Journal of Coastal Conservation
https://doi.org/10.1007/s11852-018-0605-1

Adding to the toolbox for tidal-inundation mapping in estuarine areas

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Received: 9 May 2017 / Revised: 12 December 2017 / Accepted: 20 February 2018

Abstract
In estuaries, land-surface and tidal elevation conspire to influence the amount of salt-water inundation in a specific location, ultimately affecting the distribution of estuary vegetation. Plants vary in their tolerances to salinity and inundation. Understanding even small changes in land-surface elevation at a site scale provides relevant information to managers seeking to design effective long-term restoration projects. Restoration of estuary habitats has been identified as a tool to mediate some anticipated effects of climate change, including flooding from sea-level rise, precipitation regimes, and storminess. Further, habitat restoration that is effective in the face of climate uncertainty is critical to the sustainable production of seafood and maintenance of ecosystem functions. We offer a simple method that links tidal elevations to upslope topography, allowing managers to determine where tidal inundation of upslope areas may occur. This method does not require complex modeling, rather we combine existing high-accuracy tide-gage information with LiDAR imagery. However, we found that if LiDAR is not flown at low tide, or at consistent tidal heights, it poses significant challenges in the interpretation of tidal elevations. Where LiDAR is consistently collected at low tide, this method of linking the tidal datum to upslope topography is not data-intensive, and does not require long-term data collection. Along with locally specific information, the types of map products that can be developed using this method should identify places that may be potentially vulnerable to salt-water inundation, along with places that may be effective migration corridors for marshes and other habitats.

Keywords Climate change · Sea-level rise · Tidal inundation · Restoration · LiDAR · GIS

Introduction

In estuaries, land-surface and tidal elevation (or sea-level) combine to influence the amount of salt-water inundation in a specific location, ultimately affecting the distribution of estuary vegetation. Because plants vary in their tolerance to salinity and inundation (Janousek et al. 2016), even very small changes in land-surface elevation can influence the extent and function of salt-marsh habitats (Janousek and Folger 2014; Valiela et al. 1978). Clearly, other processes, including cyclical salinity patterns, storm surges, sedimentation rates, salinity levels, interspecies competition, and seasonal freshwater inputs, are also strong determinants of the type of estuary habitat that may develop in a particular place (Mann 1982; Pennings and Callaway 1992). In Oregon, land-surface elevation, in relation to tidal elevation (or sea-level), has been identified as a strong predictor of the type of vegetation community that may be found in a specific location (Janousek and Folger 2014). Owing to the utility of land-surface and tidal elevations in predicting the distribution of different types of estuary habitats, tools that enable the consistent and accurate collection of these data may assist in restoration, conservation, and protection efforts.

Most estuaries have been significantly altered by humans during the past century, reducing the quantity and diversity of available habitats (Dahl and Stedman 2013; Good 2000) and the capacity of estuarine systems to absorb change (Folke et al. 2004; Lotze et al. 2006). Land-management agencies have responded with projects to restore and enhance rare estuary and ecotonal habitats, often through partnerships with private and non-profit organizations (i.e., Neskowin Coastal Erosion Adaptation Plan 2013). However, predicted changes in inundation patterns that are anticipated with sea-level rise (Craft et al. 2009; Flitcroft et al. 2013; Glick et al. 2007) could render many current restoration projects ineffective over time

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Published online: 12 March 2018

(Callaway et al. 2007). Vertical accuracy of digital elevation models utilized for mapping of tidal inundation from sea-level rise is another component of accurate modeling to correctly plan for future tidal elevation scenarios (Fraile-Jurado and Ojeda-Zújar 2013). Planning for habitat restoration that considers the need to keep pace with climate change will be critical to the sustainable production of seafood and ongoing maintenance of ecosystem function (Flitcroft and Giannico 2013; Montefalcone et al. 2011).

