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Elevation Uncertainty in Coastal Inundation Hazard Assessments

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1. Introduction

Coastal inundation has been identified as an important natural hazard that affects densely populated and built-up areas (Subcommittee on Disaster Reduction, 2008). Inundation, or coastal flooding, can result from various physical processes, including storm surges, tsunamis, intense precipitation events, and extreme high tides. Such events cause quickly rising water levels. When rapidly rising water levels overwhelm flood defenses, especially in heavily populated areas, the potential of the hazard is realized and a natural disaster results. Two noteworthy recent examples of such natural disasters resulting from coastal inundation are the Hurricane Katrina storm surge in 2005 along the Gulf of Mexico coast in the United States, and the tsunami in northern Japan in 2011. Longer term, slowly varying processes such as land subsidence (Committee on Floodplain Mapping Technologies, 2007) and sea-level rise also can result in coastal inundation, although such conditions do not have the rapid water level rise associated with other flooding events.

Geospatial data are a critical resource for conducting assessments of the potential impacts of coastal inundation, and geospatial representations of the topography in the form of elevation measurements are a primary source of information for identifying the natural and human components of the landscape that are at risk. Recently, the quantity and quality of elevation data available for the coastal zone have increased markedly, and this availability facilitates more detailed and comprehensive hazard impact assessments.

1.1 Elevation–based inundation hazard assessments

Elevation is one of the most important parameters that determine the vulnerability of coastal lands to inundation from flooding events and sea-level rise (Gesch et al., 2009). In many coastal inundation impact assessments conducted at various scales, elevation is a primary variable that is analyzed to determine vulnerability to adverse effects of rising water levels. These assessments require use of topographic maps or digital elevation models (DEMs) to identify low-lying lands with low or no slope that are at risk (Committee on Floodplain Mapping Technologies, 2007). Numerous studies over the last three decades have used elevation data in various forms to map areas and tabulate statistics of lands that would be

affected by a given water level increase, oftentimes due to sea-level rise and/or storm surges (Dasgupta et al., 2009; Dasgupta et al., 2011; Demirkesen et al., 2007; Ericson et al., 2006; Kleinosky et al., 2007; Li et al., 2009; McGranahan et al., 2007; Najjar et al., 2000; Neumann et al., 2010; Rowley et al., 2007; Schneider and Chen, 1980; Small and Nicholls, 2003; Titus and Richman, 2001; Titus et al., 1991; Weiss et al., 2011; Wu et al., 2002; Wu et al., 2009).

The accuracy and resolution with which coastal elevations have been mapped directly affect the reliability and usefulness of coastal inundation impact assessments. To many, it may seem straightforward to simply "raise the water level" on a coastal DEM to map and assess the vulnerability of land and its corresponding resources to inundation. However, recent research (Gesch, 2009; Gesch et al., 2009; National Ocean Service, 2010) has demonstrated that the qualities of the underlying geospatial data, especially the DEM, must be well understood to properly model potential inundation for reliable hazard assessment findings.

1.2 Elevation data accuracy

Because elevation data are such a critical component in coastal hazard assessments, the qualities of the data, especially vertical accuracy, exert a strong influence on the reliability of the results. As such, the vertical accuracy must be well characterized and well understood so that the data are applied properly. Absolute vertical accuracy is an expression of the overall quality of the elevations contained in a DEM compared to the true ground elevations at corresponding locations. The root mean square error ($RMSE_z$), as described by Maune et al. (2007), is a widely accepted metric to describe the absolute vertical accuracy of elevation data:

$$RMSE_z = sqrt[\sum(z_{data\ I} - z_{check\ I})^2/n] \qquad (1)$$

where $z_{data\ I}$ is the vertical coordinate of the Ith check point in the elevation dataset, $z_{check\ I}$ is the vertical coordinate of the Ith check point in the reference dataset, n is the number of points being checked, and I is an integer from 1 to n. Another common metric for expressing the vertical accuracy of elevation data is the "linear error at 95% confidence" (LE95). LE95 may be calculated directly from the measured $RMSE_z$ (Maune et al., 2007):

$$LE95 = 1.96 * RMSE_z \qquad (2)$$

As described below, the absolute vertical accuracy is useful for determining the minimum increment of inundation that can be reliably modeled, and, in the case of sea-level rise, the minimum time period over which sea-level change can be effectively modeled.

1.3 Uncertainty in inundation assessments and maps

Uncertainty should be an important consideration in any modeling exercise. For flood inundation mapping, there are several sources of uncertainty, but they are often not quantified due to lack of awareness of the sources or lack of suitable data to quantify them (Bales and Wagner, 2009). These sources of uncertainty include water level, or hydrologic, data (Brown et al., 2007; Chu-Agor et al., 2011; Purvis et al., 2008), the hydrologic or hydraulic model itself (Bales and Wagner, 2009; Gallien et al., 2011), input parameters to the flooding model (Brown et al., 2007; Cowell and Zeng, 2003), and input topographic (elevation) data (Colby and Dobson, 2010; Wilson and Atkinson, 2005; Wechsler, 2007).

