This year, a massive earthquake measuring 8.0 on the Richter scale caused a monstrous tsunami that hit Samoa, American Samoa, and Tonga, claiming at least 1,000 total lives. In 2004, another tsunami, caused by a 9.0 earthquake, killed over 200,000 throughout the countries of the Indian Ocean. Avoiding these natural disasters is a top priority among geophysicists, and thus far, they have attempted to model these incredible forces.

In this study, our goal was to compare the devastation of potential tsunamis caused by varying earthquakes on seven different cities. Our model takes into account two of the largest factors in measuring the strength of a tsunami when it hits land: the energy from the earthquake itself and the distance between the epicenter and the coast, where devastation is proportional to energy but inversely proportional to distance.

The main advantage of our model is its simplicity in comparison to others. Most of those use the topography of the surrounding ocean, geography of the bay the city lies in, and the stress released by the fault during the earthquake. None of these make for a simple equation. On the other hand, ours strikes a balance between accuracy and simplicity, and even though we aimed to optimize simplicity, ours is still very accurate.

In confirming our model, we used data from four different earthquakes: the 2009 Samoan earthquake to create the model and three others to reinforce it. These three included both Aceh's and Sri Lanka's death tolls from the 2004 Sumatra-Andaman earthquake and Flores's death toll from the 1992 Flores Sea earthquake.

To execute our model, we used five scenarios. The first scenario used data from the 2004 Sumatra-Andaman earthquake, which we related to how far inland water from the tsunami came. Therefore, we measured the death toll in each city as if the water had came in to shore two kilometers. The second and fourth scenarios were computed using the largest earthquake ever recorded (9.5) and the smallest one that ever produced a deadly tsunami (5.2) respectively. The third used a value for the average earthquake that produced a deadly tsunami, while the fifth and final found the smallest sized earthquake that would displace only one person.

To summarize our results, Hilo would be entirely demolished but Juneau would be left comparitively unharmed in scenario one due to their respective low and high land areas. For equal sized earthquakes (scenarios two through five), Juneau would be hit the hardest but Hilo would be hit the least. Oddly, the smallest earthquake-causing tsunami killed about 38 times as many people as expected (3 observed/.08 expected); we contributed this to some special incident in the actual case, such as evacuation.

So while our model aimed to maximize simplicity rather than exactness, it still provides a very accurate representation of tsunamis hitting various cities in the United States.

Statement and Analysis of the Problem

On December 26, 2004, an earthquake produced the largest trans-oceanic tsunami in over 40 years, affecting twelve countries and killing over 227,898 people, more than any tsunami ever recorded (NGDC, 2009). The Sumatra-Andaman tsunami rose up to 50.9 meters in height and reached up to 2 kilometers inland (Pearce, & Holmes, 2005). Each year, an estimated 500,000 detectable earthquakes take place around the world; of these, about 100 cause damage (USGS, 2009). Nevertheless, scientists have been unsuccessful in predicting earthquake location, time, or magnitude. However, it is known that the worst damage from earthquakes in the past have resulted from undersea subduction of two tectonic plates at a fault line.

While tsunamis have various causes, the most common are those created by earthquakes. Earthquakes are sudden slips on a fault between two tectonic plates moving against one another, resulting in ground shaking and radiated seismic energy (USGS, 2009). When an earthquake occurs underwater, the sea is displaced by a great amount in a small amount of time. This causes a surge of a series of waves to propagate out from the point of the earthquake's origin at the earth's surface, known as the earthquake's epicenter. The surge has an extremely long wavelength but a short amplitude. This allows it to travel unnoticed and without losing much energy. When the tsunami reaches the shore, the depth of the ocean decreases, which in turn decreases the wave's velocity and wavelength but increases its height, creating a massive wave able to wipe out entire cities.

Since three of the United States' four borders are touched by sea, tsunamis are a notable threat to our coastal cities; as we saw with Hurricane Katrina, coastal disasters can disrupt factors such as the economy for years. In this study, our goal was to compare the devastation of potential tsunamis caused by varying earthquakes on seven different cities: San Francisco, California; Hilo, Hawai'i; New Orleans, Louisiana; Charleston, South Carolina; New York City, New York; Boston, Massachusetts; and a seventh city of our own discretion: Juneau, Alaska. While all of these cities are directly on the coast line, they have varying risk factors based on their respective populations and distances from fault lines. Juneau, Alaska was chosen because Alaska is both the most earthquake-prone state in the U.S.A. and one of the most seismically active regions in the world, experiencing a magnitude 7 earthquake almost every year, and a magnitude 8 or greater earthquake on average every fourteen years. (USGS, 2009)

To calculate the devastation of a tsunami hitting these cities, the amount of people displaced and the number of household units damaged were calculated based on five separate scenarios:

1. The first scenario used inundation data collected from the Sumatra-Andaman earthquake's tsunami from 2004, the deadliest tsunami in recorded history.
2. The second scenario used calculated data assuming the most devastating tsunami resulting from the largest magnitude earthquake ever recorded, M_s=9.5.
3. The third scenario used the average of the magnitudes of earthquakes who triggered deadly tsunamis, M_s=7.6.
4. The fourth scenario used the magnitude of the smallest earthquake recorded that caused a deadly tsunami, M_s=5.2.
5. The fifth scenario calculates the minimum magnitude of an earthquake necessary to displace one person in each of the cities.

Assumptions

In order to model a scenario for a potential tsunami, assumptions were made. To determine the closest possible earthquake to each city, it was assumed that earthquakes only occur at fault lines and that every fault line would be capable of producing an earthquake which can in turn cause a tsunami. Thus, the distance between the city and the closest point along the closest fault line to that city were used to model a potential tsunami. It was also assumed that the tsunami's wave front would impact the coast perpendicularly, causing the worst possible damage. Furthermore, the model assumed that the devastation caused to the city would be the result of the first series of waves hitting the city and not the following aftershock waves.

We assumed that the city's area was in the shape of a square with one side directly on the shoreline and that both the population density and housing density were constant throughout the city. This assumption was made because any other shape, such as a circle about the center of the city, would result in the city overlapping the water in varying amounts, indicating that people would have to live in the water, which is not possible. The city's limit was placed directly on the shoreline because all of the cities used were directly on the coast; otherwise, this would need to be changed.

