Chapter 14
Integration of Tsunami Analysis Tools into a GIS Workspace – Research, Modeling, and Hazard Mitigation efforts Within NOAA's Center for Tsunami Research

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Abstract The National Oceanic and Atmospheric Administration's (NOAA) Center for Tsunami Research (NCTR) uses geospatial data and GIS analysis techniques in support of building an accurate tsunami forecasting system for the US Tsunami Warning Centers. The resulting forecast products can be integrated into applications and visualizations to assess hazard risk and provide mitigation for US coastal communities ranging from small towns to large urban centers. NCTR also conducts basic research on the nature of tsunami propagation and inundation, which relies on accurate geospatial information. In this chapter, we discuss how we have used both open source and commercially available geospatial technologies to address issues in tsunami research and hazard mitigation – including model visualization, data delivery, and emergency management products. Additionally, we discuss the development and coupling of tsunami model results with coastal risk, vulnerability, and evacuation models, raising the issues of integration, visualization, proliferation of mapping applications, and the ease of use and intended audience of these products.

Keywords Tsunami · GIS · Modeling · Inundation · Hazard assessment · Data management · Bathymetry · Mapping · Emergency management · Coastal processes

14.1 Introduction

The December 26, 2004 Sumatran event showed the world the devastating impact of a large-scale tsunami. Geographic Information System (GIS) and remote sensing information was integral to the rapid assessment of the situation and was later used to support recovery and rebuilding efforts. National Oceanographic and Atmospheric Administration (NOAA) scientists delivered rapid assessments of this event

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using GIS to compare tide gauge and buoy measurements, for field surveying of damaged sites, and to make comparisons with model output (Venturato et al. 2005).

At NOAA's Center for Tsunami Research (NCTR) geospatial information such as imagery, digital elevation models (DEM), LIDAR, and GIS data are applied and integrated into the tsunami research and forecasting workflow. Currently we are expanding our use of techniques for analyzing inundation model output and rapid visualization of forecast events through the use of spatially enabled databases, the use of Python and model building capabilities in ArcGIS™, creating Google Earth™ KML, and integrating the GeoTools (an open source JAVA GIS toolkit; GeoTools 2008) library into desktop and web based applications.

It is well known that models do not operate independently of their data. In the case of hazard mitigation, modelers need to integrate real-life data into their workflow. The integration of GIS into disaster response and mitigation has proven invaluable as shown for Hurricane Katrina and other large-scale disaster recovery efforts (Eveleigh et al. 2006; Merati et al. 2007; Vance et al. 2007).

14.2 Tsunami Research and GIS

NCTR is located at the Pacific Marine Environmental Laboratory in Seattle, Washington. NCTR evolved from NOAA and state-funded programs, including the National Tsunami Hazard Mitigation Program (NTHMP). The NTHMP started as a joint effort by NOAA, USGS, FEMA, and the states of Hawaii, Washington, California, Alaska, and Oregon to prepare US coasts and coastal urban centers for tsunami events. Through the efforts of the NTHMP program, the Pacific Marine Environmental Laboratory (PMEL) became the home of the Tsunami Inundation Mapping Efforts (TIME) program, whose aim was to integrate geospatial data and techniques to support tsunami research and hazard mitigation. The 2004 Indonesian Sumatra event elevated GIS efforts at PMEL and led us to better incorporate geospatial information and technologies into our data processing and into the generation of products for researchers and our clients – the tsunami warning centers and emergency managers. The NTHMP has now been expanded to include all US coastal states, territories, and possessions.

NCTR's mission is three-fold. First, NCTR works to design and develop tsunami detection devices and build monitoring systems. Second, NCTR provides research, development, and implementation of numerical models to increase the speed and accuracy of operational tsunami forecasts and warnings provided by the NOAA Tsunami Warning Centers (TWC). Third, NCTR conducts research and development to improve methods of predicting tsunami impacts on populations and the infrastructure of coastal communities (http://nctr.pmel.noaa.gov/tsunami-forecast.html). All three mission goals require some dependence on geospatial infrastructure – whether we are building a site suitability map or designing a model to determine at-risk population within an inundation zone. Examples include buoy siting optimization studies, producing static maps for briefings and updates, building database applications for data dissemination and storage, and development of stand-alone analysis and visualization tools. Additionally, GIS data and technologies are currently integrated into the NCTR development of the Short-term Inundation Forecasting for Tsunamis (SIFT) software used locally for analysis and deployed to NOAA Tsunami Warning Centers for operational use. NCTR has long recognized the need to provide information in a GIS format to emergency managers and state partners. In this chapter, we outline how NCTR integrates geospatial technologies in the daily workflow for data access, for modeling support and error checking, and for producing products used by our partners.

NCTR uses geospatial techniques, information, and applications to directly support two of three of our mission goals – the development and implementation of numerical models to increase the speed and accuracy of tsunami operational forecasts and warnings, and research and development to improve methods of predicting tsunami impacts on population and infrastructure of coastal communities. ArcGIS™ is used for grid development, bathymetric error checking, scripting, and basic GIS analysis capability. NCTR uses Python to script our tsunami model output and perform data conversions as well as for geoprocessing routines. Data management procedures utilize OpenGIS Consortium standards using PostgresSQL and PostGIS. Our data warehouse relies on web mapping services using the Minnesota Map Server (MapServer 2008).

Model integration and functionality is achieved by using GeoTools, an open source library that allows us to build GIS functionality and products into the MOST inundation web interface (http://geotools.codehaus.org/). A standalone GIS application called Tsunami GIS uses ESRI's™ ArcEngine and Java to visualize inundation and to analyze results.

New tools developed by the atmospheric and modeling community to integrate netCDF file types into the ESRI™ suite, including time series analysis and rapid automation of animations, increases the use of GIS by the modeling community. While not necessarily replacing the functionality of products such as MATLAB®, these new tools add the ability to interrogate layers for a given point or adding other layers of information.

14.3 Tsunami Modeling – MOST Model

A tsunami is a series of waves generated in a body of water by a disturbance that vertically displaces the water. These disturbances push water upwards, sideways, or downwards to create tsunami waves. The waves have extremely long wavelengths and periods and can propagate across the oceans, inundating coastal areas. Most often caused by earthquakes and landslides, tsunamis can also be caused by volcanic eruptions (NCTR 2008b).

