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Author: Gesch, Dean B.

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Analysis of Lidar Elevation Data for Improved Identification and Delineation of Lands Vulnerable to Sea-Level Rise

Dean B. Gesch

U.S. Geological Survey
Earth Resources Observation and Science Center
47914 252nd Street
Sioux Falls, South Dakota 57198
Phone: 605-594-6055
Fax: 605-594-6529
gesch@usgs.gov

ABSTRACT

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The importance of sea-level rise in shaping coastal landscapes is well recognized within the earth science community, but as with many natural hazards, communicating the risks associated with sea-level rise remains a challenge. Topography is a key parameter that influences many of the processes involved in coastal change, and thus, up-to-date, high-resolution, high-accuracy elevation data are required to model the coastal environment. Maps of areas subject to potential inundation have great utility to planners and managers concerned with the effects of sea-level rise. However, most of the maps produced to date are simplistic representations derived from older, coarse elevation data. In the last several years, vast amounts of high quality elevation data derived from lidar have become available. Because of their high vertical accuracy and spatial resolution, these lidar data are an excellent source of up-to-date information from which to improve identification and delineation of vulnerable lands. Four elevation datasets of varying resolution and accuracy were processed to demonstrate that the improved quality of lidar data leads to more precise delineation of coastal lands vulnerable to inundation. A key component of the comparison was to calculate and account for the vertical uncertainty of the elevation datasets. This comparison shows that lidar allows for a much more detailed delineation of the potential inundation zone when compared to other types of elevation models. It also shows how the certainty of the delineation of lands vulnerable to a given sea-level rise scenario is much improved when derived from higher resolution lidar data.

ADDITIONAL INDEX WORDS: *accuracy assessment, digital elevation model, geospatial data, hazards, maps, uncertainty*

INTRODUCTION

One of the most critical scientific issues in the coastal environment today is determining the physical response of coastlines to predicted sea-level rise (Fitzgerald *et al*., 2008; Gutierrez, Williams, and Thieler, 2007; Leatherman, 2001; Leatherman, Zhang, and Douglas, 2000). However, as with many natural hazards, communicating the risks associated with sea-level rise remains a challenge. Part of the challenge may stem from the fact that sea-level rise is a long-term, slowly varying process, and the consequences are often not immediately observable.

To accurately identify and delineate lands in the United States that are vulnerable to eustatic sea-level rise, the underlying coastal processes and the relationships among them must be well understood. Topography is a key parameter that influences many of the processes involved in coastal change; therefore, up-to-date, high-resolution, high-accuracy elevation data are required to model the coastal environment. Maps that locate and describe areas that are subject to the adverse effects of sea-level rise, often called vulnerability maps, have great appeal to planners and managers who are charged with mitigating the risks. However, many of the maps produced to date are simplistic representations derived from coarser elevation data and do not differentiate among the physical processes driving coastal change (Rowley *et al*., 2007; Schneider and Chen, 1980).

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Maps of lands vulnerable to sea-level rise have been produced by numerous researchers based on coastal elevation data (Dasgupta *et al*., 2007; Mazria and Kershner, 2007; Rowley et al., 2007; Titus and Richman, 2001). These types of reports often include estimates of the affected population in the zone of potential inundation (Ericson *et al*., 2006; McGranahan, Balk, and Anderson, 2007; Small and Nicholls, 2003). Despite the use of coarse elevation data, such studies are used to identify at-risk lands and populations. For example, the study by Titus and Richman (2001) is often referred to in discussions of vulnerable land in the United States. They document quite well the method they used to produce the maps. However, because they used very coarse elevation data (derived from U.S. Geological Survey 1:250,000 scale topographic maps), the resulting products are very general and limited in their applicability. Titus and Richman (2001) recognize the limitations of their results and clearly list the caveats for proper use of the maps. Nevertheless, their report is often cited as the definitive study of U.S. coastal vulnerability to date.

The importance of an accurate delineation of vulnerable lands has been recognized by the U.S. Climate Change Science Program (CCSP), which is producing a synthesis and assessment report on coastal elevations and sensitivity to sea-level rise, due to be completed in late 2008 (see U.S. Climate Change Science Program, 2008). In the prospectus for the assessment, the CCSP identifies the four primary factors contributing to the sensitivity of lands to sea-level rise as low elevations, coastal erosion, wetland dynamics, and human modifications. The prospectus asks, "Which lands are currently at an elevation that could lead them to be inundated by the tides without shore protection measures?" The prospectus also asks, "What are the population, economic activity, and total property value within the area potentially inundated, eroded, or subject to increased flooding due to sea-level rise, given alternative levels of shore protection?" Clearly, elevation is only one of a number of interrelated factors that determine the vulnerability of coastal lands to the effects of sea-level rise, but it is a primary one that is easily examined. Delineation of land at or below a given sea-level rise scenario is the necessary first step in any study of the potential effects of a rising sea, and, as demonstrated in the studies cited above, coastal elevation data in the form of digital elevation models (DEMs) are commonly used for such a delineation.

Previous Sea-Level Rise Studies with Elevation Data

A variety of elevation datasets has been used in previous studies to quantify the amount of land and affected population subject to potential inundation from sea-level rise. The scale, or horizontal resolution, of the elevation data ranges from a coarse resolution of about 1 kilometer for global and regional assessments to a fine resolution of a few meters for local studies. In most cases, the uncertainty of the elevation data is not accounted for in a quantitative manner, so the final results may not present a complete picture of potential inundation. For their studies of the global population at risk from coastal hazards, Small and Nicholls (2003) and Ericson *et al*. (2006) used GTOPO30, a global 30 arc-second (about 1 kilometer) DEM produced by the U.S. Geological Survey (USGS) (Gesch, Verdin, and Greenlee, 1999). Rowley *et al*. (2007) used the GLOBE 30 arc-second DEM (Hastings and Dunbar, 1998), which is derived mostly from GTOPO30. GTOPO30 is based on several different source datasets and, as such, has variable absolute vertical accuracy (Gesch, 1998; Harding *et al*., 1999). The reliability of estimates of land area and population at risk as derived from 30 arc-second global DEMs is questionable because of the inherent vertical uncertainty of the elevation data. Potential inundation zones defined by 1 meter vertical increments (Rowley *et al*., 2007) are well within the statistical uncertainty of the elevation model. Small and Nicholls (2003) recognize that the elevation data do have vertical uncertainty, using 5 meters as an estimate. They also conclude that improvement in base datasets, including elevation, is necessary for better global analyses.

