# Managing Tsunami Risk in the Aftermath of the 2004 Indian Ocean Earthquake & Tsunami

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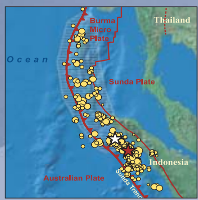
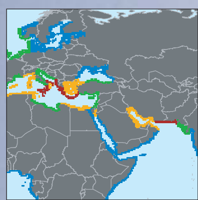
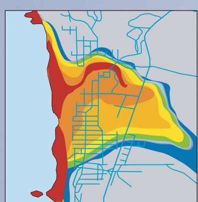





| Economic Losses ($ million) | Insured Losses* ($ million) |
|---|---|
| 4,500 | 500 |
| 1,000 | 500 |
| 1,000 | 100 |
| 1,000 | 100 |
| 500 | 50 |
| 2,000 | 50 |
| 10,000 | 1,300 |

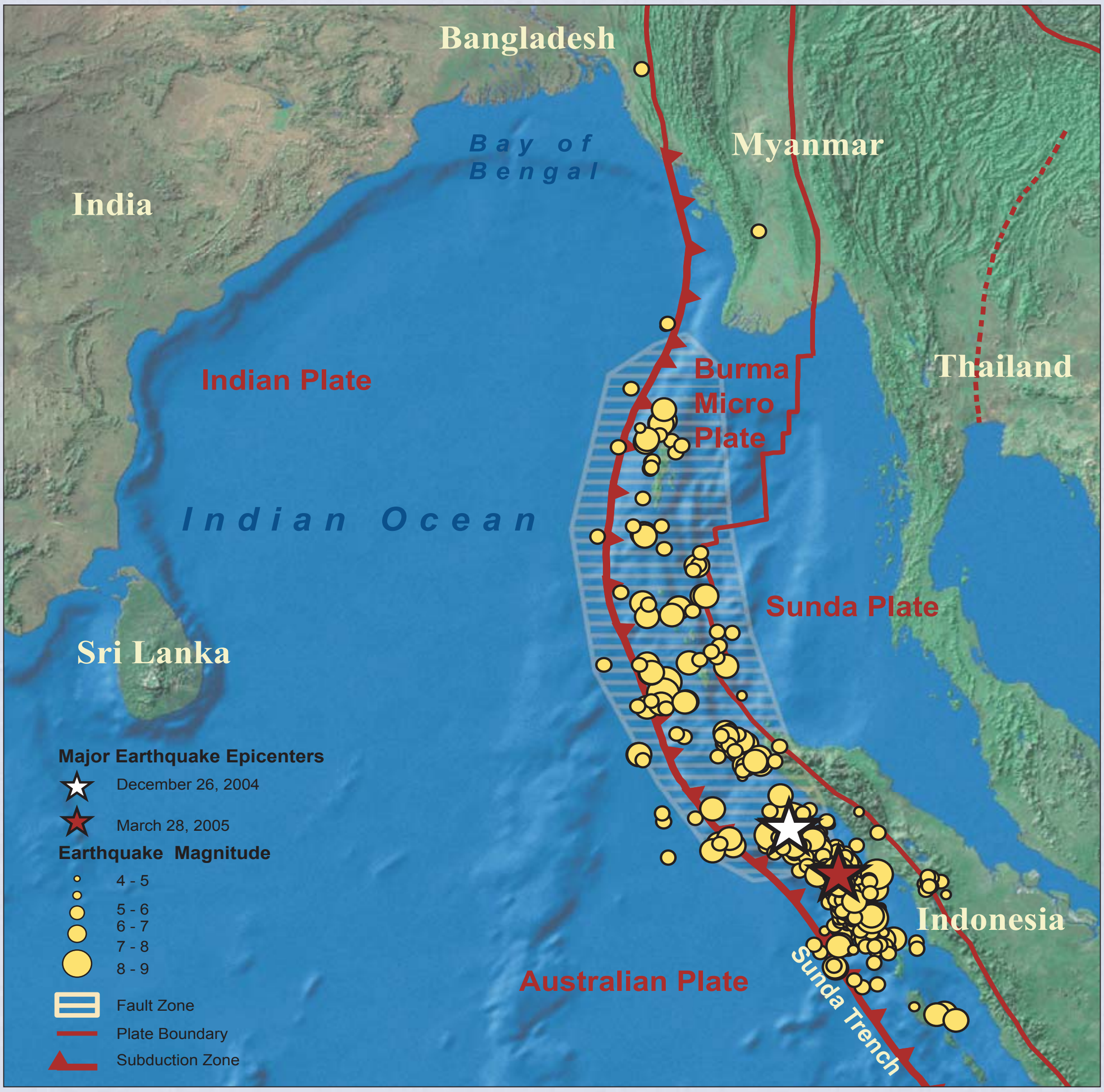






# The Earthquake and Tsunami of December 26, 2004

On December 26, 2004 at 07:58:53 local time (00:58:53 GMT), a fault rupture was initiated off the west coast of northern Sumatra, Indonesia along the Sunda Trench subduction zone plate boundary, triggering a devastating tsunami around much of the Indian Ocean. The epicenter (the point on the Earth's surface above which the rupture initiated) was located at 3.31ºN and 95.95ºE, approximately 250 km (155 mi) south-southeast of Banda Aceh, the capital city of the Aceh Province in northern Sumatra, Indonesia. From this point, the rupture continued to expand northward for more than 1,200 km (745 mi), generating a massive M9.3 earthquake, the largest to have occurred since the 1964 M9.2 Alaska Earthquake and the second largest ever recorded (the largest recorded was the 1960 M9.3 Chile Earthquake). The earthquake rupture was located at a relatively shallow depth along the subduction zone; estimates of the focal depth range from 10 to 30 km (6 to 19 mi). The aftershock distribution suggests a main fault rupture zone of 90 km (56 mi) in width, extending along the 1,200 km (745 mi) rupture up to the Andaman Island chain. Total fault movement was around 15 m (49 ft) near Sumatra, with decreasing displacement to the north. In this region, the Indian Ocean plate is moving down to the east under the Burma Microplate at a rate of 6 cm (2.4 in) per year, so the displacement represented up to 250 years of accumulated plate motion. Hundreds of




*Map showing the earthquake epicenter, aftershocks, and the extent of the main fault rupture for the M9.3 December 26, 2004 earthquake; the M8.7 March 28, 2005 earthquake, which caused a local tsunami affecting Simeulue Island, Nias Island, and parts of mainland Indonesia is also shown approximately 200 km (124 mi) to the southeast of the December 26, 2004 earthquake* aftershocks were recorded in the following days and months, including a second significant, M8.7 earthquake on March 28, 2005 at 23:09:36 local time (16:09:36 GMT). This earthquake was located at 2.076°N, 97.013°E, southeast of the epicenter of the December 2004 earthquake. This second major shock caused further building damage and triggered another, albeit much smaller and localized, tsunami.

## Ground Shaking

On islands located close to the fault rupture, the violent shaking from the 2004 earthquake caused many building collapses. The Modified Mercalli Intensity (MMI) is a scale that measures the intensity of the earthquake and ranges from the minimum of level I (no noticeable tremors) to level XII (damage is nearly total and large rock masses are displaced). According to the USGS, the intensity in Banda Aceh, Sumatra reached IX: the violent shaking caused the collapse of some mid-rise reinforced concrete structures. The earthquake also provoked panic in the Aceh Province of Sumatra and the neighboring province of Sumatera Uttara, as this level of ground shaking had not been experienced in the region in recent history.

The closest inhabited locations to the fault rupture were on the Indian-administered Andaman and Nicobar Islands, where many buildings were damaged. In the capital city of Port Blair, roads were cracked and buildings damaged. People were knocked to the ground by the severe shaking on Car Nicobar Island, and some buildings within the Indian Air Force base were seriously damaged.

