TSUNAMI INUNDATION MAPPING FOR THE NORTHERN HALF OF NEW JERSEY STATE

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Abstract

This document reports the development of tsunami inundation maps for the northern half of the New Jersey state. Section 1 describes NTHMP requirements and guidelines for this work. The location of the study and the bathymetry data utilized are described. Tsunami sources that potentially threaten the upper East Coast of the United States are briefly discussed. Modeling inputs are described in the Section 3, including model specifications and simulation methods such as nesting approaches used in generating inundation maps. The process of generating inundation maps from tsunami simulation results is described in Section 4, along with other results such as arrival time of the tsunami. GIS data sets and organization, including inundation maps, maximum velocity maps, maximum momentum flux maps, are described in Appendix A. Modeling inputs for simulation are provided in Appendix B for interested modelers. In Appendix C, NTHMP guidelines for inundation mapping are provided.

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1 Introduction

The US National Tsunami Hazard Mitigation Program (NTHMP) supports the development of inundation maps for all US coastal areas through numerical modeling of tsunami inundation. This includes high-resolution modeling and mapping of at-risk and highly populated areas as well as the development of inundation estimates for non-modeled and low hazard areas. This report describes the development of inundation maps for the northern part of the New Jersey State which in not covered by the Atlantic City NGDC tsunami DEM (Taylor et al, 2009, Tehranirad et al., 2015).

In section 2, background information about the mapped area is provided. Possible tsunami sources that threaten the upper United States East Coast (USEC), and are considered in this analysis, are described. Modeling inputs are described in section 3. Section 4 presents simulation results and the development of mapping products. The process of obtaining the tsunami inundation line, which is the most significant result of this work, is explained in this section. Three appendices provide information about GIS data storage and content (Appendix A), modeling inputs (Appendix B), and NTHMP inundation mapping guidelines (Appendix C).

2 Background Information about Map Area

2.1 Location of coverage, and communities covered

The National Oceanic and Atmospheric Administration (NOAA), National Geophysical Data Center (NGDC) have generated digital elevation models (DEM) as input for studies focusing on hazard assessment of catastrophes like tsunamis and hurricanes at a number of U. S. coastal areas. The Atlantic City NGDC DEM covers the southern portion of the State of New Jersey (Taylor et al., 2009, Tehranirad et al., 2015). The northern half of the New Jersey, however, is not covered in this DEM. Therefore,a DEM for the northern half of the state was extracted from FEMA region II surge study DEM (FEMA, 2014). This DEM covers several populated coastal communities including Seaside Heights, Spring Lake, and Perth Amboy. Bathymetric data was extracted from the DEM used for the FEMA Region II storm surge modeling study. This data covered the water around New York City, along the Hudson River, and throughout the Long Island Sound and waters south of Long Island along New Jersey. The bathyemtric data was then combined with numerous land-based, lidar-derived topographic datasets on the coasts of New York, New Jersey, and a small area of Connecticut. The final topographic-bathymetric DEM mosaic covers several populated coastal communities including Seagate, Manhattan, and several locations in Long Island. Figure 1 shows the coverage area of the final DEM mosaic. The bathymetric and topographic data is provided in latitude/longitude coordinates with 1/3 arc-second resolution. The DEM vertical datum is mean high water (MHW), and vertical elevations are in meters. More information about the bathymetry data is given in Section 3.2.

2.2 Tsunami sources

The northern part of New Jersey has rarely experienced tsunami inundation. A general overview of historic and potential tsunamigenic events in the North Atlantic Ocean is provided by Atlantic and Gulf of Mexico Tsunami Hazard Assessment Group (2008). In this

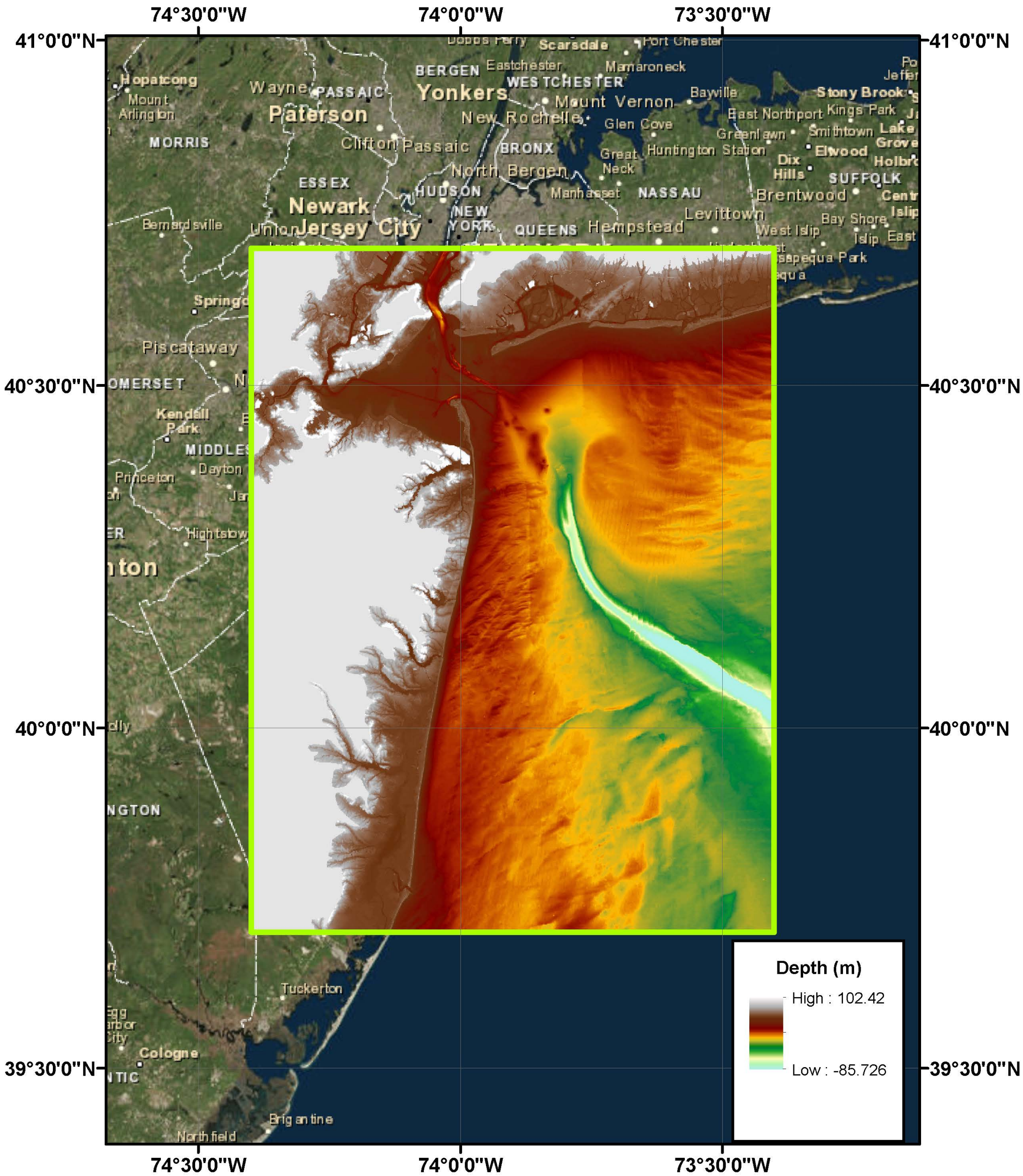


Figure 1: Location of the Norhtern New Jersey DEM. Color bar shows depth values in meters for areas inside of the DEM boundary.

project, tsunami sources that threaten the upper US East Coast (USEC) were categorized into three main categories, and have been studied separately due to their differences in physics and location. First, two seismically active sources in the Atlantic Ocean were used; a subduction zone earthquake in the Puerto Rico trench, and a simulation of the historic Azores Convergence Zone earthquake of 1755. A far field subaerial landslide due to a volcanic collapse in Canary Islands is also modeled. Finally, near-field Submarine Mass Failures (SMFs) close to the edge of USEC continental shelf are used here as well. A brief introduction and references to detailed studies of the sources are provided in this section.

2.2.1 Coseismic sources

2.2.1.1 Puerto Rico Trench: Previous research has confirmed the possibility of large earthquakes in the Puerto Rico Trench (PRT) in the Caribbean Subduction Zone (CSZ) (e.g. Grilli et al., 2010). These studies implied that an extreme event with return period of 200 to 300 years could be powerful enough ($M_w = 9.0$) to rupture the entire PRT and initiate a tsunami that will influence the USEC. Grilli and Grilli (2013a) have carried out detailed computations for that event for use as initial conditions for tsunami inundation modeling on the USEC.

2.2.1.2 Azores Convergence Zone: The other coseismic source used here is located on the Azores Gibraltar plate boundary, known as the source of the biggest historical tsunami event in the North Atlantic Basin (Gonzalez et al., 2007). The 1755 Lisbon earthquake ($M_w = 8.6-9.0$) generated tsunami waves with heights between 5 to 15 meters, impacting the coasts of Morocco, Portugal, Newfoundland, Antilles, and Brazil. The procedure for obtaining the initial condition for tsunami propagation is quite similar to the PRT rupture and is discussed in Grilli and Grilli (2013b).

2.2.2 Volcanic cone collapse

In recent years, a potential cone collapse of the volcanic cone Cumbre Vieja (CVV) in the Canary Islands has received attention as a possibly catastrophic source threatening the USEC. In this project, a multi-fluid 3D Navier-Stokes solver (THETIS) was used to compute the volcanic collapse tsunami source (Abadie et al., 2012; Harris et al., 2012). Detailed description of the CVV modeling for use in this project is described in Grilli and Grilli (2013c). Two different slide magnitudes were studied for this work; an 80 km^3 slide, representing a plausible event in a return period window on the order of 10,000 years, and a 450 km^3 source, consistent with estimates of the maximum event for the geological feature. The magnitude of the latter event is significantly larger than all of the other cases studied in this project. Thus, it was decided to exclude the 450 km^3 source from inundation line calculations, and illustrate its results separately as a representation of the worst case scenario condition. This is due to the fact that this source return period is expected to be much more than 10,000 years.

2.2.3 Submarine mass failure

The US East Coast is fronted by a wide continental shelf, which contributes to the dissipation of far-field tsunami sources, and diminishes the damage caused by simulated waves from these sources on the coastline. On the other hand, it has been noted in literature (e.g. Grilli et al. 2014) that there is a potential of a Submarine Mass Failure (SMF) on or near the continental shelf break, causing tsunamis that affect adjacent coastal areas. Considering the fact that the only tsunami event that has caused fatalities on the US East Coast was an SMF tsunami (Grand Banks, 1929), it is necessary to study possible impacts and consequences of such catastrophes with respect to heavily populated coastal communities on the USEC. In this project, four different locations are chosen as the most probable to experience a submarine mass failure tsunami. The process of obtaining the initial condition for near-shore propagation and inundation modeling for all of these sources are comprehensively documented in Grilli et al. (2013). The landslide movement is simulated with the NHWAVE model (Ma et al., 2012; Tehranirad et al., 2012) and the results shown here are interpolated into 500 meter grids for propagation and inundation modeling 800 seconds after slump movement is initiated (Grilli et al., 2013).

3 Modeling Inputs

3.1 Numerical model

Tsunami propagation and inundation in this study is simulated using the fully nonlinear Boussinesq model FUNWAVE-TVD (Shi et al, 2012a). FUNWAVE-TVD is a public domain open-source code that has been used for modeling tsunami propagation in ocean basins, nearshore tsunami propagation and inland inundation problems. The code solves the Boussinesq equations of Chen (2006) in Cartesian coordinates, or of Kirby et al. (2013) in spherical coordinates. A users manual for each version is provided by Shi et al (2011). FUNWAVE-TVD has been successfully validated for modeling tsunami wave characteristics such as shoaling, breaking and runup by Tehranirad et al. (2011) following NTHMP requirements (see Appendix C). Additional description of modeling specifications and input files is provided in Appendix B.

One key specification in the model is the choice of friction coefficient defined for tsunami simulation. Geist et al. (2009) have performed a study on sensitivity of tsunami elevation with respect to a range of bottom friction coefficients and demonstrated that large coefficients will unrealistically damp tsunami wave height. A review of the existing literature suggests that a value of $C_d = 0.0025$ represents a reasonable friction coefficient for tsunami simulations, as suggested by several researchers (e.g. Grilli et al., 2013), and this value is used here.

3.2 Bathymetric Input Data

3.2.1 FEMA Region II Bathymetry

The bathymetric component of the integrated, seamless bathymetric-topographic (topo-bathy) DEM used in this project was obtained from the US Federal Emergency Management Agency (FEMA) Region II as part of their storm surge modelling efforts. The FEMA Risk Assessment, Mapping, and Planning Partners (RAMPP) team assembled the bathymetric dataset from several sources, including those form the NOAA National Geophysical Data Center (NGDC), the USACE, and local New York and New Jersey surveys. FEMA compiled the various datasets, along with adjacent land-based topographic datatsets, at high spatial resolution and resampled to 10 meters in UTM Zone 18 (NAD83) coordinate system. Elevations below the zero-line referenced to North American Vertical Datum of 1988 (NAVD88) were extracted as a bathymetry-only dataset, which was integrated into the current project's seamless topobathy DEM. More details on the associated data sources and processing steps used by FEMA in developing the bathyemtric dataset can be found in the FEMA, 2014 document. The Northern New Jersey DEM covers the coastline in the area from Barnegat Township, NJ up to Perth Amboy, NJ in the north (Figure 1). However, to cover NTHMP requirements the DEM was converted to Mean High Water (MHW) for inundation mapping using the Vdatum software provided by NOAA (Park et al., 2003). The resolution of FEMA region II DEM is 1/3 arc-second (FEMA, 2014), which with respect to study location means that the North-South resolution is 10.27 meters, and East-West direction grids are 7.93 meters (computed using the latitude in the middle of the domain). All of the runs in this domain have been performed in Cartesian coordinates. The domain shown in Figure 1 is extracted from the FEMA region II DEM. Also, the maximum recorded elevation data was about 100 meters and there were no data available for higher elevated area. However, since the tsunami did not inundated those areas at all (Several test runs were performed to make sure), a fixed value equal to the maximum recorded elevation was chosen for those areas (White parts shown in Figure 1). Considering the coverage area of this grid, the difference between Cartesian grid and spherical grid (Simply comparing the total length of domain in Cartesian grid and spherical grid) is about 1.5 meters for the whole domain. This means that the average offset for each point is of O(10^{-6}) meters. Therefore, because of the negligible differences between Cartesian and spherical grids, this grid was used as Cartesian grid directly to capture fully nonlinear effects of the tsunamis nearshore. Further information about this grid is also given in Table 1.