Elevation data from the Shuttle Radar Topography Mission (SRTM) (Farr *et al*., 2007) are available at a 3 arc-second (about 90 meter) resolution with near-global coverage. Because of their broad area coverage and improved resolution over GTOPO30, SRTM data have been used in several studies of the land area and population potentially at risk from sea-level rise (Dasgupta *et al*., 2007; McGranahan, Balk, and Anderson, 2007). As with other large area studies, the vertical uncertainty of the elevation data and its effect on the resultant estimates were not addressed in these studies. The 1 meter vertical increments used by Dasgupta *et al*. (2007) to report estimates of affected land area, population, and land cover types are within the statistical uncertainty of the SRTM data.

Lidar (light detection and ranging) elevation data have been used successfully in several sea-level rise studies (Johnson *et al*., 2006; Larsen *et al*., 2004) for sites in Maryland. Slovinsky and Dickson (2006) used very accurate lidar data to map the potential effects of sea-level rise for a location in Maine.

Maps and Visualizations of Sea-Level Rise Impacts

Maps and visualizations, including computer simulations, of the spatial extent of potential sea-level rise are a common method of attempting to communicate the risk to coastal areas. Often the maps are included in assessment reports issued by various non-governmental organizations, universities, state and local agencies, and other private groups. Numerous web sites provide both static and dynamic displays of rising sea level and its impact on the land for scientific and general public audiences. For instance, GTOPO30 and SRTM data are employed to portray potential inundation areas on several sites. Higher resolution data from the USGS National Elevation Dataset (NED) (Gesch, 2007) have also been used to produce maps of potential inundation from sea-level rise (Mazria and Kershner, 2007). None of the assessment reports or web sites address the uncertainty of the elevation data in a quantitative manner, although some offer general caveats about limitations of the data and that the maps are for illustration only and should not be used for detailed planning.

Lidar Elevation Data

In the last several years, vast amounts of high quality elevation data derived from lidar have become available, and they are highly suitable for detailed study of the physical processes related to sea-level rise. Improved understanding of these interrelated physical factors is the key to accurate identification and delineation of vulnerable lands, ultimately resulting in significantly enhanced maps.

The significantly better spatial resolution and vertical accuracy of lidar-derived elevation data provide clear advantages for use in delineating lands subject to a given sea-level rise scenario. Lidar elevation data have been successfully used for flood modeling in low relief areas (Bales *et al*., 2007; Sanders, 2007), and they are well suited for improving identification of coastal lands vulnerable to potential inundation from rising seas. The following analysis includes a quantification of the vertical accuracy of the various DEM datasets that have been used to model potential sea-level rise impacts and a demonstration of how the improved quality of lidar data leads to more precise delineation of vulnerable coastal lands.

METHODS

Data Sources and Study Area

Lidar-derived elevation data, in addition to NED, SRTM, and GTOPO30 data, were processed and analyzed for coastal North Carolina (Figure 1), including the Outer Banks and the Albemarle-Pamlico Sound estuarine system. The study area is contained within the Pasquotank, Chowan, Roanoke, Tar-Pamlico, Neuse, and White Oak river basins. The lidar data were collected as part of a statewide collection by the North Carolina Floodplain Mapping Program (NCFMP) (see State of North Carolina, 2008a). The availability of high quality lidar data over a broad, diverse coastal area provides an excellent opportunity to examine how the resolution and accuracy of elevation datasets affect sea-level rise analysis.

The NCFMP distributes lidar elevation models with horizontal cell sizes of 20 feet (6.1 meters) and 50 feet (15.2 meters). However, the nominal lidar point spacing supports a higher resolution grid, so the original lidar mass points and photogrammetrically compiled breaklines were used to produce an elevation model at a 1/9-arc-second (about 3 meter) grid spacing. This processing was done to prepare the data for integration into the multiresolution NED, which is continually upgraded with newer, high-resolution sources (Gesch, 2007).

NED 1 arc-second (about 30 meter) data (Gesch *et al*., 2002) were included in the analysis because they are commonly used in earth science applications in the United States. When higher resolution source data are integrated into the NED 1/9-arc-second (3 meter) layer, as described above, the newer source data are also used to update the NED 1/3 arc-second (about 10 meter) and 1 arc-second layers, and this was done with the NCFMP lidar data. However, this study used an older version of the 1 arc-second NED layer derived from U.S. Geological Survey 30 meter 7.5 minute quadrangle map-based DEMs. These 30 meter DEMs were produced from 1:24,000 scale contours, spot heights, and mapped hydrography (Osborn *et al*., 2001). The NED 1 arc-second data derived from 30 meter DEMs were compared to lidar-derived 1/9-arc-second NED data because for much of the country the best available source data are still the map-based DEMs. Currently, only about 5% of the conterminous United States is covered by the 1/9-arc-second NED layer derived from lidar and other high-resolution elevation data sources. Much of that coverage is along the coast, and current NED production includes work on several other large coastal lidar data collections.

Because they have been used in numerous sea-level rise studies and are the most widely available global DEMs, GTOPO30 and SRTM have also been included in the analysis over the North Carolina study area. The elevation datasets compared in this study comprise a range grid spacings, horizontal resolutions, and vertical accuracies (Table 1). The methods used to quantify the vertical accuracies are described in detail below.

