated.” The only other warning Mariner F – On board received was from another person in the marina who yelled to leave, noting that the sirens had not gone off [“Gone off” or “Go off” is a phrasal verb in English which, in this context, means for the tsunami sirens to make a characteristic noise. Saying that the sirens “had not gone off” or “didn’t go off” is equivalent to saying that the sirens did not sound]. Similarly, at the time that Mariner G – On board heard about the eruption, they “heard ... that a tsunami was not possible from this event,” and thus were more concerned about the cyclone. Mariner G – On board further pointed out that they did not receive an alert on their cell phone, which caused them to question “how come there wasn’t an alarm?”

Environmental and social cues

The on-board interviewees’ threat perceptions about the tsunami appeared to increase once they observed environmental and social cues associated with the tsunami, such as odd and unfamiliar sounds, shouting in the marina, and police lights. Mariner A – On board described that as they were getting ready for bed, they heard an unusual noise “like a train wreck.” They went to the cockpit to look outside and “saw boats get taken out.” After this observation they “thought it was a tsunami!” and described it as “more violent and chaotic than storm surge.”

Mariner E – On board said that they were watching TV at around 21:30 NZDT when they heard a “huge bang,” causing them to look outside. Similarly, they saw that boats were “gone” or moved. At around the same time, Mariner F – On

board felt some strong movements in the water and a loud banging sound as well. Mariner F – On board then heard someone yell “we’ve gotta get out of here” and felt their pier move and “[form] a horseshoe” around their boat.

Mariner G – On board described how their family of three returned to the boat around 20:30-21:30 NZDT. Around 22:15 NZDT, they heard their teenage daughter yell “tsunami! Tsunami!”. They said “what are you talking about? There’s no alarm” and proceeded to check their phone and the coastguard, where they “saw nothing.” Mariner G – On board indicated that their daughter had apparently seen a “partially submerged” boat float past them and described the water outside as a “washing machine.” The family decided to evacuate to higher ground, and subsequently noticed police lights in the marina. On their way to their vehicle that was parked in the marina, they received confirmation from the police that it was a tsunami and they had to leave.

Business Owner A – In marina has a fleet of boats in the marina. They were hosting a large function that night with approximately 60 guests in the marina. The first alert Business Owner A – In marina remembered seeing that night was a text message from another local business owner in the marina “about something happening in the marina.” They initially thought that storm surge was causing damage but realized that it could have been a tsunami after the fellow business owner further described seeing the water level in the marina drop and said that they had closed and taken their patrons up the nearby marked evacuation route. Business Owner A – In marina thought it was “a strange message to hear that the water dropped.” At this point, Business Owner A – In marina “announced to the guests that we think it’s storm surge. It could be a tsunami, but we don’t think it is because the sirens haven’t gone off and we haven’t received any alerts.” Business Owner A – In marina described how they kept receiving messages of more waves coming and breaking over the fuel jetty, which caused them to “wonder if it was a tsunami but is storm surge exacerbating it?”

Table 4. Summary of the experiences of interviewees who were on their boats at the time of the wave activity in the Tūtukākā Marina that has been associated with the HTHH eruption-induced tsunami and ex-TC Cody on the night of 15 January 2022

	Awareness and risk perceptions	Activities at the time	Environmental and social cues	Advisories, alerts, warnings, sirens	Information Seeking	Protective action
Mariner A - On board	Found out about HTHH eruption from doing own research. Prepared for storm surge from ex-TC Cody. Knew about bad weather from the news.	Getting ready for bed.	Heard unusual noise (like a train wreck).	Received no alert. "Would've expected an alert."	Went to cockpit and looked outside, saw boats get taken out. It was more violent and chaotic than storm surge.	"Thought it was a tsunami!" Self-evacuated. Packed valuables and toothbrush. Had no difficulty leaving the boat. The boat is a material thing. Warned others on shore. Got in the car and went to higher ground.
Mariner E - On board	Heard about eruption. Looked it up on GNS or Geonet or civil defense.	Was watching TV around 21:30 NZDT and looking after a friend's dog.	Heard a huge bang.	Heard about the advisory that said to keep away from the water, "which they usually say." "No f***** warning."	Went outside to look and saw that boats were 'gone' or moved.	His boat got squished. He tried to push the other boat off. Tried to tie things down and prevent any more damage from happening. Was ordered by police to leave. Passed dog to fireman. Stayed at friend's place up on hill. Waited for flashing lights to go then snuck back down and secured things.
Mariner F - On board	Heard about the eruption on the news. At that point it was "terribly underestimated."	Was below deck on boat, around 21:30 NZDT.	Felt some strong movements in the water. Heard loud banging. Ex-TC Cody "wasn't too bad."	A guy yelled "we've gotta get out of here!" That was the only warning he received. Sirens did not go off.	As he was going upstairs, he felt the pier moving and formed a horseshoe around his boat.	Got off boat and went to higher ground.
Mariner G - On board	Heard about HTHH eruption. Heard at the time that a tsunami was not possible from this event. Was more concerned about ex-TC Cody.	Got back to boat at around 20:30-21:30 NZDT. Went to bed.	Around 22:15 NZDT, daughter yelled "tsunami, tsunami!" Daughter saw a partially submerged boat float past them, described it as a washing machine.	"Why haven't our phones gone off?"	"What are you talking about? There's no alarm." Checked phone and Coastguard app, saw nothing. Said "don't be silly, there's nothing, otherwise we would've heard warnings."	Grabbed computers, packed up and left. Got in car. Noticed police lights. Asked policed 'what's going on.' Police said "tsunami, you've got to leave." Went to friend's place up the hill.

(Continued on next page)

Table 4. Continued

	Awareness and risk perceptions	Activities at the time	Environmental and social cues	Advisories, alerts, warnings, sirens	Information Seeking	Protective action
Business Owner A - In marina	In the middle of ex-TC Cody with strong winds.	Had a function underway in the marina. Fully booked accommodation. Lots of visitors in the marina. Several people came in on their boats, others by bus.	Thought storm surge was causing damage. A restaurant owner saw the water drop, closed business for the night and evacuated staff and customers to higher ground. "it was a strange message to hear that the water dropped."	Received text from restaurant owner about something happening in the marina. Got one alert but it was a warning "that didn't indicate anything ... it didn't cause us to go holy moly."	Kept getting messages of more waves coming and breaking over the fuel jetty. Started to wonder if it was a tsunami but is storm surge exacerbating it?	One business co-owner went straight to boats to check on them. He saved many boats and is considered a hero in the community. The other business co-owner was focused on guest safety. Announced to guests that they think it is storm surge. Could be a tsunami but do not think it is because the sirens haven't gone off and they received no alerts. Called buses to take guests back early.