There are several tools available for estimating the spatial extent of sea-level rise (SLR) in estuaries and along coasts. One key element in all of these methods is the determination of tidal elevation, which is critical for the interpretation of how changes in tidal elevation (from SLR, or storm surges) will affect lowland areas. For example, the Digital Coast Sea-Level Rise viewer (https://coast.noaa.gov/digitalcoast/tools/slr) provides a visual means to explore scenarios of SLR and tidal inundation across broad spatial extents. This sophisticated tool incorporates VDatum as a key method for determining tidal elevation. VDatum is a comprehensive and seamless tidal datum developed by the National Ocean Service at NOAA (NOAA NOS), available for most of the west and east coasts of the US. This datum is based on interpolation of tidal heights between stations (VDatum: http://vdatum.noaa.gov/). One challenge in the use of VDatum is that this datum may only extend a short distance above mean high water and may not include all estuarine habitats (NOAA OCM 2017). Another tool for exploring SLR is the Sea Level Affecting Marshes Model (SLAMM; https://coast.noaa.gov/digitalcoast/tools/slamm). Unlike the Digital Coast Sea-Level Rise viewer, which is intended to assess large portions of the U.S. coastline, SLAMM often focuses on specific locations. In applications in Spain, SLAMM developed with LiDAR imagery was shown to provide a useful framework for predicting sea-level rise on salt marshes, but additional information such as saltmarsh accretion rates and historical trends in sea-level were critical in concert with elevation information (Núñez 2016). Further, understanding the importance of vegetation elevations when using remotely-sensed imagery such as LiDAR may be critical in developing accurate bare-earth models that will directly affect predictions about future inundation patterns due to sea-level rise (Ewald 2013; Fernandez-Nunez et al. 2017).

The Digital Coast Sea-Level Rise viewer and SLAMM both rely on data that describe land-surface and tidal elevations. Digital data sets that describe topography are common in geographic enquiry, but vary in grain size and extent. Digital elevation models (DEMs) are a commonly used topographic tool, derived from a variety of different types of elevation data including aerial photography and light detection and ranging (LiDAR) data. LiDAR is an increasingly common form of elevation data collected on aerial surveys with equipment that sends and receives laser signals. The interval between the emission of laser signals by the equipment and the return time when signals bounce back from the earth's surface to the receiver allows for the calculation of surface elevation. Because LiDAR lasers bounce off the top-most surface, interpretation of the "cloud" of return points is needed to identify the bare-earth model (the lowest laser returns) or the land surface with no vegetation. Additional analysis can be done to identify vegetation heights or physical structures. Two forms of LiDAR data are available: topographic LiDAR (often called infrared or red LiDAR) that does not penetrate water; and bathymetric LiDAR (often called blue-green LiDAR) that can penetrate as deep as 70 m into water, depending on clarity and other factors (Gao 2009).

Here we offer a simple geographic information system (GIS) method that links LiDAR bare-earth data models with the local tidal datum for spatially explicit investigation of inundation potential at the site level. This simple method can be used in places where SLAMM or VDatum are unavailable, or the Digital Coast Sea-Level Rise Viewer output is too coarse for site-specific planning. By interpreting LiDAR elevation using the local tidal datum, we can show the intersection between tidal elevation and upslope topography. Using this method, we mapped potential changes in tidal inundation for three estuaries on the Oregon coast: Salmon River, Alsea Bay, and Coos Bay. Along with locally specific information, map products like these offer a window into potential planning alternatives for restoration, land use, and land-development efforts by identifying areas that are potentially vulnerable to saltwater inundation, or places that may serve as effective migration corridors for marshes and other habitats.