Vertical Accuracy Assessment

To properly portray the uncertainty in potential inundation levels calculated from elevation data, the absolute vertical accuracy of the data must be known. The absolute vertical accuracy was calculated for of each of the four elevation datasets. The accuracies of the 1 arc-second NED, SRTM, and GTOPO30 data were calculated by comparison with an independent reference set of high-accuracy geodetic control points from the National Geodetic Survey (NGS). The geodetic bench marks include more than 13,000 points distributed throughout the conterminous United States that NGS uses for gravity and geoid modeling (Roman *et al*., 2004; see also Roman, 2003). As such, they provide an excellent independent reference against which elevation data can be assessed over a large area. Located throughout the study area (Figure 1B), 489 control points were used to measure the accuracy of NED (1 arc-second), SRTM, and GTOPO30 data.

The procedure used to determine the vertical root mean square error (RMSE) was the same as that used for accuracy assessment of the entire conterminous U.S. NED, and is documented in Gesch (2007). The RMSE, as described in Maune, Maitra, and McKay (2007), is a commonly used metric to express vertical accuracy of elevation datasets:

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

where $z_{\text{data I}}$ is the vertical coordinate of the I^{th} check point in the elevation dataset, $z_{\text{check I}}$ is the vertical coordinate of the I^{th} check point in the reference dataset, n is the number of points being checked, and I is an integer from 1 to n.

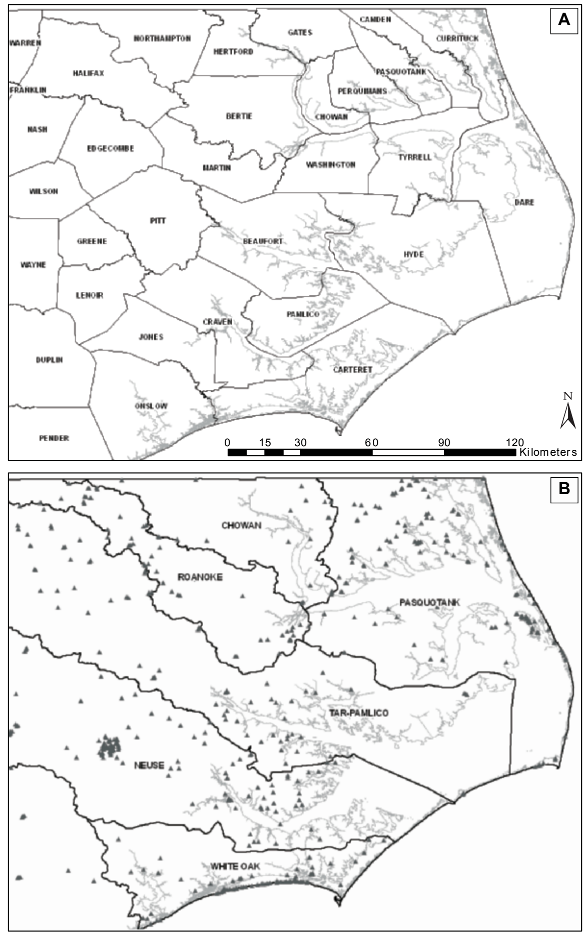

Figure 1. Study area in eastern North Carolina, with (A) counties and (B) river basins identified. The triangles on (B) denote the locations of the reference geodetic bench marks used in the accuracy assessment of the elevation datasets.

In addition to the RMSE for each elevation dataset, the linear error (L.E.) with a 95% confidence level, which is the metric used by the National Standard for Spatial Data Accuracy (NSSDA) (Federal Geographic Data Committee, 1998), was also calculated (Table 1). For NED (1 arc-second), SRTM, and GTOPO30, the methods described in Maune, Maitra, and McKay (2007) were used to convert the measured RMSE to the equivalent NSSDA expression:

$$\text{L.E. at 95\% confidence} = 1.96 * \text{RMSE} \qquad (2)$$

For the 1/9-arc-second NED from the lidar, the vertical accuracy is an average of the RMSE reported by the NCFMP for each of the 21 coastal counties in the study area (see State of North Carolina, 2008b). The lidar data for each county were subject to thorough accuracy assessment and reporting (see Thompson and Maune, 2001, 2004). Because of the comprehensive nature of the county-based lidar accuracy assessments, it was determined that these results are a better representation of the lidar elevation accuracy than could be calculated based on the more sparse NGS control points.

The RMSE of 14 centimeters for the lidar elevation data is at the level of accuracy generally achieved when data are collected and processed with current industry standard practices. The RMSE of 1.27 meters for the 1 arc-second NED is better than the RMSE of 2.44 meters for all of the conterminous NED (Gesch, 2007), which is logical given that the study area is low relief and is mostly covered by topographic maps with a 5 foot contour interval. Assuming that the maps meet National Map Accuracy Standards (NMAS), the best accuracy that could be expected is 46.3 centimeters RMSE (Maune, Maitra, and McKay, 2007). That level of accuracy would be retained in a DEM made from the topographic map only if the contour-to-grid, analog-to-digital conversion did not introduce any vertical error. Some loss of spatial detail and vertical accuracy is inevitable as a 30 meter grid spacing DEM is derived from 1:24,000 scale hypsography.

The measured RMSE of 3.13 meters for the SRTM 3 arc-second data is better than the product specification of 9.73 meters RMSE (Farr *et al*., 2007), most likely due to the low relief of the study area. Because the SRTM employed an imaging radar system, users of the data should note that the elevations represent the height of the "first reflective surface," which is the first surface the radar signal encountered. In open terrain, the SRTM elevation will be ground level, but in vegetated and built-up areas, the SRTM elevations will be above ground level. This characteristic of SRTM data has been well documented (Carabajal and Harding, 2006; Hofton *et al*., 2006). The mix of bare ground and non-bare ground elevations in SRTM data could be especially problematic for inundation mapping in forested or built-up coastal areas.