To determine the effects of the tsunami, this model defined "devastation" as the number of people displaced and households damaged. It was also assumed that the cities would have no advance warning of the approaching tsunami and that the population could not evacuate. This was assumed because each city would have its own function for evacuation, making the model too specific to one city. Thus, the population density at the tsunami's point of impact would be no different from the normal density. It was also assumed that all of the inundated land was damaged and damaged equally such that the coast of the city was affected no differently than the innermost point covered by water. Hence, any contact with water from the initial impact of the tsunami would cause displacement or damage.

Oncoming waterways, walls, and other infrastructures cannot be taken into account because they are too particular to each scenario and vary greatly from city to city. These structures also have little mass in absorbing the kinetic energy and momentum of the wave (See Appendix C, Figure III). Thus, it was assumed that once the tsunami hits, the buildings and other structures would not affect the spreading of water.

Initial assumptions also included factors that could not be accounted for in this model due to lack of historic data regarding these factors. This model does not account for changing in water density. It also does not account for wind or any other external forces as these would be specific to the time and place of the tsunami and cannot be included in a universally applicable model. The model also disregards wave interference caused by bays, obstacles, and other geographical features. This model accounts only for immediate damage done by the incoming water and does not account for resulting fires, storms, human destruction, or other factors that would vary from city to city. It also doesn't account for environmental displacement because there are not significant animal or vegetation populations within the cities. Shelf topography, harbor geometry, and fault slip topography were not taken into account. This is because each city has a unique, intricate shoreline with various islands and obstructions.

It should be noted that wind generated waves differ from tsunami waves in that tsunami waves are not sinusoidal as they build up at the shoal. (See Appendix C, Figure II) Therefore, tsunami waves do not have a directly predictable amplitude, frequency, wavelength, or period as they reach the shore, leaving energy, momentum, and distance traveled as predictable values that correlate to the earthquake's magnitude.

Variables

Several variables were calculated to use in determining the devastation of the cities. For each city, the population (Ω), land area (α), number of households (Ψ), and population density (Φ) were found using data from the 2000 census taken from the United States Census Bureau database. The distance from the nearest fault line (Δ) was taken from Google Earth and was found by taking the shortest distance from the center of the city to the closest point on the closest fault line. The variables $\sqrt{\alpha}$ (length of one side of the city), Γ (length of city inundated), Λ (area of city inundated), Λ_p (population displaced), and Λ_h (households displaced) were defined so they can be derived in the development of the model.

Figure I: Variables

Ω	population (ppl)
α	area of city (km^2)
$\sqrt{\alpha}$	length of one side of a square city (km)
Φ	population density (ppl / km^2)
Ψ	number of households ($homes$)
κ	house density ($homes / km^2$)
Δ	distance of city from nearest underwater fault line (km)
Γ	length of city inundated (km)
Λ	area of city inundated (km^2)
Λ_p	population displaced (ppl)
Λ_h	households damaged ($homes$)
C	determined constant ($\frac{km^3}{J}$)
E	energy released by the earthquake (J)
M_s	magnitude of the earthquake as measured on Richter Scale

Proposed Solution

In the process of finding a model, we needed a way to determine "devastation." Although we would use more variables in our definition of "devastation," total population affected by the tsunami (Λ_p) had the most readily available historical data. Since it was assumed that each city had a constant population density (Φ) over its total area (α), the amount of people affected by the tsunami water could be determined by calculating the amount of people displaced (Λ_p) by attaining the land area covered by the tsunami (Λ). Assuming that the city were a square, we could then know how far inland the tsunami would travel (Γ) by dividing the area inundated by the tsunami by the length of one side of the square city, or the square root of the total land area ($\frac{\Lambda}{\sqrt{\alpha}} = \Gamma$).

A model was then created to link an earthquake's magnitude (M_s) to how far inland it traveled (Γ). The model was used to calculate the area of a city inundated based on the energy released by the earthquake (E) that was left over after tsunami beaming (See Appendix C, Figure II). Tsunami beaming refers to the higher wave amplitudes in a direction perpendicular to fault orientation during deep ocean propagation. Thus, the farther the wave travels, the more the energy will diffuse outward. Complexity of the earthquake source and the effects of refraction and scattering during propagation alter tsunami beaming patterns and therefore are simplified such that the energy of the tsunami (E) would be proportional to the distance traveled between the city and the earthquake's epicenter (Δ).

With our equation in mind ($\frac{\Lambda}{\sqrt{\alpha}} = \Gamma$), we consider that the two most significant factors that contributed to how far inland the wave would travel were the energy released by the earthquake (E) and the distance between the city and the epicenter (Δ). After doing some basic research, we determined that E was proportional to Γ, but inversely proportional to Δ (See Appendix C, Figure II). Thus $E = C \cdot \Gamma / \Delta$, where C is a constant we need to determine - rearranged $\Gamma = C \cdot \frac{E}{\Delta}$. Because we also knew that $\frac{\Lambda}{\sqrt{\alpha}} = \Gamma$, we could substitute this value for Γ because there are no exact recorded values for this in many tsunamis. Furthermore, knowing that $\Lambda = \frac{\Lambda_p}{\Omega}$, we came up with an equation with well-recorded values with which we could determine Γ:

$$\frac{\Lambda_{p \cdot \alpha}}{\Omega} = C \cdot \frac{E}{\Delta}$$

The only problem is that E is not readily known. Fortunately, there is a conversion factor for moving the Richter Scale value (M_s) into E: $log_{10}(E) = 4.8 + 1.5(M_s)$.

We used the data from the 2009 Samoan tsunami to determine C because it was a most recent earthquake example with comprehensive data. Using 3697.2 km for Δ, 8.0 for M_s, 189 for Λ_p, 179000 for Ω, and 2831 km^2 for α, we determined the value of C to be about 1.7515×10^{-13}. So our final model would be:

$$\Lambda_p \quad \frac{C\cdot\Omega\cdot E}{\Delta\cdot\alpha},$$

where $C=1.7515\times10^{-13}$

and $log_{10}(E)=4.8+1.5(M_s)$.

For the purposes of this paper, it will be known as the "AWES Model."