In the USA the period to determine MHW spans 19 years and is referred to as the National Tidal Datum Epoch. For this project, inundation mapping processes have been performed with MHW datum maps following NTHMP requirements (see Appendix C).

There are different approaches to relate MHW to NAVD88 values in the literature, and also, one can use existing datum conversion models to investigate the difference (e.g. Vdatum generated by NOAA). However, it should be noted that the difference between these values is not constant for the whole domain. For Barnegat Inlet, NJ, MHW is at NAVD88+33.2 cm. For Sandy Hook, NJ, MHW is at NAVD+58.2 cm.

3.2.2 NGDC Coastal Relief Model (CRM)

Bathymetry data for shelf regions lying outside the FEMA region II DEM are obtained from the NGDC's 3 arc-second U.S. Coastal Relief Model (CRM) (Divins and Metzger, 2003). This data delivers a complete view of the U.S. coastal areas, combining offshore bathymetry with land topography into a unified representation of the coast. However, the deeper part of the Ocean beyond the shelf break is not covered in this data.

3.2.3 ETOPO 1

Bathymetry data for deeper parts of the ocean beyond the shelf break is taken from the ETOPO1 DEM (Amante and Eakins, 2009). ETOPO1 is a 1 arc-minute global relief model of Earth's surface that combines land topography and ocean bathymetry. It was built from numerous global and regional data sets, and is available in ”Ice Surface” (top of Antarctic and Greenland ice sheets) and ”Bedrock” (base of the ice sheets) versions. Here, we use the Bedrock version in areas where the CRM data is not available.

3.2.4 Lidar-based Topographics DEMs

In addition to the bathmetry data mentioned above, lidar-based topographic (inland) datasets were obtained from numerous counties in New York, New Jersey, and Connecticut. Although the numerous datasets were generated from lidar flown at various times, using various technologies and processing standards, the best available bare-earth DEM datasets (which only represent earth's natural surface, man-made objects such as buildings or bridges are not included) were obtained at the time of this project. All of the data, except NYC and CT DEMs described below, were obtained from the FEMA Region II Support Center in New York City through Dewberry, Inc. under contract with FEMA RAMPP team. All data were also referenced to NAVD88 vertical datum.

In northern New Jersey, this included Bergen County, Union County, Essex County, Hudson County, and the Hudson Valley. Data were obtained in NJ State Plane (NAD83) feet at 10 ft spatial resolution. For the New York area (not included New York City), this included Richmond County, Kings County, Queens County, West Chester County (also obtained in NJ State Plane (NAD83) feet but at 6.56 ft resolution) as well as Nassau and Suffolk Counties on Long Island (obtained in NY Long Island State Plane (NAD83) feet at 10 ft resolution.)

Elevation data from New York City was obtained from the City of New York Department of Environmental Protection, based on lidar flown in April and May in 2010. The elevation values were referenced to NAVD88 vertical datum and distributed in NY Long Island State Plane (NAD83) meters in 1 ft spatial resolution. The NYC DEM More information about the NYC dataset is available, as well as download access information, on the NYC OpenData Portal at https://data.cityofnewyork.us/City-Government/1-foot-Digital-

Elevation-Model-DEM-/dpc8-z3jc

The northeastern portion of the study area overlapped with southwestern Connecticut. For this area, elevation data was extracted from the USGS National Elevation Dataset (NED.) The NED includes multiple digital elevation models from across the US, combined into a seamless, nationwide digital elevation model at approximately 30 meter resolution. Data can be extracted and downloaded for custom rectangular areas (clipped from the compiled seamless DEM.) Additional, higher resolution data can also be downloaded for certain areas, if available. For the current required region in CT, high resolution data at 1/9 arc-second was available for most of the area while the remaining area covered by 1/3 arc-second data. Both datasets, available in geographic coordinates (NAD83) referenced to NAVD88 vertical datum, were obtained for this project. More information about the USGS NED as well as download access information, is available at http://ned.usgs.gov/.

3.2.5 Integration of Elevation Data Sources

All of the bathymetric and topographic data in the nearshore region, approximately 20 datasets, were combined into a seamless mosaic dataset using ArcGIS Desktop software from ESRI. The ArcGIS Spatial Analyst extension Blend method was used for the majority of the work when merging various data into a single raster dataset. The Blend method uses a distance-weighted algorithm to determine the value of overlapping pixels while merging two datasets. The weight of each input pixel is based on the distance from the pixel to the dataset edge within the overlapping area; the closer to the edge, the less weight the pixel carries. Although the most computationally intensive option for raster mosaicking within ArcGIS Desktop, it provides a smooth surface in the transition zone between datasets.

The first step was to mosaic all of the land-based topographic data to a common 10 ft spatial resolution grid. Data from the five NYC boroughs were merged first all all values less than zero (NAVD88) were removed; this was due to the fact that most water bodies in these data were hydro-flattened (assigned a constant value across entire water body) and the FEMA R2 dataset included much of these data. Long Island datasets, New Jersey datasets, and CT datasets were also each merged together in their respective coordinate systems and resolutions. The next step was to merge all of these regional datasets into a common coordinate system (NY Long Island State Plane NAD83) and resolution (10 ft.) The complete land-based topographic dataset was then projected to UTM Zone 18 north coordinate system and resampled to 10 m to match the FEMA R2 bathymetric dataset. These two datasets were them merged with small data gaps filled using multiple iterations of the GDAL utility program gdal_nodatafill.py (http://www.gdal.org/gdal_fillnodata.html). The final topobathy DEM was projected to geographic coordinates at 1/3 arc-second (approximately keeping the same 10 m resolution) and clipped to the study area boundary for input into the hydrodynamic model.

3.3 Model Grids

Although the Northern New Jersey DEM satisfies the bathymetry data requirements for nearshore simulations, proper offshore bathymetry data is required to model the tsunamis far from the shoreline. Accordingly, Grids A and B (Figure 2) are generated for low resolution modeling over the ocean basin and continental shelf. The input data for the tsunami sources is divided into two categories. The first category consists of Cosiesmic and CVV sources, which were simulated in larger scale ocean-scale model runs, with results recorded on the boundaries of Grid A. The ocean-basin simulations in which this data were recorded was performed with a 16 arc second spherical grid. Grid A was generated in order to keep the nesting scale 4 or less (see section 3.4), and continue the simulation with a 4 arc second grid. The grid sizes of the Grid A are 503.2 m in the north-south direction and 535.0 m in east-west direction (Table 1). On the other hand, the SMF sources fall within the modeled region and are initially modeled with a Cartesian grid using NHWAVE (Ma et al., 2012) with 500 m resolution. The input data was in the form of initial conditions, in contrast to the first category where the data is in form of boundary conditions. Therefore, it was required to generate another grid larger than Grid A to allow space for model sponge layers (or damping regions) on the boundaries. Also, in order to directly use input data as generated by NHWAVE, the grid sizes for Grid B were chosen to be 500 m.

Depth values for these grids were obtained from the 1 arc-minute ETOPO-1 database, while nearshore bathymetry and topography were obtained from the CRM. The horizontal datum and vertical datum are set to be WGS84 and MHW, similar to Northern New Jersey DEM. These grids are mapped from spherical coordinates into a Cartesian grid. This means that there are some mapping errors considering the magnitude of these grids. For example, for Grid A, the total difference between two different coordinate systems is 132 m comparing the arc length (spherical) with the straight line (Cartesian). The average offset difference for each grid point between two coordinates is 12 cm, which is negligible considering a grid size of about 500 m. To minimize the error around the mapping area, the grid is lined up close to the Northern New Jersey DEM. The total difference between spherical and Cartesian coordinates for Grid B is 465 meters. The average offset difference between two coordinates is 31 cm for each point of this gird. To make the error as small as possible for the western parts of the domain (close to Sandy Hook, NJ), this grid is also lined up with the mapping area. Therefore, larger error values shows up in the eastern and southern parts of the domain, which is not of concern because they fall within the sponge layer region.

Figure 2 shows the location of these grids, as well as the location of the SMF sources simulated in this project. Further information about these grids are provided in Table 1. Figure 3 shows the initial surface elevation of each SMF source mapped onto Grid B. The results of the simulations using Grids A and B were recorded on the Northern New Jersey DEM boundaries in order to perform higher resolution modeling in nearshore regions. This process is described in the next section of this document.

3.4 Nesting approach

In order to save computational time, an appropriate nesting approach is required to decrease the grid sizes from coarser grids offshore to finer grids nearshore. Accurate nesting should insure that there would not be a loss of data on any of the boundaries on which coupling is performed. The nesting scale represents the change in the grid size between two levels of simulation. For example, if the 500 m grid results are used to perform a 125 m simulation, the nesting scale is 4. Although the coupling capabilities of FUNWAVE-TVD are such that large nesting scales could be used, a largest nesting scale of 4 has been used in this study in order to avoid any loss of data. As described in previous sections of this report, Grids A and B are used to generate data on Northern New Jersey DEM boundaries. Both of these grids have grid sizes of roughly 500 meters and larger. Next,

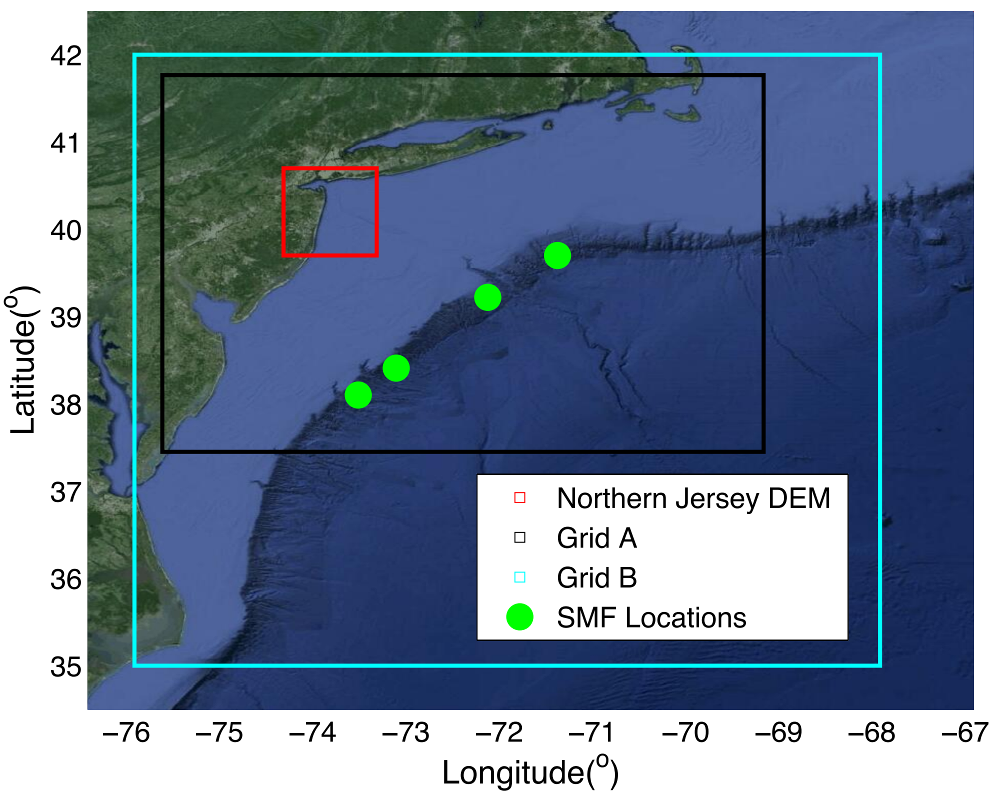


Figure 2: Locations of the Grids used in this project and also the center of SMF sources simulated here.