PMEL uses the Method of Splitting Tsunami (MOST) numerical model for tsunami research and software development to develop faster and more accurate tsunami forecasts. The MOST model is a finite difference model that simulates, in three distinct phases, tsunami behavior due to underwater earthquakes – generation of the earthquake, transoceanic propagation of the earthquake, and inundation of dry land (Titov and González 1997). The MOST model is currently being refined to create products for NOAA's Tsunami Warning Centers forecasting operations as well as products for inundation modeling of coastal communities. The model is used to determine wave height, arrival time and inundation extent and depth for tsunami events. This effort requires pre-processing of propagation data so that, as real time data from the Deep-ocean Assessment and Reporting of Tsunami (DART) buoys come in, the warning centers and tsunami modelers are able to determine more precisely the coastal forecast (Percival et al. forthcoming; Venturato et al. 2007). These forecasts are output as netCDF files. Geospatial technologies and products, such as accurate bathymetric and topographic models, source data, and archived historical records are all available to the MOST model. Inundation of coastal areas, using pre-selected scenarios based on past events and simulations, are used to develop tsunami inundation maps used by emergency managers to plan evacuations. Currently, MOST is being expanded by NCTR personnel to allow for desktop use by the warning centers for real-time forecasting and for post-event analysis (Denbo et al. 2007).

As part of the tsunami forecast system, NCTR is building Stand-by Inundation Models (SIMs) for 75 US coastal communities. The work is to be completed by the end of 2011. SIMs are pre-calculated 4-hour simulations of tsunami wave inundation, run-up, and created using high-resolution bathymetric and topographic data covering a specific community or harbor area. They are implemented into the tsunami forecast system (SIFT) and optimized to run within a few minutes during an tsunami event (Wei, in prep.). The SIMs model scenarios using likely earthquake source locations for the area in question and earthquakes at a variety of probable magnitudes. Historical observations are used to validate the model results. To date, 35 communities have been completed. The urban areas for which SIMs has been completed include San Diego, San Francisco, and Los Angeles (the Harbor area), California; Honolulu, Hawaii; and San Juan, Puerto Rico.

14.4 DEM Development

The MOST model relies on accurate bathymetric and topographic information, especially for near-shore environments. GIS techniques have proven effective for building seamless DEMs of bathymetry and topography at finely scaled resolutions. An abundance of new data, including LIDAR, multibeam sonar, and other remotely sensed imagery, plus rapid dissemination of these data make the development of DEMs faster and more accurate. Since 1995, NCTR has developed merged bathymetric and topographic grids at varying scales for areas of interest, from basin-wide to cities and coastal communities. DEMs are built using the best available data including shorelines, bathymetry, and topography from a variety of sources. Stringent quality checking is performed as each DEM is developed. Of particular concern is the transition between edges – along and between the data sources of varying quality and resolution, which could cause a grid mismatch. Developing a bathymetry grid that has been error checked and standardized to one vertical datum using GIS software insures the MOST model will run smoothly (NCTR 2007). For inundation modeling, output grid cell spacing ranges from 1/3 to 1 arcsec (approximately 10−30 m) depending on the source data.

In the past, NCTR performed in-house development of grids for areas of interest. As the number of areas undergoing modeling increased, we contracted with NOAA's National Geophysical Data Center (NGDC) to develop DEMs for tsunami modeling (NGDC 2008a). To develop a DEM, NGDC acquires data from federal, state, and local sources, then quality-checks the data using ArcGIS™. Careful vertical datum adjustments are necessary as bathymetric and topographic data may be measured relative to differing vertical datums. Data are edited to remove outliers and clipped to the correct dimensions. If the data are sparse, which can be the case for older single beam bathymetric surveys, NGDC uses Generic Mapping Tools (GMT) to interpolate or infill these data sets. Data are finally gridded using MB-System software to extract the xyz data from ESRI™ shapefiles and to assign weighting in order to use the best data value for each cell value. A spline is used to interpolate data and assign a value to each DEM grid cell.

While NCTR and NGDC strive to create the best DEM for each area, issues commonly encountered during processing include geomorphologic and anthropogenic coastline change that occurs between the time the data were collected and the time they are used, data mismatches, and data quality errors. Tools such as Google Earth™ and satellite imagery allow for rapid validation of features that are in question. In addition, ArcGIS 3D Analyst™ and Spatial Analyst tools (e.g., hill shading, slope calculations) allow scientists to view DEMs in perspective and note outliers that may need to be regridded and edited (NGDC 2008b).

14.5 Community Model Interface for Tsunami (ComMIT)

The Second Session of the Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (ICG/IOTWS II; December 2005) in Hyderabad, India recommended establishing a web-based community model for tsunami modeling. It was envisioned that the Community model and associated tools would be the primary avenue to transfer modeling expertise and capabilities to and between Indian Ocean countries. Funding was provided by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) and the United States Agency for International Development (USAID). NCTR was tasked with developing the Community Model Interface for Tsunami (ComMIT). It was quickly apparent that ComMIT would have applicability not only in the Indian Ocean, but world-wide as a tool for web-based modeling, elementary forecasting, model development, education, and emergency management.

The framework of ComMIT is based on the Short-term Inundation Forecasting for Tsunamis (SIFT) forecast system designed at NCTR. The Standby Inundation Models (SIMs) from SIFT give very accurate results for inundation and current velocity in the area of interest. Typical SIMs cover several kilometers of shoreline and extend inland to cover densely populated urban areas (Wei, in prep.). Running a

SIM requires the modeled propagation results, combined in such a way that they best match the deep-ocean buoy measurement of the incoming tsunami wave. The propagation model (a linearized version of MOST), outputs two velocity components, as well as sea-surface height, in three netCDF files covering an entire ocean basin. It became apparent that there was a need to quickly create a subset of the propagation model output, perform the scaling and combination, feed them to the inundation model, and track the output. ComMIT was designed to address that need.

ComMIT is written in the Java programming language and accesses a database of propagation model netCDF output files using the OPeNDAP interface (NCTR 2008a). ComMIT allows the user to easily select among these files according to the deep-ocean buoy measurement, launch the MOST code, and monitor the inundation. Figure 14.1 shows the ComMIT application main window. The window has a map (upper left) of the ocean basin, with rectangular seismic fault planes covering subduction zones. Each rectangle represents a single propagation model run (approximately 5.5 Gb each, for a total database size of 1.5 terabytes). In the example, four fault planes have been selected (in red) near the Aleutian Islands, and the Crescent City SIM has been selected as the at-risk community. ComMIT downloads subsets of these propagation model files, sized to cover the outermost of the three nested grids that the inundation MOST model requires, and launches the computational code.

