# Visualizing Tsunami Inundation

Rebecca Butler
Seattle Pacific University
Seattle, WA 98119, USA
butlerr1@spu.edu

Sarah Parbhu
Post Doctoral Fellow, Civil Engineering
Clemson University
Clemson, SC 29634, USA
saurabhp@clemson.edu

Sez Atamturktur
Associate Professor, Environmental Engineering and Earth Science
Clemson University
Clemson, SC 29634, USA
sez@clemson.edu

## ABSTRACT

Tsunami inundation is the measure of flooding resulting from a tsunami. Having an accurate forecast of the potential extent of inundation after a tsunami is vital for assessing the resulting damage and for appropriate construction planning in hazardous areas. In order to evaluate the size of a tsunami, the earthquake which triggered it must first be predicted. From this expected earthquake magnitude, the tsunami wave height is found via a regional-specific logarithmic relationship between earthquake and tsunami magnitudes. This predicted inundation level can then be plotted in geographic information system such as ArcMap. This paper covers three basic methods of mapping inundation levels using Esri Software. These methods are by raster calculation, by contour mapping, and by three dimensional modeling. In the case of Las Ventanas, Chile the contour mapping method was optimal, but the other methods could prove optimal under other geographic conditions.

## KEYWORDS

earthquake, probabilistic seismic hazard analysis, tsunami inundation

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## 1 INTRODUCTION

It is well known that earthquakes cause considerable physical damage. While ground motion alone produces devastating effects, tsunamis generated by earthquakes also have a large impact on the total extent of the damage done to an area or population. As a country with 6,435 km of coastline situated upon the juncture of the Nazca and South American plates, Chile is especially susceptible to the ramifications of a seismic event. A depiction of tsunami inundation depth and run up distance shown in Figure 1 are vital for accurately assessing the expected fallout from a seismically triggered tsunami event. The aim of this project is to visualize the potential tsunami inundation in Las Ventanas Bay, Chile via modeling in ArcGIS. This site is of particular interest as there are industrial facilities and residential developments along the shores of this bay. From concerned landowners to structural and risk engineers, the resulting map will provide a variety of individuals with a convenient and easily understood forecast of tsunami inundation in this region of Chile.


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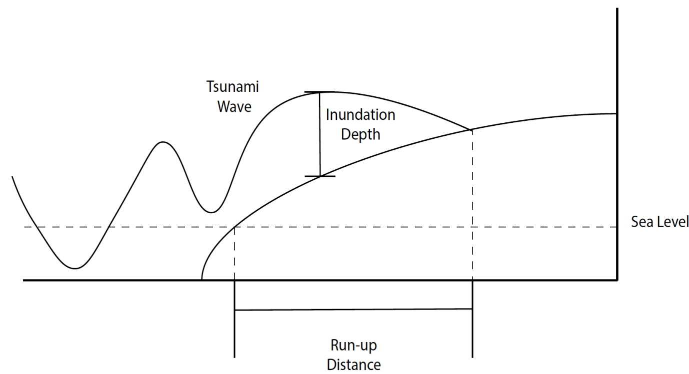


**Figure 1: Tsunami inundation and run-up distance are shown in this image. While tsunami inundation describes the depth of water at a loction, run-up describes how far inland the water has traveled.**