Methods

Study areas

We chose three Oregon estuaries for this study, including, from north to south, Salmon River (438-acre [177-ha or 1.77-km^2] estuary, 190-km^2 drainage basin), Alsea Bay (2516-acre [1018-ha or 10.18-km^2] estuary, 1209-km^2 drainage basin), and Coos Bay (13,348-acre [5402-ha or 54.02-km^2] estuary, 1521-km^2-drainage basin) (estuary area from Oregon Coastal Atlas http://www.coastalatlas.net/) (Fig. 1). The Salmon River estuary is underlain by a complex mix of recent sedimentary and volcanic rocks and drains a relatively small area. However, this system has the most extensively restored salt marsh and lower estuary on the Oregon coast (Flitcroft et al. 2016). Alsea Bay and Coos Bay, are located on the central Oregon coast and are characterized by older marine sedimentary geology. These estuaries are classified

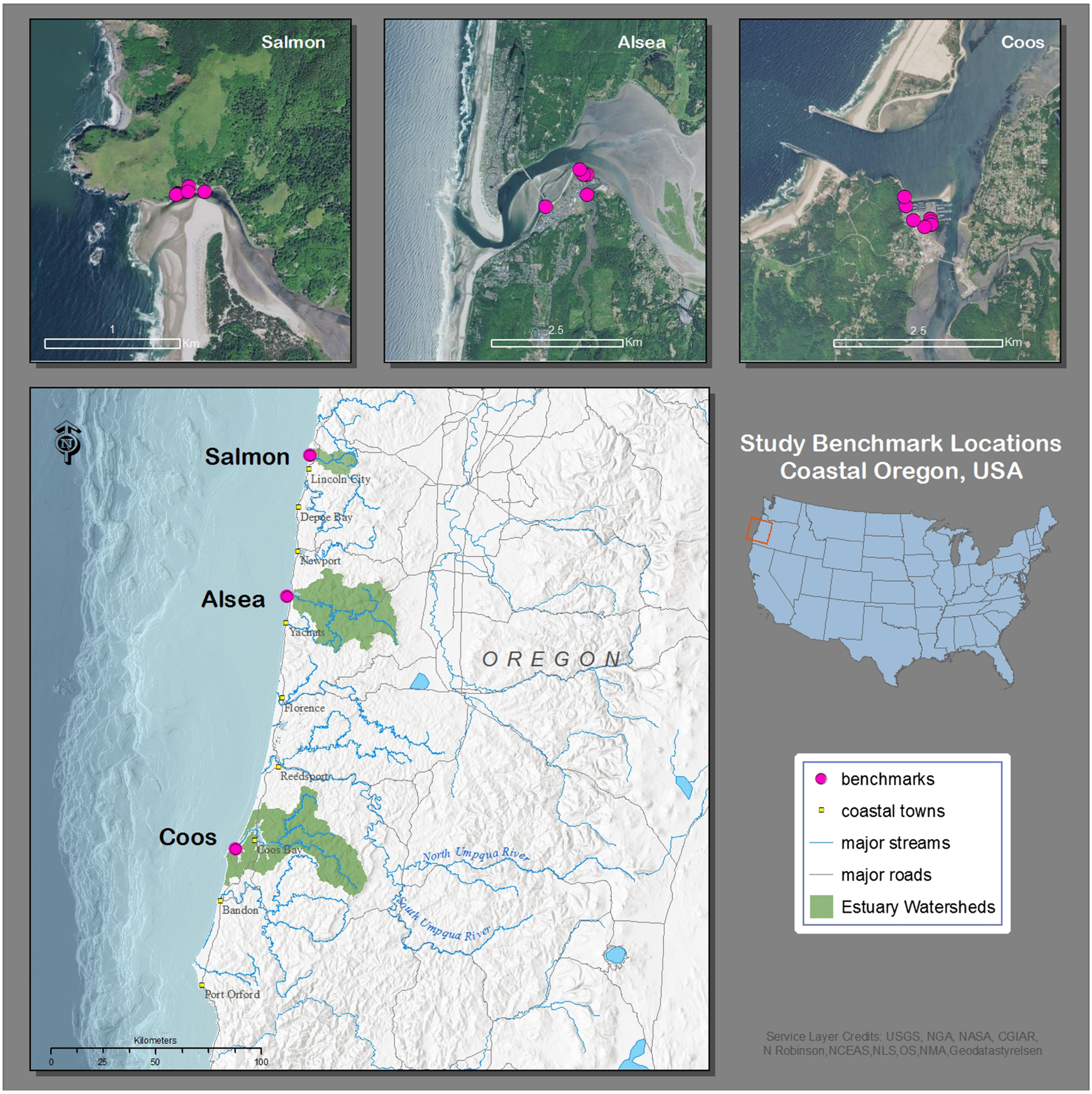

Fig. 1 The three estuaries chosen for this study were Salmon River, Alsea Bay, and Coos Bay. Multiple benchmark locations were mapped for the NOAA tidal station identified for each system (shown in top row of maps)

as drowned river-mouth systems. Additionally, salt water dominates estuaries in the summer when freshwater inputs are low, but salinity is reduced in winter owing to precipitation falling over large watersheds upstream (Cortright et al. 1987). Similar estuary habitat types in all estuaries include high and low salt marsh, mudflat, and eel grass beds (Fig. 2). All three Oregon estuaries are part of watersheds with headwaters in the Oregon Coast Range. Land use for all watersheds includes timber harvest in the headwaters, with varying amounts of land held in public and commercial timber ownership. Agriculture and rural residential land use are found in the lowlands of all three estuaries, with urban areas occurring in the Alsea and Coos Bay systems. Recreational fisheries are present in all estuaries, with commercial fishing fleets based in the Alsea and Coos Bay systems. The Oregon coastal climate is generally mild, with average temperatures varying between 6.1 °C in winter and 18.3 °C in summer; precipitation ranges from 1.5 to 4.06 m per year, falling predominantly as rain, with some winter snow but no permanent snowpack (PRISM Climate Group; http://www.prism.oregonstate.edu/).

