Mapping Coastal Inundation Primer

National Oceanic and Atmospheric Administration (NOAA)
Coastal Services Center

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NOAA Coastal Services Center

LINKING PEOPLE, INFORMATION, AND TECHNOLOGY

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Introduction

Mapping can be a very important part of understanding coastal inundation issues or preparing for an assessment process. The ability to visualize the potential depth and inland extent of inundation gives officials and the public a better understanding of the corresponding impacts and consequences. By mapping inundation in a geographic information system (GIS), the user has the ability to overlay the potentially impacted areas with other data such as critical infrastructure, roads, ecologically sensitive areas, demographics, and economic information. If these maps are provided on the Web by using Internet mapping technologies, the user is able to interact easily with the information, visualizing inundation with various data layers turned on or off.

This document provides some basic information about mapping coastal inundation and provides examples of short-term inundation events (storm surge) and longer-term climate-induced events (sea level rise). It is not a step-by-step method for creating an inundation map but, more accurately, provides guidance on methods to use, ways to determine which data to use, and resources that could be helpful. This document outlines three broad areas for mapping coastal inundation:

1. **Obtain and Prepare Elevation Data**
   Elevation data serve as the base data layer for mapping coastal inundation. Before using elevation data for inundation mapping, it is important to understand requirements and specifications of the data, how to assess the quality of the data, and where to obtain the data. This section answers the following questions:
   What type and quality of data do I need?
   Where can I find elevation data and products?
   How do I select data appropriate for me?
   How do I create an elevation surface?
   How do I build a digital elevation model (DEM)?

2. **Prepare Water Levels**
   A water surface is a two-dimensional representation of the interface between the water and the air. To map inundation, a water surface must be generated. The surface can be based on model output, an interpolated surface, or a single depth value. Different models and approaches to modeling an inundation surface are discussed in this section, which answers the following questions:
   What type of water surface do I want to map?
   What vertical reference datum should I use?
   What steps are necessary to prepare water levels?

3. **Map Inundation**
   With a digital elevation model (DEM) and water level information, GIS processes can be used to create layers that represent inundation extent and depth. This section answers the following question:
   How do I map the water surface?

Obtain and Prepare Elevation Data

What Type and Quality of Data Do I Need?

Before beginning to look for or consider acquiring elevation data, it is helpful to have a basic understanding of the most commonly used and available types of data, including their specifications and applications.

Learn More

For more in-depth information on lidar technology, data, and applications, take the NOAA Coastal Service Center *Introduction to Lidar* training:

www.csc.noaa.gov/digitalcoast/training/intro-lidar

Data Needs and Considerations

The type and specifications of elevation data needed for coastal inundation mapping will vary according to what type of information is desired from the mapping effort. Aspects such as geographic extent, cost, detail, magnitude of process, required accuracy, and technical capability wil largely determine the appropriate type and quality of elevation data.

Geographic Scale

The geographic scale of the inundation map being created may vary depending on the purpose of the map. For example, a coastal manager interested in the effects of seasonal high tides on local road networks has very different elevation needs from those of an emergency manager trying to prepare for the potential impacts of a large storm. The first may only need elevation for a city or a small part of the county. Working with a smaller geographic area (large map scale) may have the advantage of being able to use a single dataset available from a single source. Working from a single data source generally results in a more consistent product across the area. As the geographic extent expands, the user may need to use elevation data collected at different times, with different resolutions, and with varying accuracy standards. It is important to note that, in general, larger geographic area (small map scale) analyses tend to be coarser, or have lower resolution.

Level of Detail

This issue is similar to scale and is relevant to the magnitude of the process being mapped or analyzed. Elevation data needed to model coastal inundation that is based on a 0.25 meter rise in sea level may be very different from data used to determine inland extent of floodwaters from a large episodic event such as a hurricane. To model a small rise in sea level, a high degree of detail and accuracy may be required to better determine water extent. Small changes in elevation can have a significant effect on the mapped boundaries of inundation around critical infrastructure. If coarse data are used, details, such as levees that might affect water flow, may be lost or obscured. Conversely, in a large area, highly detailed data may be unnecessary. In this situation, a smaller, lower resolution (or less detailed) dataset may be sufficient, resulting in shorter processing times and allowing faster access to critical information.

Vertical Accuracy

The quality of the data is dependent on the accuracy. Accuracy requirements depend on the intended application; high vertical accuracy is normally required for floodplain management applications. Keep in mind that the age of the data may also affect the accuracy. For example, data collected 10 years ago that would have been considered extremely accurate at the time may no longer be considered accurate in some locations because of development, erosion, or filling in of wetlands.

Spatial Resolution

Spatial resolution needs to be considered when collecting data. Resolution is expressed as the size of the pixels (or cell size). The coarser the resolution (i.e., the larger the pixel size), the more ground area represented by a single pixel.

Elevation Data

Inundation mapping and assessment projects rely on a wide variety of datasets that reflect existing physical conditions, as well as projections of future conditions and impacts. This section focuses on geospatial data needed to accurately determine inundation impacts, including references to existing data sources and further technical guidance. The primary datasets needed to accurately map and assess the impacts of coastal inundation can be broadly grouped into the following types (summarized from NRC 2009):

Learn More

To obtain coastal lidar, visit the coastal lidar page of NOAA's Digital Coast:

www.csc.noaa.gov/lidar

Base Surface Elevation

Land surface elevation, or topography (figure 1), is the base surface used for inundation mapping projects. Topography is reported in relation to a reference datum. A vertical datum, or the location where the elevation is zero, and a method of measuring heights relative to that zero elevation must be established on the Earth, where it can be used for all types of height measurements. More information on datums can be found on page 7 or by visiting *www.ngs.noaa.gov/faq.shtml#Datums*.

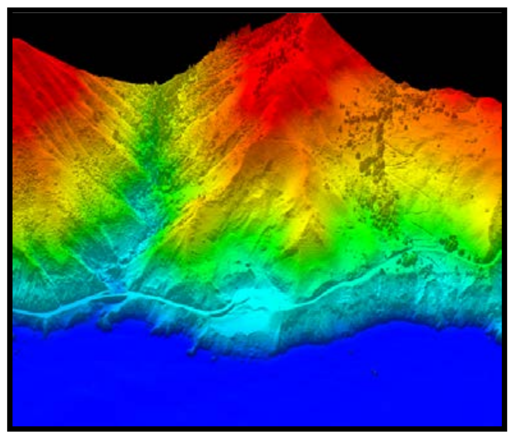


Figure 1: Topography

Topography is often expressed as the height of a location relative to an ellipsoidal or orthometric datum. The following sections provide more information about some of the different types of topographic data and suggestions for accessing the data.

Water Surface Elevation

Inundation projects are concerned with examining the impacts of differing water levels on the surrounding areas. In addition to elevation and topography, information about the location of the air–water boundary surface relative to the base surface elevations is needed.

For mapping and assessment purposes, "sea level" is determined by a coastal tide gauge. Water surface height is measured with stream and tide gauges, or derived from hydrodynamic model outputs. The location and elevation of the gauges must be determined accurately to correctly relate water surface measurements to other elevations.

