Tsunami Science and Technology Advisory Panel (TSTAP) White Paper on Prioritizing Upgrades to Tsunami Forecast Capabilities to Protect Public Safety in Large Coastal Population Centers and Complicated Waterways

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Executive Summary

Existing tsunami alerting and forecasting procedures support the protection of lives and property along most coastlines vulnerable to tsunami impact. However, the system currently in place does not allow proper forecast capability and flexibility for many miles of coastline in bays and sounds with large coastal populations and dense infrastructure. Additional forecast capabilities need to be prioritized for safety and proper alerting and forecasting for these complicated waterways.

The US Tsunami Warning System needs to be capable of alerting all coastal waterways of an impending tsunami before a tsunami arrives. The TSTAP's review of the Tsunami Warning System and the Tsunami Warning Centers (TWCs) revealed that the existing system is not equipped to accurately alert all coastal regions, particularly within bays and complicated waterways, at the level of detail necessary before locally (and in some cases even distantly) generated tsunami waves arrive. The TSTAP addressed these concerns in our 2021 TSTAP Quadrennial Report Recommendations 1.1, 1.4, 3.3, 4.1, and 4.2, and the recommendations were further substantiated in the 2022 TSTAP Tonga Post-Tsunami Report. These recommendations specifically address the urgent need for improving tsunami forecast capabilities that include additional site-specific forecast location information, additional subdivision of forecast areas (i.e., breakpoints), and use of Special Procedure Areas (SPAs). These improved decision-support products will better protect large coastal population centers such as Seattle, Tacoma, Honolulu, Anchorage, and San Francisco Bay from potentially under or over evacuating in a tsunami event.

Although NOAA agreed that these improvements were important and needed, the TWCs indicated they cannot make these essential and urgent improvements to forecast and special procedure areas because they have lost the personnel and institutional knowledge to make changes to their tsunami forecast computer coding since 2014 when they last performed these types of improvements. Despite requests from numerous states and territories over the past decade and more, regaining this knowledge to update the system does not appear to be an immediate priority despite solutions the TWCs were capable of implementing, such as changes to the tsunami forecast computer coding in 2014. The TWCs indicated they will not be able to implement improvements such as these until they have executed a "second phase" of the Tsunami Advanced Weather Interactive Processing System (AWIPS) and have completed the implementation of a common analytic system (CAS). Depending on available resources the CAS implementation could take more than a decade to implement and thus is not a viable short-term solution for an event that may happen any day.

The TSTAP understands that providing forecast information accurately to all impacted communities at the level of detail necessary to make informed decisions is a multipart problem that requires improvements in each facet:

- Enhanced granularity and forecast information for alerting areas (the focus of this white paper).
- A better constrained tsunami source which requires more observational equipment (such as increased DART coverage, GNSS, fiber optic cable bottom pressure sensors, or other modern solutions).
- Improved tsunami forecast software to be able to better refine the source, monitor the wave, and forecast the tsunami as it travels.
- Improved alert messaging to ensure up to date information meets the needs of those having to make decisions based on the tsunami alert information.

The need for increased detection and observational systems, software, and improved alert messaging were addressed in the 2021 Quadrennial report; the need for this equipment and software is not the purpose of this paper. Rather, this paper focuses on changes that can, in theory, be made using the existing equipment, software, and systems, in place at the TWCs today and can be an intermediate step to improving the existing system while new and improved long-term technologies are being implemented. This paper aims to provide a summary of the alerting issues and the lingering requests made by local, state, and territory officials to the TWCs to add more forecast locations, additional breakpoints, and changes to special procedure areas.

Background

The goal of the NWS Tsunami Warning Program is to protect lives and property from tsunami hazards by providing timely, accurate, reliable, and effective tsunami information to coastal populations and emergency management within the area of responsibility; and advancing other aspects of tsunami hazard mitigation such as community preparedness and public education. The primary operational warning system objectives for carrying out this mission are to rapidly locate, size, and otherwise characterize major earthquakes; determine their tsunamigenic potential; predict tsunami arrival times; predict coastal runup when possible; and disseminate appropriate warning and informational products. The mission of the NWS itself is to provide: "…forecasts, warnings, and impact-based decision support services for the protection of life and property and enhancement of the national economy." For this reason, the needs of local decision makers and the public at large are considered paramount.

The present tsunami warning system forecasts include two actionable tsunami alert levels: an "Advisory" level for potential beach, waterfront, and maritime tsunami hazards; and the highest "Warning" level for both maritime hazards as well as potential tsunami flooding on-land which may require significant evacuations.