The input elevation information is a primary contributor to the uncertainty associated with inundation hazard assessments. In a study conducted for the Federal Emergency Management Agency (FEMA), the agency responsible for mapping flood hazards across the United States, the primary finding was that "topographic data are the most important factor in determining water surface elevations, base flood elevation, and the extent of flooding and, thus, the accuracy of flood maps" (Committee on FEMA Flood Maps, 2009). The study also recommends that flood map accuracy should be quantified and communicated by thorough documentation of the data and mapping and modeling methods used to develop the products. The resolution and accuracy of elevation data are especially critical for modeling inundation risks in low-relief, low-slope coastal settings (Coveney et al., 2010; Coveney and Fotheringham, 2011; Gesch, 2009). Gesch et al. (2009) and Lichter et al. (2011) review existing large-area sea-level rise vulnerability studies that employ elevation data and note that in many cases uncertainty is not considered. Gesch et al. (2009) also make suggestions on accounting for elevation uncertainty in future sea-level rise assessments.

Maps that depict areas vulnerable to potential inundation are useful to planners and land managers who are responsible for communicating and mitigating risks. Often, these maps are accompanied with corresponding statistical summaries of population, infrastructure, property value, economic activity, or other variables within the mapped impact zone. In many cases, the studies that have produced these maps and statistical summaries have not considered the uncertainty (inherent vertical error) of the underlying elevation data. There has been some recognition that hazard studies should include and report uncertainty in project results; for example, Merwade et al. (2008) have demonstrated that a modeled inundation area has uncertainty associated with it by depicting a buffer around the flood boundary. Smemoe et al. (2007) and Bales and Wagner (2009) have suggested adding probabilities to flood hazard maps as a way to communicate the uncertainty associated with modeled inundation areas, a concept which has been successfully demonstrated by Leedal et al. (2010). The use of probabilities (expressed as confidence levels) to communicate uncertainty should also be extended to the statistical summaries of impacted land area, population, and other socioeconomic variables (Gesch et al., 2009). Merwade et al. (2008) have also recommended such an approach for floodplain mapping, stating that the flood inundation extent should be reported as being "in the range from x units to y units with a z% confidence level."

2. Methods

Because the vertical accuracy of the input elevation data in coastal inundation hazard assessments is such a critical parameter that significantly affects the veracity of the modeling results, it must be described fully according to standards and accepted best practices. In many cases, the elevation data producer provides accuracy information, but overall dataset statistics may not be adequate to fully characterize the performance of the elevation model in extreme low-relief settings, which are often the target of inundation assessment studies (Coveney et al., 2010). If a suitable accuracy statement is not available for an elevation dataset, then the user must conduct an accuracy assessment; several standards and guidelines describe the best practices for doing so (Maune et al., 2007).

2.1 Elevation accuracy assessment

As described above, the RMSE is a common method of testing and reporting the vertical accuracy of elevation datasets. However, there are other methods used in the literature, and it is important to understand how the different metrics are related. Also mentioned above is LE95, or the use of the 95% confidence level. This convention follows the U.S. National Standard for Spatial Data Accuracy (NSSDA), which states that the "reporting standard in the vertical component is a linear uncertainty value, such that the true or theoretical location of the point falls within +/- of that linear uncertainty value 95-percent of the time" (Federal Geographic Data Committee, 1998).

Some data producers and studies report absolute vertical accuracy as "linear error at 90% confidence" (LE90), which derives from the older U.S. National Map Accuracy Standards (NMAS) issued in 1947, long before the age of digital elevation data. The NMAS state that "vertical accuracy, as applied to contour maps on all publication scales, shall be such that not more than 10 percent of the elevations tested shall be in error by more than one-half the contour interval" (U.S. Geological Survey, 1999). An alternative way to state the NMAS vertical accuracy standard is that elevations obtained from the topographic map will be accurate to within one-half of the contour interval 90% of the time. Even though the NMAS were developed for hardcopy topographic maps, the terminology is sometimes still applied in reference to digital elevation data, such as specifying accuracy for an elevation data acquisition that meets "2-foot contour accuracy." In this case, digital elevation data that supports a 2-foot contour interval would exhibit an RMSE of 18.5 centimeters. Maune et al. (2007) provide a useful comparison of NMAS equivalent contour interval, LE90, RMSE, and LE95 vertical accuracy metrics.

When testing and reporting the vertical accuracy of elevation data, if the measured errors have a mean of zero and are normally distributed, then the RMSE is the equivalent of the statistical standard deviation of the errors. Simple conversion factors can be applied to convert among the various vertical accuracy measures (Greenwalt and Shultz, 1962; Maune et al., 2007). Whichever accuracy metric is used, it must be identified. Too often, an accuracy number is cited for a DEM but no metric is identified, so the accuracy statement is meaningless.

In some cases, elevation data errors do not follow a normal distribution, so an alternative method is used to report the 95% error metric (Maune et al., 2007). Elevation data derived from lidar (light detection and ranging) remote sensing are often used in coastal areas because of their high vertical accuracy and high spatial resolution (Brock et al., 2002; Sallenger et al., 2003; Stockdon et al., 2007), but lidar measurements are sensitive to ground cover so in some cover types the lidar sensor may not detect ground level. This can lead to measured errors in an accuracy assessment that do not follow a normal distribution, thus the need for an alternative 95% confidence error metric. The U.S. National Digital Elevation Program (NDEP) has developed guidelines, or best practices, for testing and reporting the vertical accuracy of such datasets (National Digital Elevation Program, 2004), particularly lidar data.