Figure 14.2 shows the ComMIT wave amplitude window with inundation output for the Crescent City harbor. This model has been optimized to run in a very short period of time (typically less than 10 min), allowing the Tsunami Warning

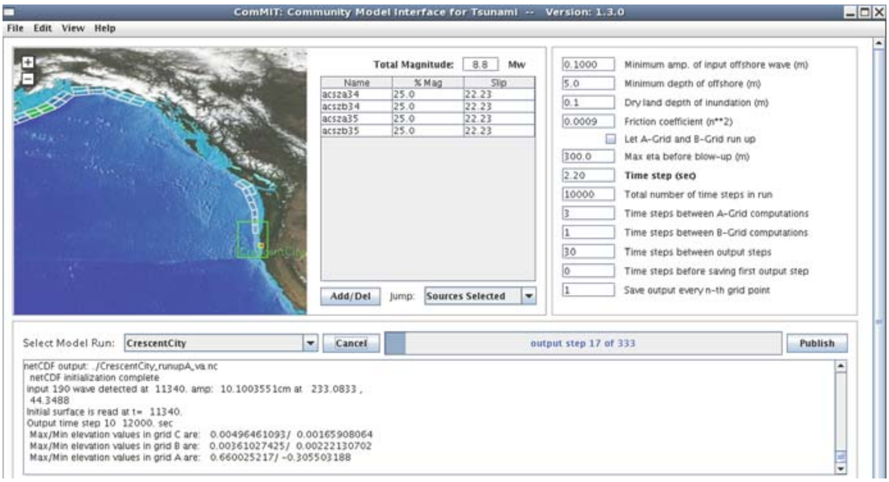

Fig. 14.1 The Community Model Interface for Tsunami (ComMIT) showing a hypothetical Mw = 8.4 seismic event generating a tsunami in the Aleutian Islands and a Standby Inundation Model (SIM) of the at-risk community, Crescent City, CA

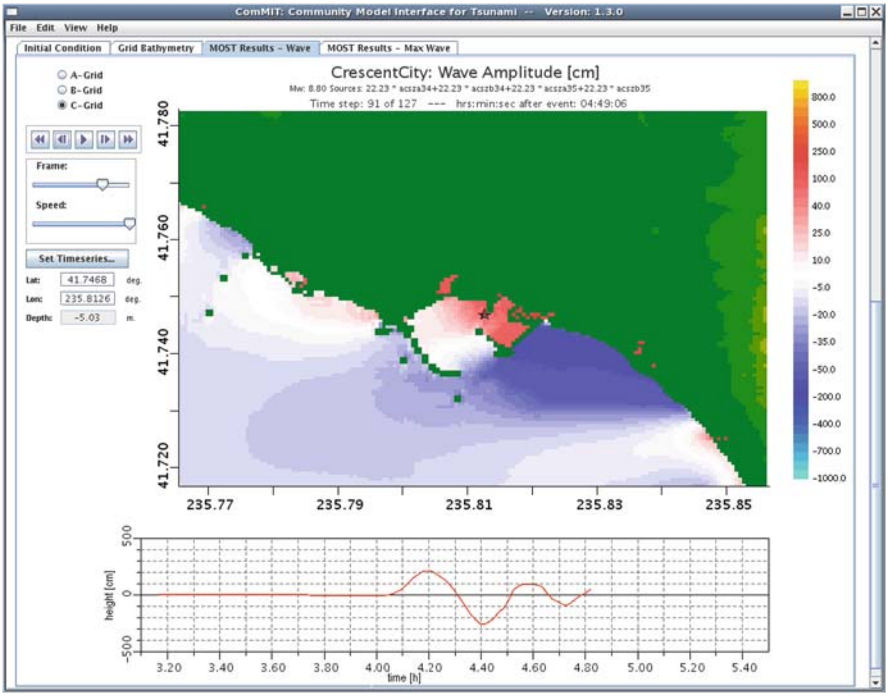

Fig. 14.2 Wave amplitude window showing MOST model results of Crescent City harbor inundation using hypothetical Aleutian Island forcing files. Note the time series location marked by the *star*

Centers to not only issue a detailed warning, but to provide detailed images and animations to emergency managers. Since the FORTRAN-based computational code outputs inundation results in netCDF format, ComMIT can return snapshots of maximum amplitude, sequences of geo-referenced images, files in standard GIS formats (e.g. netCDF for native read, shapefiles, ASCII raster) or Google Earth^{TM} files (Fig. 14.3).

ComMIT allows control of all of the MOST model input parameters, and access to the model output files for analysis. Selecting the scaling of the propagation files requires using a data assimilation inversion technique as part of the NCTR forecast system. ComMIT interfaces with the forecast system to receive this inversion information, and can perform the scaling automatically, allowing ComMIT to act as a forecast model during an event.

ComMIT has been found valuable both in developing SIMs, validating for historical accuracy, and as an educational tool to teach the basics of tsunami modeling and the NOAA tsunami forecast system. During 2007, four courses to teach how to use ComMIT were held in Melbourne, Australia (January), Bangkok, Thailand (June), Seattle, Washington (July), and Jakarta, Indonesia (September). Three courses were been offered in 2008 in Mahe, Seychelles (January), Cadiz, Spain (April), and Valparaiso, Chile (May).