Topographic Data

Topography is defined as the general shape or form of the land surface, determined by analyzing the elevation of the land. Topography is a crucial dataset for determining coastal inundation because the shape of the physical landscape influences the direction that water flows over it, where it accumulates, and how and where it drains. The accuracy with which topography has been mapped directly affects the reliability and usefulness of coastal inundation impact assessments (CCSP 2009) and is the most important factor in determining accuracy of flood maps (NRC 2009). In coastal areas characterized by flat topography, small changes in water level cause greater changes in the extent of areas inundated by water level rise or exposed by water level fall than coastal areas with higher topographic relief.

Topographic Data Types

Topographic data are available in several different forms (e.g., raw points, triangular irregular networks, contours, regularly gridded digital elevation models) and can be collected using different sensors and methods. Among the more common sources of topographic data are the following:

> **Learn More**
>
> To find topographic data, visit the NOAA Coastal Services Center's Topographic and Bathymetric Data Inventory tool: *www.csc.noaa.gov/digitalcoast/tools/topobathy/index.html*

Land Survey (captures centimeter-scale elevation changes) – Land surveying is the technique and science of accurately determining the terrestrial or three-dimensional position of points and the distances and angles between them. These points are usually on the surface of the Earth, and they are often used to establish land maps and boundaries for ownership or governmental purposes. It was the first technology used to collect elevation data. Today, most survey-grade equipment uses Global Positioning System (GPS) data in a kinematic differential mode to obtain relative ellipsoidal or orthometric heights precise to 30 to 40 millimeters (mm) (root mean square error, or RMSE), in areas of a few tens of kilometers in radius. GPS is the most accurate way to obtain heights but can only be done one point at a time, which is very labor-intensive and costly.

> **Learn More**
>
> What is root mean square error (RMSE)? RMSE is the standard deviation used when referring to elevation data.

Aerial Image (Photogrammetry) – Stereo aerial imagery has commonly been used to derive elevations for use in generating digital elevation models. The technique provides accurate information and is used extensively in highway and road projects. However, it is less cost-effective when working on larger areas, and its accuracy suffers in areas of dense vegetation. This method can yield elevations with vertical accuracy on the order of 10 centimeters (cm) (RMSE).

Topographic Lidar – Lidar (light detection and ranging) is an active sensor that transmits laser pulses to a target and records the time it takes for the pulse to return to the sensor receiver. This technology is now being used for high-resolution topographic mapping by mounting a lidar sensor, integrated with GPS and inertial measurement unit (IMU) technology, to an aircraft and measuring the pulse return time to determine surface elevations. Since this technology relies on detection of light, data collection during cloudy conditions is a challenge. Lidar can yield vertical accuracy of 10 cm (RMSE).

IfSAR – Interferometric Synthetic Aperture Radar (IfSAR or InSAR) is an aircraft- or satellite-mounted sensor designed to measure surface elevation, though its primary strength is in measuring elevation *change*. IfSAR generally yields 1 meter (RMSE) vertical accuracy, although it can detect elevation change on the order of millimeters (see *www.csc.noaa.gov/digitalcoast/data/coastalifsar/index.html*).

Where Can I Find Elevation Data and Products?

Public domain elevation data and products are available in a range of extents, accuracies, and formats. The list below represents a sampling of websites providing access to elevation data. While this list may not be all-inclusive, it may be used as a guide for users interested in acquiring elevation datasets for their areas of interest. Those interested in obtaining elevation data are encouraged to also contact their state and local GIS staff members regarding available elevation data.

Data

Digital Coast (NOAA Coastal Services Center) – The NOAA Coastal Services Center's online data are provided via Digital Coast. Data are available in several point (.txt, LAS), line (.shp, .dxf), and raster (geotiff, floating point, ASCII grid) formats. See *www.csc.noaa.gov/lidar*.

National Elevation Dataset (NED) (varying accuracy based on geography) – A derived topographic dataset that is nationally available is the U.S. Geological Survey (USGS) National Elevation Dataset (NED) (*http://ned.usgs.gov*), which has been developed by merging the highest-resolution, best quality elevation data available across the U.S. into a seamless raster format. The NED has a consistent projection (geographic) and elevation units (meters). Nationwide coverage is available for data at a 1 arc-second (30-meter) post spacing; there also is substantial coverage at 1/3 arc-second (10-meter) post spacing. The horizontal datum is the North American Datum of 1983 (NAD83), except for Alaska, which is NAD27. The vertical datum is the North American Vertical Datum of 1988 (NAVD88), except for Alaska, which is NAVD29. NED is a living dataset updated bimonthly to incorporate the best available DEM data. As more 1/9 arc-second (3-meter) post spacing data covering the U.S. become available, they will be added to the seamless dataset. Published accuracy of the NED can be found here: *http://ned.usgs.gov/downloads/documents/NED_Accuracy.pdf*.

USGS Topobathy Viewer – The topobathy viewer provides a dynamic online map interface that can be used to view U.S. Geological Survey topobathy DEMs (*http://edna.usgs.gov/TopoBathy_Viewer*).

NOAA's National Geophysical Data Center Digital Elevation Model (DEM) Discovery Portal – The Discovery Portal is an online geospatial catalog of Web-published DEMs that enables users to locate, preview, and link to DEMs for download (*www.ngdc.noaa.gov/mgg/dem/demportal.html*).

Center for Lidar Information Coordination and Knowledge (CLICK) – The USGS CLICK website provides access to publicly available lidar point file datasets. The goal of CLICK is to facilitate data access, user coordination, and education about lidar remote sensing for scientific needs (*http://lidar.cr.usgs.gov*).

National Center for Airborne Laser Mapping (NCALM) – The NCALM data distribution website, supported by the National Science Foundation, provides public access to high-resolution airborne laser mapping data, documentation, and tools to analyze digital elevation datasets (*http://calm.geo.berkeley.edu/ncalm/ddc.html*).

Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) – JALBTCX performs operations, research, and development in airborne lidar bathymetry and complementary technologies to support the coastal mapping and charting requirements of the U.S. Army Corps of Engineers (USACE), the U.S. Naval Meteorology and Oceanography Command, and NOAA. The

JALBTCX staff includes engineers, scientists, hydrographers, and technicians from the USACE Mobile District, the Naval Oceanographic Office (NAVOCEANO), the USACE Engineer Research and Development Center (ERDC), and NOAA National Geodetic Survey. JALBTCX research and development supports and leverages work in government, industry, and academics to advance airborne lidar and coastal mapping and charting technology and applications (*http://shoals.sam.usace.army.mil*).

Open Topography – This portal provides access to high-resolution topographic data and tools, as well as community interaction (*www.opentopography.org).*

How Do I Select the Data Appropriate for Me?

No dataset or source is perfect. There may be gaps or errors, and there are a number of considerations when choosing a particular dataset (e.g., presence of breaklines, tidal collection, among many others). This section offers information about how to determine if the data meet the necessary standards for the intended use.

Metadata

Metadata are vital to ensuring the accuracy and utility of inundation mapping and assessment products. A key way to locate and discover the origin and quality of a particular dataset is to refer to its metadata—that is, information about the data. Metadata should be regarded as a critical component of any dataset. Generally, metadata contain the dataset's definition, structure, and administration of data files, with all contents provided in context to facilitate data use and archiving. For geospatial datasets, metadata should contain information sufficient to answer the following questions:

> **Learn More**
>
> To read more about metadata in general, visit *www.fgdc.gov/metadata.*

- Who created the data?
- Who maintains the data?
- When were the data collected? When were they published?
- Where is the geographic location?
- What is the content of the data? The structure?
- Why were the data created?
- How were they produced (data acquisition and processing methods)?
- Where are the data stored?
- What are the vertical and horizontal datums and reference systems?
- How are accuracy, precision, and uncertainty (total propagated error for vertical and horizontal) defined?