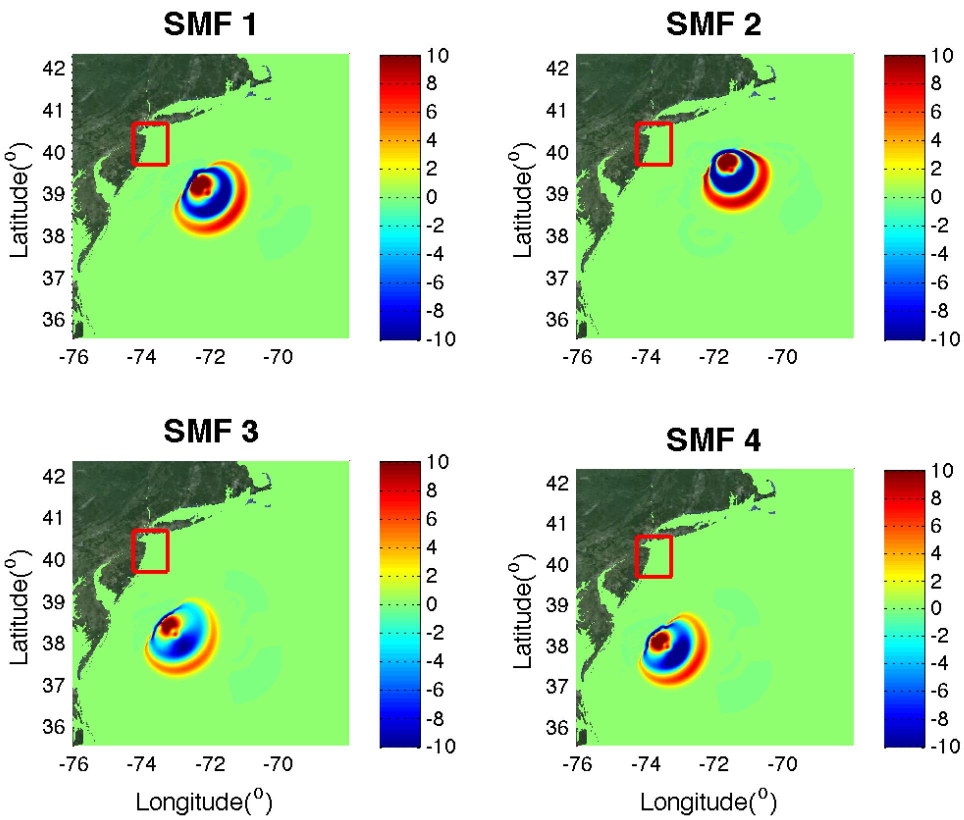


Figure 3: Location of Grid B and the Northern New Jersey DEM used in this project, and also the initial stage of SMF sources.

using the recorded data on the boundaries of Northern New Jersey DEM, simulations with grid sizes of roughly 125.0 meters (about 4 arc-sec) are implemented on this grid to record proper data around four DEMs with resolution of 1 arc-sec (extracted from 1/3 arc-sec Northern New Jersey DEM) in the main region to resolve tsunami inundation inland (and near-shore) with 30 meter (about one arc-sec) grid size. Grilli et al. (2014) have used the similar nesting approach and confirmed the values chosen here. Figure 5 depicts the diagram for the nesting approach performed in this project. In addition, characteristics of each grid are defined in Table 1. All of the runs in this document were performed in Cartesian coordinates.

4 Results

This section describes the data recorded for each inundation simulation and its organization as ArcGIS rasters for subsequent map development. The tsunami arrival time is an essential piece of information for evacuation planners. The results are categorized into onshore and offshore results. The onshore results depict the characteristics of the tsunami on the land during inundation. Onshore tsunami effects are mainly demonstrated through three parameters,

1. Maximum inundation depth
2. Maximum velocity
3. Maximum momentum flux

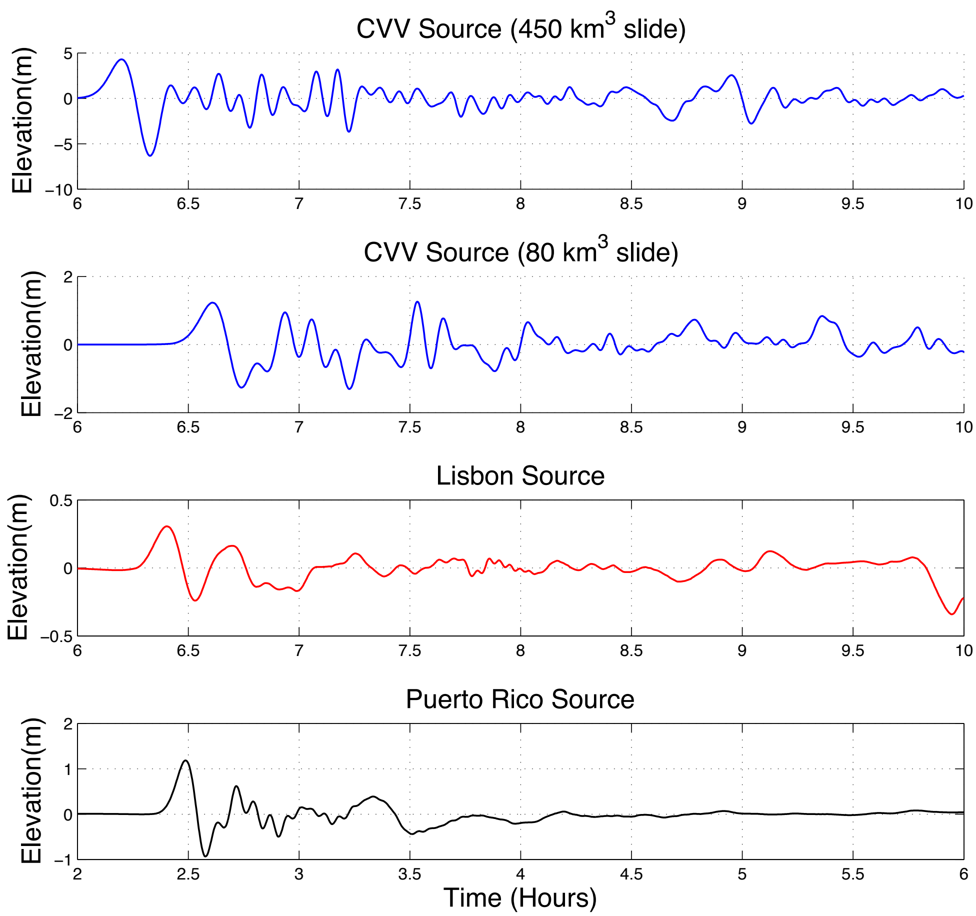


Figure 4: Gauge data at the southeastern edge of Grid A for coseismic and volcanic collapse sources

Grid Name	Grid Numbers		Grid Size (m)		Boundary Coordinates			
	mx	ny	dx	dy	E	W	S	N
Grid A	1100	900	503.20	535.50	-69.25	-75.70	37.45	41.80
Grid B	1500	1500	500.00	500.00	-67.50	-76.00	35.00	42.00
NJ_4arc (Same bondaries with the Northern New Jersey DEM)	900	900	95.16	123.24	-73.40	-74.40	39.70	46.70
NJ_1arc_1	1080	1080	23.79	30.81	-74.02	-74.32	39.72	40.02
NJ_1arc_2	1080	1080	23.79	30.81	-73.99	-74.29	39.94	40.24
NJ_1arc_3	1080	1080	23.79	30.81	-73.95	-74.24	40.20	40.50
NJ_1arc_4	1200	1080	23.79	30.81	-74.06	-74.39	40.37	40.67

Table 1: Grid specification for all of the grids used in this project

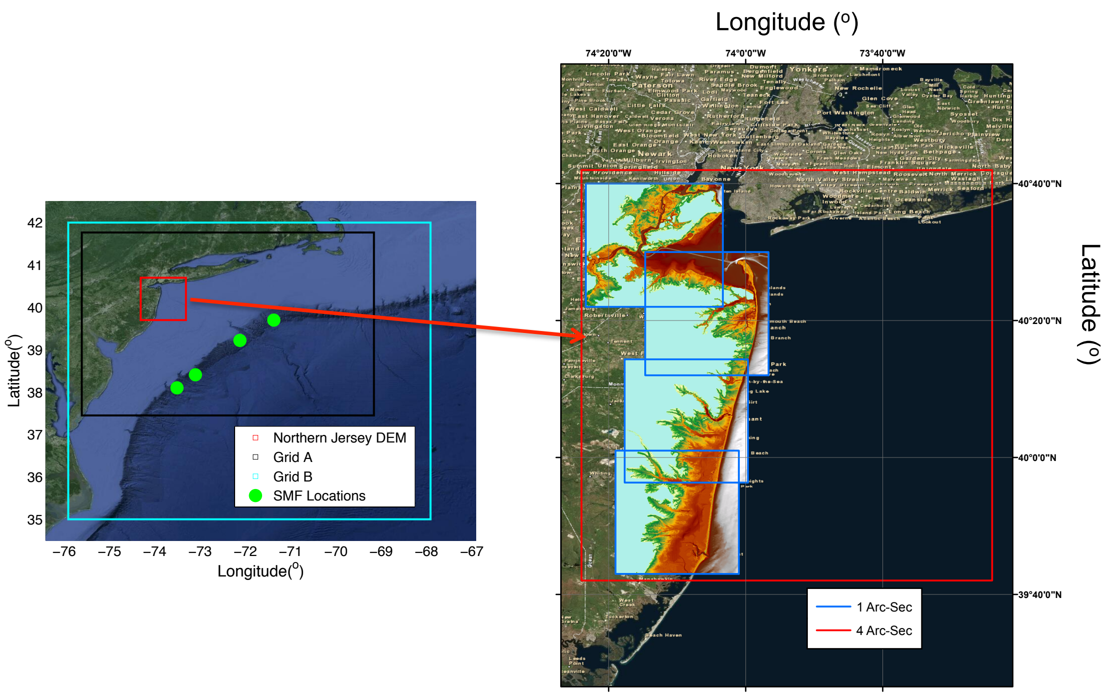


Figure 5: The sequence of grid nesting. The figure on the top left depicts the Grid A and B as well as the location of the Northern New Jersey DEM. The figure on the right show the 1 arc-sec grids described in Table 1.

Yeh (2007) reported different forces created by a tsunami on structures and concluded that, having the three mentioned quantities, one can calculate good estimates of forces on onshore structures resulting from tsunamis. Moreover, tsunamis can affect ship navigation; therefore, in order to cover maritime planning and navigational issues during a tsunami, three other parameters are recorded and depicted offshore in this project. These three offshore parameters include,

1. Maximum vorticity
2. Maximum velocity
3. Maximum recorded water surface elevation

All six variables are recorded for each of the modeling domains introduced in Table 1 for all of the tsunami sources discussed in previous sections. Appropriate rasters are generated which are compatible with ArcGIS and other GIS software for mapping purposes. Finally, the inundation line, which is calculated from the envelope of tsunami inundation extent for each source, will be presented.

4.1 Arrival time

Tsunami arrival time plays an important role in evacuation planning during the occurrence of an event. It is vital to report the arrival time of each tsunami relative to the time of initial detection of an event. Here, the arrival time of the tsunami is based on the time that the first tsunami bore passes the shoreline. Table 2 reports tsunami arrival times for several places located in Northern New Jersey DEM. For each location, arrival times of all different tsunami sources have been reported. The arrival time for each city in Table 2 is a value for that particular location with about a 5 minute error margin. Since tsunami propagation in the ocean is constrained by bathymetry, the propagation of tsunamis toward the study area is quite similar for all of the different sources.

The southern part of the domain (e.g. Seaside Heights, NJ) is the first spot that would face the tsunami. However, within 5 to 10 minutes difference, the northern part of the domain that is facing Atlantic Ocean (e.g. Spring Lake, NJ) will be affected by the tsunami as well. Because of the bathymetric features close to the study area such as Hudson River Canyon, the most energetic part of the waves impact the southern parts of this domain. However, within 20 to 30 minutes lag in comparison to the southern parts of the domain, tsunami would reach parts of the domain close to the Lower New York Bay (e.g. Sandy Hook, NJ). Figure 6 demonstrates the location of gauges where the recorded surface elevation was used to assess tsunami arrival time for all of the sources (Table 2). SMF sources are clearly the closest source to the location of study, and will reach the entire domain within 1 to 2 hours. The tsunami induced by Puerto Rico Trench (PRT) will affect the Northern New Jersey greater area between 4 to 5 hours after the earthquake. The Lisbon historic event and the Cumbre Vieja Volcanic collapse (CVV) sources have similar transoceanic travel time, and will influence the domain 8 to 9 hours after the incident.

Location	SMF1	SMF2	SMF3	SMF4	PR	LIS	CVV^1	CVV^2
Seaside Heights, NJ	85	95	100	95	295	535	545	510
Spring Lake, NJ	85	100	100	100	300	535	545	515
Sandy Hook, NJ	100	110	175	130	320	560	565	535

Table 2: Arrival time in minutes after tsunami initiation for different locations and sources in Northern New Jersey DEM based on the location of the gauges. CVV^1 and CVV^2 refer to 80 km^3 and 450 km^3 slide volumes respectively.

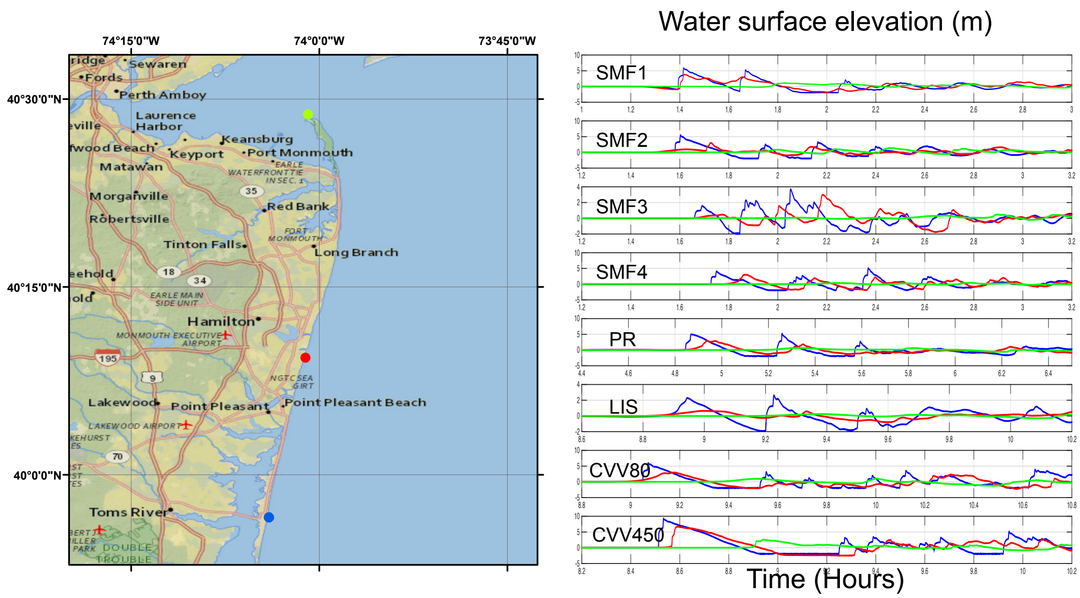


Figure 6: Recorded surface elevation for gauges located in different locations in Northern New Jersey DEM, Seaside Heights (Blue), Spring Lake (Red), and Sandy Hook, NJ (Green).