Testing the Model

To test our model and make sure that it functions effectively, we compared three different real-world tsunami impacts: Aceh during the 2004 Sumatran earthquake, Sri Lanka during the 2004 Sumatran earthquake, and Flores during the 1992 Flores Sea earthquake. The most impacted location nearest to the epicenter was taken from Google Earth. The magnitude of earthquake and number of deaths were taken from the NGDC (See Appendix A). The total population and the total land area for the location were taken from the United States Census Bureau database. To summarize the data:

Figure II: Testing the AWES Model Using Historical Tsunami Data

Values	Aceh in 2004	Sri Lanka in 2004	Flores in 1992
Distance from Epicenter (Δ)	82.81 km	1597.48 km	92.07 km
Magnitude (M_s)	9.0	9.0	7.8
Number Dead (Λp)	21411	167736	2500
Total Population (Ω)	21324791	3930000	1600000
Total Land Area (α)	65610	57366	13540
AWES Model Estimated Magnitude	8.8	8.7	7.5
Percent Error	1.8%	4.0%	4.0%

Comparing Devastation Between the Seven Cities

In order to determine the devastation of the city, the number of people (Λ_P) and households (Λ_H) inundated needed to be calculated. Since the population density (Φ) and the house density (κ) were assumed to be equal throughout the city, Λ_P and Λ_H could be found by determining the area of the city inundated (Λ). Since we have the total area of each city (α) and are assuming that the city is square, we can calculate the length one side of the city by as $\sqrt{\alpha}$. Assuming that the city's limit extends to the shoreline, how far the tsunami travels inland also represents the length of city inundated (Γ). Then Λ can be calculated by the rectangular area displaced as a function of Γ and $\sqrt{\alpha}$ (See Appendix C, Figure I). Once Λ has been calculated, the population and house density can be used to find Λ_P and Λ_H using the equations $\Lambda_P = \Phi \times \Lambda$ and $\Lambda_H = \kappa \times \Lambda$.

__Scenario I__

The first scenario was tested to determine a worst-case scenario of inundation using impact data from the Sumatra-Andaman tsunami of 2004, the deadliest tsunami in recorded history where the tsunami reached 2 kilometers inland. Using $\Gamma = 2$ as the defined parameter, we can find Λ using the equation $\Lambda = \Gamma \times \sqrt{\alpha} = 2\sqrt{\alpha}$. Then the people and households inundated were found using $\Lambda_P = \Lambda \times \Phi$ and $\Lambda_H = \kappa \times \Lambda$. The percentage of the total population displaced and home damage costs were also found for comparison (See Appendix B, Scenario I).

__Scenario II__

The second scenario was used to analyze the devastation in each city if the largest known magnitude of an earthquake was recreated. Scenario 2 used the AWES model to calculate the length inundated (Γ) from the largest recorded seismic magnitude, $M_s = 9.5$, from the Chilean earthquake of 1960. Γ was used to find the area inundated (Λ) using the equation $\Lambda = \Gamma \times \sqrt{\alpha}$, and the devastation was calculated (See Appendix B, Scenario II).

Scenario III

The third scenario was used to test the effects of an average size tsunami. Using data from the National Geophysical Data Center, we found the average seismic magnitude of every earthquake that has caused a deadly tsunami, M_s=7.58. We used this magnitude in the AWES Model to determine Λ and the devastation for each city (See Appendix B, Scenario III).

Scenario IV

The fourth scenario was designed to test the effects of a small earthquake and its resulting tsunami. The smallest magnitude of an earthquake that produced a deadly tsunami was an M_s=5.2 earthquake in Southern California in 1930 which killed three people. Scenario 4 used the AWES model to calculate the length inundated (Γ) using M_s = 5.2 and the devastation (See Appendix B, Scenario IV).

Scenario V

The fifth scenario was used to determine what the minimum magnitude of an earthquake must be to produce a tsunami which would displace at least one person. The AWES Model was set up for each city with Λ_p=1 and their respective data for Ω, α, and Δ, and then solved for the variable M_s, which gives the value necessary to produce a destructive tsunami (See Appendix B, Scenario V).

Strengths and Weaknesses

The main strength of this model is its simplicity. It takes a unique approach to modeling tsunamis which directly relates cause (earthquake) to effect (devastation) without having to muscle through steps and steps of calculations based on the tsunami. The variables and physical intricacies of wave propagation on shore were ignored to make prediction more applicable to final devastation and to create a more streamlined approach. Since these data are likely not available after the earthquake happens and before the tsunami hits, it would be useless to have a model using these parameters if one were trying to predict the devastation of a tsunami before it hits.

Another main strength is the accuracy of the AWES Model when compared to historical tsunami data. When the magnitude of the earthquake was estimated based on the number of people displaced by the tsunami for the Flores earthquake in 1992, Aceh earthquake in 2004, and Sri Lanka earthquake in 2004, the AWES Model yielded a very low percent error when compared to the actual magnitudes. This precison most likely comes from the fact that our historical data were taken from reliable resources.

The main weakness of the AWES Model was that it measured devastation in people displaced yet did not take into account any form of human reaction. The model did not allow for a warning to occur prior to the tsunami's impact. In reality, a warning would allow for at least some to evacuate in the case of a tsunami. Also, the energy given off by the earthquake was calculated as if all the energy released, based on the magnitude, was perpendicular to the fault line in the direction of the city. In reality, when an earthquake slips, it has various angles between perpendicular and parallel to the ocean floor in which it can occur. Since horizontal displacement has little effect on the energy of the wave, not all of the energy of the earthquake goes into creating the tsunami. The model also disregarded friction and drag of the wave as it propagates through the water. Although this amount would be small, it would have some effect on the wave's final momentum as it reaches the shore.

The model also acts as if all the cities were exactly the same, such that cities like Hilo or New Orleans would not have barriers protecting them against the impact. On a similar note, the model did not account for variations in tsunami spreading and propagation on shore due to topography or coastline building and structures. In reality, these physical features would direct the momentum and energy of the wave resulting in various effects on each city. The model also does not account for differences in damage caused by fires, falling buildings, water damage, or any other aftereffect. Although all areas in the model will be flooded, the damage of buildings on the coastline will be affected more than buildings that are one kilometer inland. This was not considered in the model.

When calculating the AWES Model constant (C), the data taken from historic earthquakes accounted for entire countries being impacted by tsunamis instead of cities. Therefore, when the AWES Model was applied to the seven cities, the constant may have become inaccurate for determining the devastation.

The cities were assumed to be squares rather than three-dimensional, irregular shapes. The population density and household density were thought to be constant throughout the city rather than varying from building to building. Devastation does not account for the negative economic, cultural, and environmental impacts which would also result from a destructive tsunami, and would likely take the city years to recover.