The measured RMSE of 3.83 meters for GTOPO30 is better than would be expected given the global assessments of the dataset that have been done previously (Gesch, 1998; Harding *et al*., 1999). The source data for the U.S. portion of GTOPO30 was better quality than for other areas (Gesch, 1998), which is most likely the reason for the relatively good accuracy exhibited by GTOPO30 over the study area. The main constraint, however, for use of GTOPO30 for the generation of maps of potential inundation from sea-level rise is the coarse spatial resolution.

Application of Vertical Accuracy as a Measure of Uncertainty

The uncertainty of elevation data affects the delineation of coastal elevation zones (Figure 2). In this example, a hypothetical sea-level rise of 1 meter is to be mapped onto the land surface, and two elevation datasets are available for map production. On a topographic profile diagram (Figure 2), two elevation datasets with differing vertical accuracies can be shown with error bars around the 1 meter elevation. One dataset has an L.E. of ±0.3 meters at a 95% confidence level, while the other has an L.E. of ±2.2 meters at a 95% confidence level. By adding the L.E. 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. As illustrated (Figure 2), the additional area representing the elevation uncertainty is much smaller for the more accurate elevation data.

Maps of Potential Inundation Areas

For the examples in this study, a 1 meter sea-level rise was used to produce maps of potential inundation areas. This amount of rise is somewhat larger than the range of modeled projections for the end of the 21st century as reported by the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) (Meehl *et al*., 2007), although the assessment does not include the full effects of possible changes in ice sheets (see IPCC, 2008). Also, for reasons cited below, delineating elevation zones on some of the elevation datasets requires use of at least 1 meter. Calculation of the potential inundation zones was accomplished with an approach similar to those used in other studies (Mazria and Kershner, 2007; Poulter and Halpin, 2007; Rowley *et al*., 2007) in which raster elevation data are "flooded" by identifying the land cells that have an elevation at or below a given sea-level rise scenario and are connected hydrologically to the ocean. As Poulter and Halpin (2007) point out, many previous studies of sea-level rise impact use a simple "bathtub" approach wherein a grid cell is inundated if its elevation is less than or equal to the projected sea level. Such an approach does not consider the hydrological connectivity to the nearby ocean grid cells. An alternative approach is to identify only those cells that are at or below the projected sea level and are connected to the ocean through a continuous path of adjacent inundated cells. Such connectivity of neighboring cells may be defined by being adjacent to an ocean or inundated cell on one or more of the four cardinal directions (4 way connectivity) or by being adjacent on one or more of the cardinal or diagonal directions (8 way connectivity). Poulter and Halpin (2007) thoroughly document the interaction between the connectivity rule used and the spatial resolution of the elevation dataset for sea-level rise modeling. For this study, 8 way connectivity was used because the desire for the maps was to show the maximum potential area of inundation given a specific sea-level rise and the accuracies of the input elevation datasets. A final step in computing potential inundation zones was to remove inland water bodies that became "connected" to the ocean by the inundation algorithm, similar to the procedure used in some previous studies (Dasgupta *et al*., 2007; Rowley *et al*., 2007).

For each of the four elevation datasets, maps of potential inundation zones given a 1 meter sea-level rise were produced by

Table 1. *Characteristics of the elevation datasets analyzed in this study.*

			Absolute Vertical Accuracy over NC Study Area	
Elevation Data	Grid Spacing	Approximate Resolution	RMSE (meters)	L.E. at 95% Confidence (meters)
GTOPO30	30 arc-seconds	1 kilometer	3.83	±7.51
SRTM	3 arc-seconds	90 meters	3.13	±6.13
NED(DEM source)	1 arc-second	30 meters	1.27	±2.21
NED (lidar source)	1/9 arc-second	3 meters	0.14	±0.27

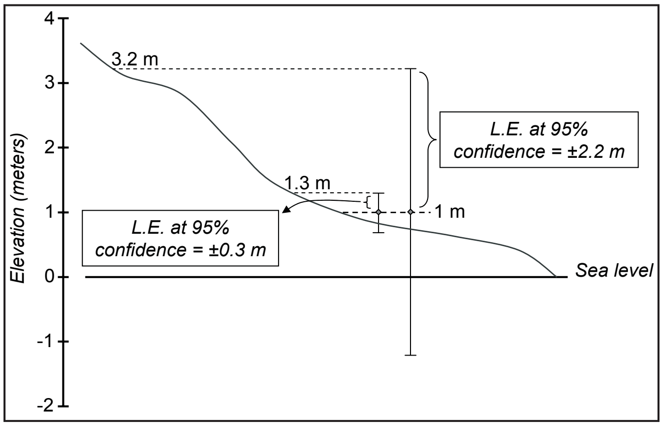

Figure 2. Diagram of how a hypothetical 1 meter sea-level rise is mapped onto the land surface using two elevation models with differing vertical accuracies. The more accurate elevation model results in a delineation of the inundation zone with much less uncertainty than when the less accurate elevation model is used.

extracting the area from the DEM at or below that elevation (using the algorithm described above) and overlaying it on a background image (Figure 3). These areas are depicted in the darker-blue tint on the accompanying maps (Figure 3). For each dataset, additional areas were delineated to show a spatial representation of the uncertainty of the projected inundation area. This delineation was accomplished by adding the L.E. at 95% confidence (Table 1) to the 1 meter sea-level increase and extracting the area from the DEM at or below that elevation using the same flooding algorithm as before. These additional areas are shown in the lighter-blue tint on the maps (Figure 3). The delineation that includes the elevation uncertainty (lighter-blue tint) will always cover more area than the delineation without (darker-blue tint), but the areas are coincident up to the 1 meter contour.

