Developing a Framework for Assessing Coastal Vulnerability to Sea Level Rise in Southern New England, USA

Ben Gilmer and Zach Ferdaña

Abstract Scientists predict that sea level rise will intensify wetland loss, saltwater intrusion, and the problems caused by waves, storm surges, and shoreline erosion (Nicholls et al., Trans R Soc 369:161–181, 2011). The ability to accurately identify low-lying lands is critical for assessing the vulnerability of coastal regions. To do this, coastal managers need elevation data and other coastal zone information, but these data are not always available at resolutions appropriate for making state and regional governance decisions on climate change and adaptation. Coastal Resilience (Ferdaña et al., Adapting to climate change: building interactive decision support to meet management objectives for coastal conservation and hazard mitigation on long island, New York, USA. In: Andrade Pérez A, Herrera Fernandez B, Cazzolla Gatti R (eds) Building resilience to climate change: ecosystem-based adaptation and lessons from the field. IUCN, Gland, 164 pp, 2010) is an ecosystem-based planning framework and web mapping application that visually displays ecological, socio-economic, and coastal hazards information to examine different adaptation solutions. This technical study highlights the limitations and opportunities of mapping sea level rise in Southern New England, USA, in order to evaluate coastal vulnerability and therefore appropriate adaptation strategies. We compared the accuracy of digital elevation data between a nationwide data set with a seamless, multi-state data set that incorporated local high-resolution data. Based on an independent accuracy assessment, the integrated elevation data approach using local- and regional-scale data was 55% (or 1.25 ft) more accurate than the national elevation data set alone. Results of this work indicate that regional elevation data sets are less accurate in determining different sea level rise scenarios than when integrating best-available local elevation data sets with regional data sets. With this approach, we can better assess the impacts of climate change to vulnerable low-lying

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B. Gilmer (✉) • Z. Ferdaña
The Nature Conservancy, 1917 1st Ave, Seattle, WA 98101, USA
e-mail: bgilmer@tnc.org; zferdana@tnc.org

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lands and help communities identify adaptation plans that protect vulnerable coastal communities and ecosystems, allow for natural resource migration, and reduce socio-economic risk to coastal hazards.

Keywords Adaptation • Digital elevation model • Resilience • Sea level rise • Vulnerability • Climate change • Ecosystem-based adaptation

1 Introduction

Coastal environments contain some of the most dynamic ecosystems in the world, and obtaining and integrating the most up-to-date and accurate digital elevation data continue to be a fundamental challenge for coastal resource managers. As sea level rise (SLR) is predicted to intensify problems caused by waves, storm surge, shoreline erosion, wetland loss, and saltwater intrusion, the ability to accurately identify low-lying lands is a critical factor for assessing the vulnerability of coastal regions (Gesch et al. 2009). Projections of sea level rise over the course of the twenty-first century vary depending on factors such as the type of model used, future emissions scenarios, polar ice sheet melting, and local effects such as land subsidence (Nicholls et al. 2011). The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment projected a rise of 0.2–0.6 m by the year 2100 unless greenhouse gas emissions are reduced substantially (IPCC 2008), though more recent studies have projected sea levels to rise by 1 m by 2100 (Pfeffer et al. 2008; Vermeer and Rahmstorf 2009). Other studies (Hu et al. 2009; Yin et al. 2009) modelling ocean currents in response to climate change predict that the Northwest Atlantic will experience even higher sea levels than the global average because of anticipated slowdowns of ocean currents in response to global warming.

Coastal Resilience (TNC 2011) is an ecosystem-based planning framework and web mapping application that visually displays ecological, socio-economic, and coastal hazards information to examine different adaptation solutions. Specifically, the Coastal Resilience project is designed to inform local communities about climate change and how ecosystem-based adaptation (EBA) can help mitigate coastal hazards. EBA includes a range of actions for the management, conservation, and restoration of ecosystems that will help reduce the vulnerability and increase the resilience of coastal communities. Starting on the shores of Long Island in New York, The Nature Conservancy (TNC) has worked with communities to map sea level rise and other coastal hazards alongside natural resources and human communities at risk (Ferdaña et al. 2010). While communities are able to utilize this information to identify potential impacts and adaptation options at a local level, larger-scale assessments on vulnerability are also critical in influencing regional governance processes. Southern New England, extending from Cape Cod, Massachusetts, to Long Island, New York (Fig. 1), faces a number of impacts resulting from SLR, including habitat fragmentation, habitat conversion, complete loss of certain coastal ecosystems and species, and threats to human communities (Weiss et al. in press; Titus et al. 2009). Assessing the vulnerability of natural and human communities