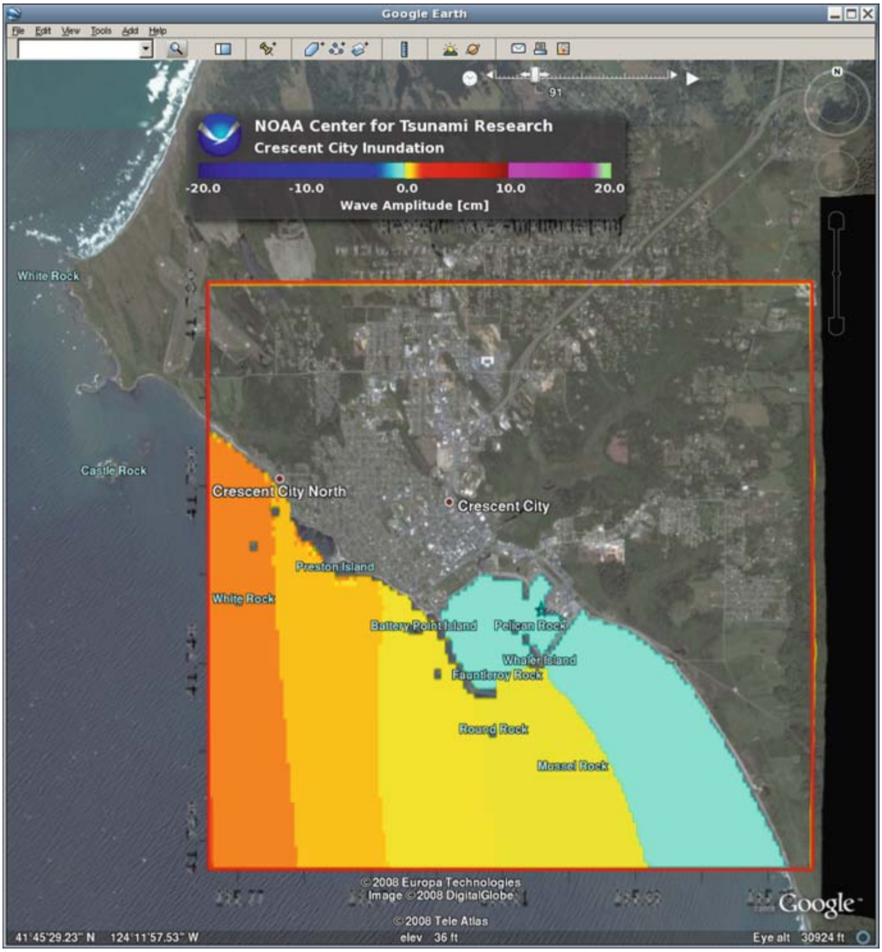

Fig. 14.3 Results from the Crescent City wave amplitude plot showing the height of a tsunami wave at a time slice during an inundation event. The amplitude is the height of the wave from mean sea level. In this case, at the current time step, the leading wave coming into the shoreline is in the trough part of its phase, thus showing a lower amplitude that the off shore amplitude which is positive. Geospatial formats such as GeoTIFFs of ComMIT output overlaid in Google Earth^{TM} provide users a way to integrate model results into an easily navigated and useable format

14.6 NCTR Atlas

The NCTR Atlas is an internal web application used to store and display information about the modeling locations and data used by NCTR for tsunami forecasting. The Atlas stores relevant metadata for the sites planned for inundation modeling, the bathymetric grids used as input to the models, and records of historic tsunami events used to validate the models. Design requirements included web accessibility for attractive, simple maps, integration with GIS and mathematical applications, and ease of use for data producers and consumers. At NCTR, the Atlas is used by scientists to discover and download the data they need for their work, by data managers to ensure that collected data are complete, and by management to track the progress of modeling efforts. The Atlas also operates as a data service, providing information in an XML-based format to other applications.

The Atlas web interface is focused around maps of the current area of interest. Users of the Atlas are presented with a map view of the area in which they are interested. The maps can be customized to display bathymetric and topographic contours of the area, extents of bathymetric modeling grids, areas of urbanization, population density, and similar layers. The Atlas tracks the progress of modeling, including initial development, testing, and documentation, and produces reports summarizing current model status by fiscal year and assigned personnel.

Grid details, including grid extents, resolution, content, relevant population centers, and type are displayed on each map view. Users can download the source grids for use in GIS applications and as source inputs for the MOST model. Written reports, documentation, and metadata are stored for each model and grid, and can be downloaded from the web interface. Model locations and grid extents are also exported as a Web Feature Service (WFS), an open GIS standard that can be read into many applications, including ArcGIS™ using the Interoperability Extension.

The Atlas stores historical and recent tsunami event information including seismic source information for each event, and recorded tide gauge and bottom-pressure recorder time series. This information is essential for validation of newly developed site-specific inundation models, and for testing potential changes to the numerical modeling codes. The Atlas can import time series data in several formats, present simple graphs of the data automatically, and export the data in text-based or netCDF formats for further analysis.

Recent work on the Atlas has focused on integration with NCTR's other software systems. In this capacity, the Atlas serves as a central database for tsunami model and event data, providing a consistent set of data to NCTR's diverse users. Through its XML-based web application service interface, the Atlas allows external software to query and update the database. For example, tsunami events are automatically added to the database as soon as they are broadcast by the tsunami warning centers; these events are then passed to the WebSIFT real-time modeling interface.

The Atlas is implemented with custom software written in the Python programming language, using the Django web framework. The application is backed by a PostgreSQL database with the PostGIS spatial extension. Mapping is done by the UMN MapServer, an open-source mapping toolkit.

14.7 Coordinated Efforts with State partners – Inundation Mapping

If one draws a buffer overlay from the shoreline to approximately one kilometer inland of the West Coast of the United States, over 1.2 million people could be affected by tsunami inundation (González et al. 2005). Inundation mapping is useful for communities and emergency managers in determining the extent of coastal storm events and tsunami inundation. Mitigation efforts include physical maps that are distributed to communities as brochures, open file reports, and evacuation routes that are found in the public service section of local phone books. Inundation maps are also available via the Internet. While to some they appear off putting, having an inundation line mapped with proximity to roads, infrastructure, and evacuation routes puts many minds at ease. Inundation maps require model runs as input along with a good level of knowledge of local landmarks and hazards that may hamper or inhibit evacuations. In the past, inundation maps had been developed by the states with little input from tsunami modelers. One of the major foci of the NTHMP was to create tsunami evacuation maps for affected coastal areas based on the threat of a near-field tsunami triggered by an event in the Cascadia Subduction Zone off the northwestern coast of the United States and other far-field earthquake sources in the Pacific Ocean.

Inundation and hazard mapping was undertaken by PMEL's TIME Center. The Center was tasked to develop an infrastructure to support tsunami inundation modeling in support of the NTHMP Program and to create tsunami inundation maps using model output. The mapping effort focused on the five states associated with the NTHMP steering committee and produced inundation maps and products useful to the states and their local emergency managers. TIME scientists worked to derive the best available bathymetry, shoreline, and topographic data to create gridded bathymetric products to run inundation models (Bernard 2005). While the best available data are used for shoreline derivation and shoreline changes, the development of a seamless DEM is not trivial. TIME scientists worked to develop a methodology to describe tidal datum distributions that use tidal harmonic constants for each tide station within Washington State's Puget Sound region to derive an accurate tidal datum for the area of interest (Mofjeld et al. 2004). The Puget Sound region is home to over 4 million people; as with other coastal urban areas, small errors in DEM interpolation could translate into miscalculating the population at risk. Numerical model results, including resulting maximum wave heights and velocities, were used to develop inundation products for the NTHMP partners. ArcGIS^{TM} products were used for grid development and error checking of these grids (Titov et al. 2003).

In all, 22 inundation maps were developed for the 113 communities identified as at risk. Figure 14.4 is an example of a typical inundation map in the event of a near-field Seattle Fault Earthquake of moment magnitude (Mw) of 7.3 showing areas around Elliott Bay that would be inundated according to output from MOST model runs.

More sophisticated levels of hazard assessment incorporate land use and land cover with inundation mapping to assess what landscape features will be adversely affected by a tsunami event. While the MOST model requires bald earth topography, incorporating wave height, velocities, and amplitudes into a GIS system can assist in understanding how and where populations and structures may be impacted by tsunami events.