Warnings

The interviewees who were at the marina on the night of the event seemed to show a reliance on or expectation of phone alerts and/or sirens to alert them of a potential tsunami and the need to evacuate. For example, when the daughter of Mariner G – On board woke her parents by shouting “Tsunami! Tsunami!”, Mariner G – On board’s first instinct seemed to be to check their phone and check the Coastguard app. Mariner G – On board indicated that they were relying on their “cell phone to go”, and initially said “Don’t be silly, there’s nothing, otherwise we would’ve heard warnings.” Afterward, Mariner G – On board questioned “why haven’t our phones gone off?” and “how come there wasn’t an alarm?” Similarly, other interviewees noted that they “received no alert” (Mariner A – On board), there was “no [expletive] warning” (Mariner E – On board), and “the sirens didn’t go off” (Mariner F – On board). Mariner F – On board also said that “where we should’ve known what was going on, we didn’t.”

Business Owner A – In marina also indicated that they were relying on phone alerts or sirens to provide an authoritative voice to initiate an evacuation with confidence. Instead, Business Owner A – In marina indicated that “we knew we’d have to act first without waiting to be alerted.” Business Owner A – In marina then described that if the sirens had gone off,

“instead of intuitively going, ‘this is big?’ We would have known ‘this is big’ [emphasis added to indicate higher level of confidence]. And I think it also would have meant that I could authoritatively tell people really early on, ‘you need to move now. This is a tsunami.’ Instead of ‘I’m interpreting what I see. I’m looking at the storm surge. I’m looking at the damage. I’m thinking something’s- you know, when when’s high tide? Can you get out of Scales Landing in Ngunguru and Keripaka.’ Doing all the local calculations that I can about what that could look like. Yet there’s no siren. There’s no- nothing from a higher level that said ‘yes, you have a situation. And this is what you need to do.’ It didn’t matter if they said ‘Yes, you have a situation and you control it,’ but we were intuitively doing it.”

Interviewees did acknowledge the complexity of the unexpected volcanic eruption happening in parallel with ex-TC Cody and noted the lack of data and models to inform decision-making. Thus, they did not express any anger about the lack of warnings, because “no one got hurt” (Mariner F – On board, Mariner G – On board). They also did not want to assign blame to any particular individual or agency, as Business Owner A – In marina said “I don’t think it was anyone’s fault. I don’t think it’s a blame game. Umm, I don’t know why the tsunami siren didn’t go off.”

However, Mariner G – On board said that they would have been “cross” if they or their family had gotten injured or if their boat had received more serious damage. Mariner A – On board indicated that they would have expected an alert and that it was “fairly negligent” that they had not received one. They further indicated that they likely would have gotten off their boat sooner had they received an alert. Mariner A – On board also expressed feeling “extremely fortunate” that they were not injured and acknowledged that one person had fallen into the water and

was fortunately rescued. Mariner F – On board indicated that while they were “not overly concerned about no warning from a personal safety perspective” they thought that the warning process was ‘backwards,’ and that the outcome of the event was “terribly underestimated.”

Behaviors and actions

The behaviors and actions in response to the interviewees’ observations range from seeking further information (e.g., checking phones and the Coastguard app, looking outside, asking the police); securing boats before evacuating; alerting other people nearby; and evacuating to higher ground either on foot or by car.

All interviewees who were on board or in the marina and saw, heard, or felt the tsunami evacuated from the marina. However, it appears that their decisions to evacuate were informed by various factors and observations and happened at different stages. For example, Mariner F – On board and Mariner E – On board described that they tried to secure boats and lines and prevent more damage from happening before seeing the “futility” (Mariner E – On board) in it and being ordered to evacuate by the police. In response to the police’s evacuation orders, Mariner E – On board indicated that they did not want to get arrested and also “thought fair enough to the cops; they didn’t know what else was coming.”

Alternatively, after initially questioning whether a tsunami was occurring, and checking their phone for more information (a behavior referred to as “milling”⁴³), Mariner G – On board and their family quickly decided to leave their boat after grabbing their laptops. Similarly, Mariner A – On board indicated that after observing the “violent” and “chaotic” wave activity outside their boat, they packed their valuables and toothbrush, and evacuated, saying that they had “no difficulty” leaving the boat as it “is a material thing.” Mariner A – On board said they then warned others on shore and evacuated via car.

Business Owner A – In marina relied on social and environmental cues that they and another business owner observed to inform their decision to send guests out of the marina. Business Owner A – In marina communicated their observations to the guests and called the buses to take the guests back to their accommodations, while their partner went into the marina to secure boats.

Evacuation and protective action decision-making considerations

Both groups of interviewees were asked about the information needs of the boating community for informing their evacuation and other protective action decisions. Interviewees identified various questions and factors that they would consider if they were deciding whether, how, and where to evacuate in relation to their boat. Some interviewees described this process as a ‘dynamic personal risk assessment’ where the individual would:

“have to assess it at the time and make a decision there, based on what was going on” and “relying on your agility” (Mariner F – On board); or

“Go through and you look at and you make sure that whatever you do with your fleet. You have to look at what’s actually happening out, what else is happening around. And case in point the tsunami or surge was at the same

time as Cyclone Cody and that impacted heavily on people’s decisions as well” (Business Owner A – In marina).

We grouped those questions or considerations that interviewees identified as part of this assessment into five themes: (1) life safety, (2) evacuation/advice, (3) tsunami specifics, (4) boating and individual specifics, and (5) other considerations such as weather conditions and time of day.

Life safety

When discussing with interviewees whether they would choose to evacuate off their boats onto land or take their boats to deeper waters in the event of a tsunami, some interviewees stressed the importance of life safety, and the use of “common sense” to decide whether they could or would attempt to evacuate by boat. As Mariner F – On board said when discussing events from that night,

“I think in a case like that where you’re unsure of things that are going to happen, you better get off and onto dry land and not worry about it. So [evacuating by boat to sea] was never an option.”