Regardless of the validity of the assumptions made producing weakness in the AWES Model, they were necessary to make this model feasible.

Conclusion

Tsunamis, though few and far apart, pose a large threat to humanity. These disasters are often ignored until it's too late to take action, and the human race is periodically reminded of their carelessness. One reminder occurred in 2004 with the Indian Ocean tsunami resulting from an underwater earthquake in Sumatra. In this paper, we have modeled the ravaging effects that tsunamis can incur upon coastal regions on virtually any continent in the world. Though our model is not perfect, it is accurate. Modeled after the abundant and comprehensive data regarding the Sumatra earthquake and its resulting tsunami, the model has the rare and invaluable balance between simplicity and efficacy. This blend offers solid results regarding the damage, both human and material, inflicted by tsunamis. Our model was derived using basic algebraic substitution, combining three equations: $\frac{\Lambda}{\sqrt{\alpha}} = \Gamma$, $\Lambda = \frac{\Lambda_p}{\Omega}$, & $\Gamma = C \cdot \frac{E}{\Delta}$. The resulting model, $\Lambda_p \quad \frac{C \cdot \Omega \cdot E}{\Delta \cdot \alpha}$, was used to predict the effects of a five different tsunami-scenarios on seven cities across the United States. Ranging from as far west as Alaska to the East

Coast city of Charleston, South Carolina, the results of these seven subjects demonstrated one common factor: no coastal cities are safe from tsunamis.

We wanted to show that the devastation in the scenarios varies because of the inherent location and parameters of the city and not because of the magnitude of the earthquake. Logically, it should change between cities because the distance to the nearest fault line, the population of the city, and the area of the city all affect the devastation. To determine if the variance in devastation was caused by the differences in cities, we ran a One-Way ANOVA test to see if the differences in means of displaced persons was caused by the city or by chance. Since we already assumed that the populations being tested are normally distributed, the ANOVA test can be used since the samples are independent of each other. When we ran an Analysis of Variance between the cities, we found the cities to be significantly different at an $\alpha -.05$ (p-value: 0.3985). This means that the differences in people displaced between the cities was because of the differences in the city and not the earthquake (See Appendix B, ANOVA Test).

This model made considerable assumptions to combat the infinitely varying geographical conditions of the earth. However, these sacrifices in specificity result in the precious advantage of versatility. Our model is extremely general and can be applied to any scenario, given the necessary parameters. Each coastal city in the world could easily calculate it's possible damage in a worst-case tsunami scenario and take the necessary actions to increase awareness, protection, and evacuation techniques to minimize the threat tsunamis pose.

In the development of the model, limits arising from time and resources prevented us from creating a model that would take into account the deeper physics of ocean wave propagation, probability and trends of earthquake occurrence, and at least vague geographical features regarding various cities. These different variables presented questions whose answers could seriously alter the model and allow it to be more accurate in predicting the real world probability and implications of an earthquake-caused tsunami.

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Appendix A: Researched Data

Year	Earthquake Magnitude	Tsunami Name	Latitude	Longitude	Maximum Water Height	Deaths
365		CRETE	35	23		5700
744		SW. KYUSHU ISLAND	32.4	130.5		1520
869	8.6	SANRIKU	38.5	143.8		1000
887	6.5	NIIGATA	37.5	138.1	4	2000
1026	7.5	OFF MASUDA, SHIMANE PREFECTURE	34.8	131.8	10	1000
1341	7	JUSANKO, TSUGARU AOMORI PREFECTURE	41	139.5		2600
1361	8.4	NANKAIDO	33	135		660
1495	7.1	KAMAKURA, SAGAMI BAY, TOKAIDO	35.1	139.5	5	200
1498	8.3	ENSHUNADA SEA	34	138.1	10	31000
1512		TOKUSHIMA PREFECTURE				3700
1570	8.8	CENTRAL CHILE, OLD CONCEPCION	-36.8	-73	4	2000
1575	8.5	CENTRAL CHILE	-39.8	-73.2		100
1586	8.2	ISE BAY	35	136.8	6	8000
1596	6.9	BEPPU BAY, KYUSHU	33.3	131.7	5	708
1597	6.4	BEPPU BAY, JAPAN	33.3	131.6	2	40
1604	8.5	S. PERU	-17.88	-70.94	16	74
1605	7.9	NANKAIDO	33	134.9	10	5000
1605	7.9	ENSHUNADA	33.5	138.5	10	1000
1611	8.1	SANRIKU	39	144.5	25	5000
1616	7.5	SANRIKU	39	144.5	2	200
1633	7.1	SAGAMI BAY	35.2	139.2	2	150
1640	6.5	SE. HOKKAIDO ISLAND	42.07	140.68	6	700
1644	6.9	HONJO, AKITA	39.4	140.1	2	117
1647	*	S. PERU	-14.2	-75.7	2.8	14
1650		ECHIZEN (FUKUI)				21
1657	8	CENTRAL CHILE	-36.8	-73.03	8	40
1662	7.6	HIUGANADA	31.7	132	1	200
1674	6.8	BANDA SEA	-3.7	128.2	100	2243
1677	7.4	OFF SE. BOSO PENINSULA	35	141.5	8	500
1687	8.5	S. PERU	-13.5	-76.5	8	5000
1692	7.7	PORT ROYAL	17.8	-76.7	1.8	2000
1696		FUKUSHIMA, JAPAN				2450
1700		CASCADIA SUBDUCTION ZONE	45	-125		2
1700		NAGASAKI PREFECTURE	32.7	129.7		1000
1700	7	TSUSHIMA, NAGASAKI PREFECTURE			6	1000

