MODELING POTENTIAL IMPACTS OF TSUNAMIS ON HILO, HAWAII: COMPARISON OF THE JOINT RESEARCH CENTRE'S SCHEMA AND FEMA'S HAZUS INUNDATION SCENARIOS

by

Matthew Kline

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List of Abbreviations

AEBM	Advanced Engineering Building Module
BLS	Bureau of Labor Statistics
DART	Deep-ocean Assessment and Reporting of Tsunami
DEM	Digital Elevation Model
DHS	Department of Homeland Security
FEMA	Federal Emergency Management Agency
FIMA	Federal Insurance and Mitigation Administration
GBS	General Building Stock
GIS	Geographic Information System
HAZUS	Hazards United States
IPSC	Institute for the Protection and Security of the Citizen
JISAO	Joint Institute for the Study of the Atmosphere and Ocean
JRC	Joint Research Centre
MOST	Method of Splitting Tsunami Model
NCTR	NOAA Center for Tsunami Research
NED	National Elevation Dataset
NOAA	National Oceanic and Atmospheric Administration
OAR	Office of Oceanic and Atmospheric Research
SCHEMA	Scenarios for Hazard-induced Emergencies Management
SWEL	Stillwater Flood Elevation
USACE	The United States Army Corps of Engineers
USGS	United States Geological Survey
USC	University of Southern California

Abstract

The city of Hilo, Hawaii is more vulnerable to tsunamis than any other location in the United States. Due to the unique bathymetry, topography, and location relative to the Cascadia Subduction Zone, in the future, Hilo could be struck by a large tsunami similar to the historic 1946 and 1960 events. The Cascadia Subduction Zone can produce a 9.5 M earthquake with the potential of generating a tsunami with maximum wave heights of over 29 feet. Before devastating economic loss occurs, it is imperative that such potential flood inundation and consequent dollar exposure are understood. This study compares the Joint Research Centre's (JRC) Scenarios for Hazard-induced Emergencies Management (SCHEMA) flood model implemented using ArcGIS with the Federal Emergency Management Agency's (FEMA) Hazards-United States (HAZUS) flood model to simulate the potential impact of a large-scale tsunami on the city of Hilo. The SCHEMA and HAZUS models, the National Oceanic and Atmospheric Administration (NOAA), and the State of Hawaii provided the spatial data required to build the financial and structural inventory database for these analyses. Field measurements recorded during the 1946 and 1960 tsunamis and corresponding historical inundation maps provided input into the models. The results of this research suggest that although the SCHEMA model has the benefit of being more customizable, the HAZUS inundation scenario can be implemented with fewer input data and produce results comparable to historical damages. Future work will involve refining the inundation scenarios to include more detailed input data such as historical terrain (digital elevation models), field-verified updates to the structural inventory database, and an increased number of predicted events based on wave height.

Chapter 1 Introduction

This research evaluated the economic impact that a large-scale tsunami inundation event caused by an earthquake from the Pacific Ocean would have on the town of Hilo, Hawaii. Hilo has been hit by several large tsunamis in the past 75 years, and the local government and has been taking steps to mitigate the impact of future events (Pararas-Carayannis 1977). These tsunamis ranged in height from 26 to 49 feet and were associated with the 1946 and 1960 tsunami events respectively (Eaton, Richter, and Ault 1961). The devastating effects of one of these tsunamis are clearly illustrated in Figures 1 and 2.

Figure 1. 1946 Hilo Tsunami (Source: University of Idaho). Hilo residents flee from the 1946 tsunami in Hilo.

Figure 2. Hilo after 1946 Tsunami (Source: NPR). This is the downtown area of Hilo after the 1946 tsunami impact.

In the context of this study, a tsunami is defined as a giant wave caused by earthquakes or volcanic eruptions under the sea (National Ocean Service 2015). This project utilized data obtained from historical tsunami events in 1946 and 1960 to estimate tsunami height as input in modeling the potential economic damage to the current structural inventory of the city of Hilo. The economic impact of a large-scale tsunami on Hilo was estimated by comparing two commonly accepted methodologies to accomplish this goal. First, the European Commission's Joint Research Centre's (JRC) Scenarios for Hazard-induced Emergencies Management (SCHEMA) (Tinti et al. 2011) flood model was implemented in ArcGIS as part of this study. Second, the Federal Emergency Management Agency's (FEMA) Hazards-United States

(HAZUS) flood model was also used to simulate the potential impacts (FEMA 2015). Third, the results obtained utilizing these two methodologies were then compared.

The background research for this project focused on the following topics: the bathymetry of Hilo Bay, the impact that the bathymetry and topography of Hilo Bay has on the size of tsunamis as they enter the bay, the size and origin of Hilo's historical tsunamis, the town of Hilo's mitigation strategies for tsunamis, and the SCHEMA and HAZUS Flood Models to help understand the potential physical damage to the built environment that may be destroyed by a large-scale tsunami. The town of Hilo has learned first-hand what tsunamis can do and has taken steps to prevent future financial loss to the structural inventory and loss of life (Pararas-Carayannis 1977). Researching land use changes over the last 75 years and newly created mitigation measures, such as stricter building codes, helped determine what Hilo has been doing to mitigate tsunami impacts (AIA 2009). Hilo Bay is particularly vulnerable to tsunamis because it reverberates tsunami waves leading to much larger events than any other location in Hawaii (Palmer, Mulvihill, and Funasaki 1965). The U.S. Army Corps of Engineers (USACE) has completed studies that examine the impact the bathymetry and topography of the bay have on approaching tsunamis. In 1946, an Alaskan tsunami impacted Hilo with wave heights as high three story buildings (Davidson 2004). Then again in 1960, a Chilean tsunami hit Hawaii with an average height of 6 to 16 feet, but Hilo Bay was impacted by a tsunami height of approximately 33 to 49 feet (Pararas-Carayannis 1977). At the time, the local bathymetry was blamed for the increased localized tsunami heights in Hilo, as the submarine ridge formations outside of the bay refract tsunami waves into the bay (Palmer, Mulvihill, and Funasaki 1965). The data from these previous tsunamis were utilized to see if either SCHEMA or HAZUS can duplicate the historical published cost of damages to the built environment. Thus, the goal of this study was to address the following research questions:

1) Can the SCHEMA and HAZUS models be used to estimate damage to the built environment of historical tsunami events in the city of Hilo, Hawaii?
2) Are the JRC SCHEMA methodology results in calculating potential tsunami inundation damage to the built environment similar or different compared to results obtained using the HAZUS coastal flood model for a given event?

It was anticipated that the damages predicted using the SCHEMA Flood Model methodology will be similar to or fall within a maximum and minimum range of damages predicted using HAZUS Flood Model program. This assumption was based on a preliminary review of the models and input data required.

To qualitatively address these research questions, historical tsunami events were modeled to determine the economic loss and dollar exposure that could occur today under similar circumstances. In the context of this thesis, dollar exposure is defined as the total economic loss in US dollars from a flooding model (FEMA 2015). By comparing the results of these models to real-world economic losses caused by historical tsunami events, future improvements to these models can be suggested after learning some of the strengths and weaknesses of each model.

1.1 Motivation

This research is important to not only evaluate the potential damage to the structural inventory that the town of Hilo may experience due to a large tsunami event but also to test two commonly accepted methodologies that can be used to evaluate economic impacts for coastal communities anywhere that the required spatial information is available. Hilo is an excellent study area for this project due to its unique location and terrain, as well as the availability of historical references that have been carefully cataloged that allow for a comparison, or validation, of the two methodologies being tested with recorded damage data of past tsunami events.

Due to Hawaii's location in the middle of the Pacific Ocean, all of the islands are extremely vulnerable to tsunamis (O'Sullivan 2015). Hilo, on the Big Island of Hawaii, is nicknamed "The Tsunami Capital of the World" due to the shape of the bay that, as mentioned previously, tends to magnify the height of tsunamis making the town more susceptible to damage. In Hawaii, tsunamis have killed more people in the last hundred years than earthquakes, volcanoes, hurricanes, brushfires, and floods combined (Natural Hazards Big Island 2015). This research is also intended to encourage the study of historical tsunami events to mitigate future tsunami impacts. Tsunamis, like inland flooding, tend to repeat themselves, but at times may not occur for hundreds of years. Pre-disaster mitigation, including urban planning for tsunamis, are the best tools for coastal communities to protect themselves from future economic damage and loss of life.

The most common cause of tsunamis in the world is earthquakes generated in a subduction zone, where the oceanic plate is being forced into the mantle (King 2016). The most active faults in the world are commonly found in the Ring of Fire (Figure 3). The Ring of Fire is the name given to the Pacific Rim due to the number of major earthquake faults surrounding the region. The coastlines in this region are the most active seismic and volcanic areas on earth. The faults have enormous potential to generate underwater earthquakes and potentially destructive tsunamis (Xie, Nistor, and Murty 2011). Figure 3 displays the major volcanoes which line this important tectonic subduction zone in the Pacific Ocean. Hawaii is centrally located in this region, which makes it vulnerable to potential earthquake tsunamis from anywhere within the Ring of Fire (Palmer, Mulvihill, and Funasaki 1965).

Figure 3. Ring of Fire (Source: World Atlas 2015). The Hawaiian Islands are located just below the label "Ring of Fire" in the middle of this map.

The Cascadia subduction zone, located off the coast of Oregon, is estimated to be capable of producing an earthquake of up to 9.5 M, which would be similar to the Chilean earthquake mentioned previously (Satake et al. 1996, Atwater, Yamagushi, and Satoko 2005). The Cascadia Subduction Zone has not experienced a major earthquake in the last few centuries, so researchers suggest that another major event is due sometime in the next 300 years (Peters, Jaffe, and Gelfenbaum 2007). Some scientists even predict that an event may strike within the next fifty years (Mazzotti and Adams 2004). Tsunami waves measuring 3 to 16 feet in height hit Japan as a result of the 1700 AD Cascadia earthquake (Satake, Wang, and Atwater 2003). The coast of Hawaii is several thousand miles closer to the Cascadia subduction zone than Japan, so the impact of the same or similar sized tsunami would potentially be greater. Thus, a Cascadia earthquake is likely the next big event to trigger a tsunami that would hit the town of Hilo and is a reason to focus on historical measurements of large tsunami events in order to forecast the economic impact on the town.

Detecting and tracking the size of tsunamis is important in order to be able to alert coastal communities of the incoming threat in time for evacuation. The most common way to detect tsunamis is by using ocean buoys to measure the sea level height, but these do not always accurately forecast the potential approaching wave height to individual communities in a timely manner. Since tsunami wave heights can be altered by nearshore bathymetry and coastal topography, the buoy measurements will probably not provide a direct measurement of tsunami energy for (Bernard 2005).

Mathematical formulas are a common way to forecast or explain tsunami wave heights, but there are currently no globally significant formulas that can translate to other areas or events. A mathematical formula that estimates tsunami size that could hit Japan related to a given earthquake occurrence may not be appropriate for predicting a tsunami occurrence in Chile. It has been common for modelers to use ad-hoc wave height amplification factors in their formulas for run-up predictions when compared to actual observations (Synolakis et al. 2008). In the context of this thesis, the run-up is defined as the maximum wave height of a tsunami.

Natural disasters are unpredictable and constantly surprise and change the paradigm that scientists believe to be possible. In 1995, the National Oceanic and Atmospheric Administration (NOAA) deployed six buoys as part of the Deep-Ocean Assessment and Reporting of Tsunamis

(DART) system (Greenslade and Titov 2008). NOAA realized immediately after the 2004 Indian Ocean tsunami that six buoys gave insufficient coverage to provide adequate tsunami warnings for all regions in the Pacific (Edward 2008). The DART II buoys were then created, and 31 additional buoys were installed to create a total of 37 Pacific Ocean buoys. The new buoys include sensors that can detect a tsunami half an inch high in water four miles deep. These upgraded buoys were developed to improve the timing and detection of tsunamis.

As evidenced, to evaluate if future disasters have been adequately mitigated and prepared for, city planners and governments must learn from the past. Hilo has a well-documented history of tsunami activity, and it has been determined by researchers that these events will continue to happen into the future. The city of Hilo has taken steps in regards to building locations and types of new construction allowed proximal to the coastline to limit the impacts of future tsunamis, but no detailed study exists to determine if enough has been done (Bernard 2005). The goal of this research is to determine if Hilo has taken all of the necessary steps to mitigate the economic impact of tsunamis and the building related dollar exposure associated with a devastating tsunami event. This research is also aimed at determining which inundation methodology is most appropriate for accurately estimating the physical damage to the built environment incurred should a significant tsunami inundation event occur in the future.

1.2 Background

The previous section discussed the dangers that Hilo could face from future tsunamis and the likelihood that tsunamis may impact Hilo. This section contains background information related to the studies of local topography and bathymetry, historical tsunamis, and NOAA's model of tsunamis in Hilo.

1.2.1. Local Topography and Bathymetry

Studying local topography and bathymetry explains why Hilo has often been impacted by tsunamis with a higher average wave height than any other location in Hawaii. USACE conducted a study in 1965 to ascertain why the tsunamis that had struck Hilo in 1946 and 1960 were more destructive due to higher wave heights than those affecting other regions of Hawaii. It was well known that Hilo's location on Hawaii is shaped like a funnel, causing incoming tsunami waves to pile on top of each other to intensify the impact on the city regarding wave run-up height. However, it was not previously explained why parts of Hilo experienced waves ten to fifteen feet higher than wave height measured out in the bay. Figure 4 displays the reflecting of waves off of the cliffs north of Hilo (Palmer, Mulvihill, and Funasaki 1965).

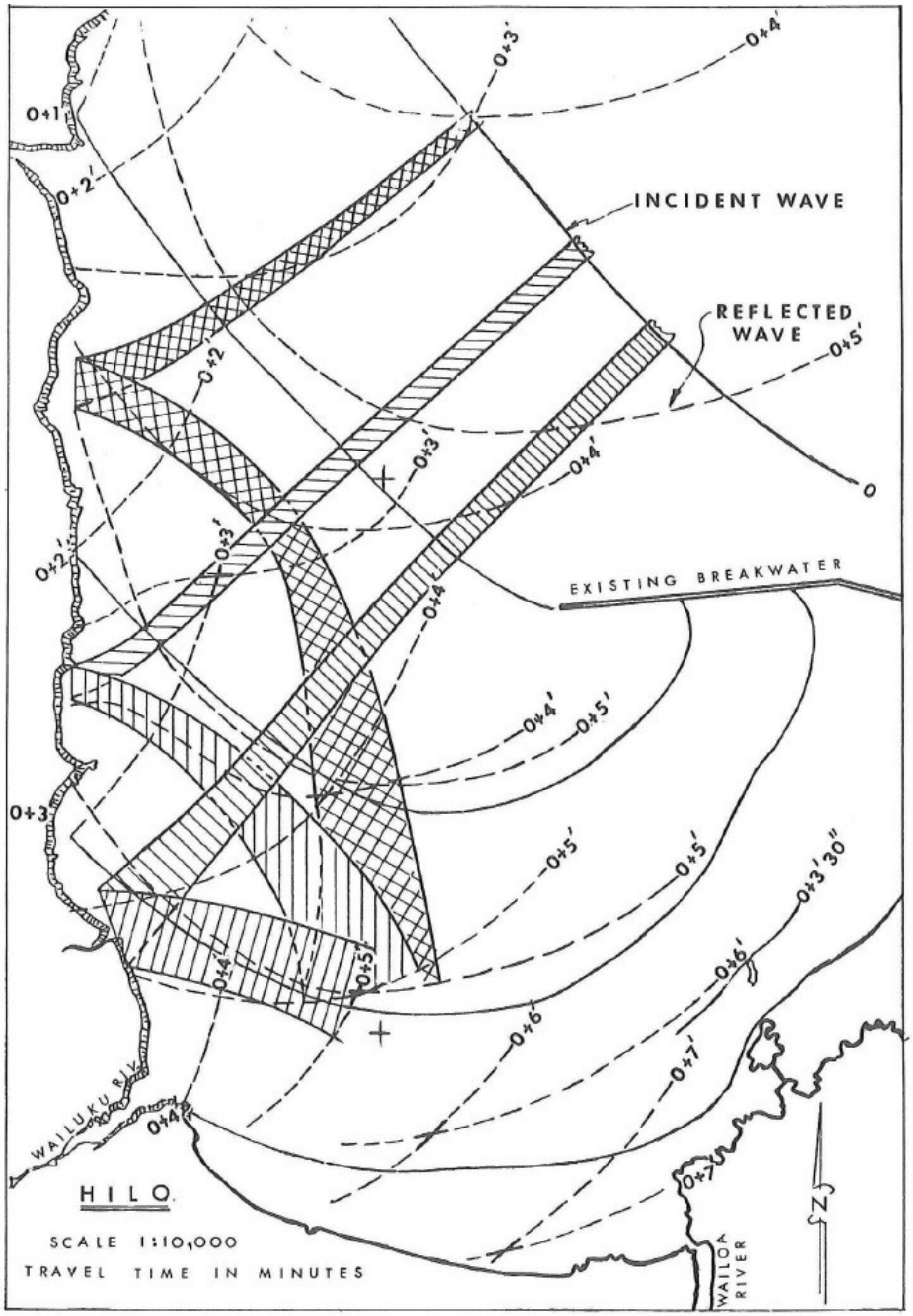

Figure 4. Reflecting of Waves in Hilo Bay (Source: Palmer, Mulvihill, Funasaki 1965).

After the 1960 tsunami, which caused wave heights of over 30 feet, the USACE built an analog, physical model of Hilo Bay composed of concrete, approximately 63 feet by 96 feet (Palmer, Mulvihill, and Funasaki 1965). The test was designed to investigate the role that topography and bathymetry have on tsunami heights in Hilo Bay. The model used a pneumatic type wave generator that created a solitary wave in order to reproduce a tsunami in Hilo harbor. The test was aimed at determining the high water marks, limits of inundation, and the time history of the wave locations, or marigrams.

After completion of the physical inundation test, the USACE and other participating scientists found that the physical features of the surrounding topography, specifically the steep cliffs that were found north of Hilo, reflected waves back towards Hilo harbor, which then impacted the original incident wave and combined to create a larger, more dangerous wave. Figure 5 illustrates the steep elevation found north of town and the comparatively lower elevation Hilo harbor. In the USACE test, the wave solitary wave generated was amplified when in bounced of the steep cliffs resulting in combined wave heights 55 to 150 percent higher than the original test wave funneled into the harbor model. Additionally, two other factors found to increase wave heights included the triangular configuration of the bay and submarine bathymetry which reflects waves towards the bay.

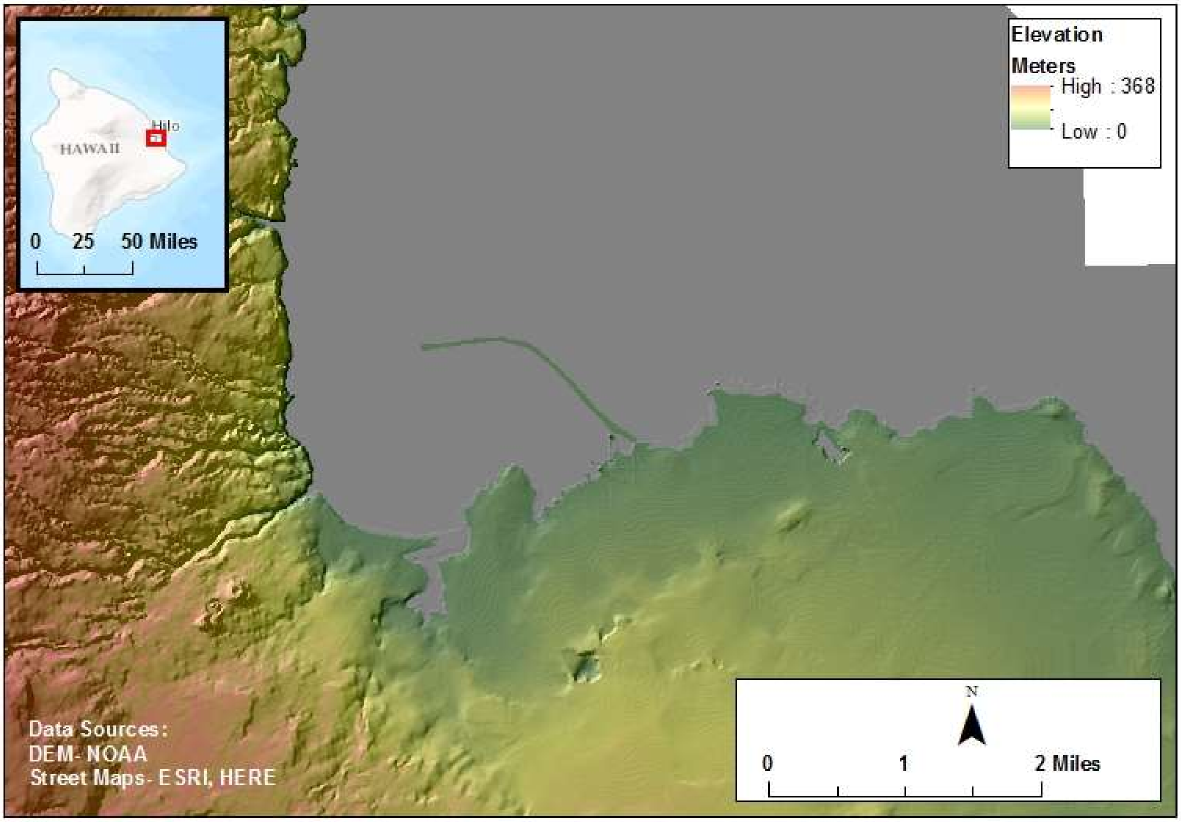

Figure 5. Hilo Topography

1.2.2. Historical Tsunamis

As previously stated, the 1960 tsunami that originated in Chile, and the 1946 tsunami that originated in Alaska, were the two most devastating tsunamis to hit Hilo in the last one hundred years. Tsunamis that originate from earthquakes are commonly seen in Hilo, but the heights of these two tsunamis were more substantial than those that have previously occurred.

An Alaskan earthquake would not be expected to cause a large tsunami that would strike Hilo, but the 7.5 M Alaska Earthquake that resulted in the 1946 tsunami was said to have reached over 45 feet on landfall in Hilo Harbor (Palmer, Mulvihill, Funasaki 1965). The third of seven waves that comprised the tsunami event was the highest and extended half a mile inland to inundate an area of 0.4 square miles

The financial impact on Hilo was $26 million in damage, while the personal loss that day was 173. This historical dollar exposure is approximately equivalent to $318 million today, based on the Bureau of Labor Statistics (BLS) inflation calculator (BLS 2016). Most of the downtown area was demolished by the tsunami with 488 buildings destroyed and 936 additional buildings damaged. The waterfront was washed out, and the breakwater was badly damaged, and the main pier was completed destroyed. This tsunami prompted the establishment of NOAA's first tsunami warning center in Ewa Beach (Pararas-Carayannis 1977).

In the context of this study, a breakwater is defined as a structure built offshore that helps to reduce the intensity of waves and prevent coastal erosion (Miller 2011). Hilo had a breakwater constructed in 1929 that was believed to have helped to mitigate the 1946 tsunami's effects by absorbing some of its energy. It was partly destroyed in 1946, then rebuilt. The breakwater was tested a second time in the 1960 event and again survived with only minor repairs required.

In the context of this study, a seawall is defined as an onshore structure that is designed to prevent tides, waves, and extraordinary oceanic events from impacting coastal communities (Miller 2011). After the 1960 tsunami, the USACE suggested building a 22-foot high seawall that would run from the Wailuku River, just west of downtown Hilo, to the Waiakea Peninsula. This seawall was never built. It is assumed that it would have been overtopped by a tsunami of similar in height to the 1946 or 1960 events.

Instead of building a seawall, an elevated highway was constructed along Hilo Bay which protects the downtown area from storm surges and moderate tsunamis (Miller 2011). This construction was chosen over a large seawall due to residents not wanting their ocean views obstructed and engineers being unable to guarantee that a seawall would protect the city in the event of another large tsunami.