Location specific tsunami forecast information (wave arrival times and amplitudes), forecast breakpoints (where alert levels are able to change such as a Warning in Oregon and an Advisory in Washington means they are separated by a breakpoint), and SPAs (complicated tsunami locations), help delineate the information provided in each tsunami event and provide critical decision-support information for improving local response. These three types of tsunami forecast tools are further defined:

- **FORECAST POINTS: Location-specific forecast points for communicating tsunami arrival times and tsunami amplitudes provide the details about the tsunami threat on which the tsunami alert forecasts are based.** These forecast data have been created in the existing tsunami warning system and are selectively shared in tsunami alert bulletins. An evaluation by the State of California in 2018 indicates these forecast amplitude data during the 2009 Samoa, 2010 Chile, and 2011 Japan event were 80-90% accurate or at least conservative at predicting real-event amplitudes. However, these detailed forecasts are not available to state and territory emergency managers at all locations where a tsunami threat exists, especially areas of the U.S. under the Pacific Tsunami Warning Center (PTWC) purview. Additionally, not all communities with a potential tsunami threat have standby inundation models (the background information necessary for the TWCS to create a forecast point) to be able to provide real time forecast information at that location, for example the city of Seattle does not have a forecast point and thus will not receive tsunami forecast information even if there is a tsunami forecasted to hit that area.
- **BREAKPOINTS: Tsunami forecast alert areas are designated between breakpoints separating areas of different tsunami hazards, geographical boundaries, and coastal conditions** (for example, an Advisory for Oregon state, and a Warning for Washington State with a breakpoint at the border). The NWS defines a breakpoint as "The geographical extent of tsunami warnings, watches and advisories in the National Tsunami Warning Center's (NTWC) Pacific Designated Service Area are defined by breakpoints which correspond with NWS public zone boundaries." Similar to forecast amplitude data, these designated areas (geographical regions between breakpoints) have been created in the existing tsunami warning system and are included in the alert bulletin but are not available for all areas of need such as the Puget Sound in Washington State.
- **SPECIAL PROCEDURE AREAS (SPAs): SPAs for tsunamis are developed by TWCs for regions with complicated waterways and unique ocean and tsunami source conditions**. Focused tsunami source monitoring tools may be needed in these regions to better monitor, detect, and forecast tsunamis. "Special procedure" areas include situations like:
    - Volcanoes / volcanic flank collapse (ex: Augustine in Cook Inlet)
    - Inside water alerting needs (ex: Puget Sound or the Strait of Georgia)
    - Landslide hazards capable of generating tsunamis (ex: Barry Arm landslide tsunami in Prince William Sound)
    - Other events where TWCs have adjusted the alerting paradigm from experience

An assessment by states/territories and the TSTAP indicate the existing use of these forecast tools lack a completeness of coverage and effectiveness for the populations at risk. For example, the current breakpoint locations used by the National Tsunami Warning Center (NTWC) separate long lengths of coastline. The entire State of Washington has 3,026 miles of open ocean and embayment coastline and is all within the same forecast/breakpoint area and thus must be under the same alert level regardless of forecast differences for different parts of the coastline. In contrast, California has 3,427 miles of coastline and has ten breakpoints, which is still insufficient to properly break this populated coastline into meaningful alert areas. The lack of breakpoints and the TWC's inability to move, change, or add them has significant consequences for both a local and distant-sourced tsunami event. In a given tsunami some areas may see significant inundation along the outer coast, while other areas, such as within the Puget Sound in Washington State, may only experience minor currents hours after the event but are required to be in the same alert level. In addition, the PTWC does not even use breakpoints to separate coastlines that are unique or exposed to different hazard levels. Having large sections of coastline in the same alert region when the tsunami forecast does not support that alert level potentially means over evacuating large population centers such as Seattle, San Francisco Bay, Honolulu, or Anchorage when there may be no tsunami threat.

Over the last two decades, emergency managers in states with Pacific coastlines have approached the TWCs to ask them to make improvements to the forecast system to resolve these issues. A number of TSTAP recommendations from the 2021 Quadrennial Report (#s 1.1, 1.4, 3.3, 4.1, and 4.2) supported state needs and identified locations where additional breakpoints/forecast areas, SPAs, and forecast locations were needed to better relay the tsunami hazard and alert forecast to coastal jurisdictions and the at-risk public. The TWCs have indicated they have lost the personnel that had the institutional knowledge of how to update and improve tsunami breakpoints, forecast areas, and locational forecast points and have no direction or immediate plan to regain that knowledge of the present tsunami alert system. However, past TWC personnel have indicated that adding forecast areas and forecast points is relatively straightforward, only requiring editing and testing code in the existing tsunami forecast software. For example, during the Science Application for Risk Reduction project and tsunami exercise in 2014, the USGS and the State of California identified that a breakpoint should be added or moved to improve regional alerting. The NTWC, known as the West Coast and Alaska Tsunami Warning Center at the time, was able to move the breakpoint and add over three dozen tsunami forecast locations to enhance hazard identification during events. However, in more recent discussions with the NTWC it has been stated many times that no breakpoints can be added into the system, effectively forcing each state or territory to make do with what they have.