2.2 Application of uncertainty information

Elevation accuracy testing supplies the knowledge of the inherent vertical error needed to account for uncertainty in inundation hazard assessment. This knowledge of uncertainty of

the foundational elevation layer should be integrated into maps, statistical summaries, and any other final products of the impact assessment (Gesch et al., 2009). However, consideration of the vertical uncertainty of the base geospatial data should also be incorporated into the inundation parameters that are analyzed in the study, specifically the minimum increment of inundation used for modeling, and, for sea-level rise studies, the minimum planning timeline. These concepts are described below.

2.2.1 Minimum increment of inundation

Inundation modeling is most often a simple process in which the water level along the shoreline on a coastal DEM is raised by selecting a land elevation above the current water level elevation and then delineating all areas at or below that elevation, thus placing them into the inundation zone. This approach has been commonly referred to as the "bathtub" method, or the "equilibrium" method (Gallien et al., 2011), and it has been improved in later studies by accounting for hydrologic connectivity (Poulter and Halpin, 2007; Poulter et al., 2008). Such a procedure is essentially a contouring process. Hunter and Goodchild (1995) recognized that vertical error in an elevation dataset contributes uncertainty to delineation of a contour line from interpolation of the DEM values. The vertical accuracy of the DEM must be taken into account to determine the contour interval that is supported. An elevation dataset can be contoured at a fine interval, but doing so does not mean that the contours automatically meet published accuracy standards. Similarly, inundation assessments can use small intervals of water level change, but the underlying DEM must have the requisite vertical accuracy to truly support those intervals. The intervals must not be so small that they are within the bounds of the statistical uncertainty of the elevation data.

It has been shown that at the 95% confidence level elevation data to be used for inundation modeling should be at least as twice as accurate as the increment of water level change (Gesch et al., 2009). Recall that the 95% confidence level (LE95) can be calculated from the RMSE (Equation 2). Therefore, in the case of sea-level rise, the minimum increment for sea-level rise modeling, $SLRI_{min}$, is

$$SLRI_{min} = LE95 * 2 \tag{3}$$

Stated in terms of the RMSE, which is commonly the error metric that is calculated and reported, the $SLRI_{min}$ is

$$SLRI_{min} = (RMSE_z * 1.96) * 2 \tag{4}$$

or more simply

$$SLRI_{min} = RMSE_z * 3.92 \tag{5}$$

Given an elevation model with a reported absolute vertical accuracy (or determined through testing) expressed as an RMSE, Equation 5 can be used to determine the smallest increment of sea-level rise that should be considered in a study using that DEM. Using an increment smaller than $SLRI_{min}$ will give questionable results as the increment will be within the bounds of statistical uncertainty of the elevation data. Table 1 lists some common sources of elevation data, the associated absolute vertical accuracies, and the derived minimum increments for inundation modeling.

Elevation dataset	Vertical accuracy: RMSE	Vertical accuracy: LE95	Minimum increment for inundation modeling
Topographic map with 1-foot contour interval	9.3 cm	18.2 cm	36.3 cm
Industry standard lidar	15.0 cm	29.4 cm	58.8 cm
Topographic map with 2-foot contour interval	18.5 cm	36.3 cm	72.6 cm
Topographic map with 1-meter contour interval	30.4 cm	59.6 cm	1.19 m
Topographic map with 5-foot contour interval	46.3 cm	90.8 cm	1.82 m
Topographic map with 10-foot contour interval	92.6 cm	1.82 m	3.63 m
Topographic map with 5-meter contour interval	1.52 m	2.98 m	5.96 m

Table 1. Minimum inundation modeling increments supported by elevation datasets with different vertical accuracies. For the topographic maps, the assumption is that the maps meet U.S. National Map Accuracy Standards for vertical accuracy at the specified contour interval.

Equation 5 can be rearranged to answer, for example, the question, "what RMSE is required for elevation data to effectively model 1 meter of sea-level rise?"

$$RMSE_z = SLRI_{min} / 3.92 \qquad\qquad (6)$$

Using Equation 6, the answer to the example question is that elevation data with a vertical RMSE of 25.5 cm (or better) is required to reliably model a sea-level rise of 1 meter.

Numerous sea-level rise assessment studies have used scenarios with sea-level rise increments of 1 meter or smaller. The example above demonstrates that highly accurate elevation data must be used to properly consider vertical uncertainty and to produce reliable maps and statistical summaries of impacted areas and resources. Such data, with an RMSE of 25 cm or better, are usually derived from lidar collections, large-scale photogrammetric mapping, or ground surveys. Thus, a challenge in assessing vulnerability to sea-level rise on the order of a meter over broad (global or regional) areas is that the required high-accuracy elevation data are generally not available for the entire study area. Global DEMs do exist, but none of them have the vertical accuracy to support modeling of a 1-meter increment of sea-level rise, which calls into question the reliability of the results of studies (Dasgupta et al., 2009; Li et al., 2009; Rowley et al., 2007) that have used such DEMs

for inundation assessment. A 1-meter increment of sea-level rise is well within the bounds of statistical uncertainty of the currently available global elevation datasets (Gesch, 2009).

The discussion here uses sea-level rise as the inundation process, but the application is the same for other types of coastal inundation, such as storm surge. Considering Table 1 and Equation 6, the inundation zone from a 2-meter storm surge should not be mapped using a topographic map with a 5-meter contour interval. However, the impact zone for that same 2-meter storm surge could be reliably mapped based on a topographic map with a 1-meter contour interval.