Mariner G – On board raised another consideration separate from evacuating from the boat to higher ground, or evacuating with the boat to deeper waters, and that was whether they would have gotten on the boat in the first place: “In hindsight, if we’d known the eruption would cause a tsunami at Tūtūkākā, we probably wouldn’t have been on the boat.” Additionally, Business Owner A – In marina described how they previously had their fleet stay out at depth during the 5 March 2021 tsunami warning as their boats were already out.

Advice

Interviewees also indicated that they would not go against official advice, which is the next theme of questions/considerations in the personal risk assessment. When discussing with interviewees what they think is needed to help inform their response decisions to a tsunami or a tsunami warning, many interviewees indicated a desire for clear advice on what to do and when before the tsunami, and what to do after.

When considering whether to take their boat out to deeper waters, Mariner C indicated that they would need assurance from “marine experts” that it was safe to take their boat out to sea. Mariner C further suggested that to provide this advice, the “advisors need to not face a risk of personal liability” and “the advisors need to be brave enough”.

Similarly, Mariner B, who lives nearby on land, “wouldn’t go against advice or common sense to go down to the boat” if they were not already there. Relating back to the night of 15 January 2022, Mariner E – On board expressed that they would have liked “a proper warning saying get your but outta here, do something, go to higher ground.” Interviewees also expressed a need for an “all clear” message to return to their boats (particularly for those on liveaboards) or to return to land if they took their boat(s) out to sea. Interviewees from the marina indicated that they had not received an all clear to return to the marina after evacuating either voluntarily or upon instruction from police.

Tsunami specifics

Interviewees indicated that within the advice or warning/advisory message, they would like to see more information about the

tsunami specifics to help with their personal assessment and decision-making process. This information includes the estimated time of arrival of the first wave or surge, the anticipated severity or intensity of it, the location of expected impact, and how far/deep to go if evacuating by boat.

Interviewees indicated that having an idea of “how bad” it will be would provide a sense of scale and help the individual assess whether there is a risk to themselves and to their boat that might necessitate either a land-based or boat-based evacuation (Mariner G – On board, Mariner D, Business Owner A – In marina, Mariner C). As Business Owner A – In marina said with regards to the night of 15 January 2022, “unusual and strong currents’ doesn’t tell me boats will be damaged.”

Indeed, some level of certainty appeared to be desirable to the interviewees, with Mariner D saying they “need certainty” but acknowledged that it “doesn’t have to be 100% certain”. Mariner F – On board indicated that if they were to evacuate out to sea, they would “need to know if it was happening and how much time” but “with such uncertainty, it’s best to go to higher ground.”

Boating and marina specifics and self-efficacy

Boating and marina specifics and self-efficacy is the fourth set of questions or considerations that interviewees mentioned when discussing their risk assessment and decision-making. The questions and considerations here are focused on the individuals’ own boating knowledge, capability and experience, as well as highly localized characteristics of the marina, bay, or other area that they and/or their boat might currently be in.

The estimated time for an individual to secure or prepare their boat is very individual- and boat-specific, while the time to exit a marina is marina-specific. Interviewees emphasized the importance of having “plenty of notice” (Mariner D). Interviewees indicated a range of time it would take for them to reach their boats (e.g., 30 min, for Mariner C), prepare their boats (e.g., 15–20 min for Mariner E – On board and Mariner D), and exit the marina and reach the required depth to be safe (e.g., 1–2 h for Mariner B). Thus, a “sense of timing” would help the individual decide if they can realistically evacuate by boat or not (Mariner C, Mariner D, Mariner G – On board).

Mariner A – On board described the importance of time factors in their decision-making:

“The amount of time you need will depend on geographic location and how long it takes to get out of the marina, and how far is it before you escape the grasp of the land. That will depend on how quickly the water deepens/drops off away from the shelf of the land. The answer overall – the more the notice you get the better.”

Some interviewees discussed assessing the current conditions in the marina, such as any damage already sustained or debris floating in the water (Mariner F – On board), and the abilities of other marina users to evacuate the marina with their boats in an efficient and orderly manner (Mariner C, Mariner B, Mariner A – On board). Having more detailed information about the estimated tsunami arrival time and anticipated magnitude and severity would help the individuals assess the most appropriate response action(s) based on their own boating capabilities and the contexts of their boat and marina.

Other considerations

Interviewees also described other considerations that are not specifically related to tsunami, such as weather conditions and time of day. For example, several interviewees indicated that they would be less inclined to take their boat out at night or during bad weather:

“If I had adequate warning (in terms of time) and the weather was good, I’d take a boat out. But if I didn’t have adequate warning or the weather was bad, I’d leave the boat. I don’t think it’s worth risking your life for. But some people do. There’s nothing you can do in a violent cyclone or a violent tsunami. You haven’t got enough strength or power to fight nature” (Mariner A – On board).

“And the fact- maybe if it was during the day, normal time, and things started happening, you’d bugger off. But it was a windy- it wasn’t raining that much, but it was windy. It was a miserable night. I know where in the Coastguard, we had a standard operating procedure then: if there’s a tsunami in here, take the boat out. And that’s what I’d probably do in the day, if there was a warning on” (Mariner E – On board).

DISCUSSION

When designing early warning systems and accompanying messages, it is important to identify the warning audiences/users and their respective needs, which may vary across groups, communities, and sectors.¹⁵ Findings from our qualitative analysis of interviews with mariners deepened our understanding of the complex decision-making processes they face during a tsunami and multi-hazard threat. We next discuss four topics of interest that emerged from our analysis to situate our findings with the broader literature and to aid in answering our research question: (1) the influence of multiple hazards on perceptions, warnings, and actions; (2) tailored and consistent warnings for mariners; (3) localized tsunami hazard awareness and response plans for mariners; (4) uncertainty in multi-hazard warnings.

The influence of multiple hazards on perceptions, warnings, and actions

Our findings indicate that, on the night of 15 January 2022, interviewees who were in Tūtūkākā Marina were primarily aware of the threat posed by ex-TC Cody and were less aware of the tsunami threat posed by the HTHH eruption. For the interviewees that received or saw the tsunami advisory issued by NEMA, they perceived ex-TC Cody to be the larger threat of the two. They did not perceive an immediate threat to the safety of themselves, their family, and/or their boat, until they observed (e.g., either felt, saw, heard, or a combination of these senses) potential tsunami activity or and/or they were instructed to evacuate by others in the marina (either fellow boaties or police). While the impacts to the marina and the individuals in it cannot be solely attributed to the HTHH eruption-induced tsunami activity due to the co-occurrence of ex-TC Cody, the interviewees who were present in the marina at the time of impact and who have

previously experienced stormy sea conditions perceived the wave activity to be caused mainly by the tsunami activity due to the intensity and the unusual sound.