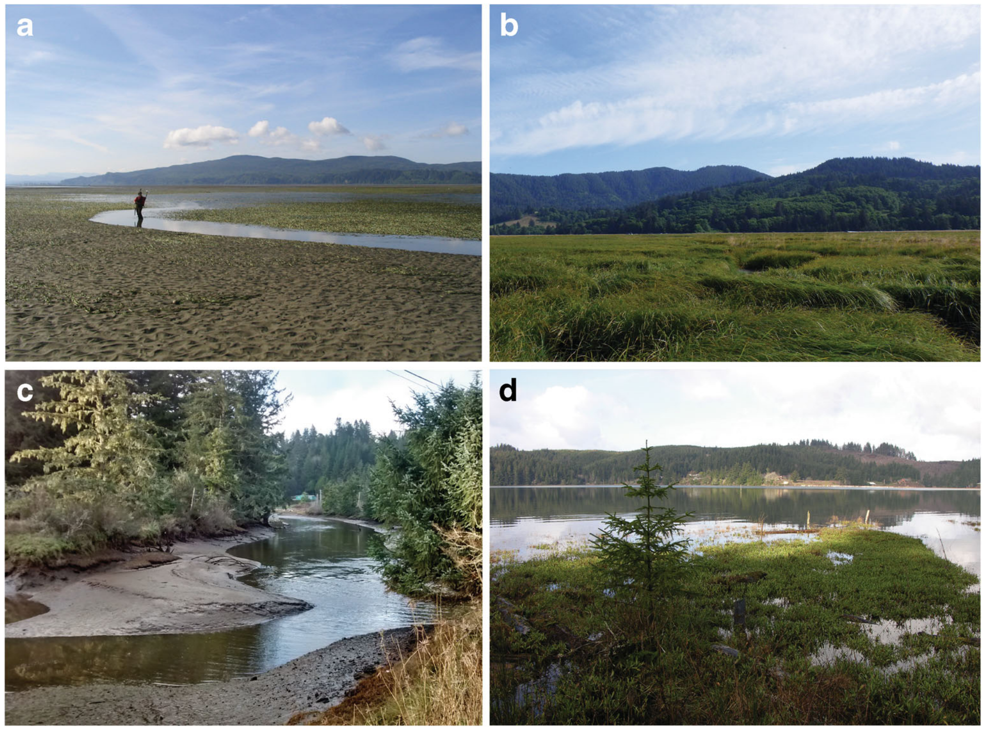

Fig. 2 Common estuary vegetation types occurring across Oregon estuaries: **a** mud flat and eel grass bed in Tillamook Bay, OR; **b** high salt marsh habitat, Salmon River, OR Photo by Megan Chellew; **c** forested brackish tidal channel, Coos Bay, OR; **d** low salt marsh habitat, Coos Bay, OR

Elevation data sets

We used two LiDAR data sets in our analysis. For our analysis of Alsea Bay and Coos Bay, we downloaded publically available LiDAR funded by a consortium of agencies and flown by the Oregon Department of Geology and Mineral Industries for the entire Oregon coast (flown October 2008; 0.9 × 0.9 m resolution) (obtained at http://www.oregongeology.org/sub/lidardataviewer/). We used the bare-earth model that was provided by the vendor but could be generated at the discretion of the user (for model specification, see http://www.oregongeology.org/sub/LiDARdataviewer/resources.htm—OLC North Coast, for the Alsea; and OLC South Coast, Oregon, for Coos Bay). Because the LiDAR data were collected to support road infrastructure maintenance, not tidal conditions, surveys were flown using the infrared spectrum, which that cannot penetrate water, without regard to tidal height.

LiDAR data that are not part of the Oregon coastal LiDAR data set are available for the Salmon River estuary. These LiDAR data were privately collected for the USDA Forest Service, flown at low tide (flown August 2007; 1 × 1 m resolution). The Salmon River Estuary LiDAR surveys were also collected using the infrared spectrum, but because they were flown at low tide, much of the bathymetry of the estuary is represented in the bare-earth LiDAR data model. We again chose to use the vendor-created bare-earth model (for additional model and data collection information, see http://www.oregongeology.org/sub/LiDARdataviewer/resources.htm - Salmon River Study Area, 2008).

We acquired tidal elevation benchmarks from the U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) at the Center for Operational Oceanographic Products and Services (obtained at http://tidesandcurrents.noaa.gov/tide_predictions.html?gid=252#listing) for one station at Salmon River, OR (4 benchmarks at Cascade Head station, #9436381); one station at Alsea Bay (5 benchmarks at Waldport station, #9434939) and; at one station in Coos Bay (6 benchmarks at Charleston station, #9432780) (Table 1). Each of the selected stations collect Harmonic predictions for the local estuary. Station benchmarks are used by NOAA to connect recorded tidal heights from the present tidal epoch (1983–2001) to the North American Vertical Datum of 1988 (NAVD88) (Zilkoski et al. 1992). The precision of the benchmark coordinates that we used was to the level of degrees-minutes-seconds-tenths of seconds.

Linking LiDAR to NOAA tidal datums and benchmarks

Each NOAA tidal-station records mean lower low water (MLLW), defined for each benchmark location. Tidal elevations are then placed into local context at the tidal gage, with reference to local elevations (Gill and Schultz 2001). To link LiDAR elevations to tidal height, we sampled LiDAR elevations at tidal benchmarks located in each of our estuaries of interest. To accomplish this, we mapped benchmark locations in a GIS (with software ESRI ArcMap V.10.3.1), using latitude and longitude coordinates, physical descriptions of the benchmark as listed by NOAA in the benchmark location

Table 1 Differences between NOAA tidal benchmark elevations and LiDAR elevations at Salmon River, Alsea River, and Coos River Estuaries, Oregon, USA