Further afield, the earthquake was widely felt all around the northern Indian Ocean in India, Sri Lanka, Thailand, Malaysia, Myanmar, and Bangladesh. In the state of Tamil Nadu in southeast India, people felt distinct tremors in most parts of the port city of Chennai. In the coastal towns and ports within Tamil Nadu, a few buildings developed cracks, although MMI intensities in general were only IV. Across eastern India, long periods of ground motion caused the water in large storage tanks and ponds to oscillate in the form of seiches. In Sri Lanka, a fairly long tremor was felt on parts of the central island. The earthquake tremor was

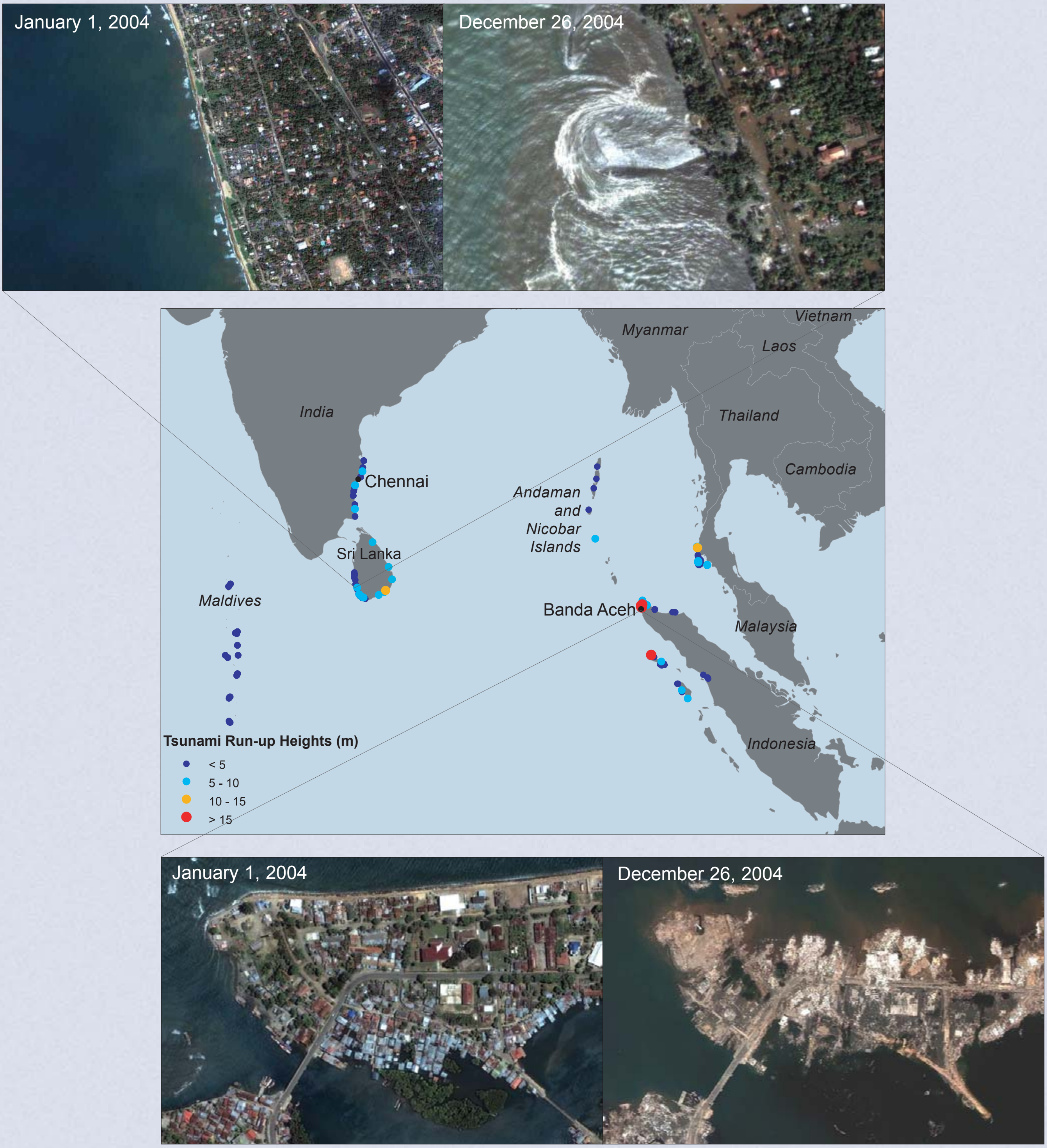

*Modified Mercalli Intensity (MMI) map of the 2004 earthquake, showing violent shaking and heavy damage (MMI level IX) on the western coast of the Aceh Province of Indonesia*

also felt in Thailand, including in Bangkok. In Malaysia, several high-rise buildings swayed and people were evacuated in Penang, but no damage was reported. In Bangladesh, the quake was experienced in the capital city of Dhaka as well as across the entire country.

## Tsunami

The sudden vertical displacement of the sea floor associated with the massive fault rupture affected the overlying water column, initiating a complex series of waves that propagated across the entire Indian Ocean and resulting in the devastating tsunami. Because the entire water column is involved, tsunamis in open oceans have long wave lengths of nearly 200 km (124 mi) and low trough-to-crest wave amplitudes. The greatest tsunami heights are propagated laterally away from fault ruptures, in the direction in which the waves have greatest coherence. In this case, the highest waves spread east-west from the north-south running fault line. To the north and south along the fault, the waves were subject to interference and reduced in size rapidly. To the east and west, the waves only gradually reduced in height as they moved beyond the Indian Ocean to the coast of East Africa. Tsunami waves travel at a speed proportional to the square root of the water depth, reaching 640 km (400 mi) per hour in the deep ocean. As the waves enter shallower coastal waters, their velocities and wavelengths reduce, and their amplitudes correspondingly increase, leading to significant and rapid inundation of low-lying coastlines. With the time from trough to crest of the waves being typically several minutes, the tsunami can flow more than 1 km (0.6 mi) inland in areas with large coastal floodplains.

The actual height of the tsunami along a particular section of coastline is a function of both the height of the open ocean wave and local factors. The greatest run-up heights from the 2004 Indian Ocean Tsunami were observed on the western side of Banda Aceh as well as in other towns and cities along the west coast of




*Tsunami run-up heights estimated by various reconnaissance teams across the Indian Ocean, showing the extent of the tsunami's impact; satellite images show the devastating effects to the southwestern coast of Sri Lanka (top) and to the Banda Aceh coastline (bottom) (Images: DigitalGlobe)*

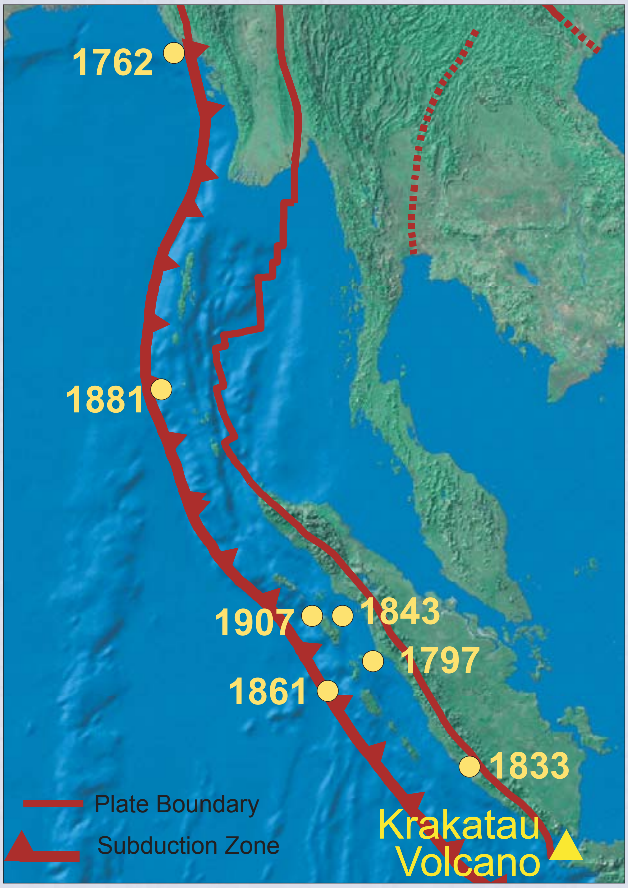
Aceh Province. Locally, tsunami run-up heights reached 30 m (100 ft) in this region, although more generally heights were around 10 m (33 ft). Further from the earthquake epicenter to the west, in southwest Thailand, run-up heights of 4 to 8 m (13 to 26 ft) were experienced. To the east in Sri Lanka, run-up heights were between 2.5 and 12 m (8 and 40 ft) with an average height of 5 m (16 ft). On the southeastern coast of India, the tsunami waves reached 3.5 m (11 ft) on average. In the Maldives, the run-up heights were lower than in Sri Lanka, typically reaching a maximum of 3 m (10 ft), primarily due to the absence of a shoaling coastline, which makes the waves steeper.

## Historical Perspective

There is a long record of tsunamis affecting the coastlines of the Indian Ocean, principally along the western coast of Sumatra, although there have been none in recent history. In 1861, an estimated M8.8-9.2 earthquake ruptured much of the subduction zone along the west coast of Sumatra, south of the 2004 and 2005 fault ruptures, causing damage all along the coast and on the offshore islands of Sumatra. Other major tsunami-generating earthquakes had occurred along segments of the subduction zone in 1797 and in 1833, when huge tsunamis flooded the southern part of western Sumatra claiming tens of thousands of lives in each incident. However, over the previous 500 years, there had never been a major tsunami originating from the section of plate boundary that broke in 2004. The largest previous event on this section was in 1881, when an estimated M8 earthquake in the Andaman Islands caused a modest 1-m (3-ft) tsunami recorded on tide gauges in Chennai, India. Further back in time, the plate boundary to the north of the 2004 fault rupture broke in a great earthquake along the whole of the western Arakan coast of Myanmar in 1762, causing significant coastal uplift and a moderate tsunami in the northern Indian Ocean. A 2-m (7-ft) rise in the water level was reported near Dhaka, Bangladesh after the event.

However, earthquakes are not the only triggers of tsunamis. A tsunami generating event took place in the region in 1883, when a cataclysmic volcanic eruption suddenly collapsed the island volcano of Krakatau located between Sumatra and Java in Indonesia, causing the deadliest tsunami in the region prior to 2004. Over 36,000 died from the waves, which had a maximum run-up of 40 m (130 ft) along the surrounding shorelines of the islands.