Southern Chile was impacted on May 22, 1960, by a 9.5 M earthquake that created substantial damage in Chile and resulted in a tsunami that even impacted distant Pacific coastal areas, like Hilo. The tsunami crested at nearly 35 feet on landfall in some places (Britannica Academic 2015). Outside of Hilo Bay, wave heights on the island of Hawaii were lower, with heights ranging between 3 and 17 feet. Figure 6 displays the difference in tsunami heights throughout the island of Hawaii (Eaton, Richter, and Ault 1961). The tsunami generated $23 million in damage, equivalent to $281 million today. The personal loss for the town was 61 lives lost. This tsunami devastated structures in downtown Hilo, where a total of 537 buildings were destroyed (Pararas-Carayannis 1977). Nearly 0.94 square miles were inundated, and half of this impacted area saw near complete destruction of all man-made structures (Eaton, Richter, and Ault 1961).

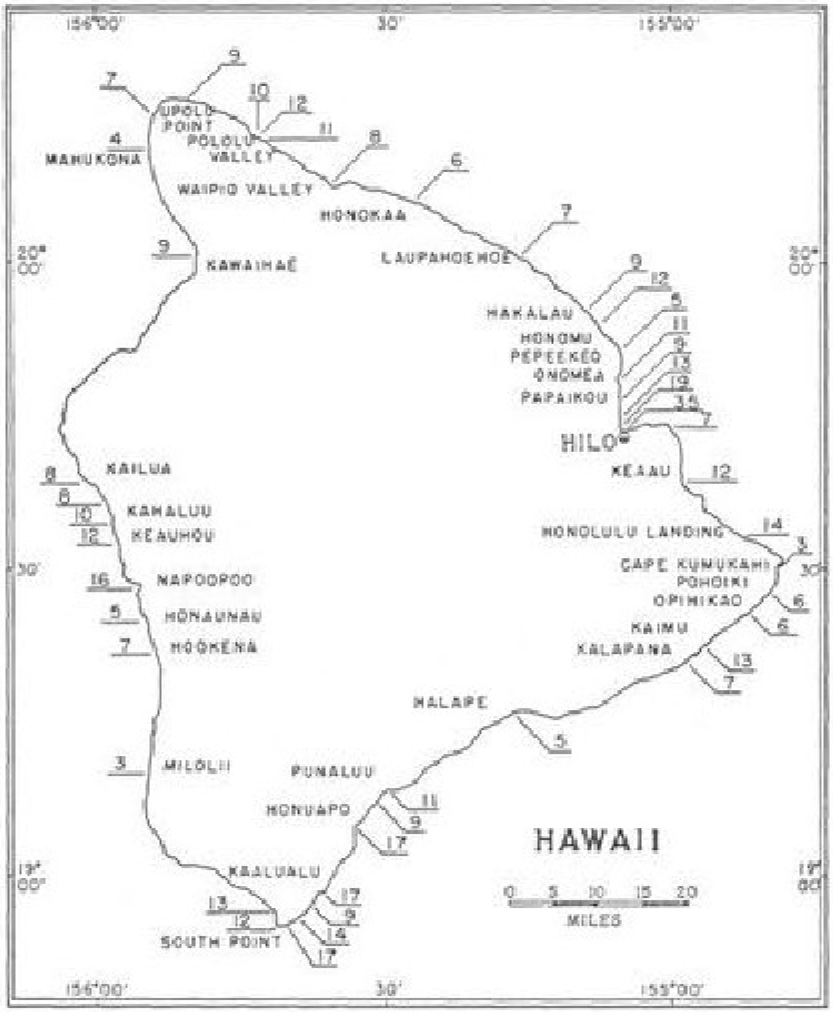

Figure 6. Tsunami Heights in 1960. (Source: Eaton, Richter, and Ault 1961). Tsunami heights are in feet.

These two tsunamis, 1946 and 1960, have been thoroughly studied and examined by engineers and scientists (Shepherd, Macdonald, and Cox 1949; USGS Hawaiian Volcano Observatory 2015; Davidson 2004). Thus, these observations were compiled to compare with the financial impact that similar events might have on Hilo today. There were several other tsunamis over the last one hundred years that impacted Hilo, but not to the extent of the 1946 and 1960 tsunamis. For example, in 1952, a strong earthquake originated near the southeastern coast of Kamchatka with a moment magnitude of 9.0. Despite the high moment magnitude, the waves that entered Hilo Bay only reached approximately 12 feet (Macdonald and Wentworth 1954). There was only minor damage reported to the main pier with some cargo floating in the bay.

During the early morning hours of March 9, 1957, a 9.3 M earthquake struck the Aleutian trench in the Aleutian Islands (USC Tsunami Research Group 2002). The 1957 earthquake did not generate massive wave heights in Hilo like the 1946 earthquake from Alaska. The 1957 event was several times stronger than the 1946 earthquake, which proves that earthquake magnitude does not always correspond to higher tsunami wave heights, as there are many other factors that can influence wave energy and height. These factors include distance from the epicenter and direction of earthquake wave propagation resulting from earthquake fault orientation and hypocenter depth and location (point within the earth where the rupture starts). The highest tsunami wave heights measured in Hilo Bay were approximately 10 feet, which resulted in only several $100 thousand worth of damage.

Another example is the 1964 Good Friday earthquake that occurred in Alaska, a 9.2 M earthquake that struck southeast of Anchorage (USC Tsunami Research Group 2011). Despite the large earthquake magnitude, due to the orientation of the generating fault, the resulting tsunami wave heights were below 13 feet and caused minor damage.

Locally generated tsunamis are rare in Hawaii, but in 1975, a 7.2 M earthquake originating just south of the Kilauea volcano, struck the Big Island of Hawaii. This earthquake caused a tsunami that struck Hawaii within minutes, and approximately 20 minutes later for Hilo. The measured waves in Hilo Bay were around 8 feet and caused damage to boats and several docks. The most dangerous aspect of this tsunami was the reduced warning time due to the earthquake occurring nearby. Typically lives can be saved with just a few hours of warning and subsequent evacuations, but this relatively mild tsunami killed two people on the Big Island due to brief advance warning (USGS Hawaiian Volcano Observatory 1998).

In 2011, Japan was struck by a 9.0 M earthquake near Tohoku (Cheung, Bai, and Yamazaki 2013). Many photographs and videos have shown the devastation caused by tsunamis throughout Japan, and after this particular earthquake, the waves that entered Hilo Bay measured approximately 6.9 feet near the harbor, yet did not create any noticeable damage in Hilo.

1.2.3. NOAA Tsunami Forecast

The National Oceanic and Atmospheric Administration (NOAA) produces tsunami forecast reports from their NOAA Center for Tsunami Research (NCTR) for areas of high risk within the United States. Hilo's history of tsunami inundation, population density, transportation infrastructure, and year-round tourism makes it crucial to develop a forecasting report for tsunami inundation. A tsunami forecast report for Hilo was generated in 2010 in cooperation with the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) and the Office of Oceanic and Atmospheric Research (OAR) (Tang, Titov, and Chamberlin 2010).

The methodology for these tsunami forecast reports involves compiling deep-ocean tsunami measurements from the Deep-ocean Assessment and Report of Tsunami (DART) buoy system combined with the Method of Splitting Tsunami (MOST) prediction model. This forecast is a two-step process which starts with collecting pre-computed tsunami measurements at DART buoy locations combined with coastal predictions by running the high-resolution MOST model. It was found that tsunami wave amplitudes increase dramatically due to shoaling in near-shore areas shallower than 65 feet. Thus the need for accurate near-shore modeling emphasizes the importance of high-resolution flood models (Tang, Titov, and Chamberlin 2010).

The 2010 NOAA tsunami forecast model runs many different scenarios to determine the areas most at risk depending on the tsunami's origin and magnitude. Maximum error from the model was determined to be within 35 percent when the observations are greater than 1.6 feet. A total of 1435 scenarios were simulated based on earthquake magnitudes of 7.5, 8.2, 8.7, and 9.3 M. The results indicated a nonlinear relationship between offshore and nearshore wave amplitudes. This means that there is not always a clear correlation between an earthquake's magnitude and buoy wave measurements. Buoy measurements varied in relation to the shoreline measurements, and the seismic magnitude cannot be used to accurately predict maximum wave amplitudes. This result proved that a high magnitude earthquake does not always create destructive tsunamis that travel across an ocean. For example, as previously stated, the 9.0 M Tohoku earthquake in Japan caused only localized damage and mild inundation across the state of Hawaii. This was a big earthquake but as mentioned above, a big earthquake magnitude does not always create a large tsunami (Cheung, Bai, and Yamazaki 2013). Results from this model determined that local bathymetry and topography play an important role in the formation of localized tsunami waves within Hilo Bay (Tang, Titov, and Chamberlin 2010).

Verification of this 2010 NOAA tsunami forecast model was completed by comparing the forecasting model with 16 historical tsunamis. The historical tsunamis' run-up boundaries were digitized while the most recent ones consisted of digital tide gauge data. The forecasting model was found to produce an error of only ±1.74 feet in the most recent 2010 tsunami generated by an 8.8. M earthquake in Chile. This was also the highest error found in any of the comparisons.

Chapter 1 has provided a detailed description of the study area, background information on tsunamis, and why tsunamis are an important aspect of Hilo, Hawaii. The remainder of this thesis is divided into four chapters. Chapter 2 describes related works, relevant Geographic Information System (GIS) models, and a tsunami study in great detail. Chapter 3 details the data required for each model, the SCHEMA methodology developed as part of this study, and the HAZUS methodology also performed as part of this thesis. Both the SCHEMA and HAZUS damage matrixes are discussed in detail to provide oversight on how the dollar exposure is measured. Chapter 4 reports the findings for each model scenario and a discussion about the other model outputs. The accuracy of each model is described in relation to the historical tsunami events. Chapter 5 points out the positives and negatives with each model, as well as the answer to the two research questions. The potential future work on this research is also discussed.

Chapter 2 Related Works

To determine the most effective spatial modeling method using Esri ArcGIS, a review of three studies was conducted. The first study review focused on an emergency management projects dealing with tsunamis and the potential damage to buildings (Tinti et al. 2011). This project methodology indicated that building damage can be modeled within a spatial computing program when elevation values are available for the bathymetry, land surface, buildings and wave inundation depths. The second relevant study described a theoretical tsunami event hitting Seaside, Oregon and the damage predicted by such an event. That study used predetermined inundation values that were imported into FEMA's HAZUS program in order to perform additional modeling (Schneider 2011). A third review included the HAZUS Flood Model technical and user manuals from the Department of Homeland Security (DHS) and FEMA. This article details the capabilities of the HAZUS Flood Model as well as the inputs required and the potential outputs that can be produced by using this model to estimate structural damage and loss of life due to a specified tsunami event (FEMA 2015).

2.1 JRC SCHEMA Methodology

In 2011 the Joint Research Centre (JRC) and the Institute for the Protection and Security of the Citizen (IPSC) released the Scenarios for Hazard-induced Emergencies Management (SCHEMA) project (Tinti et al. 2011). A total of 39 months of effort contributed to the SCHEMA project to document and study tsunami scenarios and their potential damages. According to Tinti et al. (2011), this is an important methodology to consider for assessing tsunami damage, including building classifications and a damage matrix to assess the impact of a tsunami based on the building class. This methodology is completely independent from FEMA's HAZUS program.

Utilizing SCHEMA, the level of inundation fluctuates throughout the inundated areas, so the type of building on each parcel needs to be classified to determine the impact on each parcel based on the height of the tsunami wave. The vulnerability of buildings is determined based on factors such as the resistance of structures, proximity to shoreline, wave heights reaching buildings, and the surrounding topography. To calculate building damage, a well-built SCHEMA project requires a standardized building topology, a standardized economic damage scale based on historical flood data, a damage function for each building related to water depth, and an inventory of buildings. The Hilo SCHEMA modeling effort utilized all four factors and is thus considered a good starting point for project methodology. Buildings are classified into seven different letter grades based on their building types. A detailed listing of each class, building type, and height can be found in Table 1 (Tinti et al. 2011).

Table 1. Building Classifications (Tinti et al. 2011)

Class		Building Types	Height or Stories
Light	A1	Beach or sea front light constructions of wood, timber, clay	0-1 level
	A2	Very light constructions without any design. Very rudimentary huts, built using wood or clay, timber, slabs of zinc	1 level
Masonry, and not reinforced concrete	B1	Brick not reinforced, cement, mortar wall, fieldstone, masonry	1-2 levels
	B2	Light and very concentrated constructions: wooden, timber and clay materials	1-2 levels
	C1	Individual buildings, villas: Brick with reinforced column & masonry filling	1-2 levels
	C2	Masonry constructions made of lava stones blocks, usually squared-off, alternating with clay bricks	1-2 levels
	D	Large villas or collective buildings, residential or commercial buildings: Concrete not reinforced	1-3 levels
Reinforced Concrete	E1	Residential or collective structures or offices, car parks, schools: reinforced concrete, steel frame	0-3 levels
	E2	Residential or collective structures or offices, car parks, schools, towers: reinforced concrete, steel frame	3 levels
Other	F	Harbor and industrial buildings, hangars: reinforced concrete, steel frames	Undifferentiated
	G	Other, administrative, historical, religion buildings	Undifferentiated

In this study, the values in this table were used for the building classification process for Hilo structures, to determine the structure on each parcel and the possible vulnerability to tsunami wave heights. The elevation of each parcel was calculated and then subtracted from the sea-level flood depth raster to determine the height of inundation. The building classification and the height of the inundation are the only two values needed to determine the damage assessment for each parcel. Additional detailed information about the SCHEMA methodology can be found in Tinti et al. (2011).

2.2 Tsunami Modeling For Seaside, Oregon

The NOAA Tsunami Research Center developed a 500-year tsunami flood depth grid for the town of Seaside, Oregon as a test trial for a tsunami workshop held in 2010 (Schneider 2011). This 500-year tsunami grid estimates the potential damages that could result from a tsunami event with a 0.2 percent likelihood of impacting the Oregon coast. The 500-year tsunami grid considers the worst case scenario for a tsunami, unlike the 500-year coastal flood grids that only estimate floods without considering a potential tsunami. In the context of this study, a coastal flood is defined as an oceanic event, such as a storm surge, tsunami, or sea level rise, that causes a coastal area to become inundated with water for a period of time. As a part of Schneider's study, this tsunami flood depth grid was imported into the 2009 version of FEMA's HAZUS program for modeling purposes.

HAZUS is an effective tool to use in flood modeling because it evaluates many potential direct and indirect values that need to be considered in a comprehensive model. HAZUS offers information on buildings, infrastructure, population, hazards, economics, and other environmental factors (FEMA 2015). Despite this wide variety of default HAZUS datasets, there are some issues when trying to model a tsunami event within this system. HAZUS utilizes a well-documented flood model but does not have a tsunami model integrated within the program. HAZUS also does not incorporate velocity damage functions within the coastal flood calculations, despite having such a methodology having been developed in the riverine model (FEMA 2015). Velocity damage is a notable variable for estimating physical damage inflicted by a tsunami, but it is a very complicated variable to model for ocean waves (Schneider 2011).

Schneider (2011) ran the flood model within HAZUS to evaluate the effectiveness of modeling a tsunami using the 500-year tsunami flood depth grid, and to determine the differences between using this custom 500-year tsunami grid and the 500-year coastal flood grid. The initial observation of the author is that the 500-year tsunami grid produced a much more significant flood in the region. The high water mark of the 500-year coastal grid was 11.1 feet, while the 500-year tsunami grid produced a high water mark of 32.8 feet. This difference is significant in terms of allowing local planners to strategize for a tsunami event with appropriate data. A 15 feet seawall could be enough for a coastal flood but would easily be overtopped by this estimated tsunami. As a comparison, a 100-year coastal flood was also modeled, and this event only found a potentially high water mark of 6.5 feet (Schneider 2011).

Schneider (2011) found that residential dollar loss, which is the replacement value and not the actual cash value of property, is another useful variable to compare the differences between the two different flood events. The total residential exposure for the area is constant at just over $1.1 billion. The residential loss for the 500-year tsunami was 2.4 times greater than the 500-year coastal flood, and 5.9 times greater than the 100-year coastal flood, as shown in Table 2.

Table 2. Tsunami Loss by Event (Schneider 2011)

Event	Total Residential Exposure ($1,000's)	Residential Loss ($1,000s)	% Loss
500-year Tsunami	1,164,790	401,329	34.46
500-year Coastal Flood	1,164,790	168,792	14.49
100-year Coastal Flood	1,164,790	68,129	5.85

The residential building damage assessment is another variable that is calculated in HAZUS through a different methodology from the SCHEMA methodology. In HAZUS, the building damage is computed with more damage tiers than SCHEMA, and with damage calculated at each foot increment in inundation. In the context of this study, a damage tier is a group of flood depths that create dollar exposures to buildings depending on the tier that they fall within. In the 500-year tsunami example, it was determined that 0.5% of residences were substantially damaged by the flooding, and no buildings escaped the inundation within the study area. Whereas in the 500-year coastal flood a total of 22.7% of residences experienced no damage, and in the 100-year coastal flood, 56.4% of residences were not damaged. Table 3 displays the breakdown between the damage increments and the three floods that were modeled (Schneider 2011).

Table 3. Number of Residences Damaged by Event (Schneider 2011)

Event	No Damage	1–10% Damage	11–20% Damage	21–31% Damage	31–41% Damage	41–50% Damage	> 50% Substantial Damage	100% Total Damage
500-year Tsunami	0	0	0	0	9	349	1,686	2,044
500-year Coastal Flood	613	5	480	1,487	2	65	41	2,693
100-year Coastal Flood	919	0	197	459	0	47	6	1,628

Schneider (2011) stated that the analysis in HAZUS only uses still-water damage functions in coastal flooding and that the velocity variable is missing from the coastal flood model. Without modeling the flow and velocity of the water, it must be noted that the damage and loss are most likely underestimated in any tsunami estimation process. This is an important variable that is missing in any analysis created in either ArcGIS using the SCHEMA methodology, or using HAZUS. Velocity modeling would need to be added to future HAZUS system models to more accurately assess loss in a given tsunami event (Schneider 2011).

Tsunami models that can utilize the NOAA tsunami flood grids can be developed for any coastal area that has a tsunami flood grid generated for that location. These tsunami models should be developed to support coastal planning and prevention strategies to potentially lessen economic and loss of life. To create more accurate tsunami models, a wide range of variables need to be incorporated into the analysis. Some of these variables include local bathymetry, topography, debris assessments, and damage estimates for vehicles. Some of these components are currently extremely difficult to model without knowledge of such real-time physical data of a given location (Schneider 2011).

2.3 HAZUS Flood Technical Manual

FEMA's HAZUS is a complex multi-hazard methodology modeling program used to determine the impacts of floods, wind, and earthquake losses (FEMA 2015). The HAZUS program is capable of producing real-time loss estimates directly following a real life event. HAZUS has the capability to receive user-supplied input data to create a refined loss estimation model. The flood model is in constant development and enhancement to provide floodplain managers and other users with the ability to protect citizens and property from floods. The HAZUS system was developed not only to estimate post-disaster losses, but also to provide an analytical support tool so communities and individuals can make informed decisions (FEMA 2015).

The HAZUS program can create many outputs, so the focus of the flood model is greatly determined by the expertise of the user. The flood model was created with a simple user interface and minimal input data required, though the user has the option of adding personal data and settings to customize the program for individual studies. HAZUS requires users to have the proper version of ArcGIS installed with the spatial analyst extension provided. The user also needs to supply a DEM since the coastal flooding model requires elevation data to determine impacted areas. Users can acquire this DEM from the National Elevation Dataset (NED) within the HAZUS interface, or provide their own DEM. With the elevation data provided users are capable of determining their damage and loss requirements based on the specifics of a customized flood model. Figure 7 displays the flowchart for the HAZUS Flood Model schematic (FEMA 2015).

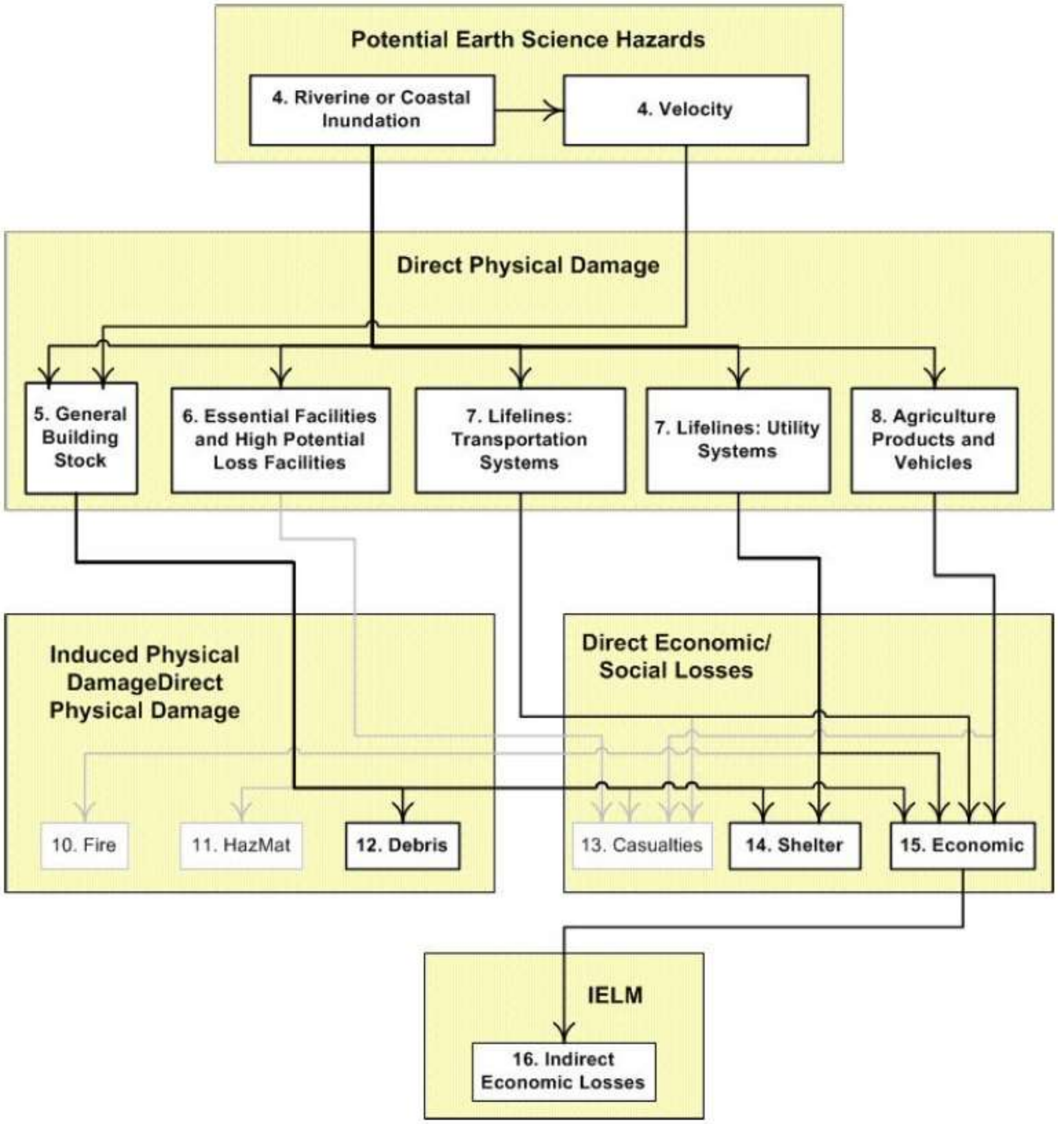

Figure 7. HAZUS Flood Model Schematic (FEMA 2015)

Building damage is determined through the HAZUS Flood Model by evaluating the General Building Stock (GBS) default dataset provided within the program. The GBS contains residential, commercial, industrial, and assorted infrastructure building data. Damage to these buildings is determined based on a percent of impact from the inundation of flood waters. One major difference compared to the SCHEMA methodology is that the GBS is aggregated for census blocks, and each block is assumed to have an even distribution of building statistics within it. Therefore, it is assumed that the SCHEMA methodology is better for evaluating smaller study areas since individual buildings can be identified, whereas the GBS data encompasses a significant amount of building inventory, by default.