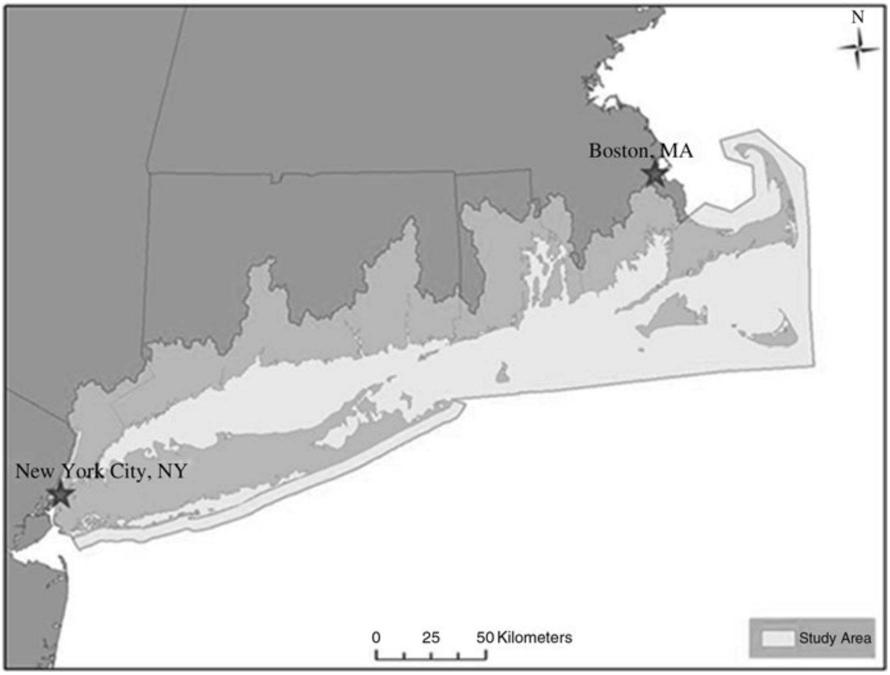

Fig. 1 Study area

from SLR is critical in planning for and adapting to the effects of climate change. To accomplish this, a critical first step is obtaining comprehensive elevation and other coastal zone information. These data, however, are often not available at the resolutions needed to make state and regional governance decisions about climate issues. In the absence of such information, coastal managers may struggle when making required adaptation planning decisions to protect communities and to provide solutions that incorporate both developed and natural infrastructure.

Coastal elevation data have been widely used to quantify the potential effects of SLR; however, the accuracy of the elevation data directly affects the quality and utility of SLR impact assessments (Gesch 2009; Poulter and Halpin 2008; Titus and Wang 2008; Najjar et al. 2000; Kleinosky et al. 2007). Broad-scale (regional and national) delineation of lands vulnerable to SLR using the best-available elevation data often requires integration of state and local data, since the best-available national data set, the National Elevation Dataset (NED; Gesch et al. 2002), does not always include the most up-to-date information. It is especially important to incorporate the most recent elevation data because of the dynamic nature of coastal processes and the rapid pace of development along coastal regions. This is particularly critical in the Southern New England study area, since it contains some of the most highly urbanized estuaries in the USA, such as Long Island Sound, with approximately eight million people living within the watershed (EPA Long Island Sound Study 2007).