1703	8.2	OFF SW BOSO PENINSULA	34.7	139.8	10.5	5233
1707	8.4	ENSHUNADA	34.1	137.8	11	2000
1707	8.4	NANKAIDO	33.2	134.8	25.7	30000
1721	*	TAINAN	23	120.2		2000
1730	8.7	CENTRAL CHILE	-32.5	-71.5	16	3
1737	*	CALCUTTA				300000
1737	*	KAMCHATKA			64	3
1741		W. HOKKAIDO ISLAND	41.6	139.4	90	1475
1746	8	CENTRAL PERU	-12	-77	24	4800
1751	6.6	NW. HONSHU ISLAND	37.2	138.1	2	2100
1751	8.5	CENTRAL CHILE	-36.83	-71.63	3.5	65
1754		LUZON ISLAND	14.002	120.993		12
1755	8.5	LISBON	36	-11	30	60000
1763	*	BANDA SEA	-4.5	130	9	7
1765		SOUTH CHINA SEA	23.133	113.333	9	10000
1766	6.9	SANRIKU	40.9	140.7	2	1700
1771	7.4	RYUKYU ISLANDS	24	124.3	85.4	13486
1774	*	NEWFOUNDLAND				300
1780		S. KURIL ISLANDS				12
1780	7.5	S. KURIL ISLANDS	45.3	151.2	12	12
1780	*	SAVANNA LA MAR	18.2	-78.1	3	10
1781		SW. KYUSHU ISLAND	31.58	130.67	6	15
1783	5.9	MESSINA STRAITS	38.217	15.633	16	1500
1783		MESSINA STRAITS	38.25	15.717		1
1787	8.3	SAN MARCOS	16.5	-98.5	4	11
1792	6.4	SHIMABARA BAY, KYUSHU ISLAND	32.8	130.3	55	4300
1792	6.9	W. HOKKAIDO ISLAND	43.5	140.6		5
1793	6.9	W. OFF AOMORI	40.85	139.95	3.6	12
1793	8.3	SANRIKU	38.5	144	4.5	732
1797	*	SW. SUMATRA	-1	100		300
1804	7.3	NW. HONSHU ISLAND	39.05	139.95	1	450
1815	7	BALI SEA	-8	115.2		1200
1819	7.7	KUTCH	23	71		1543
1820	*	FLORES SEA	-5.1	119.4	25	500
1821		ST HELENA	-15.95	-5.7		3
1833	7.4	NW. HONSHU ISLAND	38.9	139.15	9	50
1835	8.2	CENTRAL CHILE	-36.8	-73	24	3
1837	8.5	S. CHILE	-42.5	-74	6	16
1842	7.7	CAP-HAITIAN	19.75	-72.2	5	300
1843	8.4	SE. HOKKAIDO ISLAND	42	146	4.5	46
1845		SE. ALASKA, AK				100

1849	7.5	GUAM, MARIANA ISLANDS	14	143.3	6.1	1
1852	*	BANDA SEA	-4.6	129.9	14.5	60
1853	6.7	CUMANA	10.5	-64.2	5	113
1854	8.3	ENSHUNADA SEA	34	137.9	21	300
1854	8.4	NANKAIDO	33.1	135	28	3000
1856	7.8	SE. HOKKAIDO ISLAND	40.5	143.5	6	26
1859	*	S. JAVA SEA	-9	111		2
1861	8.5	SW. SUMATRA	-1	97.9	7	1105
1861	7	SW. SUMATRA		98		750
1864	7.8	NW. IRIAN JAYA	-1	135	3	250
1865	*	CENTRAL PERU	-12	-77.1	2	5
1867		LAKE MAGGIORE	46	8.7		16
1867	7.1	PELOPONNESUS, GREECE	36.5	22.25	6	12
1867	7.5	VIRGIN ISLANDS	18.1	-65.1	10	30
1867	6	E. CHINA SEA	25.5	121.7		200
1868	7.9	HAWAII	19	-155.5	13.7	47
1868	8.5	N. CHILE	-18.6	-71	18	25000
1871		RUANG	2.28	125.425	25	400
1872	7.4	SW. HONSHU ISLAND	34.9	132	3	804
1878		CENTRAL PERU	-12	-77		5
1878		S. CALIFORNIA	35.18	-120.731	1	1
1882	7.9	SAN BLAS ARCHIPELAGO	9.5	-78.9	3	100
1883		KRAKATAU	-6.102	105.423	35	36000
1894		PUYALLUP RIVER DELTA, TACOMA, WA	47.286	-122.445	3	1
1896	7.6	SANRIKU	39.5	144	38.2	27122
1899		AZORES	38.7	-28.2		1
1899	7.8	BANDA SEA	-3	128.5	12	2460
1900	*	LITUYA BAY, AK	58.6	-137.5		5
1900	7.8	BISMARCK SEA	-4	140		5
1902	*	GUATEMALA-EL SALVADOR	13.5	-89.5	5	185
1905		LOEN	61.866	6.85	40.5	61
1905	7	JAPAN: OFF FUKUSHIMA	37.4	142.6		41
1906	8.8	OFF COAST	1	-81.5	5	1000
1907	7.6	NW. SUMATRA	2	94.5		400
1908	7.1	MESSINA STRAIT, IONIAN SEA	38.183	15.683	13	220
1909	6.9	ANEGAWA, JAPAN	35.4	136.3	1.8	41
1909		LOUISIANA: GRAND ISLE				300
1911	*	TAAL, LUZON ISLAND	14.002	120.993	3	50
1911	8	RYUKYU ISLANDS	28	130	2	6
1914	7.1	SEIKAIDO	31.6	130.6	3	35
1915		SAMOA	-5	-155	2.4	3