		Site ID	NOAA benchmark elevations above MLLW (m)	LiDAR estimate (m)	Difference (m)	Average difference (m) by estuary
Salmon River Estuary (1.77-km^2; 190 km^2 watershed)	Cascade Head Station #9436381	6381 A 2013	4.763	4.631	−0.132	0.846
		6381 B 2013	4.078	9.681	5.003	
		6381 C 2013	4.500	2.694	−1.806	
		6381 D 2013	3.642	3.959	0.317	
Alsea River Estuary (10.18-km^2; 1209 km^2 watershed)	Waldport Station #9434939	×79 1933 EL 12	4.906	4.747	−0.159	−0.440
		4939 A 2013	4.060	3.918	−0.142	
		4939 B 2013	3.954	3.258	−0.696	
		A2 1936 13.4	5.241	4.063	−1.178	
		2 1933	4.682	4.658	−0.024	
Coos River Estuary (52.02 km^2; 1521 km^2 watershed)	Charleston Station #9432780	Tidal 8 1970	4.838	4.536	−0.302	−0.140
		Tidal 9 1970	5.000	4.807	−0.193	
		Tidal 10 1970	5.212	5.029	−0.183	
		Tidal 11 1974	5.208	4.864	−0.344	
		b Tidal 1981	4.636	4.483	−0.153	
		c Tidal 1981	4.798	5.133	0.335	

In each study estuary, NOAA tidal benchmarks were mapped. MLLW elevation was determined from tide-gage records and also identified on LiDAR imagery. The average difference between these measurements was calculated for each estuary and became the adjustment factor used to translate LiDAR elevations into tidal elevations

description (obtained at: http://tidesandcurrents.noaa.gov/benchmarks.html?id=9436381; http://tidesandcurrents.noaa.gov/benchmarks.html?id=9434939; http://tidesandcurrents.noaa.gov/benchmarks.html?id=9432780), and aerial photography (using Google Earth). We sampled the elevation on the LiDAR data at the site of the mapped benchmark. We compared the MLLW elevation documented by NOAA at the benchmark with our sampled elevation from the LiDAR data set (Fig. 3).

For each estuary, we calculated the difference between the NOAA recorded MLLW elevation at the benchmarks with the sampled LiDAR elevation. We then calculated the average of these differences for all of the benchmarks at each location. The average difference became an "adjustment factor" that we could then use to interpret existing LiDAR data values as tidal elevations (Fig. 4). This allowed the mapping of tidal inundation scenarios above Mean High High Water (MHHW) on the upland topography captured by the LiDAR imagery. We mapped two scenarios: 50 cm above MHHW, and 100 cm above MHHW.

Results

Linking LiDAR to NOAA tidal datums and benchmarks

The difference between tidal benchmarks at MLLW and LiDAR surface elevations varied by estuary (Table 1). We found the largest average difference at the Salmon River estuary, a value of 0.846 m (range 5.003 m to −1.806 m). Alsea Bay had the next largest average difference (−0.440 m; range − 1.178 m to −0.024 m), and Coos Bay the smallest average difference (−0.140 m; range − 0.344 m and 0.335 m).

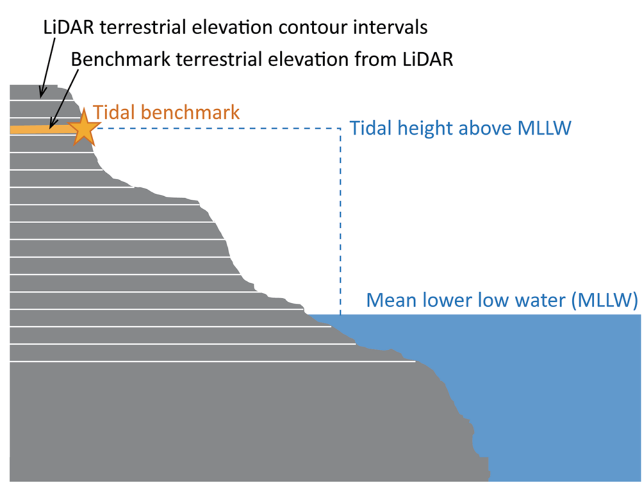

Fig. 3 To interpret LiDAR data through the lens of tidal elevations, we selected tidal stations with multiple benchmark locations. We identified the terrestrial elevation of each benchmark on the LiDAR. We then referenced the tidal elevation for that location. We calculated the average difference between benchmarks and sampled LiDAR elevations for each station. This became the "adjustment factor" used to interpret LiDAR with the tidal datum