Some studies combine the effects of climate change, through increased eustatic sea level, and storm surge to model potential future inundation scenarios (Dasgupta et al., 2011; Kleinosky et al., 2007). The concept of minimum inundation increment is applicable in both cases, to the sea-level rise increments and to the storm surge heights used in the study. Neither of them should be smaller than the vertical increment that is supported by the inherent accuracy of the base elevation dataset used in the modeling.

2.2.2 Minimum planning timeline

The time period for many coastal inundation events is measured in terms of minutes (for tsunamis), hours (for storm surges and tidal flooding), or occasionally days (extreme precipitation). However, sea-level rise is a much slower, long-term process that is usually assessed over years, centuries, and millennia. A common timeframe for assessing potential sea-level rise impacts is about 100 years, or from the present to the year 2100, as this timeframe was the general framework for the most recent Intergovernmental Panel on Climate Change (IPCC) analysis and report (Meehl et al., 2007). As with the minimum inundation increment described above, the minimum planning timeline for sea-level rise assessments is also controlled by the inherent accuracy of the foundational elevation data.

Sea-level rise impact assessments assume a given sea-level rise rate, usually a linear one. For instance, the latest IPCC report (Meehl et al., 2007) cites a maximum eustatic sea-level rise of 0.59 meters by the end of the 21st century, or an annual rate of 5.9 mm/yr. Given an annual sea-level rise (SLR) rate and the minimum sea-level rise increment, the minimum planning timeline can be calculated:

$$\text{Timeline}_{min} = \text{SLRI}_{min} \text{ / annual SLR rate} \tag{7}$$

In terms of the vertical RMSE of a given elevation dataset, the minimum planning timeline can be expressed as

$$\text{Timeline}_{min} = (\text{RMSE}_z * 3.92) \text{ / annual SLR rate} \tag{8}$$

As an illustration, assume the annual rate of sea-level rise for a study is 5.9 mm/yr, or the maximum rate from the most recent IPCC report. Also assume the elevation data to be used for modeling have a vertical RMSE of 9.25 cm, which would be the equivalent of a 1-foot contour interval topographic map that meets NMAS (Maune et al., 2007). Applying Equation 8, the minimum planning timeline is approximately 61 years. In other words, given the sea-level rise rate, it will take more than 61 years to reach the minimum sea-level rise increment afforded by the elevation data. In this example, mapping the potential sea-level rise impact zone 40 years hence would give unreliable results as the cumulative rise in

sea-level would represent an increment smaller than the allowable minimum inundation increment.

If the accuracy of the input elevation model is held constant so that the minimum sea-level rise increment remains the same, the minimum planning timeline will decrease if a higher rate of sea-level rise is used. Conversely, if a lower rate of sea-level rise is used, the minimum planning time will be extended (it will take more years to reach the minimum inundation increment). Further illustrations using the IPCC sea-level rise rates are presented and discussed below.

3. Results

The following examples illustrate the application of elevation uncertainty information to coastal inundation hazard assessments. Sea-level rise is the subject of these example results, but the concepts and approach of accounting for elevation uncertainty would be the same for other higher frequency, higher magnitude types of coastal inundation.

3.1 North Carolina case study

The following case study (Gesch, 2009) illustrates the advantages of using high-resolution, high-accuracy elevation data for coastal inundation hazard assessment. In this case, lidar remote sensing is the source of the elevation data, a primary input data resource for coastal hazard impact assessments.

North Carolina on the mid-Atlantic coast along the eastern United States has a broad expanse of low lying land, so it is a good site for a mapping comparison for a sea-level rise (or inundation) application. Lidar data at 1/9-arc-second (about 3-meter) grid spacing were analyzed and compared to 1-arc-second (about 30-meter) DEMs derived from 1:24,000-scale topographic maps. The potential inundation zone from a 1-meter sea-level rise was mapped from both elevation datasets, and the corresponding areas were compared. The analysis produced maps and statistics in which the elevation uncertainty was considered. Each elevation dataset was "flooded" by identifying the grid cells that have an elevation at or below 1 meter and are connected hydrologically to the ocean through a continuous path of adjacent inundated grid cells. For each dataset, additional areas were delineated to show a spatial representation of the uncertainty of the projected inundation area. This was accomplished by adding the LE95 value to the 1-meter sea-level increase and extracting the area at or below that elevation using the same flooding algorithm. The lidar data exhibited a ±0.27 meter error (LE95) based on accuracy reports from the data producer, while the map-derived DEMs had a ±2.21 meter error (LE95) based on an accuracy assessment with high quality geodetic control points.