Before investing significant time and effort in obtaining or applying a dataset that pertains to inundation, users should critically review the metadata. If metadata are incomplete or absent, or there is no readily apparent way to collect the missing information from the data originator(s), users may reconsider use of that dataset or qualify their project results accordingly.

Accuracy of Elevation Data

The quality of models or depictions of change in water levels or inundation extents is inherently tied to the accuracy of the elevation surface. The most common way to express accuracy is through the root mean square error (RMSE). The RMSE is used to measure the difference between an estimated value (e.g., lidar surface) and known values (e.g., GPS points collected on the Earth's surface). The RMSE is a way to provide a standard deviation of the measured differences. The other term that is common is $Accuracy_z$ which provides the error value that 95% of the data adhere to when the data are normally distributed. The $Accuracy_z$ equates to about twice (1.96) the RMSE (with normally distributed errors). For example, users can be confident that the elevations in a dataset with an $Accuracy_z$ of 25 centimeters will be within ±25 centimeters of the value provided 95% of the time. Most lidar data have normally distributed errors in open terrain; however, in forests and difficult-to-penetrate areas, the data can have non-normally distributed errors. In these cases the 95% confidence is determined by setting the value equal to the measured error at the 95% value (i.e., 95% of the measurements were better than this value) and is a more appropriate measure of the error than the RMSE.

In general, increasing accuracy raises the cost of the data; therefore, level of accuracy should be specified based on the needs of the project or likely uses. When considering "likely uses," it is probable that future uses will benefit from higher accuracies, thereby increasing the shelf life of the dataset.

Datums

A datum is a reference from which measurements are made. When creating elevation surfaces, special care must be taken to use matching horizontal and vertical datums. Neglecting this step will introduce error into the final elevation surface. A thorough discussion on resolving datum issues can be found in the NOAA Coastal Services Center's publication, "Topographic and Bathymetric Data Considerations: Datums, Datum Conversion Techniques, and Data Integration" (*www.csc.noaa.gov/digitalcoast/_/pdf/topographic-and-bathymetric-data-considerations.pdf*). For more details and specifics on datums, see the section "What Vertical Reference Datum Should I Use?"

Collected Point Density and Final Cell Size

Elevation data are generally collected at a series of discrete locations (i.e., points) and then interpolated to create a digital elevation model (DEM). The appropriate cell size limits are controlled by the point spacing (point density), such that the resolution and the accuracy of the resulting elevation surface are directly influenced by this parameter. Increasing point density as well as increasing native point accuracy can be major cost drivers. The major advantage of increasing sampling point density is the ability to accurately portray elevation (i.e., increased resolution). If the points are spaced far apart, important variations in the elevation surface may be missed. As the native point resolution increases, so can the native DEM resolution (e.g., smaller cell sizes) to capture the additional detail. For lidar, while the laser pulse density can be controlled, the point density on the ground is a function of the land cover, since not all pulses make it through the vegetation or other cover. It is usually the nominal pulse density that is provided for a data set.

Learn More

For more information about datums, visit the NOAA National Geodetic Survey's FAQ page:

www.ngs.noaa.gov/faq.shtml#Datums

While there are no hard rules for determining the appropriate DEM cell size from a given point density, as a general rule, the DEM should not have a higher resolution than the data it was generated from (point density). With high density data, it is possible to down-sample to a smaller dataset, but increasing the DEM resolution beyond the point spacing will not provide addition resolution, even though the elevation surface may appear smoother. As cell size increases, the detail generally decreases, but sometimes the trade-off in DEM usability is worth the sacrifice in resolution. Smaller cell sizes allow for finer detail to remain but often at the cost of DEM size (storage) and processing time. The effect of changing the cell size for an elevation dataset is demonstrated below (Figure 2); in this case, a DEM technique was chosen to progressively remove artifacts (e.g., trees, houses).

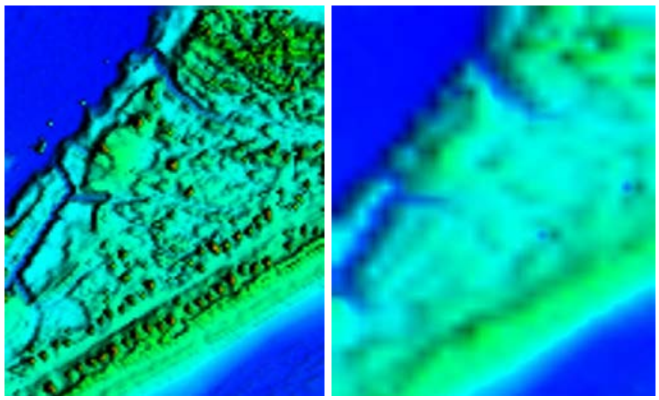


Figure 2. Elevation surfaces created at 5-meter (left) and 20-meter (right) pixels

Point Classification (Lidar Only)

A point set is often created from the lidar data to show only the returns that hit the “bare ground.” When creating a DEM, it is possible to remove all extraneous points to create the best possible representation of a bare-earth surface (Figure 3).

After the data have been collected and all considerations addressed, the next step is to create an elevation surface. The following section outlines the process for this.

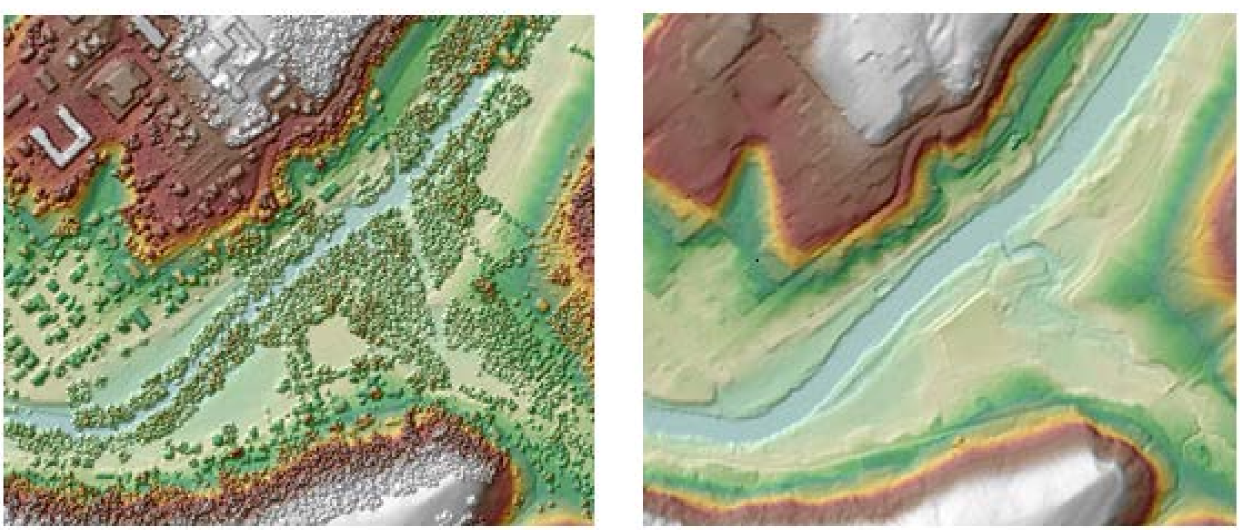


Figure 3. First-return DEM (left) compared to bare-earth DEM (right)

How Do I Create an Elevation Surface?

