Tsunami Modeling and Mapping: Guidelines and Best Practices

Part VI: Guidelines and Best Practices for Tsunami Hazard Analysis, Planning, and Preparedness for Maritime Communities

National Tsunami Hazard Mitigation Program
Mapping and Modeling Subcommittee, Mitigation and Education Subcommittee, Warning Coordination Subcommittee, and Mitigation and Response Planning Workgroup

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Purpose of Maritime Planning and Preparedness Guidelines

The purpose of these guidelines is to develop recommended standards for NTHMP partners to use to develop consistent and reliable tsunami preparedness products for maritime communities: those communities with commerce and/or population infrastructure having either a reliance on waterways, or that are near water. With recent tsunamis, including the 2011 Great East Japan (Tohoku) event causing over $100M in damage to U.S. ports and harbors, there is a need to develop guidelines and consistent products that help maritime officials plan for and reduce tsunami hazards. These impacts include vessel damage from strong currents, fluctuating water levels, and sediment and debris movement. Guidance for both offshore and onshore evacuation, as well as the expected time of strong currents would reduce overall exposure to tsunamis. The NTHMP develops guidelines for tsunami products (such as evacuation maps) to standardize symbology, promote a consistent message, make signage recognizable, and support cross state/territory user needs. This document outlines recommended standards for maritime tsunami products, including modeling, map making, preparedness products, maritime response, and guidance documents. The NTHMP cannot require an individual state or territory to comply with these guidelines; however, NOAA -funded agencies producing tsunami hazard products and maps should adopt these guidelines. For consistency, and to minimize public confusion, all other organizations doing similar work are also strongly encouraged to adopt these guidelines.

Objectives and Scope of the Guidelines are:

- To promote accurate and consistent tsunami hazard mitigation and recovery products to provide information that users (emergency managers, harbor masters, general public citizens, etc.) may base their actions.
- To depict the area(s) affected by tsunami hazards and possibly safe areas from a tsunami.
- To assess maritime community risk using tsunami modeling and/or community information.
- To facilitate and encourage coordinated emergency response planning activities between federal, state, local, and maritime partners.

These guidelines are divided into several sections based on the needs of the product developers and users. The four NTHMP subcommittees/work group, Mapping and Modeling (MMS), Warning Coordination (WCS), Mitigation and Education (MES), and Mitigation and Recovery Planning Work Group (MRPWG) are responsible for developing and maintaining the following sections of this guidance document:

- **Section 1: Tsunami hazard analysis, modeling, and mapping (MMS)**
- **Section 2: Tsunami response, preparedness, and education (MMS, MES and WCS)**
- **Section 3: Tsunami mitigation and recovery (MMS, MES, and MRPWG)**

The following Section 1 addresses guidance for tsunami hazard analysis, modeling, and mapping products for the maritime community. This section covers aspects of tsunami hazard analysis, associated modeling and mapping products that demonstrate the tsunami threat for maritime communities, and addresses some aspects of tsunami response and preparedness as they relate to specific hazard analysis products.

Intended Audience

These guidelines and best practices are intended for government and non-government entities responsible for emergency response planning and overall safety of harbors/ports; this group is referred to in this document as the "maritime community." These entities may include:

- Federal Government– NOAA, Coast Guard, other military/Dept. of Defense, U.S. Army Corp of Engineers, U.S. Geological Survey, Federal Emergency Management Agency
- State Government – emergency services, geological surveys, coastal hazards organizations, boating/waterways, departments of transportation
- Tribal Government – emergency services, port authorities, coastal hazards organizations, boating/waterways, police/fire
- Local Government – emergency management, police/fire, port authorities, lifeguards, park rangers
- Quasi-governmental or Special Districts - port and harbor district officials such as harbor masters, harbor patrol, harbor engineers
- Non-government – private harbor masters, port captains, harbor patrol, harbor engineers, some vessel owners, county ferries
- Academic – researchers, engineers, modelers

It is essential that local emergency managers, tsunami scientists, and maritime communities work closely together to produce accurate and seamless tsunami response plans. We recommend that states and territories form "Maritime Advisory Committees" or Work Groups to help guide product development and implementation of these products. All planning should be coordinated with state tsunami programs and local emergency managers responsible for on-land tsunami evacuations. Though these guidelines apply to partners who receive NOAA NWS tsunami funding, they are also recommended for use by other organizations looking for direction in producing similar products. A simplified approach to follow this guidance reflects the following:

- Entities planning to create local maritime guidance or products should consult with the maritime communities to a) share examples of products, which can be produced for tsunami planning; b) determine what response capabilities the maritime communities have; and c) match the products to their needs and capabilities.
- All numerical models used should be verified and meet NTHMP benchmark criteria and should follow the acceptance process developed by the NTHMP Mapping and Modeling Subcommittee.
- Modelers should use source parameters that appropriately capture the tsunami hazard for planning.
- Topobathy digital elevation models used in numerical tsunami modeling should have an adequate resolution (1/3" or better is preferred) that would accurately capture permanent structures, such as jetties and/or levees, within the harbor or port of interest.
- All products should be accompanied by detailed explanations of their purpose, limitations in modeling, and how they were produced.
- Planning tools should be straightforward for use by maritime authorities but should also allow for response to tsunamis of different sizes, especially those with Advisory and Warning alert levels. These tools should also include a response plan for local source tsunamis, as there will not likely be enough time for tsunami warning centers to issue official alert information.
- Maritime communities should be encouraged to consistently exercise their tsunami response activities on a regular basis.

Section 1: Guidance for Tsunami Hazard Analysis, Modeling, and Mapping

These guidelines have been developed based on the tsunami response and planning experience of various interstate and territory maritime communities, and the results of detailed tsunami hazard analyses by government and academic institutions. Example projects (e.g. California harbor improvement studies, Washington, Oregon, and Hawaii maritime studies/strategies) have provided valuable analyses and practical solutions. Where appropriate, these examples are referenced in the guidance.

To determine the appropriate tsunami mapping products and guidance for use by maritime communities, possible tsunami hazards and damage should be assessed using the most up-to-date scientific information available. Examples of maritime tsunami hazards and potential related damages:

- Sudden and significant water-level fluctuations, which can cause:
    - Vessels and docks to hit bottom (grounded) as water level drops,
    - Vessels and docks to overtop piles as water level rises.
- Strong, unpredictable, and damaging currents typically occur where there are narrow passages, channels, or harbor openings, in addition to notable bathymetric and topographic features or man-made structures that form constrictions.
- Tsunami induced bores, seiches, and amplified waves can swamp vessels and damage docks.
- Eddies/whirlpools can cause vessels to lose navigation control.
- Drag forces on deep draught vessels can add to the hydrodynamic forces and potential damage to the docks they are moored to.
- Free floating boats, docks, ice and/or debris in the water can collide with each other and harbor structures.
- Long duration of dangerous tsunami conditions, potentially for tens of hours after first wave arrival, can cause problems for inexperienced and unprepared boaters who may try to move their vessels within harbors, take their boats offshore during such prolonged tsunami conditions, and try to return to harbors still experiencing strong currents.
- Sediment movement that causes both erosion and deposition/sedimentation can create hazards to navigation and cause damage to harbor structures.
- Hazardous material issues with debris and contaminants in the water can cause environmental hazards and slow recovery processes in ports and harbors.

1.1 Use of Numerical Tsunami Models and Digital Elevation Models

All entities receiving funding from NOAA through the NTHMP should demonstrate the validity/accuracy (e.g. model benchmarks, pilot studies) of the numerical model(s) used to develop maritime products and guidance documents. For maritime work, the accuracy of numerical modeling of tsunami currents should be first verified prior to using a particular model.

During the 2011 NTHMP Model Benchmarking Workshop, a suite of numerical models was verified and benchmarked for use to determine tsunami inundation and run-up (NOAA, 2012; Horrillo et al., 2014). In 2015, a tsunami current benchmarking workshop, similar in process to that of the 2011 workshop, was held to address the adequacy of tsunami models to capture current velocities. This was accomplished by comparing model results to real tsunami velocity data from controlled wave-tank experiments, acoustic doppler current profiler (ADCP) data, and video interpretation (Lynett et al., 2017). Results from the workshop indicated that most models proposed for use by NOAA and NTHMP members are similar in their ability to identify areas of high currents, but vary in accuracy for predicting current velocity magnitudes, especially where jetting and eddies occur. In general, models of increasing physical complexity provide better accuracy, and low-order three-dimensional models are superior to high-order two-dimensional models (Lynett et al., 2017). Model-data errors and inter-model differences were found to be especially large inside navigation channels, marinas, and waterways affected by eddies, such that the errors may be comparable to the magnitude of the mean flow. In view of these deficiencies, Lynett et al. (2017) concluded that currents in areas where eddies form and are expected to migrate might be better simulated by: 1) evaluating multiple numerical models and combining the results to capture the maximum current velocities; 2) binning modeled current velocities into numerical categories related to damage potential, to reduce the reliance on absolute accuracy of the velocities; and/or, 3) identifying and encircling the areas where eddies are expected to be generated and migrate. These three options will be addressed in more detail in later sections.

In addition to accurate numerical models, high-resolution digital elevation models (DEMs) should be used to adequately capture maritime structures and other important features within harbors and ports. Lynett et al. (2014) demonstrated that the relative accuracy of DEMs starts to converge between 10m and 30m resolution. Therefore, the NTHMP recommends using DEMs of at least 10-meter resolution (if available) to capture details within harbors and ports, if such 10m resolution DEMs are available. If models rely on DEMs coarser than 10m resolution, modelers should verify that modeling results have converged at the coarser resolution based on results of the benchmark problems.

DEMs should be constructed using the best available bathymetric and topographic elevation data at the time of development and should then be evaluated by local experts familiar with the region of interest. For most areas of the U.S. coast, the NOAA National Centers for Environmental Information (formerly National Geophysical Data Center) has produced bathymetric-topographic DEMs at 10m resolution or better, specifically for use by numerical tsunami models. High resolution (1m to 2m) bathymetric and topographic LiDAR data have been recently collected in many coastal areas and are now being used to update the topography of existing tsunami DEMs. It is important to cite the source and date of the DEM(s) used in the modeling, in addition to noting any corrections made, prior to modeling. Modelers may also want to consider undertaking tsunami simulations that account for dynamic (fluctuating) tides and where applicable, riverine discharge. Analyses of these effects in the Hudson River estuary (New York) and along the Oregon coast demonstrated the importance of non-linear interactions between tsunami, tides and river flow in ports and harbors and especially at the mouths of estuaries (e.g., Shelby et al., 2016; Allan et al., 2018). These non-linear responses were also apparent in distal upriver locations where later arriving tsunami waves sometimes coincided with high tides or strongly ebbing currents, producing higher water levels than expected from a linear superposition and, hence, greater potential for inundation. However, the biggest differences observed were in the magnitude of the currents generated. In the absence of more sophisticated modeling, simulations on the Oregon coast confirmed that modeling undertaken using static tides (MHHW/MLLW, or MHW/MLW as in Washington maritime strategies), with appropriate friction, generally produced results that were sufficiently conservative for developing tsunami maritime hazard maps (Allan et al., 2018). However, this was not the case within long and narrow estuaries such as in the Hudson River (Shelby et al., 2016). It is thus recommended that modelers use their best judgment and make the most conservative hypotheses in situations where strong tsunami/tide interactions may be suspected to occur.

1.2 Maritime Tsunami Hazard Preparedness Products

Maritime tsunami hazard preparedness products may include maps, plans, and brochures that are printed, digital files, or interactive/web-based information. Specific tsunami hazard mapping products that are likely most useful to maritime communities are:

- **Identification of areas of past tsunami damage and strong currents**
- **Mapping current velocities and their relationship to damage**
- **Identification of areas of potentially large water-level fluctuations**
- **Identification of areas with potential bores, seiches, or amplified waves**
- **Identification of time frame for damaging currents**
- **Identification of safe minimum offshore depth**
- **Identification of tsunami inundation and evacuation options for maritime residents or employees**

Discussion of these products follows and will be the focus of the modeling and mapping portion of this guidance. Guidance will be provided for both the "development" and "use" of each of these products. Where appropriate, hazard product developers should reference and utilize the general map instructions that can be found at the end of this section of the guidance, unless it conflicts with other more specific guidance for each tsunami hazard product. Simulations showing current velocities and directions could provide a visualization of hazard analyses that would help educate harbor personnel as well as the public regarding the potential impacts of such hazards.

Product 1: Identification of Areas of Past Damage and Strong Currents

Historical documents, personal accounts, and videos from past tsunamis should be researched to determine if, where, and how much damage occurred in a specific maritime community during past documented tsunamis. The NOAA National Centers for Environmental Information historical tsunami database is the most comprehensive data source and should be a starting point for information and other references. Newspapers and private photo collections might also be sources for information. For more recent or modern tsunamis, current velocity instruments (e.g., ADCPs), online and security camera videos, and interviews with harbor personnel may provide the most accurate information. One should, however, keep in mind that although the general public may provide personal accounts of tsunami currents and damage, experience has shown that such accounts may be exaggerated or inaccurate due to the general public's lack of experience in making such observations. In addition to noting areas of damage, it is recommended to collect information on where strong currents and sediment movement were observed as well as areas where strong currents seemed absent.

Guidance recommendations:

Once sufficient historical information is obtained, create a database and possibly maps showing the areas impacted by past tsunamis. For example, Wilson et al. (2012) developed maps showing where strong and erosional currents had developed in Santa Cruz Harbor during the March 11, 2011, Tohoku-Oki tsunami (Figure 1). Table 1 also demonstrates how historical tsunami information, especially in maritime communities, can be summarized. Historical information will help members of maritime communities understand the severity of past tsunamis for future reference. If there are sufficient details, the historical database should also include information on how and where the damage occurred. This information can be used to not only develop tsunami response scenarios for a particular harbor, but it can also help validate numerical models of tsunami currents and damage. The State of California has produced harbor-specific tsunami response decision support tools that are scenario-based guides for port and harbor officials. These are referred to as "California Maritime Tsunami Response Playbooks" and they address tsunami currents, wave heights, potential damage, and offshore safe depths for vessels. The guides were developed following the California Geological Survey's Special Report 241 (Wilson et al., 2016).

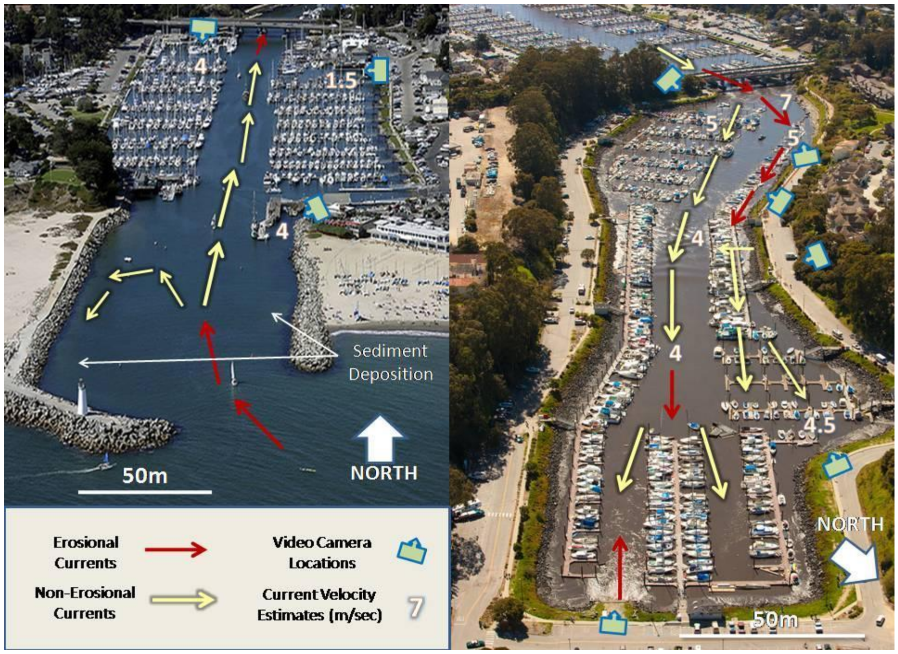


Figure 1: Location of strong and erosional currents inside Santa Cruz Harbor during the 2011 Japan tsunami (from Wilson et al., 2012).