The vertical accuracy of the NED has also been found to be inadequate for mapping local, low-level inundation estimates and thus has been deemed unsuitable for local and even regional decision-making (Titus and Wang 2008; Gesch 2009). In the USA, local and state agencies typically collect and maintain the most up-to-date and accurate elevation data, but coastal managers often have trouble effectively integrating these data with federal data due to inconsistent geospatial frameworks such as varying projections, data, and data formats (Gesch and Wilson 2002). Nonetheless, many regional and national studies of coastal environments require seamless topographic data, since hydrologic, demographic, and ecological processes often go beyond the limits of municipal or state boundaries. If forced to choose, many coastal managers have also noted that they favour data consistency over data accuracy for many of their applications (Gesch and Wilson 2002).

The primary purpose of this study is to highlight both the limitations and opportunities of mapping SLR at regional scales across varying elevation data sets to determine whether this information can accurately assess coastal vulnerability to SLR. Previous studies have analysed elevation data in the context of mapping vulnerable coastal areas in the conterminous USA (see review by Gesch et al. 2009), but this study is unique in that it focuses on the challenges and prospects of assessing SLR vulnerability from the perspective of a coastal manager; it is these managers that must make the critical decisions regarding adaptation solutions to climate change. We examined available topographic information consisting of both national- and regional-scale data and assessed the accuracy of disparate elevation data sets. The methodology used in this study was based on previous studies by Gesch (2009) and Gesch and Wilson (2002). Based on our results, we recommend best practices for coastal managers attempting to conduct regional SLR vulnerability assessments in support of climate change adaptation planning efforts. The main objectives of this study were to (1) evaluate potential improvement of a seamless regional elevation data set that was currently available (i.e. the National Elevation Dataset, or NED, from USGS) and compare the mapping of inundation zones using two different approaches to integrating elevation data, and (2) determine achievable SLR projections at which we could accurately and realistically map zones of inundation while spatially illustrating uncertainty. Having the most accurate information possible while accounting for uncertainty gives coastal managers the necessary information to augment their adaptation planning processes with data on climate change.

2 Methods and Results

The process to construct a regional elevation framework to examine coastal vulnerability and adaptation to sea level rise was twofold. First, we evaluated two different integrated elevation data approaches to be used for regional, multi-state SLR inundation mapping. Second, we determined the SLR value to map that was appropriate, based on the elevation data accuracy.

Dataset	**Format upon acquisition**	**Vertical accuracy (RMSE)**	**Horizontal resolution**
National Elevation Dataset(NED)	Grid DEM (multiple sources)	244 cm	10 m
CT LiDAR	Grid DEM (LiDAR derived)	68 cm	3 m
MA DEM	Grid DEM (photogrammetrically derived)	150 cm	5 m
NY Suffolk County DEM	Grid DEM (LiDAR derived)	13 cm	1.5 m
NY Westchester County contours	Contour lines (photogrammetrically derived)	60 cm	5 m
RI Contours	Contour lines (photogrammetrically derived)	20 cm	3 m
RI City DEM	Grid DEM (LiDAR derived)	9 cm	1 m

Fig. 2 Elevation data used in study

We gathered existing digital elevation data that included LiDAR (Light Detection and Ranging) and other data sets, such as the NED, where high-resolution LiDAR data were not available, from a range of federal, state, and local government agencies. We integrated multi-scale, multi-source elevation data sets for the purposes of SLR inundation mapping using an innovative method developed by Gesch and Wilson (2002) (Fig. 2).

This method was employed in an attempt to improve the best-available regional seamless elevation data set by integrating the most up-to-date high-resolution local elevation data, where applicable.

Many types of elevation data sets have been used in previous studies to quantify the potential inundation from SLR (see Gesch et al. 2009). Poulter and Halpin (2008) detail the various approaches used to model sea level rise, ranging from the “bathtub fill” approach to inundating lands that are hydrologically connected to the ocean. The bathtub fill approach simply fills low-lying elevation points. Often this method can create erroneous inundated areas that are not connected to the ocean as all areas equal to or below the given SLR interval become inundated, therefore creating “islands” of inundation. The hydrologically connected approach forces coastal inundation to occur only where low-lying elevation is hydrologically connected to the ocean. It is worth noting that Gesch (2009) stated as follows, “[the] development of large-scale spatially explicit maps presents a new set of challenges. At scales useful for local decision-making, the hydrological connectivity of the ocean to vulnerable lands must be mapped and considered”. Though we are in full agreement with this assertion, the time required to adequately condition the DEM to allow for accurate hydrological connectivity was beyond the scope of this project.