1918	8.3	CELEBES SEA	5.4	125.2	7.2	6
1918	8.2	S. KURIL ISLANDS	45.5	151.5	12	23
1918	7.3	PUERTO RICO: MONA PASSAGE	18.5	-67.5	6.1	142
1922	8.5	N. CHILE	-28.5	-70	9	300
1923	8.3	KAMCHATKA	54	161	8	3
1923	7.2	KAMCHATKA	56.5	162.5	30	18
1923		ROCKAWAY BEACH, NY	40.6	-73.5		2
1923	7.9	SAGAMI BAY	35.1	139.5	13	2144
1926		PALMERSTON ISLAND				1
1927	5.7	CALIFORNIA	32.5	-115.5		1
1927	6.3	SULAWESI	-0.7	119.7	15	50
1928	6.9	S. PERU	-13	-69.6		10
1928	7.8	S. MEXICO	16.25	-98	0.2	4
1928		FLORES SEA	-8.32	121.708	10	128
1928	7.3	CELEBES SEA	7	124		4
1929		TJALANG, N.W. SUMATRA	4.633	95.567		6
1929	7.2	GRAND BANKS, NEWFOUNDLAND	44.69	-56	7	28
1930	7.3	MYANMAR COAST	17.3	96.5		550
1930	5.2	S. CALIFORNIA	34.03	-118.643	3.05	1
1930	6.5	BISMARCK SEA	-1.3	144.3	12	23
1931		ATLANTIC CITY, NJ	39.35	-74.417	3	4
1931	7.9	SAN CRISTOBAL ISLAND	-10.5	161.75	9	50
1932	8.1	CENTRAL MEXICO	19.5	-104.25	3	400
1932	7	CENTRAL MEXICO	19	-104.5	10	75
1933		KHARIMKOTAN, N. KURIL ISLANDS	49.12	154.508	9	2
1933	8.4	SANRIKU	39.1	144.7	29	3022
1933		E. SAMAR ISLAND	12.77	124.05		9
1934		TAFJORD	62.228	7.417	64	40
1935		LOEN	61.87	6.851	74	73
1937		RABAUL	-4.271	152.203	2.5	500
1938	7.6	MAKASSAR STRAIT	-1	120	3	17
1938	6.1	E. HOKKAIDO ISLAND	43.6	144.3	0.9	1
1938	7.7	SANRIKU	37.1	141.7	1.1	1
1939	6.6	SEIKAIDO	32.3	132	0.8	1
1939	8.1	SOLOMON ISLANDS	-10.5	158.5	10.5	12
1940	7.5	W. HOKKAIDO ISLAND	44.2	139.5	3.5	10
1941	7.4	SEIKAIDO	32	132.1	1.2	2
1944	8.1	OFF SOUTHEAST COAST KII PENINSULA	34	137.1	10	1223
1945	8.3	MAKRAN COAST	24.2	62.6	15.24	300
1946	8.1	UNIMAK ISLAND, AK	53.32	-163.19	35.05	165
1946	8.1	NORTHEASTERN COAST	19.3	-68.9	5	1790

1946	7.9	NORTHEASTERN COAST	19.71	-69.51	0.6	75
1946	8.1	HONSHU: S COAST	33	135.6	6.6	1362
1948	8.3	SULU SEA	10.5	122		2
1949	7.2	E. LUZON ISLAND	18	121		16
1951	6	COSIGUINA VOLCANO	13	-87.5		1000
1952	8.1	SE. HOKKAIDO ISLAND	42.15	143.85	6.5	33
1953	6.8	FIJI ISLANDS	-18.2	178.3	15	5
1954		MICHIGAN CITY, IN (LAKE MICHIGAN)	41.7	-86.883	3	8
1955	7.1	CENTRAL CHILE	-30	-72	1	1
1956	7.8	AMORGOS ISLAND, AEGEAN ISLANDS	36.9	26	30	3
1958	7.6	COLOMBIA-ECUADOR	1.5	-79.5		4
1958	8.3	SE. ALASKA, AK	58.34	-136.52	525	2
1960	9.5	CENTRAL CHILE	-39.5	-74.5	25	1263
1960	6.8	N. PERU	-6.8	-80.7	9	66
1963		CORINTH GULF	38.4	22.1	6	3
1964	9.2	PRINCE WILLIAM SOUND, AK	61.1	-147.5	67.1	124
1964	7.5	NW. HONSHU ISLAND	38.65	139.2	5.8	26
1965	7.6	SANANA ISLAND	-2.4	126.1		71
1965	6.9	NORTH CORINTH GULF	38.4	22.4	3	1
1965		TAAL, LUZON ISLAND	14.002	120.993		200
1967	5.5	MAKASSAR STRAIT	-3.7	119.3		13
1968	7.3	E. LUZON ISLAND	16.5	122.2	0.16	1
1968	7.8	BANDA SEA	0.2	119.8	10	200
1969	6.9	MAKASSAR STRAIT	-3.1	118.9	4	600
1969		LUZON ISLAND	19.077	122.202		3
1970	7	PAPUA NEW GUINEA	-4.9	145.5	3	3
1971	7.9	BISMARCK SEA	-5.5	153.9	6	2
1975	7.2	PHILIPPINE TRENCH	12.54	125.993	4	1
1975	7.1	HAWAII	19.334	-155.024	14.3	2
1976	8.1	MORO GULF	6.262	124.023	8.5	4456
1977	8	SUNDA ISLANDS	-11.085	118.464	15	189
1979		LEMBATA ISLAND	-8.6	123.5		539
1979	7.9	IRIAN JAYA	-1.679	136.04	2	100
1979		FRENCH RIVIERA (LIGURIAN SEA)	43.7	7.25	10	6
1979	7.7	COLUMBIA: OFF SHORE, PACIFIC OCEAN	1.598	-79.358	6	600
1983	7.8	NOSHIRO, JAPAN	40.462	139.102	14.93	100
1988	7.2	JAMUNA RIVER, ARICHA, BANGLADESH	25.149	95.127		3
1988	7.6	SOLOMON ISLANDS	-10.366	160.819	0.09	1
1991	7.7	LIMON, PANDORA	9.685	-83.073	3	2

1992	7.7	NICARAGUA	11.742	-87.34	9.9	170
1992	7.8	FLORES SEA	-8.48	121.896	26.2	2500
1993	7.7	SEA OF JAPAN	42.851	139.197	54	230
1994	6.9	SOUTHERN SUMATRA	-4.967	104.302	0.1	7
1994	7.8	JAVA, INDONESIA	-10.477	112.835	13.9	250
1994	6.8	HALMAHERA	-1.258	127.98	3	1
1994		SKAGWAY, AK	59.5	-135.3	7.62	1
1994	7.1	PHILIPPINE ISLANDS	13.525	121.067	7.3	78
1995	6.9	TIMOR	-8.378	125.127	4	11
1995	8	MEXICO	19.055	-104.205	11	1
1996	7.9	SULAWESI	0.729	119.931	3.43	9
1996	8.2	IRIAN JAYA	-0.891	136.952	7.68	110
1996	7.5	N. PERU	-9.593	-79.587	5.1	12
1998	7	PAPUA NEW GUINEA	-2.961	141.926	15.03	2183
1999	7.6	KOCAELI, TURKEY	40.748	29.864	2.52	150
1999	7.5	VANUATU ISLANDS	-16.423	168.214	6.6	5
2001	8.4	S. PERU	-16.265	-73.641	7	26
2004	9	OFF W. COAST OF SUMATRA	3.295	95.982	50.9	227898
2005	8.7	INDONESIA	2.085	97.108	3	10
2006	6.7	SERAM ISLAND	-3.595	127.214	3.5	4
2006	7.7	JAVA, INDONESIA	-9.254	107.411	10	664
2007	8.1	SOLOMON ISLANDS	-8.46	157.044	10	54
2007	6.2	S. CHILE	-45.285	-72.606	6	3
2009	8.1	SAMOA ISLANDS	-15.559	-172.093	16.3	180

http://www.ngdc.noaa.gov/

Appendix B: Calculated Data

Scenario I

City	Population Density	Area of City	Side Length City	Area of City Inundated
San Francisco, CA	1293.10	9128.2	95.542	191.08
Hilo, HI	269.29	13175	114.78	229.56
New Orleans, LA	534.35	9726.6	98.624	197.25
Charleston, SC	327.05	3517.0	59.304	118.61
New York City, NY	6594.60	17405.0	131.93	263.86
Boston, MA	2537.90	11683.0	108.09	216.18
Juneau, AK	3.64	8430.4	91.817	183.63