Table 1: Example table showing impacts from historical tsunami events in Santa Cruz County, modified from the Maritime Tsunami Response Playbook for Santa Cruz Harbor (CGS et al., 2020).

Notable Historical Tsunamis in Santa Cruz County

Run-up amplitude, in feet, above normal tide conditions

OBS = observed tsunami activity
NR = No damage or severe conditions reported

- Distant Source - Tsunamis without felt earthquakes

- Local Source - Earthquake and tsunami together

Date	Magnitude-Source area	Tsunami location	Run-Up/ Amp	Remarks
1/16/1840	M6.3? (storm)	Santa Cruz	OBS	flooding 200 yds inland
10/8/1865	M6.5 - San Andreas Fault	Santa Cruz	OBS	"...tide rose and fell with convulsive throbs..."
		Soquel	OBS	"...(ocean) very rough and cross cutting..."
10/21/1868	M6.8 - Hayward Fault	Santa Cruz	OBS	"...(San Lorenzo River) commenced rushing upstream..."
5/10/1877	M8.3 - Chile	Santa Cruz	4-5 ft	NR
6/15/1896	M8.5 - Japan	Santa Cruz	4-5 ft	destroyed protective dike; damage to ship
11/11/1922	M8.5 - Chile	Santa Cruz	OBS	strong currents; no damage
2/3/1923	M8.5 - Kamchatka	Santa Cruz	OBS	strong currents; no damage
4/1/1946	M8.8 – Aleutian Islands	Santa Cruz	10 ft	One drowning; some damage
11/4/1952	M9.0 - Kamchatka	Santa Cruz	OBS	boat damage; "...(swells) running for several days..."
5/22/1960	M9.5 - Chile	Santa Cruz	3 ft	flooding up to base of boardwalk
		Capitola	OBS	flooding over seawall
3/28/1964	M9.2 – Alaska	Santa Cruz	10 ft	boats sunk leaving harbor; $100k in damage to boats, infrastucture
		Capitola	6 ft	flooding over Esplanade seawall
		Rio Del Mar	OBS	dramatic tidal changes
2/4/1965	M8.2 - Aleutians	Santa Cruz	2 ft	NR
10/18/1989	M6.9 – Loma Prieta	Santa Cruz	1 ft	minor dock damage from tidal fluctuations
9/29/2009	M8.0 – Samoa	Santa Cruz	1-2 ft	strong currents; no damage
2/27/2010	M8.8 – Chile	Santa Cruz	2-3 ft	minor damage in harbor; strong currents
3/11/2011	M9.0 - Japan	Santa Cruz	5-6 ft	significant damage in harbor; $22M in damage
1/15/2022	Tonga-Region Volcanic Eruption	Santa Cruz	5-6 ft	flooding on beach and inside harbor (tsunami+high tide); $6.5M in damage

California Department of Conservation California Geological Survey Seismic Hazards | Tsunami Unit
Cal OES
USC
AECOM
FEMA
THE NATIONAL TSUNAMI HAZARD MITIGATION PROGRAM (U.S.)

Product 2: Mapping Current Velocities and their Relationship to Damage

Much of the tsunami damage that happens inside harbors can be directly attributed to strong currents. Maps identifying areas of strong tsunami currents, as well as areas where little or no currents are likely to exist can be a useful tool for harbor response and mitigation planning. Although maps showing historical tsunami information are helpful, tsunami currents from numerical modeling of historical or scenario tsunami events will be more useful for harbor response planning purposes because they can address multiple scenarios.

As previously noted, there are potential limitations to models in both accuracy and adequately capturing areas where eddies form and subsequently move away from the generating area. Therefore, additional precautionary steps should be taken to ensure that areas where dangerous tsunami currents may occur are correctly identified. In addition, it is recommended that products for tsunami planning be as simple as possible to understand and use.

Guidance recommendations:

Once a numerical model is verified as being adequate[1] for use, the following guidance for modeling and resulting map production should be followed:

- Select a suite of historical events and synthetic tsunami scenarios as model input. These scenarios should represent various events that would trigger Advisory-level alerts and small, medium, and large Warning-level alerts. The considered scenarios can be utilized for planning harbor response for future events. Ideally, it would be helpful to model scenarios that can identify the threshold(s) where damage starts to occur and where in-harbor actions are necessary.
- Use DEMs with a minimum grid resolution of 1/3" or better (or best available) that captures all important solid, permanent structures within the harbor/port, which could influence currents. DEMs should incorporate recent bathymetric data that represents the average depths considering dredging activities. Make sure that structures that allow for water movements beneath (wharfs, docks, piers) are not solid features in the DEMs. Prior to any modeling, DEMs should be checked for accuracy by local harbormasters and/or other local authorities.
- Consider modeling scenarios at both high and low tide conditions to determine if there is a significant impact on the current velocities and flow dynamics in the harbor. As previously mentioned in section 1.1, modeling of dynamic currents may be useful in areas of strong fluctuating tides, such as riverian settings. Low tides can increase currents where flows are restricted, and high tides can increase flooding of land adjacent to harbors because of increased flow depths.
- If feasible, save the time-history of the numerical modeling output results for all runs. This information can be used for production of other tsunami hazard products discussed in this guidance. Once the currents are modeled accurately, current velocity maps or derivative maps relating currents to damage (e.g., through momentum force, which increases with the square of current velocity) can be produced.

Lynett et al. (2014) determined that damage in harbors might vary based on the age and location of docks and boats yet noted some generalities about the relationship between tsunami currents and damage. One such generality, as shown in Figure 2, is the trend of increasing damage with increasing current speed. In these data, there is a noticeable threshold for damage initiation at ~3 knots [~1.5 m/s]. When 3 knots are exceeded, the predicted damage level switches from a no-damage to minor-to-moderate damage category. Thus, in the simulated data, 3-knots represents the first important current velocity boundary. The second threshold is at ~6 knots [~3 m/s], where damage transitions from moderate to the major category. A third current speed threshold is less clear but seems to be around 9 knots [~4.5 m/s], where the damage level moves into the extreme damage category. Additional damage observations with correlated current predictions are needed to better define the latter threshold. More recent data indicate that although the 3-6-9 knot thresholds work for newer (<30-40 years old) and well-maintained docks and

[1] To improve identifying areas of potentially dangerous currents, modelers may consider an ensemble modeling approach; one in which multiple verified models are run and then the maximum value at each pixel/grid from the multiple runs is selected. In selecting specific models, a modeler is encouraged to include as part of their ensemble modeling, a high-order or 3-D model to verify results.

harbor infrastructures, velocity thresholds of 2-5-7 knots might be more appropriate for older (>40-50 years old) and less maintained docks (Pat Lynett, personal communication).

Damage Index:	Damage Type:
5	Complete destruction
4	Major dock/boat damage, large vessels off moorings
3	Moderate dock/boat damage, mid-sized vessels off moorings
2	1-2 docks/small boats damaged, large buoys moved
1	Small buoys moved
0	No damage

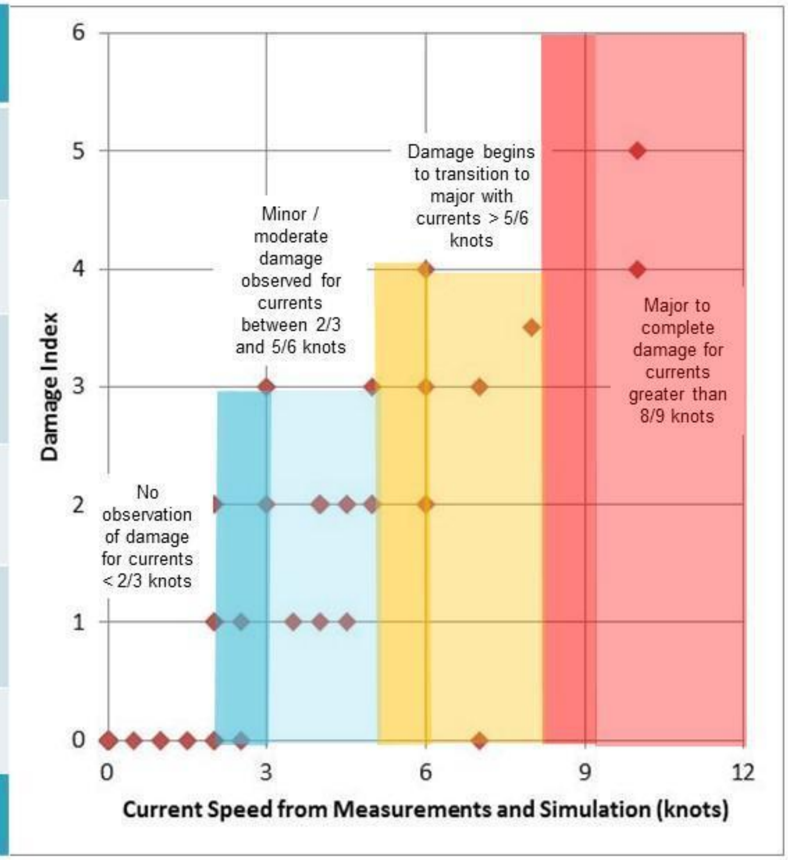
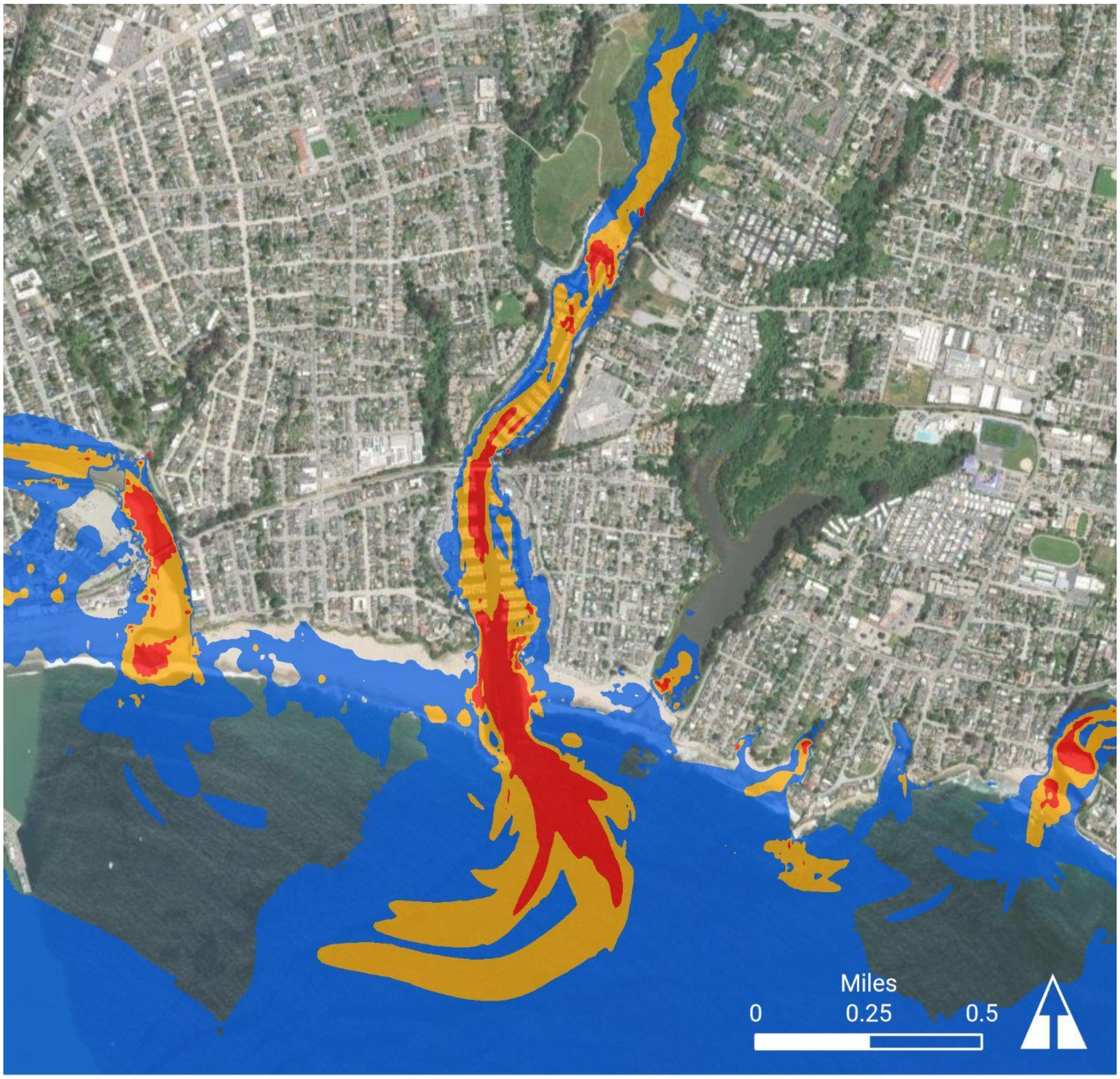


Figure 2: Graphic showing the relationship between tsunami current velocity and damage in a number of harbors and real events. The red points represent damage-current data from past events and tsunami modeling (modified from Lynett et al., 2014).

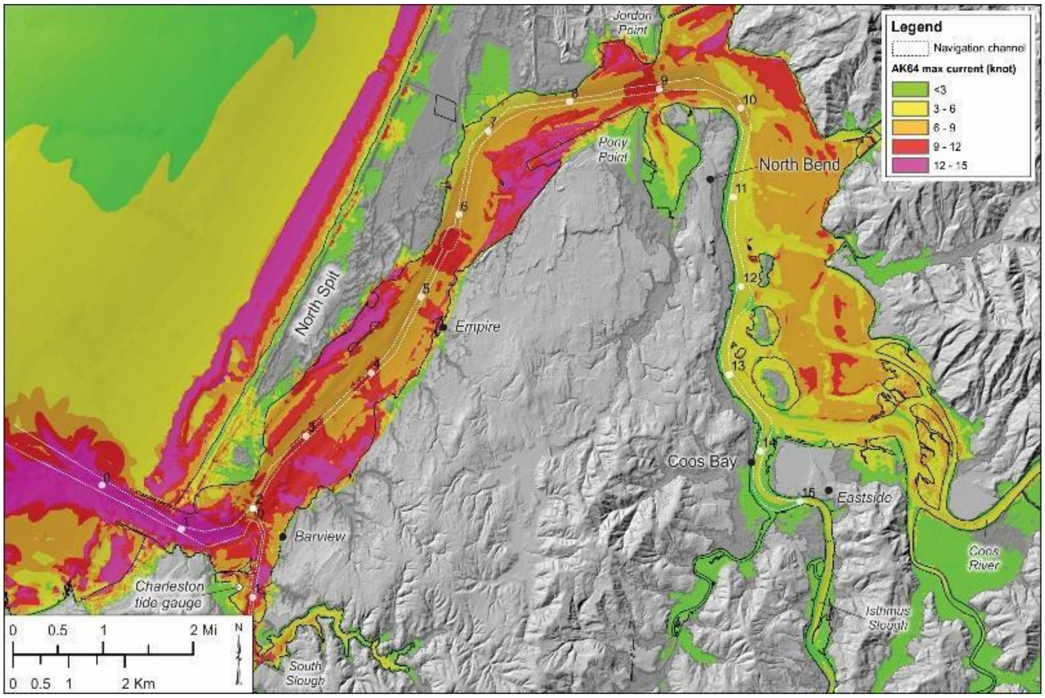
Figures 3 and 4 illustrate how classes based on the three current thresholds can be used to categorize potential damage levels in analysis of tsunami currents in ports and harbors. These maps can be displayed as individual scenarios representing a variety of potential tsunami events of various sizes, or all scenarios can be combined into one single envelope map to demonstrate what the "worst case" conditions might be throughout the harbor. Model results should be carefully reviewed to ensure that eddy formation and movement are accurately captured. Figure 3 shows an example of how these areas of potential eddies or strong currents not fully defined by the modeling can be identified for maritime planners. The final products should be in line with what the maritime communities and the local emergency managers would like to use in response and mitigation planning. When displaying multiple scenarios, the colors chosen to represent and distinguish the current thresholds should have a consistent scale for the best comparison.