4.2 Raster Data

One of the most important results of this work is the inundation map corresponding to each tsunami source. In order to facilitate the GIS work, appropriate rasters which are compatible with any GIS software such as ArcGIS are created for all of the grids mentioned in Table 1. As an example, Figure 7 depicts the inundation depth for the CVV 80 km^3 slide for the Northern New Jersey DEM grid with 1 and 4 arc-second resolutions. In this figure the domains in which 1 Arc-second resolution runs have been performed are displayed as well.

Figures 8-11 show the maximum inundation depth for the 1 Arc-second domains shown in Figure 7. These figures provide a comparison for different sources studied in this project. This includes the envelope inundation map for SMF and coseismic sources as well as both CVV sources. The inundation depth for SMF sources are similar to each other, however, the inundation depth values for SMF1 is larger for the most part in comparison to the other SMF sources. This is probably because of the fact that the SMF1 is the closest SMF source to the location of study. Also, the PRT event is the dominant coseismic source by far, and its inundation pattern is similar to SMF sources with some differences especially behind the barriers. Since coseismic sources have larger wavelengths, they are able to penetrate behind the barriers with less attenuation in comparison to SMF sources. Figures 8-11 show that the CVV 450 km^3 source is clearly the dominant source for the area studied here, and represents worst case scenario by far in comparison to other sources. However, because its return period is estimated to be beyond 10000 years, it is excluded from inundation line calculations at this point. The 80 km^3 slide CVV has a similar inundation pattern to Puerto Rico source and SMF1. Except for some few locations SMF1 source is the dominant source among all other sources, excluding the CVV 450 km^3 slide source.

The other important criteria required to be reported for inundated area, is the maximum momentum flux. Figure 12 is an example of the maximum momentum flux which is extracted from NJ_1arc_1 domain for the SMF1 tsunami. Maximum-recorded velocity is another essential quantity required to be reported for inundated area. Maximum velocity is also an important factor for navigational issues during a tsunami. Therefore, for better realizations of maximum velocity maps, two different maps are acquired for maximum velocity on land (basically inundated area) and maximum velocity offshore, which are shown in Figure 13. Finally, the other important variable for navigational problems during a tsunami, which is the maximum vorticity is also reported with the similar method as the other gridded values. Figure 14 depicts the maximum vorticity in Barnegat inlet, NJ during SMF1 tsunami. All of the rasters in this project have the Mean High Water (MHW) datum and have ASCII format. In each raster file, the grid size (number of row and columns), the latitude and longitude coordinates corresponding to the southern and western boundaries of the domain, and cell size that defines the resolution of the simulation are included. Also, no data value for each raster is defined as well to limit the information to the inundated areas or other areas of interest. More information about the raster data is provided in Appendix A.

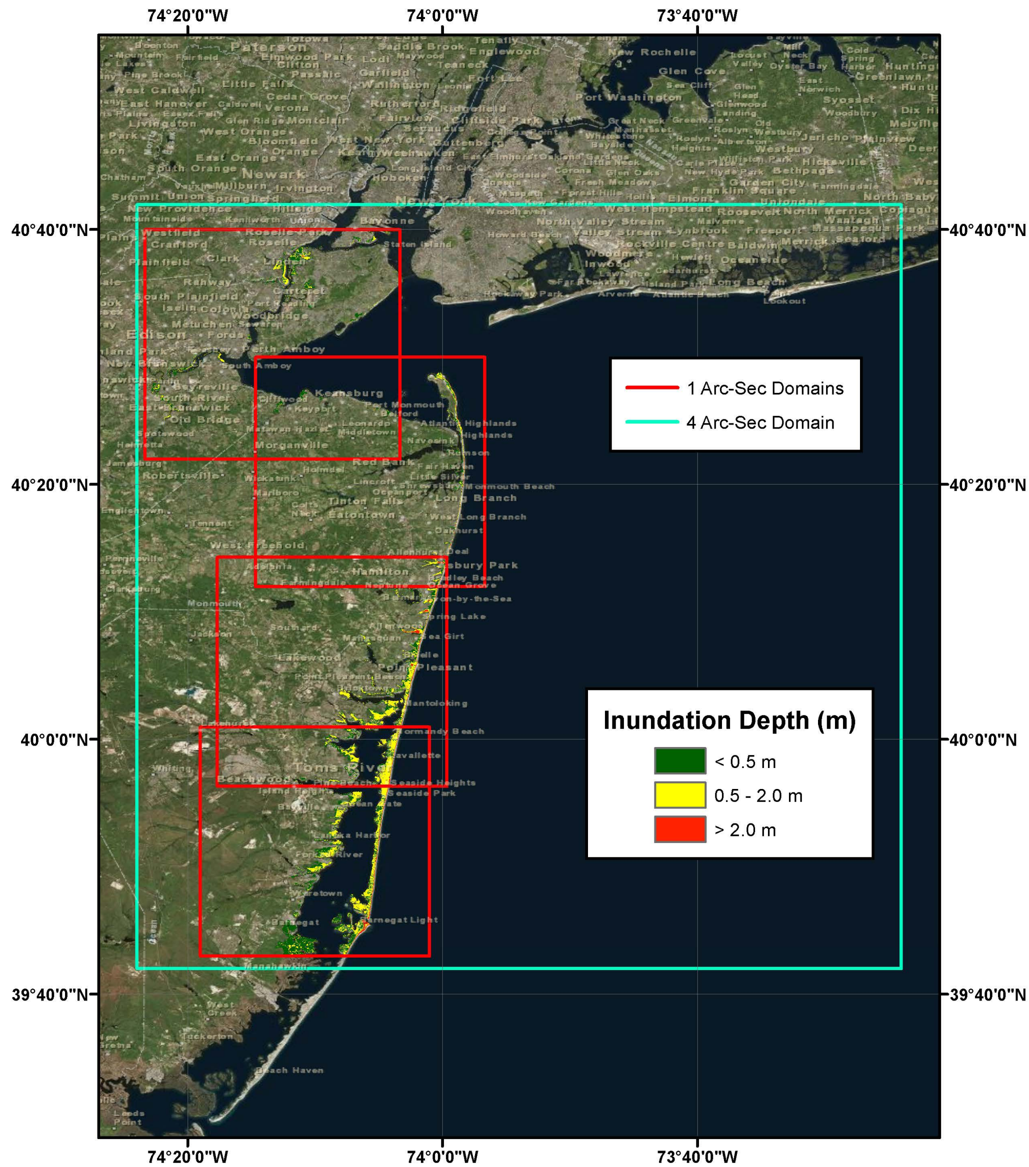


Figure 7: CVV 80 km^3 slide Inundation Map for the Northern New Jersey DEM with 4 arc-second resolution. Red squares depicts the 1 arc-second resolution domains

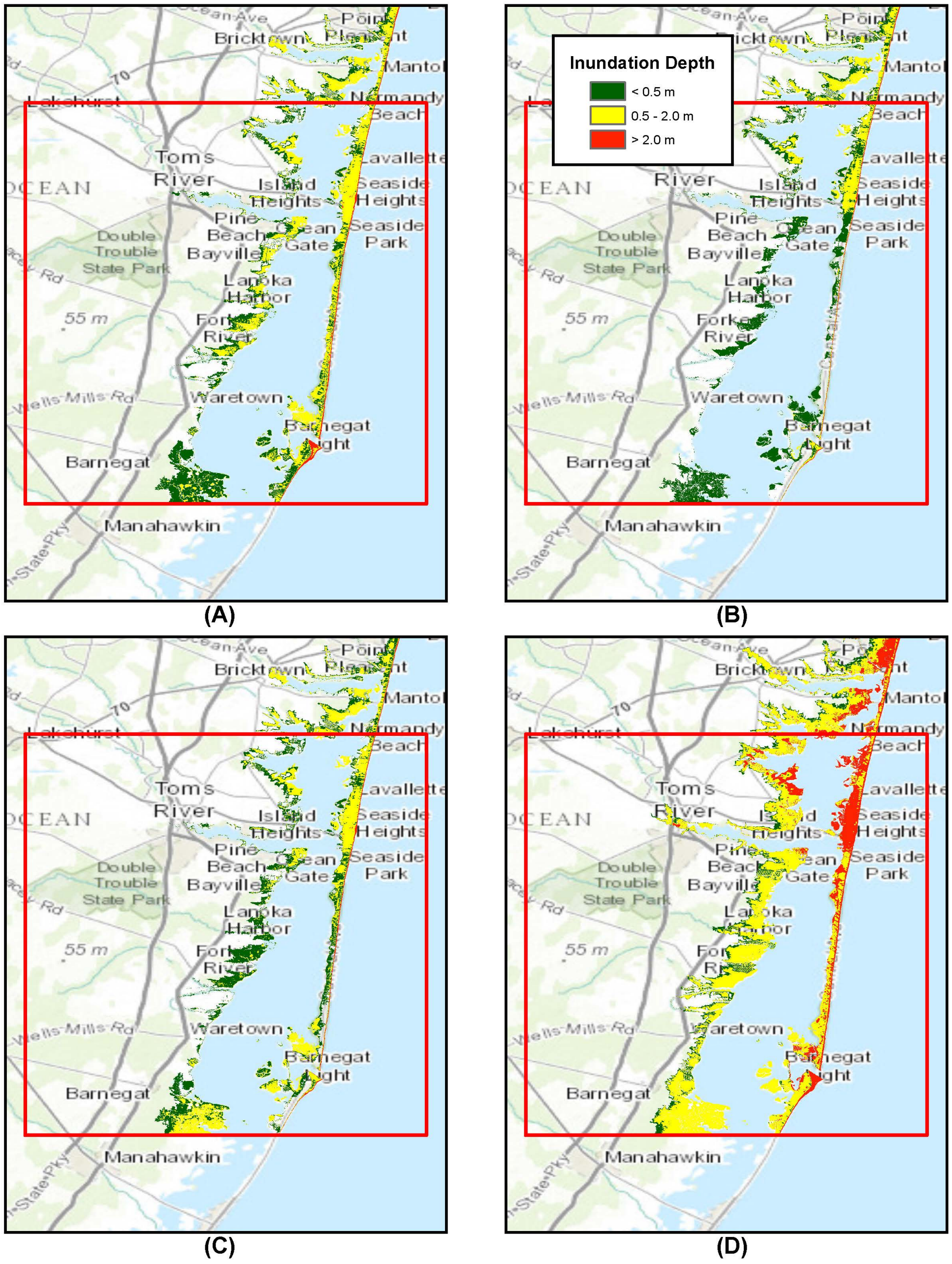


Figure 8: Inundation depth for NJ_1arc_1 domain, A) SMF Envelope, B) Coseismic Envelope, C) CVV 80 km^3 slide, and D) CVV 450 km^3 slide. Red box depicts NJ_1arc_1 domain boundaries.

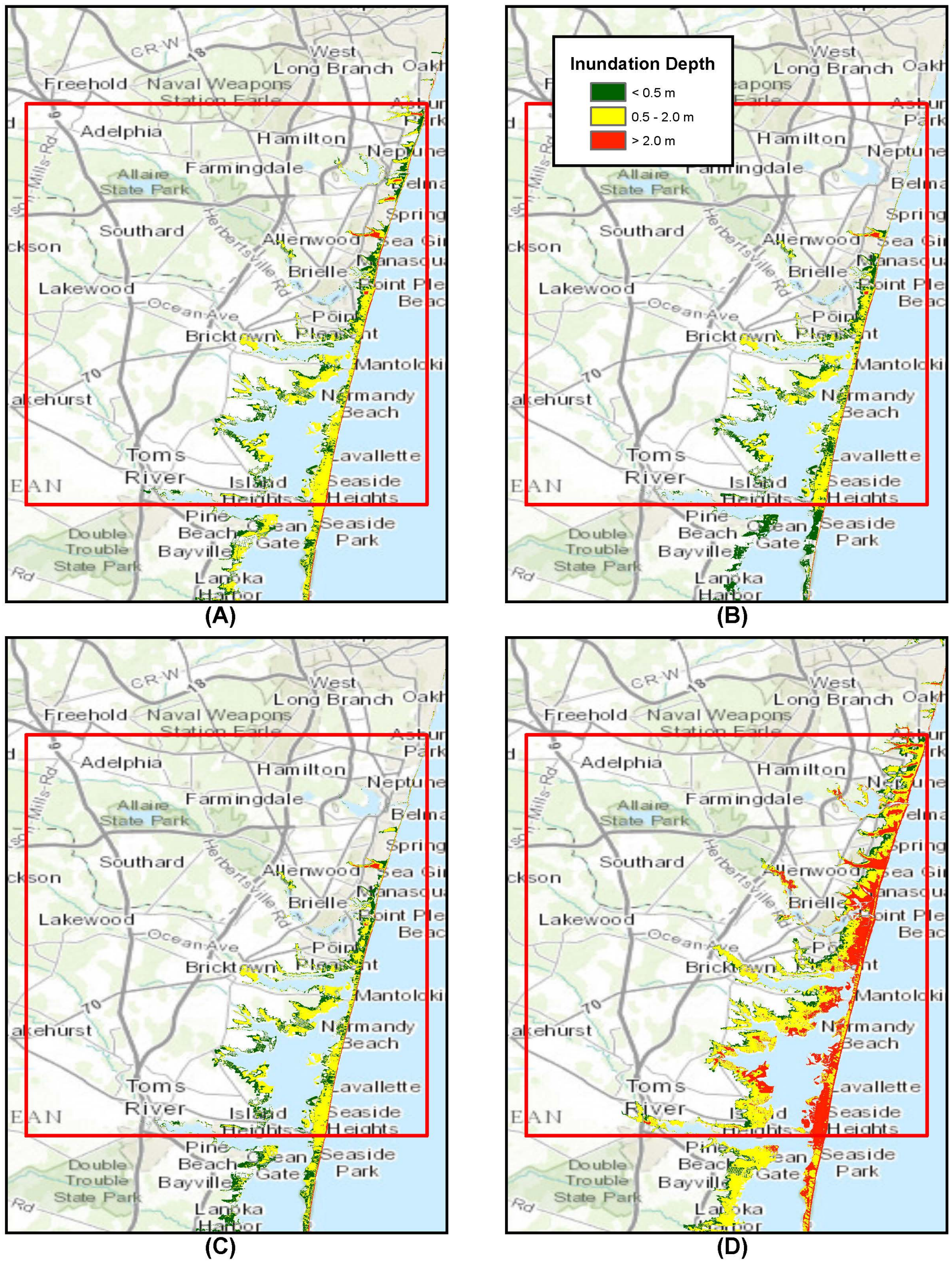


Figure 9: Inundation depth for NJ_1arc_2 domain, A) SMF Envelope, B) Coseismic Envelope, C) CVV 80 km^3 slide, and D) CVV 450 km^3 slide. Red box depicts NJ_1arc_2 domain boundaries.