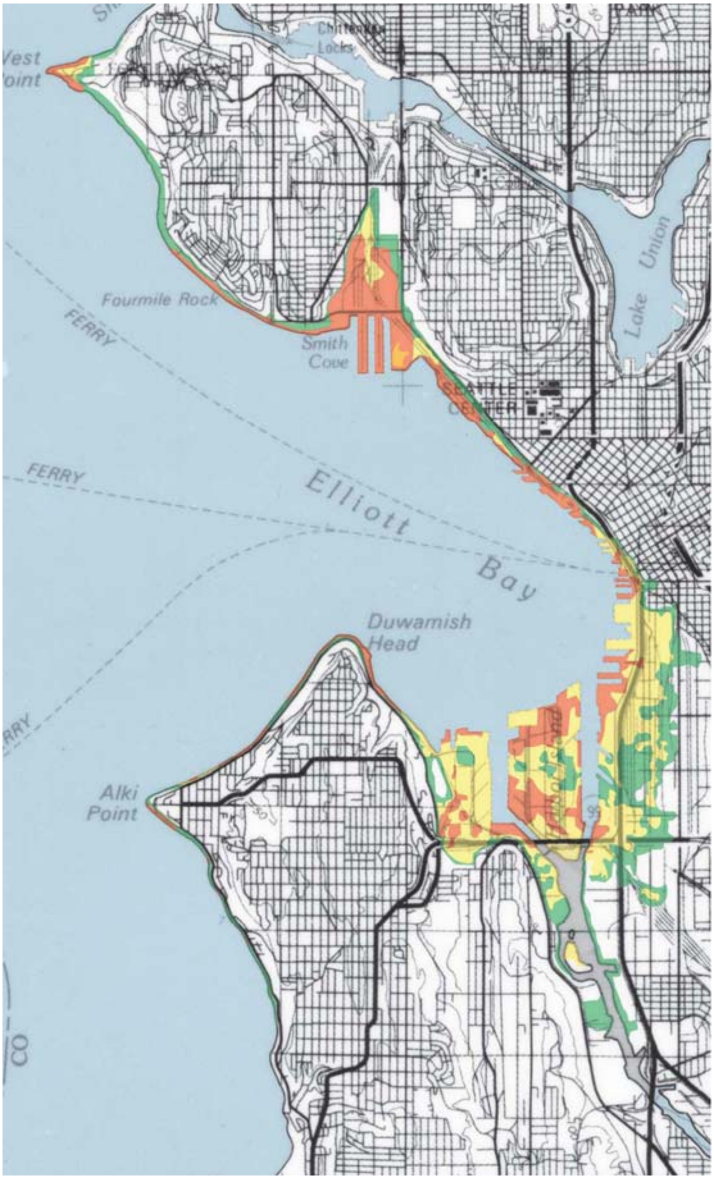

Fig. 14.4 Blow up of Tsunami Hazard Map of Elliott Bay Area, Seattle, WA: Modeled tsunami inundation from a theoretical moment magnitude (Mw) 7.3 along the Seattle Fault (not pictured). Green areas are inundated 0–0.5 m, yellow areas 0.5–2 m and orange from 2 to 5 m in depth (Source: Walsh et al. 2003)

In 2006, NCTR was asked to evaluate the suitability of Ford Island at Pearl Harbor, HI, which is under construction as the new home for the Pacific Tsunami Warning Center, in relation to the likelihood of tsunami inundation. Modeling scenarios used far field tsunami sources to model the impact of a tsunami affecting Oahu and the site of the new building. Model results demonstrated that historical and modeled scenarios produced no inundation higher than 1.5 m above mean high water. The proposed building height is at 3 m above mean high water. While GIS was not used for the suitability analysis, GIS software and the building of detailed bathymetry, topography, and satellite imagery was used to ground truth the data (Tang et al. 2006). Subsequent research to improve our methods is described in the following section.

14.8 Technical Aspects

The geoprocessing functions in ArcGIS™ simplify the process of selecting, projecting, processing, buffering, and converting data into formats that work well with each other. Models are created in Python and run in batch form using scripting formulas for converting from census information to the correct format and correcting for the area of each block group that is affected by inundation. Modifications can be made to the code to allow users (emergency managers or GIS analysts) to rerun the population-at-risk calculations for areas that may not have been analyzed yet or to adjust the parameters of the algorithm to better suit their area of interest. For example, by using the likely maximum wave height for tsunami events developed from each SIM area, we were able to build an accurate assessment tool for coastal areas of interest (Merati et al. 2007).

Recently, ESRI has supported the use of Python as a scripting language. Python is an object-oriented programming language that is widely used for a variety of applications. Its simple syntax and flexible, dynamic nature make it easy to learn, and there are libraries available to support many scientific analysis tasks (van Rossum 2006). The use of Python allows GIS programmers to create models and scripts that can run within ArcGIS™ or stand alone to provide geoprocessing and batch scripting for file configuration, model iteration, or complex modeling actions.

Python's base level of code and libraries is extensive and extendible. In ArcGIS™, anyone can write Python scripts to call different functions and interact with data. The ability to call scientific Python to do more complicated spatial functions provides a level of functionality beyond standard GIS processing that makes it more appealing to the modeling community. NCTR has created Python scripts to convert between model native formats and ArcGIS™ formats (ESRI™ grids and xyz triplets, commonly used by modelers) and for grid resampling. The scripts are used as stand alone scripts or as ArcToolbox add-ins.

Using ArcGIS™ Model Builder and integrating multidimensional tools into ArcGIS™ allows NCTR modelers to add their data to ArcMap, build a model to grid and resample their data, create rasters and interpolate the results, and then display their data. The addition of iteration, feedback loops, and automation allows researchers to process their data using ArcGIS^{TM}. Outputting Model Builder results into Python and adding code to place the output into specific directories and clean-up temporary files makes processing and creation of tsunami output more efficient. Using Modelbuilder to automate the generation of images from MOST model results utilizes the Animation toolbox in ArcGIS^{TM}. Resulting animations can be played as standalone visualizations of scenarios or embedded within other applications

The resulting images or raster data sets can easily be added to raster catalogs and animated to display the results of tsunami wave propagation or inundation for different scenarios Creating a 3-D view of the inundation or propagation event and combining this with building footprints, topographical features, and hazardous areas enhances planning and mitigation efforts. The ability to perform geoprocessing on raster layers, add vector data such as shorelines, population centers and hazards, and critical infrastructure, then interact with the data makes this a much richer application than standard 2-D animations and static maps. One drawback is that it takes longer to generate than a MATLAB animation, which reduces its utility in real-time situations, but it is still useful for post-event processing and scenario testing. An added benefit is that placing the animation into ArcGlobe provides researchers the opportunity to show the public and policy makers a powerful visualization of the global impact of historic tsunami events (Merati et al. 2007).