While all interviewees in this study indicated that they would not have considered evacuating their boat to sea to avoid tsunami damage during the ex-TC, the co-occurrence of these two hazards raises questions around the influence of co-occurring, compounding, and cascading hazards on threat perceptions, and whether individuals know what protective action they should take to remain safe from all threats, particularly if the protective action for one hazard might put them in danger of another hazard. This phenomenon of conflicting protective actions has presented challenges with communicating warnings and protective actions for tornado and flash flood (TORFF) events in the USA.^{44,45} More specifically, Henderson et al.⁴⁵ identified ways that US National Weather Service warning operations can unintentionally amplify or attenuate one threat (e.g., tornado) over another (e.g., flash flood) during a TORFF. In this context, Henderson et al.⁴⁵ found three ways of amplification to be: (1) forecasters' underlying assumptions about the danger of different threats, (2) threat terminology and coordination with national offices to shape multi-hazard risk communication, and (3) organizational arrangements and spatial layouts of the forecasting offices.

Given the emphasis that interviewees put on their experiences with MetService weather warnings, the long lead-time with accompanying messages around the ex-TC Cody threat days before expected impact, and the unexpected eruption of the HTHH volcano, it is possible that MetService warnings were unintentionally amplified over the tsunami advisories. Some of the recommendations from Henderson et al.⁴⁵ around reducing this attenuation or amplification may be applicable. For example, forecasters could become more aware of lower public threat perceptions and concerns relating to a particular hazard (such as tsunami, in this case) and highlight those threats and the dangers they pose to the public.⁴⁵ More specific advice on how individuals might assess their specific threats based on their location relative to the hazard can also help to increase awareness of the threats.⁴⁵

Henderson et al.⁴⁵ also recommend focusing on the magnitude of impacts from the multiple hazards together, rather than outlining the characteristics and threats from each hazard separately, to emphasize the danger they pose to the public. This aligns with current national trends toward integrated multi-hazard impact-based warnings.^{28,30,46} Some strategies to facilitate this initiative include reconfiguring the warning spaces to integrate broader expertise for improved consistency and coordination.⁴⁴ One example is the collocation of forecasters and scientists for difference hazards.^{45,47,48}

Tailored and consistent warnings for mariners

Advice for mariners around what to do in response to a tsunami threat has been developed both internationally and domestically.^{49,50} Within NZ, a minimum evacuation depth of 50 m is recommended for boat-based evacuations, with further instruction to “not stop at the 50 m line but continue to head to deeper water which is safer from tsunami currents and waves” with a disclaimer to: “please note that the minimum safe distance for

boats is indicative only and based on current science and modeling as at date maps published”⁴⁹ (Note that the Tsunami Evacuation Zones: Director's Guideline for Civil Defense Emergency Management Groups [DGL 08/16] containing this advice are currently under review with an update of this advice to be provided in the next iteration). This advice does not appear to consider the complex decision-making process and personal risk assessments that mariners might undergo when deciding whether to evacuate themselves and their boat, as demonstrated in our interview results.

Some individuals' attempts to secure boats and prevent any further damage from happening before evacuating suggests that they did not initially perceive an immediate threat to their personal safety compared to the safety of the boat(s). However, several factors appear to have changed the individuals' perceptions and triggered their evacuation response: (1) social and verbal cues from others in the marina, (2) the arrival of an authoritative figure, i.e., the police, to evacuate the marina, (3) environmental cues such as the ongoing damage caused by the wave activity which proved efforts to be futile; and (4) the ongoing ex-TC at night. The individuals thus determined that the most appropriate action to take was to evacuate to high ground in their vehicles or by foot, rather than to stay on their boat.

The decision about whether or not and how to evacuate appears to depend, at least in part, on the individual's context at the time of receiving a tsunami warning or alert; primarily if they are (1) on land (away from their boat), (2) at the marina/shoreline on or near their boat, (3) on their boat moored in a bay, or (4) already out at sea. Additionally, time and distance appeared to strongly factor into the interviewees' decision-making processes about when, how, and where to evacuate in relation to their boat. Figure 3 provides a visualization of these four contexts; key questions for which the individuals might seek out answers to inform their decision-making process; and the time and distance to evacuate or reach a safe location.

The first context is for a boat owner/operator who is on land, some distance from their boat or the shoreline. In this context, the boat owner/operator might consider whether they and their family are already in a safe area, if they need to evacuate to a safe area on land, or if they have time to reach their boat, either to secure it or remove it from the risk area (either by pulling it out of the water or taking it out to deep waters to avoid the impact).

The second context is for a boat owner/operator who is either near or on their boat in a marina. In this context, the boat owner/operator might consider where the nearest high ground is, and how much time it would take them to reach higher ground (either on foot or by car) versus the total time it would take them to prepare their boat for sea, exit the marina, and reach the minimum required depth before the arrival of the first tsunami wave.

The third context is for a boat owner/operator who is on their boat that is moored in a bay. This individual might consider whether they have time to reach land and evacuate to higher ground or take their boat out to depth.