We used the bathtub fill approach to identify the most vulnerable lands for a 1-m SLR. It was determined that 1 m was the appropriate SLR interval to map based on the accuracy of the elevation data. In other words, mapping levels smaller than 1 m could not be supported by the data, given the data’s vertical accuracy. Expanding on recent work by Gesch (2009), we mapped a 1-m SLR scenario using new methods to spatially illustrate the uncertainty of SLR inundation maps as determined by the input elevation data’s vertical accuracy.

2.1 Data Integration

We incorporated attainable local and state, high-resolution elevation data into the best currently available seamless multi-state elevation data set, the National Elevation Dataset (NED). Based on an independent accuracy assessment using US Geological Survey benchmarks, the multi-state seamless elevation data approach from multiple sources was 55% (or 1.25 ft) more accurate than the NED alone (Fig. 3).

Although this integrated approach proved to be successful throughout most of the study area, several areas failed to integrate adjacent data sets of contrasting sources and accuracies. Errors were discovered in cases where two data sets of vastly differing accuracies were brought together (Fig. 3). In these areas, we found that although the reported accuracy of the LiDAR data set in question was very high, several errors in the data set had likely occurred during the LiDAR point classification process. Since we acquired this data set from the end user in raster format, and not from the source of the data, we were unable to correct these errors. We therefore suspect that this LiDAR data set compounded the errors when combining it with the much coarser NED. Thorough examination of LiDAR is important here, and one cannot assume that LiDAR is free of errors because it is of high spatial resolution. Careful examination of high-resolution data is also critical to mapping SLR accurately. The blending procedure can create more errors in the integrated DEM than might be found in the NED without integration.

Even with the above-mentioned erroneous area included in the integrated data set, the overall root mean square error (RMSE) of the integrated data set proved to be 55% more accurate than the seamless NED. It is important to note, however, that because data integration errors can be masked by accuracy assessments derived from point benchmark data, as we found in our study, we recommend the use of additional accuracy assessment metrics in combination with the benchmark data.

Specifically, additional metrics should be able to assess the quality of the overall integrated elevation data set and especially the quality of the blending procedure. For example, cross-sectional transects could be placed along the seams of data sets that are to be blended together. The cross-sectional profiles of the topography would allow comparisons to be made between the most accurate data set (i.e. LiDAR) and the integrated DEM (e.g. a mosaic of the LiDAR and the NED). This additional accuracy assessment metric would also be an effective and rule-based way to determine an appropriate transition zone width for the blending procedure.

Following Gesch and Wilson (2002), blending two disparate elevation data sets requires the identification of a "blending zone" width within which data from each of the two elevation data sets are extracted and interpolated into a new transition zone DEM. The transition zone DEM is composed of elevation values from each of the original disparate DEMs and overlaps both DEMs within the blending zone. The overlapping transition zone DEM is combined with the original DEMs using a blending procedure that forces the output cell values of overlapping areas to be a blend of values. Since the identification of a blending zone width can be somewhat