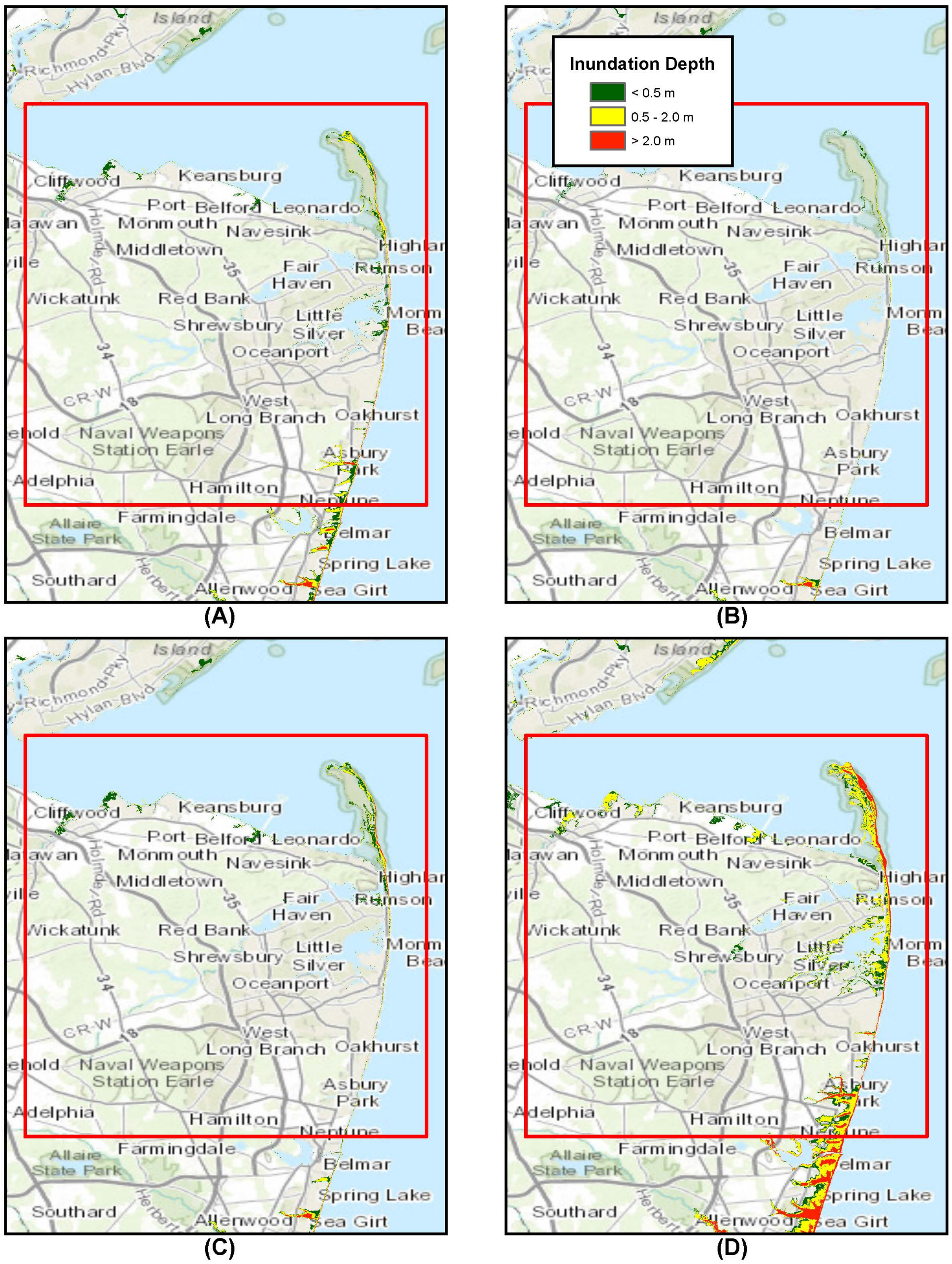


Figure 10: Inundation depth for NJ_1arc_3 domain, A) SMF Envelope, B) Coseismic Envelope, C) CVV 80 km^3 slide, and D) CVV 450 km^3 slide. Red box depicts NJ_1arc_3 domain boundaries.

Figure 11: Inundation depth for NJ_1arc_4 domain, A) SMF Envelope, B) Coseismic Envelope, C) CVV 80 km^3 slide, and D) CVV 450 km^3 slide. Red box depicts NJ_1arc_4 domain boundaries.

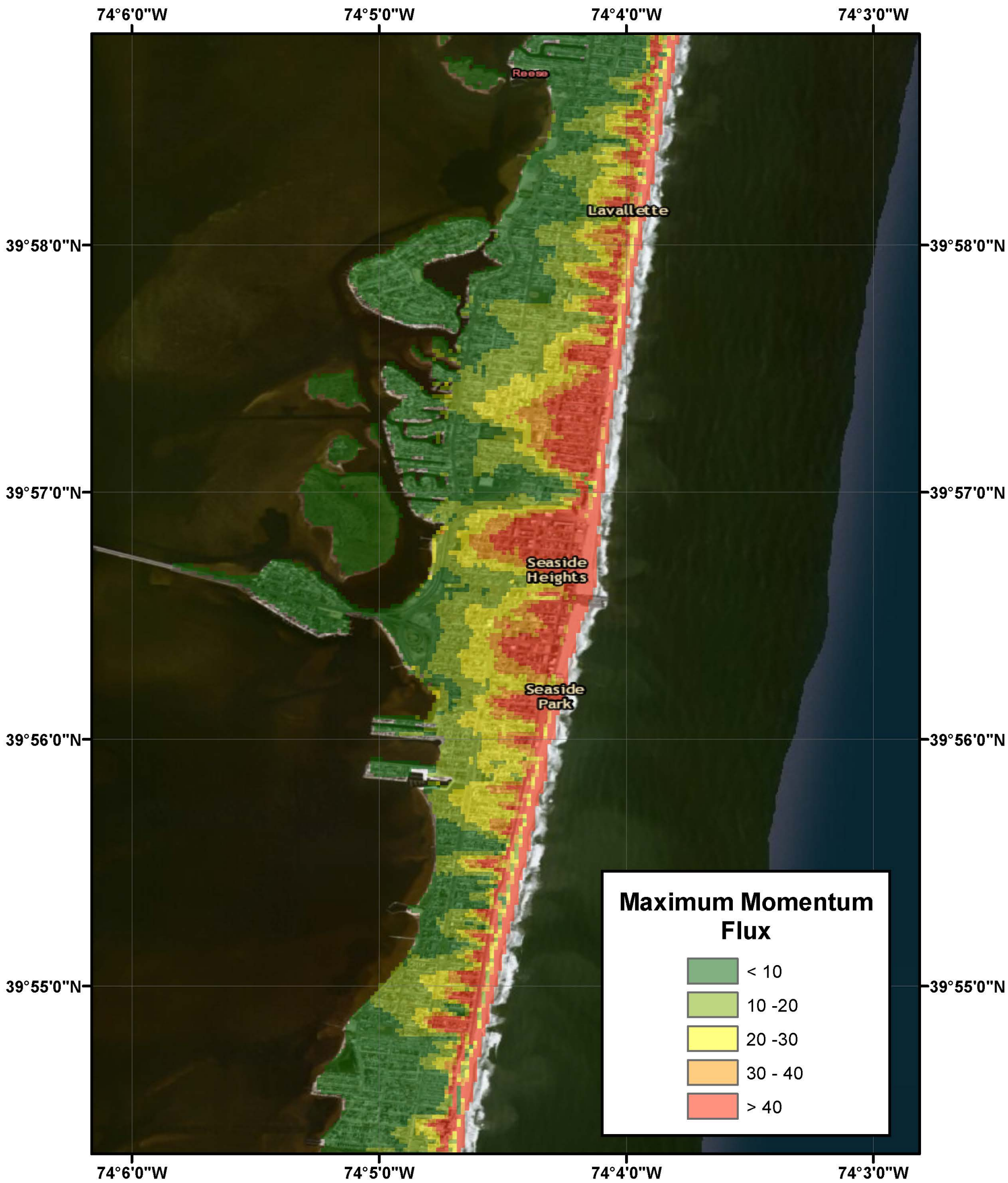


Figure 12: (Maximum Momentum Flux Map for Seaside Heights during SMF1 tsunami (Colorbar values are in m^3/s^2)

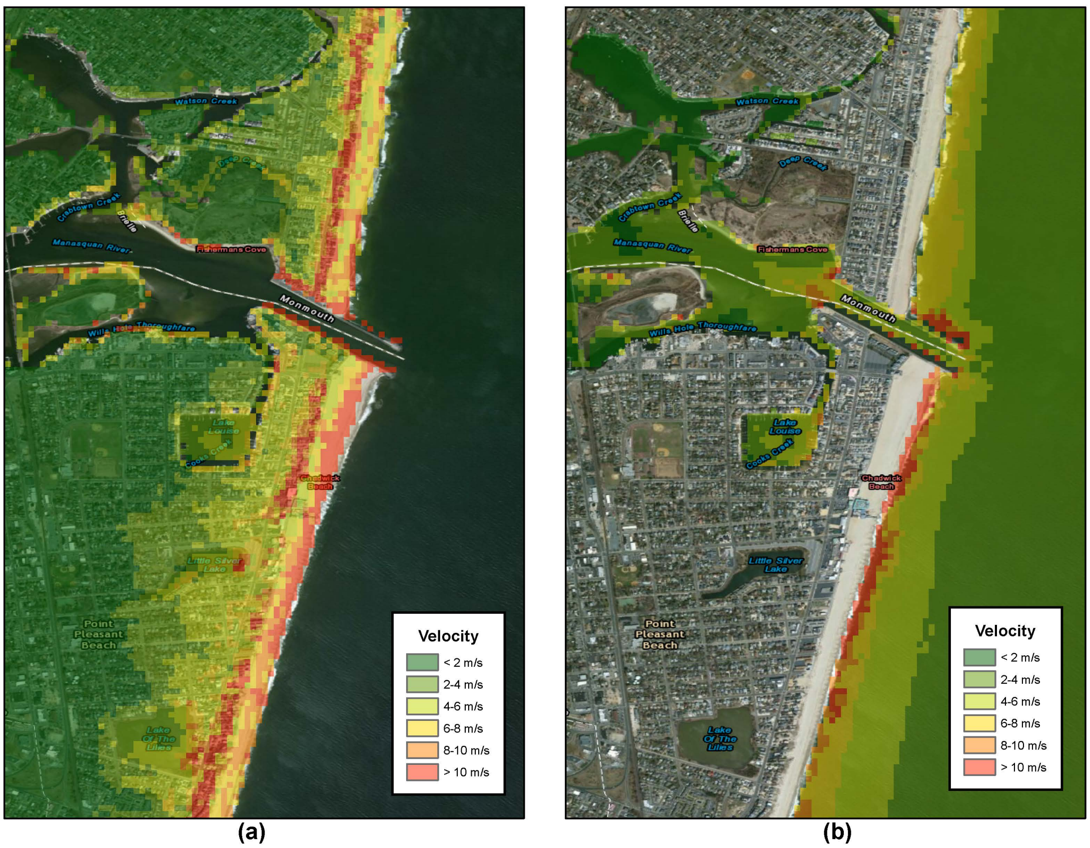


Figure 13: (a) Maximum Velocity map for inundated area around Manasquan inlet (SMF1) (b) Maximum Velocity map for Manasquan Inlet for offshore areas (SMF1)

