ShakeAlert® activities for formal and informal learning settings

Modeling Factors that Influence Tsunami Inundation

Tabletop Wave Container Investigations

Version 02/11/22

Activity modified from "Investigating Factors That Affect Tsunami Inundation" by Bonnie Magura

OVERVIEW

Not all tsunamis act the same. A small nondestructive tsunami in one place may be very large and violent a few miles away. This is because coastal areas have different beach slopes and different offshore and coastal geographical features, such as reefs, bays, and river inlets.

This activity investigates the factors that affect how tsunami waves interact with submarine and shoreline topography. In the 5-minute activity, learners discover how coastal topography dramatically impacts how far a tsunami wave can travel. The 15-minute activity allows learners to explore several topographic features using a container to model tsunami waves. Building on the 15-minute activity, the 45-minute activity investigates how two related landforms, such as a straight coastline compared to a coastline with a river inlet, affect how far a tsunami wave travels inland. Learners gather data, summarize their observations, and explain the importance of tsunami wave inundation for community preparedness.

Why is it important to learn about earthquakes and their effects, such as tsunamis? Over 100,000 people along the Pacific Northwest and Northern California coastal areas could be affected by a major tsunami. An understanding of the size of an earthquake and its potential to cause a tsunami is fundamental to tsunami hazard preparedness. The ShakeAlert® Earthquake Early Warning system for the West Coast of the U.S. detects significant earthquakes quickly, so that alerts can be delivered to people and automated systems. A vocabulary in Appendix A provides helpful terms.

OBJECTIVES

Learners will be able to:

- Explain how scientists have discovered evidence of past tsunami inundation along coastlines and rivers.
- Investigate how tsunami waves interact with topographic features and other factors using a model.
- Distinguish between tsunamis of distant and local origin.
- Design an investigation to test tsunami inundation of different landform features using a model.

Beginner

5 min | 15 min | 45 min

Large Group | Small Groups

Student Investigation | Materials

Time: 5-, 20-, and 45-minute guided activities that can be adapted for audience and venue.

Audience: This can be done with novice and experienced geoscience learning groups.

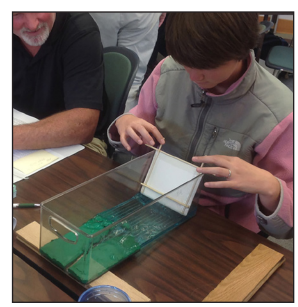

Figure 1: Learners generate a tsunami with the model. Wood blocks elevate the wave container; green clay demonstrates landforms.

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MATERIALS, TOOLS AND CONSTRUCTION

Materials for the 5-minute activity

- Computer with projection system
- Appendix B—Tsunami Evacuation signs
- Appendix C—Niawaikum River, Washington tsunami sand layers

Materials for the 15-minute activity

- Computer with projection system
- Appendix D—Tsunami wave container construction Instructions
- Appendix E—Tsunami wave container topography variables
- Tsunami wave tank set ups for each learner group

Materials needed to build one tsunami wave container and paddle

For each tsunami wave container, one set up for each learner group:

- Rectangular plastic storage container that is long for water run up and narrow to minimize amount of clay needed, such as Linus™ Deep Drawer Binz Clear 6″ x 16″ x 5″ h
- Non-hardening modeling clay for land features
- Ruler
- Container for water
- Blue food coloring
- Blocks of wood to tilt container
- Colored toothpicks to mark the distance the tsunami wave travels
- Knife to cut the clay into thin landform pieces
- Paper towels
- Small cup to adjust water level

Tsunami wave making paddle:

- Heavy plastic such as HDPE (High Density Polyethylene) 1/32″ sheets or heavy-plastic report cover
- Heavy bamboo skewers to make the paddle and the horizontal bar that limits the distance the paddle can pivot forward to make the waves
- Ruler
- Scissors to cut the plastic for the paddle
- Wire cutter pliers (to cut skewers)
- Packaging or strapping tape to attach the skewers onto the plastic paddle

Materials for the 45-minute activity:

- Appendix E —Tsunami wave container topography variables
- Appendix F—Tsunami Wave Variables Data Table for each learner group
- Tsunami wave container set ups for each learner group

RELEVANT RESOURCES

Videos

- [Tsunami wave simulation for Willapa Bay, Washington (2:45 min)]
- [Tsunami wave simulation for Washington State (2:25 min)]
- [Demonstration of the wave container paddle] (19 sec)

Media and interactive tools as relevant background

- [Ghost Forests—Evidence for a Giant Earthquake & Tsunami in the Pacific Northwest] (7:20)
- [Tsunami Simulation Videos] for Washington
- [Tsunami events (1850–Present) Time-lapse animation]

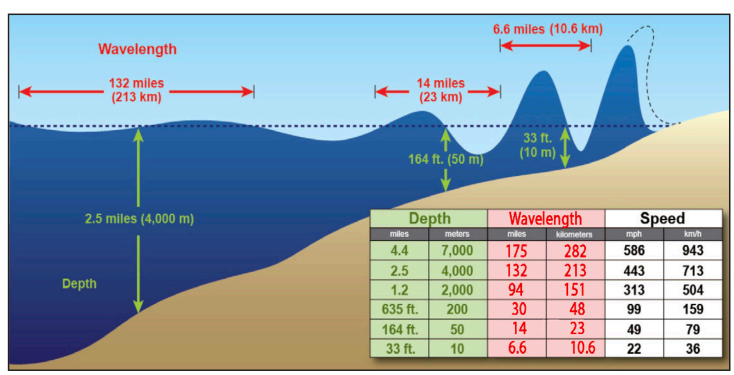
Publications as relevant background (optional)

[Science Inquiry Activity: Investigating Factors that Affect Tsunami Inundation]

- USGS free book: [The Orphan Tsunami of 1700: Japanese clues to a parent earthquake in North America]
- [Extraordinary Voyage of Kamome: A Tsunami Boat Comes Home]

INSTRUCTOR PREPARATION

The topography of the seafloor and shape of the coastline affect a tsunami's appearance and behavior. Typically, the ocean floor rises as it nears land. As the tsunami moves from deep water to shallow water, the change in water depth forces the energy of the tsunami to compress,



Depth		Wavelength		Speed	
miles	meters	miles	kilometers	mph	km/h
4.4	7,000	175	282	586	943
2.5	4,000	132	213	443	713
1.2	2,000	94	151	313	504
635 ft.	200	30	48	99	159
164 ft.	50	14	23	49	79
33 ft.	10	6.6	10.6	22	36

Figure 2: Tsunami wave height changes. See graphic in Appendix G.

shortening the wavelength of the tsunami and slowing the tsunami velocity. (Figure 2 and Appendix G.)

As the velocity of the wave diminishes, the wave height increases considerably. A typical tsunami approaching land will slow to speeds around 30 mph (50 kph) from 500 mph in open ocean, and the wave heights can reach over 100 feet (30 meters) above sea level.

Tsunamis usually arrive as a series of swift, powerful floods of water, not as a single, enormous wave. However, a large vertical wave called a bore may come with a churning, turbulent front. Rapid floods of water often follow bores, making them particularly destructive. Other waves can follow anywhere from 5–90 minutes (or for hours) after the initial strike, sometimes lasting 24–48 hours after the initial wave. The tsunami wave train, after traveling as a series of waves over a long distance, crashes into the shore and up onto the land, sometimes reaching miles inland.

- Familiarize yourself with the Resources and Appendices which provides helpful background information related to the activities.
    - APPENDIX A—Vocabulary
    - APPENDIX B—Tsunami Evacuation Signs
    - APPENDIX C—Niawaikum River, Washington tsunami sand layers
    - APPENDIX D—Tsunami Wave Tank Construction Instructions
    - APPENDIX E—Tsunami Wave Container topography variables
    - APPENDIX F—Tsunami Wave Variables Data Table
    - APPENDIX G—How Tsunamis Interact With Land
    - APPENDIX H—Differences Between a Wave and a Tsunami
    - APPENDIX I—Earthquake-induced Tsunami Events, Sources, and Impacts.

ACTIVITIES AND DEMONSTRATIONS

IF YOU HAVE 5 MINUTES

Did You Know?

- Did you know that scientists have discovered evidence of tsunami-carried sand miles up coastal rivers?

Geologists look for tsunami sand deposits along coastal streams and rivers to find evidence of historic earthquakes and tsunamis. The distance that tsunami-carried sand travels depends on the shape and slope of the shoreline. Scientists have found buried sand layers along coastal rivers, as far inland as 10 miles (16 km) to places where sand is typically not found (See Figure 3). These buried sand layers help researchers create maps that show where and when tsunami inundation has occurred in the past and will happen again in the future. These maps are critical for community planning, zoning, and emergency preparedness.