The presence, or absence, of a word for tsunami in the different countries and cultures around the Indian Ocean highlights the historical precedent. The word for tsunami exists in Sumatra but is absent in Sri Lanka and Thailand. On the Andaman and Nicobar Islands in Sumatra, the indigenous peoples were sufficiently knowledgeable of the hazard following major earthquakes in 1883 and 1941. After experiencing the strong shaking of the earthquake and recognizing the signs of an impending tsunami, they fled to higher ground. In Sri Lanka and Thailand, without awareness of the signs and consequences of a tsunami wave, evacuation was slower and consequently yielded more casualties.




*Location of tsunami triggers in the Indian Ocean since 1762*

With 174,500 casualties, 51,500 missing, and roughly 1.5 million people displaced, the toll of human casualties from the 2004 Indian Ocean Tsunami has no modern historical equal. To understand the distribution of the casualties, the tsunami-affected region can be segmented into three areas: the nearfield along the coasts of Sumatra, which account for approximately 70% of the total; those at intermediate distances (between 1,000 and 2,000 km, or 620 and 1240 mi) in Thailand, India, Sri Lanka, Myanmar, and the Maldives; and those in the farfield on the coasts of Africa and on islands in the western Indian Ocean, such as the Seychelles Islands.

Most of the loss of life occurred in the nearfield in Sumatra, Indonesia. The tsunami destroyed virtually every village, town, road, and bridge built at below 10 m (33 ft) elevation along a 170-km (106-mi) stretch of the western coast of Aceh Province. While inundation did not extend more than 1 km (0.6 mi) in most places, the waters reached up to 4 km (2.5 mi) inland in the flat and densely populated city of Banda Aceh. From the reports of fatalities in individual towns along the west coast of Aceh Province, it is estimated that on average 50% of the people in the coastal region died.

| Country | Confirmed Casualties |
|---|---|
| Indonesia | 126,900 |
| Sri Lanka | 31,000 |
| India | 10,700 |
| Thailand* | 5,400 |
| Somalia | 300 |
| Maldives | 80 |
| Malaysia | 70 |
| Myanmar | 60 |
| Tanzania | 10 |
| Seychelles | 2 |
| Bangladesh | 2 |
| South Africa | 2 |
| Yemen | 2 |
| Kenya | 1 |
| Total | 174,500 |

* Estimate includes foreign tourists

*While the majority of lives lost were in Indonesia, the tsunami's impact was felt as far away as the east coast of Africa*

Of the 31,000 lives lost in Sri Lanka, 80% were in the most heavily affected areas of the eastern and southern provinces. The casualty rate among the population living within 1 km (0.6 mi) from the coast was between 15% and 20%. The eastern side of the Northern province was similarly affected. In India, 75% of the 10,700 fatalities were in the southeastern state of Tamil Nadu.

In Thailand, the tsunami affected residents and foreign tourists in the densely inhabited Phuket Island and the surrounding southern coastal provinces. The lethality rate among the tourists – between 7% and 10% – was twice the rate of the local residents, as many of the tourists were on the beach or in beachfront hotels when the tsunami struck.

RMS has estimated the lethality rates for resident population and tourists within the first 0.5 to 1 km (0.3 to 0.5 mi) of the affected coasts. There was some loss of life in the areas with 2 to 3 m (7 to 10 ft) tsunami waves, and coastlines hit by 4 to 5-m (13 to 16-ft) waves experienced 5% mortality rates. The largest life loss was seen along coastlines hit by 8 to 10 m (26 to 33 ft) waves, where the mortality rate was around 40% of the population.

## Property Damage

Although the earthquake shaking caused significant building damage in the Aceh Province and on the Andaman and Nicobar Islands in Indonesia, the large majority of property damage was caused by the tsunami waves. Along coastlines of most of the affected countries, the majority of the buildings consisted of poorly constructed houses primarily made out of wood, masonry, and concrete, which make them more vulnerable to damage from a tsunami. On the southern coasts of Sri Lanka and along the Indian Ocean coastline of Thailand, tourist resorts and hotels sustained heavy damage.

Buildings in this equatorial region are situated closer to sea level than is typical of higher latitudes. As a result of the reduced Coriolis force (associated with changes in the Earth's rotational velocity with latitude), a band running 10 degrees north and south of the equator is free from tropical cyclones and their associated storm surges. Thailand and Sri Lanka, which are located in this band, do not frequently experience high winds or even severe earthquakes, so buildings are not typically designed to withstand any significant loading. This contrasts with the eastern coastline of India, for example, where relatively frequent storm surge hazard discourages building at elevations of less than 2 to 3 m (7 to 10 ft) above sea level.

RMS surveyed the affected coastlines of Sri Lanka and Thailand in order to assess the relative vulnerability of the different building types to the force of the tsunami. In general, the local construction quality was no match for the rapid flow of water, particularly for structures within the first 100 m (330 ft), and especially those lacking protection from other properties or trees.

In Sri Lanka, the most common housing construction type is unreinforced masonry, which is particularly vulnerable to collapse from the tsunami wave. In one surveyed town in western Sri Lanka, almost all of the masonry houses within 20 to 30 m (65 to 100 ft) of the shoreline were destroyed. The typical failure mechanism involved an out-of-plane collapse of the masonry wall panels caused by the pressure of the advancing surge of water. Many commercial structures and some more recently constructed detached single-family houses are reinforced concrete frames with infill masonry. While the concrete frames generally held in these buildings, the infill panels typically collapsed, leaving gaping holes in the structures.

In Thailand, typical construction classes include low and mid-rise reinforced concrete, wood frame, and bamboo buildings. Traditional Thai architecture uses wood framing and bamboo for construction, resulting in a lightweight frame with large openings. The roofs of these buildings are typically either thatched or tiled. On Phuket Island, for example, very few such buildings survived the tsunami, especially when the run-up heights exceeded 3 m (10 ft).

In the beach resort areas of Phang Nga Province, timber frame structures near the shore were destroyed.

*Tsunami damage to beachfront property on Phi Phi Don Island, Thailand*

Many of the hotel structures were located on the beach and took the full brunt of the waves. Others were more than 100 m (330 ft) inland but still suffered extreme levels of damage due to the height and speed of the waves. Many of the hotels were bungalow style, with a number of single-story wood and bamboo structures scattered over the property. These resorts suffered the most damage, especially where the wave heights exceeded 8 m (26 ft).

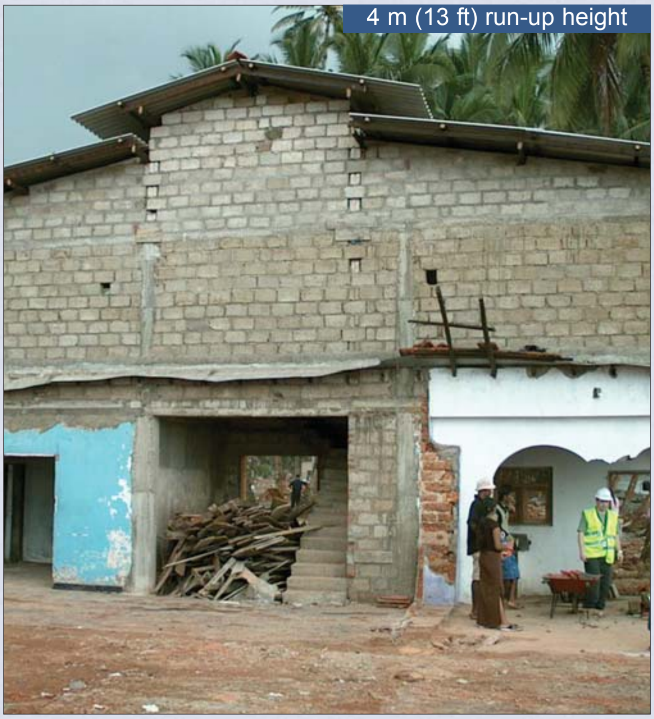
Other hotels on Phuket Island are mid-rise reinforced concrete of superior construction standards. These buildings typically have shear walls in the transverse direction, larger columns, and other walls formed by cast-in-situ (cast in place rather than pre-fabricated) unreinforced masonry panels. Some of these structures performed remarkably well, even in locations where the tsunami reached or even exceeded the higher floors of the buildings.

In all of the affected regions, there was large loss of small water craft, including local fishing boats, yachts, and even small cargo ships in various ports across the Indian Ocean. In particular, the port of Chennai on the east coast of India sustained moderate damage. The local fishing fleet was affected, with a number of boats overturned or washed ashore within the harbor.