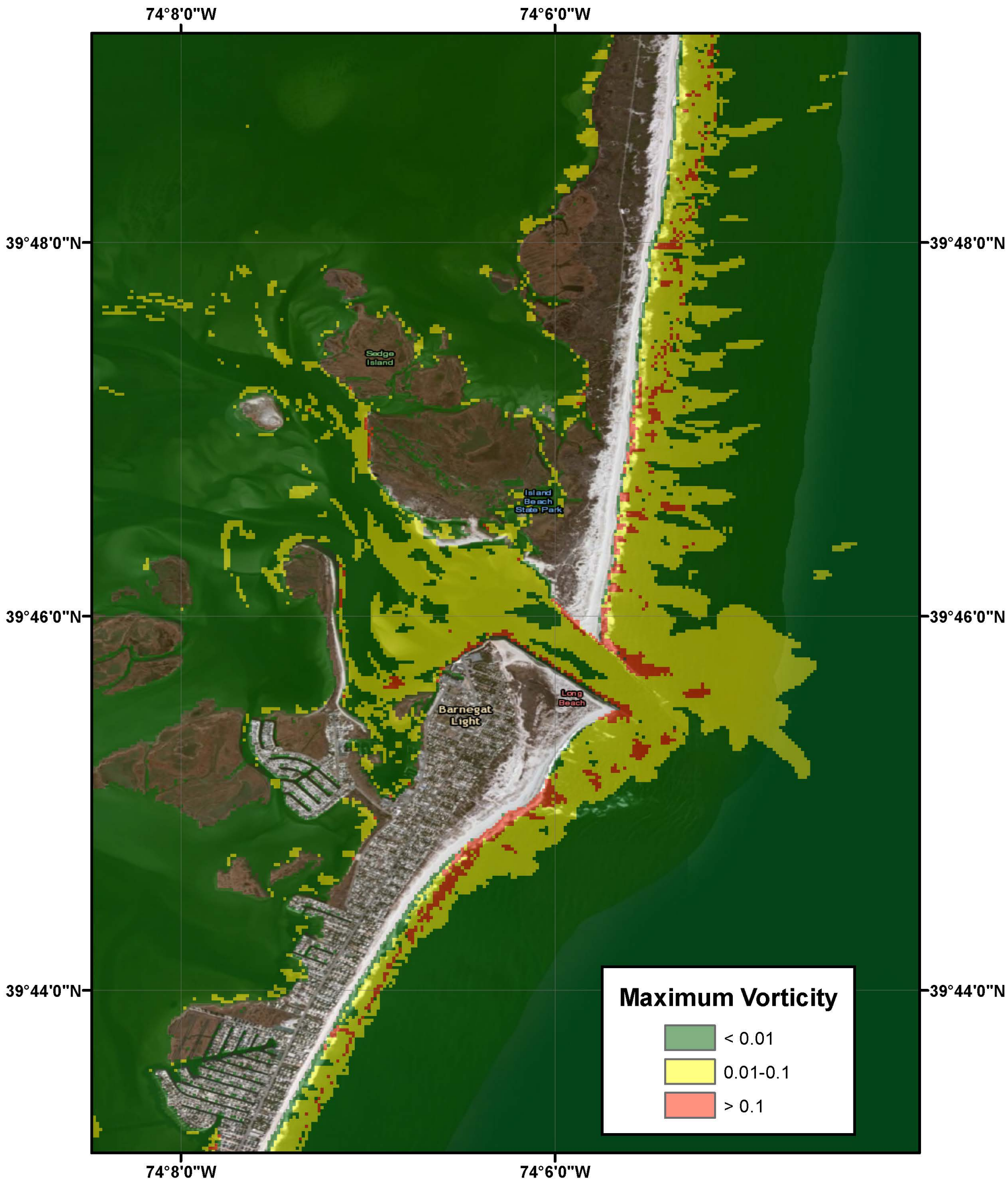


Figure 14: Maximum Vorticity map for the area around Barnegat inlet

4.3 Inundation line

Tsunami inundation line is the main result of this project. The inundation line demonstrates the envelope of the onshore maximum inundation extent of all tsunamis studied in this work. We extracted the inundation line from inundation depth data. For each location an envelope inundation depth map was generated from all of the tsunami sources. Then, the zero contour of that map represents the inundation line, which is the extent of tsunami inundation inland. As mentioned in the previous section, the 450 km^3 CVV source is excluded from the inundation line calculations, and its inundation line is separately demonstrated as the low probability worst case scenario (shown in blue (Figure 15)). The main inundation line is the envelope for all of the other cases studied here (shown in red (Figure 15)). The inundation line for 4 arc-sec and 1 arc-sec domains were very close to each other for all of the sources. For most areas, the SMF1 source (which is the closest SMF source to the mapping location) was the dominant source controlling the inundation line; however, in a few locations the inundation line representing the 80 km^3 CVV source was the dominant tsunami source. It must be noted again that the 450 km^3 CVV source would have been the dominant source by far if it was not excluded from the inundation line calculations. Also, it should be noted that the inundations line in the overlapping areas between different domains were almost identical for most of the cases, which is result of a well performed nesting process. The inundation lines are saved as a shape file (.shp) in order to simplify the inundation map generation process. More information about file formats and names is provided in Appendix A.

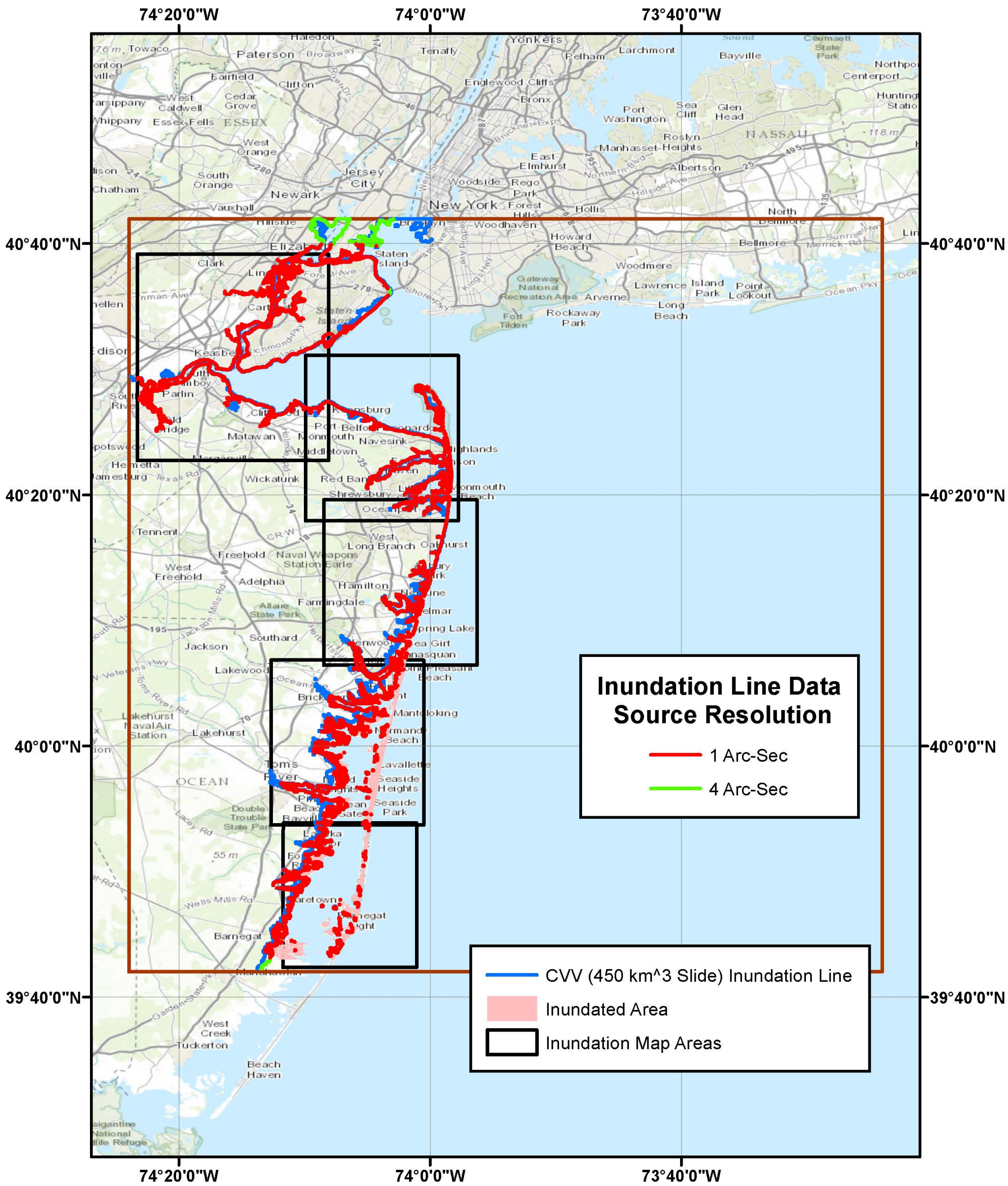


Figure 15: Tsunami inundation line for Northern New Jersey DEM area based on tsunami sources simulated in this project. The blue boxes show the location of the inundation maps discussed in Section 5.

5 Map Construction

The final results of this project are inundation maps that can be used for emergency planning. The inundation line shape files (.shp) provide the main resource for constructing these maps. These shape files are mapped over USGS and ESRI topographic maps to construct the inundation map. In addition to the inundated area and the inundation line, information regarding the map construction is provided on each map. The tsunami sources used to obtain these maps are mentioned in these maps. Also, the process of map construction is briefly described on the map. Figures 16-20 show the draft inundation maps for the "Barnegat Township, NJ" in 1:35000 scale, "Seaside Heights, NJ", "Spring Lake, NJ", "Sandy Hook, NJ" in 1:40000 scale and "Perth Amboy, NJ" in 1:50,000 scale. The location of these maps are shown in Figure 15. The basemaps for these figures are the USGS topographic maps obtained from (http://basemap.nationalmap.gov/ArcGIS/rest/services/USGSTopo/MapServer

It must be noted that the southern parts of the Northern New Jersey domain studied in this work were the most impacted areas (e.g. Seaside Heights). On the other hand, the northern parts facing the Atlantic Ocean were not impacted as much (e.g. Sandy Hook), and the areas inside the Lower New York Bay were barely impacted (e.g. Perth Amboy).

Acknowledgement

Special thanks for J. Andrew Martin, CFM, at Dewberry, FEMA Region II Support Center Coordinator for providing access to the various digital elevation model datasets.

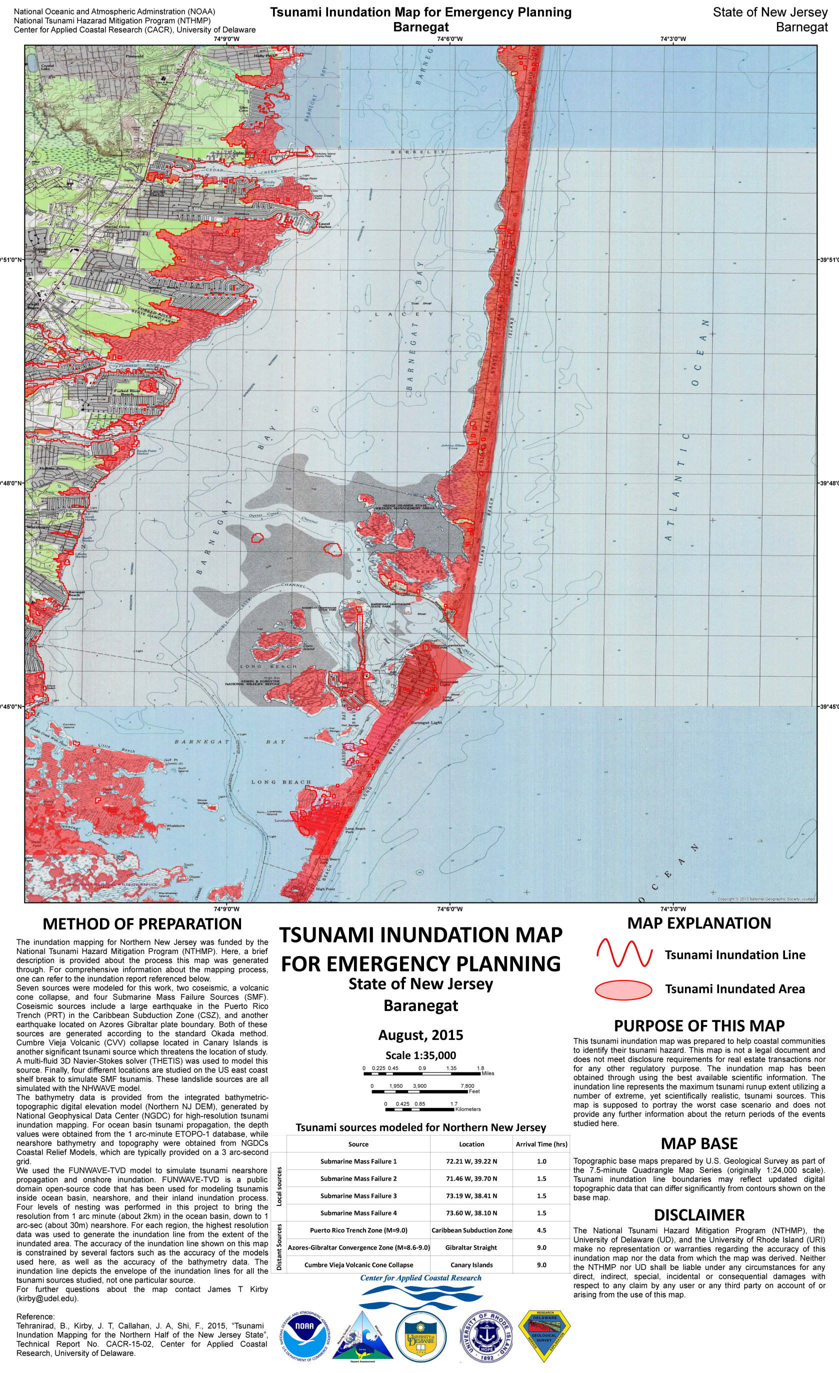


Figure 16: Inundation map for emergency planning for Barnegat Township, NJ, NJ in 1:35,000 scale. The inundated area is covered in red, and the thick red line represents the inundation line for this particular area.