City	Population Displaced	Households Damaged	% of Population Displaced	Average Home Price	Home Damage Cost
San Francisco, CA	2.5E+05	7.3E+03	3.2E+01	656700	4.8E+09
Hilo, HI	6.2E+04	2.8E+02	1.5E+02	260634	7.3E+07
New Orleans, LA	1.1E+05	4.4E+03	2.2E+01	140300	6.1E+08
Charleston, SC	3.9E+04	1.5E+03	4.0E+01	180400	2.7E+08
New York City, NY	1.7E+06	4.9E+04	2.2E+01	403600	2.0E+10
Boston, MA	5.5E+05	4.7E+03	9.3E+01	387800	1.8E+09
Juneau, AK	6.7E+02	4.2E+03	2.2E+00	324000	1.4E+09

Scenario II

City	Area	Households/Area	Energy	Length Inundated	Area Inundated
San Francisco, CA	9128.2	37.962	1.12E+19	678.30	6.4806E+04
Hilo, HI	13175	1.2164	1.12E+19	327.45	3.7585E+04
New Orleans, LA	9726.6	22.114	1.12E+19	1388.0	1.3689E+05
Charleston, SC	3517.0	12.671	1.12E+19	525.71	3.1177E+04
New York City, NY	17405	183.908	1.12E+19	530.37	6.9970E+04
Boston, MA	11683	21.564	1.12E+19	578.53	6.2532E+04
Juneau, AK	8430.4	1.4569	1.12E+19	3063.5	2.8128E+05

City	Estimated People Displaced	% of Pop	Households Affected	Average Home Price	Household Destruction Cost
San Francisco, CA	5.8E+04	7.4	2.5E+06	656700	1.6E+12
Hilo, HI	1.0E+03	2.5	4.6E+04	260634	1.2E+10
New Orleans, LA	6.9E+04	14	3.0E+06	140300	4.2E+11
Charleston, SC	1.4E+04	15	4.0E+05	180400	7.1E+10
New York City, NY	2.4E+05	3.0	1.3E+07	403600	5.2E+12
Boston, MA	2.9E+04	5.0	1.3E+06	387800	5.2E+11
Juneau, AK	1.1E+04	36	4.1E+05	324000	1.3E+11

Scenario III

City	Area	Households/Area	Energy	Length Inundated	Area Inundated
San Francisco, CA	9128.2	37.962	1.5E+16	0.89417	85.431
Hilo, HI	13175	1.2164	1.5E+16	0.43166	49.547
New Orleans, LA	9726.6	22.114	1.5E+16	1.8297	180.45
Charleston, SC	3517.0	12.671	1.5E+16	0.69302	41.099
New York City, NY	17405	183.91	1.5E+16	0.69916	92.238
Boston, MA	11683	21.564	1.5E+16	0.76265	82.434
Juneau, AK	8430.4	1.4569	1.5E+16	4.0385	370.80

City	Estimated People Displaced	% of Pop	Households Affected	Average Home Price	Household Destruction Cost
San Francisco, CA	76	0.0098	3.2E+03	656700	2.1E+09
Hilo, HI	1.3	0.0033	6.0E+01	260634	1.6E+07
New Orleans, LA	91	0.019	4.0E+03	140300	5.6E+08
Charleston, SC	19	0.020	5.2E+02	180400	9.4E+07
New York City, NY	3.2E+02	0.0040	1.7E+04	403600	6.8E+09
Boston, MA	38	0.0065	1.8E+03	387800	6.9E+08
Juneau, AK	15	0.048	5.4E+02	324000	1.8E+08

Scenario IV

City	Area	Households/Area	Energy	Length Inundated	Area Inundated
San Francisco, CA	9128.2	37.962	4.0E+12	0.00024067	0.022994
Hilo, HI	13175	1.2164	4.0E+12	0.00011618	0.013336
New Orleans, LA	9726.6	22.114	4.0E+12	0.00049247	0.048570
Charleston, SC	3517	12.671	4.0E+12	0.00018653	0.011062
New York City, NY	17405	183.91	4.0E+12	0.00018818	0.024826
Boston, MA	11683	21.564	4.0E+12	0.00020527	0.022187
Juneau, AK	8430.4	1.4569	4.0E+12	0.00108698	0.099803

City	Estimated People Displaced	% of Pop	Households Affected	Average Home Price	Household Destruction Cost
San Francisco, CA	0.020	2.6E-06	0.87	656700	5.7E+05
Hilo, HI	0.000	8.8E-07	0.016	260634	4.2E+03
New Orleans, LA	0.025	5.1E-06	1.1	140300	1.5E+05
Charleston, SC	0.005	5.3E-06	0.14	180400	2.5E+04
New York City, NY	0.087	1.1E-06	4.6	403600	1.8E+06
Boston, MA	0.010	1.8E-06	0.48	387800	1.9E+05
Juneau, AK	0.004	1.3E-05	0.15	324000	4.7E+04

Scenario V

City	Estimated People Displaced	Area	Population	Distance Traveled	Magnitude
San Francisco, CA	1	9128.2	7.7673E+05	2897.3	6.3260
Hilo, HI	1	13175	4.0759E+04	6001.6	7.4965
New Orleans, LA	1	9726.6	4.8467E+05	1415.9	6.2737
Charleston, SC	1	3517	9.6650E+04	3738.2	6.7271
New York City, NY	1	17405	8.0083E+06	3705.4	5.9086
Boston, MA	1	11683	5.8914E+05	3396.9	6.5236
Juneau, AK	1	8430.42	3.0711E+04	641.5	6.8018