Land Cover and Population Impacts

Two other geospatial datasets were intersected with the delineated inundation zones from two of the elevation datasets to demonstrate the effects of elevation uncertainty on estimates of impacted land cover types and population. Such an overlay operation has been done in many previous sea-level rise studies to help characterize the impacts of potential sea-level rise (Dasgupta *et al*., 2007; Ericson *et al*., 2006; McGranahan, Balk, and Anderson, 2007; Rowley *et al*., 2007). For this study, the USGS National Land Cover Dataset (NLCD) (Vogelmann *et al*., 2001) and the LandScan global gridded population dataset (Dobson *et al*., 2000) were used in the analysis.

RESULTS

Vulnerability Maps and Area Statistics

In addition to maps of vulnerable lands, most studies examining the impacts of sea-level rise also report the total area of the inundation zone. The area of inundation from a 1 meter sea-level rise was calculated from the four elevation datasets, including error effects (Table 2). As the vertical accuracy of the elevation model increases, the difference between the area below 1 meter in elevation and the area below 1 meter plus the uncertainty (L.E. at 95% confidence) decreases. On the vulnerability maps, this decrease in uncertainty is reflected in the decreased area of the lighter-blue tint. If the input elevation data had no vertical uncertainty, there would be no lighter-blue tint on the map. In reality there will always be uncertainty associated with the elevation data, but these results demonstrate that the use of highly accurate lidar data improves the delineation of inundation zone. In this case, the lidar-based delineation is greater by only 14% (at the 95% confidence level) when the accuracy of the elevation model is considered. For the delineations from the GTOPO30 and 1 arc-second NED data, the inundated area more than doubles when the elevation uncertainty is considered, which calls into question the reliability of any conclusions drawn from delineations based on those datasets.

The results for SRTM data show a very large discrepancy between the inundated areas delineated with and without consideration of elevation uncertainty (Table 2 and Figure 3B). Close examination of the SRTM 3 arc-second elevation model shows that many nearshore inland grid cells with an elevation of zero are identified by the inundation algorithm as having hydrological connectivity to the ocean when a sea-level rise of 1 meter is applied. By definition, the algorithm does not select cells with an elevation of zero because they are already at sea level; therefore, these cells are not included as part of the inundation zone. Inspection of the 1/9-arc-second NED elevations for the corresponding locations of these cells indicates that most of the areas have an elevation between zero and 1 meter as measured by the lidar. SRTM data are quantized only to whole meter levels, so it appears that many of these locations with very low submeter elevations have been mapped to zero in the SRTM data. The result is that SRTM significantly underestimates the area vulnerable to a 1 meter sea-level rise when compared to other elevation datasets of this study area. While GTOPO30 does not exhibit the same conditions with zero elevations as SRTM, its elevation values also are quantized only to the nearest whole meter, which limits its usefulness for coastal inundation mapping (Rowley *et al*., 2007).

Maps of some subsets of the study area at a larger scale (Figure 4) were developed to emphasize the difference between two of the elevation sources, namely the 1 arc-second NED (derived from USGS 30 meter DEMs) versus the 1/9-arc-second NED (derived from lidar). The delineations differ not only because of the increased spatial resolution of the lidar data (Figure 5) but also because of the better vertical accuracy of the lidar, which is reflected in the much smaller area of uncertainty (the lighter blue tint). Most of the topographic quadrangle maps from which the 30 meter DEMs are derived have a 5 foot (1.5 meter) contour interval in low relief coastal areas. The maps were compiled to NMAS, so elevations represented on the map should be accurate to within 90.8 centimeters at the 95% confidence level (Maune, Maitra, and McKay, 2007). Thus, the level of uncertainty inherent in the source map, even without any additional error contributed by the DEM generation process, is nearly the amount of sea-level rise (1 meter) that is modeled in many studies. Lidar elevation models with accuracies quantified in the 25 centimeter range (at 95% confidence) are much more appropriate for identification of areas vulnerable to sea-level rise in the meter range.