NOAA has stated in their response to the 2021 TSTAP Quadrennial Report and through continued discussions with TSTAP that they cannot address these issues until the present tsunami forecast and communications system is upgraded to Tsunami AWIPS, and the "second phase" of Tsunami AWIPS and the Common Analytical System (CAS) between the two TWCs is implemented. Since initial scoping of the second phase for the Tsunami AWIPS and development of the CAS have not even started, these improvements could take a decade or more to complete because of a perceived lack of urgency or resource issues. **The TSTAP supports state and local requests for immediate action and finds that these improvements are urgent**. The following information is provided to further support the urgency of these changes.

Supporting Information

The necessity for tsunami forecast improvements from the TWCs stems from potentially dangerous conditions and observed gaps in decision-support information at the local level, predominantly in large coastal population centers. Another reason for providing these products is to help rectify some of the ongoing inconsistencies between the TWCs which provide different outputs during a tsunami alert forecast, despite the fact that the TWCs are meant to act as backup for each other during tsunami events if necessary. For example, the NTWC provides location-specific forecast tsunami amplitudes and arrival times for local decision makers and uses tsunami forecast breakpoints to separate coastal areas that exhibit different tsunami hazards and alert levels during events. The PTWC does not provide forecast tsunami amplitudes, nor does it use forecast alert breakpoints to separate areas of different hazard levels. In addition, NOAA has indicated that neither TWC possesses the ability to upgrade their existing systems due to loss of personnel who are familiar with the one-of-a-kind computer software used. Example areas of major necessary improvements are summarized below:

- *New breakpoints, SPAs, and forecast areas in Washington State (including separating the major cities and ports of Seattle and Tacoma from the outer coast)*: SPAs for tsunamis are developed for regions with complicated waterways and unique ocean conditions (example of the Salish Sea SPAs in Figure 1). These SPAs are only designed for specific local earthquake events ranging from magnitude 7.1-7.5. While unlikely, it is possible that crustal faults that cross this region are capable of producing earthquakes with magnitudes greater than 7.5 which would therefore not trigger the SPA alert procedure, but instead would trigger the subduction zone alerting procedure for Washington's outer coast. In this hypothetical scenario, a magnitude 7.6 earthquake in the Puget Sound, the existing TWC procedures would alert and warn the outer coast for a tsunami instead of the Puget Sound where the earthquake and tsunami would have the greatest impact. This nuance between SPAs and subduction zone alert regions has the potential to cause confusion and misinformation in a tsunami event due to inaccurate alert areas being displayed on tsunami.gov, and inaccurate tsunami bulletin information for the event. This could lead to unnecessary evacuations on the outer coast and no official alert message for the Puget Sound where the tsunami is expected to hit downtown Seattle in three minutes after the earthquake starts. **The TWCs have indicated they do not have the capability to update this magnitude threshold or the SPA areas with their current staff, resources, or software**. While this example demonstrates the issues in magnitude thresholds for SPAs in Washington state, this is an area of concern for other complicated waterways where crustal faults exist, such as inlets in Alaska, straits in British Columbia, and other populated bays and inlets such as San Francisco.

  In addition, Washington State's 3,026 miles of coastline sit entirely between two breakpoints. This means that for a distant tsunami which may require evacuations on Washington's outer coast but have little to no impact on Washington's inner coast, the entire state will be placed under the same alert level regardless of forecasted impacts to inland waters such as the Puget Sound. For example, in an Alaskan tsunami event that is forecasted to hit Washington's outer coastline in just 3-4 hours, the entire state will be placed under a tsunami warning. This means millions of people in coastal areas on both the outer and inner coasts will receive evacuation alerts by phone, TV, radio, and tsunami siren. This could lead to unnecessary evacuations on the inner coast (for example the entire waterfront of the City of Seattle) that are costly and can cause injury or fatalities. In addition, this also means that for more distant events, like the 2022 Tonga tsunami, Washington's entire coastline must remain under a tsunami alert as long as any single location along the coast meets the minimum thresholds of the alert level, greatly extending the overall length of time for response and taxing local and state government. **There is a need for additional breakpoints to be able to provide different alerts (as tsunami forecast information warrants) for Washington's coastline**. Figure 2 illustrates a proposed breakpoint/forecast area plan implementing the minimum number of necessary breakpoints that the State of Washington requested from the NTWC. These breakpoints can also help with improving the SPA for the inner waterways.