*Single-story unreinforced masonry house located 170 m (560 ft) from the shoreline in Paiyagala village in Sri Lanka that was protected from the power of the waves by dense plantation and sustained only flood damage; a local resident indicates a water mark at approximately 2.5 m (8 ft)*


*Damage from run-up heights between 3 and 3.5 m (10 to 11 ft) to a reinforced concrete hotel 100 m (330 ft) from the coastline on Phuket Island, Thailand; since contents and non-structural damage was limited to the ground floor, clean up operations were completed by the time this photo was taken just one month after the event*


*Typical damage to unreinforced masonry homes within 100 m (330 ft) of the coast in the village of Paiyagala in southwest Sri Lanka; run-up height at this location measured at 4 m (13 ft)*




*Damage to a two-story reinforced concrete frame building within 100 m (330 ft) of the coast that survived but suffered failure to the infill wall panels facing the onslaught of the wave; run-up height at this location was 4 m (13 ft)*


*Damage to reinforced concrete commercial structures from wave run-up height of about 4 m (13 ft) within 100 m (330 ft) of the shore in the city of Galle in southern Sri Lanka; structural damage was limited to the ground floors of these structures (note undamaged curtain wall panels above the ground floor level)*


*Damage to unreinforced masonry buildings within 100 m (330 ft) of the shore in Galle, near the reinforced concrete structures pictured on the left; wave run-up height in this area measured at 4.5 m (15 ft), destroying the structural integrity of the buildings*


*Damage to a two-story reinforced concrete structure located 200 m (660 ft) from the northern shore of Phi Phi Island in Thailand, where wave run-up height exceeded 5.5 m (18 ft) above the foundation*


*Complete damage to a pre-cast reinforced concrete hotel within 100 m (330 ft) of the shore in Phang Nga Province of Thailand, where wave run-up height exceeded 7 m (23 ft)*

# Economic and Insured Losses

Overall economic losses from the 2004 Indian Ocean Earthquake and Tsunami disaster are estimated at $10 billion, with 75% of the loss attributed to the damage in the Indonesia, Thailand, Sri Lanka, and India. These losses include damage to residential and commercial buildings and infrastructure, including roads, water supply systems, electric power systems, schools, hospitals, and other healthcare facilities. Even though the large majority of the damage was along the west coast of Sumatra, Indonesia, and to a lesser extent the countries of India and Sri Lanka, the economy of the Maldives, which lies only a few meters above sea level, was most heavily impacted. Losses in the Maldives represented approximately 45% of its gross domestic product (GDP). While Indonesia suffered $4.5 billion in economic loss, representing the entire GDP of the Aceh Province, the loss resulted in a minimal impact on the overall Indonesian economy, lowering the projected growth by approximately 0.2% in 2005.

## Insured Property Loss

In the worst affected countries of Indonesia, India, and Sri Lanka, the insurance penetration to cover flood or earthquake related perils was extremely low. Further afield, the key insured exposure concentrations in Kuala Lumpur, Malaysia and Singapore were unaffected by the earthquake and tsunami, although building occupants in these cities felt the ground shaking. In Indonesia, basic residential earthquake coverage includes tsunami damage, and extended coverage for tsunami damage is available for commercial and industrial risks with a standard fire policy. However, non-life penetration in Indonesia is a fraction of the penetration rates seen in the U.S., New Zealand, and Japan.

Insurance coverage for tsunamis varies by country and line of business. Often tsunami coverage is an extension to a standard fire policy and/or a separate endorsement to earthquake or flood coverage. In some cases, it is covered under an all-risks contract. In the U.S., residential tsunami coverage is purchased with flood coverage through the National Flood Insurance Program (NFIP). In New Zealand, residential tsunami damage is covered under the geological disaster insurance purchased through the Earthquake Commission. In Japan, coverage for a flood or tidal wave resulting from an earthquake can be added to a commercial earthquake insurance policy, which is an extended coverage to the standard fire policy. Residential coverage for earthquake shock and fire, volcanic eruption, and tidal wave following earthquake is a separate policy purchased in conjunction with a basic household policy.

| Country | Economic Losses ($ million) | Insured Losses* ($ million) |
|---|---|---|
| Indonesia | 4,500 | 500 |
| Thailand | 1,000 | 500 |
| Sri Lanka | 1,000 | 100 |
| India | 1,000 | 100 |
| Maldives | 500 | 50 |
| Other | 2,000 | 50 |
| Total | 10,000 | 1,300 |

* This includes property insurance only; life and health losses are estimated at $250 million and travel losses at $50 million

*$8 billion of the $10 billion total economic loss is attributable to Indonesia, Thailand, Sri Lanka, India, and the Maldives, where insured property losses reached $1.3 billion with an additional $300 million in life, health, and travel insurance*

At most, 12% of the $4.5 billion in Indonesian economic losses were insured. Similar insured loss patterns were experienced in India, where the loss or damage to property is covered under a standard fire and special perils policy for residential and commercial risks. In Sri Lanka, less than 2% of the affected population had property insurance, and therefore few of the 93,000 destroyed homes resulted in a claim.

In Thailand, however, property coverage more commonly involves all-risks policies, which include a provision for earthquake-related damage. This type of coverage, combined with a relatively high insurance penetration compared to the other countries in the affected region, resulted in a higher proportional insured loss in this country. The majority of the 50,000 policies in the six most seriously affected Thai provinces were covered. Within a week of the disaster, over 500 claims amounting to nearly $25 million had already been filed.

Among all the buildings damaged and destroyed across the Indian Ocean, only a small proportion of the higher value shoreline industrial or hotel facilities were insured. These include a small number of factories in Sumatra, as well as hotels in Sri Lanka, the Maldives, and Thailand. Of all the affected areas, the wealthiest was the tourist economy along the Thai coast, where hotels as well as higher value houses and stores had insurance. The RMS estimate for the total cost of all properties claims is around $1.3 billion. While this total is derived from several lines, including a few large industrial risks in Indonesia and port facilities in India, the large portion of the insured loss is primarily due to damage to tourist resorts and business interruption rather than industrial or manufacturing installations. In January 2005, the Tourism Authority of Thailand reported that nearly 20% of Phuket Island's hotel capacity was disrupted by the tsunami. One year following the event, while nearly all of the damaged hotels on Phuket Island have reopened, Phuket was still struggling to revive the regional tourism industry.

## Life, Health, and Travel Insurance Costs

The total life and personal accident insurance claims from local populations were small due to low penetration of life insurance in India, Sri Lanka, and Indonesia. While up to one-tenth of the population in India had life and personal accident insurance, most of those affected were lower income residents who had limited or no coverage through a personal accident policy. Similarly, while over 10% of Indonesians have life insurance, few of the 30,000 residents living in the devastated city of Banda Aceh near the epicenter of the earthquake held life insurance policies.

Insurance claims for health, life, and travel cover were almost entirely from foreign tourists affected by the event in Thailand, Sri Lanka, and the Maldives. They were paid out in many separate countries according to the number of those affected. Around 2,200 foreign tourists died or are presumed dead from the tsunami. The highest numbers of casualties were from Sweden and Germany – each country with more than 500 confirmed dead. Other countries with more than 100 casualties include Switzerland, Finland, and the United Kingdom. On average, 30% of European travelers vacationing overseas have travel insurance. Many travel insurance policies include limited cover for accidental death but more extensive cover for medical treatment and repatriation. Injuries are consequently more costly to travel insurers. Therefore, the injuries sustained by foreign tourists made up a significant portion of the overall travel insurance loss. Based on information available in the months following the disaster, the total life, health, and travel insurance claims were less than $300 million.

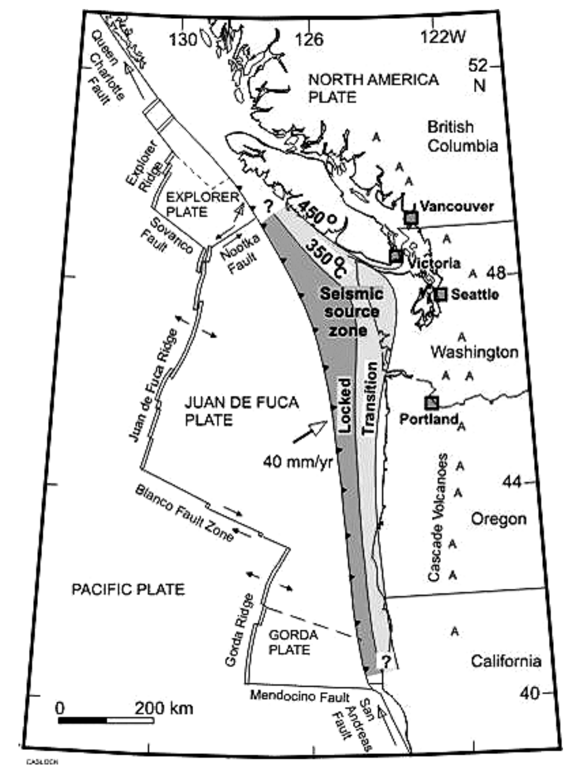
Combining the property loss with the potential life, health, and travel insurance costs, the total insurance loss from this event is around $1.6 billion. If the event were to take place in another part of the world and under different market conditions, the insured loss could have been much more significant. Disasters like this highlight the importance of managing exposure accumulations and appropriately pricing disaster risk, as the 2001 World Trade Center attacks also illustrated.