Preparation

- Watch Demonstration of the wave container paddle.
- Computer and projection system link set for: Tsunami wave simulation for Willapa Bay, Washington (2:45 sec.) Since the video has no sound, be prepared to help interpret and pause at time codes:
    - 0:07 Point out the terms: tsunami wave amplitude, wave trough, wave peak, mean high tide, and tsunami inundation depth.
    - 0:24 Point out: a) the color keys for wave amplitude and inundation depth, and b) time elapsed.
    - 0:42 Notice that the water is yellow, and land is black, and the transitions in the map view, such as how the Willapa Bay rectangle on the map enlarges for closer examination.
    - 0:55 Point out the location of Bay Center on the east side of Willapa Bay and the approximate location of the Niawaikum River which is just east of Bay City. We will focus on the Niawaikum River, which is identified in Appendix C, but not labeled on the map in the video. Point out the text as the video resumes stating, "Land and water drop following earthquake (subsidence)."
    - Notice how the tsunami inundates the land and follows river inlets entering Willapa Bay in several places.
    - Notice how the colors change in the area of all the inlets into Willapa Bay but particularly the

Figure 3: Tsunami carried sand layers (gray) overlay a former marsh (now peat layer) on the Niawaikum River, Washington. See Appendix C, Figure D for further description of the arrows.

Niawaikum river. Colors reflect both the change in tsunami height in the bay waters, but then change to red as the tsunami runup covers the land.

- 1:06 at Long Beach and 1:11 near Bay Center, notice how the red intensifies over time with each wave, which is a factor of both the land level dropping (subsidence) and the tsunami runup. Also notice how the tsunami wave wraps around the end of the peninsula and enters the bay. This is called the wraparound effect (See Appendix G).

- Print Appendix B—Tsunami Evacuation Signs.
- Print or computer project Appendix C—Niawaikum River, Washington Tsunami Sand Layers.
- Note: The video, Ghost Forests—Evidence for a Giant Earthquake & Tsunami in the Pacific Northwest (7:20) provides additional helpful background to understand the content of this activity.
  Also this interactive tool: Tsunami events (1850 to Present) Time-lapse animation explores tsunami inundations in other parts of the world.

Procedure

1. Introduce the topic of tsunami wave inundation. Ask learners to raise their hands if they have ever been to the coast and seen tsunami evacuation signs (see Figure 4). Show image of tsunami evacuation signs Appendix B. Tsunami sign locations are unique to each part of the coastline. This is because tsunamis are impacted by factors that affect both the run up (highest elevation a tsunami wave reaches) and inundation (the distance a tsunami wave travels). Other factors affect how tsunami waves travel, bending and reflecting as they interact with the coastline topography.
2. Explain to learners that they will watch a short video. The video is a computer simulation of how tsunami waves from a M9.0 subduction zone earthquake interact with a section of the Washington coastline. The coastline in the simulation includes the northern portion of the Long Beach peninsula and Willapa Bay with many river inlets. The video has no sound so pay attention to the written explanations. We will focus on how the tsunami surge inundates river inlets which open into Willapa Bay.
   a. Start the video pointing out key features which explains the simulation.
   b. Pause exactly at 55 seconds and point out the location of Bay Center, which is opposite the tip of Ledbetter point on the Long Beach Peninsula across Willapa Bay.
   c. Ask learners to watch the shape of the incoming tsunami waves and see what they notice. Then, play the remaining video.

Question for Discussion:

- What did you notice about the tsunami waves? (*Answers vary but may include land and sea level drop with subsidence; the wave crest (red) is followed by a wave trough (blue); the tsunami wave inundates the Long Beach Peninsula and pushes into Willapa Bay; and tsunami waves enter bays, inlets and rivers flooding the land. Waves swirl, interact, reflect, and repeat as new waves enter the bay*.)

3. Explain that we are going to look at the Niawaikum River, (nee-ah-wai-kum) which enters Willapa Bay near Bay Center. Show Appendix C either by paper or computer projection.
   a. Show the location of the Niawaikum River on the map (Figure A). Notice that the mouth of the river opens toward Willapa Bay and that tsunami waves enter the bay from the ocean.
   b. Explain that tsunami geologists have researched this area to prove that it has experienced a M9 subduction zone earthquake in the past, and that an earthquake of that size will in fact, happen again (Figure B).
   c. Show the sequence of events that scientists use as evidence of a great earthquake and tsunami (Figure C). Show the image and describe the steps.
   d. Figure D shows multiple gray sand layers carried in by individual tsunami waves. The sand layers cover the former coastal marshland, which is now a buried peat layer. Mud and clays cover the sand and silt layer as the land dropped and was flooded. Since the tsunami in 1700, the land level has risen, as the earthquake cycle repeats and lifts the tsunami evidence up for us to see.

Questions for Discussion:

- What does the tsunami sand evidence mean for people who live along rivers that open to bays or to the ocean? (*Tsunami wave inundation makes communities vulnerable to tsunamis several miles inland just as much as communities right along the coastline.*

Figure 4: Tsunami evacuation signs. See Appendix B for large-scale copies and links to sources.

People who live on or visit the coast need to be aware of the tsunami inundation zone and evacuation signs.)

- What would the example for Willapa Bay mean for communities all along the Pacific coast? (*All communities along the coast of the Pacific Ocean are vulnerable to tsunamis and should know how tsunami inundation and run up could affect their specific communities and region. The same is true for other subduction regions, such as the Caribbean.*)

IF YOU HAVE 15 MINUTES

Did You Know?

- Did you know that tsunami waves generated from the same earthquake have different characteristics?

Many factors affect how tsunami waves interact with coastal and nearshore land. We will look at tsunami waves generated by an offshore subduction earthquake on the Cascadia Subduction Zone. This is not the only way in which tsunamis happen. Tsunamis also may be locally generated by landslides released by earthquake shaking. The factors that affect tsunamis have enormous significance for communities along coastlines as well as communities along bays, harbors, and rivers that open to the ocean.

Instructor Preparation

- Content presented in the 5-minute activity should precede this activity.
- Computer and projection system link set for: [Tsunami wave simulation for Washington State] (2:25 min)
- Tsunami wave container set ups for each learner group including:
  - Plastic wave container with clay to represent the land surface
  - Plastic knife to help cut and shape coastal landform features
  - Extra clay to help create landform features
  - Pieces of wood to raise the elevation of the land end of the container
  - Tsunami wave paddle
  - Wave paddle restraining bar (pre-cut bamboo skewer)
  - Container of blue colored water (about a 1 ½ –2 cups)
  - Paper towels
  - (Optional: Have learners use the engineering design process to create and test their designs. See Appendix J.)

Procedure

1. Review key concepts from the 5-minute activity.
   - Land topography and subsidence (land and water drop following an earthquake) can dramatically affect the distance a tsunami wave travels inland.
   - The evidence of deposits of tsunami-carried sand provides valuable evidence of past tsunamis and their extent.
   - Scientists use tsunami science to create tsunami inundation maps for community planning, zoning, and emergency preparedness.
2. Explain that each group of learners will have their own tsunami wave container to explore different landforms. They can reshape the clay to create their own landforms for investigation.
3. Show Appendix E with some landform examples learners may want to explore.
4. Demonstrate how to use the tsunami wave model, pointing out the parts (see Figure 5) and give instructions for the investigation:

   a. Create the clay landform you will investigate.

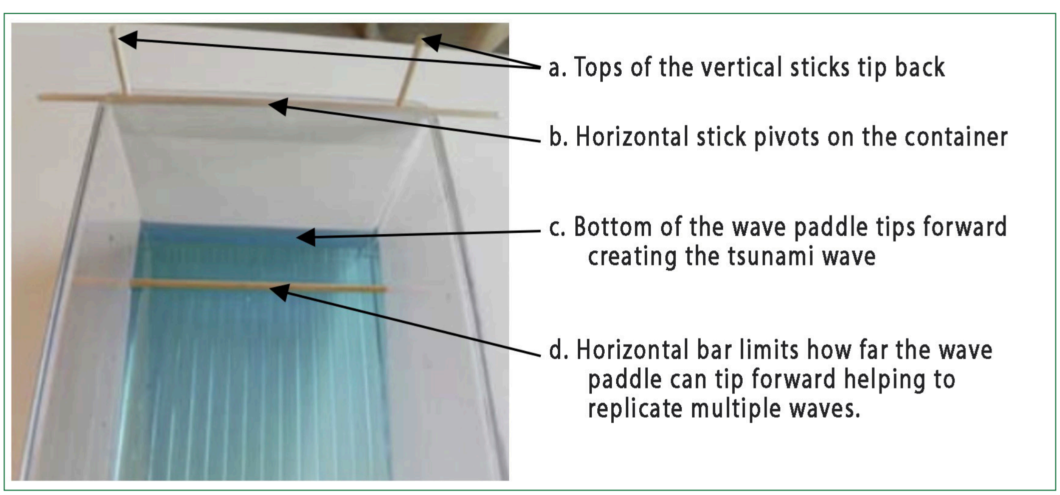


Figure 5: Tsunami container with paddle in the 'starting' position against the back of the container. See the video, [Demonstration of the wave container paddle]

b. Raise the height of the land end of the container at least 2″ using the pieces of wood provided.
c. Add blue colored water to the container so the water line reaches just below the clay where land begins. (Color makes the water more visible.)
d. Position the wave paddle limiting horizontal bar about 1½ to 2″ from the water end of the container near the bottom of the container. The bar stays in place by friction (See Figure 6).
e. Place the wave paddle against the back wall of the container.
f. Assign one person to create each of the tsunami waves for consistency.
g. Practice creating a tsunami wave (watch [Demonstration of the wave container paddle]):
  - Gently tip the top sticks of the wave paddle back, so that the wave paddle pivots on the top horizontal bar causing the bottom of the wave paddle to tip forward creating a wave.
  - The ideal wave almost reaches but does not touch the back wall of the wave container. Adjust the horizontal bar to limit the extent the wave paddle can pivot forward so each of the following waves can be replicated.
  - Continue to practice creating the ideal size of wave by: 1) adjusting the limiting bar position, or 2) using more or less force tipping the wave paddle.