Washington State has several forecast point locations, places where the NTWC can provide forecasted tsunami arrival times and forecasted tsunami amplitudes, primarily located along the outer coast. However, in the Puget Sound, where over four million people live, work, and recreate, there are only two forecast locations: Tacoma and Bellingham. **In a tsunami event impacting the inner coast there will not be any forecast information (wave arrival times, or estimated amplitudes) for major population and maritime centers such as Seattle, Everett, Bremerton, and Olympia.** This lack of forecast information is likely to confuse people because they may not be aware they are in the alert area or have the information necessary to issue evacuation or support other decisions as necessary. Additional forecast locations have been requested but have not been supported by the NTWC.

- *New forecast area for San Francisco Bay:* **Placing a tsunami forecast breakpoint to separate the outer coast of central California from interior San Francisco Bay would reduce the potential for needless evacuations of over one-hundred-thousand residents and workers within the San Francisco Bay during minor to moderate tsunami events**. For example, Figure 3 shows the observed maximum amplitudes from the 2022 tsunami from Tonga where Advisory/Warning-level tsunami amplitudes (greater than 0.3 meter; response recommended) were observed outside the Bay and sub-Advisory conditions (less than 0.3 meter; no response needed) were observed within the Bay (Wilson et al., 2022). The State of California has made note to the NTWC of similar results from historical tsunamis and other distant source tsunami scenarios inside and outside this and other large bays. However, the NTWC has indicated they do not have the capability to make this change.

- *New forecast amplitude information and forecast area for Honolulu:* All counties (i.e., islands) in the State of Hawaii are combined under one alert level through the PTWC despite showing different hazard levels and impacts during historical events. This has caused the City of Honolulu to undergo full tsunami evacuations of over a hundred-thousand people during at least three forecasted "Warning" level events (2010 Chile, 2011 Japan, and 2012 Haida Gwaii), despite not experiencing tsunami inundation of dry land in those events. In 2012, evacuations in Hawaii led to significant road traffic with one person dying while trying to evacuate. Figure 4 shows the significant difference (at least 2-to-3 times) in the tsunami amplitude and hazard between Honolulu and Hilo over historical time, a difference also seen in other parts of Oahu outside of Honolulu. **Providing tsunami forecast amplitude information and developing forecast areas using breakpoints separating the City of Honolulu from other portions of Oahu and the State of Hawaii will lead to significant reductions in business closures and unneeded and potentially dangerous evacuations.**

- *New forecast amplitudes and additional forecast areas elsewhere:* All U.S. regions covered by the NTWC and PTWC would benefit from provision of location-specific tsunami forecast arrival times and amplitudes. For example, cities along the Columbia River, such as Portland, Oregon, and inland waterways in Alaska, such as near Anchorage, could use additional forecast information support. Another example is that the U.S. Commonwealth of the Northern Marianas Islands is working with the State of California to develop tsunami response "playbooks" for the island of Saipan where forecast amplitude information is directly associated with secondary (less than maximum) tsunami evacuation and maritime response plans. To implement this tsunami playbook process, the tsunami forecast amplitudes and arrival times are required to be shared by the PTWC during an event, however the PTWC does not share this detailed forecast information. **Other states and territories have made similar requests for acquiring location-specific forecast information from both TWCs. The NTWC provides this information for many areas. The PTWC should be consistent and unified with the NTWC and also work towards sharing this same information with their state, territory, and local officials for decision support during an event. This is especially vital if the TWCs are to be fully prepared to support one another during a tsunami event if the primary TWC is impacted for whatever reason and cannot provide information to its service area.**

TSTAP Finding:

In its 2021 Quadrennial Report, the TSTAP recommended that the TWCs implement additional tsunami decision-support tools such as tsunami alert breakpoints improving forecast areas, SPAs for complicated waterways, and location-specific forecast amplitudes, many within a number of critical and highly populated areas. These recommendations reinforce similar requests from numerous state and territory officials to enhance the decision-support tools available to local emergency managers to determine their tsunami evacuation and response actions. In some cases, the improvements require updates to existing computer code but in others, especially for SPAs, the TWCs may also need to alert at a greater granularity by investing in and integrating additional tsunami detection sensors.