Tsunamis are generated by large and rapid displacements of water, principally from sudden and large scale changes in the configuration of the sea floor associated with fault displacement or gigantic underwater landslides. Other rarer sources include volcanic collapses in which a major explosive eruption empties a large subterranean magma chamber, as with the 1883 Krakatau Volcano Eruption. Massive objects falling into the sea, such as the flanks of island volcanoes and asteroids, can also generate tsunamis, but such events are extremely rare.

Tsunami hazard along a coastline is therefore a compound of all the potential sources of tsunamis that lie in the neighboring sea or ocean. The large majority of significant tsunamis with run-up of 5 m (16 ft) or greater (generated by earthquakes and submarine slides) are only damaging locally, generally within 100 to 200 km (60 to 125 mi) of the source. The fault or landslide scarp (a line of cliffs produced by faulting or erosion) is typically only tens of kilometers in length, and the wave becomes attenuated as it radiates in all directions out into the ocean. The total volume of sea floor deformation in such local tsunamis (experienced somewhere every few years) is thus typically a few cubic kilometers. The largest tsunami sources, however, can deform tens of cubic kilometers of sea floor and affect coastlines thousands of kilometers away. Sometimes the alignment of the sea floor deformation can focus the energy of the wave in one particular direction like a searchlight. The 2004 Indian Ocean Tsunami, involving an estimated 30 km³ (7.2 mi³) of sea floor deformation, was one of these 'basin-wide' mega-tsunamis.

To provide an overview of global tsunami hazard, RMS explored the locations of potential tsunami sources worldwide, which include all underwater zones of active tectonic deformation as well as unstable slopes along the continental margins and on the flanks of the largest volcanic islands. For each tsunami source, the information relating to the size and return period of potential sea floor deformation events was considered.

Sources capable of generating M8.0 or greater earthquakes are of concern as potential sources of




*Tsunami hazard along the Cascadia subduction zone near the Pacific Northwest coastline of the United States (Image: Canada Geological Survey)*

regional tsunamis. Almost all major tsunamis are caused by shallow overthrust earthquakes associated with subduction zone or collisional plate boundaries. Large normal faults – sometimes above subduction zones – can also act as local tsunami sources.

In assessing the tsunami hazard along each section of coastline, four probability ranges were developed based on the range of return periods of tsunamis of around 5 m (16 ft) elevation. The assessed hazard is the general elevation along that coastline and does not account for localized variations in tsunami heights caused by seafloor topography or coastline shape.

The highest tsunami hazard has an estimated return period of less than 500 years. This hazard probability is common on coastlines adjacent to highly active subduction zones with plate convergence of a few centimeters each year. It includes the subduction zones of eastern Japan, the Chilean trench along southwestern South America, and the Cascadia subduction zone in the Pacific Northwest of North America. There are also a few areas of concentrated crustal extensional faulting associated with subduction, as in Calabria and Eastern Sicily, Italy that also have return periods of under 500 years for major tsunami.

Moderate tsunami hazard occurs along coastlines where a tsunami over 5 m (16 ft) has an estimated return period between 500 and 2,000 years. Coastlines adjacent to active continental faulting with slow or distributed plate boundary collision zones fall into this category. Moderate hazard coastlines, such as in Sri Lanka and southern India, are those at regional distances from subduction zones, where only the largest (M9.0) earthquakes have the potential of generating significant tsunamis in the farfield.

Magnitude 9 earthquakes are often cascade fault ruptures extending for 1,000 km (620 mi) along the subduction interface. Subduction zones can also rupture in smaller (M8.0) earthquakes, with rupture lengths of 100 to 300 km (62 to 186 mi). The M8.7 2005 earthquake that occurred along the Sumatra subduction zone is one such example. Magnitude 8 events are much less likely to generate damaging tsunamis at regional distances. For this reason, the recurrence interval of tsunamis as large as those of the 2004 Indian Ocean Tsunami along the coasts of Sri Lanka and Thailand is considered to be greater than 500 years.

The Pacific Ocean is surrounded on three sides by subduction zone plate boundaries capable of generating major tsunamis. However, given the ocean's width, a mega-tsunami generated on one side would be only locally damaging on the other side. Only certain islands in the middle of the Pacific such as Hawaii can be hit by tsunamis from a range of circum-Pacific sources. In contrast, subduction zones in narrow oceans present the highest hazard to opposing coastlines. In particular, the Mediterranean Sea and the northeastern Indian Ocean have sections of coastline with moderate risk.

The slow collision of the Africa and Eurasia plates reflects a complex mix of subduction and continental crustal faulting. In the eastern Mediterranean, a large tsunami in 365 C.E. was caused by a major subduction zone earthquake beneath Crete. The 1755 Great Lisbon Earthquake generated a tsunami that affected the coastlines of southwestern Portugal and Spain as well as northwestern Morocco. Coastlines with moderate tsunami hazard may also include areas where the hazard is driven by earthquake-induced submarine slides, such as along the southern flank of the Puerto Rico trench to the north of Puerto Rico.

Coastal locations where a tsunami source has been identified but its return period is greater than 2,000 years are considered low hazard regions. Tsunami sources for such areas include the largest mega-tsunami submarine slides, such as Storegga along the Norwegian continental margin, and the largest volcanic landslides, as on the flanks of active volcanoes in Hawaii and the Canary Islands. Low hazard coastlines also include locations that could be affected by regional tsunamis from hypothetically large earthquakes such as the southern coast of France and the northern coast of Algiers.

On coastlines where there is no identified terrestrial tsunami source capable of causing a tsunami with a height greater than 5 m (16 ft), the hazard is negligible. The Atlantic Ocean coastlines of South America and Africa are in this category. In these regions, unless new sources of tsunamis are identified, the hazard is dominated at the longest return periods (tens to hundreds of thousands of years) by tsunamis from remote asteroid impacts.

*Inundation from a tsunami in Japan after the 1960 M9.5 Chile Earthquake (Image: USGS)*

## High Hazard

**Return Period:** Less than 500 years

**Characteristics:** Adjacent to zones with vertical fault displacements and high earthquake hazard, mostly in very active subduction zones

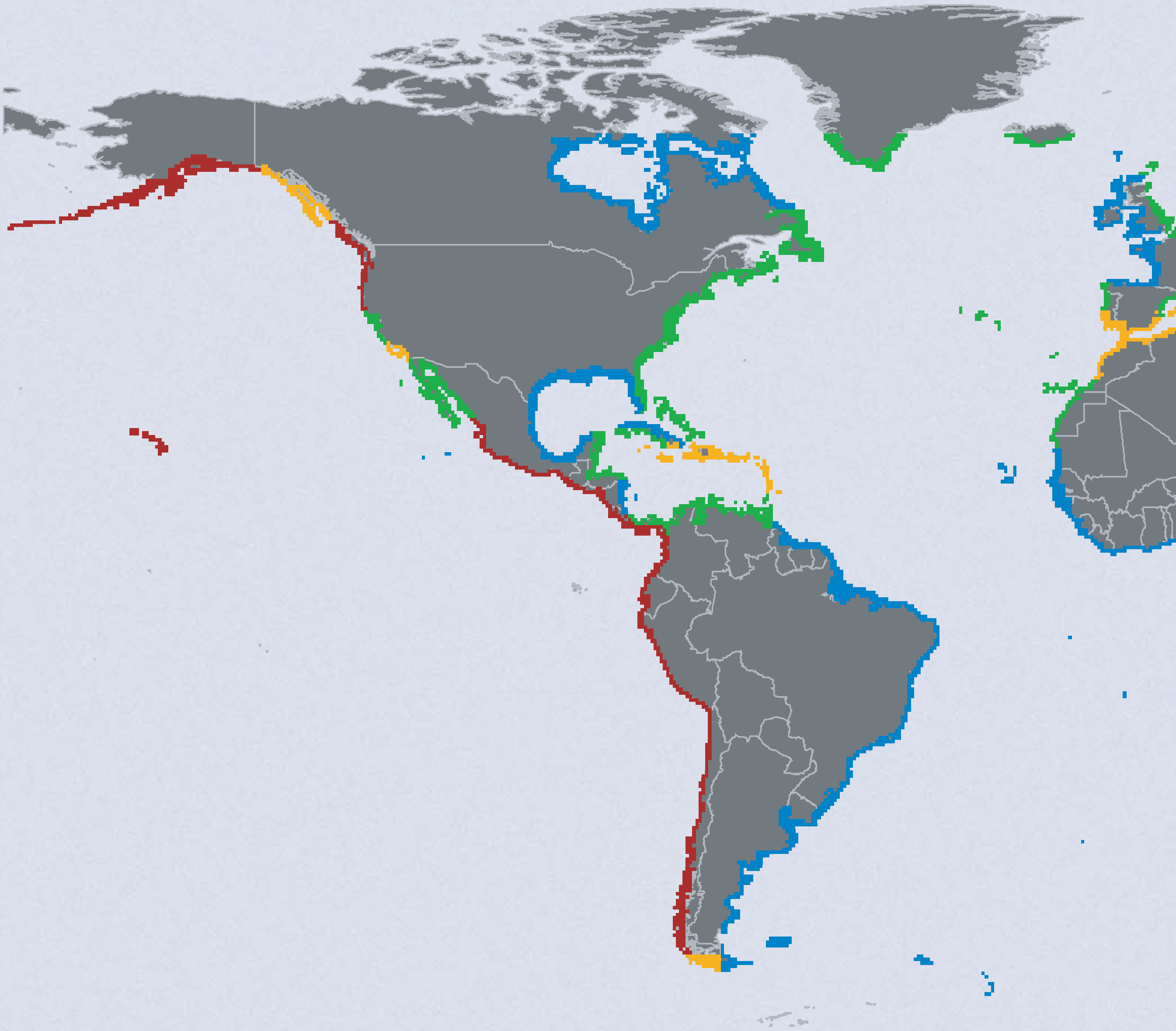
**Example Coastlines:** Eastern and southern Honshu Island in Japan, western South America, Pacific Northwest