TSUNAMI CURRENT SPEED AND POTENTIAL DAMAGE

Current Speed	Damage Type	Potential Damage
0-3 Knots	No Damage	HAZARDOUS CONDITIONS in coastal waterways may still exist for swimmers, surfers, and boaters.
3-6 Knots	Minor/Moderate Damage	STRONG CURRENTS & POTENTIAL SCOUR. Docks/small boats damaged, large buoys moved.
6-9 Knots	Moderage/Major Damage	STRONG CURRENTS & DANGEROUS CONDITIONS. Potential for moderate dock/boat damage, mid-sized vessesl off moorings.
>9 Knots	Major/Complete Damage	DANGER! Potential for extreme currents, major dock/boat damage, and large vessels off morrings.

Figure 3: Example map from the Maritime Tsunami Response and Mitigation Playbook for Santa Cruz Harbor showing areas of potential damage due to strong currents (in development CGS et al., 2025).



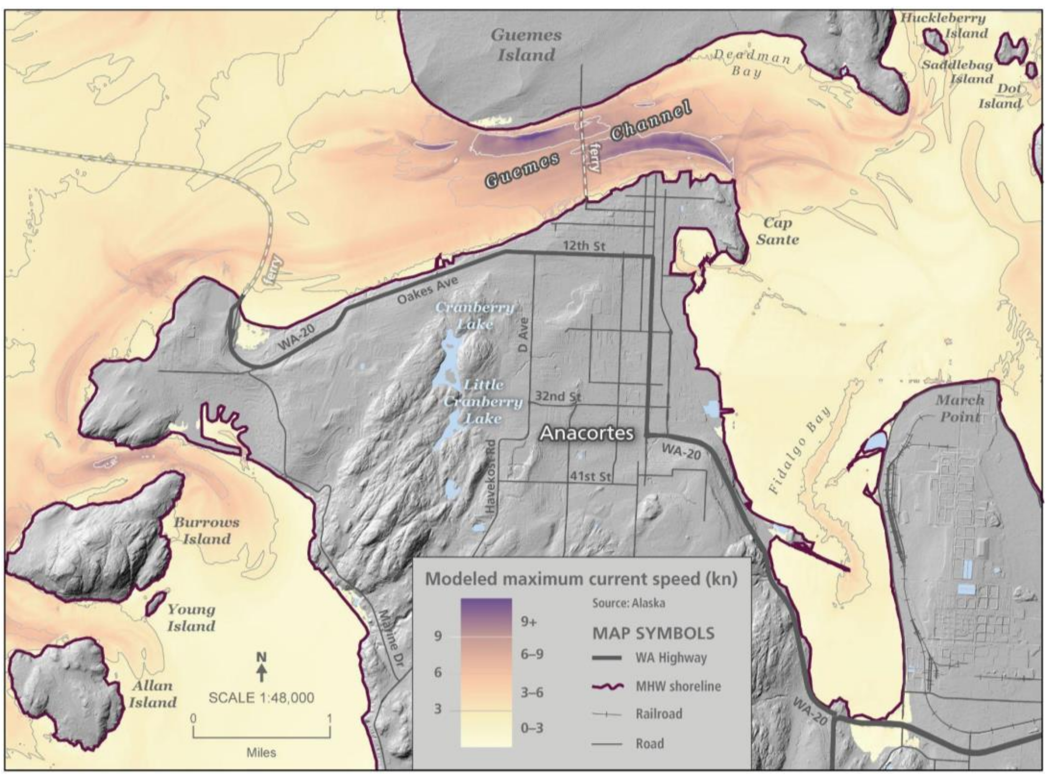


Figure 4 Top: Example map from Coos Bay, Oregon showing modeled currents generated by an Eastern Aleutian, Alaska (AKMax) tsunami (Allan et al., 2020), which may indicate where damage would be concentrated.
Bottom: Example map from Guemes Channel Maritime Strategy, Anacortes Washington showing modeled tsunami currents generated by a M9.2 earthquake simulated along the Alaska-Aleutian Subduction Zone, which may indicate where damage would be concentrated (Washington Emergency Management Division, 2024).

Product 3: Identification of Areas of Potentially Large Water-level Fluctuations

Sudden large water-level fluctuations during a tsunami can lead to a variety of hazards inside harbors. As the water level shallows, the keel of boats can be damaged by impacting the seafloor or may become stuck in muddy bottom sediment or debris. Vessels moored alongside docks and piers can torque and break mooring lines and/or collide with the docks themselves and cause damage. In addition, as water levels increase, vessels can also float onto the top of docks or piers, causing damage to harbor infrastructure. If water-levels are high enough, docks may overtop their piles and float away, creating additional debris and damage. For example, although ports may appear less vulnerable to tsunami damage, free floating vessels, docks, and other debris from small boat basins within ports can impact large ships and block waterways within ports. Relocating ships within waterways during a tsunami is generally not recommended as large sudden drops in water level could occur, creating shallow conditions and associated strong currents in navigation channels. However, in certain instances, relocation of specific vessels areas of lesser risk (or removal from the waterways) may be recommended in some distant tsunami scenarios after considering numerous event-specific factors. These factors include, but are not limited to the following: 1) the size of the tsunami, 2) the timing of tsunami impacts, 3) the time and distance required for safe relocation, 4) the preparedness and skill level of crew, 5) the current weather and tide stage; and if for vessel removal from the waterway, the time needed for removal in addition to the time required to evacuate from the hazard zone prior to onshore tsunami inundation.

An approach to include both tsunami forecast amplitudes and sea-state conditions has been developed as part of the California Tsunami Evacuation and Maritime Response Playbook Series, which are decision support tools for emergency response (Wilson et al., 2016). The approach incorporates National Tsunami Warning Center forecast amplitudes, along with anticipated maximum tidal and storm conditions centered around the expected time of tsunami arrival, within computed error bounds. The tsunami <u>F</u>orecast <u>A</u>mplitudes, <u>S</u>torm and <u>T</u>idal conditions, <u>E</u>rrors in the modeling, and <u>R</u>un-up potential (FASTER) method (Wilson and Miller., 2014), provides a conservative total-water elevation value, which can be used to identify secondary evacuation plans for response. Additionally, the FASTER value may be used to indicate approximately how high the water will get within a harbor and can be used to identify docks that might overtop piles and any area of normally dry land that is expected to flood.

Figure 5 provides an illustration of how the FASTER total-water elevation value is utilized in real-time to determine whether water level will be high enough for docks to overtop piles. Although this method was not available during the January 15, 2022, Hunga Tonga tsunami, because forecasts of tsunami amplitudes were not available, the combination of high tides with a moderate Advisory-level tsunami resulted in water-level increases and flooding of land around Santa Cruz Harbor (Patton et al., in press).

Guidance recommendations:

Maps identifying the magnitude of total water level change (maximum surge and drawdown), as well as the highest and lowest water levels relative to a set elevation or tidal datum could be developed. Products showing total predicted surge and drawdown could prove to be useful information to harbormasters when deciding vessel-specific mooring locations within a harbor or marina. Figure 6 provides an example of both tsunami surge and drawdown estimations at the Hilo Harbor from Hawaii (Cheung, 2018), while Figures 7 and 8 provide various examples showing the highest and lowest water levels relative to a model datum. Modeled wave variations recorded at specified synthetic tide gauges can also depict how the sea surface may fluctuate over the course of a tsunami event (Figure 9). In the absence of modeling, harbors can measure the height of the lowest dock piles and lowest shoreline around the harbor to understand at what point docks may overtop piles or dry-land inundation might first occur. When modeling is planned for a specific harbor or port, the following steps should be followed to produce tsunami hazard maps that will help identify potential areas of large water fluctuation (peak and trough elevations) and where shallow harbor conditions might occur during an event:

1. Simulate scenarios for significant potential tsunamis and utilize modeled time history results from the suite of runs to develop a map that shows the difference between the maximum peak and trough amplitudes through the harbor.
2. Using a common tidal datum, subtract the layer showing the maximum trough or low water from the bathymetric DEM. Areas of negative values will represent the potential areas where the harbor bottom will be

exposed, as well as where shallow areas will exist within the channels. Calculating the maximum low tsunami water level from a Mean Lower Low Water or Mean Low Water (MLLW/MLW) datum will provide a conservative picture for potentially exposed areas.

- Drawdown values (or inversely surge values) can be calculated by subtracting the minimum water depths from the initial modeled tide stage (or maximum water depths if surge). The absolute value of this calculation equals maximum drawdown.

3. Identify the expected high-water level. The modeled maximum flow depth added to the Mean Higher High Water or Mean High Water (MHHW/MHW) datum can be used to identify how high water can get. This could be compared with elevations of permanent piers and docks to see where ships might overtop them. Ensure that all comparisons are based on the same vertical/tidal datum or zero elevation.

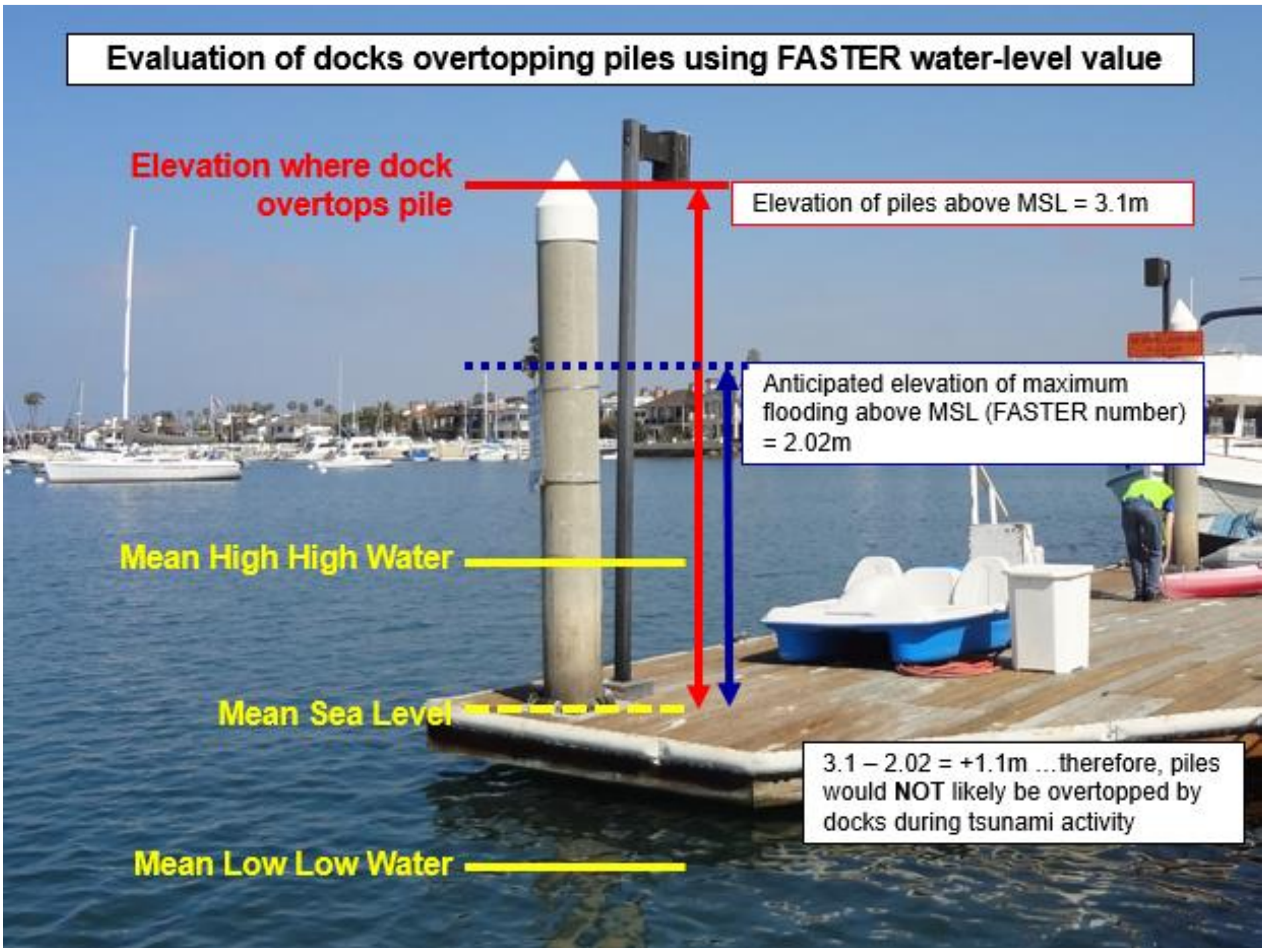


Figure 5: FASTER water-level value or elevation considers forecasted tsunami amplitude, tidal height, and storm surge level. It represents the potential maximum flood elevation during tsunami activity (different from tsunami amplitude by itself). The FASTER number can be compared to the absolute pile height to help determine if docks will overtop piles or tsunami flooding will inundate dry land around the harbor.