Figure 1 and Table 2 show the results of the comparison. In Figure 1 the darker blue tint represents the area at or below 1 meter in elevation, and the lighter blue tint represents the additional area in the vulnerable zone given the vertical uncertainty of the input elevation datasets. By adding the LE95 value to the projected 1-meter sea-level rise, more area is added to the inundation zone delineation, and this additional area is a spatial representation of the uncertainty. The additional area is interpreted as the region in which the 1-meter elevation may actually fall, given the statistical uncertainty of the original elevation measurements. Note how use of the more accurate lidar data for delineation of the

vulnerable area results in a more certain delineation; in other words, the zone of uncertainty is small.
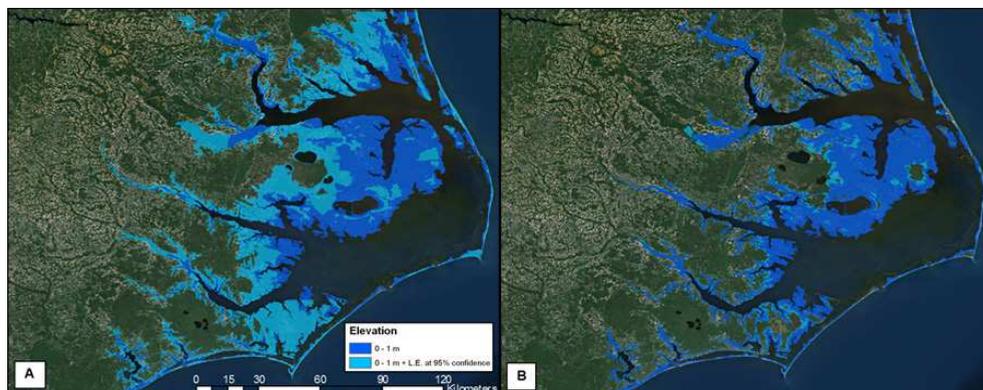

Fig. 1. Lands vulnerable to a 1-meter sea-level rise, developed from topographic map-derived DEMs (A) and lidar elevation data (B). The darker blue tint represents the area at or below 1 meter in elevation, and the lighter blue tint represents the additional area in the vulnerable zone given the vertical uncertainty of the input elevation datasets. The background is a true color orthoimage.

Elevation dataset	Area ≤ 1 meter in elevation (sq. km)	Area ≤ 1 meter in elevation at 95% confidence (sq. km)	Percent increase in maximum vulnerable area when elevation uncertainty is included
1-arc-second (30-meter) DEMs derived from 1:24,000-scale topographic maps	4,014	8,578	114%
1/9-arc-second (3-meter) lidar elevation grid	4,195	4,783	14%

Table 2. The maximum area of land vulnerable to a 1-meter sea-level rise as calculated from two elevation datasets (see Figure 1), as well as the area of vulnerability when the uncertainty of the elevation data is considered.

Table 2 compares the vulnerable areas as delineated from the two elevation datasets. The delineation from the topographic map-derived DEMs more than doubles in area when the elevation uncertainty is considered, which calls into question the reliability of any conclusions drawn from the delineation. It is apparent that for this site the map-derived DEMs do not have the vertical accuracy required to reliably delineate a 1-meter sea-level rise inundation zone. Lidar-derived elevation data are the appropriate data for finding out how much land in the study site is vulnerable to a 1-meter sea-level rise (3,548 to 4,783 square kilometers at a 95% confidence level). This range accounts for the LE95 of ±0.27 meters applied to the 1-meter sea-level rise increment, whereas Table 2 shows only the

maximum potential inundation area given the elevation data uncertainty (1 m + 0.27 m for a total of 4,783 sq. km).

This case study emphasizes why a range of values should be given when reporting the size of the inundation zone (and the amount of resources within it) for a given sea-level rise scenario, especially for areas where high-accuracy lidar data are not available. Without such a range being reported, users of an assessment report may not understand the amount of uncertainty associated with area delineations from less accurate data and the implications for any subsequent decisions based on the reported statistics.

3.2 Assateague Island case study

Assateague Island is a 60-kilometer long barrier island located in the states of Maryland and Virginia on the mid-Atlantic coast along the eastern United States. Figure 2 shows a portion of the island and a graphical portrayal of the results of an accuracy assessment of a lidar elevation dataset covering the island. In this case, the elevation data are 1-meter EAARL (Experimental Advanced Airborne Research Lidar) data (Nayegandhi et al., 2006) collected in 2008. The lidar elevation data exhibit a vertical RMSE of 0.23 meters when tested against a set of high-accuracy survey benchmarks on the island. Following Equation 2, the LE95 value

RMSE = 0.23 m
LE95 = ± 0.45 m

95% confidence interval
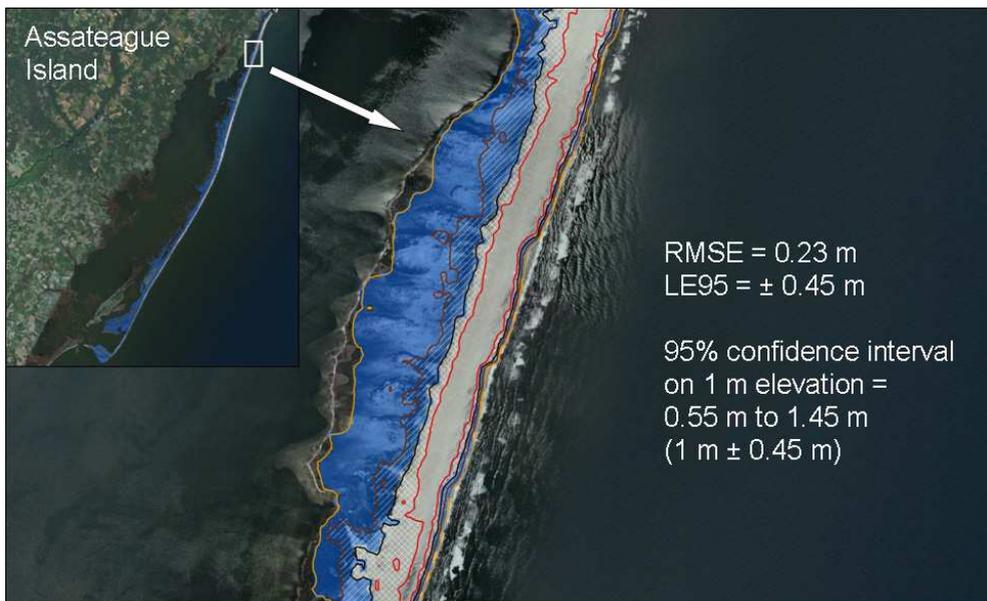on 1 m elevation =
0.55 m to 1.45 m
(1 m ± 0.45 m)