An elevation surface is a raster layer that represents the topography of the area of interest. Creating a digital elevation surface is necessary when mapping inundation to see the relationship between sea level and features on land.

Elevation Surface Generation

Often, elevation data are only available as point data, and the user will need to create a raster dataset for use in modeling and visualization. Software and methods for performing this step are varied and can range in complexity and cost.

How Do I Build a Digital Elevation Model (DEM)?

Several different methods exist for building a digital elevation model (DEM). There is no one perfect process for deriving the optimal elevation surface. The DEM can be a topographic data model or a merged topographic and bathymetric (topobathy) surface. While this primer does not focus on inundation over existing bodies of water and does not include a detailed discussion about bathymetry, bathymetry data may be of interest for those interested in changes in water depth in relation to sea level rise. For more information about bathymetry data and where this type of data can be accessed, visit *www.csc.noaa.gov/digitalcoast/tools/topobathy*.

The first step in building a DEM is to obtain the appropriate elevation data for the specific application. The horizontal and vertical accuracy of the data should be appropriate for the application. Another consideration is to obtain data with the appropriate density for creating a DEM that is suitable for the application. Note that a greater density of data will allow for a higher resolution DEM to be created, which can result in a more detailed inundation map.

Attaining the necessary coverage, or areal extent, of elevation data is important. Additionally, obtaining data processed to the appropriate level should also be considered. For a particular inundation scenario, the user could ask, what is the appropriate model for this scenario? Is it a bare-earth model (elevations of the ground, free from vegetation, buildings, and other anthropogenic structures) or a digital surface model (depicting the elevations of the top surfaces of buildings, trees, towers, and other features above the bare-earth surface)?

Learn More

Access guidelines for analyzing lidar’s vertical accuracy from the American Society for Photogrammetry and Remote Sensing:

www.asprs.org/society/committees/lidar/Downloads/Vertical_Accuracy_Reporting_for_Lidar_Data.pdf.

To learn more about topographic and bathymetric data and considerations for creating a seamless digital elevation model, read the Center’s “Topographic and Bathymetric Data Considerations”:

www.csc.noaa.gov/digitalcoast/_/pdf/topographic-and-bathymetric-data-considerations.pdf

Besides acquiring data that fit the specific application, having the data in a point format assists with easing datum transformations, blending, and gridding. The next step is to transform all the data into a common horizontal and vertical datum. For the vertical component, the topography is usually in an ellipsoidal or orthometric datum. Converting the diverse datasets to a common reference system helps minimize the discontinuities or stair-step effect between the data sources. After the data are commonly referenced, the next step is to grid the data for a combined surface. Considerations should include what data model to use, the appropriate resolution, and what construction method or interpolation technique to employ. Again, there are several different pathways for gridding the elevation information, and the method of choice should be based on the exact application for which the data are being used.

Learn More

For more detail about kriging, binning, inverse distance weighted, and TIN surfaces, read *Digital Elevation Model Technologies and Applications: The DEM Users Manual*, 2nd Edition (Maune 2007).

Considerations When Generating DEMs

Often, elevation data are only available as point data, and the user needs to create a raster dataset for use in modeling and visualization. Software available to assist in the creation of elevation surfaces ranges from freeware to costly commercial packages. When selecting a software package, cost is an important factor. Increased cost often results in increased functionality and analysis power, but a trade-off may be complexity of use. Inexpensive or free software may have fewer sophisticated analysis capabilities but may provide the needed tools in a simple interface.

Many statistical approaches exist to generate a DEM (surface) from point data; they include nearest neighbor, kriging, binning (min, max, median, mean, mode), inverse distance weighted, and gridding from a TIN (triangulated irregular network) surface. The most common are the gridded TIN and inverse distance weighted approaches.

The cell size should be chosen to accurately represent the elevation data, while considering the cost and time needed to build and run through inundation models. Although commonly in raster format, DEMs can also have other structures and forms.

The structure of the DEM grid (structured or unstructured) should also be considered. A structured grid has a uniform grid cell shape—a rectangle—with elevation values at each of the cell's four nodes or at the center of the cell. An unstructured grid (such as a TIN) has grid cells with a triangular shape so that elevation values are at each of the three nodes. Cell size can be highly variable in an unstructured grid and therefore show more detail in areas of a DEM where elevation change may be variable, such as at the shoreline, and less detail in areas of uniform elevation.

Review of the DEM Surface

Quantitative Accuracy

The accuracy values are calculated by comparing surveyed ground control points (GCP) to the elevation surface. A TIN surface generated from the lidar elevation data is compared to the GCP data. A TIN surface is used because there is very little chance that the GCPs will exactly coincide with the lidar elevation data points, and a TIN is a straightforward method for interpolating a value from the nearest points.

In most cases, 20 GCPs are collected per land cover or classification category, and five different land covers or terrain types are chosen. Use of the data for specific applications may depend on the accuracy of the data for specific land covers. For example, shoreline delineation requires only a high level of accuracy in the bare-earth category, whereas flood mapping requires that both bare-earth and forested areas have accuracies suitable for creating a specific contour interval. If a dataset has a high bare-earth accuracy but was poorly classified for vegetation, then it may not be usable for flood mapping; however, the dataset may still work well for shoreline delineation.

Qualitative Accuracy

Unlike the clearly-defined statistical accuracy requirements, the qualitative accuracy of the data is more subjective. While it does not commonly receive the same amount of attention on the front end, attention to the qualitative side is a critical check for the successful use of the data. In essence, the accuracy assessment tests only 200 to 300 points in a dataset of up to a billion points, so the qualitative review can be seen as a test of the other billion or so points. However, there are no specified qualitative accuracy procedures, so familiarity with lidar data in general and the location and intended use in particular are necessary. This fuzzy analysis is generally best performed by a third party, the purchaser, or a user group. Some of the most common qualitative errors are flight line mismatches, high-frequency noise (e.g., corn rows), formatting, misclassification, and data holidays or voids. While many of these problems can be fixed, high-frequency noise is more difficult to remedy. Ultimately, there are no perfect datasets, but there is generally a level at which the data lose some of their usability, and that threshold should be considered when specifying the data.

Learn More

Vertical datums:

www.ngs.noaa.gov/faq.shtml

Tidal datums :

http://tidesandcurrents.noaa.gov/datum_options.html

Prepare Water Levels

What Type of Water Surface Do I Want to Map?

Just as the surface of the Earth is not flat, neither is the surface of the ocean. For instance, the absolute water level height is higher along the west coast of the United States than it is along the east coast. The elevation of the sea surface varies throughout the globe.

The term “global sea level,” refers to the average height of all the Earth’s ocean basins. “Global sea level rise” refers to the increase in the average global sea level trend. “Local sea level” refers to the height of the water measured along the coast relative to a specific point on land. Tide stations measure local sea level. “Relative sea level trends” reflect changes in local sea level over time. This relative change is the one most critical for many coastal applications, including coastal mapping, marine boundary delineation, coastal zone management, coastal engineering, sustainable habitat restoration design, and the public enjoying its favorite beach.