5. Tell learners how much time they have for the investigation (8–10 minutes).

After learners have had time to experiment with their wave container, summarize the activity by asking the groups to share what landform they investigated and what they observed.

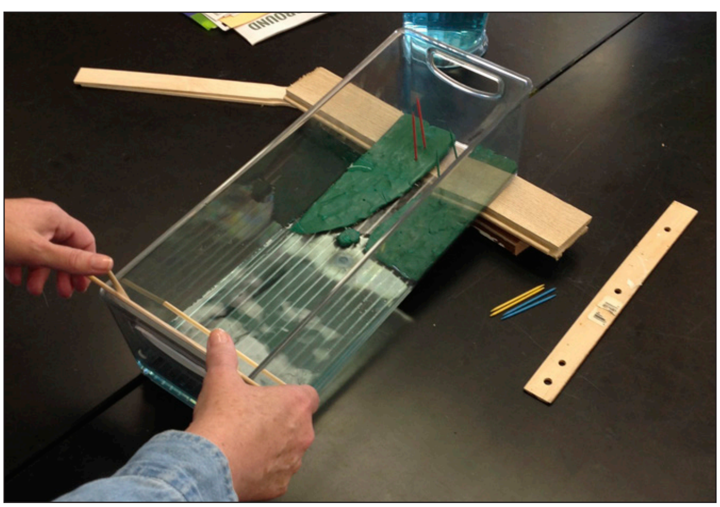


Figure 6: Learners investigate a river inlet with the tsunami wave model. Image source: UNAVCO

Questions for Discussion

- Describe one thing you learned from investigating your variables? (*Answers vary*.)
- In what way is the model like and unlike reality? (*Answers vary but could include: Like reality, The wave paddle moves water to the ocean floor, the waves interact with landforms, the waves demonstrate both wave run-up (height) and inundation (distance). Unlike reality, waves surge and remain for many minutes, waves are not clear water but contain a dense mixture of disturbed sand and debris, tsunamis affect wide areas of coastlines rather than a small area*.)

IF YOU HAVE 45 MINUTES

Did You Know?

- Did you know that an earthquake can cause tsunamis impacts to coastlines both locally and far away?

An example of a local tsunami to the Pacific Northwest is a megathrust earthquake on the Cascadia Subduction Zone, which last occurred on January 27th, 1700 - and also hit Japan as an orphan tsunami. A tsunami generated by a Cascadia earthquake would arrive on the Pacific Northwest coast within 20–30 minutes (local tsunami) while Japan and Alaska would receive the tsunami many hours later (distant tsunami). The Orphan Tsunami of 1700: Japanese clues to a parent earthquake in North America provides an optional fascinating background about the science of discovery.

An earthquake on a subduction zone across the ocean could cause a distant tsunami to impact local coastlines. For example, the 2011 M9.1 Tohoku-Oki, Japan earthquake created a devastating local tsunami for Japan, and the distant tsunami caused damage to coastlines of the Pacific Northwest to California. Both distant and local tsunamis have significant risks for coastal communities; see the Extraordinary Voyage of Kamome: A Tsunami Boat Comes Home which tells the story of personal and community connections across the ocean years after the Tohoku-Oki earthquake and tsunami.

In the past century, several damaging tsunamis have struck the West Coast of the United States from distant origins such as Alaska, Chile, and Japan causing widespread damage and fatalities (see Figure 7 and Appendix I). Fortunately, distant earthquakes and tsunamis provide four or more hours of advance warning before the first surge arrives.

Understanding how tsunamis affect individual communities involves specific, localized research by

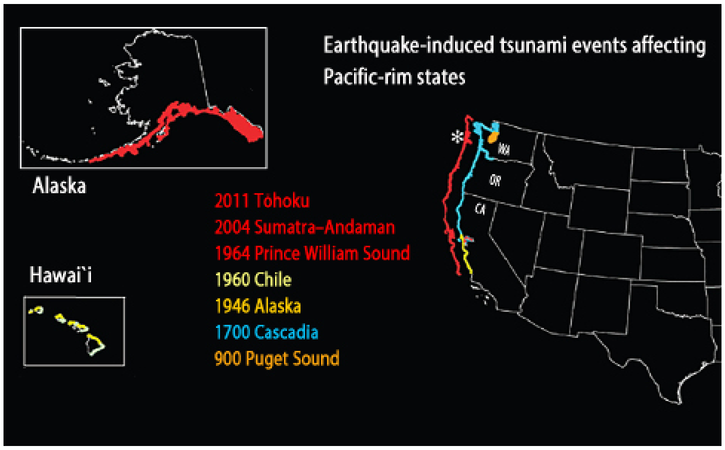


Figure 7: Map of earthquake-induced tsunamis on the Pacific shores of the United states. See Appendix I for larger copy of this graphic.

scientists. Scientists measure coastline and ocean bottom topographies as they change on local scales. Their work in mapping both local and distant tsunami inundation is critical for emergency management, planning, and preparedness.

Instructor Preparation

- Basic tsunami information should be presented to learners prior to this investigation, to include the relevance of tsunami inundation and mapping for community planning and emergency preparedness.
- Print enough copies of Appendix E (variables) and Appendix F (data tables) for each learner group.
- Have a computer projection system ready to show Appendices E and F.
- Review APPENDIX G—How Tsunamis Interact with Land, and Appendix H—Differences Between a Wave and a Tsunami
- Tsunami wave container set ups for each learner group, to include:
    - Plastic wave container with a clay land surface
    - Plastic knife to cut and mold the clay
    - Extra clay to help create landform features
    - Toothpicks to mark how far the wave travels
    - Pieces of wood to raise the elevation of the land end of the container
    - Tsunami wave paddle
    - Wave paddle restraining bar (pre-cut bamboo skewer)
    - Container of blue colored water (about a 1 ½–2 cups)
    - Paper towels
    - Ruler
    - Small cup to adjust water level
    - (Optional: Have learners use the engineering design process (see Appendix J) to create and test their designs.)

Procedure

1. Explain that subduction zone earthquakes from both distant and local origins can affect the west coast of the United States with damaging consequences.
2. Ask learners to compare characteristics of distant and local source tsunamis in the Pacific Northwest as a pre-assessment and teachable moment (examples in Table 1). Present a fact about a distant tsunami and then ask learners to provide the local tsunami comparison based on their understanding. Fill in information that may be missing from their answers.
3. Explain that learner teams will investigate how tsunami waves interact with various coastal landforms, which affect wave run-up distance (Appendix I).
4. Computer project or distribute paper copies of Appendix E Tsunami wave container topography variables.
5. Review each of the variables to check for understanding. One such variable is near shore bathymetry, which is created by changing the elevation of the land end of the wave container with blocks of wood. Explain that teams

Table 1: Characteristics of distant- vs. local-source tsunamis.

Distant source tsunami	**Local source tsunami**
Several hours advance warning	*Minutes warning or severe ground shaking or rapidly receding water as the warning*
Wave run-up of ~30 feet	*Wave run-up of up to 100' or higher*
Damage limited to coastal areas in inundation zone	*Widespread damage from both earthquake and tsunami*
Several subduction-zone sources, so recurrence is more frequent. Closest distant source is in the Gulf of Alaska	*Generated by a nearby subduction zone earthquake. The Cascadia Subduction Zone (CSZ) has a recurrence interval of ~300–500 yrs. Last occurrence was 1700.*
Warning from official sources (Tsunami alerts, tsunami sirens, National weather service)	*Warning from natural signs: Earthquake shaking, water moving out, roaring sound from the ocean.*

could also create their own variable to explore, such as introducing a bay or harbor.