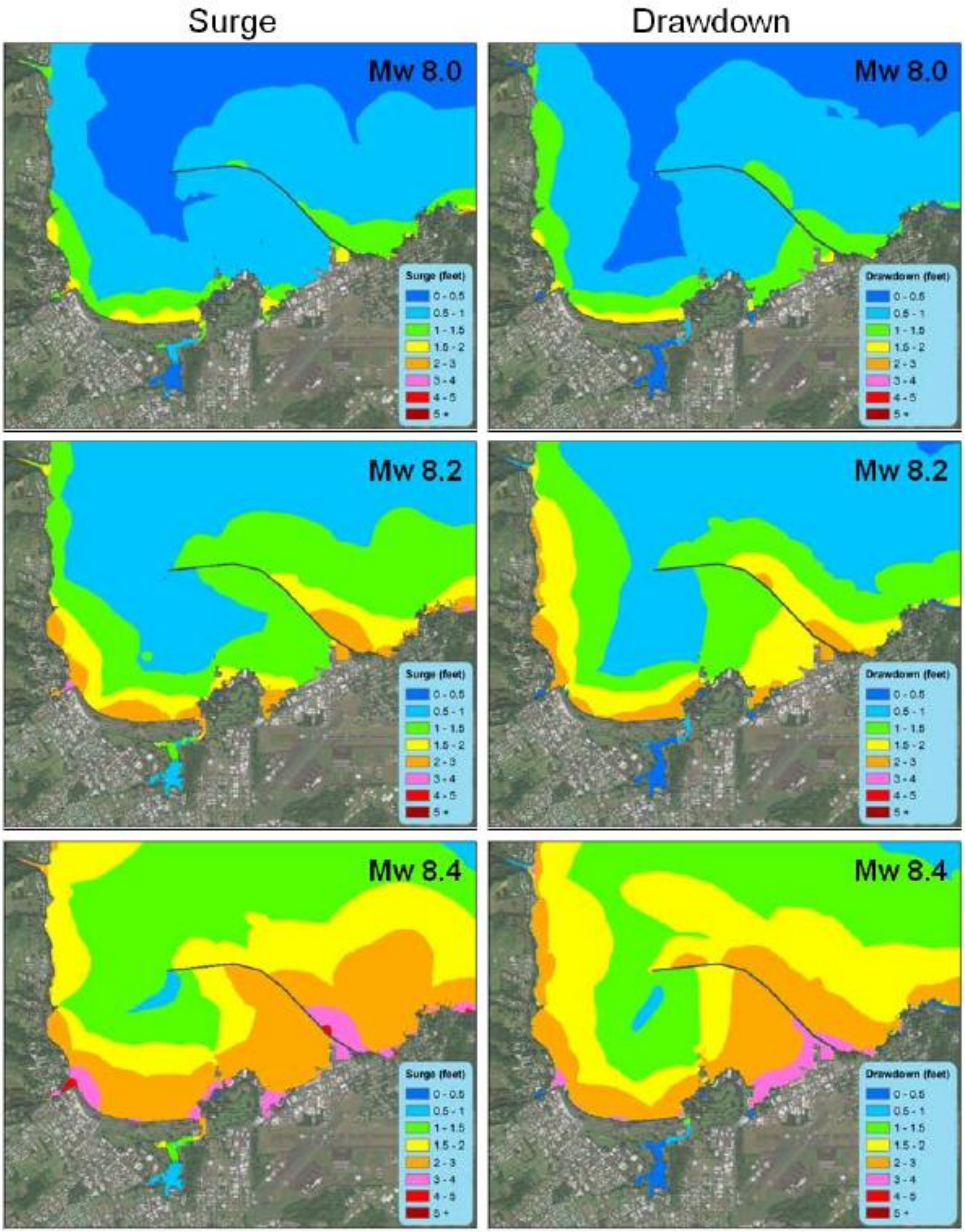


Figure 6: Maximum surge and drawdown at Hilo Bay for the Mw 8.0, 8.2, and 8.4 Kamchatka events (Cheung, 2018).

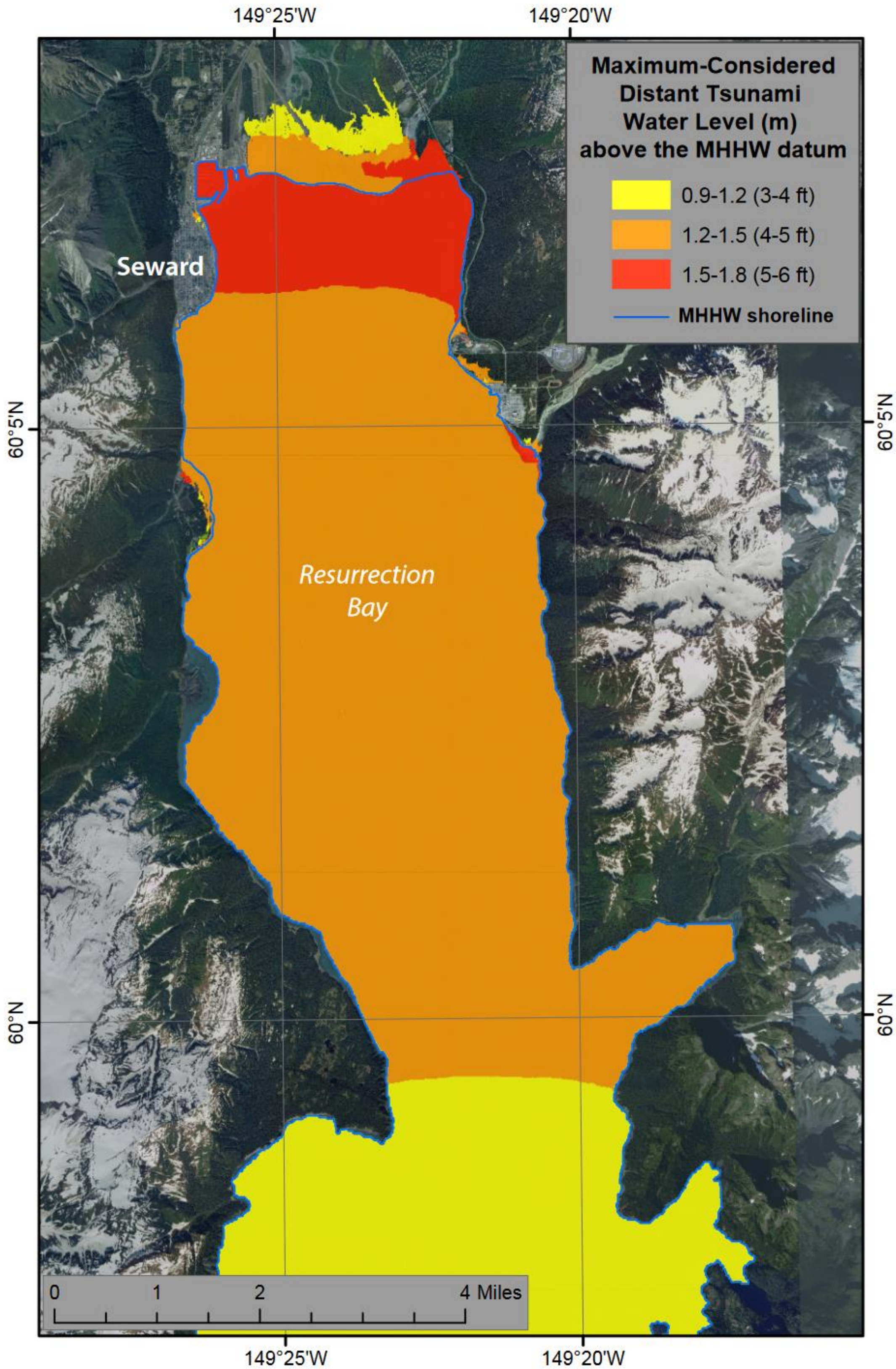


Figure 7: Maximum height above tide map in Resurrection Bay, Alaska, for a maximum-considered distant source tsunami. Note that the Mean Higher High tide is 4.3 feet above geodetic Mean Sea Level (Nicolsky et al., 2020).

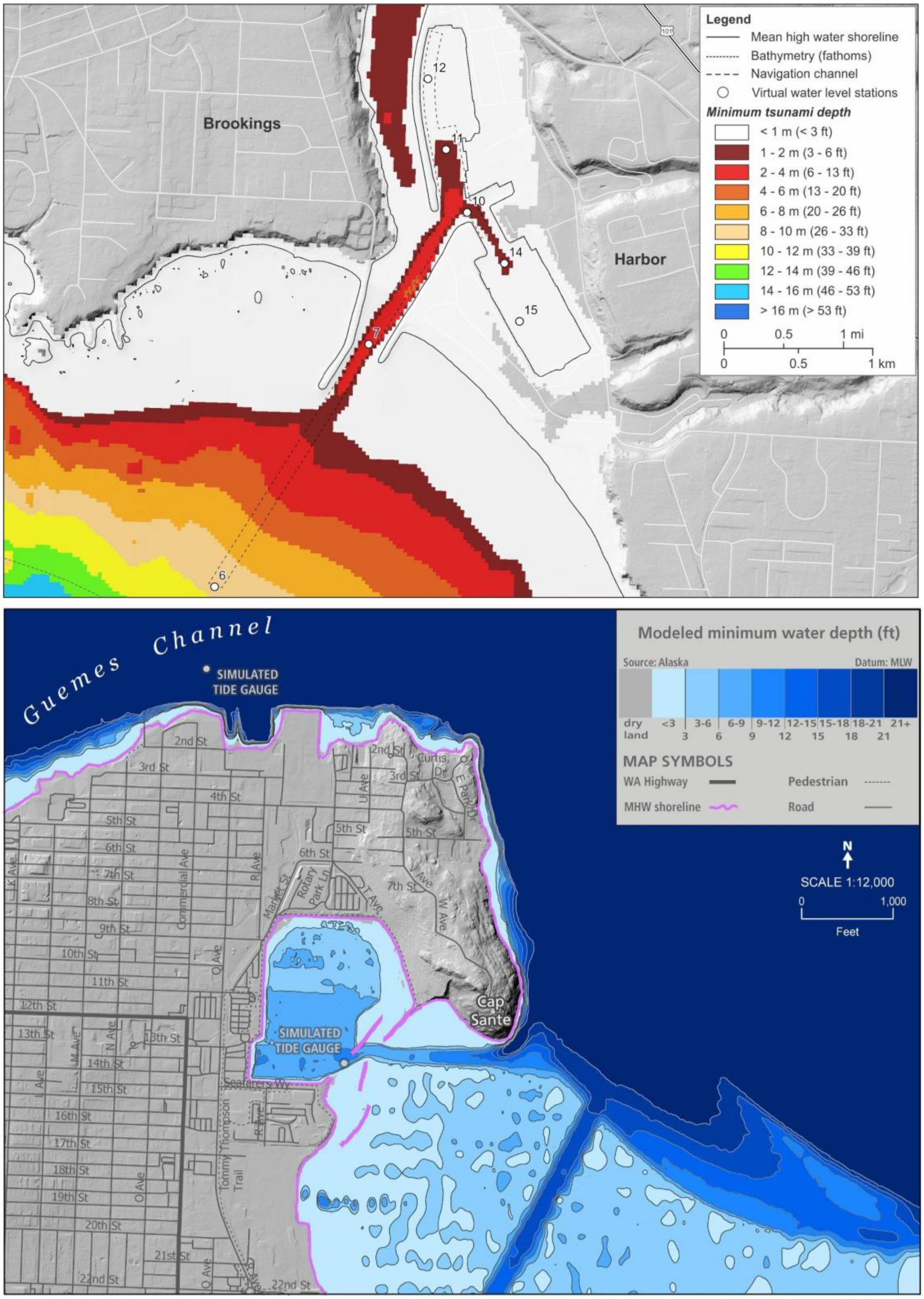


Figure 8 Top: Minimum tsunami flow depth of Brookings, Oregon, for a maximum-considered tsunami from Alaska. Mean Higher High Tide is 7.3 feet NAVD88 (Allan et al., 2024).
Bottom: Modeled minimum tsunami water depth using the Mean Low Water tidal datum at Cap Sante Marina in Anacortes, Washington from a M9.2 earthquake simulated along the Alaska-Aleutian Subduction Zone (Washington Emergency Management Division, 2024).

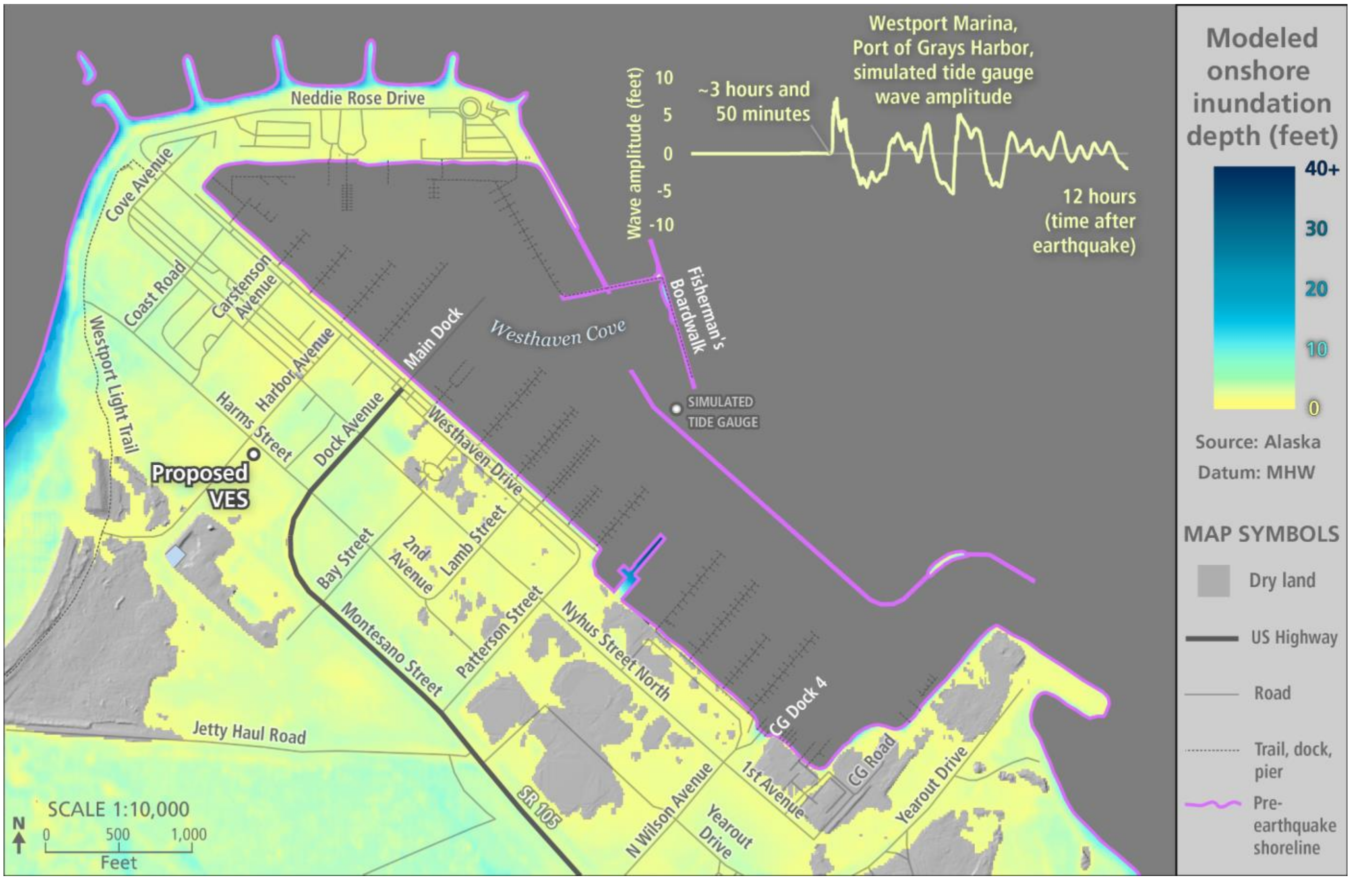


Figure 9: Maximum modeled inundation mapped at Westport Marina, Port of Grays Harbor, Washington, with the inclusion of a simulated tide gauges depicting variations of the tsunami waveform overtime from a tsunami generated from a Mw 9.2 Alaska-Aleutian Earthquake scenario. Maximum tsunami surge and drawdown can be calculated by the differences in the peak and trough from the modeled sea-level datum (Mean High Water), respectively (Washington Emergency Management Division, 2022).

Product 4: Identification of Areas of Potential Bores, Seiches, and Amplified Waves

Bores and amplified waves, as well as other unique tsunami conditions, may cause damage to portions of harbors where wave activity is uncommon. Bores typically occur in rivers or inside channels where a tsunami may be funneled. As was observed during the 2011 tsunami, several single, amplified waves over one meter in height, were generated and subsequently propagated deep into the Santa Cruz Harbor, three hours after the first arrival of the tsunami from Japan. As seen in Figure 10, these tsunami waves caused significant damage to docks and boats (Wilson *et al.*, 2013).

Seiches and amplified waves can occur within isolated water bodies, bays, large ports, and crescent-scaped embayments. Seiches are large standing waves caused by sloshing within a confined water body. They can cause damage to developed waterfront areas and within harbors and ports. Amplified waves occur where two positive amplitude waves interact and grow in size. Amplified waves not only form in enclosed water bodies but also along the leeward side of islands where tsunamis can wrap around and collide. Outgoing tidal currents may also cause wave amplifications as well. Conditions for both wave hazards should be investigated in ports and harbors.