Sea levels change in response to astronomical forces (sun and moon) and to meteorological forces (winds, pressure changes, etc.). Over time these changes can be observed, averaged, and modeled into the future to predict what the water surface will look like at some point in the future. This is done on various time scales. Sea level rise predictions usually go out to a century, based on global climate models. Tidal predictions are monthly, and storm surge and tsunami forecasting are done at the event scale (minutes to hours).

What Is Mean Sea Level?

The term "mean sea level" is often misused and misunderstood. Many users have assumed that the base vertical reference datum for topographic information was mean sea level. Some of this confusion comes from colloquialism and some from naming issues. The datum originally used for the USGS Quadrangle was the National Geodetic Vertical Datum of 1929 (NGVD29), which was previously called the Sea Level Datum of 1929. The USGS topographic quadrangle maps now have heights in the North American Vertical Datum of 1988 (NAVD88), which should be used when performing analyses involving only land elevation data. Older sources of topographic information should be transformed into NAVD88 using a datum transformation tool such as VDatum. See section on VDatum later in this document.

The accuracy of the elevation data and desired product are also important, and the incremental elevations being used for the product come into play. However, a source transformation may not be necessary if the source elevation data only have accuracies to several centimeters. For instance, the difference between local mean sea level and NAVD88, for some areas of the country, may only be a few centimeters.

To accurately map any predicted ocean surface, that surface has to be modeled, interpolated from tidal or water-level gauges or high-water marks, or estimated as a single value of the study region. Ocean surfaces are usually referenced to local tidal datums and have to be converted to terrestrial or orthometric datums like NAVD88 (see datums section).

Modeled Water Surfaces

In many cases, maps that depict inundation are based on output from a hydrodynamic model, or a combination of hydrodynamic and wave models, that was used to calculate a total water level surface. Some prevalent examples of this type of map include the FEMA Flood Insurance Rate Maps (FIRMs) and storm surge zone maps. The FIRMs depict the 1% annual chance flood zone based on studies that incorporate several different models, such as the Advanced Circulation (ADCIRC) model, Wave Height Analysis for Flood Insurance Studies (WHAFIS), and others. Storm surge zone maps depict the potential extent of storm surge from hurricanes based on model output from the NOAA Sea, Lake, and Overland Surges from Hurricanes (SLOSH), ADCIRC, or other models.

Learn More

SLOSH: *slosh.nws.noaa.gov/sloshPub/index.php*

ADCIRC: *www.unc.edu/ims/adcirc*

MOST: *http://nctr.pmel.noaa.gov/model.html*

SLOSH is a computerized model run by the National Hurricane Center to estimate storm surge heights and winds resulting from historical, hypothetical, or predicted hurricanes.

ADCIRC is a system of computer programs for solving time-dependent, free-surface circulation and transport problems in two and three dimensions. These programs utilize the finite element method in space, allowing the use of highly flexible, unstructured grids. Typical ADCIRC applications have included modeling tides and wind-driven circulation, and analysis of hurricane storm surge and flooding. The ADCIRC code system is freely available but is typically run by universities and federal agencies. Therefore, the output may be made available from a variety of sources.

In the U.S., tsunami run-up maps are based on output from NOAA's Methods of Splitting Tsunami (MOST) model.

Sea level impact maps may use the output from the NOAA VDATUM model (based on ADCIRC), which estimates averaged tidal surfaces over a region. This is the desired water surface to use for mapping because it will most accurately depict the varying heights of the water surface over the study area.

Interpolated Water Surfaces

In areas where tidal and surge model output is not available, one has to resort to interpolating between known data points, usually tide and water level gauges. In this scenario, only a few tide or water level gauges may exist for a given study region. This is often the case when trying to re-create a water surface using field-collected high water mark data from a specific flood event. The data points may be coarse and not normally distributed. The method to derive a water surface connecting either values of tidal datums from gauges or high water marks is essentially the same. An interpolation between points has to be performed. This is often done using spatial analysis techniques in a GIS. The result is a water surface based on the point data that gives coverage for an entire study area. The challenge with this method is that, in having to rely on a small number of tide gauges, water level gauges, or high water marks (as is often the case), the surface may not be correct where there is a lack of known values. Different spatial techniques can be used to interpolate a surface. ESRI has a short white paper explaining these methods: *www.esri.com/news/arcuser/0704/files/interpolating.pdf*.

Single Value Water Surfaces

The least desirable approach is creating a single value water surface based on a single numerical value representing a water level, which is then applied consistently over an entire study area. Essentially, this method simply "raises the water surface" (also commonly referred to as "fill the bathtub") or delineates a contour based on the selected value, also known as linear superposition. This does not necessarily mean that models were not used, since the selected value may be based on atmospheric, climate, or other empirical models. This approach is most commonly used for mapping sea level rise for a local area where only one tide gauge or water level gauge is used for the transformation.

In summary, maps of inundation will generally be based on a water surface. Modeled surfaces and interpolated surfaces are the preferred choice to most accurately depict reality. The guidelines in this section and the following section on mapping provide the steps to prepare water levels and create inundation maps using either approach and for a variety of applications (e.g., for sea level rise or storm surge).

What Vertical Reference Datum Should I Use?

When developing analyses using elevation data, it is extremely important to know the vertical reference datum of the source data, as well as to obtain metadata documenting information on the reference datum.

When merging elevation data with different vertical datums for a map depiction or GIS layer display, the various layers must be displayed appropriately relative to a common reference datum. This ensures that any subsequent analyses are not subject to datum shifts that will bias the final analysis. This usually involves a datum transformation of one or more layers.

The specific vertical reference datum used also depends on the application and analyses to be performed, as well as the accuracy desired. For inundation studies for which estimates are required to determine the amount of land affected by sea level inundation, the elevation of a tidal datum (such as mean high water (MHW), or mean higher high water (MHHW) in areas with diurnal tides) is often used as the base elevation. A high water datum is chosen because it represents the elevation of the normal daily excursion of the tide where the land area is normally inundated. Taking this normal extent of inundation into account is important when trying to delineate land areas inundated by abnormal events such as storm surge, tsunami run-up, or sea level rise.

North American Vertical Datum of 1988 (NAVD88)

The current official vertical datum for all surveying and mapping activities of the federal government is NAVD88. The datum is *defined* as the surface of equal gravity potential to which orthometric heights shall refer in North America, and which is 6.271 meters (along the plumb line) below the geodetic mark at Father Point/Rimouski (PID TY5255 in the NGS Integrated Database). However, it is *realized* (i.e., its primary method of access is) through over 500,000 geodetic bench marks across North America with published Helmert orthometric heights, most of which were originally computed from a minimally constrained adjustment of leveling and gravity data, holding the geopotential value at Father Point/Rimouski fixed.

Datums

Tidal datums are based on averaged stages of the tide, such as mean high water (MHW) and mean lower low water (MLLW). To minimize all the significant daily, monthly, and yearly sea level variations, a tidal datum such as MHW is defined as the average of all the high water elevations tabulated over an 18.6-year period (rounded to 19 years to obtain closure on the annual cycle). The National Tidal Datum Epoch (NTDE) is a specific 19-year period defined by NOAA. The present epoch is the 1983-2001 NTDE. Figure 5 shows the accepted 1983-2001 NTDE tidal datum elevations relative to an arbitrary station datum at San Francisco, California. This Web-based information also includes the elevation of the geodetic North American Vertical Datum of 1988 (NAVD88) relative to the same station datum and includes the tabulated highest and lowest tides of record. Refer to *http://tidesandcurrents.noaa.gov* for products and information.