Fig. 2. Results of an accuracy assessment of lidar elevation data over a portion of Assateague Island. The orange line is the mean high water (MHW) shoreline. The black line is the 1-meter contour (above MHW), and the brown lines and cross-hatch patterns delineate a buffer around the 1-meter elevation. This buffer represents a spatial projection of the area of uncertainty associated with the 1-meter elevation (the 95% confidence interval, or 1 m ± 0.45 m). The blue tint covers the area between the MHW shoreline and the 1-meter elevation. The background is an orthoimage.

is ±0.45 meters. To model a 1-meter sea level rise, the LE95 value is applied (added and subtracted) to delineate the high and low extents of the zone of uncertainty. Applying Equation 5, the minimum sea-level rise increment that should be modeled is 0.90 meters, so this lidar elevation dataset is acceptable for assessing the potential effects of a 1-meter sea-level rise.

In Figure 2, the orange line is the mean high water (MHW) shoreline. The black line is the 1-meter contour (above MHW), and the brown lines and cross-hatch patterns delineate a buffer around the 1-meter elevation. This buffer represents a spatial projection of the area of uncertainty associated with the 1-meter elevation (the 95% confidence interval, or 1 m ± 0.45 m). The blue tint covers the area between the MHW shoreline and the 1-meter elevation. Note how the area of 1-meter or less in elevation is relatively broad on the back-barrier side of the island where marsh land cover is prevalent, but on the ocean side of the island the area between the MHW shoreline and 1-meter elevation is thin on the relatively steep beach face. To calculate the land area subject to a 1-meter increase in sea-level, the lower end of the range would be the area between the MHW shoreline and the 0.55 m contour (1 m – 0.45 m), and the upper end of the range would be the area between the MHW shoreline and the 1.45 m contour (1 m + 0.45 m). This range accounts for the vertical uncertainty in the elevation data, and the reported areas are expressed with a 95% confidence level.

Assateague Island provides a useful example of a site where simple inundation might not be the primary response to a rising sea-level. The response of a coastal region to sea-level rise can be characterized by one or more physical processes, including land loss by inundation, land loss due to erosion, wetland accretion and migration, conversion of wetland to open water, and saltwater intrusion (FitzGerald et al., 2008; Leatherman, 2001; Valiela, 2006). Barrier islands, in particular, may migrate or break up in response to sea-level rise. The specific response of a stretch of the coast to sea-level rise can be dependent on the collective influence of a number of local factors such as framework geology, sediment supply, and wave energy (Gutierrez et al., 2007). Elevation-based sea-level rise impact assessments generally delineate vulnerable areas that occur below a specified elevation, but because of the complexity of coastal processes it cannot be assumed that all of the delineated areas will simply become flooded or inundated. The challenge remains to better characterize the specific response to sea-level rise that will be exhibited in specific coastal settings (Gesch et al., 2009). Nonetheless, elevation-based assessments are useful for inventorying the amount of land and other resources that are potentially impacted by sea-level rise, whether it is in the form of simple inundation or another physical process.

3.3 IPCC sea-level rise scenarios

Examination of the concepts of minimum inundation increment and minimum planning timeline using IPCC sea-level rise scenarios helps demonstrate application of the knowledge about the uncertainty inherent in the foundational elevation data used in inundation hazard assessments. The eustatic sea-level rise projected for the end of this century ranges from 0.18 meters to 0.59 meters across the six IPCC scenarios. Applying Equation 6 to determine the vertical RMSE required to reliably map those increments of sea-level rise results in an RMSE of 0.046 meters for the 0.18-meter sea-level rise scenario, and an RMSE of 0.15 meters for the 0.59-meter scenario. Collected under industry standard current best practices, lidar-derived elevation data routinely achieve vertical accuracies on the order of 15 centimeters (RMSE),

thus mapping of the upper end of IPCC sea-level rise projections is quite attainable. However, elevation data with better than a 5-centimeter RMSE would be very difficult to produce cost effectively with current remote sensing approaches, so reliable mapping of the low end of IPCC sea-level rise projections would not be possible with any routinely available elevation sources.