In HAZUS, the building classification types and inundation level determines the inundation damage (FEMA 2015). Specific building characteristics are required for an advanced flood model to have accurate loss estimates. The GBS models for structural damage are not only based on the inundation level but also on a wide range of variables. The building age is an important variable that is used in the HAZUS model. While building structure type is important, the age plays a significant role in estimating how vulnerable a building may be due to building styles of a given time period. Foundation style and building materials are also found in the GBS dataset to help determine the potential for debris from that structure. Buildings with weak foundations or built on slabs are more likely to break away in a heavy flood and impact other buildings. Lastly, the building model type and structure material are crucial to estimating the building damage. Each building type has different components within the model that can potentially increase debris, or prevent total destruction due to resistance to flooding. Table 4 displays the typical building types, and characteristics found within HAZUS (FEMA 2015).

Table 4. Model Building Types (FEMA 2015)

No.	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Feet
1	Wood	Wood (light frame and commercial and industrial)		All	1 to 2	14 to 24
2	Steel	Steel frame structures including those with infill walls or concrete shear walls	Low-rise Mid-rise High-rise	1-3 4-7 8+	2 5 13	24 60 156
3	Concrete	Concrete frame or shear wall structures including tilt-up, precast, and infill walls	Low-rise Mid-rise High-rise	1-3 4-7 8+	2 5 12	20 50 120
4	Masonry	All structures with masonry bearing walls	Low-rise Mid-rise High-rise	1-3 4-7 8+	2 5 12	20 50 120
5	MH	Mobile Homes		All	1	10

The HAZUS model determines direct physical damage to the GBS based on the foundation type, inundation vulnerability level, and estimated water depths for a given area. The vulnerability level is defined as the grouping of building characteristics for structures that determines how likely they may be impacted by floods of various depths. These three variables allow HAZUS to estimate the damage throughout a census block as previously mentioned. However, the velocity variable is missing from these calculations for floods. Velocity has a huge impact on tsunami models, and it is currently only mentioned in the methodology but not coded into the HAZUS loss estimation calculations (FEMA 2015).

In the HAZUS Flood Model, the inundation vulnerability and water depth estimates are used in a damage curve to find the percent of damage for each structure type within a given census block, illustrated in Figure 8. FEMA Building Flood Depth-Damage Curve (FEMA 2015). These damage curves exist for many different types of structures, foundations, and building material types. Each curve is customized based on the vulnerability of the building characteristics and flood inundation. These curves are created also using information provided by USACE districts, as well as the Federal Insurance and Mitigation Administration (FIMA). FEMA initially created these damage curves for use in the actuarial rate settling process, but they are also useful in estimating damage in a flood model. The curves were first generated in the 1970's then were improved over time As additional damage information is collected, the curves can be fine-tuned and estimate potential damage with increased accuracy. Figure 8. FEMA Building Flood Depth-Damage Curve (FEMA 2015)demonstrates an example of what the damage curve looks like (FEMA 2015).

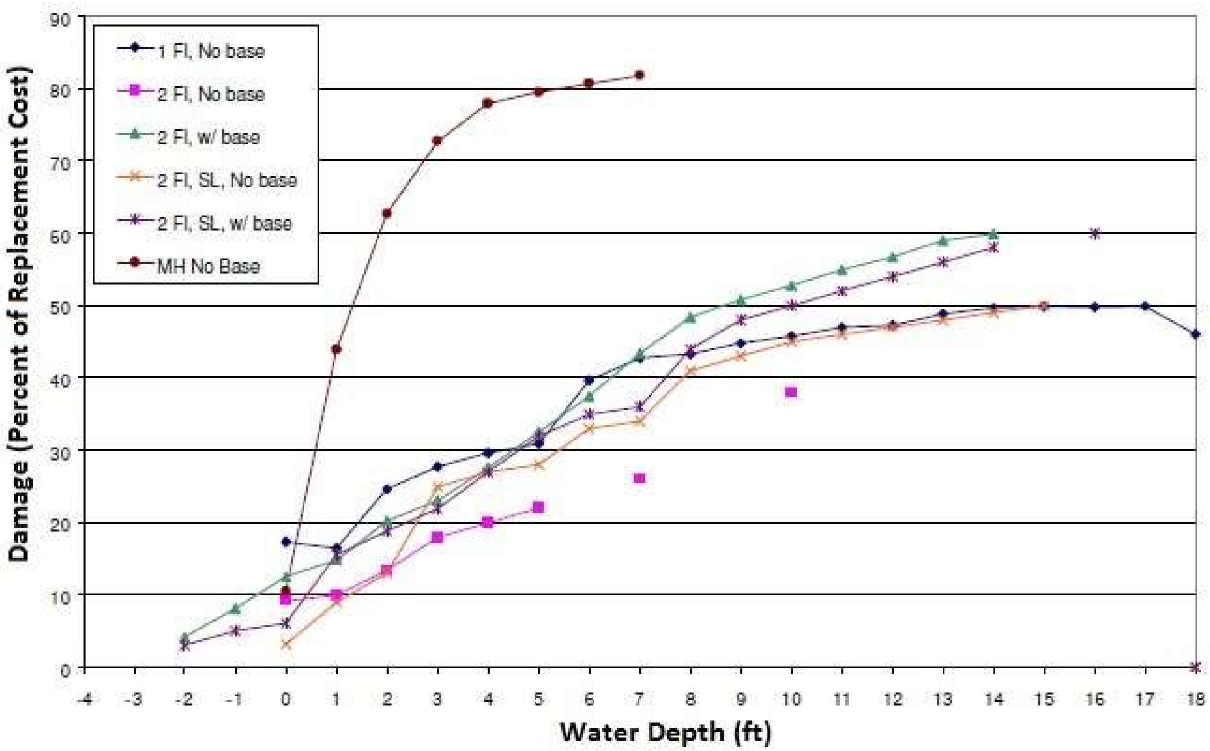

Figure 8. FEMA Building Flood Depth-Damage Curve (FEMA 2015)

A major limitation of HAZUS is the lack of an environmental debris calculation within the flood model. Debris disposal can be another costly expense after a flood, on top of the economic loss from damaged buildings. But while the HAZUS flood debris calculation focuses on building-related debris, it does not factor in environmental debris such as vegetation and sediment. This flood model debris calculation is built similarly to the earthquake debris calculation that determines the structural components and foundation materials for each structure, while excluding vegetation and sediment. However, the flood-related debris model focuses on the internal components of buildings, unlike the earthquake model that takes into account both structural and internal components. This debris estimate is one important part of the HAZUS flood methodology that is not currently available with the SCHEMA methodology. Table 5 shows an example of the debris weight values based on each building type, occupancy, and example depth of flooding (FEMA 2015).

Table 5. Debris Weight by Occupancy Class (FEMA 2015)

Occupancy	Depth of Flooding	Debris Weight (Tons/1000 sq. ft.)			
		Finishes	Structure	Foundations	
				Footing	Slab on Grade
RES1 (without basement)	0'-4'	4.1			
	4' to 8'	6.8			
	8'+	6.8	6.5	12.0	25.0
RES1 (with basement)	-8' to -4'	1.9			
	-4' to 0'	4.7			
	0' to 6'	8.8			
	6'+	10.2	32.0	12.0	25.0
RES2	0' to 1'	4.1			
	1'+	6.5	10.0	12.0	25.0
RES3 (small 1 to 4 units)	0' to 4'	4.1			
	4' to 8'	6.8			
	8'+	10.9	6.5	12.0	25.0

Even though there are some limitations, the outputs of HAZUS are very comprehensive. Each scenario can generate a wide variety of data which may or may not be helpful to the user. The flood model specifically generates statistics for the direct damage to buildings, essential facilities, transportation and utility systems, and damage estimates for debris generation. Indirect losses are also included with a focus on supply shortages, sales declines, opportunity costs, and economic losses (FEMA 2015).

Overall the HAZUS flood methodology is very diverse and a great example of how a wide variety of variables can be factored in to provide reasonably accurate estimates of damage and economic loss. In this study, the HAZUS model was used to model the two historical tsunamis that hit Hilo and the results were compared to each historical tsunami model using the JRC's SCHEMA methodology for building inundation damage sustained by a tsunami. Schneider's study in Oregon described some helpful ways to incorporate data from HAZUS into ArcGIS and vice-versa. This technique is also employed by processing data in ArcGIS and using it within the HAZUS Flood Model.

Chapter 3 Methodology

The SCHEMA methodology and the HAZUS Flood Model are comprehensive resources for creating a spatial tsunami inundation flood model. Both have their strengths and weaknesses, so this research was aimed at determining which methodology is more suitable for determining physical economic loss from tsunami inundation in Hilo, Hawaii.

3.1 Data

The spatial data that was needed for this research is from the SCHEMA methodology, HAZUS, the United States Geological Survey, and the State of Hawaii's GIS Program. The essential spatial files for the economic portion of the SCHEMA model are parcels downloaded from the State of Hawaii (State of Hawaii 2015). The parcels were used to evaluate the economic damage and inundation vulnerability associated with a given tsunami event. The necessary building stock required for HAZUS are already included in the HAZUS package. This building stock information was last updated in 2014 and is the only required economic spatial data used in the HAZUS model.

In this study, the default inventory of building stock provided by HAZUS was used for modeling purposes. Also, HAZUS provides advanced structural inventory modeling through the Advanced Engineering Building Module (AEBM) which includes building-specific damage and loss analysis (FEMA 2014). For the purposes of this study, it was determined that the AEBM dataset was not needed since the default HAZUS building stock inventory is recent, last updated in 2014. In the city of Hilo, damage and loss functions for generic building types are considered to be reliable predictors of economic loss for large groups of buildings present today.

The parcel layer, as well as many other files used in the SCHEMA model, were found on the State of Hawaii website. This parcel layer appears to accurately overlay with the aerial and elevation raster of Hilo. This is important because this data must accurately overlap with the digital elevation model (DEM) used in the analysis. This parcel layer contains not only the land monetary value but also the building monetary values as well. For the purpose of estimating the potential economic damage of a given tsunami, damage to the built environment was the main focus of this study. Each parcel was manually classified into a building category based on the construction methods and materials of the largest building on each parcel. This is required because the SCHEMA damage matrix sets different levels of estimated damage depending on the type of building construction and materials. This information comes from the County of Hawaii's Real Property Tax Assessment website that provides property taxes each year, recently updated in 2015. Perhaps due to the variability of tax assessments, the exact day and month of the most recent tax assessment was created for each parcel is not provided, so for consistency, it is assumed that all values were updated in 2015.

Light Detection and Ranging (LIDAR) data is a remote sensing technology that collects 3-dimensional points of the Earth's surface (USGS 2015). LIDAR is a helpful tool to estimate the height of buildings by comparing LIDAR data against a DEM that was created around the same time period as the LIDAR data was taken. Due to the SCHEMA models using historical elevation data, it was not ideal to use LiDAR data that would be created from a time frame different from the historical events. Also due to known terrain changes between 1946 and 1960, the accuracy of the data would be questionable.

Non-economic input data required for the SCHEMA model included historical topographic maps, historical wave heights, historical inundation maps, and the SCHEMA Damage Matrix (FEMA 2015; NOAA 2015; State of Hawaii 2015; Shepherd, Macdonald, and Cox 1949; USGS Hawaiian Volcano Observatory 2015). Historical documents were used to ensure that each model was using input data from the same time period as the events. The landscape and coastal area around Hilo have changed over the last century, so it was imperative that historical elevation measurements were used. The historical USGS topographic maps were manually digitized as part of this study, then converted into historical DEM files for use in the 1946 and 1960 tsunami event tests. A 1943 topographic map was used for modeling the 1946 event, while a topographic map dated 1963 was used to model the 1960 event.

Historical tsunami inundation maps were previously created after each historical tsunami event and used as figures in websites and journal articles (Shepherd, Macdonald, and Cox 1949). As part of this study, these historical tsunami inundation maps were manually digitized for the 1946 and 1960 events to create historical inundation polylines. The inundation polylines represent the inundation boundary for the study area. Each historical map was georeferenced to ensure that it was in the correct location using the coastline and major intersections as reference points. Figure 9 displays the historical inundation map for the 1946 tsunami event.

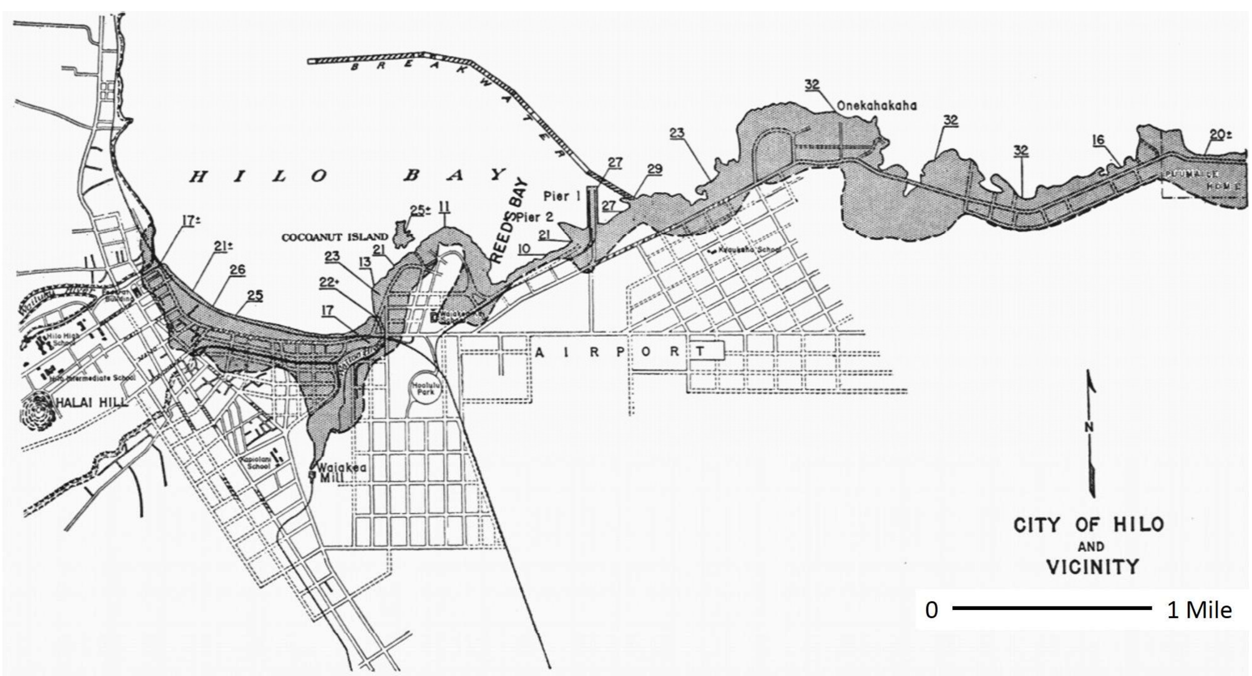

Figure 9. Hilo 1946 Tsunami Inundation (Shepherd, Macdonald, and Cox 1949)

The 1946 historical inundation map extends to the city boundaries in both directions, so additional information was not required to manually digitize the inundation polylines all the way to the city boundary. Figure 10 displays the historical inundation map for the 1960 tsunami.

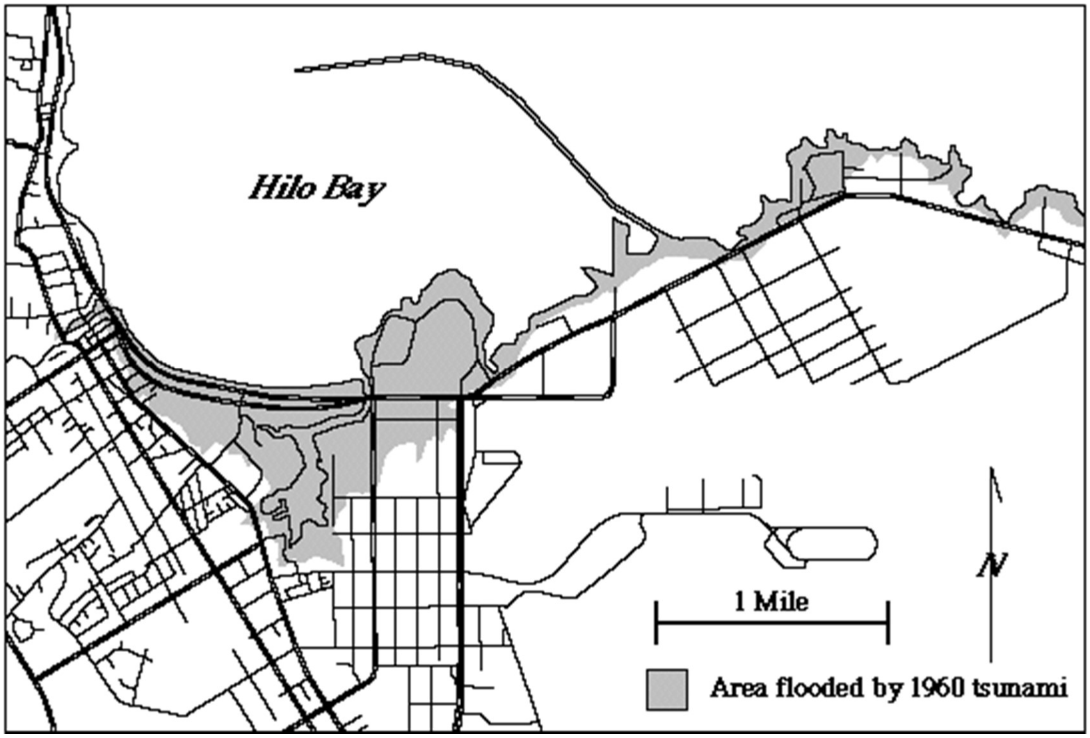

Figure 10. Hilo 1960 Tsunami Inundation (USGS Hawaiian Volcano Observatory 2015)

The 1960 historical inundation map does not extend to the city boundaries of Hilo in the east. This was corrected by extrapolating the nearest point data from the historical tsunami wave heights to estimate inundation to the city limits.

Historical tsunami wave height measurements were reported along the coastlines of Hawaii after previous tsunamis (State of Hawaii 2015). Point spatial wave height data was collected throughout Hilo Bay, and along the coastline to the east. This wave height data is available from the State of Hawaii and was used with the elevation of the inundation boundaries to create an accurate inundation raster file. This raster file was then used to calculate the inundation of each parcel in order to determine the impact on buildings in each parcel.

There are fewer non-economic data required for the user to input into HAZUS due to the comprehensive databases available with the program. The only required files not provided by HAZUS were elevation data, inundation data, and the historical tsunami wave heights.

The same inundation data and historical tsunami wave heights files used in the SCHEMA model calculations were used in the HAZUS model runs. These files were pre-processed before using them as inputs in HAZUS. For the elevation data, both the 1943 and 1963 historical DEM files were used to ensure that each model is using the same elevation data. Since HAZUS uses a distinct wave height value to simulate flooding in coastal areas, it was also possible to create a new scenario using the maximum values from each tsunami event. This new maximum event was mapped using current elevation data to estimate potential maximum economic damage if a large tsunami event were to occur in 2016. For this scenario, a recently updated DEM was required. A 1/3 arc-second DEM from NOAA was available from NOAA's Tsunami Inundation DEM website (NOAA 2015). The DEM layer is considered a very accurate high-resolution elevation model. The DEM file also contains bathymetric data that was helpful to visualize the underwater terrain of Hilo Bay. This DEM was last updated in 2008.

The debris and turbidity of tsunami events were not measured in the SCHEMA model. Inundation is the focus of calculating economic damage, and the SCHEMA methodology focuses on structural damage caused by flooding from a tsunami. HAZUS has the capability of estimating debris, but this information was ignored since it would create significant discrepancies with the SCHEMA results. The additional debris information would give the HAZUS model a significant advantage in estimating overall tsunami damage, even without factoring in velocity, which the model is currently unable to do in the coastal flood model (FEMA 2015).

3.2 Methodology

The methods used in this research are rooted in the research and data exploration stages (Figure 11). After research was completed and the data was acquired and processed, the economic impact model was built within ArcGIS according to the SCHEMA methodology, and then the exiting flood model in HAZUS was utilized.

3.2.1. SCHEMA Model in ArcGIS

Each historical tsunami event first required an accurate elevation file to begin the analysis. The historical topographic maps from 1943 and 1963 were georeferenced so the contour lines could be digitized. Due to the 1943 topographic map having only 50 foot contour lines, it was essential that the gaps were filled with the closed temporal elevation data. The 1963 20 foot contour lines were included with the 1943 contour lines to help create a more accurate DEM. The contour lines generated were then used with the ArcGIS Topo to Raster tool to create an elevation raster for each year.

The height of inundation is determined by finding the elevation of the historical tsunami inundation polylines. After each historical tsunami polyline had been digitized, points were constructed every 150 feet along the polylines to extract elevation values. These points were then combined with the historical tsunami wave height values to create an inundation depth raster. Next, a raster was created using the Empirical Bayesian Kriging method to ensure accurate predictions throughout the study area (ESRI 2016). This inundation depth raster uses an assumed elevation of sea-level so that it can be compared with the historical elevation and determine specific levels of inundation on each parcel. Figure 11 provides a methodology flowchart displaying the steps involved in running the SCHEMA Flood Model to produce tsunami inundation loss estimates in the form of a vector dataset.

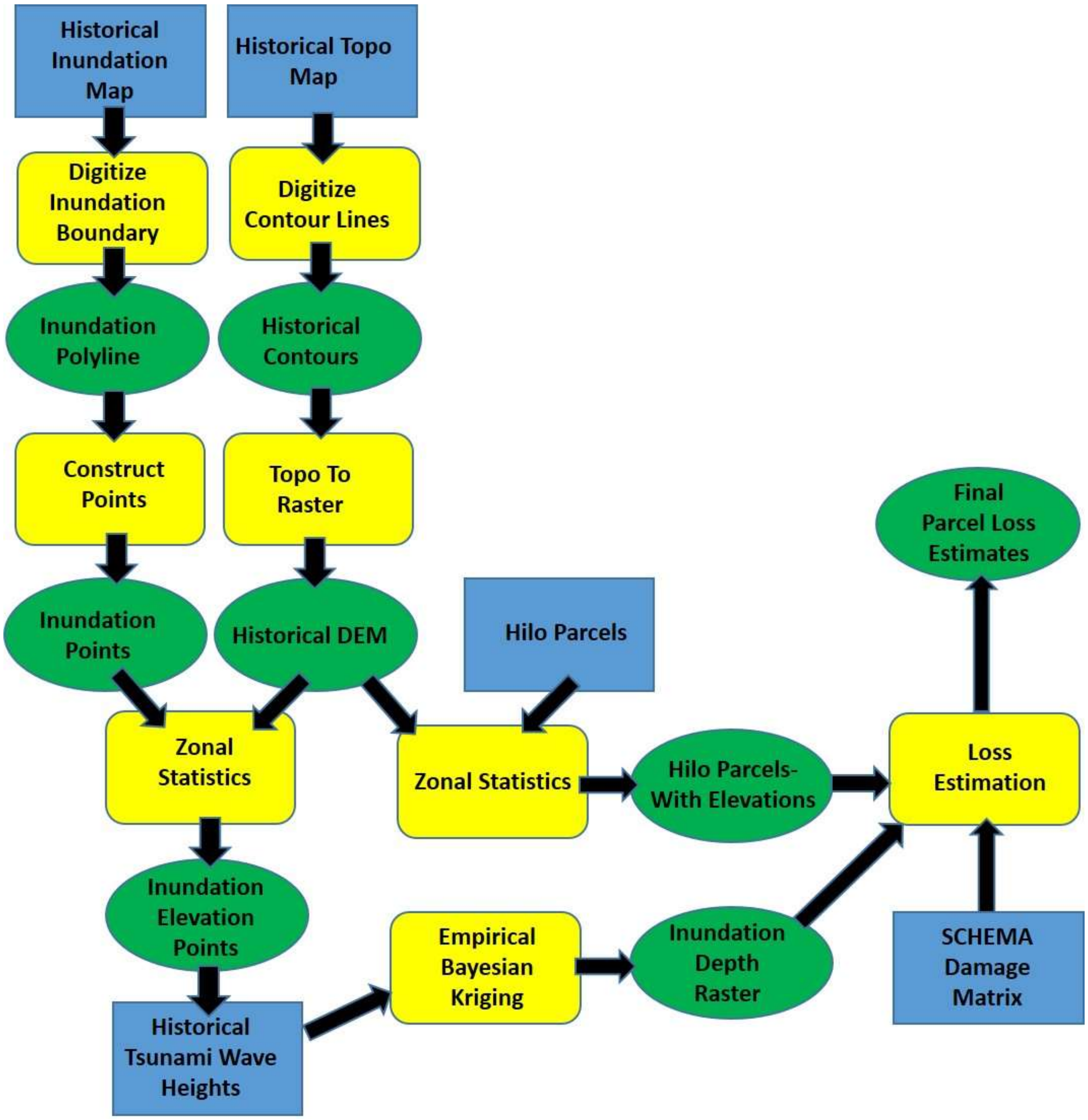

Figure 11. Overview of the SCHEMA Tsunami Flood Model. Green ovals are outputs, blue squares are inputs, and yellow squares are tools or calculations.