## 2 TSUNAMI INUNDATION ASSESSMENT

### 2.1 Seismic Event Prediction

In order to assess the expected severity of a tsunami, the magnitude of the seismic event which generated the wave must be predicted. This is a difficult undertaking as the regional mechanisms and conditions which produce seismic activity are not yet completely understood from a geoscientific perspective. In light of this problem, researchers use Probabilistic Seismic Hazard Analysis (PSHA) to predict a relationship between some measure of ground motion intensity and the mean return period for that intensity at a specified location. This analysis can be broken into five basic steps, the first of which is to identify all seismic sources which could potentially generate seismic events that effect a particular site of interest. These sources are fall into two broad typologies: faults and areal regions. Faults are physical breaks between two large portions of rock and are relatively simple to identify through geologic observation . In cases where a specific fault cannot be located, the seismic source is depicted as an areal region across which seismic events have an equal likelihood of occurring. The second step of PSHA is to determine rates at which various earthquake magnitudes are expected to reoccur at the location of interest. This rate is classically calculated using the Gutenberg Richter Recurrence Law. Thirdly, the distance from the source to the location of interest must be calculated. This a fairly straightforward calculation, as it can be found through the geometric arrangement of the source and the site of study. The only potential pitfall when calculating these distances is the choice of of source location. While some studies measure from the epicenter to the site of interest, others may use the hypocenter, nearest point of surface rupture. After this, a ground motion prediction model must be determined. This equation gives the magnitude of ground motion intensity as a function of a number of predictive parameters including but not limited to the magnitude of the earthquake, the faulting mechanism, distance to the hypocenter, and soil conditions. As previously mentioned, there is a relatively small amount of observational data for earthquakes of large magnitudes, but there is enough data to develop ground motion prediction models via statistical regression of large ground motion intensity data libraries. Finally, the location, return rate, distance, and Ground Motion Intensity Model must all be combined to achieve the desired result of the predicted rate of exceedance of some measure of ground motion intensity. These elements are combined using several probabilistic equations, which Baker describes in detail. [1] PSHA is a computationally demanding process when considering all sources in a region for a large number of sites. OpenQuake is a widely-used open source engine which performs seismic hazard and risk analyses, developed and continually improved in a collaborative effort involving researchers from several countries. [3] In regards to seismic hazard, the user need only input a site location model, time frame, the ground motion intensity of interest, a seismic source model, and a ground motion prediction equation logic tree. From this information, the OpenQuake-engine will compute the probability of exceedance of the specified ground motion, under the particular designations set by the user. Although the utilization of the OpenQuake-engine significantly reduces the human computation effort involves in PSHA, the development of the seismic source model and ground motion prediction equation logic tree often require large interdisciplinary efforts. One such effort completed in 2015, the South American Risk Assessment (SARA) project, has produced updated seismic hazard and risk models for the continent of South America.

### 2.2 The Relationship Between Tsunami and Earthquake Magnitudes

As earthquakes are the most common triggers of tsunamis, the expected earthquake magnitudes are used to predict the run-up height of tsunamis within this period. As one would would expect, a larger tsunmigenic earthquake will cause tsunamis of larger magnitudes, while earthquakes of smaller magnitudes will result in smaller tsunamis. This intuitive relationship is validated through almost 500 years of data regarding tsunami run-up for events on the coast of Chile. The relationship between earthquake magnitude and tsunami wave height is linear on a logarithmic scale; however, the equation relating the two quantities varies from region to region. This is because tsunami magnitude and run-up height are largely effected by regional geographic features. These geometric and topographic nuances of a particular area can have large effects upon the propagation of tsunami waves from the generative source to the location of impact. [2] The relationship for Las Ventanas, Chile is shown in equation 1 where h is the height of the wave and M is the magnitude of the earthquake which generated the tsunami. From this, and taking into consideration maximum bounding factors, the worst-case-scenario tsunami for this region is expected to have a wave height of 9 meters.

$$\log(h) = (-9.48 + 1.39) + 1.2M \tag{1}$$

## 3 VISUALIZING TSUNAMI INUNDATION

### 3.1 Introduction

While the quantitative value of the potential tsunami wave heights as described in the previous section is informative as a stand-alone value, the significance of this value is more easily communicated by way of visual representation. This desire for visual communication of possible disastrous events is achieved through a geographic illustration showing the extent of inundation across Las Ventanas Bay. Three methods have been developed to accomplish this task, all of which rely upon a Digital Elevation Model of the area being assessed and use Esri GIS mapping software. A Digital Elevation Model (DEM) is a raster file which contains elevation data for a given area of interest. When used in a geographic information system, the DEM visually displays the terrain of the selected region. The DEM used in this study was developed by The Shuttle Radar Topography Mission, an international collaborative effort which produced a high-resolution DEM of the earth in late 2015. The project resulted in a DEM with a resolution of 1 arc-second, or approximately 30 meters, for entire globe with the exception of Antarctica and far northern latitudes.