For emergency management purposes, model output needs to be integrated with socio-economic and infrastructure data, as well as evacuation routes and the location of vulnerable populations. These types of data are easily accessible in GIS formats. A prototype application containing such types of data was developed using ESRI's ArcEngine, providing a way to visualize results and perform common analysis functions found in a GIS but often difficult to run in modeling software packages. ArcEngine is an ESRI developer product for creating and deploying ArcGIS^{TM} solutions that can be customized for the user community. The product is a simple API-neutral cross-platform development environment for ArcObjects – the C++ component technology framework used to build ArcGIS^{TM}. ArcObjects is at the core of ArcGIS^{TM} functionality and includes tools such as: intersect, proximity (buffer or point distance), surface analysis (aspect, hillshade, or slope), and data conversion (shapefile, coverage, or DEM to geodatabase) (Vance et al. 2007). Using ArcEngine, solutions can be built and deployed to users without requiring that ArcGIS^{TM} Desktop applications (ArcMap, ArcCatalog) be present on the same machine. This product is a developer kit as well as a deployment package for ArcObjects technology. Desktop deployment of ArcGIS^{TM} is not required to run these scenarios, which eases deployment of this tool in field situations or to developing countries (Vance et al. 2007).

14.9 GIS Case Study Illustrating the NCTR Workflow

14.9.1 Seaside, Oregon – Probabilistic Modeling and Modernization of Flood Hazard Maps

Probabilistic modeling has been used to estimate flood inundation, landslide hazard and hydrodynamic modeling. Integration of these models with GIS is reviewed in the literature (Martin et al. 2005; Zerger and Wealands 2004; Zerger 2002).

The US Federal Emergency Management Agency (FEMA) has developed flood insurance maps for areas within traditional flood prone areas (e.g., low-lying flood plains). Flood Insurance Rate Maps (FIRM) serve as the official FEMA document marking flood hazard zones and the resulting insurance premium zones for each community mapped. Hydrological models and meteorologists use long time series of river gage data to determine the probability of flood risk within a given area. The same concepts were applied in a pilot study to determine if predictive inundation mapping could be used to map the probability of tsunami inundation at 100- and 500-year levels. One hundred and 500-year flood levels are defined as the possibility that the (average) water elevation would be exceeded 1% or 0.2% of the time in any year (Wong et al. 2006).

The community of Seaside, Oregon was selected for testing for a variety of factors, including the availability of paleotsunamic and seismic records, recent tsunami flooding, earthquake source recurrence, and excellent availability of baseline data for tsunami modeling. Probabilistic Tsunami Hazard Analysis (PHTA) was used in this study to model the magnitude of tsunami flooding from a variety of sources at different recurrence rates (Wong et al. 2006). The development of the hazard analysis required development of a DEM for the area in question for use by the MOST model. Near-field sources (the Cascadia Subduction Zone) and far-field sources (Kuril-Kamchatka, Aleutian/Alaska, and Chilean Subduction zones) were also used to run the MOST model at various earthquake magnitudes. Maximum wave heights from the MOST model were input into the PTHA model. These data were combined with tidal data and inundation data for each grid point to determine if a grid cell would exceed a given flooding threshold and become flooded or not. The grid cells were contoured to create the 1% and 0.2% contours that translate to the 100- and 500- year occurrences. Figure 14.5 compares the 100 and 500 year tsunami inundation line for Seaside using probabilistic analysis using a combination of near and far source scenarios modeled.

Results from the 100-year study showed that a small area of the study site would be flooded. However, in the event of a 500-year inundation, a large area of Seaside was flooded with wave heights exceeding 4 m. This study demonstrated that model data were easily integrated into a probabilistic GIS model to create hazard curves for assessing risk. The results of this study were later used by Dominey-Howes et al. to assess vulnerability to Seaside structures using tax parcel information and the US multi-hazard loss estimation software (HAZUS-MH) database (Dominey-Howes et al., submitted).

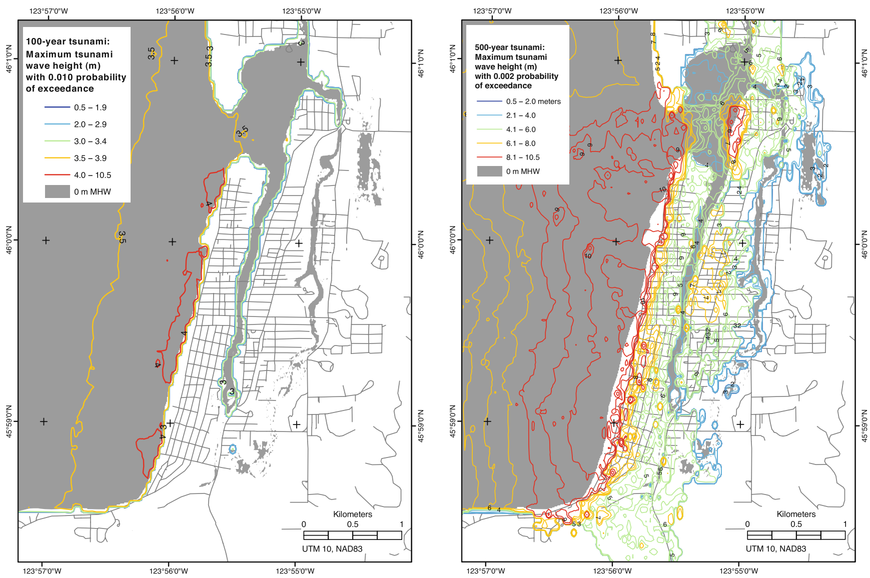

Fig. 14.5 Tsunami wave heights (in meters) of the 1% (*left-hand panel*) and .2% (*right-hand panel*) probability of exceedance for Seaside, Oregon (Source: Wong et al. 2006)

14.10 Tools for Use by Emergency Managers and Urban Planners

14.10.1 Tsunami GIS

While we have focused on the use of geospatial tools and analysis by tsunami modelers, the information we produce must ultimately be used by planners and emergency managers to prepare for and mitigate the impact of tsunamis. Scenario testing and collaborative GIS use by emergency personnel, city managers, and first responders requires a streamlined GIS application that is portable and customizable with newly created data, especially in the case of rapid response.