6. Each team decides which variables they will want to investigate. Each variable should be related to the other so that one will act as a "control" and one as the variation to the control. Examples include: a coastline with or without offshore islands, or a coastline with or without a river inlet (Figure 8).
7. Note that every condition in the investigation will remain the same, except for the one change in the landform variable. Conditions that remain the same include:
   - the size of the wave generated (keeping the wave restraining bar in the same position and using the same motion to create the wave)
   - the height of the land end of the wave container (Step 5),
   - water level
   - If exploring bathymetry, the landform remains the same and the height/slope of the wave container is the variable that changes.
   - If exploring near or distant tsunami sources, adjust the size of the wave by moving the horizontal restraining bar limiting the energy into the wave. (Variable 7 shown in Appendix E)
8. Demonstrate how to use the tsunami wave model (Watch the short video [Demonstration of the wave container paddle](#) (19 sec)).
   a. Create the first of two clay landforms that you will investigate.
   b. Raise the height of the land end of the container at least 2" using the pieces of wood provided.
   c. Add blue colored water to the container, so that the water line reaches just below the clay where land begins (Figure 6).
   d. Position the wave paddle limiting horizontal bar about 1½ to 2" from the water end of the container. The bar stays in place by friction.
   e. Place the wave paddle against the back wall of the container.
   f. Assign one person to create the tsunami waves each time for consistency.
   g. Practice creating a tsunami wave:
      - Gently tip the top sticks of the wave paddle back, so that the wave paddle pivots on the top horizontal bar. This will cause the bottom of the wave paddle to tip forward, creating a wave.
      - The ideal wave almost reaches but does not touch the back wall of the wave container. Adjust the horizontal bar to limit the extent that the wave

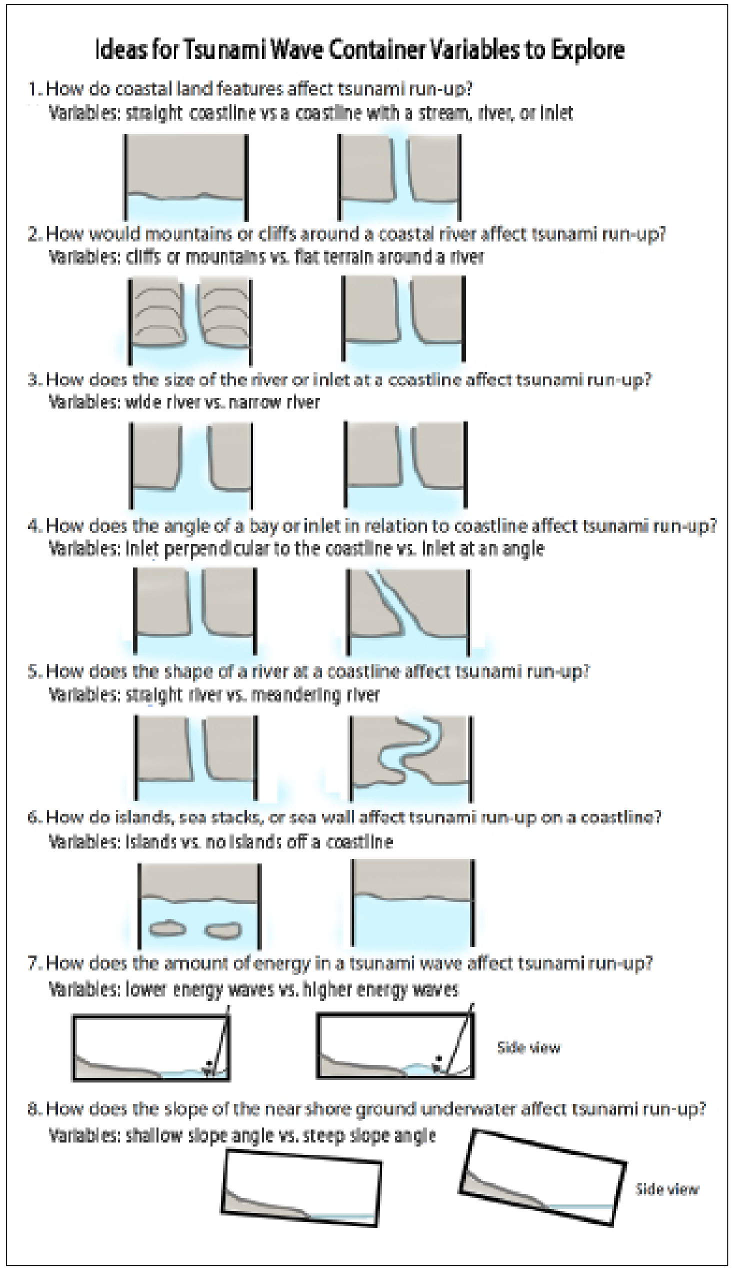


Figure 8: Tsunami wave container topography variables. See Appendix E for a larger copy of this graphic.

paddle can pivot forward, so each of the following waves can be replicated.

- Continue to practice creating the ideal size of wave by:
  1) adjusting the limiting bar position, or
  2) using more or less force tipping the wave paddle.
- Adjust the water level by adding or removing water with a small cup.

9. Distribute Appendix F—Tsunami Wave Variables Data Table and review directions for the investigation:

   a. Instruct learners to practice making tsunami waves and observing how their model works. Choose one person to make the waves for the experiments to create an optimal-sized wave for the investigation.

   b. Practice sending the tsunami wave to the first variable of your choosing in Appendix F. Make sure the water level and wave size are appropriate. (See step g above.)

   c. Send at least three (3) measurable tsunami waves over the first landform variable. Mark the distance each wave travels with a toothpick. Measure the distance each wave travels from the edge of land to the toothpick in cm. Record the distances and observations on the Tsunami Wave Variables Data Table.

   Note: You may also record a video of your tsunami in slow motion to help with recording observations for each variable.

   d. Make changes to the landform to create your second variable. Carefully check to make sure all other conditions remain the same for testing.

   e. Send at least three (3) measurable tsunami waves over the second variable. Mark the distance each wave travels with a toothpick. Measure the distance the wave travels from the edge of land to the toothpick in cm. Record the distances and observations on the Tsunami Wave Variables Data Table.

   f. Complete the data table by determining the average of the three tests for each variable. Draw the bird's eye view of each variable in the rectangle provided.

   i. If testing bathymetry, record the height of the back edge of the wave container while the landform remains the same for each variable height! Also record the tsunami inundation distance for each slope tested.

   g. Write a summary statement comparing the average tsunami inundation distance of each variable and what implications this would have for a community.

10. When the investigation is complete, encourage groups of learners to visit other table groups to see what variables they were investigating.

Questions for Discussion

- What variables were you investigating in your group? (*Answers vary*.)
- How did tsunami inundation or run up change between the variables? (*Answers vary*.)
- What did you learn about tsunami inundation that was new to you or surprised you? (*Answers vary.*)
- In what way is the model like and unlike reality? (*Answers vary but could include: Like reality, the wave paddle moves water to the ocean floor, the waves interact with landforms, the waves demonstrate both wave run-up (height) and inundation (distance). Unlike reality, waves surge and remain for many minutes, waves are not clear water but contain a dense mixture of disturbed sand and debris, tsunamis affect wide areas of coastlines rather than a small area*.)

APPENDIX A—Vocabulary

Bathymetry— "submarine topography," or the depths and shapes of underwater terrain.

Cascadia Subduction Zone (CSZ)—a 600-mile (1,300 km) fault that runs from northern California up to British Columbia and is about 70–100 miles (112–160 km) off the Pacific coast shoreline.

Diffraction—when waves get to a barrier (such as an offshore rock) or pass through a small gap (such as the opening to a harbor), they bend and spread around an object. Diffraction allows wave energy to reach 'shadow zones' at ports, harbors, built structures, and offshore islands.

Distant-source tsunami — a tsunami that originates from a distant source, typically defined as more than 1,000 km (620 mi) away or three hours' tsunami travel time from the area of interest.

Interference—when two waves travelling in different directions meet, they combine their energies and form interference patterns. This can result in regions of very high waves when they add up (constructive interference) alternating with regions of diminished or no waves when they cancel out (destructive interference).

Local-source tsunami—a tsunami that originates from a nearby source and arrives onshore within an hour, or sometimes within just minutes. Destructive effects are confined to coasts typically within 100 km of the source.

Mean high tide—The mean average of all the high tides (high tides and low high tides) occurring over a certain period of time, usually 18.6 years (the tidal epoch).

Reflection—A tsunami wave can reflect off continental shelves, ocean ridges and large reefs under the sea as well as coastlines with a steep cliff or a seawall.

Refraction—is the change in the direction of a wave as it slows down. In shallower water near the coast, waves slow down because of the force exerted on them by the seabed. Refraction is important for tsunamis because (unlike other waves) they interact with the seabed even in deep water—so they are always undergoing refraction. This affects the direction that the tsunami travels through the ocean. Tsunamis also refract around land masses.

Resonance—when the frequency of the tsunami wave is similar to the natural oscillating frequency (resonant frequency) of the body of water in a bay. Resonance can push the water level much higher, making the effect of the tsunami greater.

Subsidence—gradual settling or sudden sinking of the Earth's surface due to removal or displacement of subsurface earth materials.

Tsunami inundation—the horizontal measurement of the path of the tsunami.

Tsunami inundation depth—the depth of the water from a tsunami, measured on shore in different locations.

Tsunami run-up —maximum vertical height onshore above sea level reached by a tsunami.

Tsunami wave amplitude —The height of a wave above the undisturbed sea surface and a particular peak or trough, usually this is equal to 1/2 the wave height.

Wave crest (or wave peak) —the highest part of a wave.

Wave height—the vertical distance of a wave from trough to peak.

Wavelength—defined as the distance between two identical points on a wave (i.e., between wave crests or wave troughs). Normal ocean waves have wavelengths of about 100 meters. Tsunamis have much longer wavelengths, usually measured in kilometers and up to 500 kilometers.

Wave trough—the lowest part of a wave.