### 3.2 Raster Calculator

The most obvious method of plotting inundation depth is via raster calculation in ArcMap. This method requires requires a license for the Spatial Analyst in ArcMap. In the Spatial Analyst ToolBox, under Map Algebra, the Raster Calculator can be located. The Raster Calculator allows the user to perform operations on a raster file. In the case of inundation modeling, this raster file is the DEM of the area of interest. Using the less than or equal to operator button within the raster calculator dialog box, one can easily find all areas below a given elevation on the DEM. In the case of Las Ventanas, the inundation depth was found to be nine meters. The raster calculator was used to find areas on the DEM less than three meters, between three and six meters, and between six and nine meters. The aesthetic qualities of these layers are up to the user to determine using the various symbols, colors, and base maps available in ArcMap. While the raster calculator is a simple method to use, in the case of low resolution elevation data, the map can appear fairly pixelated as shown in Figure 2. This method is best suited for cases in which a high resolution elevation model is available, or when the area of study is large enough that the pixilation becomes visually negligible.

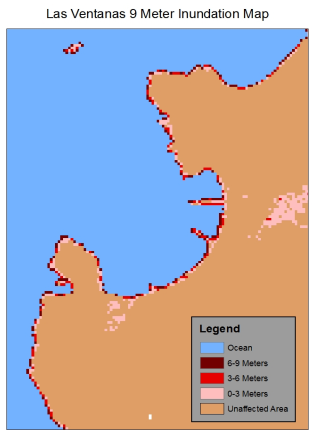


**Figure 2: An inundation map of Las Ventanas generated by raster calculation.**

## 3.3 Contour map

When a high resolution DEM is not available for a region in small enough that the raster calculator results in a highly pixelated map, a contour map can be generated. This again requires the Spatial Analyst license in ArcMap. Under surface within the Spatial Analyst tools, select contour to create a contour map for a given surface raster. In the contour dialogue box, simply enter the desired contour interval and generate the map. In the case of Las Ventanas, the contour interval was set to 3 meters. If the contours appear boxy or pixelated, they can be smoothed out by adjusting the base contour, which defaults to zero. Offsetting the base contour by a value as small as 0.0001 helps to smooth contour lines by diverting their passage from the center of each cell. The effect of this method is shown in Figure 3. Additionally, the data can be smoothed using the mean statistic or the sum statistic and a weighted kernel file. Both of these tools can be found within the focal statistics tool of the spatial analyst package. While adjusting map aesthetics if fairly straightforward using the raster calculation method, this process becomes much more difficult using the contour method. This is because each raster calculation produces an individual layer, but the entire contour map is a single layer. It is possible in some cases to create filled contours, but this tool does not always produce the desired results. In many cases, it is much more straightforward to fill the contours using Adobe Illustrator, or a similar software. The color filled map for Las Ventanas is shown in Figure 4. This method is best suited for situations in which the elevation data has a fairly low resolution. The coloration of the map may be challenging when using this method, but it is exceptionally effective for smoothing elevation contours.

## 3.4 3D Display

In some scenarios, it may be beneficial to visualize the extent of tsunami inundation in a three dimensional model. This can be done using ArcScene, an Esri software. Simply import the DEM and select the Base Heights tab from the properties menu to transform the