The next step in this analysis was to calculate the inundation value for each parcel. First, zonal statistics was used to find the mean elevation for each parcel using the historical DEM. Next, zonal statistics was used again to attach the inundation elevation for each parcel from the inundation depth raster file just created. The mean inundation elevation for each parcel was then subtracted from the mean elevation to find the level of inundation for each parcel. The level of inundation was used with the building classifications in Table 1 to find the potential dollar exposure based on the SCHEMA methodology. To save time, only areas vulnerable to a tsunami had their buildings classified. Figure 12 shows the tsunami evacuation zones generated with the help of forecasting models and also historical tsunami measurements (Office for Costal Management 2015). This tsunami evacuation zone forms the boundary for building classifications.

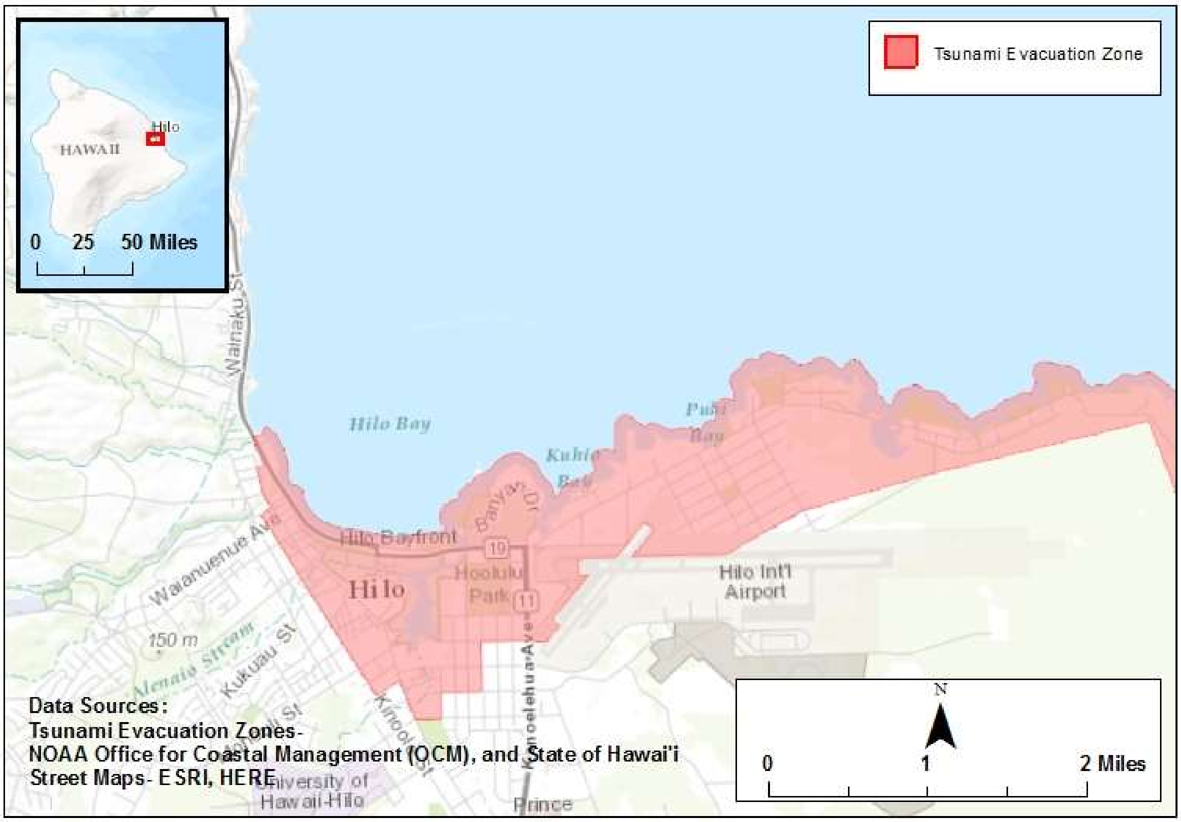

Figure 12. Hilo Tsunami Evacuation Zones (Adapted from NOAA 2015).

The building classification process employed in this study was based on visual confirmation using Bing Maps Bird's Eye Imagery and Google Street View. Visual exploration is the best way to assess building classification values when current documentation was not available from current data sources. The visual confirmation was not foolproof, but the construction methods appeared to be consistent throughout Hilo, and are generally easy to identify through such brief visual inspection. Many blocks are made up of consistently constructed buildings, and several blocks in from the ocean are now mostly residential buildings that are universally categorized as B, light wooden or brick structures between one and two stories high.

The SCHEMA methodology includes a building classification table, a damage scale, and a damage matrix that determines the level of destruction for each building based on inundation. The damage scale ranges from D0, no damage, all the way to D5, total collapse. Table 6 displays the Building Damage Scale from the SCHEMA methodology.

The SCHEMA damage scale includes six different levels of damage that cover all possible tsunami damage values. Note that D3, D4, and D5 all result in demolition and total destruction of a building. Only values of D0, D1, and D2 prevent total economic loss for a given parcel or structure. Once the buildings are classified and the inundation of each parcel is known, the damage scale can be used in the building damage matrix to determine which damage level each parcel falls into. Table 7 displays the building damage matrix and the corresponding values of economic loss. The percentage of economic loss refers to the percentage of the repair costs in relation to the total value of the structure.

Table 6. Building Damage Scale. Source: (Tinti et al. 2011)

Damage Scale			
Damage Level	Damage on Structure	Use as shelter / post crisis use	Detection by Earth observation
D0 No damage	No significant damage	Shelter / immediate occupancy	No sign of damage visible on building and surrounding environment. The absence of damage cannot be proved only through space imagery.
D1 Light damage	No structural damage - minor damage, repairable: chipping of plaster, minor visible cracking, damage to windows, doors.	Shelter / immediate occupancy	Barely visible
D2 Important damage	Important damage, but no structural damage: out-of-plane failure or collapse of parts of wall sections or panels without compromising structural integrity, leaving foundations partly exposed.	Unsuitable for immediate occupancy, but suitable after repair	Damage on roof hardly visible. Other damage not visible.
D3 Heavy damage	Structural damage that could affect the building stability: out-of-plane failure or collapse of masonry, partial collapse of floors, excessive scouring and collapse of sections of structure due to settlement.	Evacuation / Demolition required since unsuitable for occupancy	Not or hardly visible if roofs have not been removed
D4 Partial failure	Heavy damages compromising structural integrity, partial collapse of the building	Evacuation / Complete demolition required	Visible
D5 Collapse	Complete collapse: foundations and floor slabs visible and exposed.	Evacuation	Very Visible

Table 7. Building Damage Matrix. Source: (Tinti et al. 2011)

	Building Class and Inundation Depths					
Damage Level	A	B	C	D	E	Economic Loss
D0 No damage	0	0	0	0	0	0%
	0	0	0	0	0	
D1 Light damage	0	0	0	0	0	30%
	5.9	6.6	8.2	6.6	9.8	
D2 Important damage	5.9	6.6	8.2	6.6	9.8	60%
	7.2	9.8	13.1	14.8	19.7	
D3 Heavy damage	7.2	9.8	13.1	14.8	19.7	100%
	8.5	13.1	19.7	21.3	31.2	
D4 Partial failure	8.5	13.1	19.7	21.3	31.2	100%
	12.5	16.4	26.2	29.5	41.0	
D5 Collapse	>12.5	>16.4	>26.2	>29.5	>41.0	100%

The inundation depth value in the damage matrix (Figure 7) provides a set of inundation ranges that define economic loss based on the building class and damage level. The heights for each value are in feet, as is the DEM. Also, all calculations completed in this study were in feet. The building classes are assigned a building class letter, while the number attached to each letter is not used for calculating damage. There are also F and G values in the damage scale, but these were not used in this study because of invulnerability to tsunami inundation or unquantifiable financial values. Most buildings are residential homes and fell under the B classification. These homes are vulnerable to complete destruction by inundation above 9.8 feet. A measurement of 9.8 feet is generally considered high enough to inundate a building's first floor. Several homes in Hilo are vulnerable to complete collapse or demolition from inundation starting at 19.7 feet in height. A 19.7 foot wave is high enough to cover a two story structure in Hilo, and while that may not destroy a well-built hotel, it is likely to cause severe structural integrity damage (Tinti et al. 2011).

The economic loss column of Table 7 was created in this study to provide a quantitative value for economic impact calculations. Damage levels D3, D4, and D5 all require full demolition so all of a given parcel's (building) value would be considered lost. The D2 damage level mentions serious damage but does not require demolition due to the comparatively greater integrity of the structure. Integrity is determined by the ability of a structure to be repaired without worry of structural failure or collapse. Damage could vary depending on the structure. In the context of this study D2 level damages were estimated at just over half the cost of the home's assessed value because most of the first floor would have been underwater and thus severely damaged. D1, or light damage, varies as well, but can range anywhere from minor cosmetic damage, to replacing the exterior and much of the interior of the structure. In this study

D1 level damage was estimated to be roughly a third of the value of a structure. Due to the variety of building types and economic damage levels, the loss estimation step of the SCHEMA model was computed manually in the attribute table of each respective tsunami event shapefile using ArcMap's default Calculation tool.

3.2.2. HAZUS Flood Model

The HAZUS Flood Model required less initial input data preparation because the program is by default comprehensive. The inputs required for HAZUS to model a flood, representing tsunami inundation, include a DEM and tsunami wave height calculations (FEMA 2015). The inundation can be created within the HAZUS program using the Stillwater Flood Elevation (SWEL) setting with the tsunami wave height calculated values. The SWEL setting determines the height of coastal flooding in comparison to sea-level elevation. This value dictates the amount of flooding that HAZUS will create when it delineates the floodplain. As previously stated, it was anticipated that the SCHEMA Flood Model damage results would fall within the HAZUS ranges for a given year.

The initial steps in the HAZUS Flood Model involve the same pre-processing of data as the SCHEMA Flood Model. The historical inundation map was manually digitized to create the inundation boundary, while the historical topographic map was digitized to create the historical contour lines (Shepherd, Macdonald, and Cox 1949; USGS Hawaiian Volcano Observatory 2015; USGS 1943; USGS 1963). These historical contour lines are presented in Chapter 4. This data was input into the ArcMap Topo to Raster tool to generate two historical DEMs. Each scenario, 1946 and 1960, had a historical inundation polyline and a historical DEM created for analysis. The inundation polyline was used to construct points along the inundation boundary. These points were used to create a depth raster through interpolation methods. The elevation of inundation in each historical tsunami event was calculated by adding the elevation from the historical DEMs to the constructed points along the inundation polyline.

The HAZUS Flood Model allows a user to input an inundation depth raster, which is a raster file that determines the depth of flooding at each pixel location. The depth raster generated as input to the SCHEMA flood model could also have been used as an input in HAZUS. Since one research goal of this study was to compare both methodology's flood models as well as the building stock information in HAZUS versus the parcel information in SCHEMA, the SCHEMA depth raster was not used as an input in HAZUS. Since the HAZUS analysis did not utilize a depth raster, the SWEL setting within HAZUS was used to flood the project area of Hilo with determined inundation values from the historical tsunami information. These values were static, and therefore, it was deemed best to determine the mean values for each year, from which a range within one standard deviation of these values could be created. The ranges provide a 68.27% chance of a similar event occurring within one standard deviation of the mean historical inundation.

In addition, to ensure accurate sampling of inundation depths, wave heights for each event were broken into two values for each tsunami strike in Hilo Bay, to take into account the influence of local topography on the wave heights inside and outside of Hilo Bay. Two transects were manually digitized that represent the coastal area outside of Hilo Bay and the coastal area within Hilo Bay. Since the topography of the northwest border of Hilo Bay has been shown to amplify the height of tsunamis, it was considered inaccurate to use a mean inundation depth for a single event in this study.

The same flood depth values from the SCHEMA model were used in the HAZUS model to determine the mean inundation depth in each transect. This is different from wave height in that inundation depth is the amount of water above ground level at a particular location, while wave height is the height of a wave measured along the coast. The mean inundation calculations also returned a standard deviation for each mean in each transect. These standard deviations were used to determine a minimum and maximum wave height by subtracting or adding the standard deviation to the mean, respectively. By using standard deviations, these minimum and maximum values are intended to produce an output of each model that will cover approximately 70 percent of outcomes for a similar tsunami event. The 1946 and 1960 events each have a minimum and maximum wave height range for the inside of Hilo Bay, and outside of Hilo Bay. The minimum inundation value is one standard deviation below the mean, used to determine a lower dollar exposure outcome, while the maximum inundation value is one standard deviation above the mean, intended to estimate a higher dollar exposure outcome. HAZUS allows one inundation value for each run, so each two calculations were performed for both 1946 and 1960, once for a minimum inundation value and once for a maximum inundation value. This differs from the SCHEMA Flood model, which results in a range of damage values as the final output, versus an exact number of damage values produced using HAZUS. Figure 13 displays the likelihood of an outcome based on the standard deviation value.

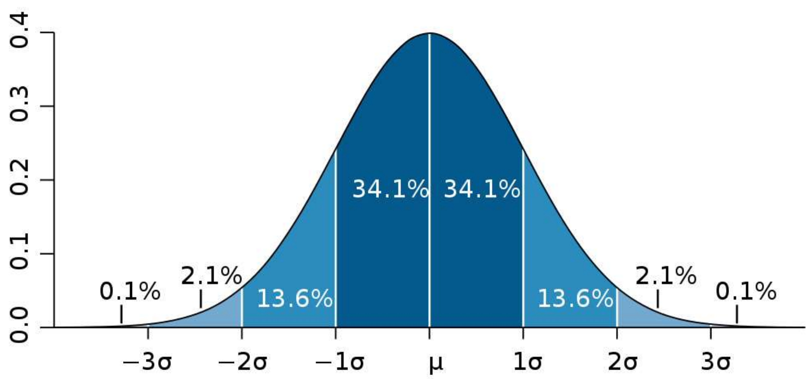

Figure 13. Standard Deviation Bell Curve (Source: Massachusetts Institute of Technology). This bell curve displays the statistical percentage of an event based on the distance from the mean.

The first step in running the HAZUS Flood Model was to create the two shoreline transects for Hilo to divide the study area into two distinct topographical areas inside and outside of Hilo Bay. After the transects had been created, HAZUS was implemented using the minimum and maximum flood depth calculation values to create an inundation raster of the coastal area. These flood depth values were placed into the 100-year SWEL field that allows the user to input a custom value. HAZUS allows the user to provide a different value for each transect created, so the minimum or maximum values were provided for each 100-year SWEL field. In effect, these inputs delineated the floodplain and created the depth of flooding raster. This depth of flooding raster was used within HAZUS to determine the degree of flooding for each census block. Figure 14 provides a methodology flowchart displaying the steps involved in running the HAZUS Flood Model to produce tsunami inundation loss estimates in the form of a vector dataset.

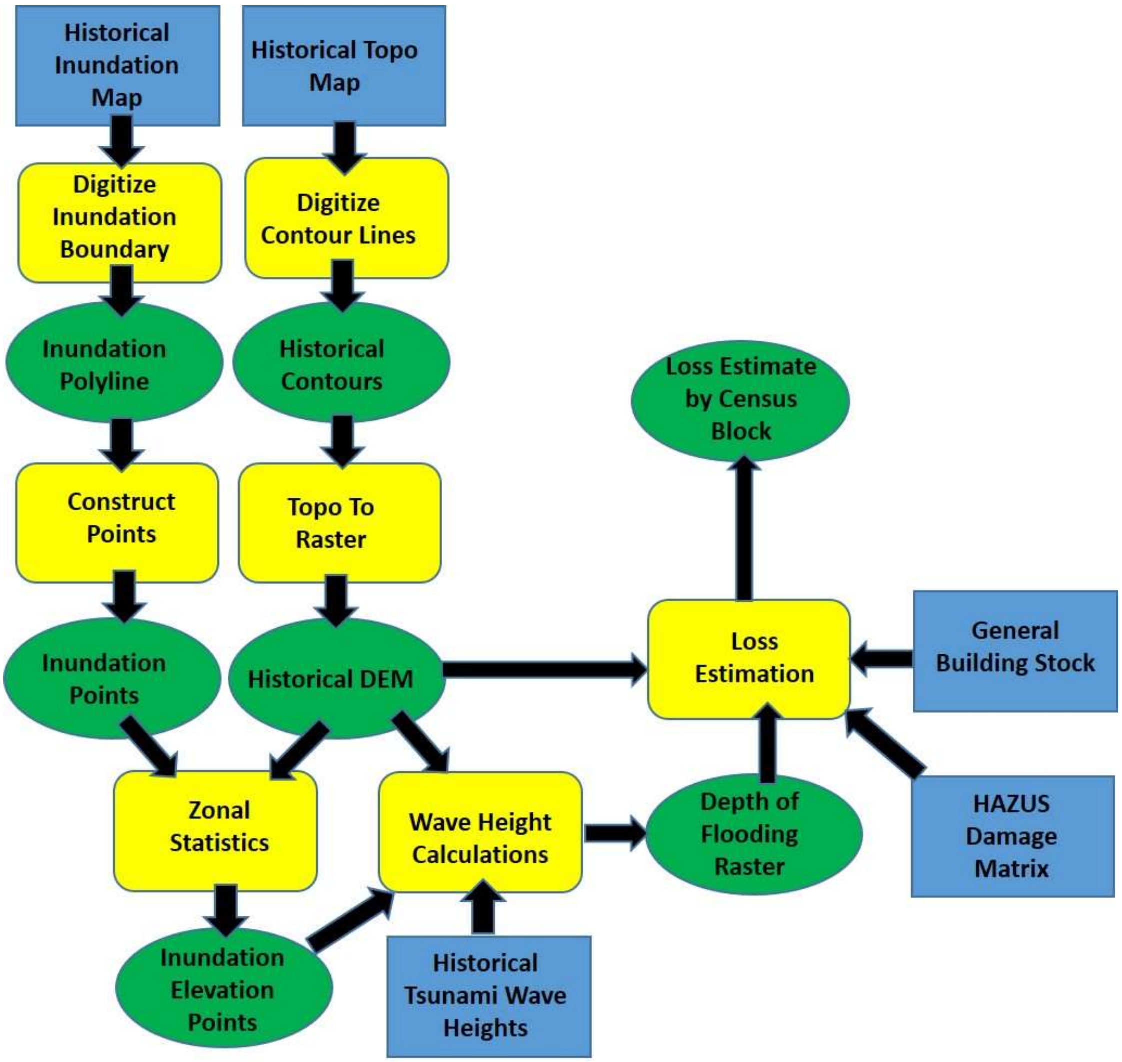

Figure 14. Overview of the HAZUS Tsunami Flood Model. Green ovals are outputs, blue squares are inputs, and yellow squares are tools or calculations. Transects were created during the Depth of Flooding Raster step.

After the flood depth raster is created, the building damage can be estimated with the HAZUS building inventory and HAZUS damage matrix described in the literature review. HAZUS has a comprehensive building dataset that summarizes building information, for example, based on critical infrastructure within census blocks. The previously created historical 1946 and 1960 DEMs were used as the input land elevation layer for each specific year. It is important for consistency that the same DEM be used for wave heights and building elevations. The HAZUS methodology has a different dollar exposure calculation for every additional foot of flooding, while the SCHEMA methodology includes only a few classifications for dollar exposure.

It is important to note that the census area analyzed in HAZUS is not the exact city boundary of Hilo, and does not match up directly with the SCHEMA Flood Model's study area. The reason for the mismatch is that the census tracts in HAZUS do not share the exact same border as the city limits of Hilo. To rectify this issue, the census blocks that were not within the city limits of Hilo were omitted after the file was imported into ArcGIS. The output from HAZUS was brought into ArcGIS to perform a select by location with the Hilo City boundary. Any areas not within the city boundary were deleted to keep the study areas consistent.

By studying the outputs of both the SCHEMA and HAZUS models, this research is intended to reveal the strengths and weaknesses of both methodologies for future tsunami flood modeling. Both models produce economic loss information as outputs that were compared with the historical loss information in order to address the original research questions. As mentioned previously, inflation is also considered regarding each monetary result, and these calculations were completed in a post-processing step. This inflation computation step ensured that historic economic losses are accurately compared to today's costs.

Chapter 4 Results

The results of this study indicated that there are several important differences between modeling tsunamis using the SCHEMA methodology versus FEMA's HAZUS Flood Model. Both models have their strengths and weaknesses, and both are very useful for different reasons. The results chapter consists of three subsections; a discussion of the SCHEMA model outputs, the results of the HAZUS model, and a historical comparison of the results of both models.

In both models, the monetary values were inflated to 2016 dollar values for structural inventory to provide a more accurate comparison between all outputs. The same elevation values were used for each comparison, 1946 and 1960, between the models to so that ground elevation would be a held constant, rather than consider it as another variable.

4.1 SCHEMA Model

During the parcel building classification, a new point file of high cost buildings was created to represent the highest economic cost structures to repair. This layer is displayed with the hotel layer on several of the maps to help explain why that area may have a high dollar exposure to tsunami inundation. Figure 15 displays the hotels and high value buildings most at risk in the Hilo costal area.

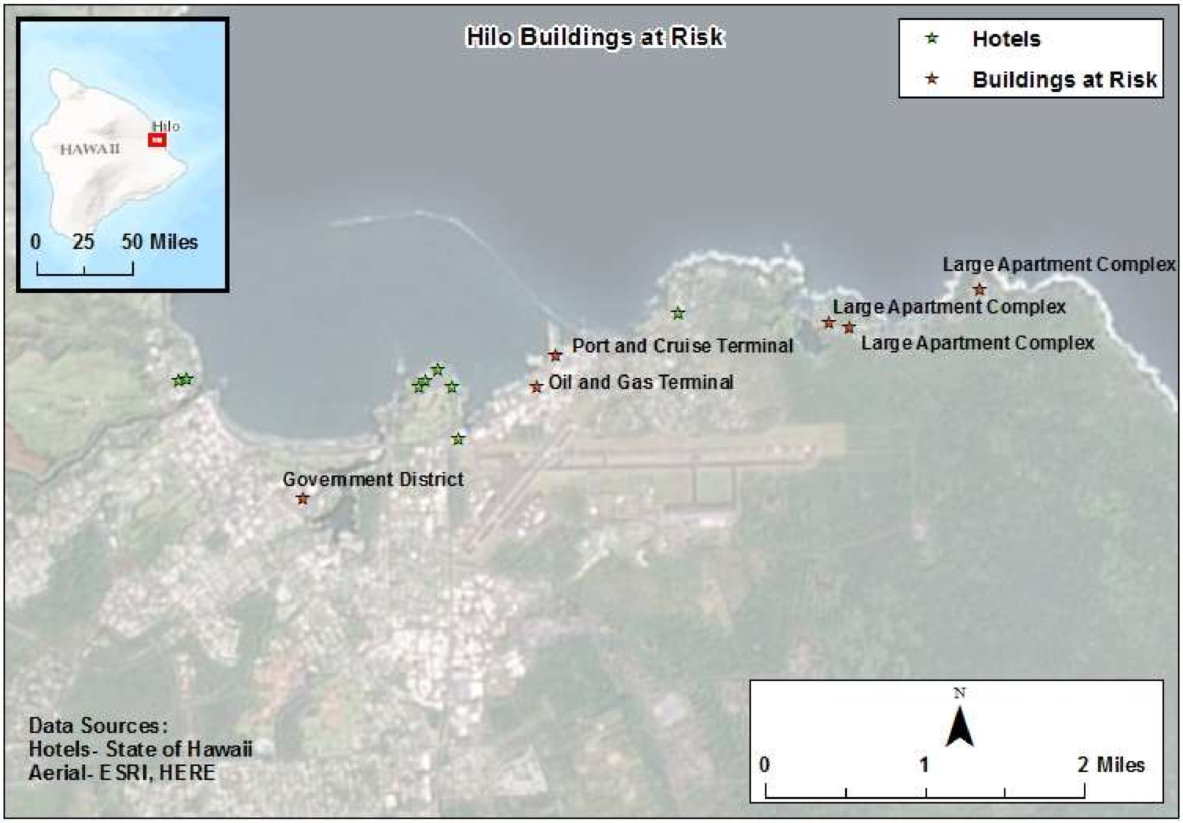

Figure 15. Hilo Buildings at Risk. Examples of high value buildings and areas potentially at risk.