APPENDIX B—Tsunami Evacuation Signs

Image sources: Tsunami Evacuation route and Tsunami Hazard Zone

APPENDIX C—Niawaikum River, Washington Tsunami Sand Layers

The Niawaikum River outlet has layers of tsunami deposits that resulted from the Great earthquake and ensuing tsunami that occurred on January 26, 1700, discovered by geologists studying evidence for earthquakes in the Pacific Northwest.

Figure A: (Right)
Map of northeast Washington, with an inset box showing the location of the Niawiakum River opening to Willapa Bay and the Pacific Ocean.

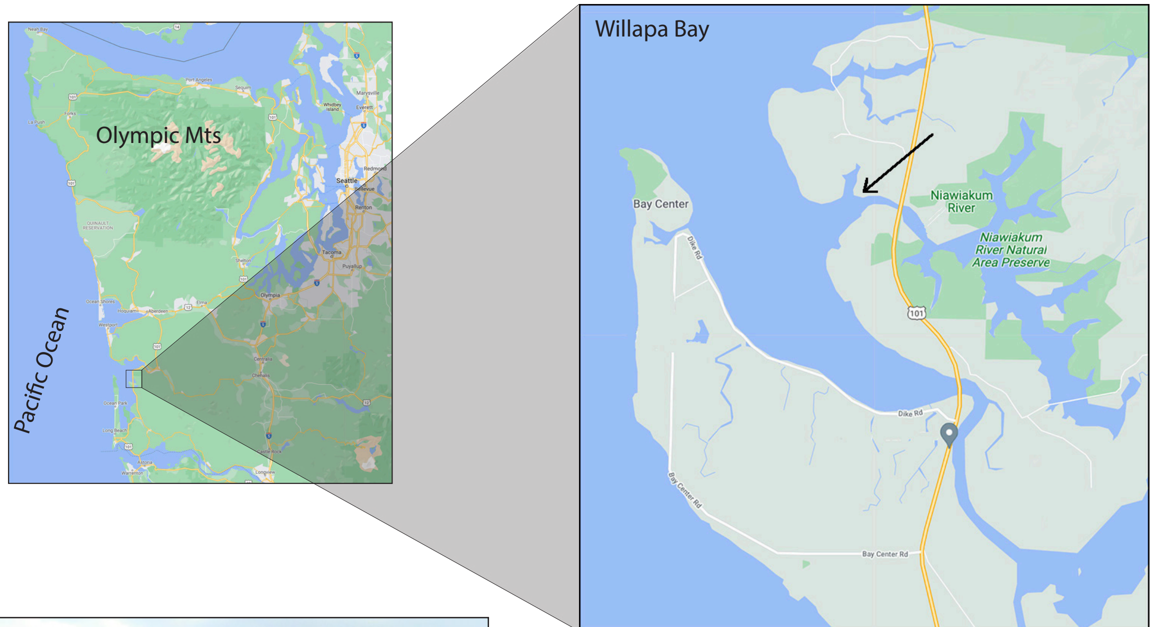


Figure B: (Left)
Workshop participants investigate evidence of the 1700 tsunami sand deposit.

See next page for a closeup photo of the deposits being dug up and a graphic that describes the process of emplacement.

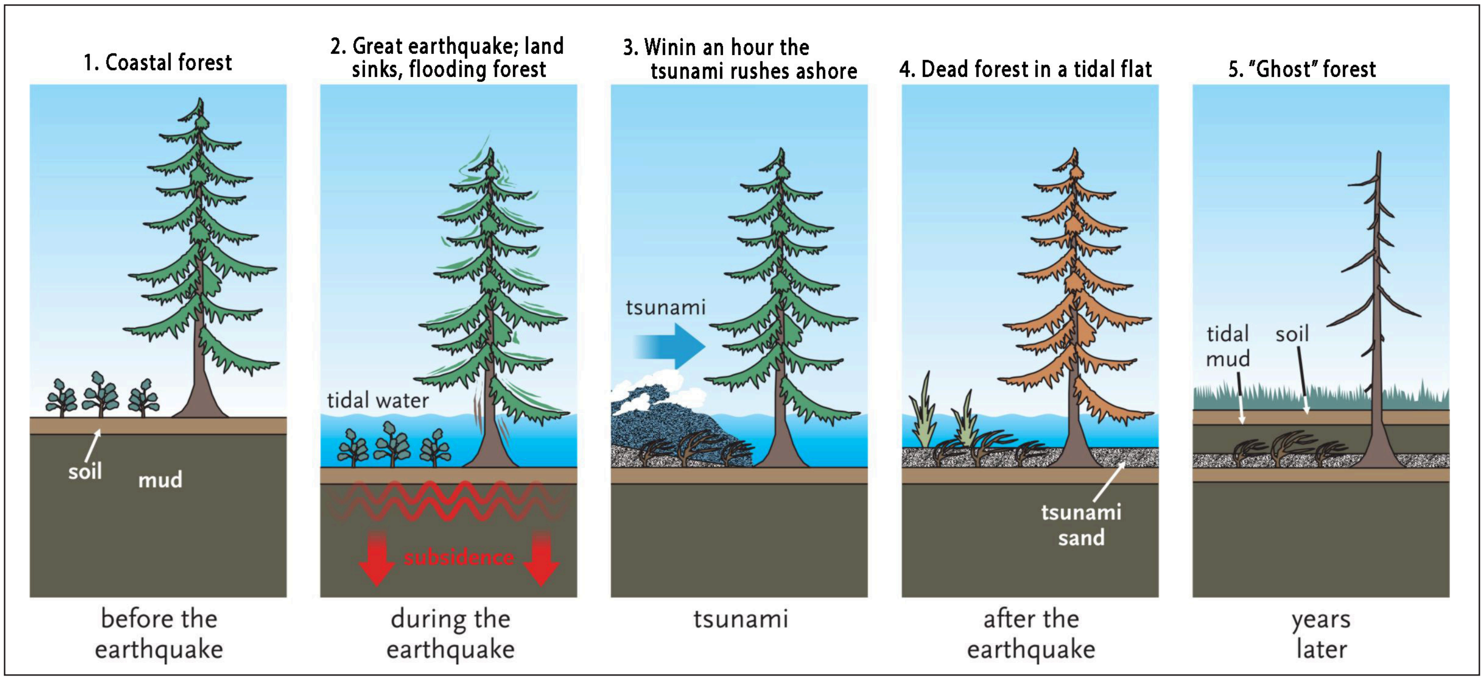


Figure C: Sequence of a great (M9+) earthquake causing subsidence. (1) The coastal forest is (2) submerged due to subsidence, (3) the tsunami rushes onshore, (4) depositing sand layers and leaving behind a dead forest. (5) Over time, the tsunami sand is covered by intertidal muds and clays. Image courtesy of John Clague, At Risk: Earthquakes and Tsunamis on the West Coast.

Figure D: Remnants of the 1700 Cascadia subduction-zone earthquake and tsunami. The tsunami sand layer (gray) overlays a former marsh, now peat layer. Notice at the bottom of the arrows, 3 thin horizontal coarse sand layers. Each layer records a boundary from a tsunami wave carrying and depositing sand. Intertidal mud and clays cover the sand layers.

APPENDIX D—Tsunami Wave Container Construction Instructions

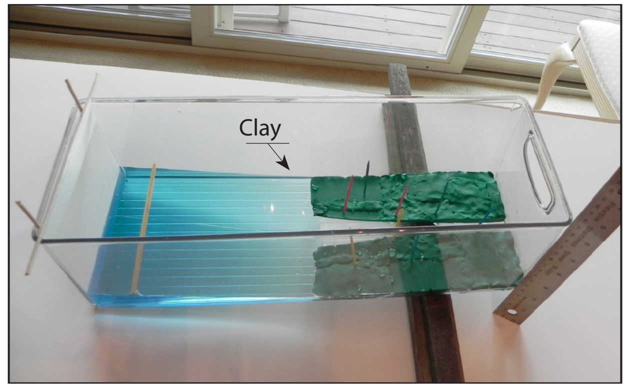
Container with landform

Materials

- Rectangular plastic storage container such as Linus™ Deep Drawer Binz Clear* 6" x 16" x 5"
- 1 lb. block non hardening modeling clay, such as Craftsmart® Plastalina Modeling Clay

Instructions

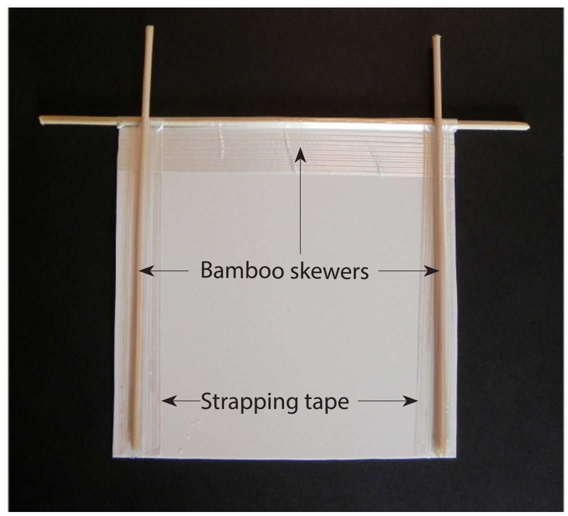
Cut pieces of modeling clay and place in the container creating a gentle sloping landform covering about a 1/3 of one end of the container. Learners will modify the landform later in the activity.