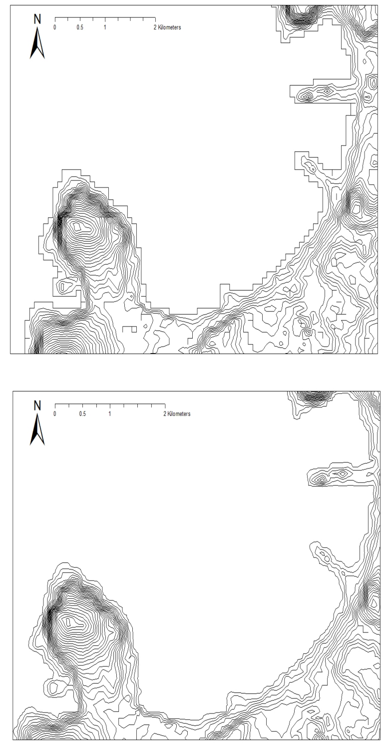

**Figure 3: Before and after adjusting the base contour value of the contour map.**

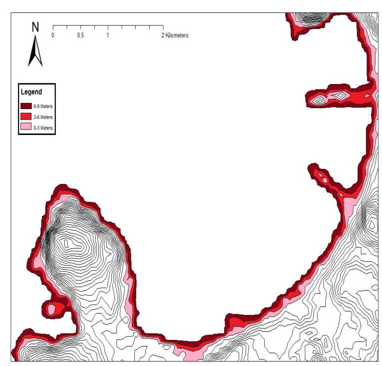

**Figure 4: A contour map of Las Ventanas with color added to show varying levels of inundation.**

DEM from a plane to a 3D surface. If the surface appears distorted, it may be necessary to use a factor to convert layer units to scene units. Once the DEM has been imported and adjusted, one plane for each interval of inundation should be added to the scene. Making the higher layers more transparent and the lower layers less transparent gives the scene a contour like appearance as shown in Figure 5. While a low DEM resolution causes pixilation as it did in the raster calculation method, this method is effective for examining

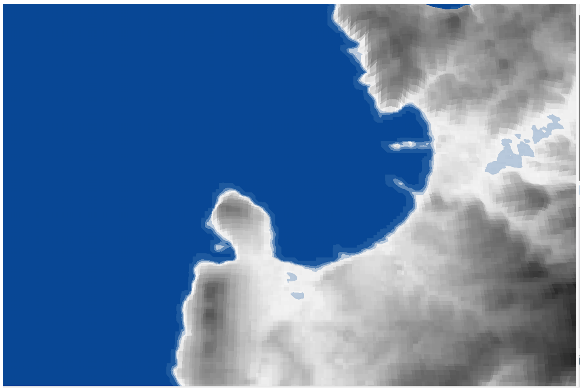

**Figure 5: A three dimensional display of inundation in Las Ventanas.**

three dimensional aspects of tsunami inundation and the potential damages thereof.

## 4 CONCLUSION

In order to predict the wave height of a tsunami, the magnitude of the tsunamigenic earthquake must be determined. These events are predicted by way of Probabilistic Seismic Hazard Analysis (PSHA). Once the earthquake magnitude has been determined, the tsunami wave height can be derived. The two values are related by a logarithmic equation which is specific to the particular site of study. This equation varies from region to region because of topographic particularities which effect the propagation of tsunami waves. Modeling predicted tsunami flood zones is vital for a variety of reasons ranging from to construction planning to evacuation planning. This task is readily accomplished using Esri GIS softwares like ArcMap and ArcScene, or other similar programs. The three modeling methods presented in this paper are suited for a variety of situations and circumstances.

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## REFERENCES

[1] Jack W Baker. 2013. An introduction to probabilistic seismic hazard analysis. *White Pap* 2, 1 (2013), 79.

[2] Evgueni A Kulikov, Alexander B Rabinovich, and Richard E Thomson. 2005. Estimation of tsunami risk for the coasts of Peru and northern Chile. *Natural Hazards* 35, 2 (2005), 185.

[3] Vitor Silva, Helen Crowley, Marco Pagani, Damiano Monelli, and Rui Pinho. 2014. Development of the OpenQuake engine, the Global Earthquake Model?s open-source software for seismic risk assessment. *Natural Hazards* 72, 3 (2014), 1409–1427.