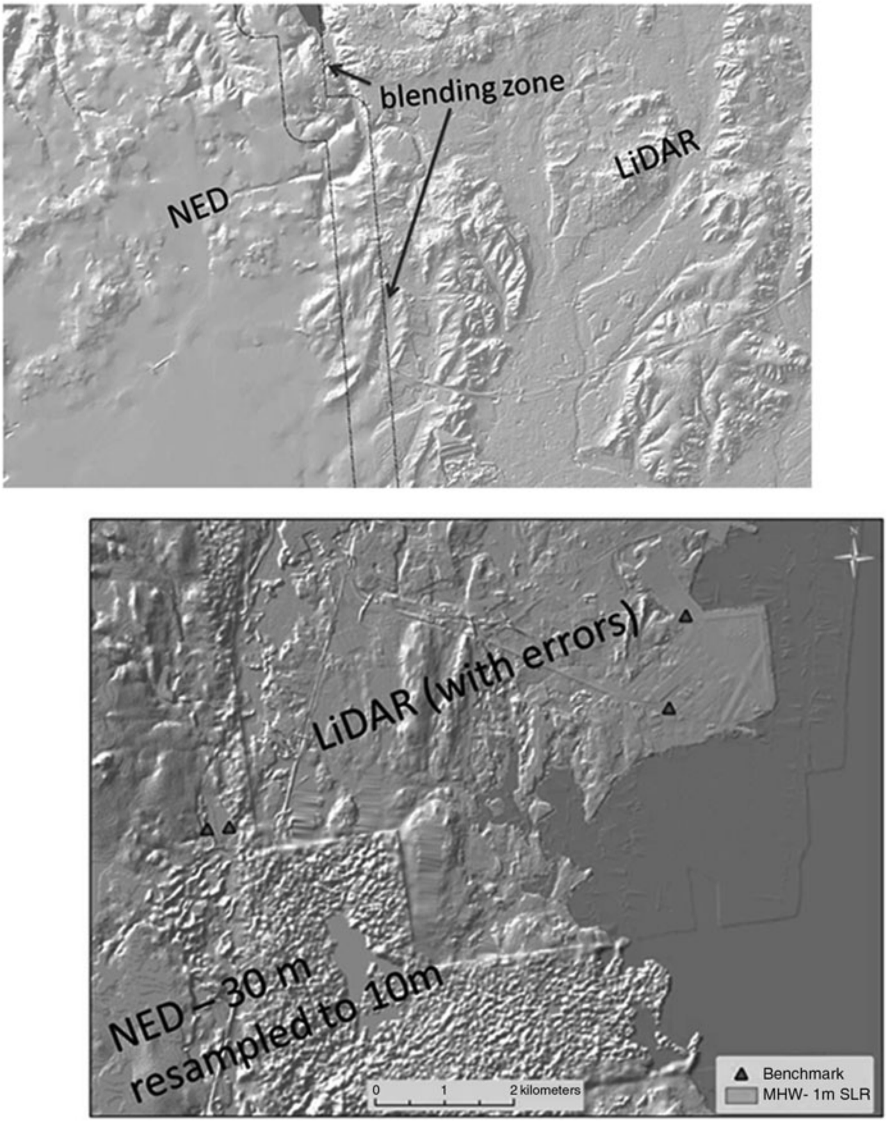

Fig. 3 Successful (*top*) and unsuccessful (*bottom*) integration of elevation data

arbitrary, transects could also be used as a method to test various zone widths to identify the best-fitting zone width via a coefficient of determination (R^2). This would, similar to above, compare the integrated DEM against the most accurate DEM (e.g. LiDAR). This approach would allow users to identify varying transition zone widths, depending on the resolution and accuracies of the input DEMs (Fig. 4).