The TWCs indicated that many of these issues and upgrades (summarized in Table 1) could be resolved when the "second phase" of the Tsunami AWIPS communications system and the CAS is completed; however, this work may not be completed for a decade or more because of uncertainties in available resources, the capabilities of the new system, and the required training needs for staff. **The TSTAP appreciates that NOAA and the TWCs recognize the need to address these issues, however it is not clear if they view the requested work as a high and immediate priority. Many of the NOAA responses to these recommendations in the TSTAP's 2021 report were referred to future programs that do not yet exist nor have dedicated funding or timelines for implementation. Solving these issues is a high priority for state, territory, and local tsunami response agencies. This paper aims to elucidate some of the complicated issues present in tsunami alerting and the urgency of implementing the changes requested by the TWC constituents, which are the emergency managers and representatives responsible for communicating tsunami alert information for local decision makers.**

REFERENCES:

State of California, 2018, Preliminary Evaluation of Tsunami Forecast Amplitude Accuracy/Error/Usability: unpublished white paper, 4 p.

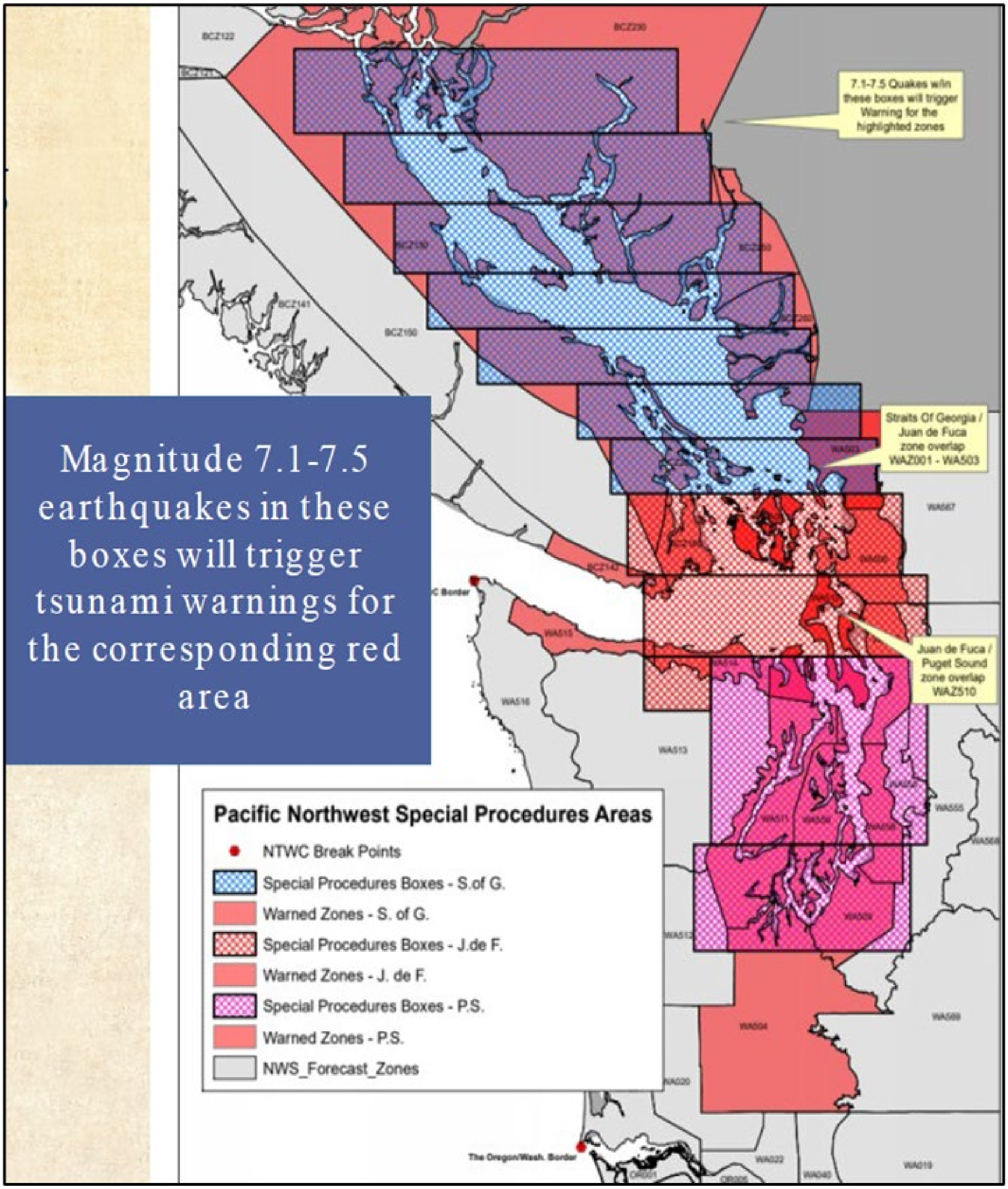

Figure 1 Special Procedure Areas (SPAs) in the Salish Sea of Washington and British Columbia, Canada.