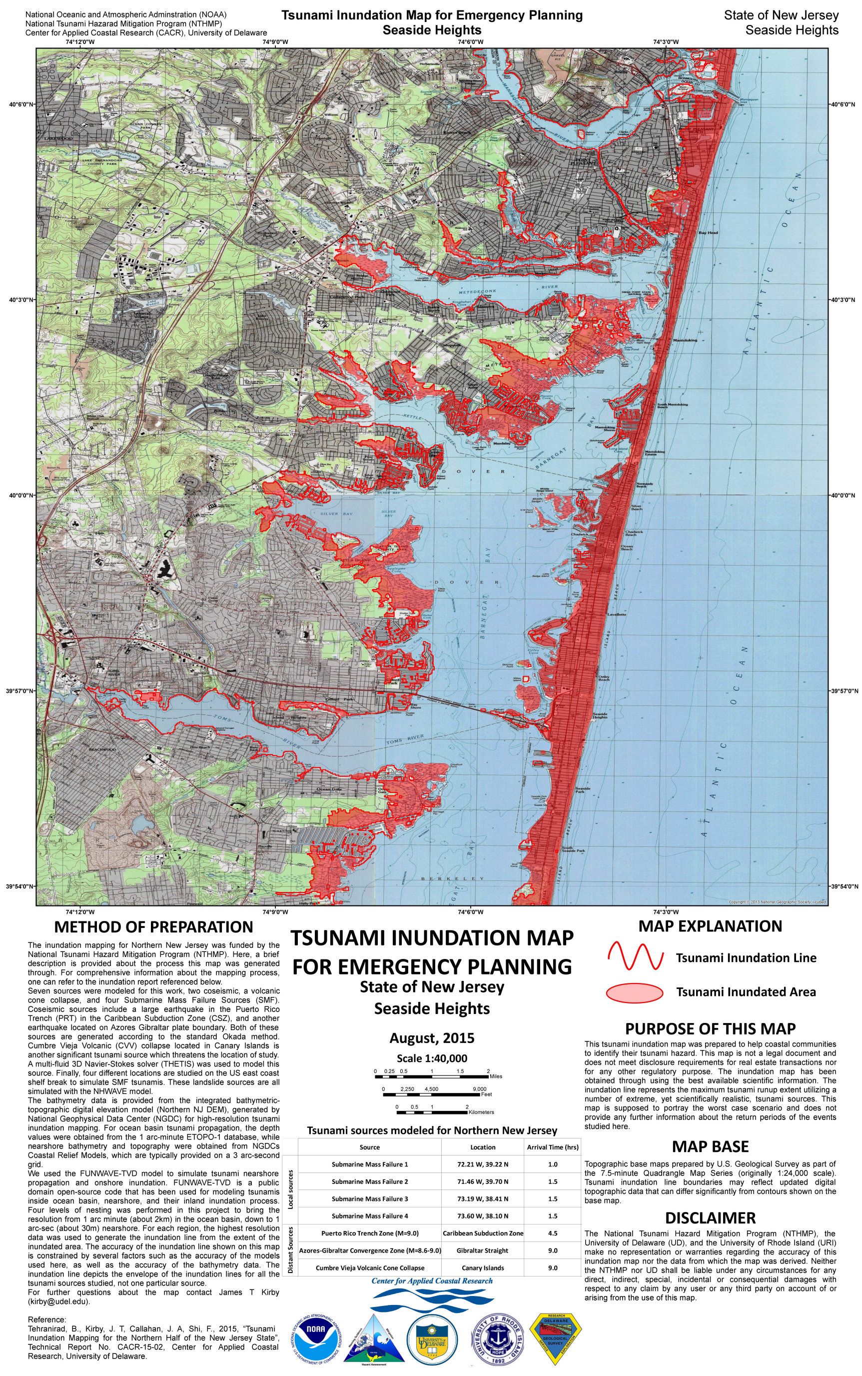
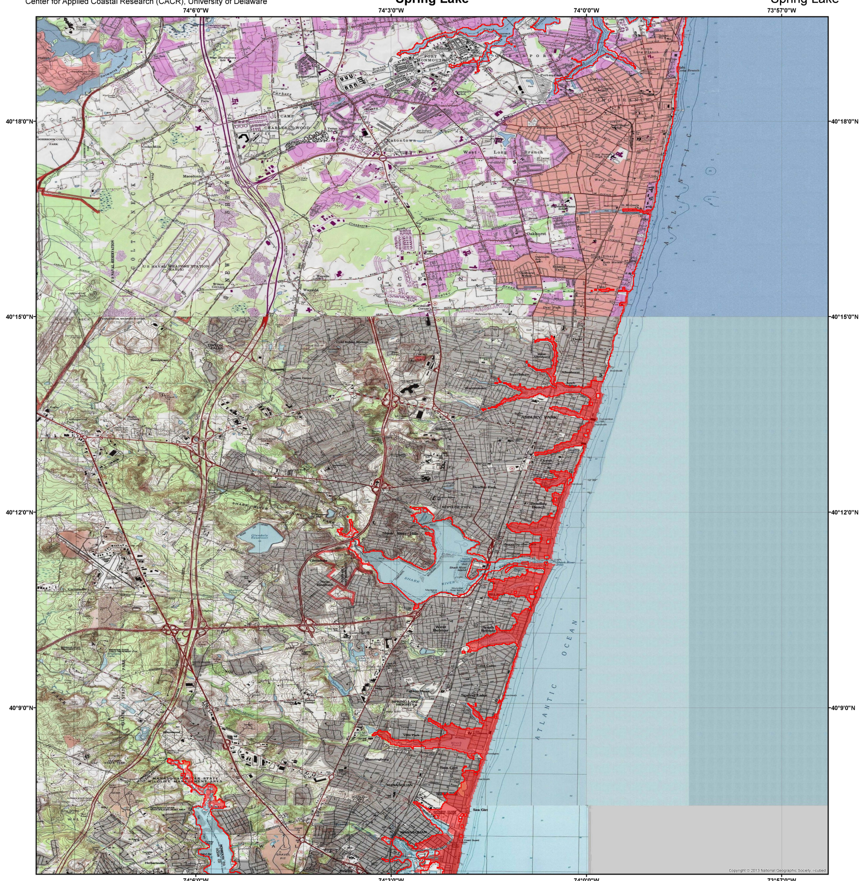


Figure 17: Inundation map for emergency planning for Seaside Heights, NJ in 1:40,000 scale. The inundated area is shown in red, and the thick red line represents the inundation line for this particular area.

National Oceanic and Atmospheric Adminstration (NOAA)
National Tsunami Hazard Mitigation Program (NTHMP)
Center for Applied Coastal Research (CACR), University of Delaware

Tsunami Inundation Map for Emergency Planning
Spring Lake

State of New Jersey
Spring Lake



METHOD OF PREPARATION

The inundation mapping for Northern New Jersey was funded by the National Tsunami Hazard Mitigation Program (NTHMP). Here, a brief description is provided about the process this map was generated through. For comprehensive information about the mapping process, one can refer to the inundation report referenced below.

Seven sources were modeled for this work, two coseismic, a volcanic cone collapse, and four Submarine Mass Failure Sources (SMF). Coseismic sources include a large earthquake in the Puerto Rico Trench (PRT) in the Caribbean Subduction Zone (CSZ), and another earthquake located on Azores Gibraltar plate boundary. Both of these sources are generated according to the standard Okada method. Cumbre Vieja Volcanic (CVV) collapse located in Canary Islands is another significant tsunami source which threatens the location of study. A multi-fluid 3D Navier-Stokes solver (THETIS) was used to model this source. Finally, four different locations are studied on the US east coast shelf break to simulate SMF tsunamis. These landslide sources are all simulated with the NHWAVE model.

The bathymetry data is provided from the integrated bathymetric-topographic digital elevation model (Northern NJ DEM), generated by National Geophysical Data Center (NGDC) for high-resolution tsunami inundation mapping. For ocean basin tsunami propagation, the depth values were obtained from the 1 arc-minute ETOPO-1 database, while nearshore bathymetry and topography were obtained from NGDCs Coastal Relief Models, which are typically provided on a 3 arc-second grid.

We used the FUNWAVE-TVD model to simulate tsunami nearshore propagation and onshore inundation. FUNWAVE-TVD is a public domain open-source code that has been used for modeling tsunamis inside ocean basin, nearshore, and their inland inundation process. Four levels of nesting was performed in this project to bring the resolution from 1 arc minute (about 2km) in the ocean basin, down to 1 arc-sec (about 30m) nearshore. For each region, the highest resolution data was used to generate the inundation line from the extent of the inundated area. The accuracy of the inundation line shown on this map is constrained by several factors such as the accuracy of the models used here, as well as the accuracy of the bathymetry data. The inundation line depicts the envelope of the inundation lines for all the tsunami sources studied, not one particular source.

For further questions about the map contact James T Kirby (kirby@udel.edu).

Reference:
Tehranirad, B., Kirby, J. T, Callahan, J. A, Shi, F., 2015, "Tsunami Inundation Mapping for the Northern Half of the New Jersey State", Technical Report No. CACR-15-02, Center for Applied Coastal Research, University of Delaware.

TSUNAMI INUNDATION MAP FOR EMERGENCY PLANNING

State of New Jersey
Spring Lake

August, 2015

Scale 1:40,000

0 0.25 0.5 1 1.5 2 Miles
0 2,250 4,500 9,000 Feet
0 0.5 1 2 Kilometers

Tsunami sources modeled for Northern New Jersey

	Source	Location	Arrival Time (hrs)
Local sources	Submarine Mass Failure 1	72.21 W, 39.22 N	1.0
	Submarine Mass Failure 2	71.46 W, 39.70 N	1.5
	Submarine Mass Failure 3	73.19 W, 38.41 N	1.5
	Submarine Mass Failure 4	73.60 W, 38.10 N	1.5
Distant Sources	Puerto Rico Trench Zone (M=9.0)	Caribbean Subduction Zone	4.5
	Azores-Gibraltar Convergence Zone (M=8.6-9.0)	Gibraltar Straight	9.0
	Cumbre Vieja Volcanic Cone Collapse	Canary Islands	9.0

Center for Applied Coastal Research

MAP EXPLANATION

Tsunami Inundation Line
Tsunami Inundated Area

PURPOSE OF THIS MAP

This tsunami inundation map was prepared to help coastal communities to identify their tsunami hazard. This map is not a legal document and does not meet disclosure requirements for real estate transactions nor for any other regulatory purpose. The inundation map has been obtained through using the best available scientific information. The inundation line represents the maximum tsunami runup extent utilizing a number of extreme, yet scientifically realistic, tsunami sources. This map is supposed to portray the worst case scenario and does not provide any further information about the return periods of the events studied here.

MAP BASE

Topographic base maps prepared by U.S. Geological Survey as part of the 7.5-minute Quadrangle Map Series (originally 1:24,000 scale). Tsunami inundation line boundaries may reflect updated digital topographic data that can differ significantly from contours shown on the base map.

DISCLAIMER

The National Tsunami Hazard Mitigation Program (NTHMP), the University of Delaware (UD), and the University of Rhode Island (URI) make no representation or warranties regarding the accuracy of this inundation map nor the data from which the map was derived. Neither the NTHMP nor UD shall be liable under any circumstances for any direct, indirect, special, incidental or consequential damages with respect to any claim by any user or any third party on account of or arising from the use of this map.

Figure 18: Inundation map for emergency planning for Spring Lake, NJ at 1:40,000 scale. The inundated area is covered in red, and the thick red line represents the inundation line for this particular area.