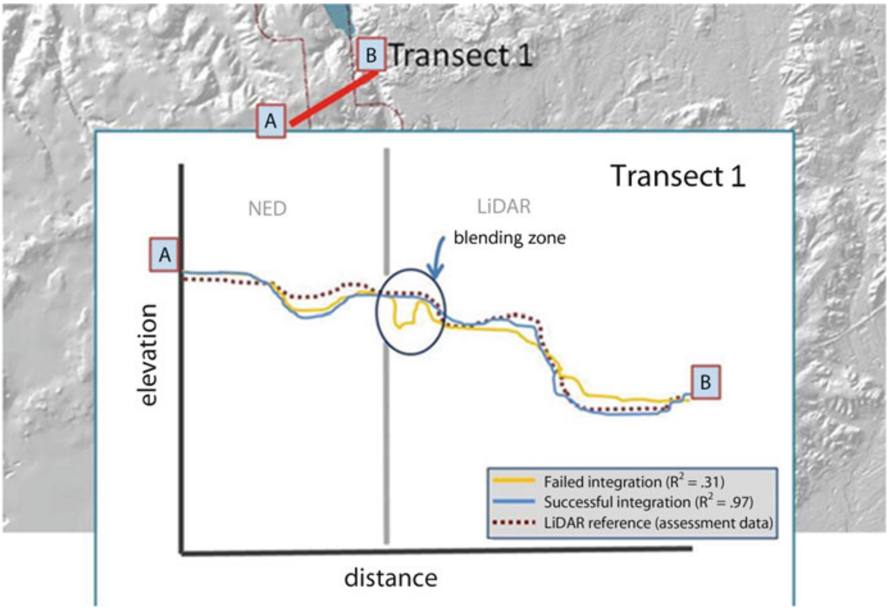

Fig. 4 Transition zone transect accuracy assessment

This study showed that the methods can be used to improve the best currently available multi-state DEM (e.g. NED). Using this methodology, users can update regional DEMs by integrating the most up-to-date and accurate DEMs as they become available. Though this study was tested over a large geographic area, similar methods could also be used for smaller areas where data sets of varying resolutions need to be integrated.

2.2 Sea Level Rise Mapping

Topography data sets such as those used in this study are usually collected for land-based applications and are therefore rarely referenced to tidal data. As we had mapped SLR, transforming the DEMs' datum from NAVD88 to mean high water (MHW) was also necessary. Several tools and techniques have been developed to assist with datum transformations, with the most popular being NOAA's VDATUM. Due to incomplete VDATUM coverage (represented as a point database in coastal waters), a single datum conversion value to go from NAVD88 to mean high water (MHW) was calculated by averaging the difference between both NAVD88 DEMs and MHW in the study area where VDATUM coverage existed. Though this likely introduced errors where local tidal ranges vary from the averaged conversion unit, using alternative methods to adjust for local tidal ranges was beyond the scope of this study (for more information on datum conversions, see NOAA 2009).

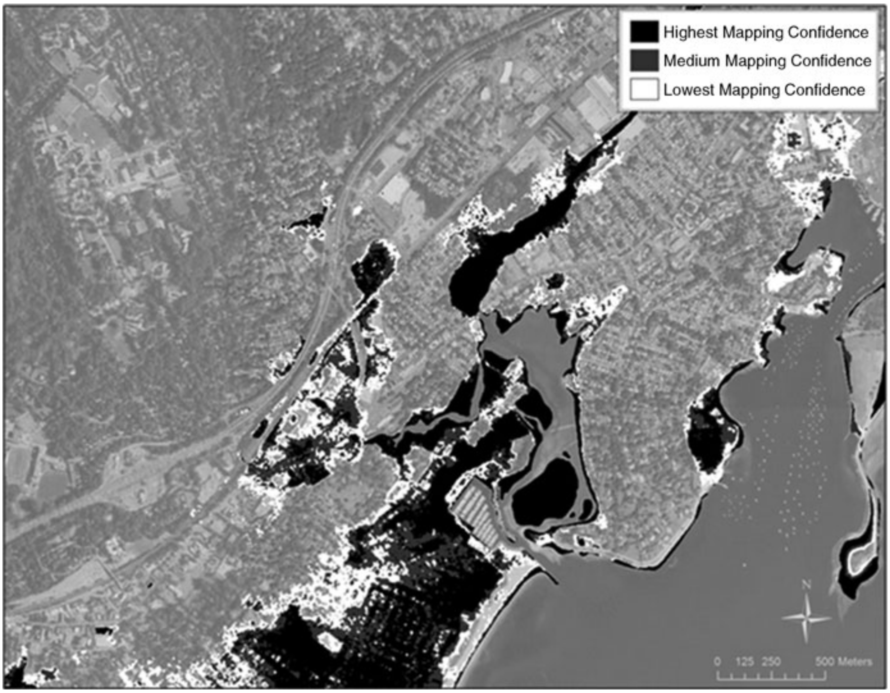

Fig. 5 Sea level rise uncertainty mapping example

Additionally, it was difficult to accurately model hydrologic connectivity while mapping SLR across our study region due to the abundance of bridges and the time required to appropriately condition the DEM (i.e. connecting stream segments through bridges picked up as barriers on the LiDAR). We were therefore constrained to using the "bathtub" SLR mapping approach, leaving low-lying areas upstream of bridges hydrologically unconnected. Given this constraint, we found that the integrated DEM had 7% less inundation than the NED. In other words, since the integrated DEM was more vertically accurate, mapping SLR produced less area of inundation. These findings were expected, since other studies have shown lower-quality elevation data sets to experience higher levels of inundation (Titus and Wang 2008; Gesch 2009). Overall, SLR mapping was more accurate with the integrated DEM, although mapping present-day mean high water (mapping the "0 m" DEM value) was not possible without additional effort because of interpolation errors that occurred during the blending process.