Orthometric datums are used for referencing orthometric heights. An orthometric height is the distance between the geoid and a point on the Earth's surface (measured along the plumb line). In general, orthometric heights are impossible to determine through a direct measurement, since this would require full knowledge of both the plumb line and the geoid, which are generally within the Earth's crust. As such, a variety of approximations are used to estimate orthometric heights. One of the most common is called a Helmert orthometric height, which relies solely on surface-leveling measurements and surface-gravity measurements.

Orthometric heights are also colloquially, but incorrectly, called heights above mean sea level (MSL). Oceanographic MSL, however, departs from the geoid through both periodic effects (such as tides) and non-periodic effects (such as western boundary currents). Furthermore, MSL is defined over the surface of the oceans only, whereas the geoid is a continuous surface, approximating the ocean's surface over the oceans, but slicing under the continents at land areas. As such, heights above mean sea level are meaningless over land.

Data Units:
○ Feet ◉ Meters [Apply Change]

Jul 30 2010 13:51 ELEVATIONS ON STATION DATUM
National Ocean Service (NOAA)

Station: 9414290 T.M.: 0 W
Name: SAN FRANCISCO, SAN FRANCISCO BAY, CA Units: Meters
Status: Accepted Epoch: 1983-2001

Datum	Value	Description
MHHW	3.602	Mean Higher-High Water
MHW	3.416	Mean High Water
DTL	2.712	Mean Diurnal Tide Level
MTL	2.792	Mean Tide Level
MSL	2.773	Mean Sea Level
MLW	2.168	Mean Low Water
MLLW	1.822	Mean Lower-Low Water
GT	1.780	Great Diurnal Range
MN	1.248	Mean Range of Tide
DHQ	0.186	Mean Diurnal High Water Inequality
DLQ	0.346	Mean Diurnal Low Water Inequality
HWI	7.53	Greenwich High Water Interval (in Hours)
LWI	0.85	Greenwich Low Water Interval (in Hours)
NAVD	1.804	North American Vertical Datum
Maximum	4.462	Highest Water Level on Station Datum
Max Date	19830127	Date Of Highest Water Level
Max Time	09:30	Time Of Highest Water Level
Minimum	0.945	Lowest Water Level on Station Datum
Min Date	19331217	Date Of Lowest Water Level
Min Time	18:00	Time Of Lowest Water Level

To refer Water Level Heights to a Tidal Datum, apply the desired Datum Value.

Figure 5. Accepted 1983-2001 NTDE datums for San Francisco. From *http://tidesandcurrents.noaa.gov*. NAVD refers to the North American Vertical Datum of 1988. Notice the differences in the values between the various datums.

VDatum

VDatum is a free software tool that is being developed jointly by NOAA's National Geodetic Survey (NGS) (*www.ngs.noaa.gov*), Office of Coast Survey (OCS) (*http://nauticalcharts.noaa.gov*), and Center for Operational Oceanographic Products and Services (CO-OPS) (*http://tidesandcurrents.noaa.gov*). VDatum is designed to transform geospatial data between a variety of vertical (and horizontal) datums. This allows users to convert their data from different vertical references into a common system, which enables the fusion of disparate geospatial data, particularly in coastal regions.

Learn More

Read more about VDatum and obtain the VDatum software:

http://vdatum.noaa.gov

VDatum currently supports vertical datum transformations that can be placed into three categories:

- **Ellipsoidal:** realized through the global navigation satellite system (GNSS).
- **Orthometric:** defined relative to a geopotential surface and realized through geodetic leveling from bench marks with published heights.
- **Tidal:** based on a tidally derived surface in the vicinity of a tide gauge. The software is currently available for certain areas of the U.S. and supports many diverse applications. The VDatum tool allows for transformation of a single height/depth or file/files of points from one vertical datum to another. Uncertainties associated with VDatum are currently being made available to inform users when transforming heights/soundings among the various supported vertical datums.

In some cases the vertical transformation is done before the elevation values are input into the model so that the same elevation datum is used. For example, the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model uses NAVD88 elevations for each grid cell for topography values. Therefore, the output SLOSH water surface elevation values do not have to be transformed using VDatum before mapping on the elevation data.

What Steps Are Necessary to Prepare Water Levels?

Approach 1: Modeled Water Surfaces

1. Obtain model output: Examples for storm surge inundation include the SLOSH model and the ADCIRC model. Examples for tidal model output include the NOAA VDatum model.
2. Note vertical reference level of model output: For example, sometimes modeled data are referenced to an orthometric vertical datum that is different from the orthometric vertical datum of the elevation data. If this is the case, then a conversion may be necessary.
3. Compute vertical datum shift: Tools are available to determine the vertical datum conversion values; see Vertcon for converting between NGVD29 and NAVD88 (*www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html*) or VDatum (*http://vdatum.noaa.gov*) for converting between tidal and orthometric datums.

Approach 2: Interpolated Water Surfaces

Tidal Surface Example

1. Obtain water surface elevation values from nearby tide gauges and their spatial location.
2. Note vertical reference level of model output: Keep in mind the zero datum for tide gauges is mean lower low water (MLLW) and elevation data are usually in NAVD88.
3. Compute vertical datum shift from the MLLW values to NAVD88 values. See step 3 from Approach 1 above.

High Water Mark Surface Example

1. Obtain the water surface elevation values from high water mark survey.
2. Note vertical reference for high water marks: Keep in mind the zero datum surveyed in high water marks will most likely be in NAVD88, same as the elevation data, so no datum conversion is needed. However, in some locations, such as the Pacific Islands, NAVD88 is not applicable and another vertical datum should be used.

Learn More

To learn about depicting elevation uncertainty in inundation maps, read "Mapping Inundation Uncertainty" by the NOAA Coastal Services Center:

www.csc.noaa.gov/slr/viewer/assets/pdfs/Elevation_Mapping_Confidence_Methods.pdf

The Intergovernmental Panel on Climate Change (IPCC) offers sea level rise projections that could be used as a baseline for a water value. Visit the IPCC's Fourth Assessment Report for more information:

www.ipcc.ch/publications_and_data/ar4/wg2/en/contents.html

Approach 3: Single Value Water Surfaces (or fill the bathtub)

1. Select a water level value to depict on a map (for example, 1.6 feet or 0.5 meters). For the case of sea level rise, there are published sea level rise projections from a variety of sources, including the Intergovernmental Panel on Climate Change (IPCC) and others. In some cases, states or local governments have chosen planning targets.