The fourth context is for a boat owner/operator who is already at sea. They might consider whether they have time to return to land to evacuate to higher ground, whether they are at the minimum required depth, or whether they need to go deeper. They

Boat owner/operator on land	Boat owner/operator on or near boat in marina	Boat owner/operator on a boat moored in a bay	Boat owner/operator on boat at sea
Am I currently safe?			
Where is my family?			
Do I need to evacuate?			
Where is the nearest evacuation route?			
What's the official advice?			
How big is the tsunami going to be?			
How long until the first wave arrives?			
What are the weather and ocean conditions like?			
What time of day/night is it?			
Should I get/stay off my boat?			
What else is happening in the marina?			
Is anyone still on their boat or in the water?			
How deep/far do I have to go?			
How long will it take to get to depth?			
Do I have time to get to my boat?		Do I have time to get to shore?	
Do I have time to secure my boat?			
Do I have time to get to sea/depth?			
Am I at depth?			
Do I have time to remove my boat from the risk area?			
Is my boat fuelled up?			
How long will it take to exit the marina/harbour/bay?			
How long will I need to stay out for?			
Do I have enough supplies on my boat?			
Is it safe to return?			
Length of time to get to boat, exit marina, and get to depth	Length of time to exit marina and get to depth	Length of time to get to land or get to depth	Length of time spent at depth
Increasing distance from land from left to right			
Key	Personal safety questions	Tsunami specifics questions	Other considerations
	Evacuation/advice questions	Boating- and individual-specific questions	

Figure 3. Example questions and behaviors the interviewees mentioned when discussing their decisions about evacuating to higher ground or to sea

The four columns represent a boat owner/operator in one of four contexts identified during the interviews that would influence the individual's decision-making process. The two bottom rows identify two factors that the interviewees identified as key to their decision-making process: length of time and distance to the safest area (either high ground or at depth). The color-coded rows indicate five types of questions or considerations that a boat owner or operator might consider after receiving a tsunami warning or advisory and deciding what to do in terms of evacuating themselves and/or their boat for each context. The length and horizontal placement of the colored rows indicates in which context(s) the question would be most applicable based on the discussions with the interviewees and subsequent analysis.

might also consider how long they would need to be out at sea, and if they have enough supplies.

When deciding what they need to do in response to a tsunami threat or tsunami warning, mariners would likely ask themselves a series of questions depending on their context, as shown in Figure 3. These questions help to identify and understand what information mariners would need to make informed decisions to protect themselves and their boats. To summarize, information that might help mariners' decision-making processes is listed in Table 5. These considerations align with those also identified by the Washington State Military Department⁵¹ for mariners who are at sea during a tsunami; our findings build on this work by identifying additional contexts for mariners on land, in a marina, or anchored in a bay.

The participants expressed a desire to know the listed information in relation to the location of themselves and their boat(s). This presents a challenge as, at present, in NZ the initiation of a tsunami warning or advisory message is at the national level with little time to adapt the message for localized areas such as marinas. Furthermore, large levels of uncertainty remain a challenge.⁵² However, research and development are actively progressing toward the improvement of the models and characterization of the uncertainty such that the aforementioned information may be provided in future, particularly for tsunami haz-

ards with seismic origins.^{53–55} Further development is needed for other tsunami triggers, including volcanic eruptions.

These personalized risk assessments relate to current trends in the literature and in practice toward developing tailored warnings to meet the needs of warning recipients.^{56,57} Communities increasingly expect to receive information about location, likelihood, and potential impacts using accessible language and our findings suggest that the Tūtūkākā boating community shares these expectations; further research is needed to understand the expectations of the wider boating community in NZ. Additional research is also needed to evaluate the efficacy of such tailored warnings for each target community, as research has found that what individuals and communities want or expect may not always lead to improved understanding, changes in risk perception, or action.^{58,59} Furthermore, providing tailored warnings may also contradict or interfere with consistent messages⁵⁶; more research is needed to determine the cost-benefit of introducing tailored warnings.

Tailored warnings may also involve the development of warning thresholds specific to the intended users' exposure, vulnerabilities, and coping capacities.⁵⁶ As discussed in the introduction, marinas and mariners are particularly exposed to tsunami threats, especially those who reside on liveboards and therefore spend all or most of their time in or near the coastal

Table 5. Information that could help mariners' tsunami response decision-making processes based on the interview results

Geographic considerations for each of ...	<ul style="list-style-type: none"> ● the estimated time of arrival of the first wave or surge; ● the anticipated severity, intensity, or magnitude of it; ● the expected impacts; ● the expected impacts to boats, marina infrastructure, and people in the marina; ● how far/deep to go if evacuating by boat; and ● how long to expect and prepare to be out of the harbor.
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environment and who consider the marine environment to be their 'home'. Thus, the warning thresholds for this group may be lower than for the general population; however, careful consideration is also needed around the risk of over-warning this community and asking people on liveaboards to leave their homes unnecessarily and causing warning fatigue.⁶⁰ A key question coming out of this research is whether the current Beach and Marine threats in NZ are meeting the needs of marine users and other individuals living close to the shore, and whether a new warning level with tailored thresholds is needed.

Localized tsunami hazard awareness and response plans for mariners

The information that the interviewees requested to help with their decision-making suggests that they are not currently aware of or receiving this information for their region or marina. Tsunami hazard awareness and response plans that are socialized and communicated in engaging, informative, and accessible formats could help to provide some of this information before a tsunami event where the detailed level of information might not be readily available in the current system and with the current science.^{5,61,62} For example, in the USA, the Washington State Department of Natural Resources (DNR) provides maritime preparedness advice to boat owners and captains,⁶³ while the Washington Emergency Management Division provides a *Boaters Guide to Tsunamis* along with plethora of other resources and education materials for mariners.⁶⁴ The *Boaters Guide to Tsunamis* provides information on what a tsunami is, tsunami hazards for boaters, tsunami preparedness (e.g., learning the hazards, making a plan, and preparing emergency kits), natural warning signs when on and off shore and actions to take if/when a natural warning sign is observed, official tsunami alert levels and what they mean, how people can expect to receive official tsunami warnings, actions to take when an official warning is received, and where to go for more information. The U.S. National Tsunami Hazard Mitigation Program⁶⁵ also provides an online resource for Tsunami Maritime Guidance which provides information on tsunami alert messaging, response and exercise, preparedness, mitigation, recovery, etc. At a higher level, the International Tsunami Information Center (ITIC) webpage provides information, including publications and technical guidance documents for tsunami preparedness in ports and maritime communities.

Lessons learned from previous and recent events have demonstrated several gaps and areas of improvement. The impacts of the 2011 Tōhoku earthquake and tsunami on marinas in the USA demonstrated a need for tsunami evacuation plans and products that can be used for various scenarios, particularly for "smaller warning-level events".⁵ Similarly, the findings from

the case study presented in this paper support that in particularly exposed and vulnerable parts of the NZ coastline, such as Tūtūkākā Marina, a response plan is needed for these "low-magnitude" events that can still pose a risk to life and property.⁶⁶ The response plan should also instruct mariners if, when, and where boats should go offshore before tsunami arrival, and when to return.⁵ Building in coordinated and community- or marina-led evacuation drills both by foot and by boat could also improve response capacity.^{61,67}

Our findings suggest that the following information listed in [Table 6](#) would aid the mariners' decision-making. Rapidly providing some of this detailed and highly localized information about the tsunami and impacts is difficult due to the amount of time required to produce such a community-oriented message. We thus recommend that marinas, harbors, and mariners work with CDEM agencies, councils, the coastguard, scientists, and engineers to develop localized preparedness and response plans. This could help to build tsunami awareness and response capacity, and potentially codevelop warning messages and thresholds in advance of a potential threat. Suggested content to include in localized and tailored preparedness and response plans for boating communities are listed in [Table 7](#).