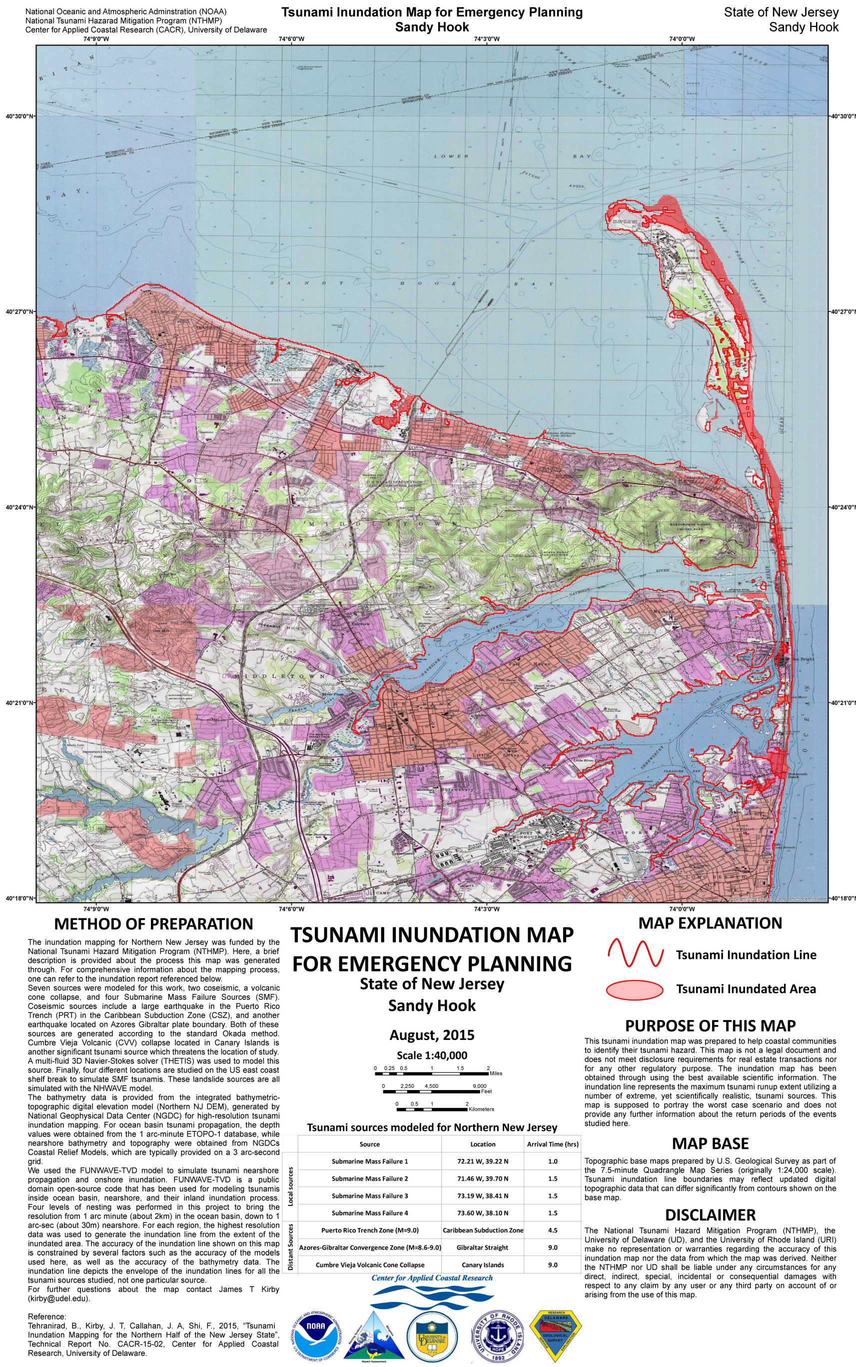
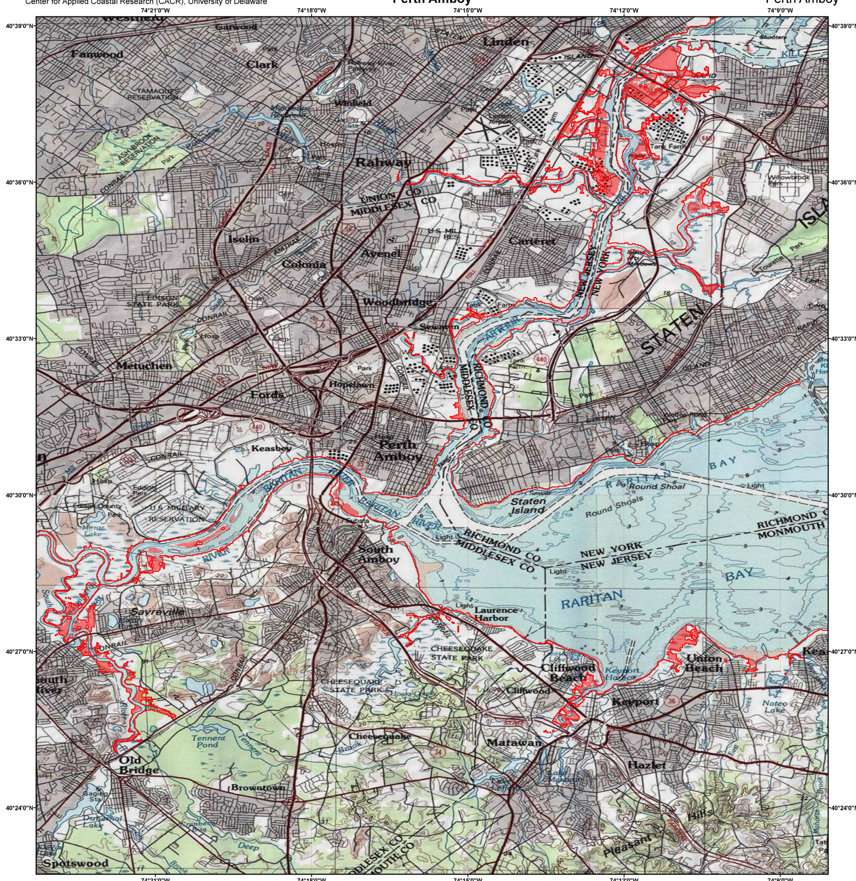


Figure 19: Inundation map for emergency planning for Sandy Hook, NJ at 1:40,000 scale. The inundated area is covered in red, and the thick red line represents the inundation line for this particular area.

National Oceanic and Atmospheric Adminstration (NOAA)
National Tsunami Hazard Mitigation Program (NTHMP)
Center for Applied Coastal Research (CACR), University of Delaware

Tsunami Inundation Map for Emergency Planning
Perth Amboy

State of New Jersey
Perth Amboy



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TSUNAMI INUNDATION MAP FOR EMERGENCY PLANNING

State of New Jersey
Perth Amboy

August, 2015

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Center for Applied Coastal Research

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Figure 20: Inundation map for emergency planning for Perth Amboy, NJ at 1:50,000 scale. The inundated area is covered in red, and the thick red line represents the inundation line for this particular area.

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Appendix A Gridded Data Information

In order to facilitate GIS work used to report tsunami inundation simulation results, the output data is saved in ESRI Arc ASCII grid format, which is compatible with GIS software such as ArcGIS. For each file, the grid spacing could have two different values (23.79,30.81) m, and (95.16,123.24) m) depending on the domain, and the coordinate system is based on Geographic decimal degrees (Longitude and Latitude). Also, the vertical datum of all rasters is mean high water (MHW), and the horizontal datum is World Geodetic System of 1984 (WGS 84). The name of each file implies some information about the file contents as well. The first part defines the type of data and could be one of the following,

Inun . . . Onshore inundation depth

Inun_area . . . Depicts the inundated area (inundation line)

Hmax. . . Maximum recorded offshore water surface elevation

Mfmx . . . Maximum recorded onshore momentum flux

Uwet. . . Maximum recorded onshore velocity

Udry. . . Maximum recorded offshore velocity

vorm. . . Maximum recorded offshore vorticity

depth. . . depth

The rasters including inundation depth, maximum momentum flux, and maximum onshore velocity (udry) are only meaningful onshore (for initially dry points, basically inundated points), and by using the bathymetry data, nodata values have been defined for onshore points in these rasters (nodata value=-9999). The reverse is performed for maximum vorticity and maximum offshore velocity (uwet) rasters by setting the offshore values to -9999 to just consider the initially wet points in the domain. The second part of the raster name defines the tsunami source used to obtain that data. This could be seven different sources and are categorized as follows,

SMF1-4. . . Submarine Mass Failure 1-4
PR. . . Puerto Rico Trench
LIS. . . Lisbon Source
CVV. . . Cumbre Vieja Volcanic Collapse.

In each file, the grid sizes (mx,ny), the coordinates for south west corner of the domain, and the grid size are included in the file heading as well as a nodata value through the following format,

ncols	9397
nrows	12853
xllcorner	-75.580046296295
yllcorner	37.679953703705
cellsize	9.2592589999999e-005
NODATA_value	-9999

Beneath the file heading, the corresponding values to each point are written in the file with the format that starts from the southwest edge of the domain, and writes each row from western to eastern boundaries of the domain from south to north. This format is different from FUNWAVE-TVD output format, and it is flipped upside down. Therefore, the FUNWAVE-TVD outputs are flipped vertically to match with ESRI Arc ASCII grid format here. The last part of the file name represents the name of the grid that the raster is built for. The names for each grid can be found in table 1. Therefore, the raster "Inun_SMF2_oc_30_1.asc" refers to the inundation depth data for the SMF2 source for the first Northern New Jersey grid (NJ_1) with the resolution of roughly 30 m ((dx,dy) = (24.30,30.81) m (corresponding to 1 arc-sec in spherical coordinates)) described in the main document (Table 1). Finally, the inundation lines are saved as shape files (.shp) for each domain and have the same name format and projection with rasters. The combined inundation line, which depicts the inundation line for the whole domain based on the finest results available in any area, is presented as "final_inundation_line.shp" in the main folder of the results. Figure 21 shows the way the data is organized. There exists a folder for each domain (NJ_1, NJ_2) and each of them involve seven folders for each tsunami source studied here. The raster data and inundation line shape file explained above are located in these folders.

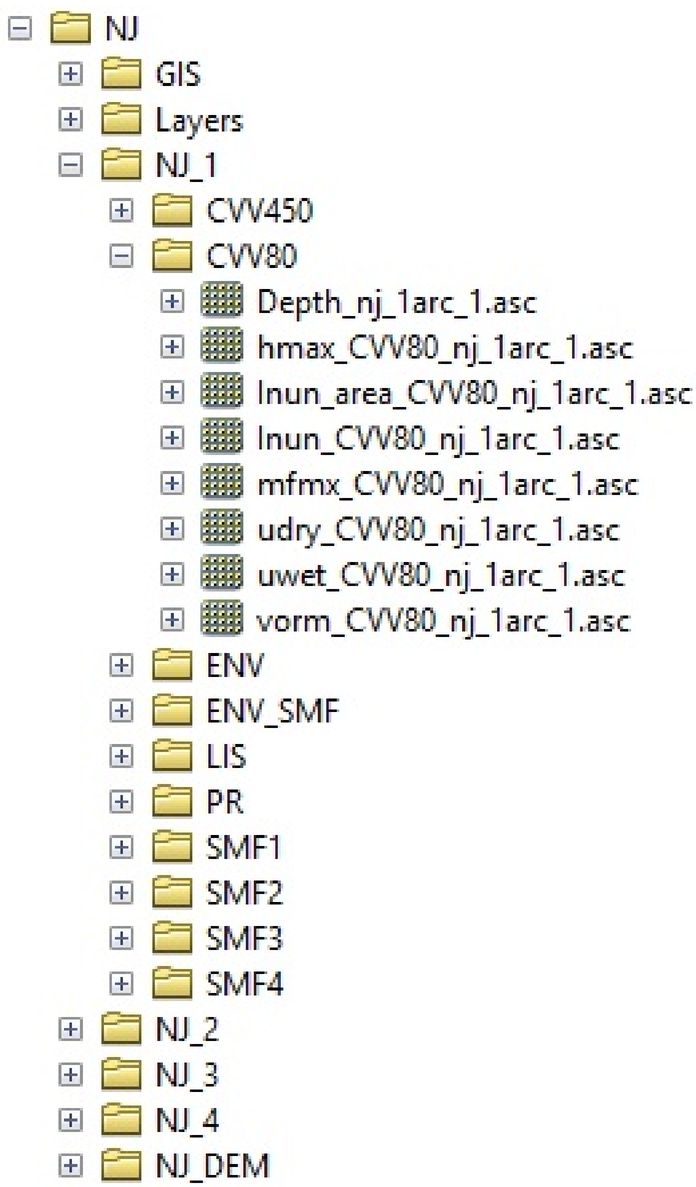

Figure 21: Screen shot of the results folder

Appendix B Modeling inputs

A brief description of model inputs that were saved during the simulation process is provided here. These files provide sufficient data for researchers who are interested to model the tsunamis on their own. In the main results folder, there exist a folder called "input" (Figure 22). In this folder, three categories of input files exist. First, depth files for each domain are provided. The file name represents the location of the bathymetry data, and one could figure it out using Table 1. For example, if the file name is "NJ_1arc_1, it is the bathymetry data for the NJ_1arc_1 domain defined previously in this report (Table 1,Figure 8). Next, the coupling file for each simulation domain is provided for seven sources studied in this work. Coupling files force the boundary conditions on the domain based on recordings from coarser grids in order to simulate tsunamis with finer resolution. Similar to the bathymetry files, names of coupling files show their domain, as well as their source. For instance, the file "smf3_ac_1arc_3.txt" is the coupling file for SMF3 source for the NJ_1arc_3 domain (Figure 10, Table 1). The coupling files can be easily distinguished from bathymetry files because bathymetry files do not have a tsunami source label included in their names.

General instructions for configuring input files for FUNWAVE-TVD may be found in the program's users manual (Shi et al., 2011), available at,
http://chinacat.coastal.udel.edu/papers/shi-etal-cacr-11-04-version2.1.pdf.

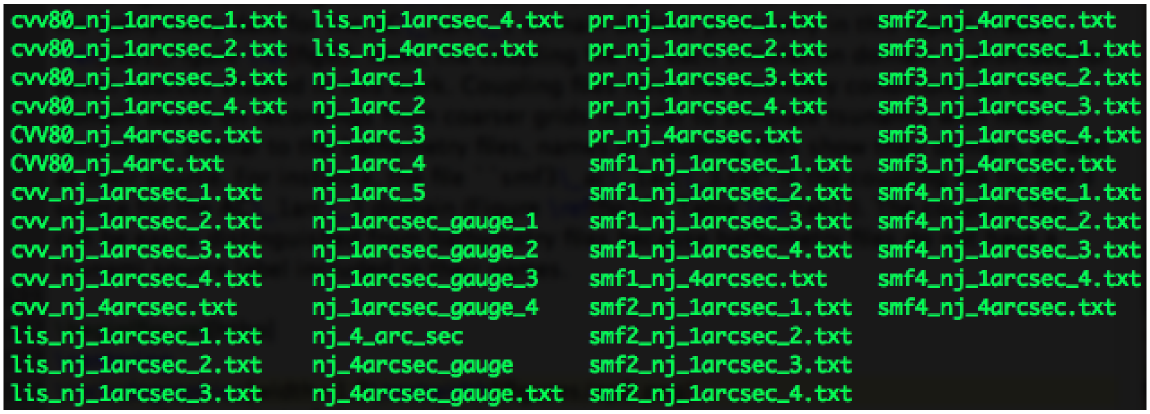

Figure 22: Screen shot of the input folder

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Appendix C Inundation Mapping Guidelines

The development of inundation maps for tsunami hazard assessment and evacuation planning is governed by three documents and a related appendix. These include:

1. NTHMP Inundation Modeling Guidelines
   Available at: http://nws.weather.gov/nthmp/modeling_guidelines.html

2. Mapping Guidelines Appendix A
   Available at: http://nws.weather.gov/nthmp/documents/MnM_guide_appendix-final.docx

3. NTHMP Tsunami Evacuation Mapping Guidelines
   Available at:
   http://nws.weather.gov/nthmp/documents/NTHMPTsunamiEvacuationMappingGuidelines.pdf

4. NTHMP Guidelines for Establishing Tsunami Areas of Inundation for Non-Modeled or Low-Hazard Areas
   Available at:
   http://nws.weather.gov/nthmp/documents/Inundationareaguidelinesforlowhazardareas-Final092611.docx