## Moderate Hazard

**Return Period:** 500 to 2,000 years

**Characteristics:** Adjacent to active continental faulting with slow or distributed plate boundary collision zones, or in regions at moderate distances from subduction zones capable of large (M9.0) earthquakes

**Example Coastlines:** Northeastern Indian Ocean, Mediterranean Sea



## Low Hazard

**Return Period:** 2,000+ years

**Characteristics:** Coastal areas subject to effects of mega-tsunamis from submarine slides, large volcanic landslides, or infrequent but large earthquakes

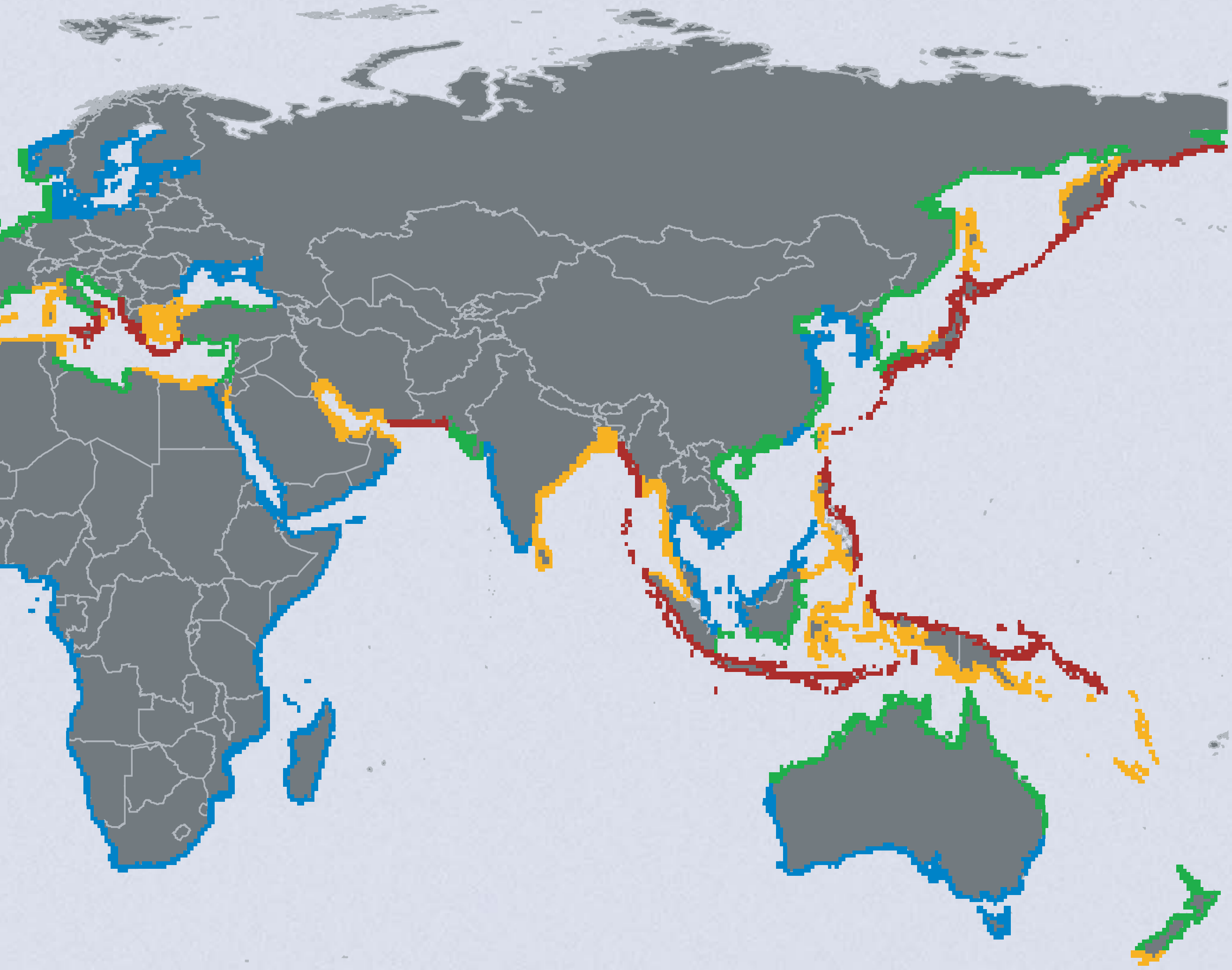
**Example Coastlines:** Northern North Sea, eastern U.S., Canary Islands

## Negligible Hazard

**Return Period:** Tens to hundreds of thousands of years

**Characteristics:** No known source capable of causing tsunamis higher than 5 m (16 ft); hazard dominated by extreme events such as asteroid impacts

**Example Coastlines:** Eastern South America, western Africa

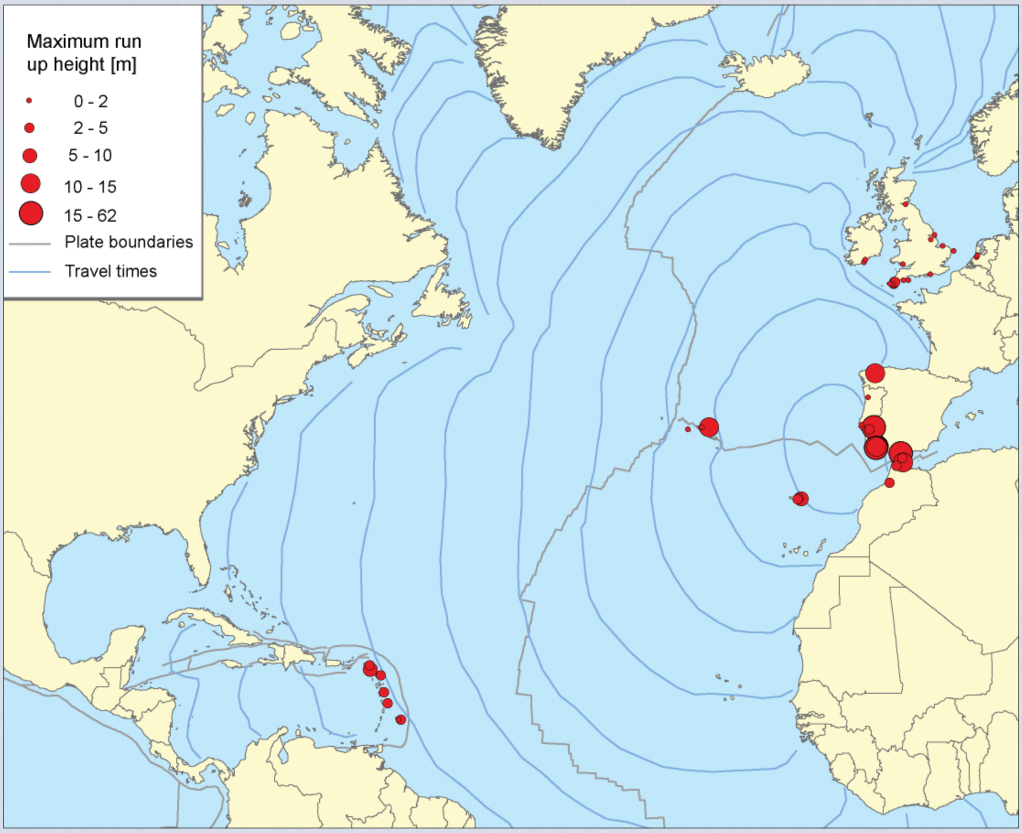


## Accumulation Zones

Tsunami hazard sources in and around the Mediterranean Sea provide good examples of how coastal property exposure can accumulate across country boundaries and insurance markets. The 1755 Lisbon Earthquake that devastated the Algarve region of Portugal generated a major tsunami, with wave heights comparable to those of the 2004 Indian Ocean Tsunami. Waves reached 30 m (98 ft) in Faro, Portugal, 15 m (50 ft) along southwest Portugal, and in excess of 5 m (16 ft) along southwest Spain and the Atlantic coast of Morocco. As with the 2004 Indian Ocean Tsunami, the tsunami waves were strongly polarized in the farfield. Thus, while the tsunami waves were not noticed in the ports along the east coast of North America, in the West Indies run-up heights reached to 5 m (16 ft) on a number of islands including Antigua, Dominica, Saba, and St. Martin.