Providing scenarios to key at-risk communities in advance of a potential threat can help communities understand their risk and develop their response plans. One example is the playbook products developed by Borrero & O'Neill⁶⁸ consisting of pre-computed modeling scenarios for maritime facilities in Northland Region of NZ. Of course, as described by some of our interviewees, it is not always possible to model for every possibility or scenario; the 2022 HTHH eruption and tsunami combined with ex-Tropical Cyclone is one such event that could not have been pre-computed. However, the existence of such plans and regular reviewing and evacuation drills both by foot and by boat can help to increase response capacity and help the mariners understand how much time would be needed prepare and act in most scenarios.^{61,67}

The unprecedented 2022 HTHH eruption and associated tsunami and its impacts on Tūtūkākā Marina and on other shorelines also revealed an urgent need for standard operating procedures and products to be developed to aid in the early warning of future volcanic eruption-generated tsunami; this has been actioned and PTWC Interim Procedures and PTWS Products have been developed.³⁷ The UNESCO Pacific Wave exercise series (also known as PacWave) provides opportunities to develop and support Pacific Tsunami Warning System (PTWS) products and procedures by creating environments for Pacific countries to practice regional coordination and cooperation, test any new products, review their tsunami response procedures, test both internal and external communication systems, and carry out

Table 6. Tsunami information to help mariners' protective action decision-making

Type of information	Details
Tsunami specifics	<ul style="list-style-type: none"> ● The estimated time of arrival of the first wave or surge. ● The anticipated severity, intensity, or magnitude of it.
Impacts	<ul style="list-style-type: none"> ● The location of expected impact(s). ● The expected impacts to boats, marina infrastructure, and people in the marina.
Advice	<ul style="list-style-type: none"> ● Clear advice to stay off of boats and out of harbors. ● How far/deep to go if evacuating by boat. ● Where and how to evacuate on land. ● How long to expect and prepare to be out of the harbor.

public education activities.⁶⁹ In September 2022, the PTWC Interim Procedures and PTWS products developed for future HTHH volcanic eruptions and associated tsunami were tested in the PacWave22 exercise. Pacific member countries' Tsunami Warning Focal Points (TWFP) or National Tsunami Warning Centers (NTWC) were strongly encouraged to participate, with the option to invite additional visitors from other agencies in the wider sector or in local communities.⁶⁹ At the time of writing, the next PacWave24 exercise was planned for November 2024.

Uncertainty in multi-hazard warnings

Our findings and discussion have highlighted various sources of uncertainty throughout the tsunami warning process, which can affect decision-making along the chain. Uncertainty in the source of the tsunami, especially in the case of the 2022 HTHH volcanic eruption, can result in significant time delays for decision-making and action taking.⁷⁰ Much work has been conducted to reduce uncertainties around seismic sources of tsunami and uncertainties in tsunami forecasting.⁷¹ Much uncertainty is still present, however, in volcanic tsunami generation,⁷² which presented significant challenges in assessing the tsunami threat from the 2022 HTHH eruption. Table 3 shows that the upgrade of the threat assessment to a Beach and Marine Threat in NZ happened once tsunami wave activity was detected in the DART network.

Additionally, in a multi-hazard context like that of the 15 January 2022, uncertainty in meteorological hazard forecasts continue to present challenges in forecasting and warning for these hazards.^{73,74} For example, as outlined in Table 3 much uncertainty was present in the forecasted track of ex-TC Cody and its associated hazards (extreme wind, rainfall, storm surge) and subsequent impacts on NZ; the forecasters' confidence in the forecast increased as the cyclone approached NZ.

It can therefore be expected that any multi-hazard assessment of cascading hazards and co-occurring hazards (such as the HTHH volcanic eruption and tsunami, and ex-TC Cody, respectively) would include compounding uncertainties in the hazard and impact forecasts, subsequent threat assessments, resulting warning or advisory messages, and response decision-making.^{75,76} These uncertainties could then be exacerbated by uncertainty in the interrelationship of these hazards, that is, how these hazards and their impacts could affect each other.⁷⁶

The time until onset of the hazards can also affect the uncertainty and subsequent communication. Events like tropical cyclones often provide several days of lead-time, which gives forecasters and decision-makers time to understand the threat.^{77,78}

Alternatively, rapid-onset events like a local or regional source tsunami may not provide enough time for forecasters and decision-makers to assess, characterize, and communicate the uncertainty effectively.⁷⁹ In an assessment of the risk perceptions of the 2022 HTHH eruption-generated tsunami among coastal emergency managers in the US Pacific Northwest, Moore et al.⁷⁰ found the time-delay in receiving information about the event created a window of uncertainty that both inhibited and helped different emergency managers' threat assessments and evacuation alerting decisions.

From the perspective of at-risk individuals, the ineffective communication of uncertainty can increase information-seeking behaviors and delay protective action.^{70,80-83} This behavior was observed in some of our interviewees, who sought information about the phenomena they were experiencing before ultimately deciding to evacuate their boats and the marina. It is important to note that our interviewees acknowledged the uncertainty around this particularly unique event (the eruption-induced tsunami) and thus did not indicate any expectations to have absolute certainty in any warning or advisory message they would have expected to receive; rather they expressed a desire for some certainty and clear advice around what to do. As noted by Business Owner A – In marina, the silence of the local tsunami siren and the missing advisory message that they did not receive resulted in a high level of uncertainty around what to do with regards to their guests in the marina.