For each Tsunami Wave Making Paddle (right)

Materials

- Heavy plastic such as HDPE (High Density Polyethylene) 1/32" sheets 24" X 47" or heavy plastic report cover
- 3 Heavy bamboo skewers to make the paddle supports
- 1 bamboo skewer to make the horizontal bar that limits the distance the paddle can pivot forward to make the waves
- Ruler
- Scissors to cut the plastic for the paddle
- Wire cutter pliers (to cut skewers)
- Packaging or strapping tape to attach the skewers onto the plastic paddle



Instructions

1. Cut plastic paddle so that it tapers to fit the sloping sides of the container.
2. Cut bamboo skewers so they extend about an inch above and to each side of the paddle shown.
3. Tape the skewers to the paddle with reinforced strapping or shipping tape.
4. Test fit each paddle in a container to make sure it hangs free. Trim to adjust.
5. Fix the 4th bamboo skewer near the water line to ensure that the paddle creates waves of the same size.

Note: Follow the directions in the activity to demonstrate how to use the tsunami wave model.

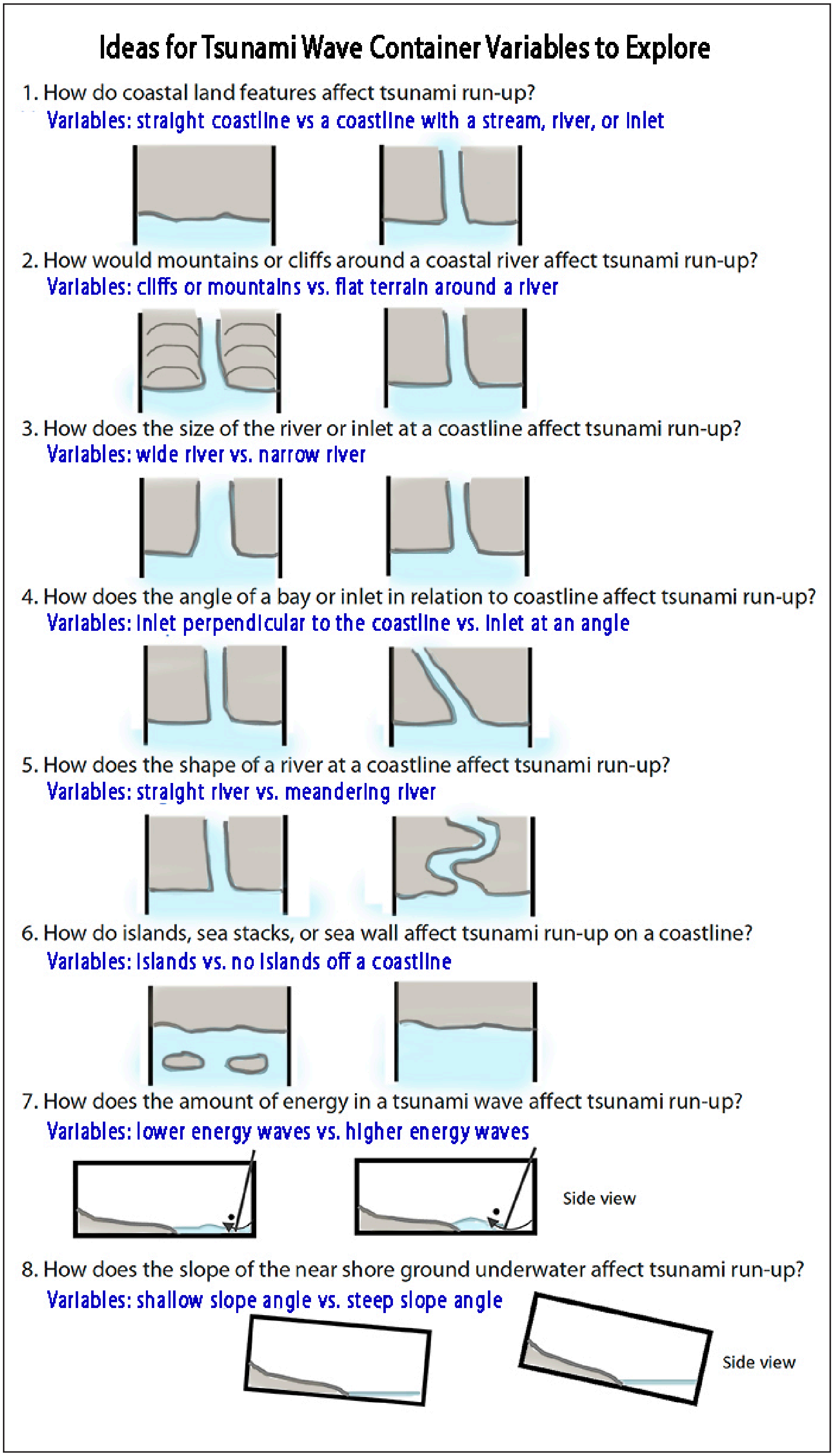


Figure A (Left): Example of variables that can be used to alter the dynamic of the tsunami behavior at the coast. Variables 1–6 are a bird's-eye view; 7 and 8 are side views. Image source: [Investigating Factors that Affect Tsunami Inundation]

Figure B: View looking into the wave container. The variable in this example is a narrow inlet perpendicular to the coastline that is wider at the mouth. In this example, toothpicks mark points on the landscape.

APPENDIX F—Tsunami Wave Variables Data Table

Names: ____

Date: ____________________ Period # ___________

Variable #1 ____ (example: straight coastline)

Test	Inundation measurement (cm from coastline to marker)	Observations
1		
2		
3		
	Average = cm	

Draw the landform for variable #1

Draw the landform for variable #2

Draw dots to indicate run-up location for each variable.

Variable #2 ____ (example: coastline with river)

Test	Inundation measurement (cm from coastline to marker)	Observations
1		
2		
3		
	Average = cm	

Write a summary statement comparing the tsunami run-up distances of each variable and what implications this would have for a community.

APPENDIX G—How Tsunamis Interact With Land

Adapted from "How Tsunamis Work"

The topography of the seafloor and shape of the coastline affect a tsunami's appearance and behavior. When a tsunami reaches land, it hits shallower water (Figure A). The shallow water and coastal land act to compress the energy traveling through the water, forcing the water upward.

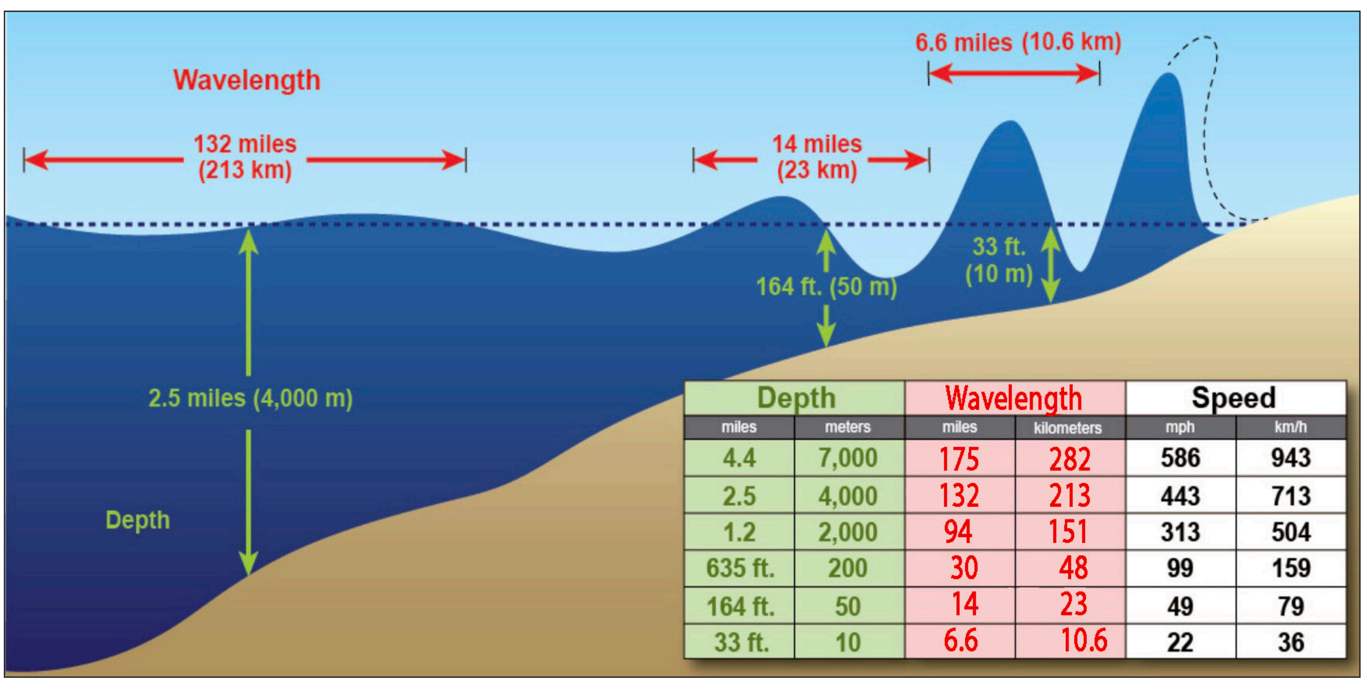
As the velocity of the wave diminishes, the wave height increases considerably. A typical tsunami approaching land will slow to speeds around 30 miles (50 kilometers) per hour, and the wave heights can reach up to 100 feet (30 meters) above sea level. As the wave heights increase during this process, the wavelengths (distance between subsequent wave crests or troughs) shorten.