The hotels and buildings at risk indicate that there are a number of areas of economic importance that may be impacted by tsunami events. The government district of Hilo is near the old downtown, which was destroyed in both the 1946 and 1960 tsunamis. However, this area has taller concrete buildings and is farther away from the ocean than in previous years. These buildings are likely to be impacted by future tsunamis, though not destroyed unless the wave height exceeds the historical event considered. There is also an oil and gas terminal with large storage tankers right next to the bay. This terminal is adjacent to the cruise terminal within the main port area of Hilo. This area is commercial and is also economically vulnerable with large buildings next to the ocean. The rest of Hilo has several large hotels and apartment complexes within several hundred feet of the ocean in some cases. These are sturdy buildings yet still vulnerable to a large tsunami event due to their close proximity to the bay.

4.1.1. 1946 tsunami event

The 1946 tsunami event in Hilo originated in Alaska and traveled directly south into Hilo Bay. This tsunami devastated the downtown area of Hilo but left the Waiakea Peninsula, which extends into the bay, mostly untouched. Figure 16 shows the inundation line of the 1946 tsunami.

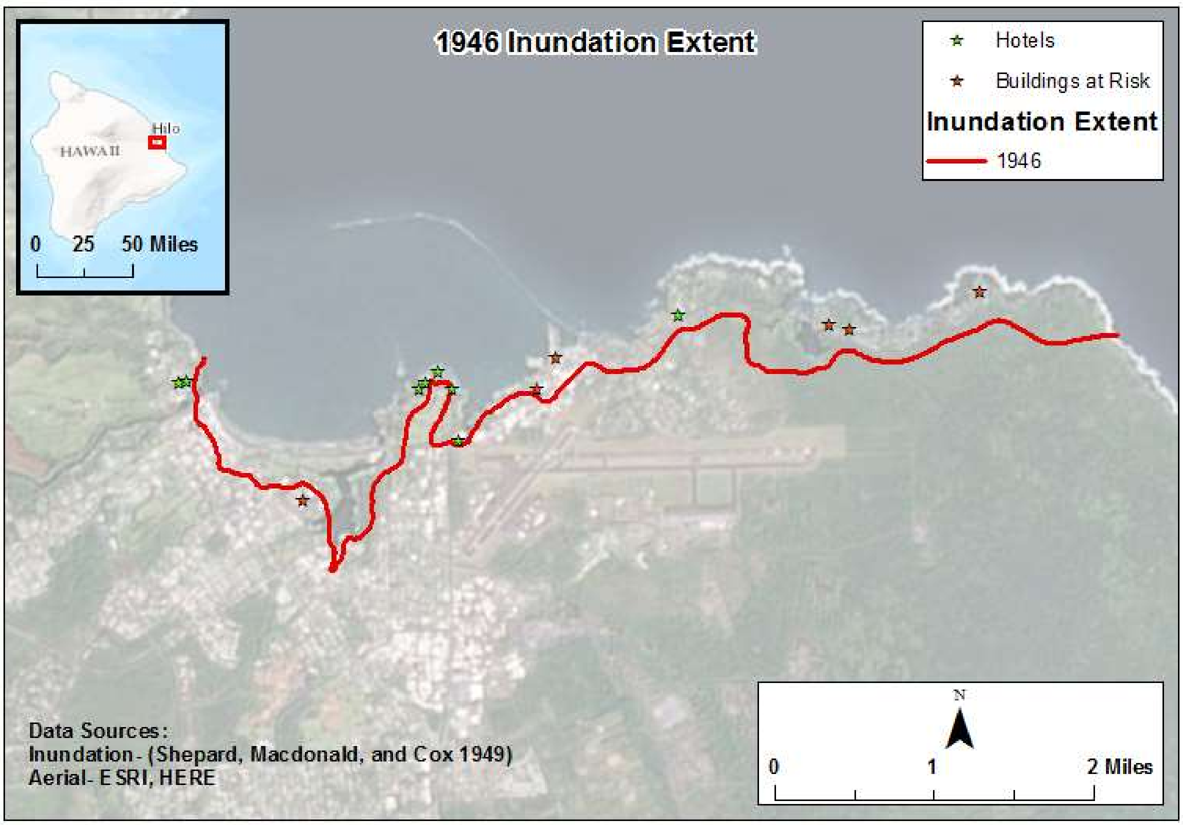

Figure 16. 1946 Tsunami Inundation

The 1946 tsunami extended far into the main downtown area of Hilo, which is directly south of the bay. The Waiakea Peninsula experienced inundation along the shoreline, but the structures there were largely untouched. However, the pier complex was devastated, and appears to still be vulnerable. The eastern area of the city outside of the bay was also inundated during this tsunami event. The inundation was reported as wave height almost uniformly all along the coast of Hilo, with the one exception of the Waiakea Peninsula. Figure 17 shows the dollar exposure of the 1946 tsunami event with 2015 parcels predicted for this event using the HAZUS Flood Model.

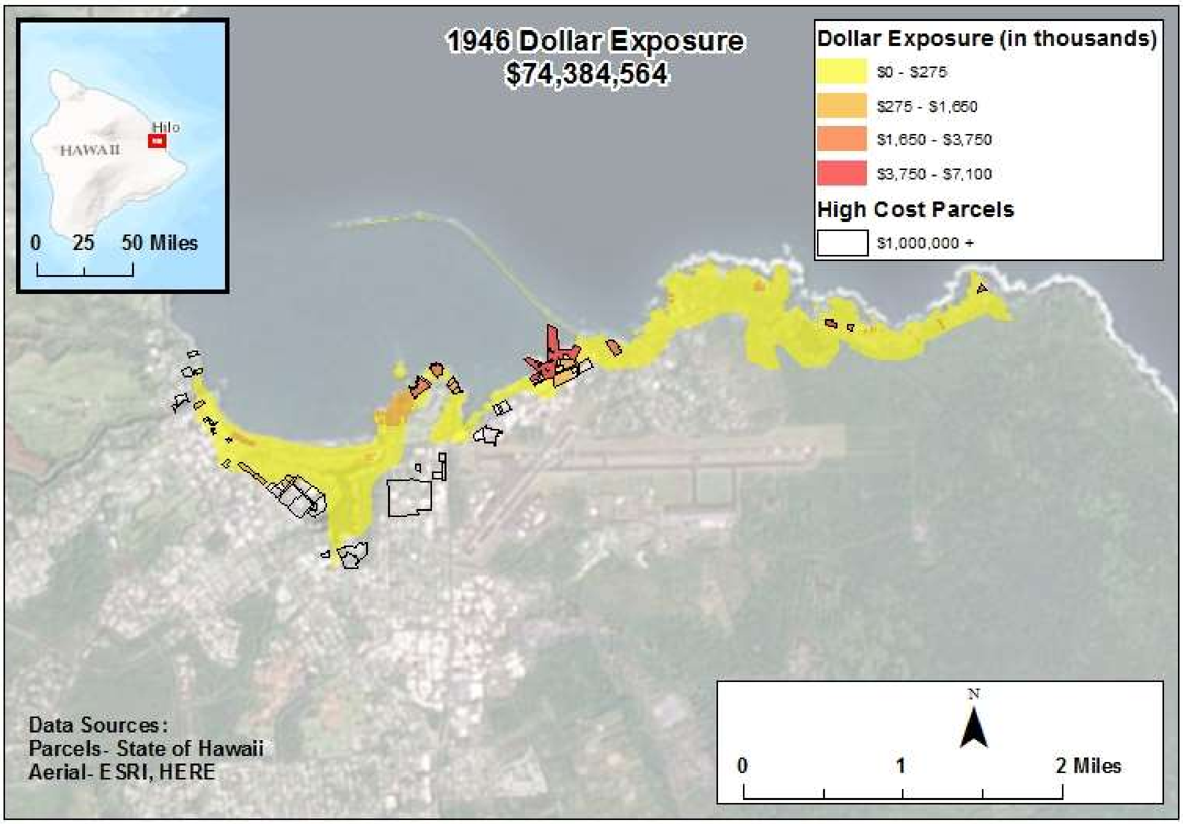

Figure 17. 1946 Hilo Dollar Exposure

The dollar exposure of the 1946 event in today's' costs shows a drop-off of economic impact compared with the historical incident (Pararas-Carayannis 1977). The historical incident reportedly cost over $317 million, while the same event with 2015 parcels resulted in a dollar exposure of just over $74 million. Some of the historical dollar exposure reported probably included damage from debris and physical objects like vehicles, as well as buildings that were damaged or destroyed. Table 8 displays the dollar exposures for the 1946 tsunami event. The reasons for the difference in these costs are hypothesized in the following discussion.

Table 8. 1946 Dollar Exposures. Source: (Pararas-Carayannis 1977)

1946	Historical Adjusted to 2016 value	Current
Dollar Exposure	$317,509,330	$74,384,564

The SCHEMA model for the 1946 tsunami event shows very little damage in the area south of Hilo Bay. This area comprised main downtown Hilo up until the 1960 tsunami. These results show that the hesitance to rebuild the old downtown area of Hilo paid off in fewer damages incurred due to the 1960 event. This area is now open greenery for several blocks along the coast. However, the present-day Waiakea Peninsula shows some areas of high dollar exposure, unlike in 1946. Several of these parcels have large hotels or apartment complexes that may be vulnerable to a large tsunami similar to the 1946 event. The old pier area also shows a lot of high dollar exposure to this event. These parcels have several large commercial businesses right next to the bay, which would be heavily impacted by a similar event. This could also become a larger-scale environmental disaster due to the oil and gas terminal at the pier. The eastern portion of Hilo, outside of the bay, was also heavily inundated. Today the parcels that were affected are mostly low in dollar exposure, but this area is now heavily residential and thus could experience many fatalities. Several parcels adjacent to the shoreline also have large hotels or apartment buildings that show a high dollar exposure potential.

4.1.2. 1960 tsunami event

The 1960 tsunami event in Hilo originated in Chile and traveled around the Big Island and into Hilo's Bay. This tsunami also devastated the downtown area of Hilo, but unlike the 1946 event, it also destroyed much of the Waiakea Peninsula. Figure 18 shows the inundation line of the 1960 tsunami.

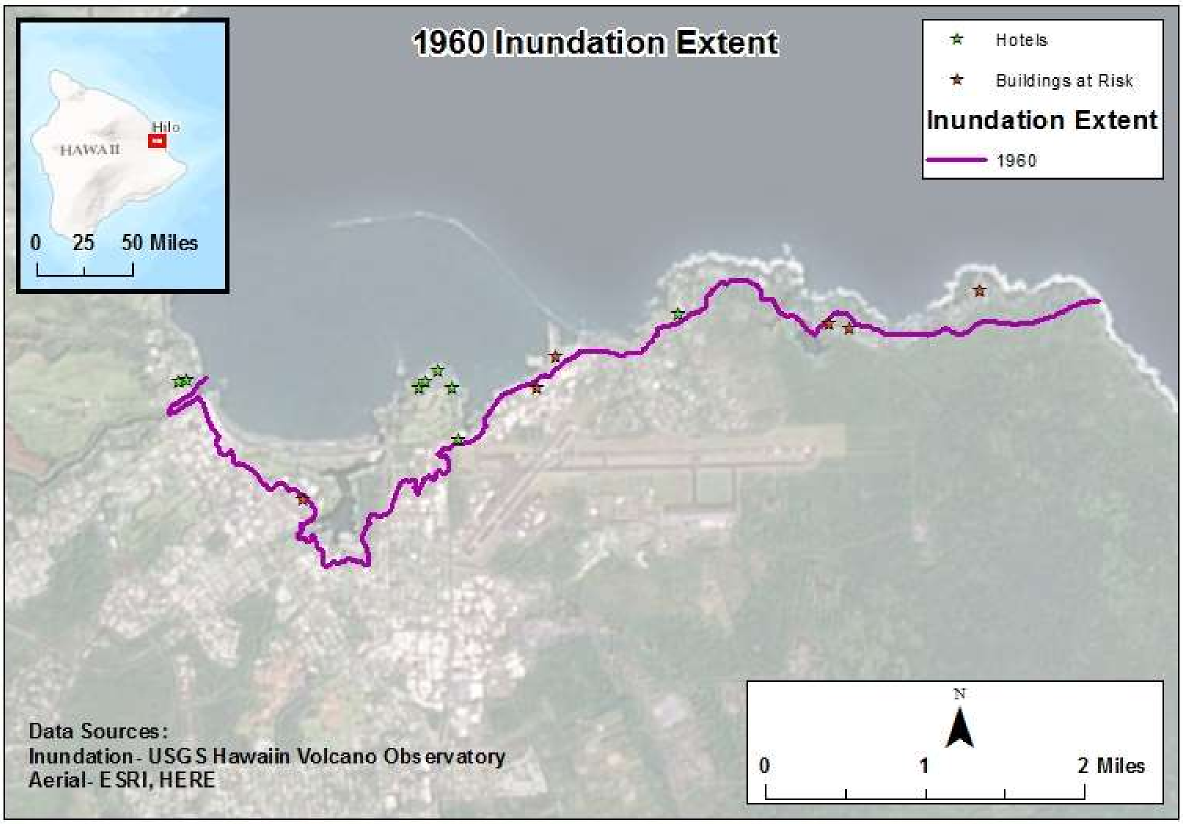

Figure 18. 1960 Tsunami Inundation

The 1960 tsunami was very similar to the 1946 event in terms of overall height, yet it impacted different areas of Hilo. The downtown area of Hilo was destroyed again, and this time, it was not rebuilt. The main difference compared to the 1946 event is that the Waiakea Peninsula was hit the hardest of any area in Hilo. In 1946 the waves wrapped around the peninsula but did not touch the center of the peninsula. In 1960, the waves completely overtopped the peninsula and greatly damaged the entire area. Many of the lives lost in the 1960 tsunami event were due to Hilo citizens believing they would be safe in the peninsula as they were in 1946. This tsunami was less destructive than the 1946 event, partly due to areas not being rebuilt and increased building standards. The tsunami did not inundate as much area to the east of the bay, most of the physical damage was within the bay. Figure 19 shows the dollar exposure for the 1960 tsunami event using 2015 parcels.

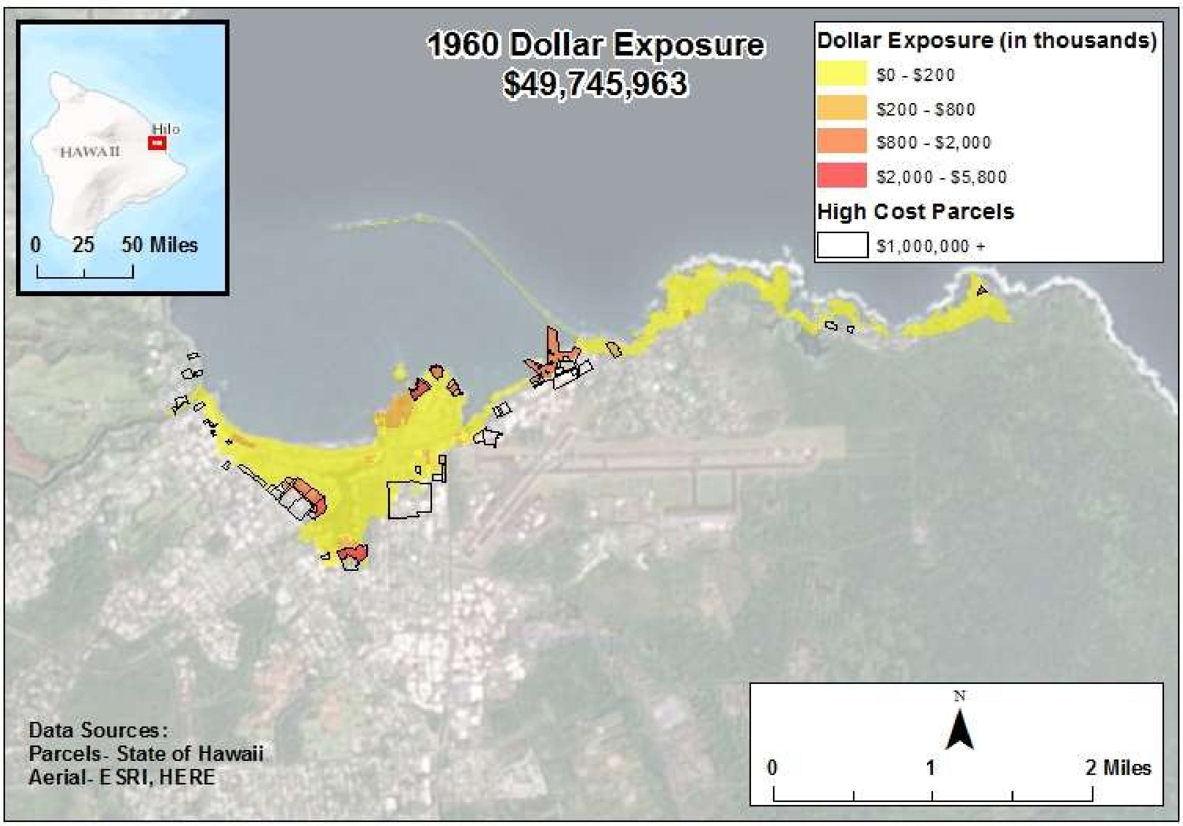

Figure 19. 1960 Hilo Dollar Exposure

The dollar exposure of the 1960 event in today's costs shows another huge drop-off of economic impact compared to the 1946 incident. The 1960 event had a dollar exposure of over $185 million, while the same event with 2015 parcels only had a dollar exposure of just under $50 million (Pararas-Carayannis 1977). Again, this can partly be explained by the lack of vehicles and debris being calculated in the ArcGIS model, but the difference is also likely due to both improved building standards and avoidance of building in areas of low elevation vulnerable to tsunamis. Table 9 displays the dollar exposures for the 1960 tsunami event.

Table 9. 1960 Dollar Exposures. Source: (Pararas-Carayannis 1977)

1960	Historical Adjusted to 2016 value	Current
Dollar Exposure	$185,035,000	$49,475,963

4.2 HAZUS Model

HAZUS is capable of modeling coastal flooding, but only with set, or know input flooding values that are static across a given study area. Due to this issue, each HAZUS scenario was run with a minimum and maximum value that is one standard deviation from the mean inundation level in order to understand a range of possible damage costs. Also, each HAZUS scenario was created using transects for calculations inside and outside of the bay because the tsunami heights within the bay tend to differ dramatically from those outside of the bay. Figure 20 displays the two transects used for each scenario.

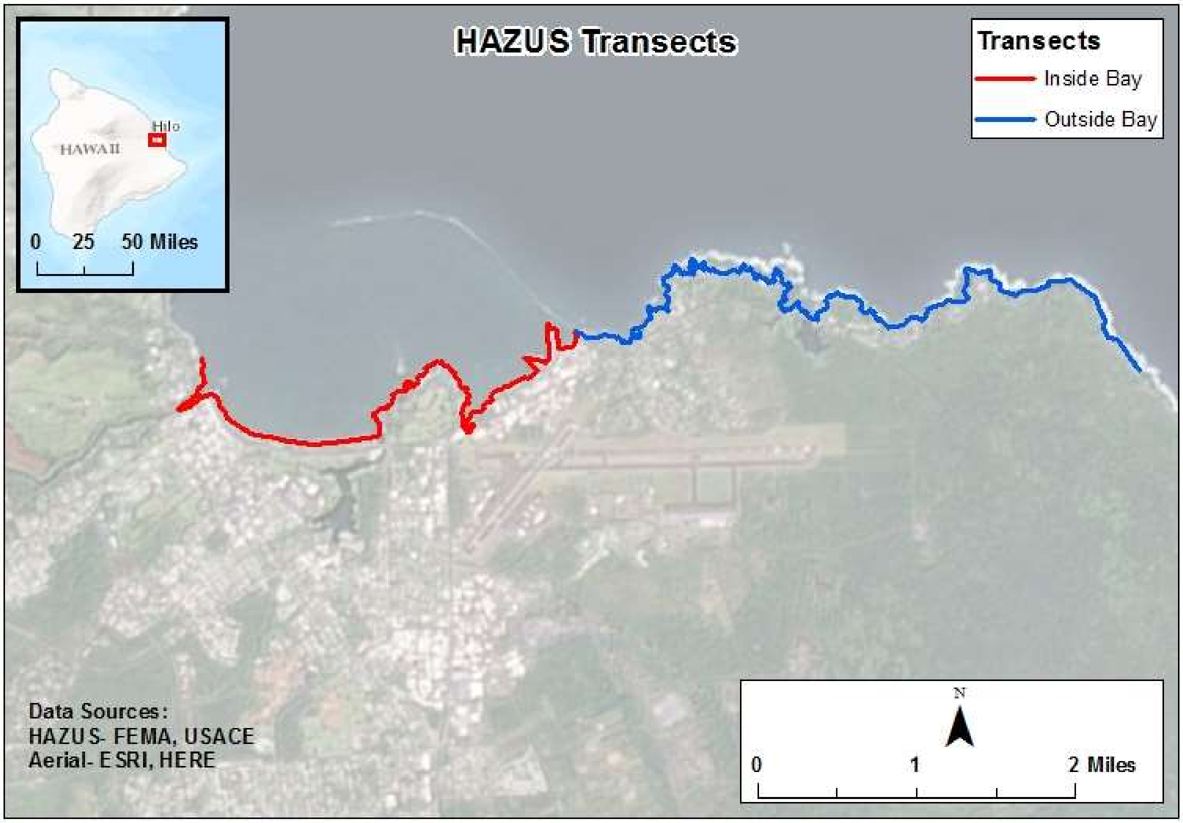

Figure 20. HAZUS Transects

4.2.1. 1946 HAZUS Inundation Scenario

The 1946 SCHEMA output suggested that the 1946 tsunami had a much larger impact on the historic downtown area of Hilo, missing most of the Waiakea Peninsula. The tsunami also hit the port area hard, as well as the area to the east of the bay. The HAZUS inundation values were calculated from the mean inundation elevation for each transect. A range of values was then created using the standard deviation of these mean values to create a minimum and maximum inundation value to use in HAZUS. Table 10 shows the inundation values used for the 1946 event.

Table 10. 1946 HAZUS Inundation Values

1946 HAZUS Inundation Values (in feet)		
Location	In Bay	Outside Bay
Minimum Inundation Depth	4.7	5.3
Maximum Inundation Depth	17.5	15.7

It is important to note that the values displayed on the maps and tables for HAZUS are in feet because that is the unit of measure used in HAZUS. The minimum inundation depths and the maximum inundation depths are both within just a few feet regardless of their location. It is an indication that the 1946 tsunami was fairly uniform when it made landfall. The tsunami came directly from the north in Alaska, which might indicate that the momentum of the water was not diverted much on its way to Hawaii. Figure 21 displays the 1946 minimum inundation depth from the HAZUS model. The amount or degree of refraction of these initial tsunami waves off of the northwestern topographic highs is not documented in the references sited in this study.