Figure 3 and Table 3 show the 21st century minimum planning timelines associated with three eustatic sea-level rise rates and three qualities of elevation data. The sea-level rise scenarios include the IPCC minimum projected rate (1.8 mm/yr), the IPCC maximum rate (5.9 mm/yr), and for comparison purposes, a rate of twice the IPCC maximum (11.8 mm/yr). This third rate (11.8 mm/yr) would result in nearly 1.2 meters of sea-level rise by the year 2100, a number that is well within the range of eustatic sea-level rise projections published after the most recent IPCC report (Jevrejeva et al., 2010; Pfeffer et al., 2008; Rahmstorf, 2007; Vermeer and Rahmstorf, 2009).
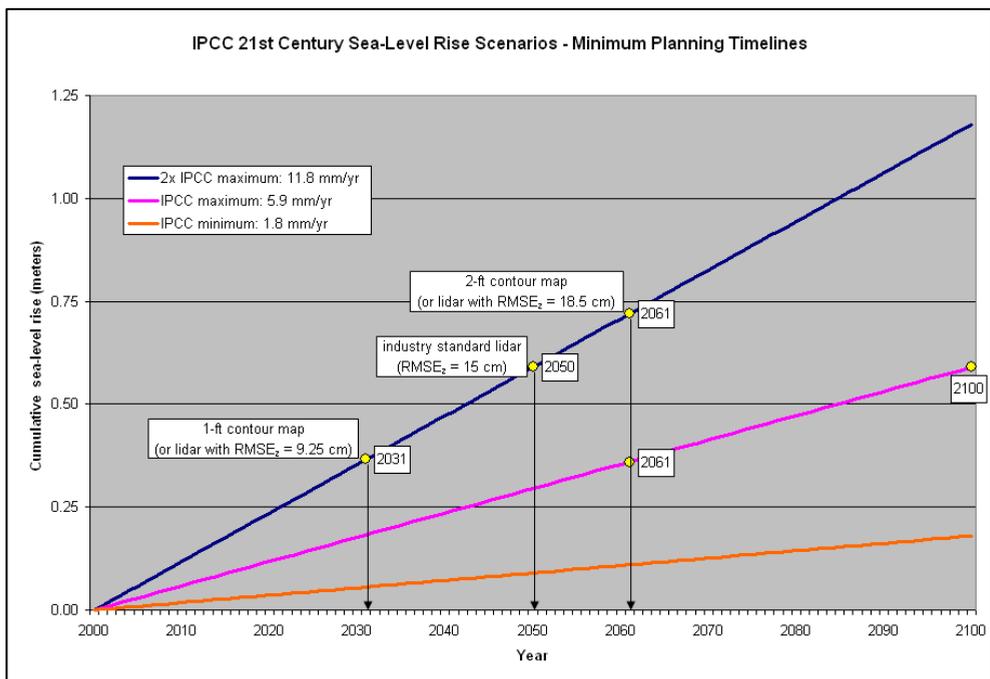

Fig. 3. Sea-level rise rates and the calculated minimum planning timelines given different types of elevation data (and their associated vertical accuracies). The minimum planning timeline is reached when the cumulative sea-level rise matches the minimum sea-level rise increment afforded by the vertical accuracy of the elevation data.

21st century sea-level rise scenario	Elevation data source for sea-level rise assessment		
	1-ft contour map (9.25 cm RMSE lidar)	15 cm RMSE lidar	2-ft contour map (18.5 cm RMSE lidar)
1.8 mm/yr	-	-	-
5.9 mm/yr	61 yrs.	100 yrs.	-
11.8 mm/yr	31 yrs.	50 yrs.	61 yrs.

Table 3. Minimum planning timelines derived from combinations of sea-level rise scenarios and accuracies of elevation datasets used for inundation modeling. Some combinations of sea-level rise rates and elevation data accuracies do not support planning timelines less than or equal to 100 years (indicated by the dashes); in other words, the cumulative sea-level rise does not reach the minimum increment for inundation modeling until after 100 years.

For a given sea-level rise rate, the minimum planning timeline is reached when the cumulative sea-level rise matches the minimum sea-level rise increment afforded by the vertical accuracy of the elevation data. For example, given an annual sea-level rise rate of 11.8 mm/yr and an elevation dataset with a vertical RMSE of 15 centimeters, the cumulative sea-level rise matches the minimum sea-level rise increment of 58.8 centimeters in 50 years, which represents the minimum timeline that should be used in the assessment. Note that when the same elevation data are applied in a study that uses a lower sea-level rise rate of 5.9 mm/yr, the minimum planning timeline extends to 100 years. In other words, in a study making use of 15-centimeter RMSE elevation data and the maximum IPCC sea-level rise scenario, no results should be presented for time slices less than 100 years. This constraint is also noted in Table 3 where planning timelines less than or equal to 100 years are not supported by some of the combinations of sea-level rise rates and elevation data accuracies. This does not imply that a specific type of elevation data should not be used in an analysis with lower sea-level rise rates but cautions that the supported timeline may be longer than the time interval of interest to planners.

4. Discussion

As has been demonstrated, the vertical uncertainty contributed by the foundational elevation data in elevation-based hazard assessments should be accounted for and documented quantitatively to improve the reliability of maps, statistical summaries, and other project findings. Although a primary source of uncertainty in inundation hazard assessments, elevation data are not the only source of error. For coastal inundation studies, especially sea-level rise assessments, uncertainty is also associated with the water level data (from long-term tide gages), the mathematically modeled tidal datums to which water levels are referenced vertically, and sea-level trends or projections (which often result from coupled climate models). For a complete picture of the total error budget, the uncertainty contributed by these other sources (besides the elevation data) should also be considered (National Ocean Service, 2010).