Tsunamis usually arrive as a series of swift, powerful floods of water, not as a single, enormous wave. However, a large vertical wave called a bore may come with a churning, turbulent front. Rapid floods of water often follow bores, making them particularly destructive. Other waves can follow anywhere from 5–90 minutes (or for hours) after the initial strike. The tsunami wave train, after traveling as a series of waves over a long distance, crashes into the shore.

The areas of greatest risk during a tsunami are within 1 mile (1.6 kilometers) of the shoreline (due to flooding impacts and scattered debris), and less than 50 feet (15 meters) above sea level (due to the wave height). Tsunami impacts will vary, depending on the type of tsunami waves and how it strikes the shoreline.

A tsunami can affect sheltered areas of the landscape if the land features and underlying seascape align. For instance, a protected bay area with a narrow inlet can give a tsunami a "funnel" to travel through, which amplifies the destructive power of the waves. River channels can also provide room for a tsunami bore to rush through and flood vast tracts of land.

Until a tsunami strikes, it's difficult to predict how it will interact with the landscape. The wraparound effect occurs along island coastlines and peninsulas when multiple waves strike different areas of the shoreline, resulting in different degrees of flooding. Harbor resonance is a chaotic and highly destructive tsunami side effect created when waves continuously reflect and bounce off the edges of a harbor or bay. Harbor resonance can cause the amplification of circulating wave heights and even increase the duration of the wave activity within the area.



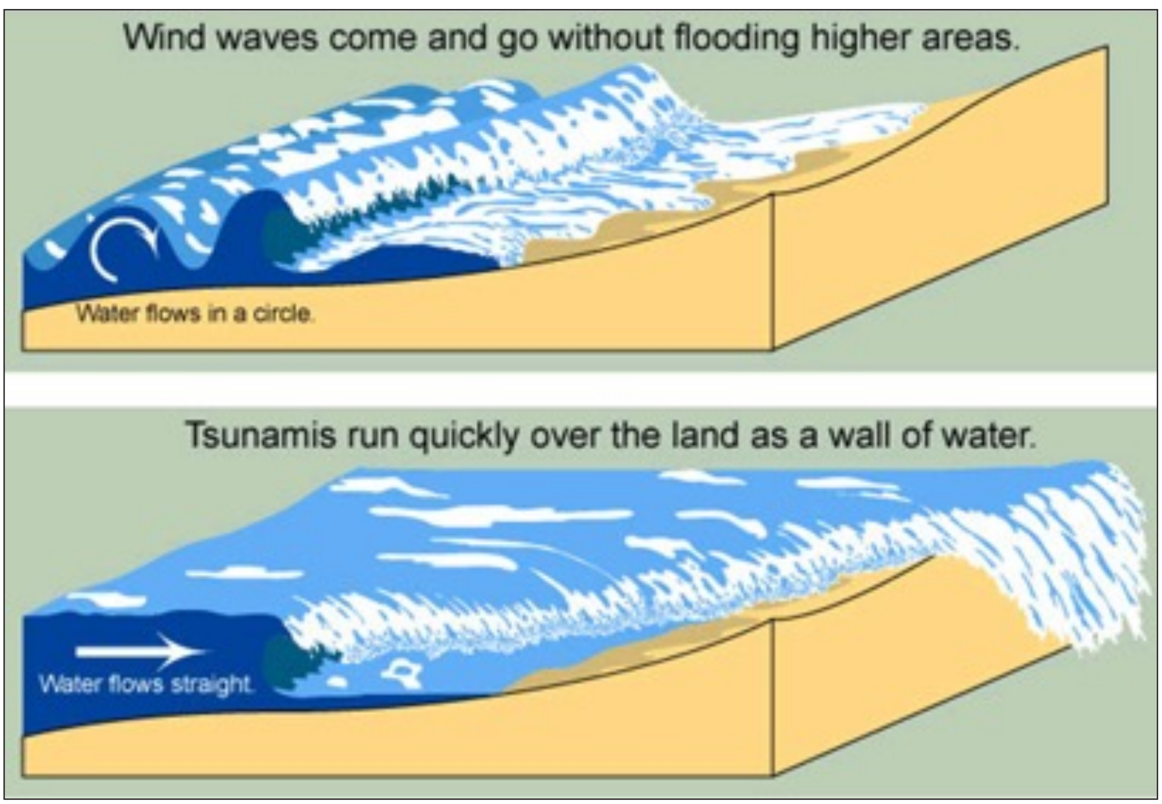
Depth		Wavelength		Speed	
miles	meters	miles	kilometers	mph	km/h
4.4	7,000	175	282	586	943
2.5	4,000	132	213	443	713
1.2	2,000	94	151	313	504
635 ft.	200	30	48	99	159
164 ft.	50	14	23	49	79
33 ft.	10	6.6	10.6	22	36

Using vertical exaggeration, this graphic shows how the shape of a tsunami wave changes as it moves into shallower water. Image from NOAA.

APPENDIX H—Differences Between a Wave and a Tsunami

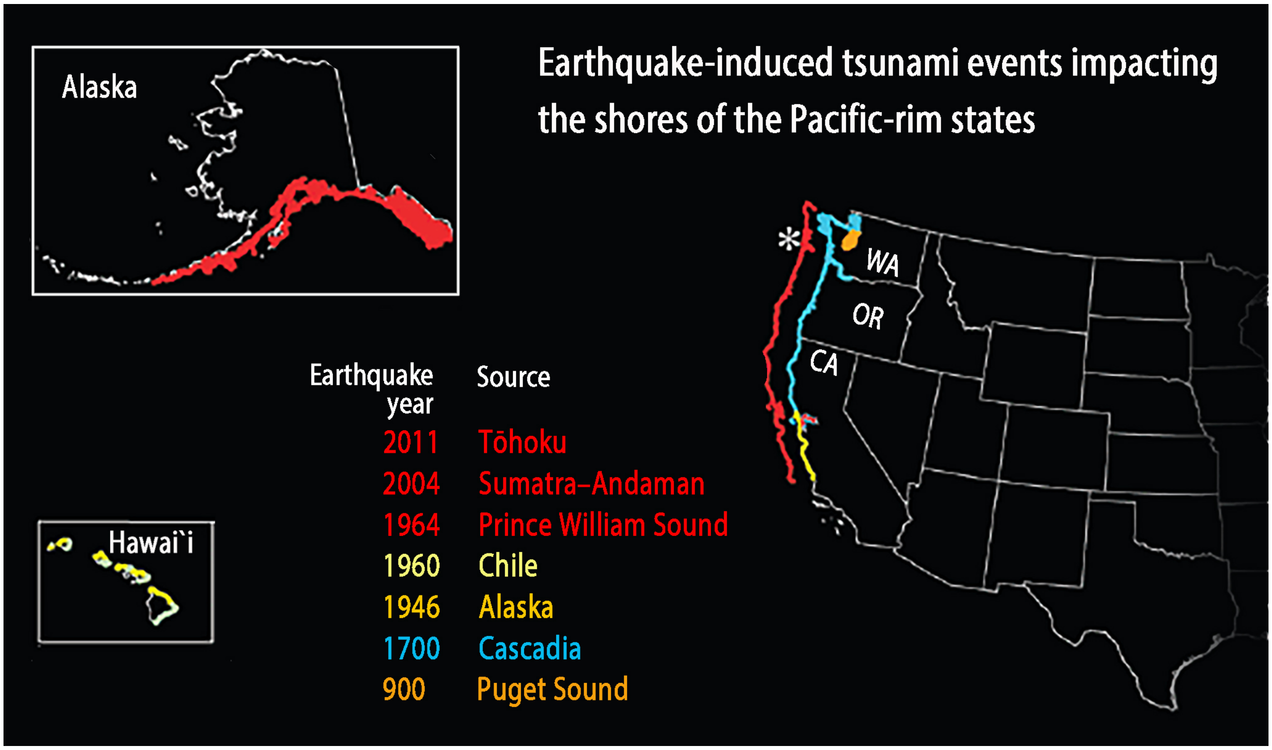
Adapted from: "Tsunamis" (Washington State Dept. of Natural Resources)

Wind Wave	Tsunami
Short wavelength (or distance between successive wave peaks or troughs)	Long wavelength of many tens of miles, making them far more powerful when they reach shore
Water flows in a circle near the surface	Water flows straight and reaches the seafloor
Often break onto the shore early and are highly turbulent	Approach the shore as a rapidly rising flow or wall of water
Break early and do not generally travel far inland	Do not break and can travel very far inland. Sometimes, the wave trough (bottom of the wave) will arrive first. When this happens, the water suddenly draws back, showing the ocean floor reefs and fish, like a very low, low tide. The time between waves typically ranges from five minutes to two hours. The first wave may not be the largest or the most damaging. Dangerous coastal flooding and powerful currents may last for several hours or days.