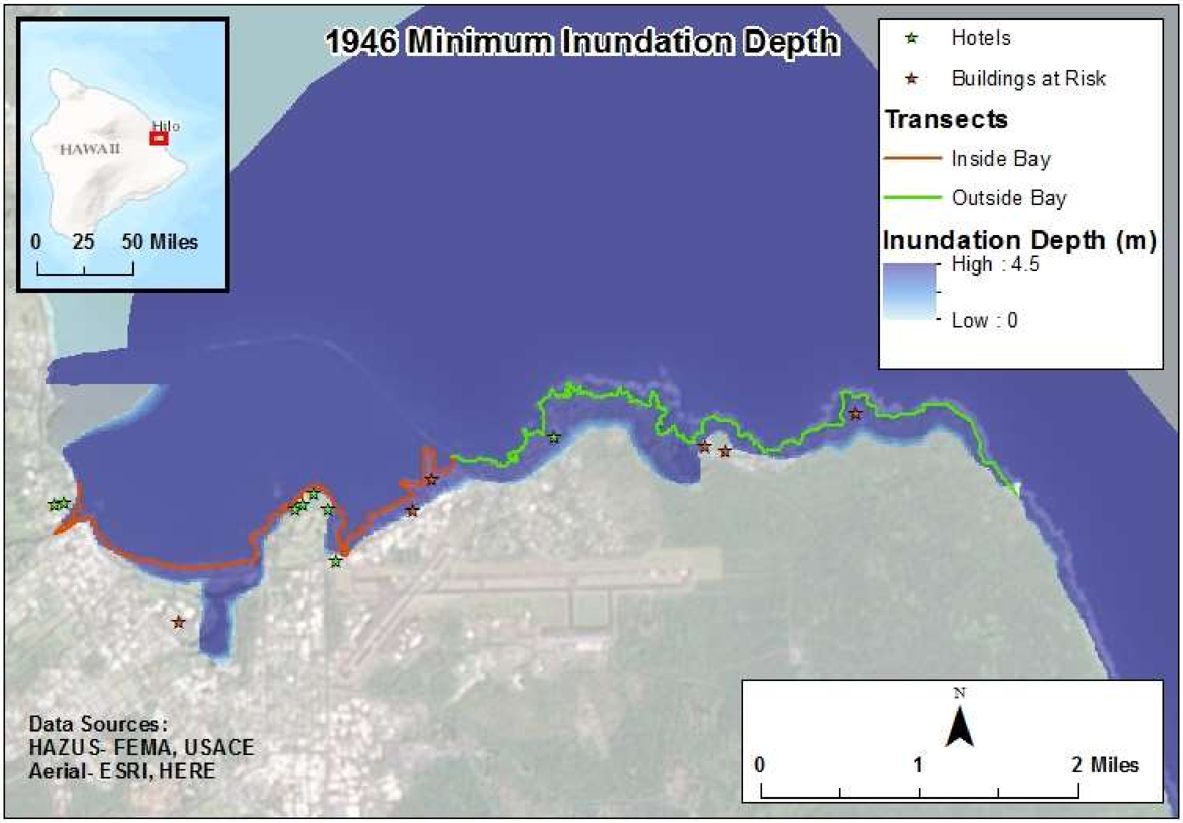

Figure 21. 1946 Minimum Inundation Depth

The 1946 minimum inundation scenario in HAZUS appeared mild in comparison to the SCHEMA scenario, as expected. This scenario shows inundation of 4.7 feet inside the bay and 5.3 feet outside of the bay. Hilo Bay experienced very little flooding outside of the immediate area near the coast. Much of this land is now parkland and is, therefore, unlikely to have a high economic impact. The tsunami did impact the port area, which would lead to moderate dollar exposure. The eastern area of Hilo, outside of the bay, experienced mild flooding along the coast which may impact several hotels or apartment buildings. Figure 22 displays the dollar exposure of the 1946 minimum inundation scenario.

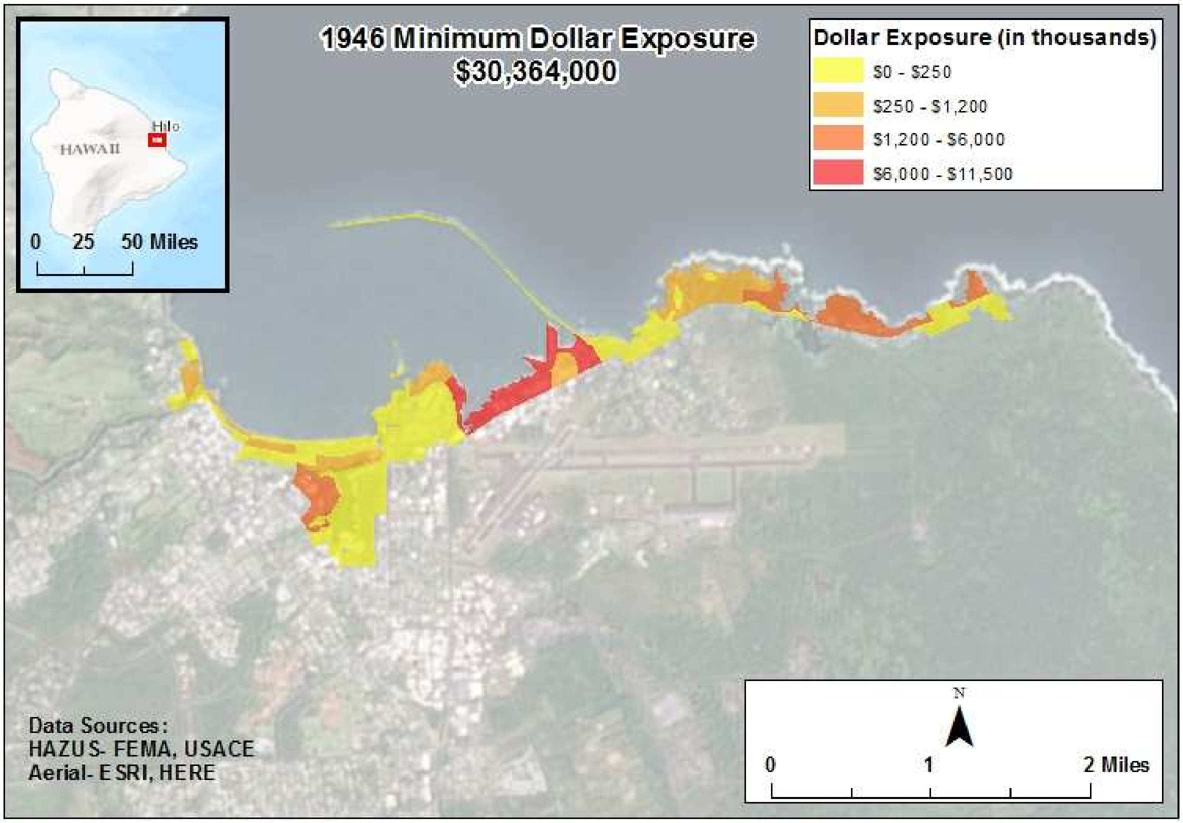

Figure 22. 1946 Minimum Dollar Exposure

The 1946 minimum dollar exposure for Hilo amounted to just over $46 million. This is quite a bit more than expected, considering the inundation levels are quite low. However, Hilo is particularly susceptible to coastal flooding because of its relatively low elevation. The areas of high dollar exposure seem to point to the same areas where hotels and buildings at risk are still located. The government district in downtown Hilo would experience some moderate dollar exposure, as do parts of the Waiakea Peninsula. The port would be the hardest hit area in this scenario as it covers a large portion of the eastern Hilo. The flooding does not seem to penetrate very deep into the mainland. Figure 23 shows the inundation depth for the 1946 maximum inundation scenario.

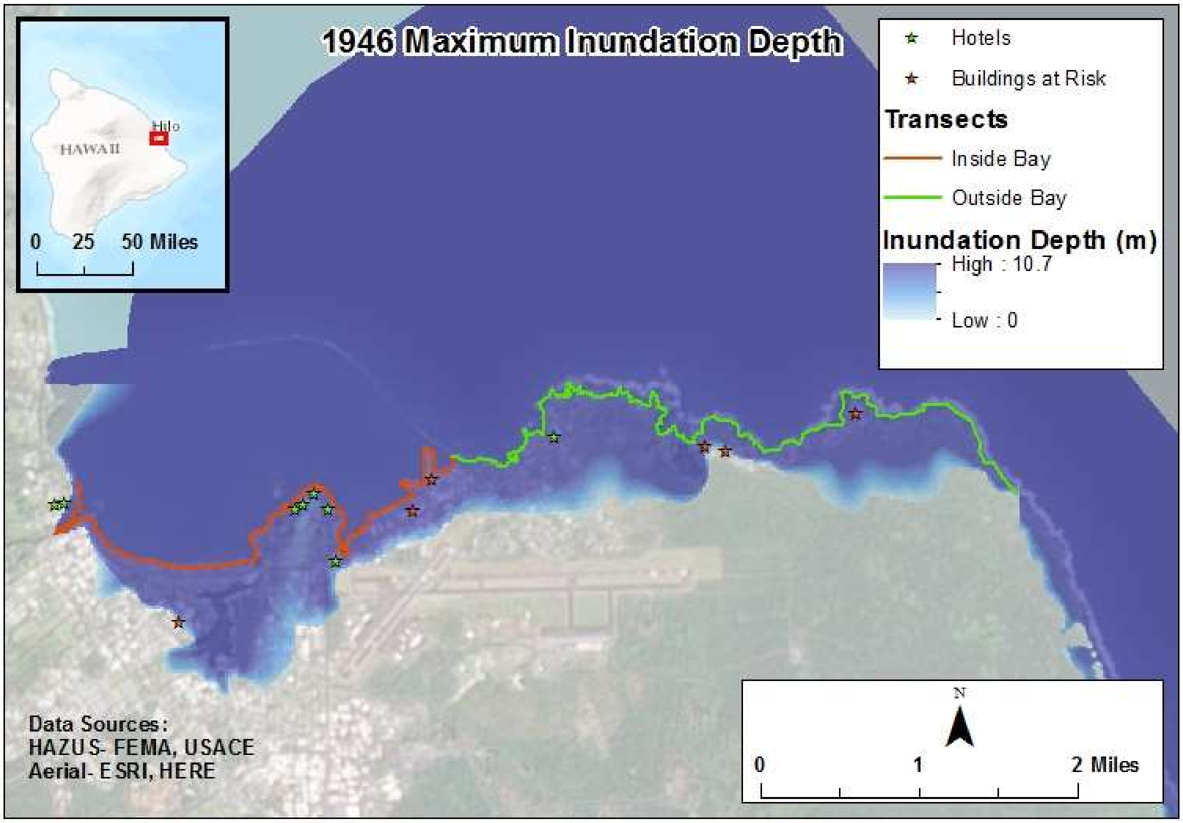

Figure 23. 1946 Maximum Inundation Depth

In contrast, the 1946 maximum inundation scenario in HAZUS appears to have penetrated much of the coastal areas of Hilo. The minimum inundation scenario had moderate flooding right along the coast, but this output shows extreme flooding several blocks into Hilo. This scenario shows inundation of 17.5 feet inside the bay and 15.7 feet outside of the bay. Hilo Bay would be subject to a great deal of flooding, and the Waiakea Peninsula would be completely inundated. The middle area of the peninsula may experience less inundation as opposed to the rest of the bay, which would be similar to what happened in 1946. The port area would be significantly flooded, as well as the government district in Hilo. The eastern portion of Hilo would also be inundated far into the island. Figure 24 shows the dollar exposure of the 1946 maximum inundation scenario.

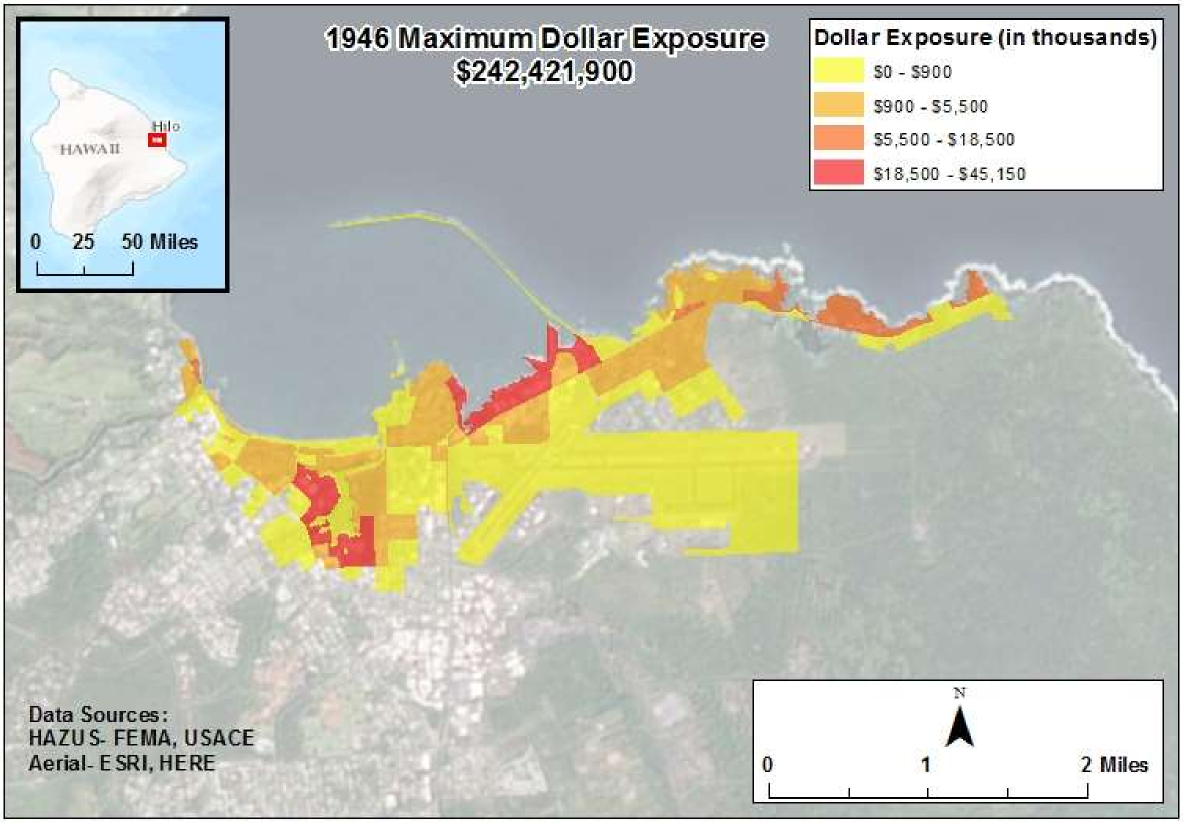

Figure 24. 1946 Maximum Dollar Exposure

The 1946 maximum dollar exposure scenario for Hilo amounted to over 242 million dollars in today costs. This is more in line with the historical accounts (Pararas-Carayannis 1977). As previously mentioned, inflated to 2016 dollars, the historical event claimed over $317 million, while including some property damage not estimated in HAZUS or SCHEMA. This brings the HAZUS estimate in line with historical estimates. The maximum scenario shows portions of the airport impacted that could wreak havoc on the local economy as well. While the inundation did not appear to reach the airport, the airport parcel is very large and extended into part of the inundated area. As a result, it is possible that several buildings on the airport grounds could be impacted. And, as expected, the government district, port terminals, and coastal area appear to be devastated in this scenario. Table 11 shows the historical, minimum, and maximum dollar exposure estimates.

Table 11. 1946 HAZUS Dollar Exposures. Source: (Pararas-Carayannis 1977)

1946 Dollar Exposure		
HAZUS Minimum	HAZUS Maximum	Historical
$46,277,435.00	$242,421,900.00	$317,509,330.00

The results for HAZUS appear to be similar to expectations. The maximum scenarios being modeled with current building parcels and census blocks would likely show less dollar exposure than the previous historical events. Many of the hardest hit areas in Hilo were either not rebuilt after 1960 or were built to withstand further tsunami events. The 1946 event was particularly devastating for the downtown area of Hilo, which no longer exists in its historical location. This seems to be a primary reason for the lower dollar exposure amounts. The 1960 tsunami event was equally devastating for Hilo, but it impacted different areas of the town.

4.2.2. 1960 HAZUS Inundation Scenario

The 1960 SCHEMA output suggests that the 1960 tsunami had a much larger impact within Hilo Bay than did the 1946 tsunami. This may be due to the increased magnitude of the tsunami originating earthquake, or possibly the direction that the tsunami waves were traveling around Hawaii. The 1960 event also had less inundation outside of Hilo Bay, to the east of Hilo. The 1960 event destroyed much of the port area and Waiakea Peninsula, which was largely spared from the 1946 tsunami. Table 12 shows the inundation values used for the 1960 event.

Table 12. 1960 HAZUS Inundation Values

1960 HAZUS Inundation Values (in feet)		
Location	In Bay	Outside Bay
Minimum Inundation Depth	4.6	1.3
Maximum Inundation Depth	21.2	7.1

Again, these units are in feet, which is the unit of measure used in HAZUS. A quick observation with the previous 1946 values is that the values outside of the bay are much lower than in 1946. The minimum inundation values are also both lower than their respective comparison values from 1946. The maximum inundation depth within the bay, however, is nearly 4 feet higher than in 1946. These values created stark differences between the areas impacted in each model. The 1960 tsunami did not uniformly impact the cost of Hilo, with some areas being much harder hit than others. Figure 25 displays the 1960 minimum inundation depth from the HAZUS model.

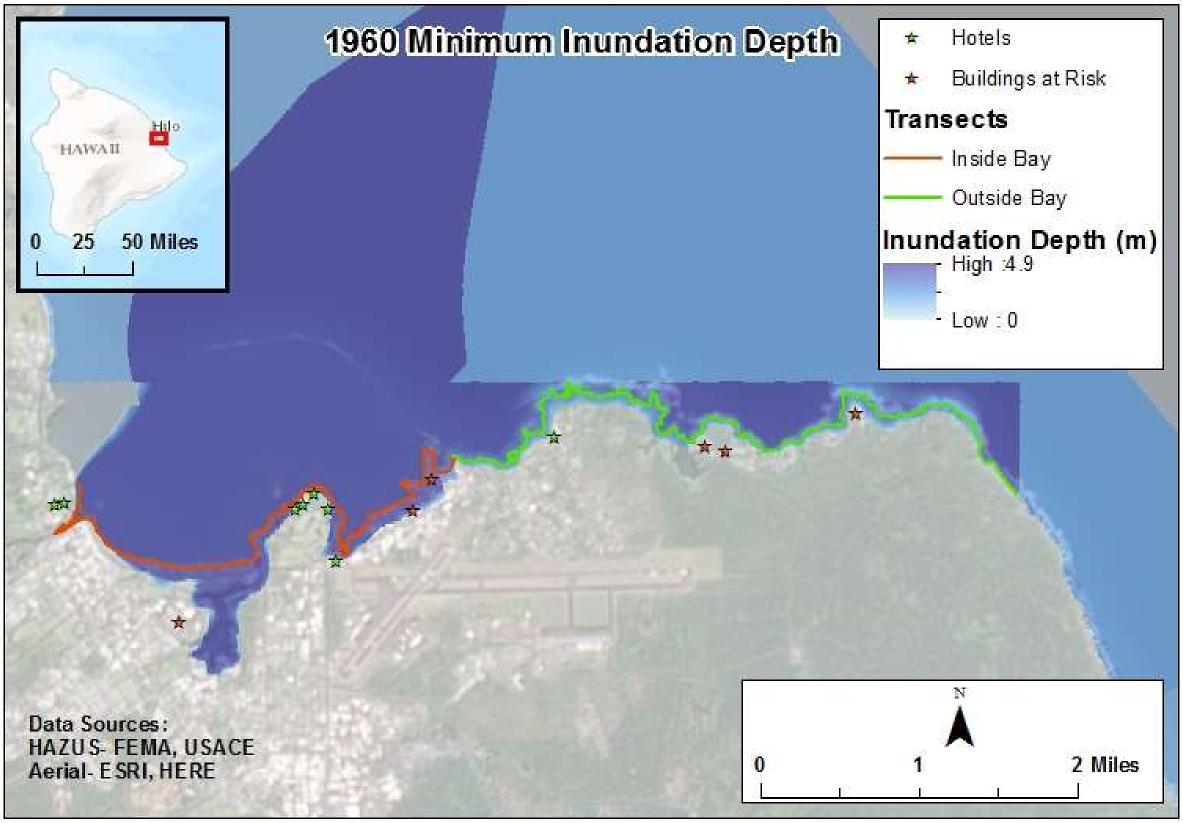

Figure 25. 1960 Minimum Inundation Depth

The 1960 minimum inundation scenario in HAZUS also seems to be very mild in comparison to the SCHEMA scenario results. With much lower values of inundation than seen in the 1946 model, the impact was relegated to only the coastal areas of Hilo. The flooding did not appear to impact anything other than beachfront properties. This scenario shows inundation of 4.6 feet inside the bay and 1.3 feet outside of the bay. Hilo Bay would experience very little flooding outside of the immediate area near the coast. The tsunami does seem to impact the port area, which would have led to moderate dollar exposure in that area. The eastern part of Hilo experienced very mild flooding along the coast, which is not likely to impact hotels or apartment buildings. Figure 26 displays the dollar exposure of the 1946 minimum inundation scenario.

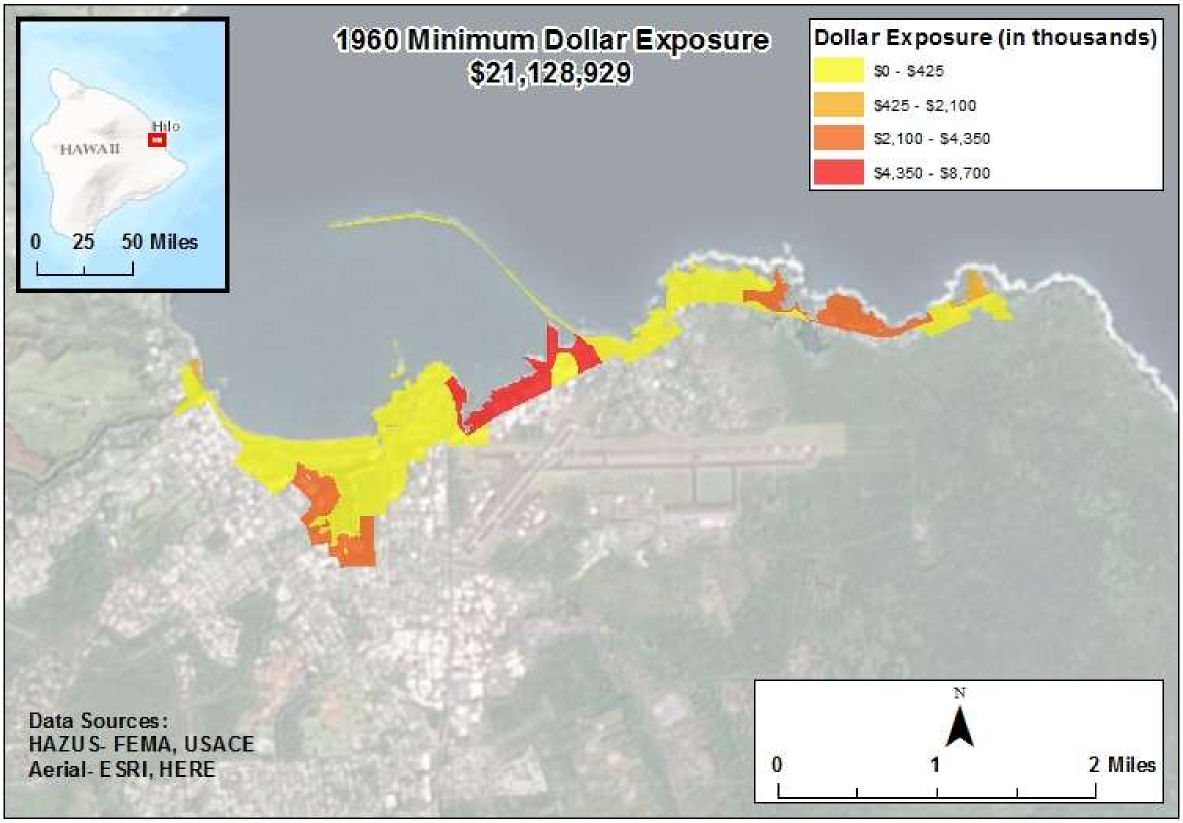

Figure 26. 1960 Minimum Dollar Exposure

The 1960 minimum dollar exposure scenario for Hilo amounted to just over 21 million dollars. This is a minor flooding event even for a large coastal community like Hilo. The dollar exposure seems to come from only a few locations. The government district shows moderate damage from inundation. These buildings are typically reinforced concrete and therefore are only expected to incur superficial damages. The port area is again one of the harder hit areas. This is a recurring theme and is expected for a coastal flooding event. A surprise in the 1960 minimum scenario is some moderate damage seen outside of the bay. One particular parcel that was hit hard, shown in the darkest color (reddish-orange), is situated at a very low elevation. This dollar exposure could be due to buildings or docks built right on the ocean. The flooding around Hilo is very mild and would be a best case scenario for a large tsunami event. Figure 27 shows the inundation depth for the 1960 maximum inundation scenario.