Land Cover Impacts

To demonstrate the effects of elevation uncertainty on areal

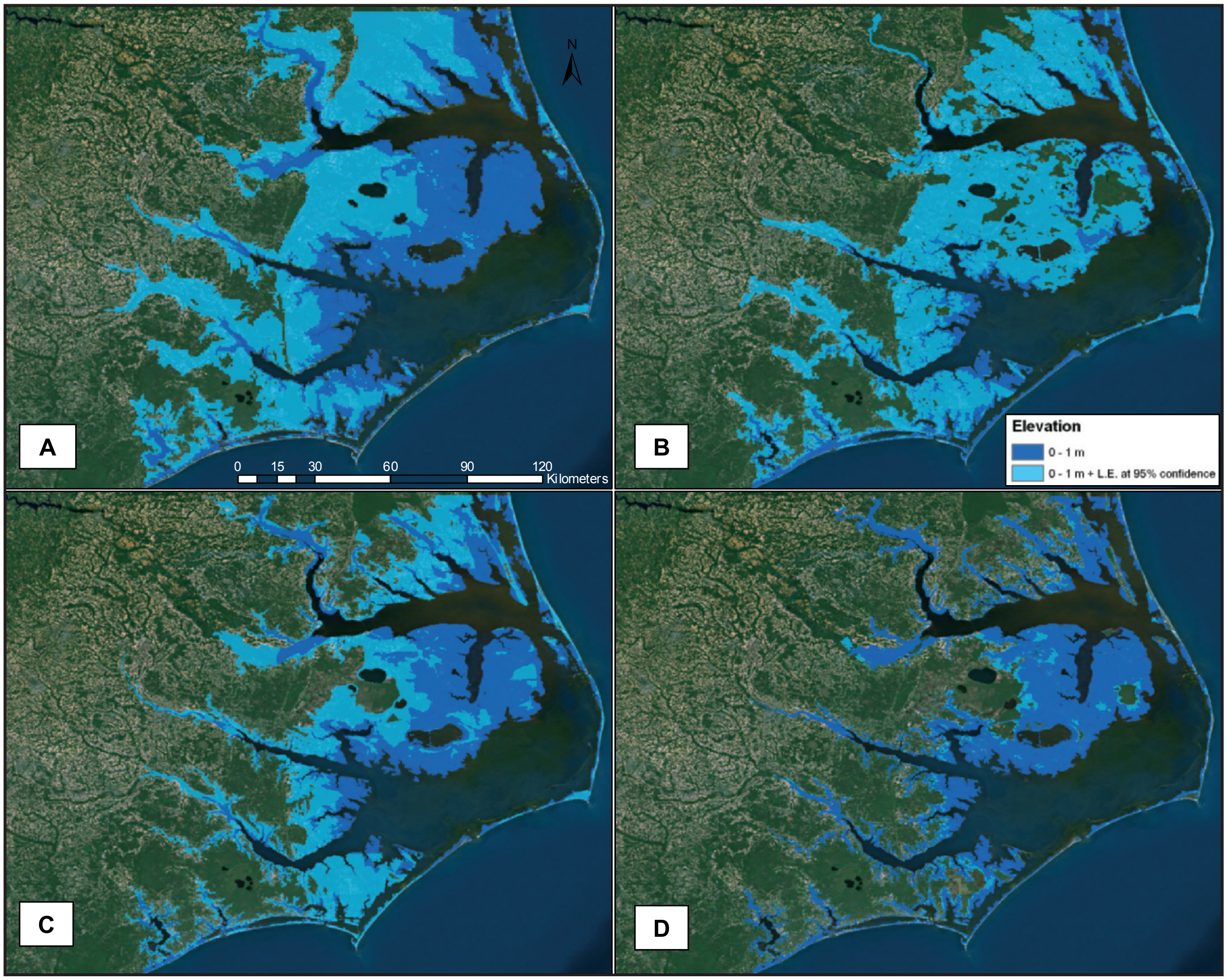

Figure 3. Maps of lands vulnerable to a 1 meter sea-level rise, derived from (A) GTOPO30, (B) SRTM data, (C) 1 arc-second NED (USGS 30 meter DEM source), and (D) 1/9 arc-second NED (lidar source). The background is a recent true color orthoimage. The darker blue shows potential inundation zones, and the lighter blue represents the area of uncertainty associated with the delineations.

estimates of land cover types impacted by potential inundation, the NLCD was intersected with the inundation zone delineations from the 1 arc-second NED. The NLCD was produced at a 30 meter spatial resolution, which is compatible with the resolution of the 1 arc-second NED. When the vertical uncertainty of the elevation data is considered, there is a large difference in the area delineated as being subject to a 1 meter rise in sea level compared to the area delineated without consideration of the uncertainty (Table 2 and Figure 3C). Such a discrepancy will clearly lead to differences in the estimates of impacted land cover, especially the affected area of critical wetland habitat (Table 3). The estimated area of impacted wetlands is larger by more than 50% when the uncertainty of the elevation data is included. Also, the portion of the vulnerable area covered by a specific land cover type changes considerably between the two delineations. Incorporating elevation uncertainty results in the inclusion of more non-wetland areas in the vulnerable category. Land planners and resource managers responsible for mitigating the effects of potential sea-level rise require estimates of impacted cover types to be as accurate as possible, thus pointing to the need for highly accurate elevation data to model sea-level inundation zones.

Population Impacts

As a demonstration of the effects of elevation uncertainty on estimates of population within areas potentially inundated by a 1 meter sea-level rise, the LandScan gridded population database was intersected with inundation zone delineations from GTOPO30. The LandScan dataset has the same 30 arc-second spatial resolution as GTOPO30, and it has been used in several studies to provide population estimates in impacted areas (Ericson *et al*., 2006; Rowley *et al*., 2007). There is a significant difference in the size

Table 2. *The area of potential inundation from a 1 meter sea-level rise as calculated from four elevation datasets, as well as the area of inundation when the uncertainty of the elevation data is considered.*

Elevation Data	Area ≤ 1 Meter in Elevation (sq. kilometers)	Area ≤ 1 Meter in Elevation at 95% Confidence (sq. kilometers)	% Increase in Vulnerable Area when Elevation Uncertainty is Included
GTOPO30	6,205.34	14,986.46	141.51%
SRTM	469.65	6,859.75	1360.62%
NED (DEM source)	4,014.03	8,577.87	113.70%
NED (lidar source)	4,195.26	4,783.17	14.01%

of the inundated area when the elevation accuracy of GTOPO30 is considered (Table 2 and Figure 3A). When these different size areas from the two delineations are overlaid with the population data, the estimates of affected population differ greatly. When the elevation uncertainty is not factored in, 102,503 people are estimated to be in the inundation zone. However, when the elevation uncertainty is included, 457,799 people are estimated to be in the inundation zone. This large discrepancy points out the severe limitations of any conclusions that might be drawn from the initial estimate that does not consider the uncertainty of the elevation data.

DISCUSSION

Need for High Quality Coastal Elevation Information

Numerous factors contribute to the degree of vulnerability of coastal lands to the effects of sea-level rise, including framework geologic setting, tidal and wave dynamics, subsidence (or uplift), and human activities. Topography is a key parameter that influences many of the physical processes active along the coast, and the measurement and representation of coastal topography in the form of digital elevation models provide important data to address critical issues such as sea-level rise. Depending on the interrelated physical factors, the response of a particular section of the coast to sea-level rise may be simple inundation, or it may be a more complex response that could include erosion, shoreline retreat, wetland accretion, or dune migration. No matter what the specific response to sea-level rise, the geomorphic setting, which is expressed in elevation and terrain characteristics, is a primary variable that helps determine the vulnerability of coastal landscapes. In regions that will have a simple inundation response to rising seas, elevation is the most important factor in assessing potential impacts. Thus, coastal elevation data have been widely used to quantify the potential effects of predicted sea-level rise, especially the area of land that could be inundated and the associated, affected population. As has been illustrated, the quality and characteristics of the elevation data used for such assessments greatly affect the reliability of the results.