Thus, uncertainty is also present in evacuation and protective action decision-making. Each consideration identified in Figure 3 is accompanied by varying levels of uncertainty that the individuals must assess. This includes uncertainty in the at-risk individual's ability to undertake a protective action and the effectiveness of the action; uncertainty in the effects of others' evacuation actions to affect their own (e.g., a traffic jam in the marina causing delayed evacuations); uncertainty in how far out to sea the individual should take their boat and how long they can expect to be out there for; and uncertainty of other hazards that may pose additional threats, such as extreme weather. Interviewees thus expressed a desire for information about the tsunami specifics (previously discussed in the results section) to aid with their decision-making and reduce their overall uncertainty around the most effective course of action to take. Characterizing and communicating the uncertainty in these tsunami specifics would be essential.^{84,85} Recommendations for communicating uncertainty have been provided by Ripberger et al.⁸⁶ As noted previously, this may be difficult to achieve in a warning context due to the time restrictions in a

Table 7. Suggested content to include in localised and tailored preparedness and response plans for boating communities.

Type of information	Examples
Localised hazard and risk information	<ul style="list-style-type: none"> ● Information about the tsunami risk to the marina and marine users in area. ● Pre-computed scenarios and estimated time of arrival for each scenario (e.g., Borrero and O'Neill⁶⁹)
Warning system information	<ul style="list-style-type: none"> ● Natural warning signs and the official tsunami warning system and alerting mechanisms for the area. ● What to do when a mariner sees, feels, hears, or receives a warning or alert.
Evacuation information	<ul style="list-style-type: none"> ● Advice on how deep/far the mariners should go for boat-based evacuations. ● Safe areas on land for land-based evacuations. ● A supply checklist for evacuation kits. ● Guidelines or considerations to aid in the decision of evacuating by foot or by boat (e.g., do not go at night, do not go alone, be fuelled up, consider other hazards and risks such as the weather). ● When to expect to return to the marina.
Regular evacuation drills ^{62,68}	<ul style="list-style-type: none"> ● By foot and by boat. ● Built into the response plan. ● Frequently occurring. ● Develop an understanding of the time needed for each type of evacuation.
Where to go for more information	<ul style="list-style-type: none"> ● Website links and QR codes. ● Pocket brochures. ● Business cards. ● Posters.

rapid-onset event. However, localized tsunami hazard awareness and response plans prepared in advance, with the community, may contain and help to increase understanding around the various uncertainties.

Conclusion and future research

Findings from this study contribute toward building our understanding of the complex decision-making of mariners when faced with a tsunami threat. This community's decision-making processes and needs can become more complex when another hazard, like a cyclone, poses an additional threat. When faced with a tsunami threat, mariners must decide when and how best to prepare and potentially evacuate based on: their location in relation to land and boat (e.g., they are on land already, on or near their boat in a harbor, on a boat moored in a bay, or on a boat at sea), the estimated time of arrival of the tsunami activity and location of impact, the magnitude or intensity of the tsunami activity, as well as the weather conditions, time of day, their own abilities as a mariner, and the advice of officials issuing any related warnings or other information.

Our findings also show the need to consider the combined risk and impacts of any other co-occurring, cascading, or compounding threats, such as cyclones. This is particularly important if threatened individuals and communities might perceive a higher risk or threat from one of the threats, rather than all threats combined. Thus, in line with the literature and in the context of our findings we suggest.

- (1) All agencies involved in the tsunami warning process coordinate with agencies who monitor and warn for other hazards (e.g., severe weather) to provide frequent and focused communication on the combined magnitude of impacts from multiple hazards to emphasize the danger they pose to the mariners;
- (2) Integrating broader expertise into the warning process for improved consistency, coordination, and credibility,

either through physical or virtual colocation of forecasters, scientists, decision-makers, communicators, and key community members/representatives.

The recommendations presented are grounded in the results of this case study and are based on additional evidence and recommendations from the broader national and international literature around tsunami and multi-hazard warnings and preparedness. Future research is needed to assess the cost-benefit of introducing tailored warnings that could hinder consistency and credibility. Research is also needed to progress model development for localized tsunami impact forecasts and warnings and to continue developing our understanding of communicating uncertainty effectively.

The expectation of tsunami sirens and Emergency Mobile Alerts (also referred to as Cell Broadcasting or Wireless Emergency Alerts) also emerged from our interviews as a theme worthy of further investigation as our findings differ from Vinnell et al.'s results in which surveyed Wellingtonians did not appear to think about sirens as prominently as our interviewees.⁸⁷ This could be due to the absence of tsunami sirens in Wellington, NZ, whereas tsunami sirens are actively used in Northland Region. Further analysis and investigation are needed to explore this apparent reliance on these warning channels on a national scale.

Limitations of the study

This case study employed a qualitative approach to understand mariners' experiences in the Tūtūkākā Marina of the 2022 HTHH eruption-induced tsunami and ex-TC Cody multi-hazard event. This case study provides empirical insights into the experiences of the Tūtūkākā boating community during and after the HTHH eruption-induced tsunami coinciding with an ex-Tropical Cyclone (Cody). The findings of this study are thus limited to the context of this community and the complex multi-hazard event. However, these experiences help to identify and

document limitations and gaps in the current warning system for mariners in such complex multi-hazard contexts, and also help to deepen our understanding of boaters' needs and expectations of tsunami warnings.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Sara E. Harrison (s.harrison@gns.cri.nz).

Materials availability

This study generated data on the qualitative themes reported in this study. This study did not generate new unique reagents.

Data and code availability

- Because of ethical and data protection reasons, the raw data of this study cannot be made publicly available. Nevertheless, materials generated in this study, e.g., thematic codes generated by the analysis, can be made available in anonymized form by the [lead contact](#) upon request.
- This paper does not report original code.
- Any additional information required to reanalyze the data reported in this paper is available from the [lead contact](#) upon request.

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AUTHOR CONTRIBUTIONS

S.E.H.: conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing – original draft, writing – review and editing. R.L.: data curation, formal analysis, writing – review and editing. L.K.: conceptualization, data curation, funding acquisition, project administration, writing – review and editing. S.H.P.: formal analysis, funding acquisition, project administration, writing – review and editing. D.J.: conceptualization.