At the eastern side of the Mediterranean Sea, the 365 C.E. earthquake located on the Hellenic Arc subduction zone is the greatest known historical earthquake in the region, causing several meters of uplift in western Crete. The earthquake created a devastating tsunami that impacted the southern coast of Crete and the northern coast of Egypt, particularly in Alexandria. The tsunami waves also traveled east towards Cyprus, west towards Malta, Sicily, and Libya and north towards the Ionian and Adriatic Seas.

Given that it had not been recognized that the oblique subduction zone north of Sumatra could generate a M9.0 earthquake, a review of other sections of subduction zones could yield unrecognized mega-tsunami sources. The most notable aspect about the 2004 Indian Ocean Earthquake was that the section of the plate boundary that ruptured had not experienced a great earthquake for at least the previous 200 years. Additionally, the Philippine Sea subduction zone that




*Map of the tsunami after the 1755 Lisbon Earthquake, with travel times (in one hour increments) and maximum run-up heights* runs from southern Kyushu Island, Japan to Taiwan has not had any major rupture for the past two centuries and has been highlighted as a potential analog to the Sunda trench north of Sumatra. A tsunami generated from this source would affect the Pacific coastline of southwest China around Shanghai, a region familiar with the impacts of typhoon storm surges and therefore less at risk than the coasts of southwest Thailand and Sri Lanka.

A second subduction zone 'gap' is located at the Lesser Antilles subduction zone along the eastern edge of the Caribbean. Apart from its northern end, which broke in 1843, this area also has not had any major plate boundary earthquakes in the past 500 years. A mega-tsunami triggered from this source would strongly affect the Lesser Antilles Islands, including the western coast of Barbados, as well as potentially propagating across the Caribbean to Central America.

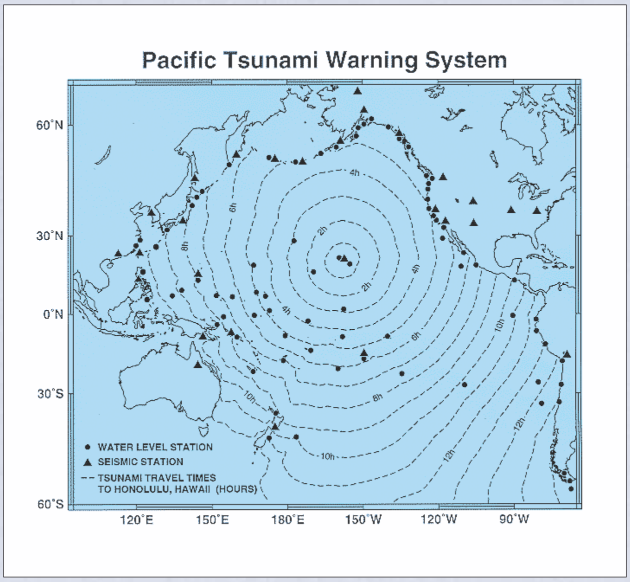
Other tsunamis that could affect several sections of coastline from the same original cause include rare but extreme events generated by underwater volcanic collapses or landslides. Lateral collapses of oceanic island volcanoes produce the largest landslides experienced thus far. Although no such lateral collapse is known in the historical record, residual debris found on the seafloor support their occurrence in recent geologic time, in particular around the most rapidly growing volcanoes such as in the Hawaiian Islands. Geologically young and extremely large landslide deposits have been mapped in all of the Canary Islands, where at least a dozen major flank collapses have occurred in the past several million years.

Geological evidence suggests that during some future eruption, the Cumbre Vieja Volcano on the island of La Palma in the Canary Island chain of the eastern Atlantic Ocean may experience a catastrophic failure of its western flank, dropping 150 to 500 $km^3$ (35 to 120 $mi^3$) of rock into the sea. The question as to how tsunami-generating such a collapse would be is much debated. In the most pessimistic and apocalyptic interpretation, the whole flank enters the sea as a single block moving at speeds greater than 100 m (328 ft) per second. However most geologists consider that the collapse would be complex, and blocks would fragment and disintegrate, as appears to have been the case in past episodes of flank collapse. In this case, there would be multiple moderately-sized tsunamis. In almost any scenario, the Canary Islands would be badly affected, but a major tsunami with run-up of 10 m (33 ft) on the U.S. East Coast requires circumstances that many geologists consider implausible.

The 2004 Indian Ocean Tsunami highlighted inherent vulnerabilities of the world's coastlines and the people who live there. Coastal populations are on the increase in many parts of the world, mostly due to the exploitation of sea resources or tourism-related activities. Adequate mitigation measures from tsunami hazard can be put in place to save lives, property, and the livelihoods of those living on the coast. A wide range of approaches can be used for mitigation, including tsunami warning systems, education, building code standards, land use planning, and other engineering solutions.

## Education and Warnings

Education is one of the easiest ways to reduce tsunami life loss. Such education needs to include knowledge of the cause of a tsunami and its association with the largest earthquakes to help individuals understand how their own observations can help them take appropriate action. Most tsunami hazard is concentrated along coastlines sufficiently close to the earthquake fault rupture, so the vibrations will be strongly felt. The duration of ground shaking is a good indicator of an impending tsunami: anything lasting a minute or more is a sign of a great earthquake with the potential to cause a life-threatening tsunami.




*Map of the Pacific Ocean Tsunami Warning System displaying reporting stations and tsunami travel times to Honolulu*

However, the earthquake may not be felt at a distance from the source, and hence it may be the movements of the sea that can provide the best indicator that a tsunami is about to arrive.

In many (but not all) tsunamis, the first movement of the sea is a withdrawal. Any occasion when the sea level recedes rapidly and inexplicably should be taken as a signal for immediate flight to higher ground. There are, unfortunately, many stories of people following the receding water to collect stranded shellfish only to be overwhelmed by the ensuing wave. Images from the 2004 event will go a long way in helping educate millions of coastal dwellers about the warning signs. In addition, the first tsunami wave is not necessarily the most devastating one. The 1960 M9.5 Chile Earthquake generated a tsunami that traveled across the Pacific Ocean. The first tsunami wave that hit the town of Hilo, Hawaii was only 1.2 m (4 ft), while the waves that followed measured up to 5.5 m (18 ft) in height.

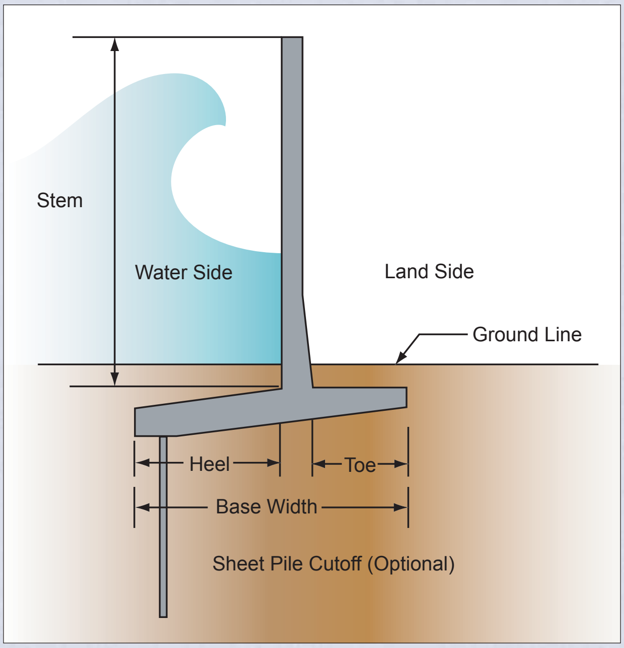
As warning systems that track the passage of the tsunami in the open ocean are being developed, self-help solutions can be supplemented with information on how to respond to official warnings, such as those delivered through radio, cellphone messages, or sirens. However, official warning systems can provide only part of the solution as information can never be effectively disseminated to everyone along a coastline. With only 10 to 30 minutes warning in the nearfield of major tsunamis, it is imperative that people are taught to take their own action rather than wait for official instruction.

The state of Hawaii has endeavored to educate its population about the danger of farfield tsunamis traveling across the Pacific Ocean. Hawaii governmental agencies post maps of tsunami risk zones and evacuation routes in hotels and along beaches. In addition, the Pacific Tsunami Warning Center run by National Oceanic Atmospheric Administration (NOAA) has been issuing tsunami warnings since 1948. After the 1960 Chile Earthquake, it issued a warning for Hawaii that saved many lives in Hilo as people evacuated to higher ground. However, according to a U.S. Geological Survey report following the event, while most people in Hilo heard the warning sirens, only a portion understood them as a signal to evacuate. Tsunami response drills are now performed regularly in Hawaii to train people how to respond. Following the 2004 tsunami, the International Oceanographic Commission (IOC) of the U.N. Educational, Scientific and Cultural Organization (UNESCO) committed to developing an Indian Ocean tsunami early warning system. Separately, Thailand launched a National Disaster Warning Center in May 2005, becoming the first country hit by the 2004 Indian Ocean Tsunami to launch an early warning system.