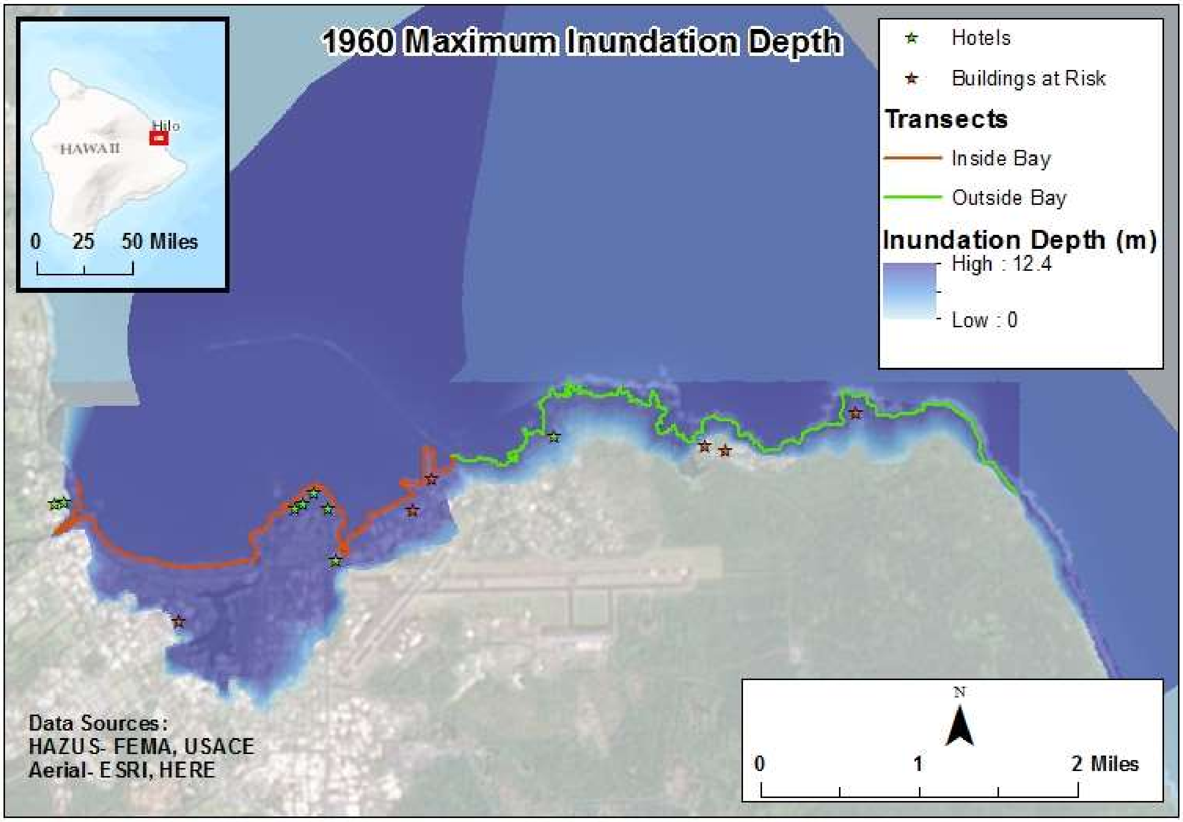

Figure 27. 1960 Maximum Inundation Depth

The 1960 maximum inundation scenario in HAZUS penetrates much of the coastal areas within Hilo Bay. The flooding outside of the bay is very moderate in comparison to the 1946 scenario. The 1960 minimum scenario had very mild flooding throughout, but the 1960 maximum scenario flooded much of the urban area around Hilo Bay. This scenario has an inundation of 21.2 feet inside of the bay, and 7.1 feet outside of the bay. The government district appears to be heavily inundated, as is much of the Waiakea Peninsula. In 1960 the historical tsunami event was well known for destroying much of Waiakea Peninsula. Since the 1946 tsunami heavily hit downtown but spared much of the peninsula, Hilo citizens who experienced the 1946 event thought that a similar event would take place and felt safe within Waiakea Peninsula in 1960. As this flooding scenario shows, the peninsula was greatly impacted and saw many lives lost throughout Hilo in the 1960 tsunami. This event overall had a much lower dollar exposure outside of the bay but saw a similar total to 1946 due to the heavy inundation within Hilo Bay. Figure 28 shows the dollar exposure of the 1960 maximum inundation scenario.

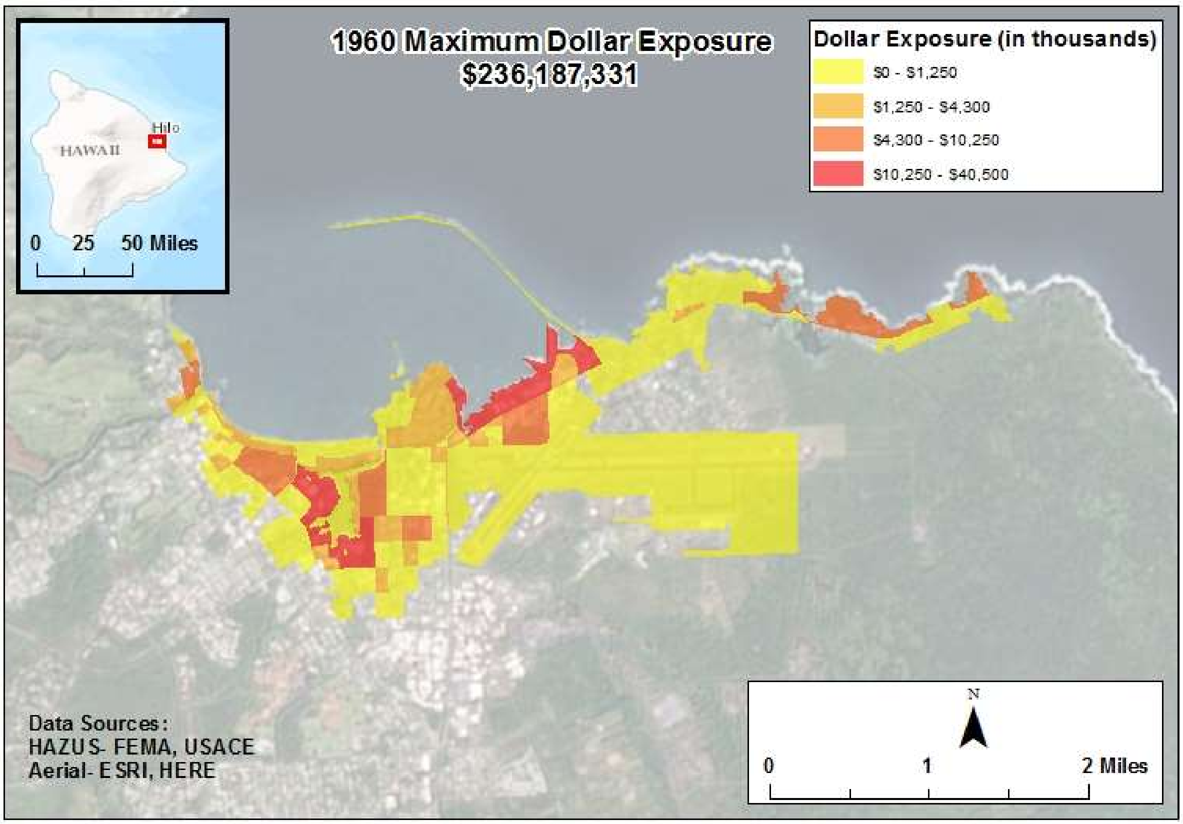

Figure 28. 1960 Maximum Dollar Exposure

As expected the 1960 maximum inundation scenario causes much of the dollar exposure within the Hilo Bay, while outside of the bay there is much less destruction. The 1960 maximum dollar exposure for Hilo amounted to just over 236 million dollars. The historical amount, inflated to 2016 dollars, comes to just over $185 million. The 1960 HAZUS maximum scenario shows a higher dollar exposure than the actual historical event. Part of this may be due to the maximum inundation traveling farther into the heart of Hilo than the actual tsunami was likely to have done. Due to the varied areas of flooding in 1960, this tsunami was particularly hard to accurately model. The areas of the highest dollar exposure to this tsunami event are again the government district and the port area. The downtown area of Hilo, which was pushed further inland, also appears to be moderately impacted by this scenario. The Waiakea Peninsula saw heavy inundation in this scenario but did not have a high dollar exposure. This is due to the type of buildings found on the peninsula. Most of the construction on the peninsula is reinforced concrete hotels and apartments which are likely to withstand even a large tsunami with only moderate dollar exposure. Table 13 shows the historical, minimum, and maximum dollar exposure values.

Table 13. 1960 HAZUS Dollar Exposures. Source: (Pararas-Carayannis 1977)

1960 Dollar Exposure		
HAZUS Minimum	HAZUS Maximum	Historical
$21,128,929.00	$236,187,331.00	$185,035,000.00

These results for the HAZUS scenario are mostly in line with expectations. The historical amount was expected to be higher than the maximum inundation scenario. However, it is reasonable to expect a higher number for the maximum scenario due to an increased area of inundation inside Hilo Bay. After the 1960 event, downtown was not rebuilt in the same location and was moved several blocks further south. This new downtown area appears to be moderately impacted by the maximum inundation scenario, which may explain the higher dollar exposure. These historical tsunami events are important to study for planning purposes, but there are many unknown risks throughout the Pacific Ocean from tsunami-earthquakes that can strike at any moment.

4.2.3. 2016 HAZUS Inundation Scenario

Hilo is always at risk of a disastrous tsunami event, but history does not always point to future results. Due to the nature of variation in earthquake occurrences, it is unlikely that historical tsunamis would happen in the same way. There are some large faults in the Pacific Ocean that have not yet created recordable tsunami events in Hilo. The Cascadia fault has not produced a large scale earthquake in hundreds of years, but it is expected to create one in the next several hundred (Atwater, Yamagushi, and Satoko 2005). This area has the potential to create a devastating tsunami that may hit Hilo. To model a worst-case scenario, the highest values from the two historical tsunamis are used in a 2016 maximum inundation scenario. This 2016 scenario uses the inside bay value from 1960 and the outside bay inundation value from 1946. Table 14 shows the inundation values for a 2016 worst-case scenario.

Table 14. 2016 HAZUS Inundation Values

2016 HAZUS Inundation Values (in feet)		
Location	In Bay	Outside Bay
Inundation Depth	21.2	15.7

These values of inundation display the highest historically referenced values for a potential maximum inundation event. These values, like the previous maximum inundation scenarios, are one standard deviation above the mean for each area. The intent is to show the impact of a plausible worst-case tsunami event that could impact Hilo. This scenario shows the devastating potential of a significant tsunami event, with a more uniform inundation throughout the entire Hilo area. Figure 29 displays the inundation from a worst-case scenario.

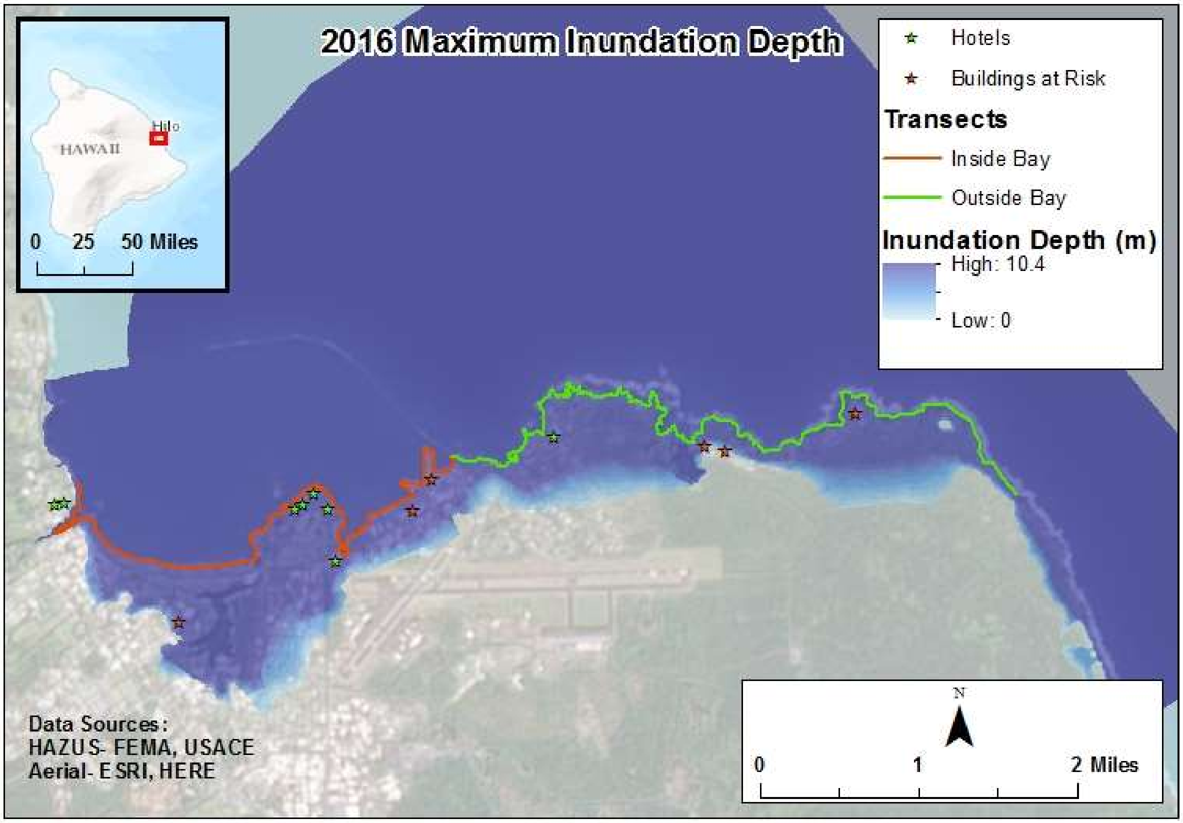

Figure 29. 2016 Maximum Inundation Depth

This 2016 maximum inundation scenario uses a modern DEM to ensure that the elevation correctly reflects current conditions. This current DEM may decrease the dollar exposure considerably as the coastal area has been reshaped and rebuilt over the years to prepare for future tsunami events. Despite using a different DEM, the scenario results are very similar to 1960 inside Hilo Bay. The downtown area still seems to be partly impacted, while the government district is heavily inundated. The Waiakea Peninsula and port area are also under a considerable amount of water. Outside of the bay, the inundation appears to be similar to 1946, with less area of inundation. The residential area north of the airport still appears to be heavily inundated, but some of the more severe flooding missed several of the larger buildings. Figure 30 shows the dollar exposure of the 2016 maximum inundation scenario.

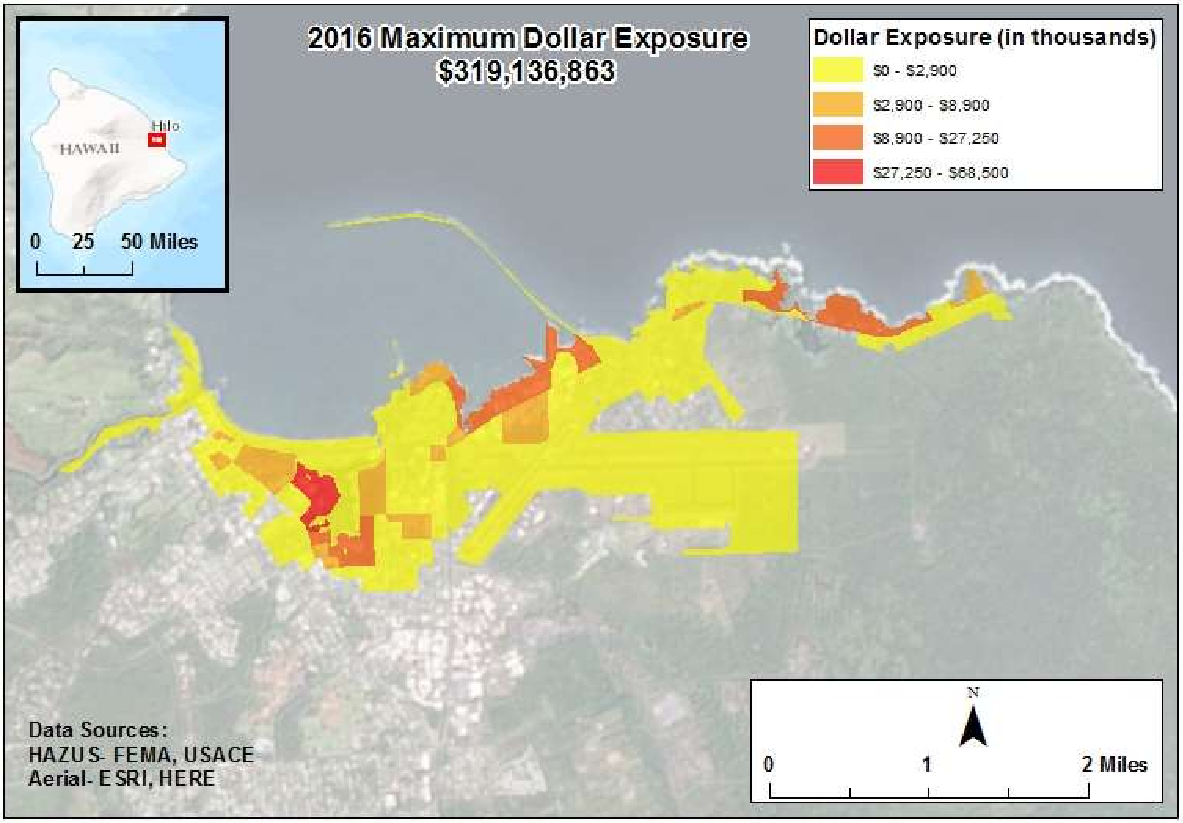

Figure 30. 2016 Maximum Dollar Exposure

The 2016 maximum inundation scenario did not result in the highest dollar exposure by a wide margin. This was expected due to the high inundation values of the historical events, although the updated DEM seemed to contribute to the analysis predicting more disastrous inundation in the eastern portion of Hilo. The downtown area and government district seem to be the hardest hit areas in the 2016 scenario. The Waiakea Peninsula and port area both seem to have significant inundation similar to the 1960 maximum inundation scenario. The real difference between the historical models and the 2016 scenario is the eastern part of Hilo, which was not hit as hard as expected. Figure 31 shows the maximum dollar exposures for each year using the HAZUS models.

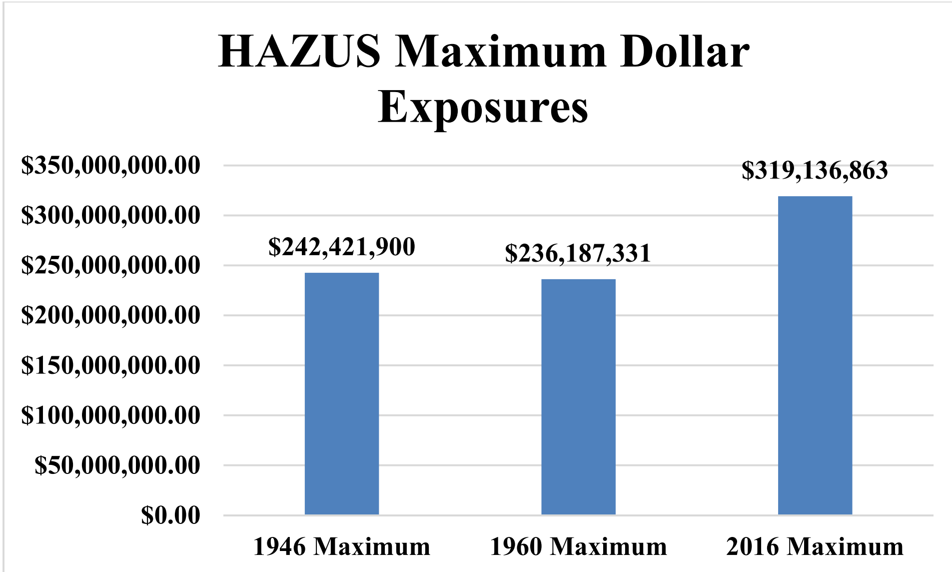

Figure 31. HAZUS Maximum Dollar Exposures

These maximum dollar exposure results were as expected. The updated DEM seems to contribute to the analysis predicting more severe inundation in Hilo, while still having the highest dollar exposure due to higher inundation values. These results suggest that despite careful planning, Hilo is still at the mercy of tsunamis.

4.3 Historical Comparison

HAZUS is a comprehensive program designed to plan for natural disasters, but it is not currently built to model tsunamis. ArcGIS is the framework for HAZUS, but it does not include the technical modeling framework within HAZUS. Before the modeling was completed, it was expected that the SCHEMA models would fall within the HAZUS output ranges for each scenario. This was proven to be correct, with each SCHEMA scenario analyzed coming closest to the outputs of the minimum inundation scenarios. Each model has its benefits but also negatives when attempting to accurately model a historical tsunami.

4.3.1. 1946 Tsunami

The 1946 scenarios results indicated uniform inundation throughout the study area. Areas both inside and outside of the bay saw moderate to severe inundation as Hilo's coastal defenses proved inadequate. Figure 32 shows the total dollar exposure for the 1946 tsunami event in each model.

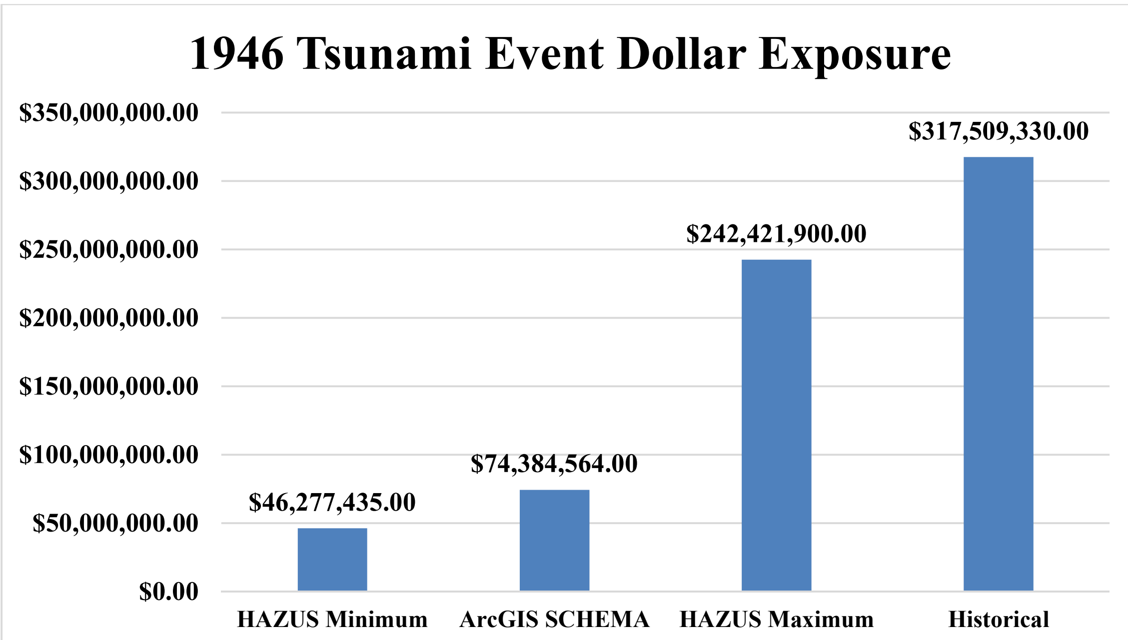

Figure 32. 1946 Tsunami Dollar Exposures

The SCHEMA model provided a promising output for total dollar exposure of buildings. It was well within the range of the HAZUS models, and significantly lower than the Historical dollar exposure total, which was expected. If an identical tsunami was to hit Hilo today, it would likely cause damages within the range of those predicted by HAZUS, and also close to the SCHEMA model outputs when considering building losses. The lower dollar exposures for each model, compared to the historical dollar exposure, suggests that Hilo has done well in preparation for similar tsunami events.