There are several options for accounting for elevation uncertainty in inundation assessments. The first, which has unfortunately been the case with many studies, is to ignore it. Some studies mention uncertainty in a very general way but don't quantify it. A second option, discussed at length in this paper, is to apply a global error estimate (RMSE or LE95) as a reflection of the vertical uncertainty. This approach tends toward a worse case scenario as it assumes the full magnitude of errors can occur throughout the study site. A third option is to model the spatial distribution of error and then perform error propagation through simulation (Wechsler and Kroll, 2006). The advantage of such an approach is that it can account for spatial autocorrelation in the errors. Application of spatial error modeling to elevation-based hazard assessments is viewed as a fruitful area for further research.

The concepts of minimum sea-level rise (or inundation) increment and minimum planning timeline have relevance for management use by planners and other land and resource managers. These methods can be used to answer questions posed by managers:

- "To model potential impacts of x cm of sea-level rise, what vertical accuracy (RMSE) do I need from the elevation data?" A common use of such a question might be when a municipality has modeled predictions of storm surge magnitudes and extents and managers want to know how those predictions will change if a storm surge is superimposed on top of future sea-level rise.
- "I have elevation data with an accuracy (RMSE) of x cm. What sea-level rise increment can I correctly model?"
- "I need to plan for x cm of sea-level rise by the year 2xxx. What accuracy (RMSE) do I need for elevation data to map the potential impact zone at 95% confidence?"
- "The harbor master for our city port facilities is interested in finding out what infrastructure might be at risk if local mean sea level rises by 50 centimeters over the next 30 years. The city is contracting for acquisition of new elevation data to support this study. What accuracy level should I include in the contract specification?"

The methods described here will allow each of these questions to be answered with proper consideration of elevation uncertainty, which will in turn lead to more reliable and defensible project results.

5. Conclusion

Elevation-based coastal inundation assessments should account for the vertical uncertainty of the base elevation data. The use of elevation data for inundation impact assessments is commonplace, but most published studies have not accounted for vertical uncertainty in a quantitative manner. Maps of potential impact zones, and statistical summaries of natural and anthropogenic resources within the impact zone, should carry an obvious expression of the uncertainties associated with the findings. For maps, this can take the form of symbology on the map itself that spatially portrays the areal uncertainty associated with a delineation, or a caveat in the map margin. For statistical summaries, ranges of variables should be reported along with a specific confidence level for the estimates. The choice of parameters for the study, especially the increment(s) of inundation to be modeled and the

time interval for analysis, should be guided by knowledge of the inherent vertical uncertainty of the base elevation layer used in the study.

Most of the examples discussed in this paper have involved sea-level rise as the coastal inundation process. The shoreline will evolve in response to rising sea-level and will change relatively slowly in comparison with other water-level hazards. Accounting for elevation uncertainty, including delineating areas of uncertainty for potential inundation zones, may be even more important for other types of inundation that happen much faster than sea-level rise, such as tsunami run-up, storm surge, and extreme high tides. A certain level of detail is needed in a DEM that is used to model tsunami and storm surge propagation, but a better level of topographic detail is needed to model the impacts of inundation on the land surface. Increased topographic information content usually brings reduced vertical uncertainty with it, but in any case the uncertainty must be accounted for quantitatively in modeling results.

Assessment of additional types of inundation hazards that can occur away from the coast, including flash floods from extreme precipitation events, debris flows, and lahars, could also benefit from rigorous treatment of elevation uncertainty. A line delineating the edge of a hazard zone – whether from sea-level rise, flooding, tsunami, storm surge, lahar, or any other topographically controlled process – is often portrayed on a map as a definite feature. In reality, the line has a degree of "fuzziness" associated with it, which is a reflection of the inherent vertical uncertainty in the data used to make the delineation. A probability, or corresponding confidence level, can be associated with a location based on how far away from the line it is (Hunter and Goodchild, 1995). Such portrayal of uncertainty adds significantly to the value of the mapped hazard information.

Increasingly, coastal inundation hazard studies are adding consideration of the uncertainty inherent in the input datasets. Future studies will benefit as best practices (National Ocean Service, 2010) are documented and published. Further advances in hazard assessment will be realized as progress is made on improving the physical models (Gallien et al., 2011) used to characterize inundation vulnerability.

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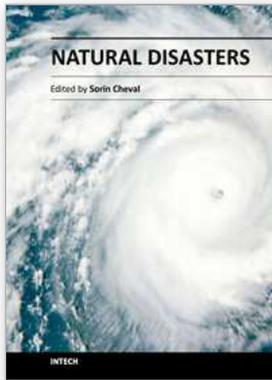
Natural Disasters

Edited by Dr. Sorin Cheval

The crossroads between a more and more populated human communities and their changing environment pose different challenges than ever before. Therefore, any attempt to identify and deliver possible solutions is more than welcome. The book Natural Disasters addresses the needs of various users, interested in a better understanding of hazards and their more efficient management. It is a scientific enterprise tackling a variety of natural hazards potentially deriving into disasters, i.e. tropical storms, avalanches, coastal floods. The case studies presented cover different geographical areas, and they comprise mechanisms for being transferred to other spots and circumstances. Hopefully, the book will be beneficial to those who invest their efforts in building communities resilient to natural disasters.

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