Figure 10: Photo showing one of several single, amplified waves that entered the back half of Santa Cruz Harbor, causing damage to several docks and boats (from Wilson and others, 2013).

Guidance recommendations:

Numerical models may be able to capture bores; however, seiches and amplified waves, which can occur hours after the first tsunami wave arrival (or before in the case of seiches from the initial seismic waves), are difficult to model. The following steps should be followed:

1. Review historical records and observations to determine whether bores, seiches, or amplified waves have been observed.
2. Evaluate the shape and depth of the harbor/port to determine the potential for bores, seiches, or amplified waves to occur.
3. If the characteristics of the harbor/port are consistent with causing these effects, run a numerical model, which best captures bores, seiches, or amplified waves. This may require running simulations for a longer time that would be necessary to capture the initial tsunami wave impact.
4. If modeling does not work, the modeler can identify on a map or within the text of the guidance where these effects might take place.

Product 5: Identification of Time Frame for Damaging Currents

The duration of strong, damaging tsunami currents is of great importance to harbormasters and emergency managers for tsunami planning and response activities to enhance public safety for mariners. Kim and Whitmore (2014) demonstrated that tsunami signal duration can be estimated from maximum amplitude at locations, although the range of uncertainty is large. Lynett *et al.* (2014) captured the envelope of wave heights and current velocity decay in numerical models run for a 60-hour tsunami duration. Of note, however, is that the authors found little phase correlation between model results and measured data. The information is none-the-less useful and can provide a general timeline of activity for site specific strong currents and estimated lengths of time before tsunami alerts could be downgraded or canceled.

Guidance recommendations:

The duration of damaging tsunami currents and gyres derived from modeled velocity and vorticity could be provided in "time-threshold" maps. For a specified current velocity level, these maps will show the time frame during which the velocity is exceeded based on numerical modeling results run for a sufficiently long duration tsunami scenario. It is recommended that the duration represent the elapsed time between the first and last time a particular velocity is exceeded, not the sum of times the threshold is exceeded. Unique site-specific conditions may dictate the use of longer model runs (e.g. tsunami shelf resonance). While this type of information should be very useful for harbor personnel to estimate the duration of dangerous conditions, the estimates will be highly source dependent and scenario specific (Lynett *et al.*, 2014). Figures 11, 12, and 13 show examples of what such maps might look like.

The following steps can be taken to produce time-threshold maps:

1. Use the modeled time-history data for various scenarios to determine the length of time during which specific current thresholds (3/6/9 knots for well-maintained harbors; 2/5/8 knots for older, poorly maintained harbors) are active.
2. Maps can be created that show the same time threshold for multiple scenarios (Figure 11), or multiple time thresholds for the same scenario (Figure 12), or for different tides (Figure 13).
3. When displaying multiple time-thresholds on a map, the colors used for the times should have a consistent scale to allow for the best comparison.

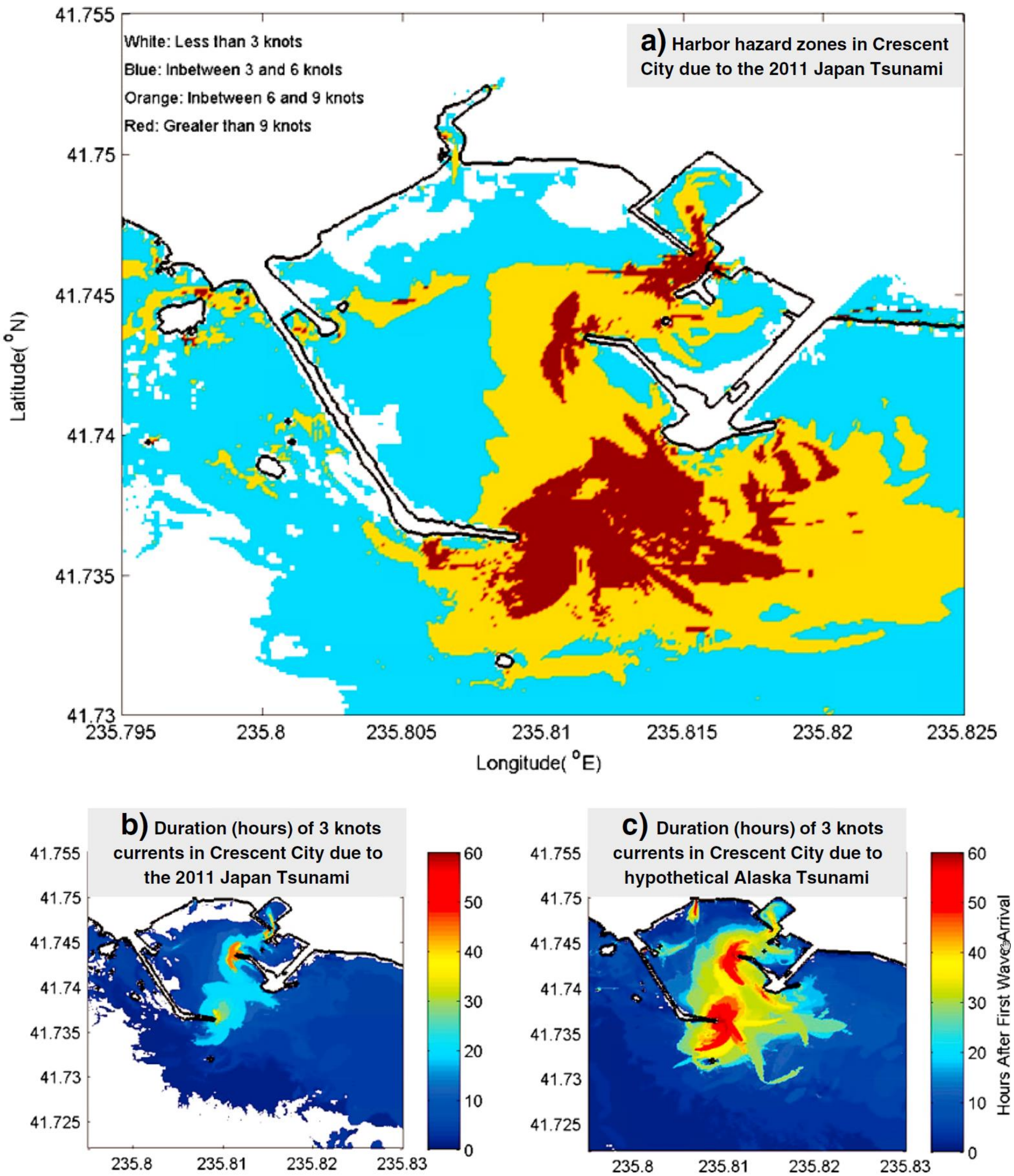


Figure 11: Example uses of the current speed hazard zones for 3/6/9 knot zonation, and time-threshold maps for two different sources in Crescent City Harbor (from Lynett et al., 2014).

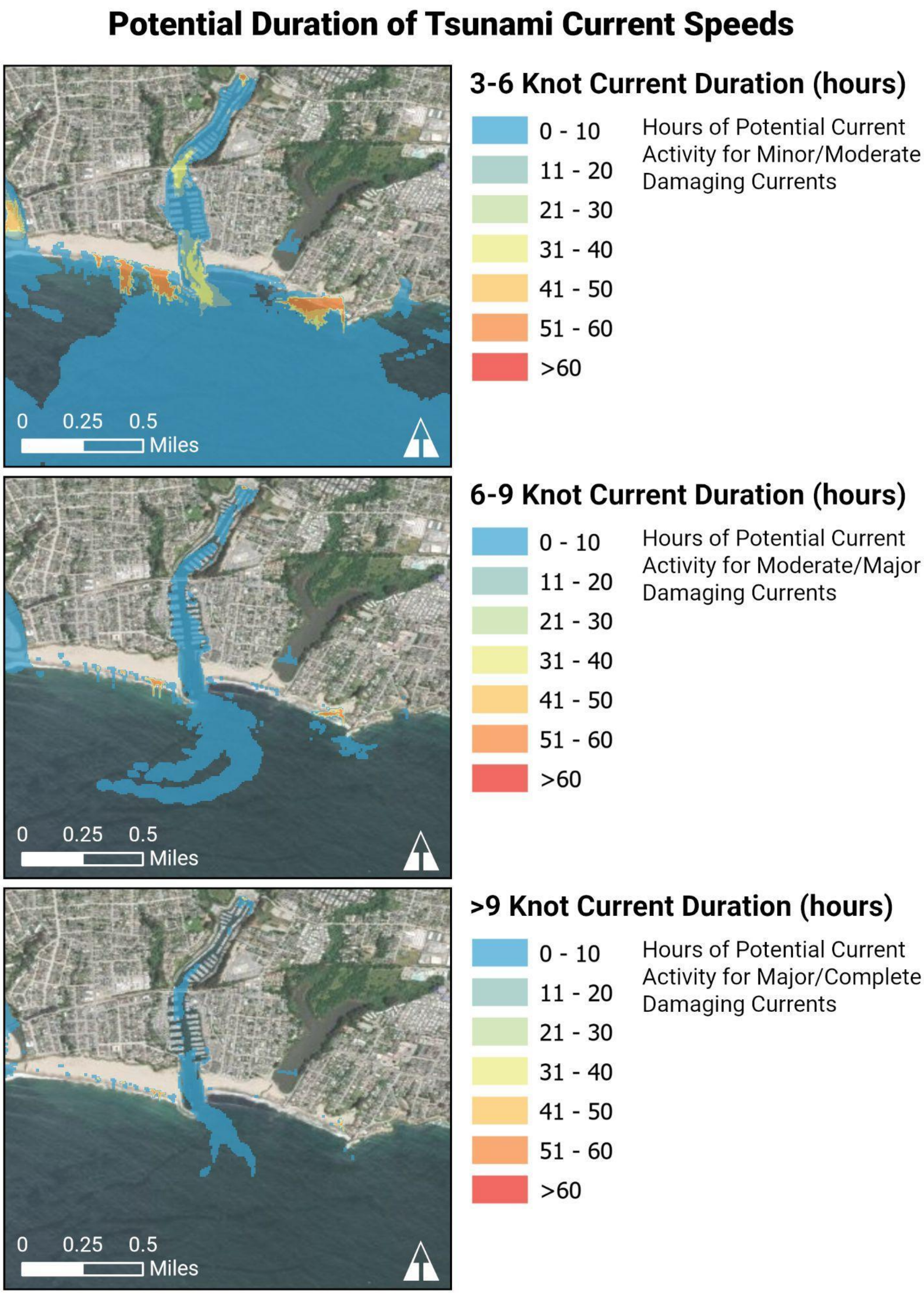


Figure 12: Example scenario from the Maritime Tsunami Response and Mitigation Playbook for Santa Cruz Harbor showing potential duration of tsunami current speeds based on current-damage thresholds of 3/6/9 knots (, in development CGS et al., 2025).

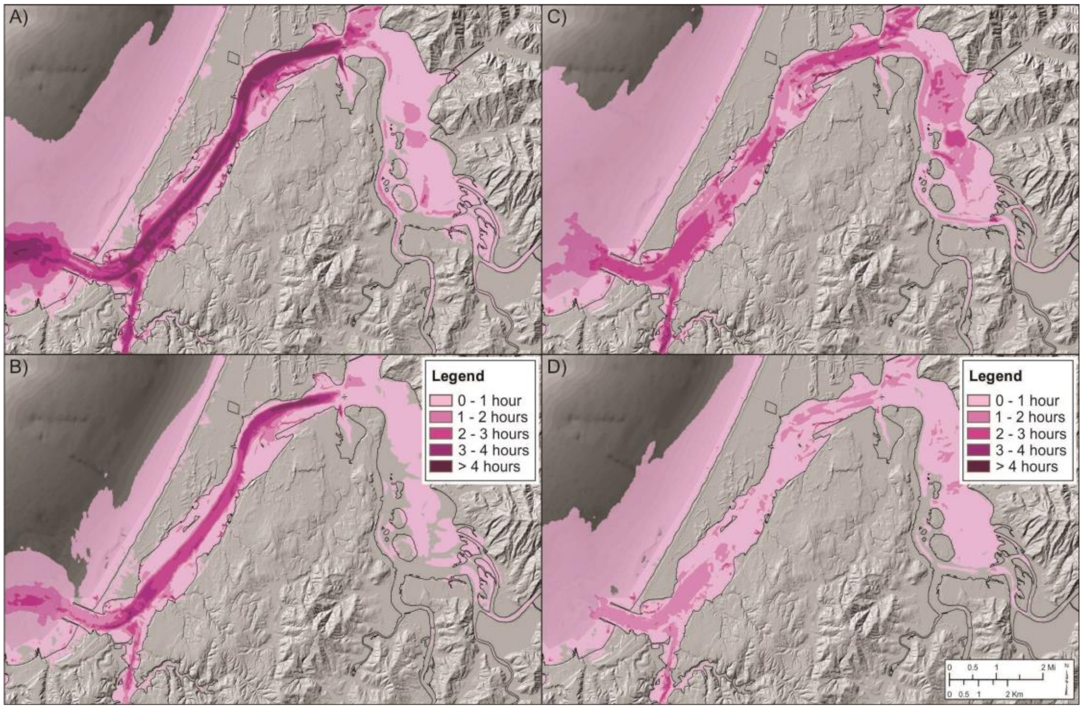


Figure 13: Example uses of the current speed hazard zones for 3 (A) and 6 (B) knot zonation for two different tidal regimes: flood tide (left) and ebb tide (right) in Coos Bay (from Allan et al., 2020).

Product 6: Identification of Safe Minimum Offshore Depth

In the event of a distant-source tsunami where there is sufficient time to safely move or evacuate vessels from a harbor, or in the event where vessels are already at sea, whether a distant or local tsunami has been generated, offshore evacuation areas can be provided for guidance. A "safe minimum depth" where hazardous conditions are not expected should be specified in fathoms, the most widely used measure of depth on NOAA nautical charts, and in feet/meters depth which is common on vessel depth finders. There are several conditions that should be met for a depth to be recommended as "safe." Such conditions include no chance of vessel grounding, negligible wave steepness, and navigable currents. Tsunami amplitudes or wave heights are relatively small offshore and, therefore, have little impact on navigation, though the large waves will likely be problematic at the mouths of rivers or bays where incoming tides and outgoing flows meet and amplify. From observations of tsunami induced coastal currents in previous events, the dominant challenges to coastal navigation are due to both strong currents and currents that are rapidly changing in both time and space.

If mariners have few options, are experienced vessel handlers, and are prepared to remain at sea for up to a 24-hour period (or longer) and travel to a safe, undamaged harbor, they may attempt to take their vessel out of harbor and transit offshore. Whether or not there is enough time to reach a designated safe depth prior to tsunami activity is a crucial decision point for whether vessels should attempt to evacuate out to sea at all. Other crucial considerations, especially if already out at sea and have sufficient time to return safely, include the individual vessel speed and capability, the skill level of the crew on board, the time before tsunami impact, the availability of communication services, the current weather, tide stage, and state of the sea, a mastery of vessel specifications such as awareness of individual draft, and the amount of provisions and equipment on board (Figure 14). Another important consideration post-tsunami event is whether there is a functional harbor to return to as well. California has also developed the acronym SAFE to aid with this potentially fatal decision to venture out to sea after a tsunami alert has been issued (Figure 15).