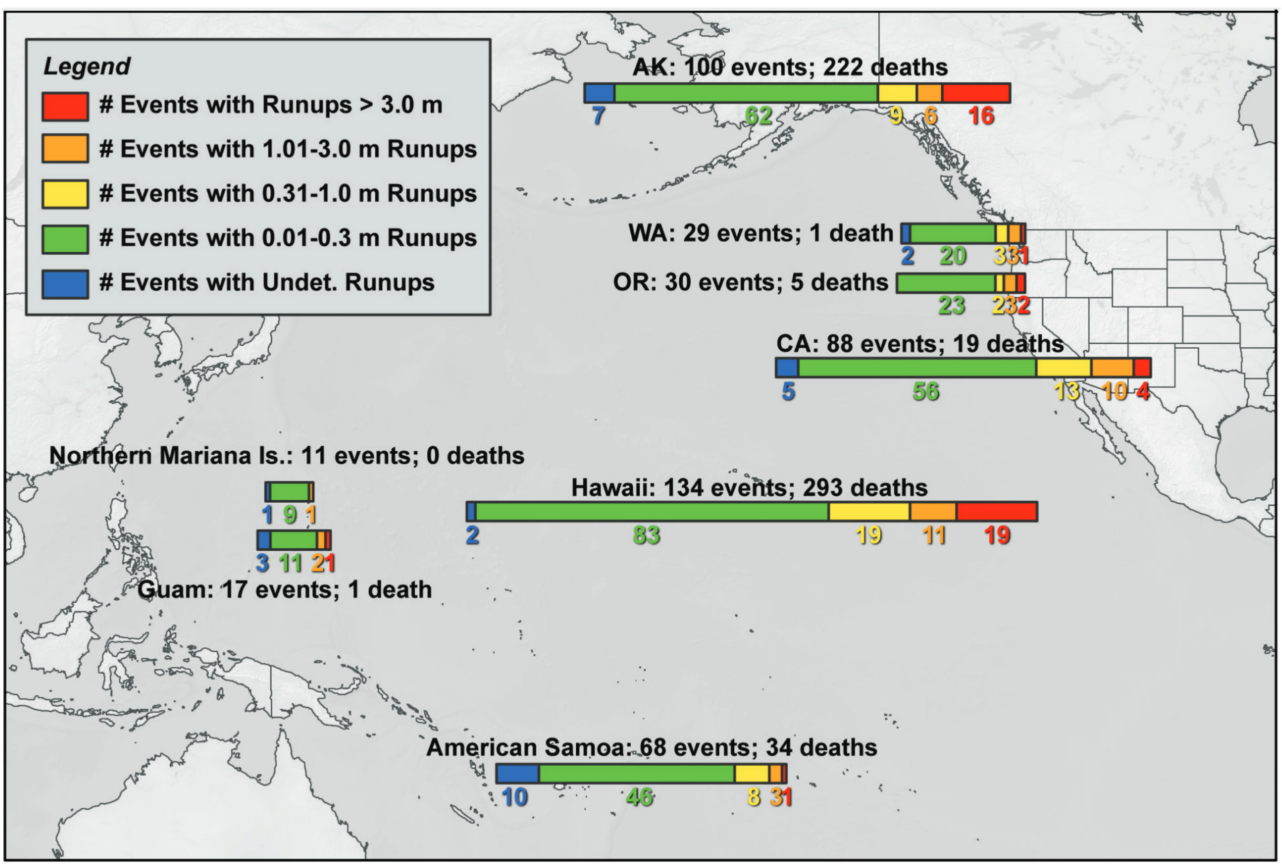


Wind waves break early and do not generally travel far inland. Tsunami waves do not break and can travel very far inland. Image by University of Washington.

APPENDIX I—Earthquake-Induced Tsunami Events, Sources, and Impacts



Map of earthquake-induced tsunamis impacting the Pacific-rim shores of the United States. Modified from the original image: [The west coast of the U.S. has experienced tsunami impacts in the past.]

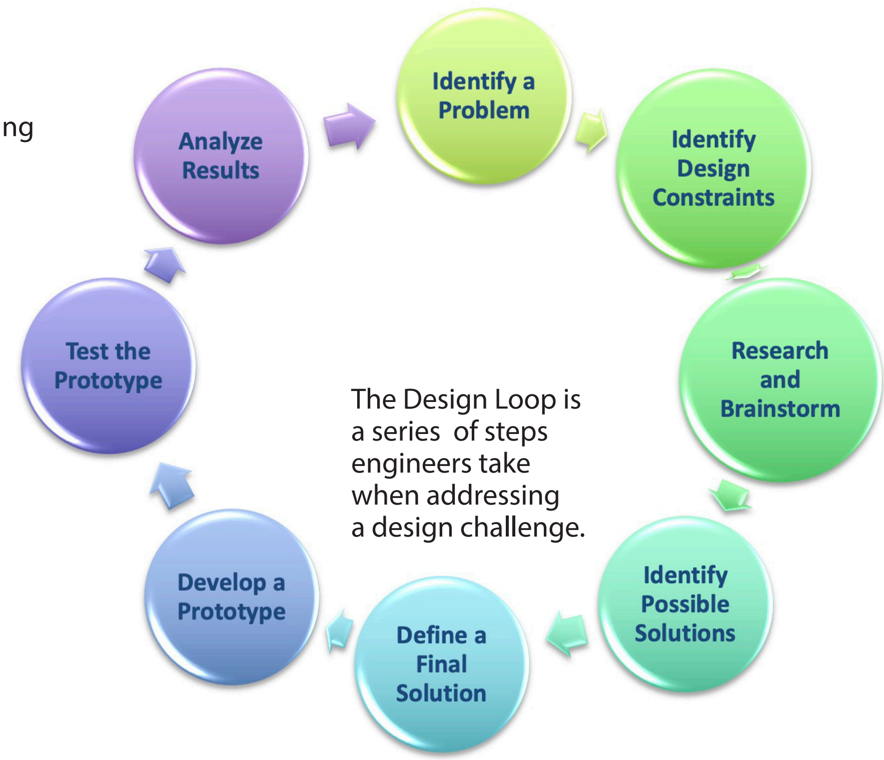


Map showing total number of tsunami events causing runup heights > 0.01 m and resultant deaths due to tsunamis impacting United States Pacific-rim states and territories, 1737–2016. Source: United States and Territories National Tsunami Hazard Assessment

APPENDIX J—NGSS Science Standards and 3 Dimensional Learning , NGSS Science and Engineering Resources

NGSS Science and Engineering Practices

1. Asking Questions (for science) and Defining Problems (for engineering)
2. Developing and Using Models
3. Planning and Carrying Out Investigations
4. Analyzing and Interpreting Data
5. Using Mathematics and Computational Thinking
6. Constructing Explanations (for science) and Designing Solutions (for engineering)
7. Engaging in Argument from Evidence
8. Obtaining, Evaluating, and Communicating Information



NGSS Engineering Design Process

1. Identify a problem
2. Identify design constraints
3. Research and brainstorm
4. Identify possible solutions
5. Define a final solution
6. Develop a prototype
7. Test the prototype
8. Analyze and communicate results

NGSS Science and Engineering Standards

Earth and Human Activity

MS-ESS3-2. Analyze and interpret data on natural hazards to forecast future catastrophic events and inform the development of technologies to mitigate their effects.

Science and Engineering Practices

Analyzing and Interpreting Data

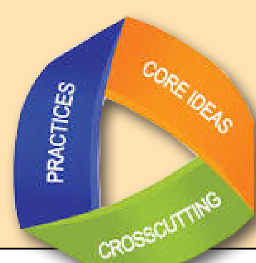
Analyzing data in 6–8 builds on K–5 and progresses to extending quantitative analysis to investigations, distinguishing between correlation and causation, and basic statistical techniques of data and error analysis.

- Analyze and interpret data to determine similarities and differences in findings.

Disciplinary Core Ideas

ESS3.B: Natural Hazards

Mapping the history of natural hazards in a region, combined with an understanding of related geologic forces can help forecast the locations and likelihoods of future events. (MS-ESS3-2)



Crosscutting Concepts

Patterns

Graphs, charts, and images can be used to identify patterns in data.(MS-ESS3-2)

Connections to Engineering, Technology, and Applications of Science

Influence of Science, Engineering, and Technology on Society and the Natural World

- The uses of technologies and any limitations on their use are driven by individual or societal needs, desires, and values; by the findings of scientific research; and by differences in such factors as climate, natural resources, and economic conditions. Thus technology use varies from region to region and over time.

IRIS

Founded in 1984 with support from the National Science Foundation, IRIS is a consortium of over 100 US universities. In partnership with its Member Institutions and the scientific community, IRIS manages and operates comprehensive, high-quality geophysical facilities that enable exciting discoveries in seismology and the Earth sciences. IRIS programs contribute to scholarly research, education, earthquake hazard mitigation, and the verification of a Comprehensive Test Ban Treaty.

NSF