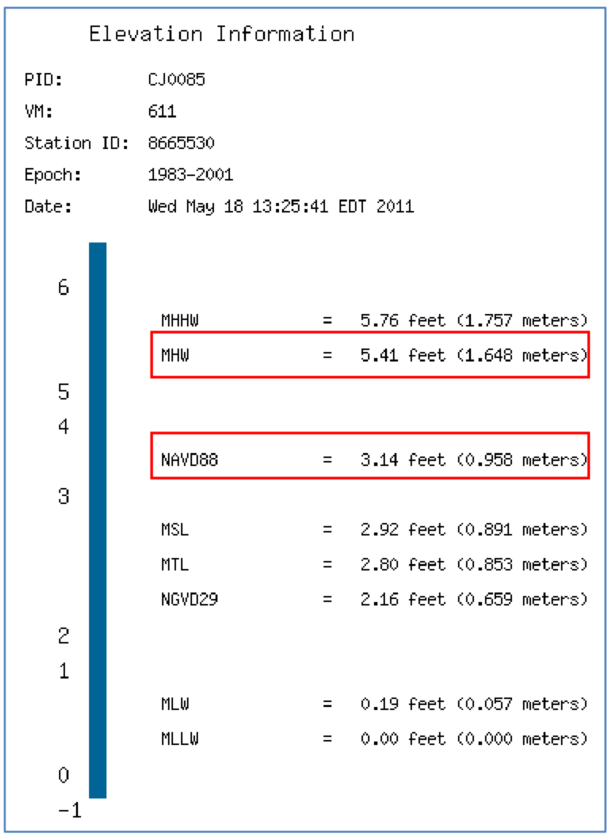
   Note: Be sure to choose water level increments that are supported by the vertical accuracy of the elevation data. The root mean square error (RMSE) of the elevation data is a useful guide, generally equal to 1 standard deviation (see previous section on accuracy) or a confidence interval of about 66%.

2. Determine the vertical reference level. To meaningfully communicate sea level rise to local decision makers, in many cases the sea level rise value is mapped relative to a tidal datum, such as mean high water (MHW) or mean higher high water (MHHW). In this manner, the map will depict the worst daily scenario from high tides.

3. Compute the vertical datum shift. The elevation data will be used to "raise the water level" or delineate a contour based on the selected water level. Since most U.S. elevation data are based on the North American Vertical Datum of 1988 (NAVD88) orthometric vertical datum, the chosen tidal water level will need to be adjusted to the orthometric datum. This adjustment from the tidal datum (such as MHW or MHHW) to NAVD88 can be done using VDatum if the transformation grids are available for the area. Alternatively, a local tide gauge can provide the conversion factor. Find a tide gauge and associated water-level data at *http://tidesandcurrents.noaa.gov*.

Example:
Prepare water levels to show a 1.6 foot sea level rise on top of MHW for Charleston, South Carolina. The elevation data provided are a DEM referenced to NAVD88.

1. A simple way to calculate the vertical datum shift in lieu of VDatum is to use a tide gauge. Go to the Charleston tide gauge at *http://tidesandcurrents.noaa.gov/geo.shtml?location=8665530*.
2. Click on the link for Datums.
3. Scroll to the bottom of the page and click on the link for the National Geodetic Survey.
4. Use the elevation information provided on the page to calculate the vertical shift between NAVD88 and MHW. See an example of the tidal gauge and calculation below.



Example: Charleston, SC

To map 1.6 feet SLR on top of MHW:

MHW = 5.41 feet
and
NAVD88 = 3.14 feet,

5.41 ft – 3.14 ft = 2.27 ft

Thus, to map MHW on top of NAVD88, a value of 2.27 feet would be used.

To map 1.6 feet of SLR above MHW:

2.27 ft + 1.6 ft = 3.87

Thus, your water level value is 3.87 feet.

Figure 6: An example of how to calculate a vertical datum shift and derive a sea level rise value

Map Inundation

How Do I Map the Water Surface?

With the prepared DEM and water level information (modeled, interpolated, or single value), GIS processes can be used to create data that represent inundation extent and depth.

Approach 1: Modeled Water Surfaces

1. Extract points from gridded model output.
2. Create a water surface by interpolating points. Two options for interpolation are inverse distance weighting and kriging.
3. Subtract the DEM from the water surface to create the inundation depth raster.
4. Convert depth rasters to polygons representing inundation extent only (optional).

Example:

Using water level information from the previous section, create inundation polygons and depth rasters showing storm surge inundation from SLOSH model output for Charleston, South Carolina.

An ESRI ArcGIS model is available to automate the following steps for mapping storm surge using SLOSH model output. More information and technical support can be found at *www.csc.noaa.gov/digitalcoast*.

1. Project the SLOSH output polygon to match the DEM's projection.
2. Create centroids of the SLOSH output polygon. After some processing, the centroids (or points) will be used to interpolate a water surface representing storm surge.
3. Remove dry points. Removing points that are "dry" allows the interpolation to more accurately represent the water surface. "Dry" points represent SLOSH grid cells where no data exist, meaning the model determined that there was no water in that cell.
4. Convert SLOSH water level values to meters. This is an optional step and only needed if the DEM's vertical unit is meters.
5. If necessary, use the previously computed vertical datum conversion to convert SLOSH points to the same datum as the DEM.
6. Clip SLOSH output points to improve processing. This step reduces processing time by selecting only the points needed to create a water surface that covers the DEM. When creating the clip layer, be sure to make it large enough to include enough "wet" points so that when a surface is created, it covers the entire DEM. This is necessary because the Natural Neighbor interpolation method will only interpolate a surface within the footprint of the input points.
7. Interpolate water surface. The Natural Neighbor interpolation method is used to interpolate a water surface from SLOSH output points after the appropriate conversions have been applied.
8. Subtract interpolated water surface and DEM to determine inundation. When subtracting the DEM from the interpolated water surface, the resulting values representing inundation will be positive (including zero).
9. Process the subtraction result. This step uses a conditional statement to preserve all values representing inundation and nullify all other values. The result is a raster that represents the depth and horizontal extent of inundation. This raster can be converted to a single-value raster or a polygon.

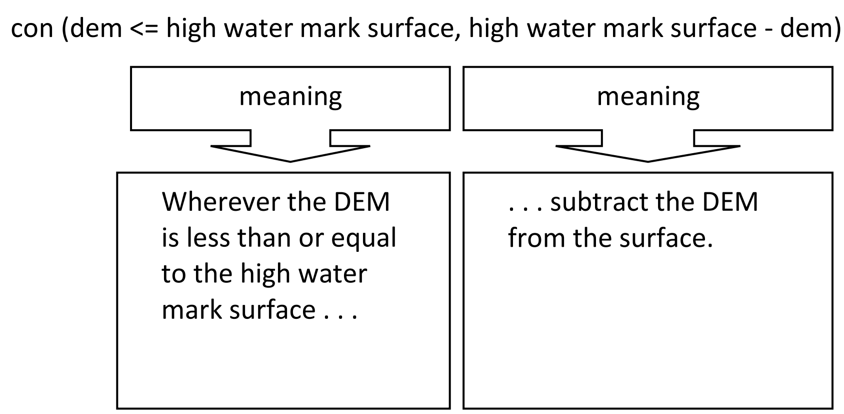
Approach 2: Interpolated Water Surfaces (Using High Water Marks)

1. Prepare the high water mark data.
2. Interpolate a water surface using the high water mark points.
3. Subtract the DEM from the interpolated high water mark surface to create the inundation depth raster.
4. Convert depth rasters to polygons representing inundation extent only.

Example:

Create an inundation polygon using high water marks from a hurricane.