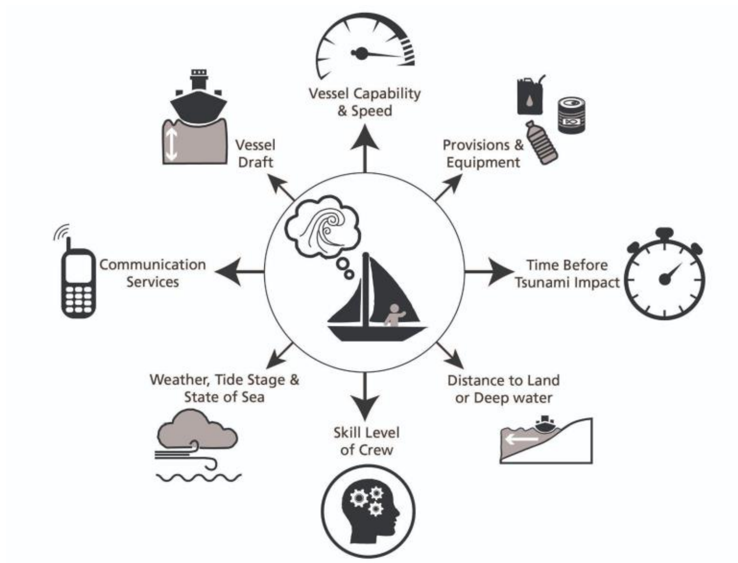


Figure 14: Schematic of crucial considerations that mariners should internally assess prior to taking their vessel out to sea or if already at sea and considering returning to harbor in the event a tsunami alert is issued. The NTHMP strongly recommends that vessel operators and captains should not be on their vessel during a tsunami when presented with the option.

Figure 15: SAFE acronym developed by California to remind mariners to ask themselves the following questions prior to taking their vessel out to sea after a tsunami alert has been issued: S) Size of the tsunami, A) Arrival time of tsunami, F) Fitness of the boat and its captain, and E) Environmental conditions.

If taking a vessel out to sea, the general recommendation from NOAA has been to travel beyond a depth of 100 fathoms (600 feet). This guidance is generally considered to be overly conservative and, off some coastal locations (e.g. Puget Sound, Washington), unrealistic. Recent analyses in California and Oregon indicate that a 30 fathom (180 foot) depth is reasonable along the Pacific coast of North America, when considering the impact of a tsunami from a distant source (Lynett et al., 2014; Oregon Marine Advisory Committee, 2014). The California analysis included a scatter plot of maximum current velocity versus water depth (Figure 16). The plot shows that maximum tsunami currents of less than 1 knot [0.5 m/s] are expected at a depth of 100 fathoms. Large variations in the possible maximum current exist to a depth of approximately 25 fathoms [150 feet], indicating that this is the greatest depth that large eddies or jets might extend to. This type of analysis was performed at five harbors in California. The results from these five cases were consistent and led to the California Tsunami Steering Committee accepting a safe depth of greater than 30 fathoms, particularly for dispersed or larger vessels.

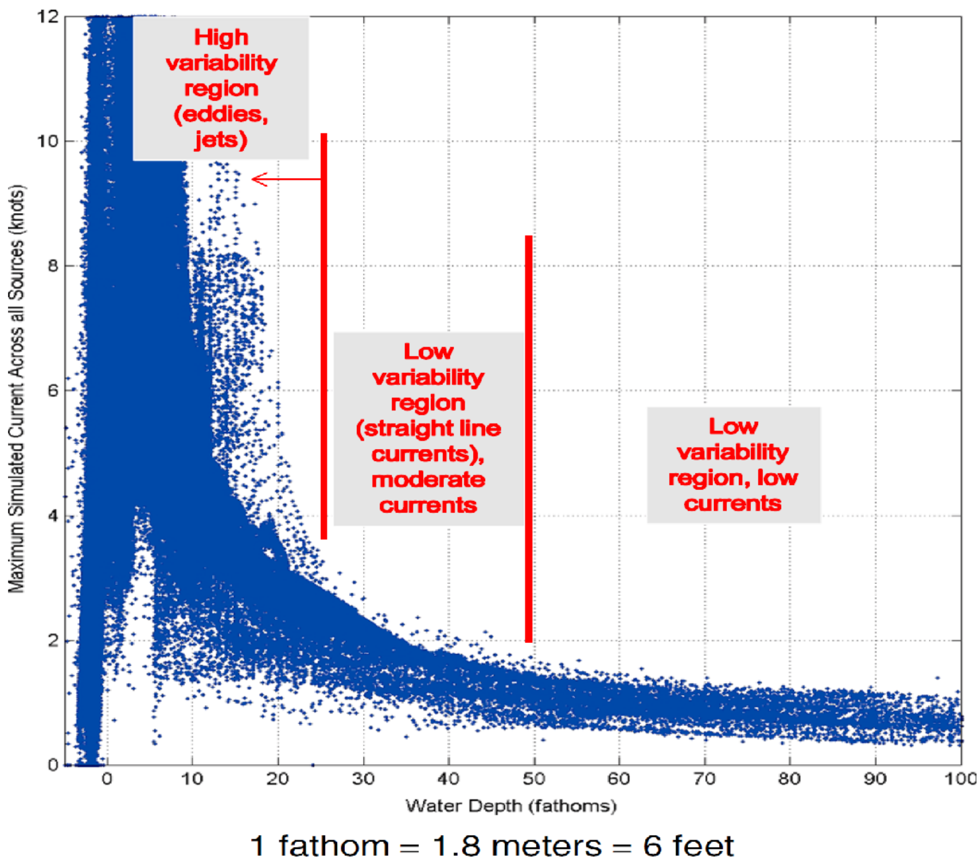


Figure 16: Scatter plot of maximum modeled current velocity versus water depth at Crescent City Harbor (Lynett et al., 2014).

The State of Oregon formed a Maritime Advisory Committee (MAC) to also address the offshore safe depth issue. Their analysis included a review of numerical modeling results of strong currents during a large local source (Cascadia) and a large distant source (Alaska). The potential for offshore vortices was also analyzed. Committee findings are summarized in Figure 17, with current velocities less than 3 knots considered ideal for safety. Based on this, the State of Oregon determined that the safe depth for distant source events should be 30 fathoms, but that vessels at sea during a local Cascadia source event should attempt to steam to a depth that approaches 100 fathoms. Harbor-specific modeling may also demonstrate regional safe-depth thresholds which are closer to shore and more practical for vessel travel and congregation (Suppasri et al., 2015). Any change to the default 30/50/100 fathom safe-depth thresholds should be justified by modeling and the need for shorter offshore travel distances.

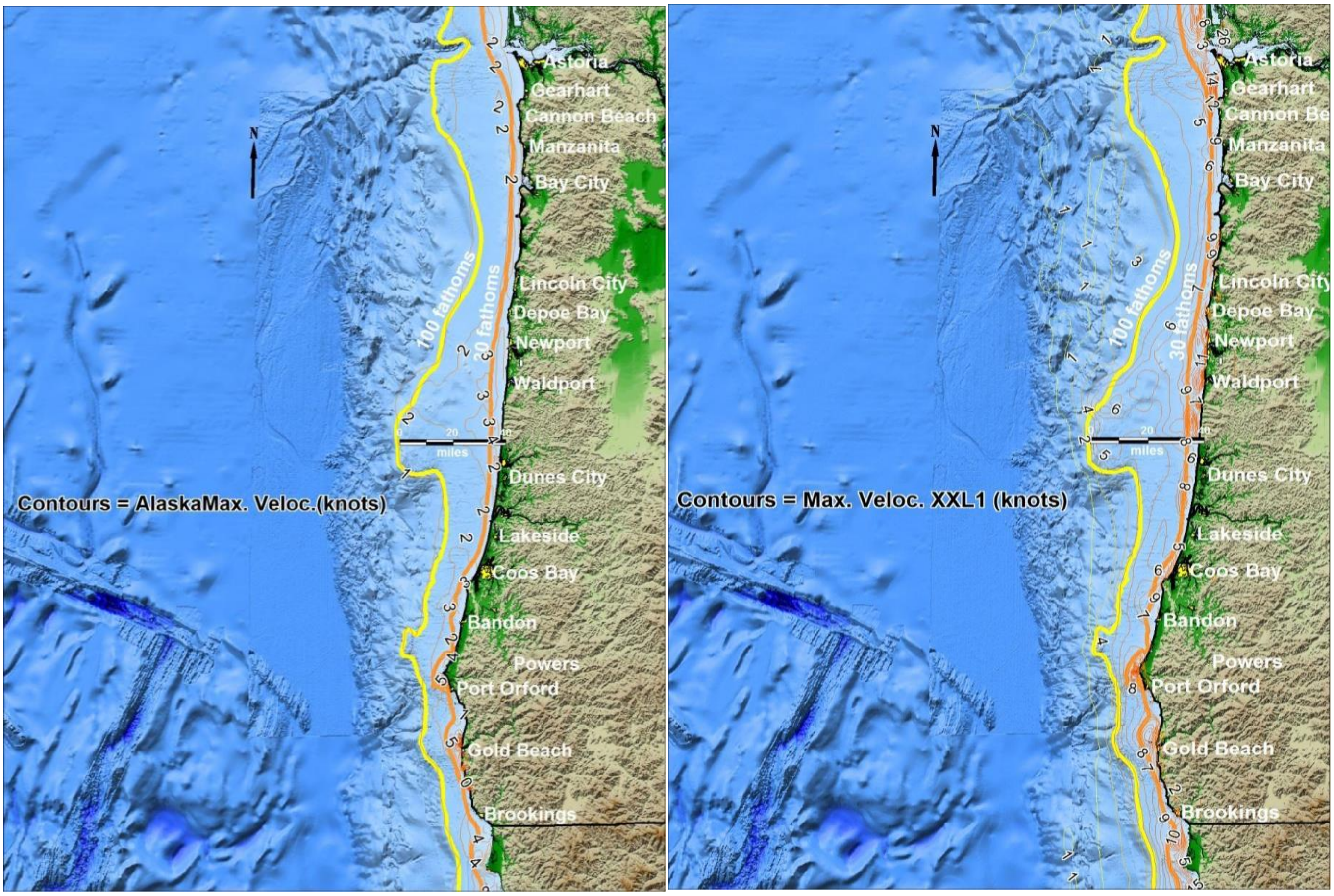


Figure 17: Analysis of recommended offshore target depths in the event of a distant (Alaska; left) vs local (Cascadia; right) tsunami event provided by the State of Oregon's Maritime Advisory Committee (MAC). Their analysis highlights two depth contours 1) 30 fathoms (orange), and 2) 100 fathoms (yellow) in relation to potentially dangerous velocity contours produced by the tsunami (numbered in knots). This analysis supports 30 fathoms and approaching 100 fathoms as target depths for distant and local tsunami events, respectively.

Guidance recommendations:

The NTHMP developed baseline or default guidance to establish offshore safety guidance for all U.S. coastlines based on the analyses being done by each state/territory. This guidance includes overarching recommendations for all members and vessel sizes of the boating community, including recreational, commercial, and large vessels. Because of the unique character and bathymetry of U.S coastlines, a single minimum offshore safe depth is not practical. Regional guidance is being developed, a summary of which is provided in Table 2. Additionally, mariners should be mindful of possible local guidance and any previous tsunami hazard analyses that may suggest more specific guidance for certain harbors. If regional or harbor-specific safe depth plans are developed, differences between harbors and regions should be accounted for in guidance to vessel owners so they are aware there may be differences in offshore safe depth between regions/harbors. For comparison, Table 3 presents summary results for different regions around the coast of Japan (Suppasri et al., 2015). The following existing guidance should be used as a "baseline" or default safe depth unless harbor-specific and/or scenario-specific information is developed to make recommendations for water depths less than 30 or 100 fathoms. Harbor-specific and updated regional guidance will allow vessels to relocate closer to shore, requiring less offshore travel time.

Table 2: Specific guidance for minimum offshore safe depths for maritime vessel evacuation prior to a tsunami's arrival (NTHMP, 2017).

State/ Territory	Distant Source (ships in harbor)	Local Source (ships at sea)	Notes
California	Default is 30 fathoms. Some ports have shallower depths.	Default is 100 fathoms. Some ports have shallower depths.	Evaluated; the State is updating this information with harbor-specific evaluations; evaluating potential safe areas within large bays and ports is ongoing
Oregon	Default is 30 fathoms. Some ports have shallower depths.	Default is 100 fathoms. Some ports have shallower depths.	Evaluated; evaluated potential staging areas for Columbia River, Coos Bay, Umpqua River, and Brookings-Harbor
Washington	30 fathoms	100 fathoms	Special conditions exist inside Puget Sound where 100 fathoms depth is sparse
Alaska	30 fathoms	100 fathoms	Evaluated; ships should be at least 1/2 mile from shore
Hawaii	50 fathoms	50 fathoms	Evaluated; implemented in Coast Guard response plans at some locations
American Samoa	50 fathoms	50 fathoms	Evaluating, guidance from others
Puerto Rico	50 fathoms	100 fathoms	Evaluated
USVI	50 fathoms	100 fathoms	Evaluating; possibly follow PR
Guam	50 fathoms	100 fathoms	Coordinated with USCG Guam Sector
CNMI	50 fathoms	100 fathoms	Coordinated with USCG Guam Sector
Gulf Coast States		100 fathoms	Evaluating; issues with long, shallow shelf complicates getting beyond safe depth
East Coast States		100 fathoms	Evaluating; issues with long, shallow shelf complicates getting beyond safe depth

Table 3 Maritime tsunami evacuation depths for select areas around the coast of Japan (Suppasri et al., 2015).

Location	Scenario	Tsunami Height (m)	Recommended Evacuation Depth (fathoms)
Japan's Fisheries Agency	local		27
Aomori Prefecture	local	5	27
		10	82
Tokushima Prefecture	local	4	38
		6	60
Iwate Prefecture			Maritime evacuation prohibited

In the absence of detailed modeling, maritime evacuation maps are recommended to be created using 30, 50, and 100 fathom lines.

Product 7: Maritime Evacuation Products

The NTHMP strongly recommends that vessel operators and captains should not be on their vessel during a tsunami or take their vessel offshore unless they are fully prepared. However, in some circumstances mariners may not have a choice and potential maritime evacuation maps could be vital for survival. Maritime evacuation maps should indicate the evacuation area/zone with a contrasting color that is easily identifiable from the surrounding landscape and that is also sensitive to those with color blindness. Detailed maritime tsunami modeling should be used to evaluate potential maritime evacuation zones, which should encompass all areas expected to be impacted by strong tsunami-induced currents and areas subject to strong eddies (vorticity). Hazardous areas and evacuation zones may be defined by a minimum current velocity contour (usually 3 knot). Additionally, at depths shallower than 10 fathoms, defining contours (or text labels) of hazardous currents exceeding 5-6 knots may also be useful to mariners. Where available, maritime tsunami evacuation maps could also include appropriate offshore features, such as: National Data Buoy Center (NDBC) buoys, navigational markers, marine banks, and place names to further help mariners identify offshore staging area locations and evacuation sites. These maps should also indicate locations of potential upriver evacuation sites, if possible, and identify unique challenges that may impede evacuation as well. Several maritime tsunami evacuation zones may be modeled that reflect contrasting levels of risk to allow for epistemic uncertainties. Multiple evacuation zones can also be displayed on one map that show multiple areas to be evacuated depending on if the tsunami is local or distant, among other possible factors. A maritime evacuation map from the State of Oregon provides an example of this where the colors, yellow and orange, are used to delineate the local versus distant tsunami evacuation zones, respectively (Figure 18). This example also includes escape direction arrows and offshore staging areas, which is recommended to help people identify the avenues of egress and safe locations where appropriate.