ANOVA Test

SUMMARY

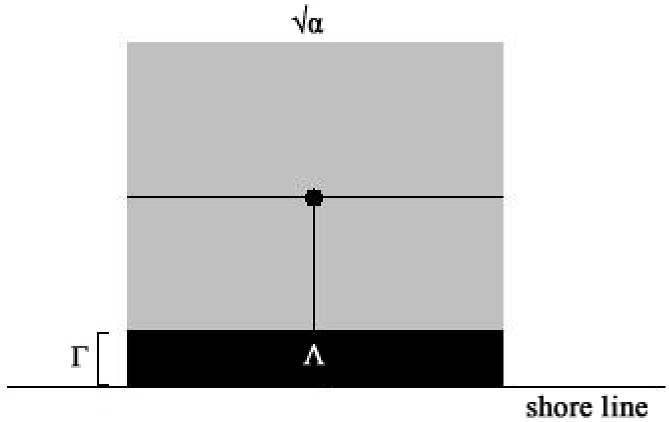
Groups	Count	Sum	Average	Variance
San Francisco, CA	4	304883.365	76220.84125	13715394641
Hilo, HI	4	62833.85249	15708.46312	945218107.6
New Orleans, LA	4	174652.9289	43663.23223	2755508888
Charleston, SC	4	53256.8961	13314.22402	334792123.9
New York City, NY	4	1984374.976	496093.7441	7.00934E+11
Boston, MA	4	577844.9191	144461.2298	72790920604
Juneau, AK	4	11843.7247	2960.931175	29975308.03

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	7.41688E+11	6	1.23615E+11	1.093237399	0.398590677	2.572711641
Within Groups	2.37452E+12	21	1.13072E+11			
Total	3.1162E+12	27				

Appendix C: Models and Figures

Figure I: Area of Displaced City



Variable	Variable Meaning
α	area of city (km^2)
$\sqrt{\alpha}$	length of one side of a square city's area (km)
Γ	length of city inundated (km)
Λ	area of city inundated (km^2)
●	center of city

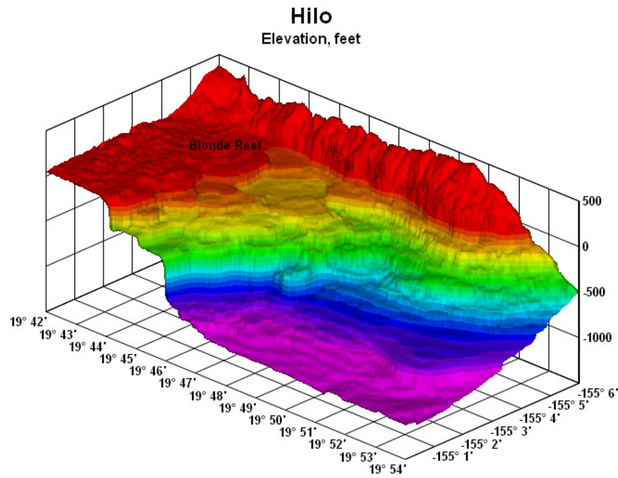
Figure I. Assuming that the the city's surrounding is a square and that the city's limit ends at the shoreline as shown, the area of the city inundated by the tsunami (Λ) can be calculated by the rectangular area displaced as a function of how far the tsunami travels inland (Γ) and the length of one side city ($\sqrt{\alpha}$). Using Γ, we can find Λ using the equation $\Lambda = \Gamma\sqrt{\alpha}$.

Figure II: Complexity of a Tsunami

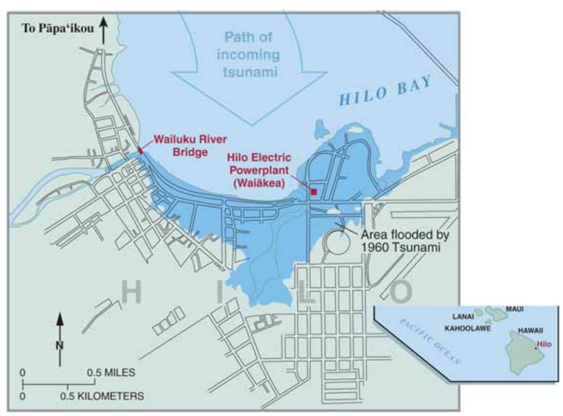
(NASA, 2005)

Figure II. Wind generated waves (bottom) differ from tsunami waves (top) in that tsunami waves are not sinusoidal as they build up at the shoal. The top image demonstrated the 2004 Sumatra-Andaman tsunami receding back into the ocean. Therefore, tsunami waves do not have directly predictable amplitude, frequency, wavelength, or period as they reach the shore, leaving energy, momentum, and distance traveled as predictable values that correlate to the earthquake's magnitude. The tsunami wave does act like a sinusoidal wave in the deep sea however. The AWES model calculated the area of a city inundated based on the energy released by the earthquake (E) that was left over after tsunami beaming. Tsunami beaming refers to the higher wave amplitudes in a direction perpendicular to fault orientation during deep ocean propagation. Thus, the farther the wave travels, the more the energy will diffuse outward. Complexity of the earthquake source and the effects of refraction and scattering during propagation alter tsunami beaming pattern and therefore are simplified such that the energy of the tsunami (E) would be proportional to the distance traveled between the city and the earthquake's epicenter (Δ). However it should be noted that the energy of the tsunami does not significantly reduce due to drag or friction; this is because the sinusoidal wave in the deep ocean has a high velocity, large period, and long wavelength, yet at the same time, it has a small amplitude.

Figure III: Complexity of Topography of City



(DPLOT, 2009)



(Atwater, 1999)

Figure III. The AWES model was used to calculate the area of a city inundated, based on the energy released by the earthquake that is left over after tsunami beaming. Shelf topography, harbor geometry, and fault slip topography were not taken into account. This is because each city has a different complicated shoreline with various islands and protections against wave fronts. As shown, the complexity of Hilo, Hawaii's topography (top) would be inadequate to coordinate with th the amount of the city affected. Other features of Hilo (bottom) show that incoming waterways, wall, and other infrastructures cannot be taken into account because they are too complicated and have little mass in absorbing the kinetic energy or momentum of the wave.