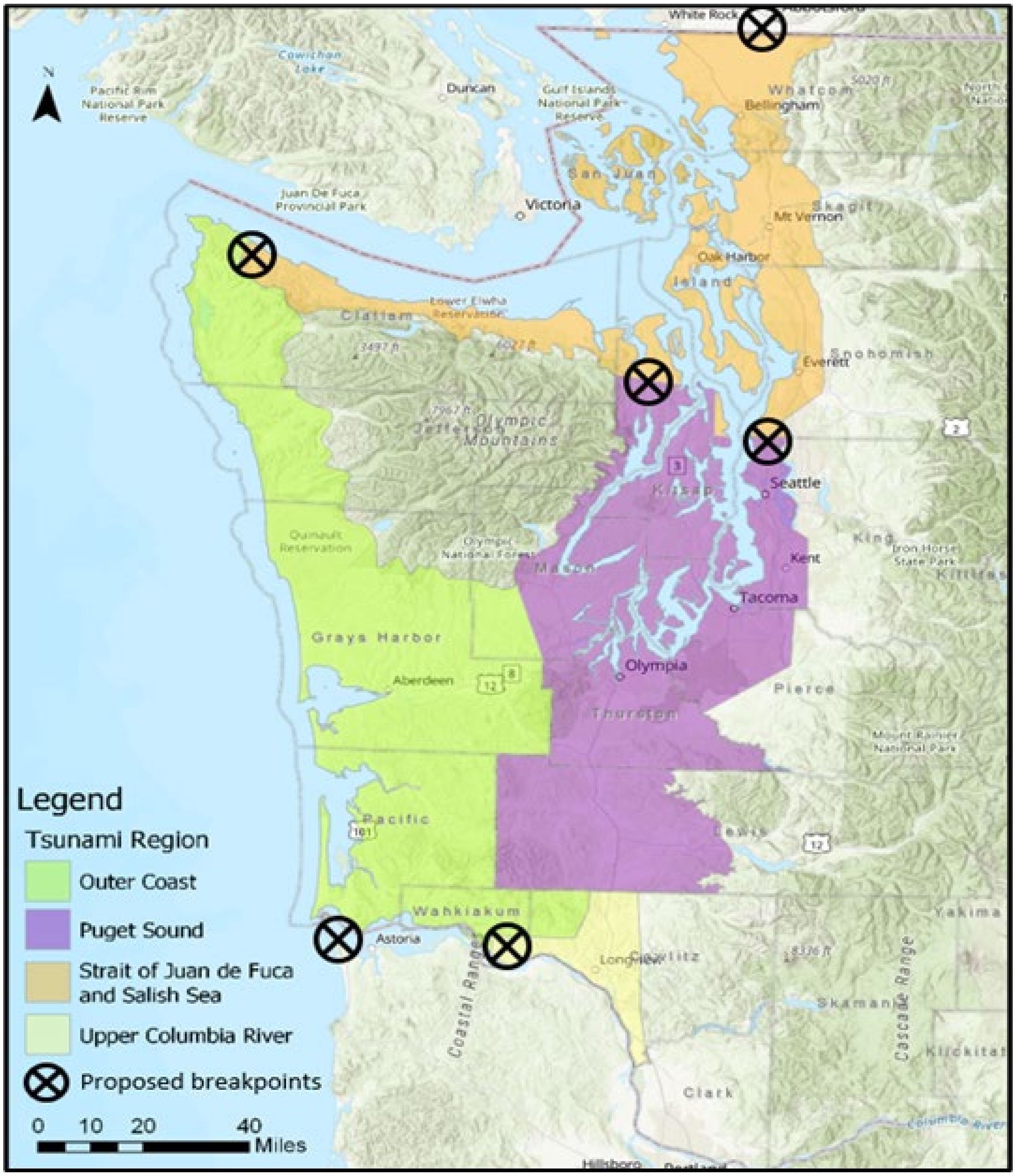

Figure 2 Breakpoints (black circles with X) requested by Washington state as a minimum number necessary to enhance tsunami alerting in Washington State.