## Physical Mitigation Measures

Japan and the Hawaiian Islands represent the territories and coastlines most frequently affected by damaging tsunamis. Since 684 C.E., Japan has had 73 tsunamis that caused over 100,000 deaths. The overwhelming majority of these tsunamis were generated from nearfield earthquakes along the plate boundaries that pass close to the coasts of Japan. As a result, Japan is a leader in tsunami mitigation, with efforts directed both toward the rapid issuance of tsunami warnings as well as to physical mitigation measures in high tsunami risk areas. After a tsunami induced by the 1933 Showa-Sanriku Earthquake seriously damaged the Sanriku Pacific coastal area, some communities were resettled to higher locations, seawalls were constructed along the coast, tsunami warning systems were established, and evacuation routes were designated. In some fishing villages, tsunami gates have been erected at the entrances to bays and harbors to protect against flooding. More recently, Japan has established stricter building codes to protect buildings from both earthquakes and tsunamis. Similarly, in Hawaii, building regulations designate the types of structures and occupancies allowed in zones deemed at risk from tsunami inundation.

In contrast to natural barriers to an approaching tsunami or storm wave such as coastal forests, seawalls are engineered structures that provide protection




*Schematic diagram of a T-type flood wall that can be designed to withstand inundation waves from a tsunami (Image: U.S. Army Corps of Engineers)*

from approaching waters. While an effective tool for tsunami mitigation, seawalls are a bulkier and costlier means of providing protection as compared to other land use measures. However, the town of Yoshihima, Japan was protected by its 6-m (20-ft) high seawall during the 1960 Chile Earthquake and Tsunami. More recently, Male, the capital city of the Maldives, was protected in the 2004 Indian Ocean Tsunami by its 3.5-m (12-ft) seawall. Without this concrete seawall, the tsunami would likely have destroyed half of the city. In India, tsunami-hit areas in Tamil Nadu are currently constructing seawalls to protect the coastline.

For coastlines where tsunamis are rare, certain building zonation rules and construction standards can be implemented. For example, if a building such as a port warehouse must be located near the sea, it can be constructed such that the bearing walls are perpendicular to the shoreline. In this way, the wave impacts the non-bearing or partition walls, and the building does not collapse. In addition, roads built perpendicular to the coastline, rather than parallel to it, can provide tsunami evacuation routes. Where coastal floodplains are so extensive that it is not possible to evacuate to higher ground inland, the challenge for structural engineers is to develop

*The damage to this modern beach hotel on Phi Phi Don Island in Thailand was limited to non-structural elements and contents*

cost-effective construction methods that guarantee survival of all those who have taken refuge on the building's upper floors. For example, for a tsunami with run-up of 6 m (20 ft) or less, such buildings can provide vertical evacuation routes to protect people against storm surge floods, as they have done in Bangladesh.

## Modeling Tsunami Risk

For any coastline, tsunami hazard reflects the range of possible heights and return periods of expected tsunamis. The run-up height versus return period curve reflects a compound of all the potential sizes and distance ranges of tsunami generating events. Tsunamis will exhibit local variations in height according to the shape of the seafloor, which is only predictable where detailed hydraulic modeling has been undertaken.

For locations in the nearfield of subduction zones, hazard will be driven by the expected size and return periods of major earthquakes along the plate boundary. As shown by the 2005 M8.7 earthquake, tsunami heights can be very sensitive to earthquake size. This earthquake only generated a tsunami with 2 to 3 m (7 to 10 ft) run-up heights, in contrast to the 30 m (100 ft) run-up heights experienced in Banda Aceh following the 2004 M9.3 event.

To calculate tsunami risk at a location, it is necessary to understand how far the tsunami wave will propagate inland, as well as the elevations of buildings and their vulnerability to the force of the water. As with all flooding, risk will depend on the elevation and particular situation. Even for the highest hazard locations, damaging tsunamis do not occur more often than once every 100 years, so the tsunami risk will always be less than 1% and generally less than 0.1% of the property value. However, for some low-lying locations along coasts with appreciable tsunami hazard, tsunamis can be a principal driver of risk, particularly for properties deliberately built close to sea level, such as beachfront hotels and port facilities. As with all flood modeling, high resolution information is needed to differentiate risk.

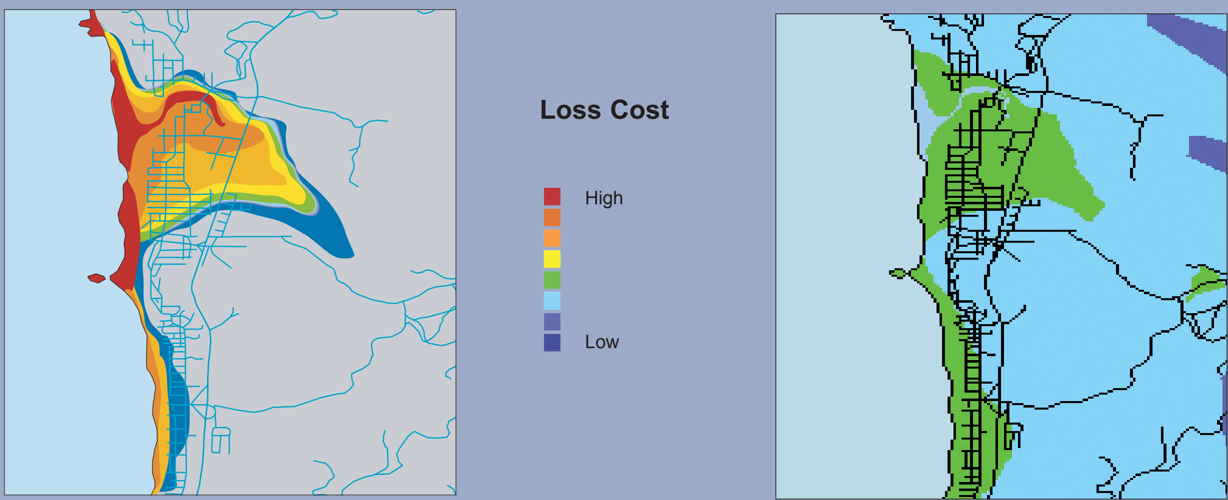
Beyond risk pricing, the 2004 Indian Ocean Earthquake and Tsunami have also highlighted issues of risk accumulation that go to the heart of reinsurance portfolio management. Significant earthquake damage affected the two territories of Sumatra and the Indian Nicobar and Andaman Islands, while five countries sustained major tsunami damage and localized impacts affected another 10 countries. It is important to consider how tsunami risk and tsunami accumulations should be taken into account where catastrophe risks are already modeled for those perils and locations.

First it must be recognized that the regional extent of the 2004 tsunami was very unusual. Most tsunami risk is concentrated in the nearfield of major subduction zone earthquake sources. A good example can be found along the Pacific Northwest coast from Crescent City, California up to southern Vancouver Island, Washington. A large Cascadia subduction zone earthquake, with the potential to rupture all or a majority of this plate boundary, would trigger a tsunami that would likely inundate low-lying communities along the neighboring Pacific coast, as happened in 1700. Fortunately, such a tsunami would be significantly attenuated by the time it passed through the inlets of the Puget Sound in Washington, although it could still cause potential losses to port and ferry facilities in the vicinity.

Tsunami losses would only comprise a minor component of the total losses, although they figure in the overall magnitude of costs to be expected from such a catastrophe. However, tsunami risk is a major component of the risk in the exposed Pacific coastal communities, where for certain properties it is likely to exceed earthquake risk.

In terms of other extreme accumulations of tsunami risk, the focus for insurers and reinsurers should be on testing accumulations along combinations of coastlines with the potential to be impacted by the same event.

The 2004 Indian Ocean Tsunami has a return period longer than 500 years, and there is no prospect of another event of comparable size being generated on this particular section of the plate boundary. However, its impacts can serve to alert the world to tsunami hazard and mitigation needs. In order to reduce the vulnerability of individuals and property on exposed coastlines around the world, protective measures are necessary. A tsunami warning system is particularly warranted in the Indian Ocean and should be well integrated with other risk assessment and mitigation strategies including education, hazard mapping, coastal bathymetry investigations, and land use planning.




*In 1964, Cannon Beach, Oregon sustained significant property damage during a tsunami generated by the M9.2 Alaska Earthquake. Tsunami hazard in this region is estimated as high due to its proximity to the Cascadia subduction zone and other earthquake sources along the Pacific basin. The map on the left shows a preliminary estimate of tsunami risk in Cannon Beach as measured in loss costs. The loss costs were compiled for single-family wood structures based on inundation frequency estimates, high-resolution digital elevation models, and RMS global damage statistics, but do not take into account localized effects. The red zone indicates the highest level of risk directly on the coastline at $7 per $1,000, while the blue zone represents minimal risk with loss costs less than $0.10 per $1,000. For comparison, a map of earthquake loss costs at the same scale with equivalent shading is presented for the same region on the right. At maximum, the earthquake loss costs are $1 per $1,000, with clustering of risk around $0.50 per $1,000. As evidenced by the maps, the gradient for tsunami risk is extremely steep and drops to negligible values less than 2 km (1.2 mi) from the coast, whereas the earthquake risk is lower overall but spread out more evenly across the region.*

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