Tsunami GIS is an application that allows users to create inundation scenarios for pre-calculated near-shore and off-shore sources for a tsunami event in a selected region. The ArcEngine development environment lets us build a stand-alone GIS application that has the look and feel of a standard ArcGIS™ desktop, but with tsunami-specific menus added to the standard ArcGIS™ functionality and editing capabilities. The geoprocessing application programming interface (API) operates in the backend to merge the gridded inundation result with census information for the area of study to create a new polygon of affected areas. Users are able to edit their own data and add new information as necessary. Census data are used to calculate estimates of populations at risk including the elderly or handicapped. Critical infrastructure – hospitals, schools, bridges, and emergency centers – within the inundation

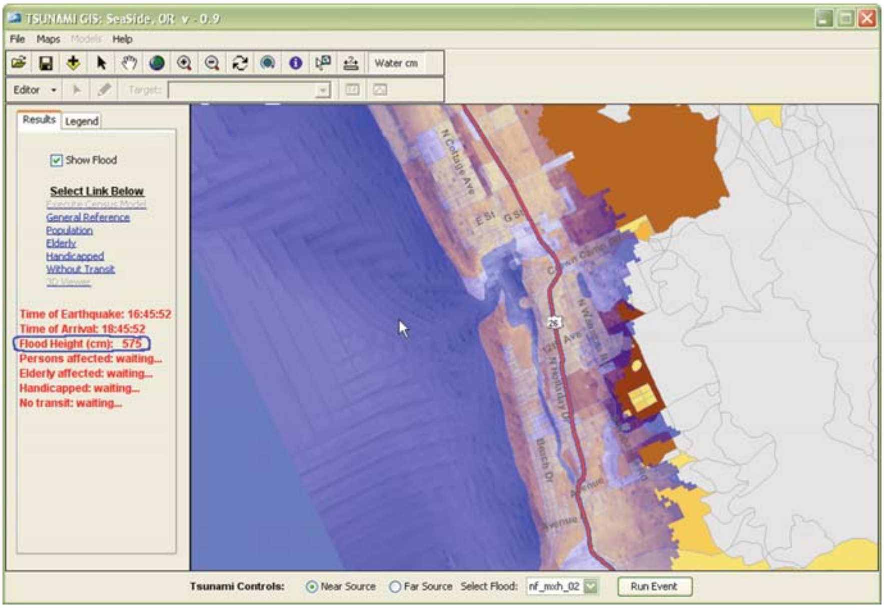

Fig. 14.6 Tsunami GIS interface shows the result of a near shore event inundating Seaside, Oregon. The census blocks covered with the inundation polygon (*blue*) (nf_mxh2) are affected by this event. The ArcEngine framework allows customization of the ArcMap window such that new tools can be added – in this case, a cursor hovers over the inundation polygon and returns a water height for the inundated area on the left hand panel of the application (*circled in blue*)

zone can be highlighted and standard geoprocessing functions such as proximity analysis run to determine mitigation strategies. Users are able to print maps and reports and export map images to be used in operation manuals and reports.

The final product is a map of inundated areas and estimates of affected population in the inundation zone. The tsunami height modeling application shown in Fig. 14.6 is an example of modeling the inundation phase for the city of Seaside, Oregon; data were derived from the probabilistic tsunami analysis work done in Seaside, and it uses both near-shore and far-field sources and the resulting inundation grids (Merati et al. 2007).

ArcEngine's framework allows users to add their own data sets (e.g., inundation grids, evacuation routes, and infrastructure) as well as links to live data feeds and servers to add current and derived data products "on the fly". The ability to customize the application using the ArcObjects modules will allow developers to implement additional models and algorithms as they are developed, from elevation data and distance from the shoreline to the calculation of populations at risk. The ability to run the tool and change parameters such as the height of the tsunami also supports scenario testing.

Tsunami GIS has made it easier to combine modeling results with related socio-economic data in support of emergency management. Being able to link models with socio-economic data provides planners with a powerful tool to plan for and mitigate the impacts of tsunamis.

14.11 Discussion

GIS packages are starting to share software code and objects to allow closer coupling of core GIS functionality and analytical/modeling tools. Through the use of Java-based APIs and connectors, a GIS front-end is directly linked with models. The Python scripting language, the proliferation of PostGIS and the PostGIS and PostgresSQL databases, native data readers (netCDF, HDF4), and visualization tools are making it easier to integrate model output into GIS. Outputting model results as Google Earth™ KML enhances products for hazard mitigation by giving the end user a visual reference – an updated map or context for decision making.

The lack of standard data formats can make integrating model output with GIS difficult. Many scientific modeling outputs are in netCDF and HDF formats with time steps for all runs in a single file. File sizes may be very large, irregularly spaced, or unstructured, and file management can be unwieldy. This issue is changing as the advent of multidimensional tools in ArcGIS™ products provides direct reading of netCDF files. These new input mechanisms allow NCTR propagation and inundation data to be easily imported into GIS, opening up new methods of analysis and visualization.

The ability to take propagation or inundation results and overlay them on infrastructure data has long been desired by stakeholders. While the majority of hydrodynamic models are visualized in custom code or visualization analysis packages that allow for post processing. In the past modelers have had to use MATLAB and other tools such as "Ferret" (Ferret 2008) (see http://ferret.pmel.noaa.gov/Ferret, an in-house visualization package) to visualize model output. To improve upon this situation, NCTR modelers and programmers developed custom code to streamline output and to visualize model results in animations and static images. This ability is especially critical during an actual tsunami event when fast response is crucial. While MATLAB and Ferret are excellent for building animations and creating 2-D maps, the results are static because it is not possible to interrogate the data, add data in real time, or perform any analysis "on the fly" (Merati et al. 2007). GIS provides a more interactive way to create and analyze data.

Emergency managers and coastal planners recognize the risk posed by near-and far-field tsunami events that can inundate coastal areas. Developers at NCTR are building at-risk community tsunami tools, working with state partners and emergency managers to determine the level of risk posed by a tsunami to coastal communities. The tools will allow us to use parameters such as distance to shoreline, elevation, and time of day to determine affected populations (Fig. 14.7).

NCTR, Tsunami Warning Centers, and the NOAA Tsunami program have identified sites for further study and inundation modeling in the United States and its territories, and are working on establishing criteria that can define what determines

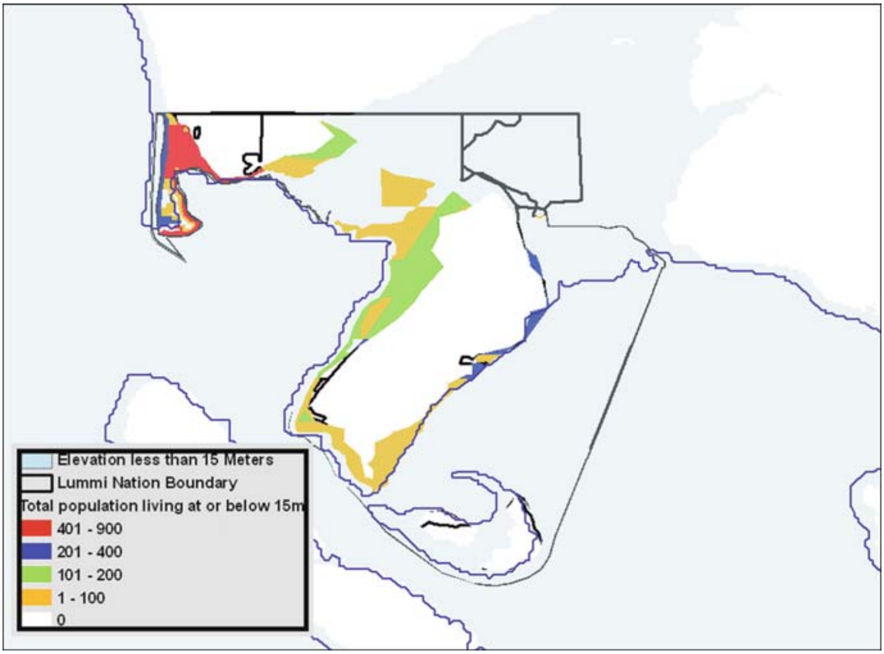

Fig. 14.7 Results of running the at-risk population tool for Washington State coastal communities, describing populations within 2 km of the shoreline at elevations lower than 15 m that would be inundated in a near field tsunami scenario