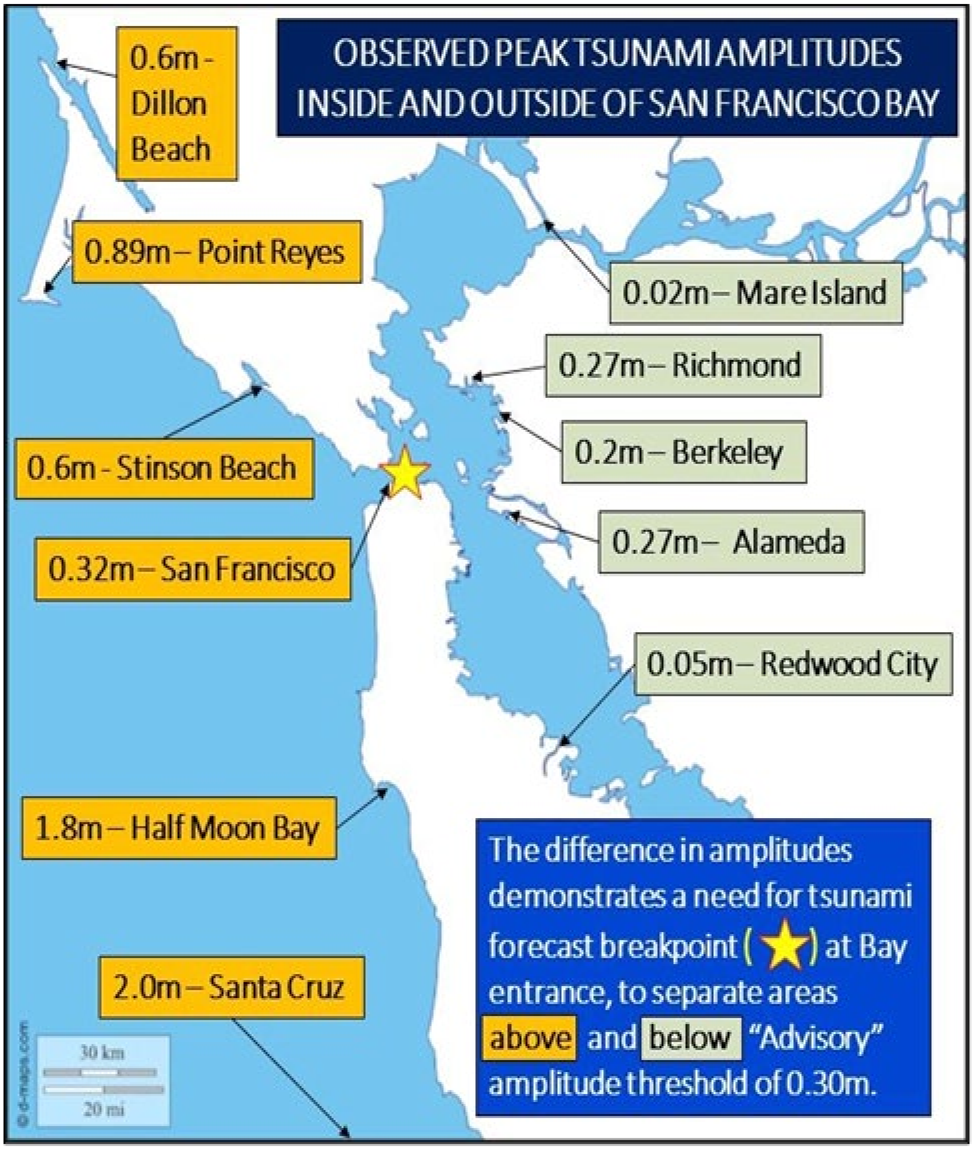

Figure 3 Peak tsunami amplitudes observed during the 2022 Tonga event demonstrate the need for a breakpoint separating these areas.