DECLARATION OF INTERESTS

S.E.H., R.L., and L.K. are social scientists at GNS Science, the science agency involved in communicating tsunami and other geohazard related science information and advice to the National Emergency Management Agency (the official tsunami warning authority in New Zealand) and other stakeholders in New Zealand. The positions of the project team members were declared to all interviewees of the study and any concerns around transparency, objectivity, and reflexivity of the researchers were discussed before moving forward with the research.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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 - Human
- [METHOD DETAILS](#)
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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Raw and analysed qualitative data	This paper	N/A
Software and algorithms		
MS Word	Microsoft Corporation	https://www.microsoft.com/en-us/microsoft-365/word
MS PowerPoint	Microsoft Corporation	https://www.microsoft.com/en-us/microsoft-365/powerpoint
MS Excel	Microsoft Corporation	https://www.microsoft.com/en-us/microsoft-365/excel
MS Teams	Microsoft Corporation	https://www.microsoft.com/en-us/microsoft-teams/group-chat-software
Windows Media Player	Microsoft Corporation	https://support.microsoft.com/en-us/windows/get-windows-media-player-8178e0d-cfce-25b1-ae3-94596b658287
Mural White Board	Mural	https://www.mural.co

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Human

This study involved open recruitment for mariners in the Tūtūkākā Marina. A recruitment poster was displayed on the Tūtūkākā Marina noticeboard, and marina management circulated a recruitment email to marina tenants on behalf of the researchers. Potential interviewees contacted the lead researcher directly to indicate their interest in participating. Communication largely happened via email to schedule the interview date and time, however in some instances the lead research was requested by the individuals to call them via telephone to book in the interview; the lead researcher did as requested.

A High-Risk ethics notification was lodged with the Massey University Ethics Committee before recruitment commenced. Individuals were provided with the study Information Sheet to read prior to consenting to participate. Interviewees provided signed and informed consent before interviews commenced. Subsequent recruitment, interviews, analysis, and reporting were conducted in accordance with the ethical guidelines.

The research team did not collect the age, sex, gender, ethnicity, socioeconomic status, or ancestry from the interviewees as it was not deemed relevant to the study. The aim of the study was not to identify any of these as influencing factors for tsunami evacuation behaviour or response to warnings.

METHOD DETAILS

Interviews

Qualitative data were collected from interviews for this study from September to October 2022. The interview script was semi-structured and organised into five general themes: (1) Background and relationship with the marina, (2) experiences of the 15 January 2022 HTHH tsunami, (3) experiences of tsunami warnings and alerts and threat perceptions, (4) behaviours and evacuations, and (5) general improvements to the tsunami warning system for the community (including ‘blue-skies’ thinking).

Eight interviews were conducted from September to October 2022 with mariners who were either in the marina on the night of 15 January 2022 or who are tenants of the marina. All interviews, except one, were conducted in person and audio-recorded with the signed consent of the interviewees. One interview was conducted virtually via Microsoft Teams to suit the interviewee’s availability. All interviewees remain anonymous and are assigned an alphabetical code (A, B, C, etc.) and only identified as a “Mariner”, or “Business Owner”; who was “on board” or “in marina” on the night of 15 January 2022 (e.g., Mariner A – On board, or Mariner B, Business Owner A – In marina).

Thematic analysis

The interview recordings were thematically analysed⁴¹ using a mind mapping approach.⁴² The process involved the lead researcher first identifying the main topics (or themes) of the interview, placing the themes in the centre of the page, and drawing out branches and nodes as the researcher listened to the recording and identified key topics and subsequent themes. This approach was chosen due to time and resource constraints for verbatim transcription.⁴² This approach allowed the researcher to simultaneously and intimately transcribe, visualise, and analyse each interview. Throughout the process, the researcher identified new themes and wrote memos to summarise these themes after completing each mind map. A mind map was created for each interview.

At the centre of the mind map, the lead researcher drew an image to represent key relevant characteristics of the interviewees for easy contextual understanding and to protect anonymity. For example, interviewees who were on their boat on the night of 15th January 2022 were labelled as “on-board” and interviewees who live on their boats were labelled as “liveaboard”; the location of their boat in the marina in relation to marina damages or the presence of family or pets were also included in the image. The length of time of the interview was also noted down.

The initial themes of the interviews were deductively identified based on the five topics in the interview script: (1) Background and relationship with the marina, (2) experiences of the 15 January 2022 HTHH tsunami, (3) experiences of tsunami warnings and alerts and threat perceptions, (4) behaviours and evacuations, and (5) general improvements to the tsunami warning system for the community (including ‘blue-skies’ thinking). The lead author began the mind mapping process by drawing main branches for each of these five themes outward from the centre of a blank page, as described by Fearnley et al.⁴² The branches were colour-coded so that topic one (i.e., ‘Background and relationship with the marina’ was the same colour in all mind maps).

The interviews were played back using Windows Media Player. While listening to the interview, the lead author created sub-branches for new sub-topics that arose from the discussion. If a key point was made during playback that would provide evidence for the reporting (i.e., providing direct quotes), the time-stamp was noted at the respective branch so that it could later be transcribed. During this process, the lead researcher did not attempt to identify the importance of any of the sub-topics or connections, rather the focus was on creating a visual transcription of the interviews for further analysis. After each mind map was completed, the lead author wrote a summary of the interview on the reverse side of the page and noted any key points, such as what the individual did in the marina after they observed potential tsunami activity (e.g., try to secure objects, inform other people in the marine, go to higher ground).

The next analytical phase involved relating the themes identified in each interview together. A virtual white board (Mural) was used to digitise and consolidate the mind maps into one consolidated mind map, with the common sub-themes from the individual mind-maps grouped into categories.⁴¹ For example, within the main theme of Behaviours and Evacuations, two categories were identified as ‘Evacuating by Boat (to Sea)’ and ‘Evacuating on Land (by foot or car)’. Within these categories, themes of ‘Lead Time and Time to Evacuate’, ‘Conditions (e.g., Time of day, weather)’, ‘Where to Go’, ‘Being out on the Water/Sea’, and ‘Issues Around Returning to Land’ were identified as common sub-themes that helped to develop an understanding of the mariners’ evacuating decision-making contexts.

The Protective Action Decision Model (PADM)¹² was used as an analytical framework to identify sub-themes within the main theme of the mariners’ experiences of the 15 January 2022 HTHH tsunami. For example, the themes of Information Seeking, Awareness, Risk Perceptions, Environmental Signals that individuals observed, and the resulting actions they took were deductively identified based on the PADM framework. Reflective notes were written for each main theme to identify and define categories and sub-themes within the categories.

The resulting categories and themes were then used to devise the key narrative and arguments which we report on next, supported by evidence from direct quotes of the interviewees.