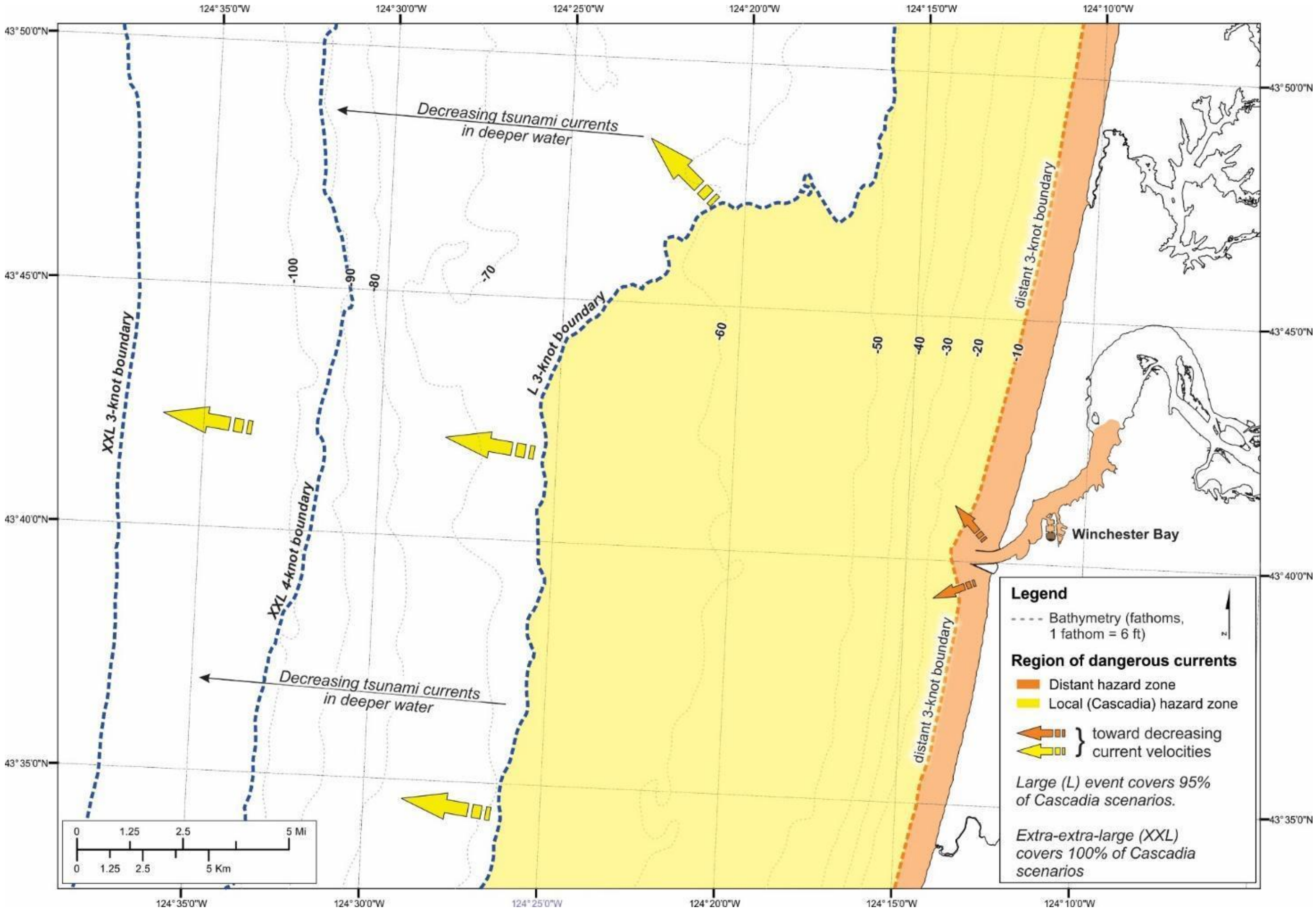


Figure 18: Offshore maritime staging areas for the Umpqua River, south central Oregon coast. Map identifies the minimum water depths to the distant (>10 fathoms) and local (>65 fathoms) maritime tsunami staging areas offshore the coast. Shaded regions define areas subject to dangerous current velocities (Allan et al., 2022).

In addition, more detailed and controlled vessel evacuation plans are recommended for ports and harbors where vessel traffic is significant. For example, the U.S. Coast Guard has developed and updated a maritime evacuation plan for some harbors and ports along the southern coast of Oahu, Hawaii (USCG, 2013; 2024). This plan is shown in Figure 19 as an example of what other maritime communities might consider replicating. Although this will likely be addressed in more detail in the preparedness and response section of this guidance, maps like these will help the maritime community better visualize evacuation.

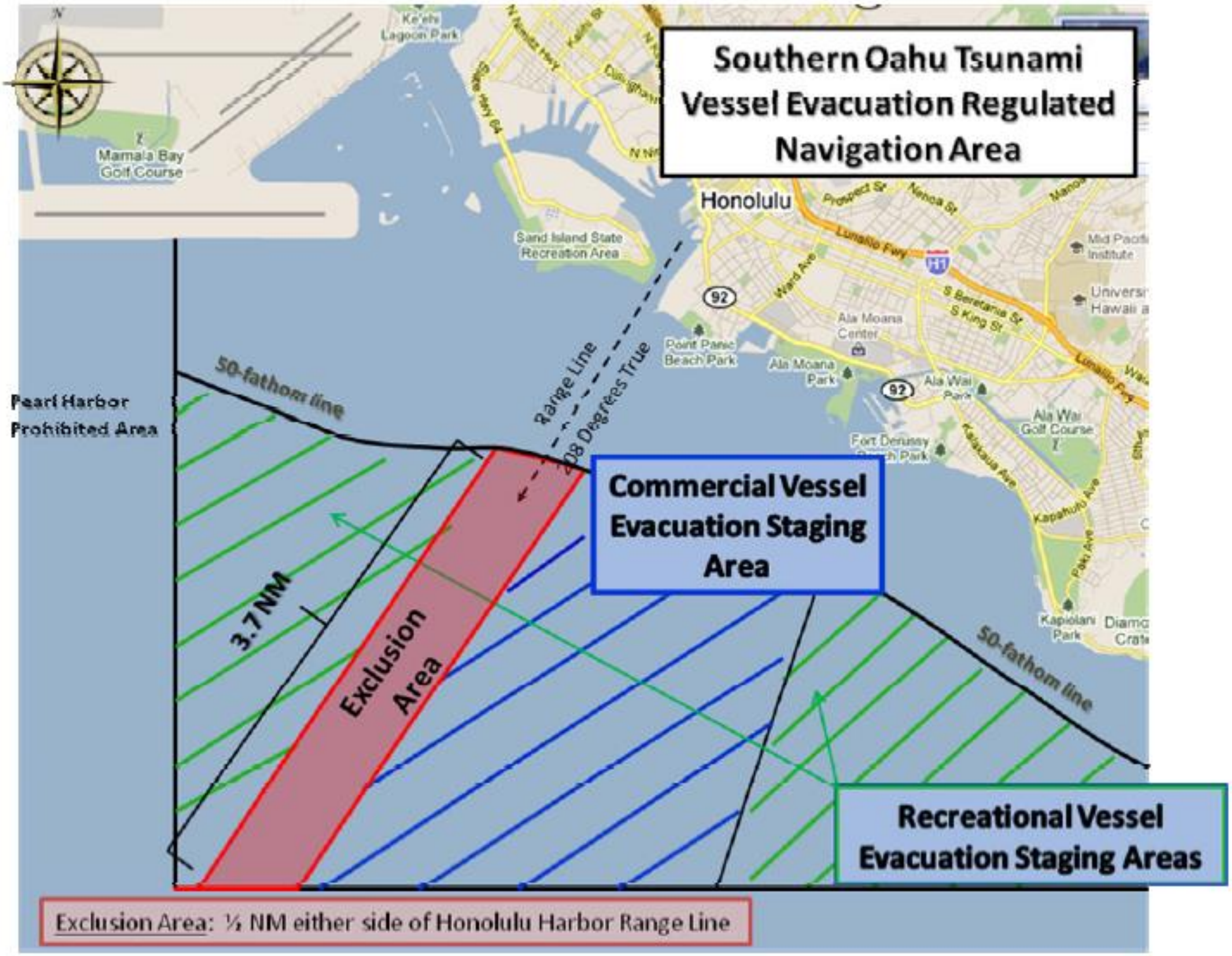


Figure 19: Map showing maritime evacuation plan for vessels in the port at southern Oahu (from U.S. Coast Guard, 2021).

In the absence of tsunami modeling, the following guidance may be used for developing maritime evacuation products (refer to Product 6):

- For a distant tsunami event (>3 hours wave arrival), proceed to depths >30 fathoms.
- For a local tsunami, proceed to depths approaching 100 fathoms.
- Indicate offshore designated staging areas or water depths and directional arrows leading away from the coast. When defining water depths to reach, include depth contours (fathoms) and feet/meters depth.

Other Products

In addition to the tsunami hazard products discussed above, there are other potential products that can assist harbormasters and emergency managers with their preparedness, mitigation, and response planning activities. These products are either very specialized, less common, or less vetted compared to the tsunami hazard maps and products discussed previously.

- Sediment Movement – Evaluation of sediment movement during a large tsunami enables harbors to determine if mitigation measures such as sediment control structures or additional dredging are needed. Dredging of sediment in a post-tsunami environment could be costly because of the high potential for sediment contamination due to fuel leakage or other toxic contamination. Wilson et al. (2012) evaluated sediment movement within Crescent City and Santa Cruz harbors during the 2011 Japan tsunami (Figure 20). Differencing pre- and post-tsunami bathymetric survey data helped identify where sediment erosion and accumulation occurred. It is important that post-tsunami bathymetric data be collected as soon as possible after the tsunami to reduce the potential addition of sediments from background erosion/sedimentation in the harbor. It is also important to make sure that all bathymetric data are set to or corrected to a common vertical datum. Cross sections from the bathymetry and sediment cores can also be a useful product for harbor recovery planning. It should be noted that tsunami sediment erosion/transport models are becoming available that have reasonable predictive skills. Tehranirad et al. (2021), for instance, were able to reasonably reproduce the observed sediment erosion and deposition in Crescent City harbor from the 2011 Tohoku-Oki tsunami impact. In August 2023, MMS organized a tsunami sediment model benchmarking workshop that is expected to inform future guidance and recommendations for this aspect of tsunami modeling.

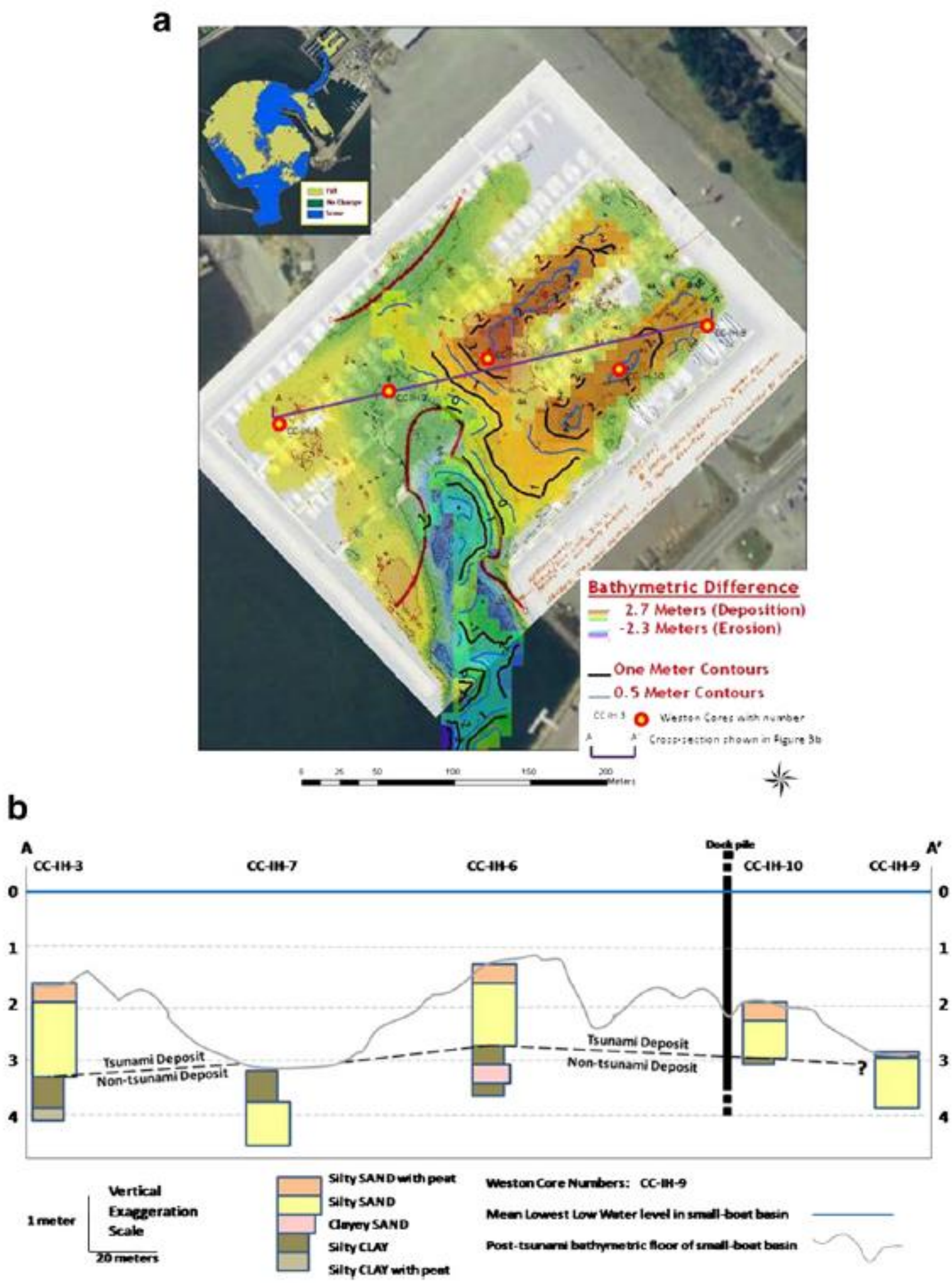


Figure 20: Areas of scour and fill in the Crescent City Harbor Small-Boat Basin determined by differencing pre- and post-tsunami multi-beam bathymetric data. The cross section shows the post-tsunami sediment composition and correlation between tsunami and non-tsunami deposits (from Wilson et al., 2012).

- Debris Movement Models – Even in cases where ships and docks may seem safe from direct damage from strong tsunami currents or water-level fluctuations during certain events, loose debris may make any location within ports and harbors susceptible to damage or navigation delays. Analysis of debris movement is an evolving field of study, but there have been some new modeling tools which could help harbors visualize where debris might come from and where it might travel. Lynett (unpublished) is developing a debris model that is based on simple particle movement within his current models. Figure 21 is a screen shot from a debris/particle movement model during a tsunami in the Port of Los Angeles. The time-history video from which this figure was extracted showed potential debris movement and demonstrated that although large ships within the Port were safe from direct tsunami damage, debris from the small boat harbors could damage larger ships and harbor infrastructure or block navigation channels. In May 2023, to assist with anticipating debris and sediment movement, the MMS and MRPWG organized a benchmarking workshop for numerical debris models. Based on those results, the ability of numerical models to account for and replicate debris movement will be assessed, and guidance and recommendations will be developed. By mid-2024, the State of Oregon will also complete a Tsunami Debris Guidance document which can be used by local planners to develop tsunami debris plans.