Advantages of Lidar Elevation Data

Because coastal elevation is such an important parameter in sea-level rise impact studies, it must be known precisely, and the data used to model elevations in the analyses must support the accurate delineation of elevation zones that correspond to specific sea-level rise scenarios. Accurate delineations are especially important if the potential inundation area is used as a mask to generate estimates of affected population, land cover types, infrastructure, or economic activity. Recent collections of high-resolution, high-accuracy lidar data provide the requisite quality in coastal elevation data for sea-level rise impact studies. The lidar-derived elevation data provide a significant improvement over elevation datasets previously used in global and regional sea-level rise assessments.

When the vertical accuracy of coarser elevation datasets like GTOPO30 and SRTM is considered, the delineation of potential inundation areas becomes very large and uncertain in comparison to areas delineated from lidar elevation models. Perhaps the best use of the coarser elevation datasets like GTOPO30 and SRTM is to portray a more general outline of low elevation coastal zones, but because of their limited vertical accuracy and integer meter quantization, their use in development of detailed inundation maps and impact assessments for sea-level rise of a few meters or less is severely limited. If coarser, less accurate elevation data are used for impact assessments, then a range of values for inundated area and affected population should be reported based on the spatial projection of the inherent vertical uncertainty of the elevation data. Even the use of medium-resolution, medium-accuracy elevation data, like the 1 arc-second NED derived from map-based standard USGS DEMs, is questionable if the goal is to produce highly accurate maps of potential inundation zones from a 1 meter rise in sea level. A rise of such magnitude is slightly above the range of the current estimates reported by the IPCC, so the level of potential rising seas for which mitigation and management plans must be made for the remainder of this century demands that analyses be based on data such as lidar that can support submeter levels of accuracy and precision.

Spatially Explicit Vulnerability Maps

When highly detailed and accurate lidar elevation data form the basis for sea-level rise analysis, then useful spatially explicit maps of vulnerability can be produced. For instance, inundation delineations over the city of Washington along the Pamlico River in Beaufort County, North Carolina were compared (Figure 4), including delineation from 1 arc-second NED (30 meter DEM source) (Figure 4C) and from 1/9-arc-second NED (lidar source) (Figure 4D). When the uncertainty of the 1 arc-second NED is included (Figure 4C), the delineation of potential sea-level rise covers a large portion of the urban area, whereas the delineation from 1/9-arc-second NED (Figure 4D) shows that only areas within the natural drains flowing into the Pamlico River and wetlands along the river are in the 1 meter inundation zone. If city planners only had access to the less accurate 30 meter DEM data for sea-level rise analysis, much different conclusions would be drawn than if the lidar data were used for the analysis. The lidar-derived map is