4.3.2. 1960 Tsunami

The 1960 scenarios resulted in very uneven inundation throughout the study area. Areas inside Hilo Bay saw the highest levels of inundation, while areas to the east of the bay only saw moderate inundation levels. It would be tough for any town to significantly prepare for inundation to the scale of the 1960 tsunami event. Figure 33 shows the total dollar exposure for the 1960 tsunami event in each model.

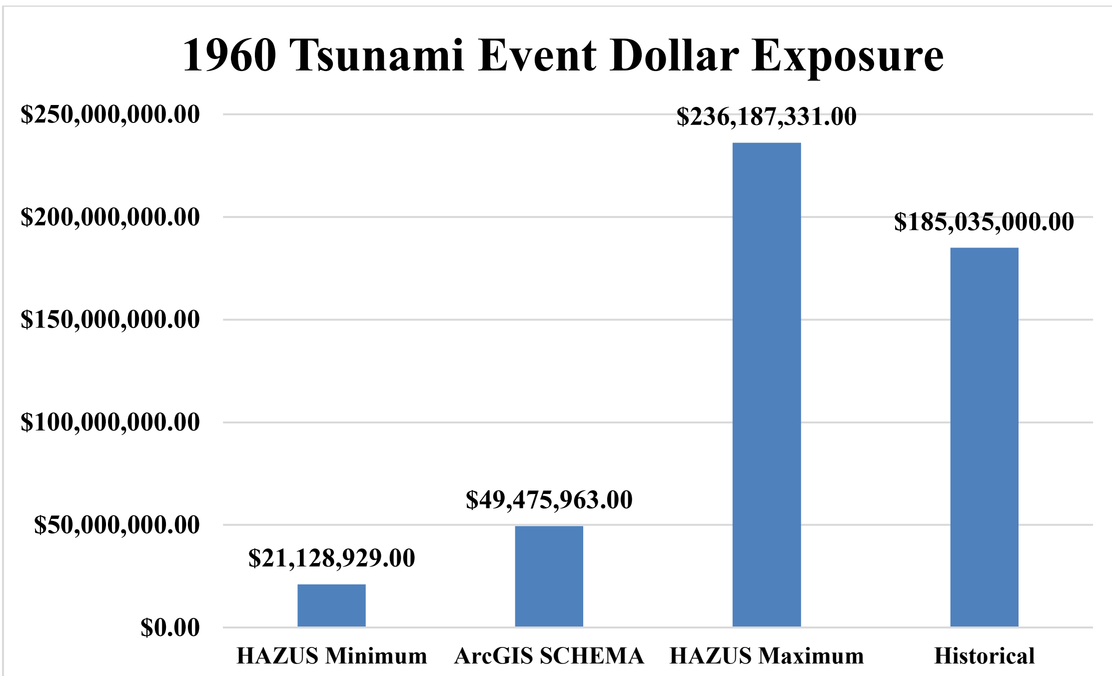

Figure 33. 1960 Tsunami Dollar Exposures

Again the SCHEMA model provided a promising output for total dollar exposure of buildings. The accuracy of the dollar exposure for the SCHEMA is very similar to the 1946 output. It is well within the range of the HAZUS models, and relatively close to the minimum inundation HAZUS output. It is also significantly lower than the historical dollar exposure total. A similar event to 1960 tsunami would likely cause less than $100 million in damage, closer to the SCHEMA model prediction when considering just building losses, as previously stated.

The HAZUS maximum value is a moderate cause for alarm, as a somewhat larger tsunami event may result in new records of dollar exposure due to the number of large buildings located near the ocean. It would take a very large event to impact many of these new buildings, but it is possible.

Chapter 5 Conclusions and Future Work

Research question 1) was to discover if the SCHEMA and HAZUS methodologies can be used to estimate damage to the built environment of historical tsunami events in the city of Hilo, Hawaii. It is clear that both SCHEMA and HAZUS are successful in providing relevant results in modeling the impact of tsunami inundation on the Hilo built environment. These methodologies tested the possibility of accurately modeling the tsunami inundation to estimate potential economic losses to the built environment caused by a large tsunami event. This research suggests that not only does the SCHEMA model compliment and compare to the HAZUS Flood Model, but both HAZUS and the SCHEMA models provided outputs comparable to economic costs incurred due to historical tsunami events.

Research question 2) was to determine if the SCHEMA model results in calculating potential tsunami inundation damage to the built environment are similar or different compared to results obtained using the HAZUS coastal flood model for a given event. There are many variables in modeling tsunamis that can make it challenging to test all possible variations within a given model. Focusing on inundation and building dollar exposure appears to have been successful using the SCHEMA model. A practical and suitable model was built to model tsunami inundation using the SCHEMA methodology was built in ArcGIS as part of this thesis work. Both SCHEMA outputs for the 1946 and the 1960 tsunamis fell within the HAZUS range of dollar exposure outcomes. The coastal flooding model within HAZUS is an accurate and proven model, which suggests that the SCHEMA model should also be a possible tool to model coastal flooding from a tsunami. Modeling tsunamis is still a work in progress due to the fact that tsunamis are not static disasters and require more comprehensive modeling techniques to increase the accuracy of models.

5.1 Recommendations

Tsunami preparedness is essential to both mitigate property loss and the loss of lives in a large tsunami event. For many coastal communities that cannot be relocated, mitigation is their only option. For most communities in the Pacific basin, the threat of a tsunami is uncertain, and in most cases the probability of occurrence and recurrence intervals are not known (Eisner 2005). Detecting areas of vulnerability is crucial for the future of coastal communities around the Pacific Ocean. Proactive coastal communities are the ones who plan for the worst but hope for the best.

Neither the HAZUS model nor the SCHEMA model factored in direction or velocity of tsunami waves when estimating the economic loss. Due to the absence of modeling the flow and velocity of waves, it is unclear if the current breakwater in Hilo would have any impact on a tsunami event, or if additional breakwaters would be beneficial. In 1946 it was determined that the breakwater, though partly destroyed, helped to absorb some of the tsunami's energy (Miller 2011). While not modeled in this study, it is likely that an upgrade to the existing seawall, or an additional seawall extended from the cliffs Northwest of Hilo Bay, would also absorb some of the impacts of future tsunamis. If it is determined that the aesthetic beauty of Hilo Bay should not be compromised by an onshore seawall, then an additional breakwater may help to mitigate future tsunamis economic impact without significantly blocking the views of the Pacific Ocean.

A highly relevant case study, in the most recent Japanese tsunami in 2011 a tsunami wave as high as 50 feet destroyed many towns along Japan's coast. Also, tsunami events in 1896 and 1933 killed a total of 439 in the small fishing village of Fudai (NBC News 2011). However, the major of the town of Fudai, Kotaku Wamura, learned from the past and decided that this would not happen again. Kotaku Wamura fought for 40 years for many years to obtain the funds to build an immense seawall construction project to project Fudai. Indeed, this 51 foot high seawall protected and saved the town from major damage due to the 2011 tsunami, while communities nearby were completely destroyed and thousands of people lost their lives (CBS News 2011). Figure 34. Fudai Seawall (Adapted from the Associated Press 2011) shows the seawall that Fudai built under the guidance of Kotaku Wamura.

Figure 34. Fudai Seawall (Adapted from the Associated Press 2011)

Since Hilo was heavily economically impacted by several tsunamis in the last 75 years, this research strongly indicates that the city of Hilo should consider building a seawall. If a seawall is determined to be the most prudent mitigation technique in Hilo, there could be a number of ways to fund such a project. A special sales tax over several decades, such as for touristic goods and services, could help fund a large seawall. Also encouraging a local tax referendum could increase tax spending to create a new revenue stream to be used for tsunami mitigation. Nevertheless, it is also important to understand the negative impacts of a seawall. Hilo may see a reduction in tourists if the views of Hilo Bay become obstructed by a new seawall. The citizens of Fudai, Japan understood their vulnerable coastal community. It is important to note that until the seawall was tested by the 2011 tsunami, it was locally despised and viewed as a waste of tax dollars (NBC News 2011). A new seawall in Hilo might also be seen as a waste of money and an eyesore until a tsunami is held at bay by such a structure in the Hawaiian Islands or other South Pacific island cluster.

The importance of this research is rooted in the knowledge that it could impart to urban planners in coastal communities in understanding the potential damages that a wide range of tsunamis may have on a coastal community. Regardless of the location, even a relatively small tsunami can cause millions of dollars-worth of damage. Urban planners with access to ArcGIS can create their rudimentary tsunami inundation models to see roughly where their communities stand against a tsunami threat. They can also use a HAZUS Flood Model to determine potential dollar exposure if they are aware of the height of flooding.

If a seawall and breakwater are not the desired mitigation techniques, increased scrutiny of construction practices and more restrictive building codes could be another positive mitigation option. Water just 7 feet deep will have pressure of 450 pounds per square foot. The deeper the water, the greater the pressure on the walls of a structure (Reid Steel 2015). According to Reid and Steel (20150, for example, if buildings are going to be built at low elevation along a shoreline, it is better to build them such that so that water can flow under them. Suspended floors with concrete framing on stilts can survive some of the force of an unexpected wave. In contract, although timber-framed buildings are good construction material in earthquake prone areas because they are light and thus the effects of earthquakes are reduced, timber is the worst possible choice in tsunami-prone areas. The wood in these buildings is easy to lift off of a foundation and will float just like a ship if not adequately tied down. These wooden structures also create floating debris which can then destroy other buildings and cause additional loss of life.

To build tsunami resistant buildings, wave surges should be avoided by building the buildings out of the projected wave paths (Reid Steel 2015). A building may need to be suspended on stilts to prevent a lower floor being inundated with water. Foundations should also be deeper than usual and braced down to the footings of the foundation. Lower floors should be made with concrete to give the building some weight, while steel frames should be used to resist substantial loads in the case of a wall collapse. Tsunami-prone areas tend also to be in Hurricane and Earthquake-prone areas as well. It is important to try and build structures that can be structurally safe in any disaster environment.

HAZUS has many capabilities that were not fully explored in this research. The research was more focused on the viability of a SCHEMA model, and HAZUS was used primarily as a way to compare and validate the output data. HAZUS also allows post-disaster debris calculations that could be completed with any coastal flooding model. Adding in this component analysis and comparing it to historical information could provide more insight to potential future dollar exposure overall. FEMA has also been working on including turbidity in more aspects of the HAZUS Flood Model, which would be crucial for modeling tsunamis. HAZUS also does not currently have the capability to integrate bathymetry data in a coastal flooding scenario. HAZUS is more focused on terrain above sea level, so bathymetry analysis capabilities would need to be created before HAZUS can model tsunamis (FEMA 2015).

For emergency management purposes, HAZUS could continue to be the go-to model when time is crucial as long as long as HAZUS default datasets are deemed adequate for the task at hand. ArcGIS models such as a SCHEMA implementation can become more comprehensive than HAZUS, but that only happens with research, access to quality input data, and time spent refining the model. There are several levels of HAZUS models that include more comprehensive datasets and input data, but the scope of HAZUS is still limited in comparison to the entire ArcGIS suite of tools and software. As additional tsunami data becomes available, both ArcGIS and HAZUS should become more accurate at replicating tsunamis and also predicting potential economic loss. HAZUS is currently more efficient at modeling specific disasters using static values, whereas with the advanced interpolation tools within ArcGIS there may be room for improvement using a customized ArcGIS model, as opposed to the closed backend data processing system of HAZUS. Most importantly, tsunamis are not static waves (floods) and are better modeled using a dynamic method. On the upside, FEMA's HAZUS team is refining their flooding models at every update and appear on track to be eventually able to model tsunamis accurately within HAZUS.

Throughout the modeling process, a range of issues arose that either redirected the project or slowed it down. Creating historical elevation models to use as a base for each historical scenario was not originally planned when starting this project. However, tsunamis and local planning projects can dramatically shape the landscape over the decades. It was essential that historical elevation models were utilized to make sure that the model was being run using historical terrain conditions.

5.2 Future Work

Future amendments to this study could be numerous depending on the goals of future research. Specifically, using data from HAZUS within a SCHEMA study, and vice-versa, could provide additional insights into the strengths of each model and the accuracy of the output data.

In the future, to further this study it is recommended that an up-to-date AEBM dataset is incorporated into the HAZUS models. The AEBM provides the most accurate building-specific HAZUS analysis (FEMA 2014). For mitigation purposes, it would be useful for users to be able to create building-specific damage and loss functions that could be used to assess potential losses at a very high accuracy. This would provide a more specific economic loss estimate compared to the general building functions found in the default data for HAZUS.

Inundation depth rasters that were created in ArcGIS for the SCHEMA model could be used in HAZUS to simulate the same flooding conditions, and to evaluate the building stock in HAZUS with the ArcGIS parcel information. This was not done in the initial research because that would only provide insight into the differences between the parcel layer and the building stock layer. It was imperative for this project to create a range, or base, of results that the SCHEMA model could be compared to. Using the building stock layer in ArcGIS could also provide more insight with how each model calculates dollar exposure. The census blocks in HAZUS may be too large regarding spatial extent to be used accurately in the SCHEMA model methodology, but it may be worth attempting. The accuracy of the SCHEMA building classification is always fair to question as the input data was compiled using visual inspection of recent aerial imagery and street view images. Finding or creating a more comprehensive building database would be essential for additional modeling.

Additional research could also include study areas of the Pacific basin where large earthquakes are likely to occur that could impact Hilo. The Cascadia tectonic boundary off the coast of Oregon and Washington has long been suspected of being capable of producing large tsunamis. There has been sediment found throughout the Pacific basin from a large tsunami event that occurred in the 1600's that may point to a future Cascadia earthquake and resulting tsunami. Further research into potential sizes of historical Cascadia tsunamis and the likelihood of future earthquakes would make for a comprehensive extension of this research.

In-depth terrain changes throughout Hilo since the 1946 tsunami would also be a worthwhile addition to this research. Aside from tsunamis changing the landscape, Hilo has built different variations of seawalls, extended the beach into the ocean, and turned previous commercial and residential areas into green space along the coast. Some of these were created to mitigate tsunamis, but the full impact has not been studied. Continuing this research by evaluating terrain changes and building code changes over the years would be helpful in finding out what may be working, and what could be useful for other coastal communities as well to help them mitigate potential tsunamis. Related to terrain changes, one challenge is to find accurate DEMs to use as historical references. Historical DEM's often were created from topographic maps that either had too few contour lines or questionably accuracy. These historical topographic maps were still very useful in creating historical DEM's as long as their limitations are understood, but there may be more efficient or accurate ways to determine historical elevation levels.

Thought this study required a great deal of time and effort to analyze the impact of such a random disaster, tsunamis are some of the most destructive natural disasters we face. Luckily, coastal communities typically receive a warning before impacts, but the physical damage cannot be mitigated in a short time. These model results appear to be indicative of stricter building codes and better urban planning and zoning. The town of Hilo seems to understand that they cannot deter future tsunamis, only try to avoid inundation or build structures that can withstand it. Even the smallest coastal communities should not overlook a tsunami preparedness plan, and should be aware of how vulnerable they may be to a tsunami event. For the safety of these communities, damage estimation models should be nurtured, and resources should be shared to educate anyone potentially impacted. It would be useful to replicate this study with refined tools, and updated data, to extend this research and help perfect the dynamic tsunami modeling process.

REFERENCES

AIA. 2009. “A Community-Based Vision and Living Action Plan for Downtown Hilo.” Paper presented at the AIA SDAT conference, Hilo, HI, May 5-8. Accessed February 25, 2016. http://www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab080963.pdf.

Atwater, Brian F., David K. Yamaguchi, Musumi-Rokkaku Satoko. 2005. “Orphan Tsunami of 1700: Japanese Clues to a Parent Earthquake in North America.” *Professional Paper* 1707: 1-42.

Bernard, Eddie N., 2005. “The U.S. National Tsunami Hazard Mitigation Program: A Successful State-Federal Partnership.” *Natural Hazards* 35, no. 1: 5-24.

BLS. 2016. “CPI Inflation Calculator.” Accessed February 23, 2016. http://www.bls.gov/data/inflation_calculator.htm.

Britannica Academic. 2015. "Chile earthquake of 1960," Accessed September 14, 2015. http://academic.eb.com/EBchecked/topic/1421130/Chile-earthquake-of-1960.

Bryant, Edward. 2008. *Tsunami: The Underrated Hazard.* Chichester, UK, Praxis Publishing.

CBS News. 2011. “The Man Who Stopped The Tsunami.” Accessed April 24, 2016. http://www.cbsnews.com/news/the-man-who-stopped-the-tsunami/.

Cheung, Kwok Fai, Yefei Bai, Yoshiki Yamazaki. 2013. “Surges around the Hawaiian Islands from the 2011 Tohoku Tsunami.” *Journal of Geophysical Research* 118: 5703-5719.

Davidson, Sarah. 2004. “Mystery of Deadly 1946 Tsunami Deepens.” Accessed February 15, 2016. http://www.livescience.com/3732-mystery-deadly-1946-tsunami-deepens.html.

Dominey-Howes, Dale, Paula Dunbar, Jesse Varner, Maria Papathoma-Kohle. 2010. “Estimating probable maximum loss from a Cascadia tsunami.” *Natural Hazards* 53: 43-61.

Eaton, J. P., D. H. Richter, W. U. Ault. 1961. The tsunami of May 23, 1960, on the island of Hawaii. *Bulletin of the Seismological Society of America* 51: 135–157.

Eisner, Richard K. 2005. “Planning for tsunami: Reducing future losses through mitigation.” *Natural Hazards* 35, no. 1: 155-162.

ESRI. 2016. “How Kriging Works.” Accessed March 21, 2016. http://desktop.arcgis.com/en/arcmap/10.3/tools/3d-analyst-toolbox/how-kriging-works.htm.

FEMA. 2014. *Advanced Engineering Building Module (AEBM) Manual – HAZUS MR1*. Washington, D.C., Department of Homeland Security.

———. 2015. *Flood Model Technical Manual.* Washington, D.C., Department of Homeland Security.

———. 2015. *Flood Model User Manual.* Washington, D.C., Department of Homeland Security.

Greenslade, Diana J. M., Vasily V. Titov. 2008. "A Comparison Study of Two Numerical Tsunami Forecasting Systems." *Pure and Applied Geophysics* 165: 1991-2001.

King, Hobart. 2016. "Tsunami Geology- What Causes a Tsunami?" Accessed April 25, 2016. http://geology.com/articles/tsunami-geology.shtml.

Macdonald, Gordon A., Chester K. Wentworth. 1954. "The tsunami of November 4, 1952, on the island of Hawaii." *Bulletin of the Seismological Society of America* 44, no. 3: 463-469.

Mazzotti, Stephane, John Adams. 2004. "Variability of Near-Term Probability for the Next Great Earthquake on the Cascadia Subduction Zone." *Bulletin of the Seismology Society of America* 94, no. 5: 1954-1959.

Miller, Holly. 2011. "Waves of Change The Role of Tsunamis in the Changing Built Landscape on Mokuola Island in Hilo Bay, Hawai'i." *Hohonu* 9:19-28.

National Ocean Service. 2015. "What is a tsunami?" Accessed March 13, 2016. http://oceanservice.noaa.gov/facts/tsunami.html.

Natural Hazards Big Island. 2015 "Tsunami Hazards Mitigation" Accessed October 1, 2015. http://hilo.hawaii.edu/~nat_haz/tsunamis/.

NBC News. 2011. "How one Japanese village defied the tsunami." Accessed April 24, 2016. http://www.nbcnews.com/id/43018489/ns/world_news-asia_pacific/t/how-one-japanese-village-defied-tsunami/.

NOAA. 2015. "NOAA Tsunami Inundation Digital Elevation Models (DEMs)." Accessed December 15th, 2015. https://www.ngdc.noaa.gov/mgg/inundation/tsunami.

Office for Costal Management. 2015 "Hawai'i Tsunami Hazard Information Service." Accessed October 1, 2015. https://coast.noaa.gov/regions/pacific/resources/tsunami/.

O'Sullivan, Mike. 2015. "Hawaii, Vulnerable to Tsunamis, Prepares for the Worst." Accessed April 24, 2016. http://www.voanews.com/content/hawaii-vulnerable-yo-tsunamis-prepares-for-the-worst/2631262.html.

Palmer, Robert Q., Michael E. Mulvihill, Gerald T. Funasaki. 1965. *Hilo Harbor Tsunami Model – Reflected Waves Superimposed.* Honolulu, HI, American Society of Civil Engineers.

Pararas-Carayannis, George. 1977. *Catalog of Tsunami in the Hawaiian Islands*. Boulder, Co, World Data Center A for Solid Earth Geophysics.

Peters, Robert, Bruce Jaffe, Guy Gelfenbaum. 2007. "Distribution and sedimentary characteristics of tsunami deposits along the Cascadia margin of western North America." *Sedimentary Geology* 200: 372-386.

Reid Steel. 2016. "How to Make Buildings Safer in Tsunamis." Accessed May 20, 2016. http://www.reidsteel.com/information/tsunami_resistant_building.htm.

Satake, Kenji, Kelin Wang, Brian F. Atwater. 2003. "Fault slip and seismic moment of the 1700 Cascadia earthquake inferred from Japanese tsunami descriptions." *Journal of Geophysical Research.* 108, no. 11: 1-17.

Satake, Kenji, Kunihiko Shimazaki, Yoshinobu Tsuji, Kazue Ueda. 1996. "Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami record of January 1700." *Nature* 379, no. 6562: 246-249.

Schneider, Phillip. 2011. *Solutions to Coastal Disasters 2011.* Washington, DC. American Society of Civil Engineers.

Shepherd, F., G. Macdonald, D. Cox. 1949. "The Tsunami of April 1, 1946." *Bulletin of the Scripps Institution of Oceanography* 5, no. 6: 6-33.

State of Hawaii. 2015. "Hawaii Statewide GIS Program." Accessed December 15, 2015. http://planning.hawaii.gov/gis.

Synolakis, Costas E., Eddie N. Bernard, Vasily V. Titov, Utku Kanoglu, Frank I. Gonzalez. 2008. "Validation and Verification of Tsunami Numerical Models." *Pure and Applied Geophysics* 165: 2197-2228.

Tang, Liujuan, Vasily V. Titov, Christopher D. Chamberlin. 2010. "A Tsunami Forecast Model for Hilo, Hawaii." *NOAA OAR Special Report, PMEL Tsunami Forecast Series* 1: 1-96.

Tinti, Stefano, R. Tonini, L. Bressan, A. Armigliato, A. Gardia, R. Guillande, N. Valencia, S. Scheer. 2011. *Handbook of Tsunami Hazard and Damage Scenarios.* Luxembourg, Publications Office of the European Union.

USGS Hawaiian Volcano Observatory. 1998. "Tsunami Generated by Magnitude 7.7 Earthquake on November 29, 1975." Accessed October 19, 2015. http://hvo.wr.usgs.gov/earthquakes/destruct/1975Nov29/tsunami.html.

———. 1998. "The 1960 Tsunami, Hilo." Accessed November 12, 2015. http://hvo.wr.usgs.gov/volcanowatch/archive/1994/94_05_20.html.

USGS. 2015. "Light Detection and Ranging (LIDAR)." Accessed May 20, 2016. https://lta.cr.usgs.gov/lidar_digitalelevation.

USC Tsunami Research Group. 2002. "1957 Aleutian Tsunami." Accessed October 9, 2015. http://cwis.usc.edu/dept/tsunamis/alaska/1957/webpages/index.html.

World Atlas. 2015. "What and Where is the Ring of Fire." Accessed September 27, 2015. http://www.worldatlas.com/aatlas/infopage/ringfire.htm.

Wu, Tso-Ren, Hui-Chuan Huang. 2009. "Modeling tsunami hazards from Manila trench to Taiwan." *Journal of Asian Earth Sciences* 36: 21-28.

Xie, Jinsong, Ioan Nistor, Tad Murty. 2011. "Tsunami risk for Western Canada and numerical modelling of the Cascadia fault tsunami." *Natural Hazards* 60:149-159.