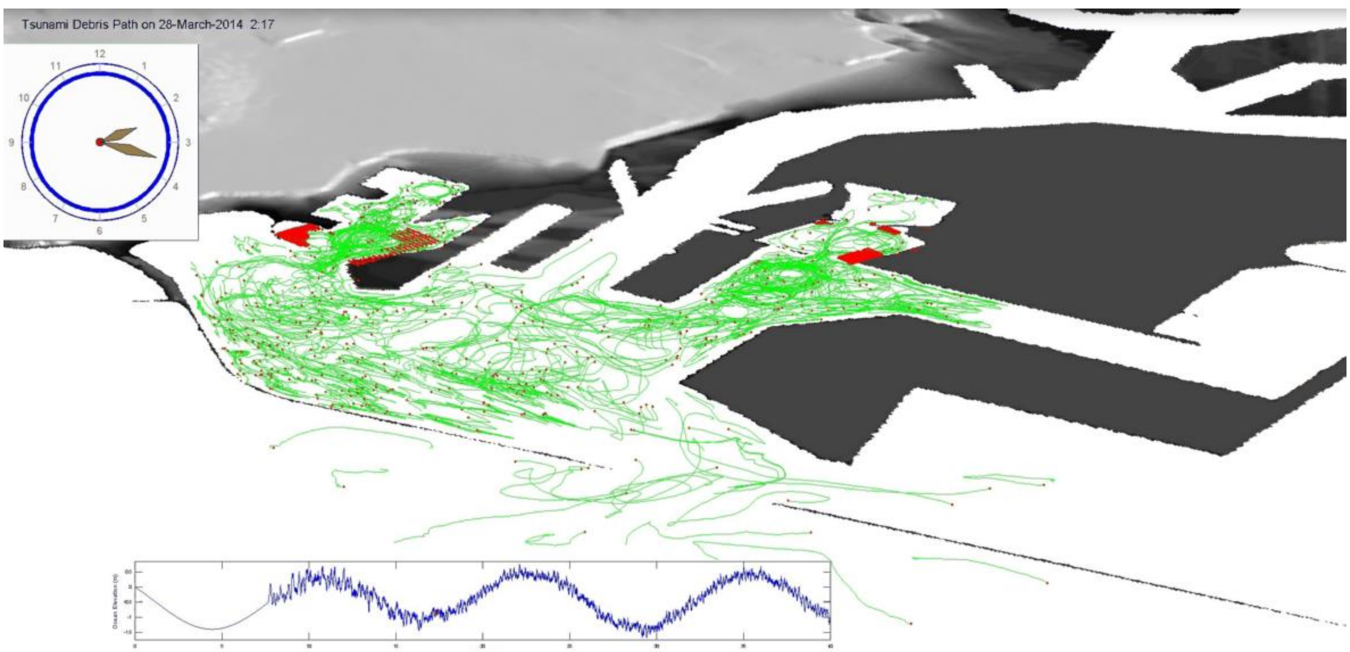


Figure 21: Modeled debris/particle movement from small-boat basins within the Port of Los Angeles (Lynett, unpublished).

- Mitigation Analysis and Products – Many harbor managers are interested in understanding the vulnerability of their harbor facilities and infrastructure to tsunami damage. Keen et al, (2021) developed a methodology through a combination of high-resolution numerical modeling and an existing statistical framework with observed damage states for structural elements, including infrastructure age and condition, to aid decision makers with risk and failure susceptibility assessments of maritime mooring systems (e.g. cleats and pile guides). A case study applied to a small craft marina in Noyo River Harbor supports this methodology, in which it was able to replicate likely failure (Keen et al., 2021). Tsunami hazard products spotlighting damage ratings / class distributes and failure probability can be derived from this methodology and assist harbor officials in determining where first-order problem areas may exist. For example, failure probability curves can be compared to the tsunami velocity and direction from various scenarios for different parts of a harbor to determine the potential for failure during these scenarios (Figure 22). These types of analyses will help identify where dock and infrastructure improvements could be implemented. The way that these products can be incorporated into hazard mitigation planning will be discussed in a later section of the guidance.

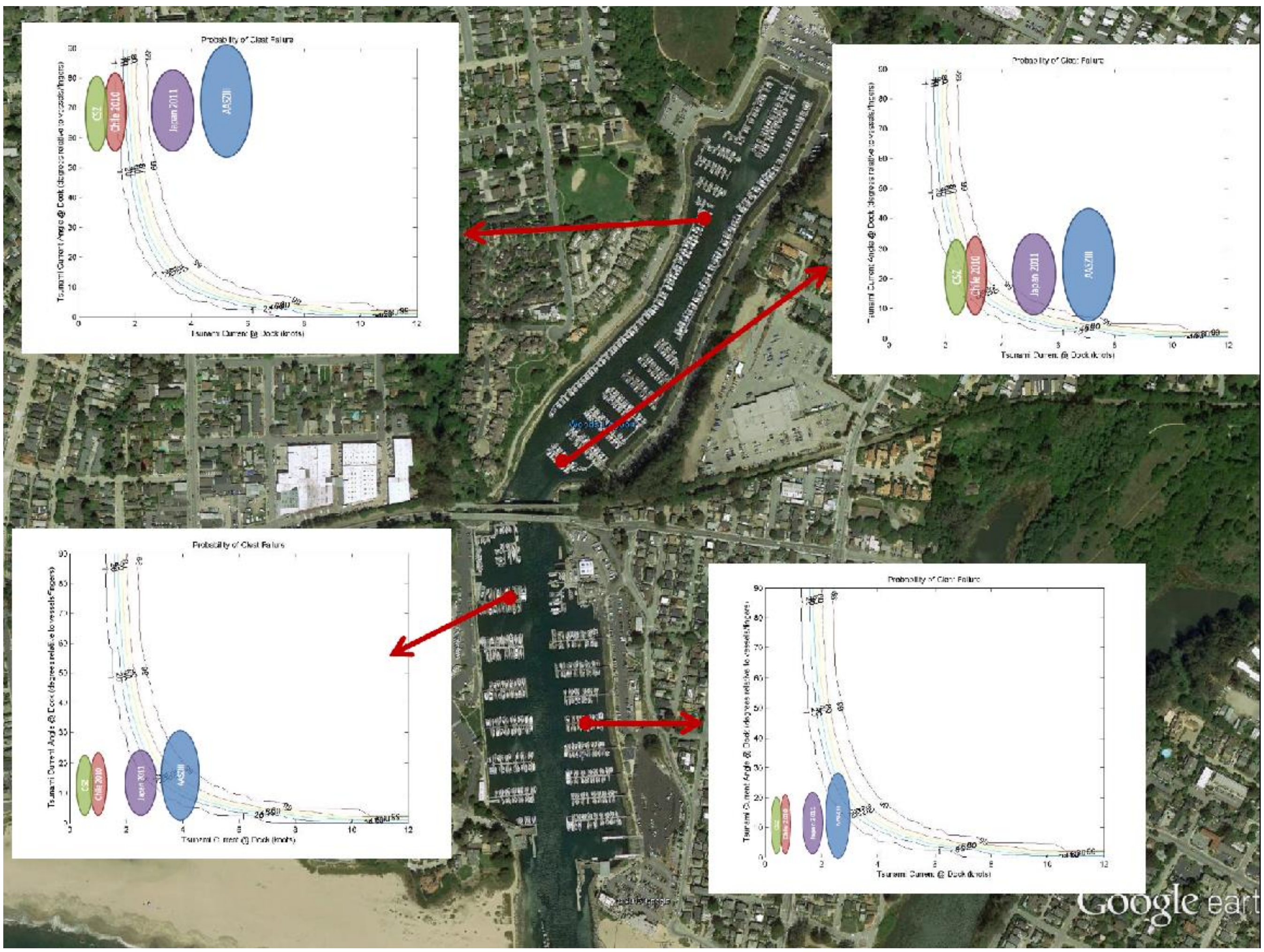


Figure 22: Failure probability curves for cleats in Santa Cruz Harbor. The current speed and direction for various modeled scenarios have been added to the curves for reference, to help determine what portions of the harbor might be most vulnerable.

1.3 Basic Guidance on Design of Tsunami Hazard Maps and Products

Maritime tsunami hazard preparedness products may include maps, brochures, and plans that are printed, digital files, or interactive/web-based information, especially for harbor-specific planning products. The following subheading represents general design guidance on developing maps and products to be consistent between all states and territories.

General Product Guidance

- All maps and products should be accompanied by references or technical documentation on how the maps/products were created and their intended use.
- If in an electronic form, a GIS-based shape or KML overlay file of the evacuation route should be developed for tsunami hazard maps. Communities who do not have the resources to create these files can contact their State NTHMP Partner for support.
- All maps and products should include a title, scale, geographic location (coordinates), and appropriate explanatory information.
- Maps and products should be legible for all users, including people with color vision disabilities.
- Communities should consult with the producers of tsunami hazard maps and products when developing preparedness, response, and mitigation plans so that the intended accuracy and limitations of these products are considered and understood. Consult with your NTHMP Scientist or Emergency Manager (see the NTHMP web site http://nthmp.tsunami.gov/ for a current list of contacts).
- In addition to being provided in printed form, to facilitate outreach, tsunami hazard maps and products should be made available digitally, considering the scale limitations and appropriate base maps.
- Maps should include streets, bridges, and other landmarks. When referring to distance to key features, use nautical miles.
- Include bilingual text where possible, with English and a secondary language.
- Include brief instructions on what to do in the event of a tsunami.

Symbols:

- For land-based evacuation, the NTHMP recommends a modified adoption of the Homeland Security Mapping Standard symbols in ANSI INCITS 415-2006 (Figure 23). These symbols are available as a true type font at http://www.fgdc.gov/HSWG/index.html.
- For maritime evacuation maps, established symbology developed for NOAA Nautical Charts may also be used. These symbols may be viewed at https://nauticalcharts.noaa.gov/publications/docs/us-chart-1/ChartNo1.pdf
- Symbols should be black. If they are against a dark background, an outline of white should separate the symbol from the background image.
- Symbols should be easily perceived in terms of size, and scalable according to the size of the final map product.
- Symbols should have precise meaning without a need for explanation on the map other than in the legend.

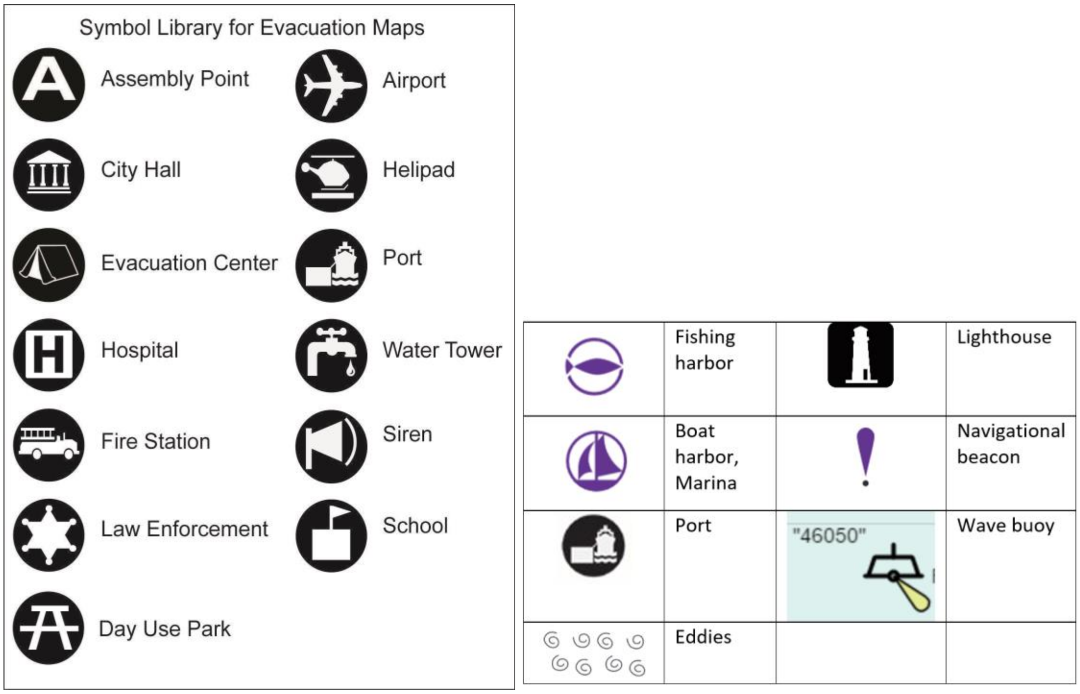


Figure 23: Standardized mapping symbols. Top) Land-based symbols. Bottom) Marine symbols.

Colors:

- A color wheel of cool (white/clear, blue, green) to hot (yellow, orange, red) colors should be used to demonstrate low to high hazard areas, respectively (Figure 24).
- If colors other than those suggested are selected, every effort should be made to ensure that the publication is readable by the color blind. Avoid putting red next to the dark green color.
- Color maps should be reproducible in black and white.

Palette for tsunami evacuation mapping guidelines

		RGB Values	CMYK Values	Hexidecimal
Yellow		255 242 0	0 0 100 0	#FFF200
Orange		251 169 25	0 38 100 0	#FBA920
Red		230 6 15	3 100 100 1	#E6060F
Blue		12 7 248	88 78 0 0	#0C07F8
Cyan		0 174 239	100 0 0 0	#00AEEF
Dark Green		74 140 3	75 23 100 8	#4A8C03
Light Green		161 187 132	40 13 60 0	#A1BB84

Figure 24: Suggested standardized colors for tsunami hazard maps and products.

Resources – Maritime References, Products, and Entities

California Tsunami Boating Brochure
https://www.conservation.ca.gov/cgs/Documents/Tsunami/Tsunamis-What-boaters-should-know.pdf

Color Blind Image Corrections
http://www.vischeck.com/daltonize/

Emergency and Hazards Mapping Symbology
http://www.desastres.org/pdf/kentuniversity.pdf

Field Guide to Humanitarian Mapping
http://www.mapaction.org/images/stories/publicdocs/mapaction%20field%20guide%20to%20humanitarian%20mapping%20first%20edn%20low-res.pdf

Hawaii Coast Guard Maritime Response Plan (2013)
http://www.gpo.gov/fdsys/pkg/FR-2013-10-03/html/2013-24150.htm

Hawaii Coast Guard Maritime Response Plan (2024)
https://mmcvqr.uscg.mil/Lists/Content/Attachments/47927/2024%20Marine%20Transportation%20System%20Recovery%20Plan%20(MTSRP).pdf

Hawaii Maritime Planning Guide
http://nws.weather.gov/nthmp/2014mesmms/HawaiiBoaters.pdf

Homeland Security Working Group Emergency Symbology
http://www.fgdc.gov/HSWG/index.html

Making U.S. Ports Resilient as Part of Extended Intermodal Supply Chains
http://onlinepubs.trb.org/onlinepubs/ncfrp/ncfrp_rpt_030.pdf

Maritime New Zealand
http://www.maritimenz.govt.nz/Commercial/Safety-management-systems/Safety-management-systems.asp

NOAA Ports Tomorrow Resiliency Planning Toolhttp://coast.noaa.gov/port/?redirect=301ocm#Hazards

Port Recovery in the Aftermath of Hurricane Sandy Improving Port Resiliency in the Era of Climate Change
http://www.cnas.org/sites/default/files/publications-pdf/CNAS_HurricaneSandy_VoicesFromTheField.pdf

Puerto Rico/Caribbean Maritime Planning Guide
http://www.srh.noaa.gov/images/srh/ctwp/TsunamiGuidelinePorts_August2011.pdf

Oregon Marine Advisory Committee
https://www.oregon.gov/osmb/pages/gac.aspx

Oregon Maritime Brochure
http://www.oregongeology.org/pubs/tsubrochures/TsunamiBrochureMaritime.pdf

Mitigation of Tsunami Disasters in Ports (PIANC)
http://www.pari.go.jp/en/files/3654/389490581.pdf

Washington Education and Maritime Resources
https://mil.wa.gov/tsunami#education

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Allan, J.C., Zhang, J., O'Brien, F.E., and Gabel, L., 2024. Brookings tsunami modeling: Toward improved maritime response. O-24-03, Portland, Oregon, 79 pp.

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