Date	Magnitude-Source area	Tsunami location	Run-Up/Amp	Remarks
11/7/1837	M8.5 - Chile	Honolulu	8 ft	Several ships ran aground
5/17/1841	M8.4 - Kamchatka	Honolulu	3 ft	Harbor and reef left dry at times
4/3/1868	M7.9 - Hawaii	Honolulu	2 ft	NDR
8/13/1868	M8.5 - Chile	Honolulu	3 ft	Moderate currents coming into harbor
5/10/1877	M8.3 - Chile	Honolulu	5 ft	NDR
6/15/1896	M8.3 - Japan	Honolulu	2 ft	NDR
2/3/1923	M8.3 - Kamchatka	Honolulu	3 ft	NDR
4/1/1946	M8.6 - Aleutians	Ewa Beach	3 ft	NDR
		Hickam Harbor	3 ft	NDR
		Honolulu	6 ft	NDR
		Waikiki	9 ft	Some inundation
		Diamond Head	12 ft	NDR
11/4/1952	M9.0 - Kamchatka	Ewa Beach	5 ft	NDR
		Hickam Harbor	3 ft	NDR
		Honolulu	5 ft	Cement barge torn from moorings strikes freighter
3/9/1957	M8.6 - Aleutians	Ewa Beach	9 ft	NDR
		Hickam Harbor	3 ft	NDR
		Honolulu	5 ft	NDR
		Waikiki	5 ft	NDR
		Diamond Head	5 ft	NDR
5/22/1960	M9.5 - Chile	Ewa Beach	9 ft	NDR
		Hickam Harbor	3 ft	NDR
		Honolulu	5 ft	NDR
		Waikiki	9 ft	NDR
		Diamond Head	6 ft	NDR
3/28/1964	M9.2 - Alaska	Honolulu	2 ft	NDR
3/11/2011	M9.0 - Japan	Honolulu	2 ft	200 boats damaged, 25 sunk
10/28/2012	M7.7 - British Coumbia	Honolulu	1 ft	One fatality from evacuation

Date	Magnitude-Source area	Tsunami location	Run-Up/Amp	Remarks
11/7/1837	M8.5 - Chile	Hilo	20 ft	14 fatalities; 66 buildings destroyed
5/17/1841	M8.4 - Kamchatka	Hilo	15 ft	NDR
1/27/1854	M? - Alaska	Hilo	8 ft	NDR
4/3/1868	M7.9 - Hawaii	Hilo	9 ft	Bridge and several houses flooded
8/13/1868	M8.5 - Chile	Hilo	15 ft	Bridge washed out
5/10/1877	M8.3 - Chile	Hilo	12 ft	5 fatalities; 37 buildings destroyed
6/15/1896	M8.3 - Japan	Hilo	8 ft	Two ships damaged
11/11/1922	M8.7 - Chile	Hilo	7 ft	Many boats washed away; other local damage
2/3/1923	M8.3 - Kamchatka	Hilo	20 ft	1 fatality; significant local damage
4/1/1946	M8.6 - Aleutians	Hilo	27 ft	96 fatalities; $26M in damages
11/4/1952	M9.0 - Kamchatka	Hilo	11 ft	Damage to boathouse; $400K in damages
3/9/1957	M8.6 - Aleutians	Hilo	14 ft	Significant damage to bridge and waterfront area
5/22/1960	M9.5 - Chile	Hilo	35 ft	61 fatalities; $23.5M in damages
3/28/1964	M9.2 - Alaska	Hilo	10 ft	Minor damage along waterfront area
11/29/1975	M7.7 - Hawaii	Hilo	9 ft	Several boats sunk
3/11/2011	M9.0 - Japan	Hilo	6 ft	NDR

Distant Source - Tsunamis without felt earthquakes

Local Source – Felt earthquake and tsunami together

Tsunami amplitude, in feet, above normal tide conditions; NDR = No damage or severe conditions reported; Source: NOAA/NCEI Tsunami Webpage

Figure 4 Tsunami amplitudes and impacts for the cities of Honolulu and Hilo from historical tsunami events. Note amplitudes for Honolulu are at least 2-to-3 times less than Hilo for the same events. Information was compiled from the NCEI tsunami database website.

Table 1 state, territory, and community locations which have requested and/or could benefit from additional tsunami forecast breakpoints/areas, locational amplitude and arrival time data, special procedure areas (SPAs), or source detection equipment; “yes” indicates they have requested or could benefit from this information.

Locations (State, Region, and Affected Cities/Communities)	Requested Forecast Breakpoint Creating New Forecast Area(s)	Requested Forecast Amplitude and Arrival Time Location(s)	Request to Implement/edit Special Procedure Area(s)	Requires Source Detection Equipment	PTWC or NTWC Designated Service Areas
WA - Salish Sea/Puget Sound; Seattle, Tacoma	Yes	Yes	Yes	Yes	NTWC
OR – Columbia River; Portland	Yes	-	-	-	NTWC
CA – San Francisco Bay; Oakland/Alameda	Yes	-	-	-	NTWC
HI – Oahu; Honolulu	Yes	Yes	-	-	PTWC
AK – Inland Waterway; Anchorage	Yes	Yes	-	Yes	NTWC
CNMI – Saipan	Yes	Yes	-	-	PTWC