To spatially illustrate the uncertainty associated with mapping a 1-m SLR, we mapped three inundation zones—high, medium, and low—while incorporating the vertical root mean square error (RMSE) of the elevation data in an effort to give users a transparent picture of the variability associated with these elevation data sets (Fig. 5).

RMSE is a measure of precision that calculates the differences between values predicted by a model and the values actually occurring in the data set being modelled. The RMSE is the same accuracy metric used for the assessment of the entire conterminous US NED (Gesch 2007) and is described by Maune et al. (2007).

Gesch (2009) recommends that two inundation zones be mapped as determined by the linear error at the 95% confidence interval in order to spatially illustrate uncertainty. The linear error (LE) is the metric used by the National Standard for Spatial Data Accuracy (see FGDC 1998 for more information). For the 1-m SLR scenario, the zones are as follows:

- High = 1-m SLR + 1.96 × RMSE
- Low = 1-m SLR − 1.96 × RMSE

Although their approach is certainly more cautious, we decided to calculate a third interval using the actual mapped value (e.g. medium = elevation $\leq$1 m), in addition to using the high and low extents noted above. This was done to provide a "middle ground" SLR estimate. It should also be noted that error can be introduced during the datum conversion process going from NAVD88 to MHW, and where possible, this should be considered here. We modified Gesch's approach and used the following rules to determine the SLR inundation zones:

- High (1 m) = elevation $\leq$1 m + (1 × RMSE)
- Medium (1 m) = elevation $\leq$1 m
- Low (1 m) = elevation $\leq$1 m − (1 × RMSE)

3 Discussion

We should note that if users intend to view or analyse inundation for a specific area, we recommend that they use the single most accurate DEM for modelling SLR and not conduct data integration. This approach would provide the most accurate SLR projection map for that area as it would utilize the most up-to-date elevation data without scaling up high-resolution data to match coarser data. This would also allow the illustration of varying inundation uncertainty zones as determined by the underlying elevation data accuracy. For example, there would be smaller uncertainty inundation zones for more accurate data sets and larger uncertainty zones for less accurate data sets. Additionally, as users moved from one data set to the next, they would be able to visualize the varying uncertainty contained within the underlying elevation data. Following our rule-based SLR mapping method detailed above, low, medium, and high zones would be calculated based on the RMSE for each individual DEM. This approach would create a transparent and accurate representation of potential inundation for decision makers viewing or analysing SLR inundation in a specific geography. However, if a seamless data set is required, we highly recommend the methods outlined above and urge that multiple accuracy assessment metrics be undertaken to ensure accuracy of the DEM blending procedures.

4 Conclusion

The costs to human and natural communities are increasing as coastal development continues and natural buffers, such as coastal wetlands and dunes, are lost. Critical information shortfalls limit the options for coastal managers to address climate change-related risks. Identifying low-lying lands that are likely to be impacted by sea level rise is a paramount first step for coastal climate change adaptation planning. This study provides useful methods for accounting for the accuracy and uncertainty associated with sea level rise (SLR) mapping. The products generated from analyses such as this allow communities to visualize and understand their exposure and vulnerability to climate change impacts and better plan for current and future conditions while considering a range of adaptation solutions. While adaptation to coastal hazards has traditionally focused on using shoreline hardening and engineered defences, ecosystem-based adaptation (EBA) as an alternative and sometimes complimentary approach to built infrastructure is critical to creating human and natural community resilience in the face of climate change. The Coastal Resilience project is designed to facilitate easy access to this information and provide a decision support platform to better inform decision-making and the implementation of EBA approaches. With better information, planners and managers can make climate change adaptation decisions that better protect both human and natural communities.

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