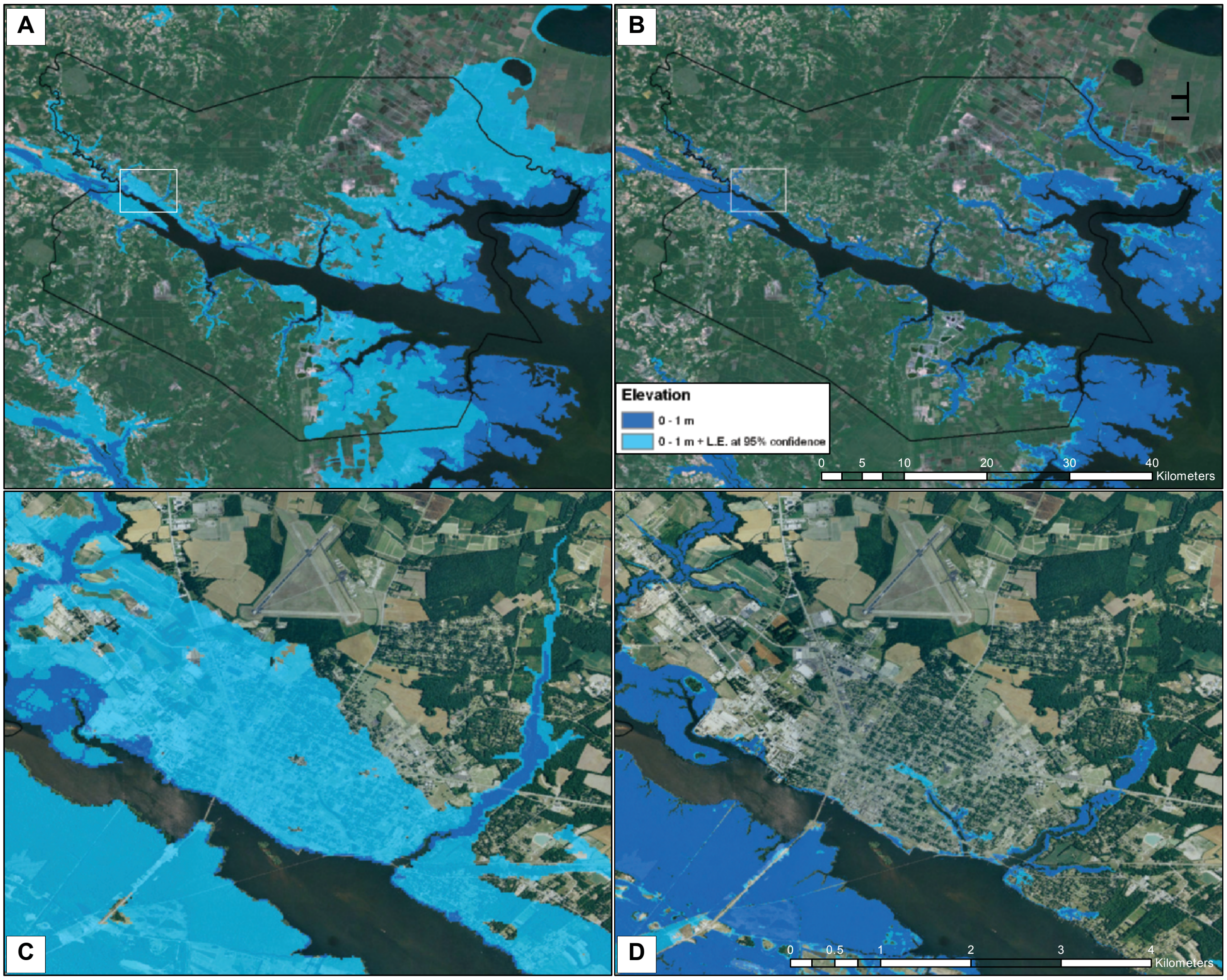

Figure 4. Maps of lands vulnerable to a 1 meter sea-level rise. (A) and (B) cover Beaufort County, North Carolina. (C) and (D) are detailed images of the city of Washington (area within the white box on B). (A) and (C) are derived from 1 arc-second NED (30 meter DEM source). (B) and (D) are derived from 1/9 arc-second NED (lidar source).

a more detailed delineation, and map users can be certain that it is an accurate delineation of the 1 meter inundation zone.

The increased spatial detail of lidar elevation data, as well as its improved vertical accuracy, provides enhanced topographic information that is advantageous to sea-level rise impact studies. The North Carolina lidar collection includes fine-scale features such as drainage ditches and dikes that often are not represented in coarser resolution DEMs. Such features are important for modeling the propagation of rising water levels onto the coastal landscape (Poulter and Halpin, 2007). The presence of such detail in the lidar elevation data allows not only accurate mapping of zones below a given future sea level but also examination of hydrological paths that continually rising water will traverse as inundation advances.

CONCLUSIONS

The requirement for using better data for improved assessments of sea-level rise impacts has been recognized and documented (Marbaix and Nicholls, 2007; Poulter and Halpin, 2007; Small and Nicholls, 2003). As demonstrated here, the increasing availability of high quality lidar in coastal areas will allow for improved assessments to be done over more areas. As more lidar data become available, they are integrated into national datasets such as the NED (Gesch, 2007) to provide improved elevation information for critical applications like sea-level rise modeling. The geospatial data user community has recognized the usefulness of lidar remote sensing as a means to provide highly detailed and accurate data for numerous applications, and there is significant interest in developing an initiative for a national lidar collection for the United States (Stoker *et al*., 2007; Stoker, Harding, and Parrish, 2008). If such an initiative is successful, then a truly national assessment of potential sea-level rise impacts in the United States could be realized.

In the near future, research should continue using lidar elevation data for improved sea-level rise impact studies. Detailed characterization of lidar elevation datasets and quantification of the effects of processing algorithms for sea-level rise modeling, as that documented by Poulter and Halpin (2007), will advance the

Table 3. *Comparison of areas of land cover types within potential inundation zones delineated with and without consideration of elevation uncertainty.*

Elevation Delineation from NED (DEM source)	Wetlands in Vulnerable Area (sq. kilometers)	Percent of Vulnerable Area Total		
		Forest	Agriculture	Wetlands
≤ 1 meter	3,071.09	11.19%	11.54%	74.95%
≤ 1 meter at 95% confidence	4,702.92	17.41%	25.51%	53.75%

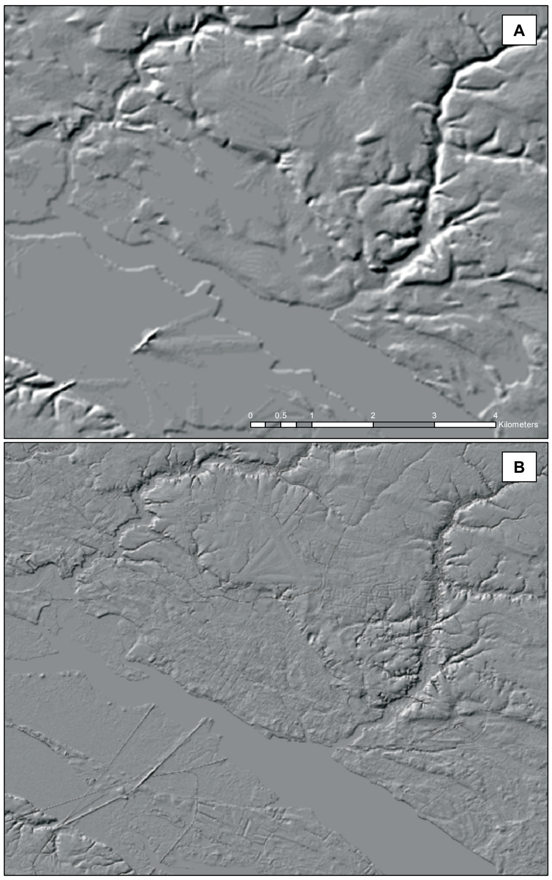

Figure 5. Comparison of the spatial resolution of (A) 1-arc-second NED (30 meter DEM source) versus (B) 1/9-arc-second NED (lidar source). The area portrayed is the same area as seen in Figure 4 (C) and (D).

science of vulnerability mapping and impact assessment. Because lidar elevation data have significantly improved vertical accuracy, inundation maps derived from them can benefit from incorporating knowledge of the differences between local mean sea level and the zero mark of the vertical datum (usually the North American Vertical Datum of 1988). Local sea-level rise trends should be included in analyses to add a time element of inundation patterns to impact assessments (Poulter and Halpin, 2007). In future assessments, use of more detailed and up-to-date data on population distribution and corresponding trends, land cover, infrastructure, and economic activity within potential inundation zones will lead to more useful and reliable information for planners and land managers. All of these advances are important for addressing the environmental and societal problem of sea-level rise that has garnered increasing attention from both the scientific community and the general public.

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