1. High water mark data will likely come in a table format or as a point shapefile. Examine the data to determine the geometry and attribute information. If necessary, format the data so they can be mapped.
2. Map the high water mark data as a point layer.
3. Using the points and the Spline interpolation method, interpolate a water surface. It is important to note that the interpolation method to use will depend on the distribution of high water mark data. It is up to the user to determine which method is most appropriate for a given dataset.
4. Subtract the DEM from the interpolated high water mark surface. One method is to write a conditional statement. Using the ESRI single output Map Algebra tool, the conditional statement will resemble the one below. It results in positive depth values.
    a. Conditional Statement: con(dem <= high water mark surface, high water mark surface - dem)



    b. The statement reads, wherever the DEM is less than or equal to the high water mark surface, subtract the DEM from the surface.
5. Use raster conversion tools to convert the inundation depth raster to a polygon, if desired.
6. Manual editing may be required to remove “ponds,” or areas that were inundated based on the elevation, even though there was no adjacent connection to water or other inundated areas.

Approach 3: Single Value Water Surfaces

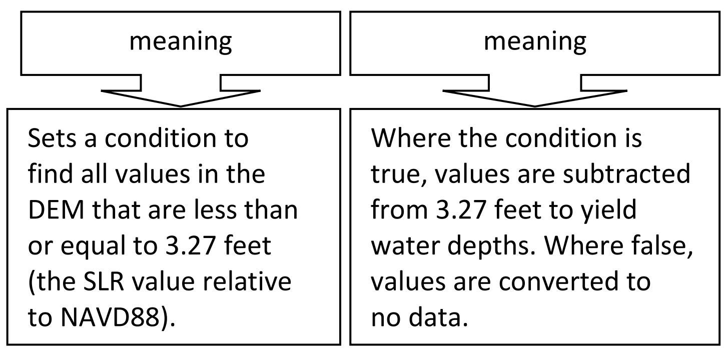
1. Use GIS tools (map algebra, conditional statement, or raster calculator) to create inundation depth rasters.
2. Convert depth rasters to polygons representing inundation extent only.

Example:

Using water level information from the previous steps, create inundation polygons and depth rasters showing a 1-foot sea level rise on top of MHW for Charleston, South Carolina.

1. Obtain DEM. Note the DEM units. If desired, convert units to represent desired final output.
2. If desired, remove pixels with a value of "No Data" from the DEM so they will not be used for inundation calculations.
3. Also consider removing pixel values of less than 0 (these might occur offshore or in rivers and waterways). This may or may not create a better final product, depending on the characteristics of the DEM. Often trial and error is a good way to determine the right strategy for a given dataset and the desired map or visualization.
4. Use the modified DEM and converted water levels from previous steps to create an inundation depth grid. One method is to write a conditional statement. Using the ESRI single output map algebra tool, the conditional statement will resemble the one below.

```
con (charleston_dem <= 3.27, 3.27 - charleston_dem)
```



5. Use raster conversion tools to convert the inundation depth raster to a polygon if desired.
6. Manual editing may be required to remove "ponds," or areas that were inundated based on the elevation, even though there was no adjacent connection to water or other inundated areas.

Technical Support

While this document does not include detailed information on how to create coastal inundation maps for specific types of inundation, there are many resources that might be of assistance. Below are a select few.

"Lidar 101": *www.csc.noaa.gov/digitalcoast/_/_pdf/What_is_Lidar.pdf*

CLICK's resources page: *http://lidar.cr.usgs.gov/knowledge.php*

Florida International University International Hurricane Research Center lidar publications: *www.ihrc.fiu.edu/lcr/research/airborne_laser_mapping/index.htm#publications*

Introduction to Lidar (online training): *www.csc.noaa.gov/digitalcoast/training/intro-lidar/index.html*

Understanding Map Projections, Datums, and Coordinate Systems (online training): *www.csc.noaa.gov/digitalcoast/training/datums/index.html*

"Mapping Inundation Uncertainty": *www.csc.noaa.gov/slr/viewer/assets/pdfs/Elevation_Mapping_Confidence_Methods.pdf*

"Technical Considerations for Use of Geospatial Data in Sea Level Change Mapping and Assessment": *www.csc.noaa.gov/digitalcoast/_/pdf/SLC_Technical_Considerations_Document.pdf*

"Topographic and Bathymetric Data Considerations": *www.csc.noaa.gov/digitalcoast/_/pdf/topographic-and-bathymetric-data-considerations.pdf*

"Top Ten Elevation Concerns for Inundation Modeling": www.csc.noaa.gov/digitalcoast/_/pdf/top10.pdf

"Detailed Method for Mapping Sea Level Rise Inundation": *www.csc.noaa.gov/slr/viewer/assets/pdfs/Inundation_Methods.pdf*

"Coastal Flood Event Frequency and Duration Calculation Method": *www.csc.noaa.gov/slr/viewer/assets/pdfs/CO-OPS_Flood_Frequency_Methods.pdf*

Sea Level Trends: *http://tidesandcurrents.noaa.gov/sltrends/index.shtml*

Tidal Datums: *http://tidesandcurrents.noaa.gov/datum_options.html*

Resources

Sea Level Rise Projections

Cayan, D., M. Tyree, M. Dettinger, H. Hidalgo, T. Das, E. Maurer, P. Bromirski, N. Graham, and R. Flick. 2009. *Climate Change Scenarios and Sea Level Rise Estimates for the California 2008 Climate Change Scenarios Assessment.* Draft paper. CEC-500-2009-014-D. California Climate Change Center.

Cayan, D., P. Bromirski, K. Hayhoe, M. Tyree, M. Dettinger, and R. Flick. 2006. *Projecting Future Sea Level.* California Climate Change Center. CEC-500-2005-202-SF. California Energy Commission.

Intergovernmental Panel on Climate Change. 2000. *Special Report on Emissions Scenarios. A Special Report of Working Group III.* Cambridge, United Kingdom and New York, New York, USA: Cambridge University Press.

Meehl, G. A., T. F. Stocker, W. D. Collins, P. Friedlingstein, A. T. Gaye, J. M. Gregory, A. Kitoh, R. Knutti, J. M. Murphy, A. Noda, S. C. B. Raper, I. G. Watterson, A. J. Weaver, and Z.- C. Zhao. 2007. "Global Climate Projections." In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller (eds.). Cambridge, United Kingdom and New York, New York, USA: Cambridge University Press.

Rahmstorf, S., A. Cazenave, J. A. Church, J. E. Hansen, R. F. Keeling, D. E. Parker, and R. C. J. Somerville. 2007. "Recent Climate Observations Compared to Projections." *Science.* Volume 316. Number 5825. Page 709.

Rahmstorf, S. 2007. "A Semi-Empirical Approach to Projecting Future Sea-Level Rise." *Science.* Volume 315. Number 5810. Page 368.

References

Climate Change Science Program (CCSP). 2009. *Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region.* Final Report of Synthesis and Assessment Product 4.1. Washington, D.C.: Environmental Protection Agency.

Maune, D.F., 2007. *Digital Elevation Model Technologies and Applications: The DEM Users Manual*, 2nd Edition. Bethesda, MD: American Society for Photogrammetry and Remote Sensing.

National Research Council (NRC). 2009. *Mapping the Zone: Improving Flood Map Accuracy*. Committee on FEMA Flood Maps; Board on Earth Sciences and Resources Mapping Science Committee. Washington, D.C.: The National Academies Press.