an "at-risk" population. Currently, age, mobility, access to transport, and income level are included as well as seasonal factors (especially in resort areas).

Data management is an important component for getting information into the hands of coastal managers and scientists at the time an event occurs. Development of the NCTR Atlas project, whose initial goal was to house static maps of modeled sites, has proven to be an invaluable tool for data display, management, and organization of all event data. Additionally, the housing of seismic and water level data in a GIS format in one location promotes more efficient retrieval of data for model validation. Extensions of the Atlas to work with ArcGIS™ desktop applications and with NCTR's WebSIFT real-time modeling application will improve its utility for modelers and data managers as events are updated in real time and assigned standardized event names and data structures, thus making data integration and management easier.

Data integration and data formats have often been a stumbling block to the acceptance of GIS to the hydrological and oceanographic community (Martin et al. 2005). The recognition of netCDF as the de facto standard of the hydrological and modeling community by ESRI™ and the move to make native file readers available to the standard mapping toolkit (ArcView™ GIS) made the integration of netCDF rasters and features much simpler for GIS analysts and scientists wishing to directly analyze their model output in ArcGIS™. Python scripting language – for stand-alone applications or for creating geoprocessing scripts within ArcGIS^{TM} – makes transformation of data formats, batch processing of large files, and integration of spatial operators much easier by taking model output and visualizing and placing it within a GIS framework. Simple tools that NCTR programmers have written to convert data between formats in Python make data interchange smoother. While the hydro modeling community has been a large proponent of these tools, the ability to integrate irregularly time-stepped or meshed-gridded datasets outputted by inundation models is largely due to work by the atmospheric community. Integration of time series tools for visual analysis and animation are also crucial to understanding coastal inundation and its impact on communities. GIS community-based tools are beginning to address the most accurate and effective way to display this information.

14.12 Conclusion

GIS and geospatial technologies have been critical to the success of NCTR's modeling efforts and the dissemination of products to its stakeholders. Development of mapping standards and techniques to create merged bathymetric and topographic models for inundation modeling, with corrections for tidal variations, have been used successfully for inundation modeling. DEM products are available to the public and are used for coastal storm modeling, fisheries studies, and estuarine habitat modeling. The use of the best available data and standard methods has streamlined the creation of the DEMs, which serve as one of the critical inputs to running the MOST model and generating accurate results. Methods of DEM development, including the accessibility and availability of current data, the use of satellite altimetry and imagery, and efforts to improve the accuracy of vertical datum adjustments for Alaska and other parts of the United States coast, will enhance the DEMs scheduled for creation in the next few years.

While we have not discussed mitigation strategies for tsunami preparedness, NCTR recognizes the importance of using model output, wave heights, amplitudes and time-of-first-wave as important parameters that localities will need to create disaster preparedness plans. Tools to assess where vulnerable populations exist, factoring in age, race, gender, income level, and access to transportation are crucial for long-term planning for coastal evacuation. The same information is useful for planning development restrictions in coastal areas. Dominey-Howes et al.'s (2009) integration of vulnerability analysis with building types for Seaside, Oregon, begins to address these issues. While NCTR has focused on providing at risk estimates based on elevation, probable maximum inundation heights, and potential flooding areas at various periods of the day, we are working on determining what factors are needed to make accurate estimates of vulnerable populations. Census information and spatial statistics along with up to date tax parcel information for city and county jurisdictions will assist in making more accurate estimations. Land cover and land change over time, especially in coastal areas, are especially subject to change. Integration of standby inundation outcomes such as a maximum inundation line could be used to build predictive models that use MOST parameters with GIS analysis.

Acceptance of GIS as a framework for emergency planning and decision making is not new in terms of hazard planning, but the tools for bringing model output to GIS requires changing the way we look at model output and how we visualize these data. The Tsunami GIS project demonstrated that gridded model output can be added to a stand-alone GIS application and used to assess the level of damage and vulnerability without having a full suite of ArcGIS™ on the user's desktop. A run-time license of the Tsunami GIS application means that we can deploy this application as part of a suite of training tools to developing nations that may not currently have a full GIS laboratory. Stand alone tools that can be extended using Java, that can read native GIS file formats, and that can produce products useful to first responders, are important for rapid assessment and response in disaster scenarios.

Adding full GIS capability and visualization tools, as seen in the ComMIT interface, has brought GIS to the forefront of hazard assessment in the Indian Ocean. Imagery that can be geo-referenced and placed on an inundation zone to provide real-time display and output into a GIS is critical for bringing modeling results into the hands of the emergency manager in a timely manner (Titov et al. 2005). The option of putting inundation results output (e.g., KML) in a Google Map™ application with the option of adding additional information makes the application more powerful and more easily delivered to the end user. Mapping mashups, while not a new technology, permit some user-based content to be placed on an image, and have also proven useful for recovery efforts.

Ideally, the MOST model could be directly integrated into ArcGIS™ or any GIS enabled package, but as others have noted model integration is not simple, nor straightforward (Eveleigh et al. 2006; Martin et al. 2005). Research is ongoing to create an interface that is user friendly to both the scientist whose model output is being used and the end user who must interpret the model's results.

The creation of a 2-D evacuation map for state hazard mitigation and the need for accurate bathymetric data for model input provided the initial foundation for the use of GIS for tsunami research, modeling, and hazard mitigation efforts at NCTR. The ability of ArcGIS™ to handle native file formats used by the MOST model and development of the Python scripting language helped move NCTR to adopting GIS as a tool to help display, analyze, and disseminate information. New research linking evacuation models with hydrodynamic models through the use of GIS have strengthened our commitment to this research. With the recent proliferation of Google Earth™ imagery and mapping applications that do not require a desktop GIS application, NCTR looks forward to many opportunities to expand its suite of geospatial products.

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