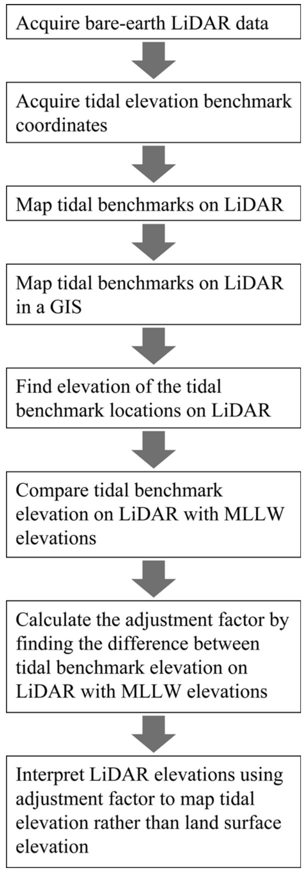

Fig. 4 Process flow chart of methods to display and interpret LiDAR elevations as tidal elevations

Local tidal inundation mapping using tidal datums linked to LiDAR

We interpreted and mapped (Fig. 5a–c) LiDAR data using the adjustment based on elevation comparisons with the NOAA tidal datum (Table 2). Tidal heights can be consistently identified using the LiDAR data set for the Salmon River and Alsea Bay (Fig. 5a, b). The small Salmon River estuary shows the inundation pattern of subsided salt marshes in the restored portions of the estuary (Fig. 5a). The drowned river-mouth configuration of the Alsea system appears to have few potential locations for salt-marsh migration under projected future conditions (Fig. 5b). The LiDAR data for Coos Bay are difficult to interpret. The striping pattern is due to the different flight lines that were stitched together to generate the composite LiDAR data for the bay (Fig. 5c). Flights flown at different times (and sometimes on different days) captured different tidal heights. Because the LiDAR data did not penetrate water, the variation in tidal heights produced the striped elevation configuration, particularly noticeable in open water. However, the gradient of elevations in the smaller tributaries and upstream in the Coos Bay system are still detectable (Fig. 5c).

Discussion

Climate change is predicted to affect a wide variety of environmental conditions in low-lying coastal systems, including increases in sea-level, frequency and intensity of storm surges, and alterations in precipitation and thermal regimes (NRC Committee on SLR 2012; Poff et al. 2002). However, because climate predictions are uncertain, enhancement and restoration of natural resilience mechanisms in native ecosystems can be a unifying goal for planning (Bottom et al. 2009; Miller et al. 2010). This approach of restoring capacity to ecosystems runs counter to engineered solutions to coastal flooding such as sea walls and armoring (Dugan et al. 2011). Tools and applications that facilitate development of site-specific restoration planning using existing and available data sets can provide support to local restoration-planning efforts. Linking the NOAA tidal datum (NAVD88) to local LiDAR elevations provides a simple method of mapping actual tidal elevations onto landward topography, producing maps that display upslope inundation at varying tidal heights. LiDAR flown at low tide (as at Salmon River), or at the same tidal height (as at Alsea Bay) makes interpretation of upslope elevations simple. LiDAR that has been mosaicked together from multiple flights (as at Coos Bay) is more challenging, but upslope elevations above mean higher high water, which are most relevant for mapping tidal inundation, can still be interpreted. These types of mapping products facilitate proactive planning by identifying areas with the greatest likelihood of future inundation, to explore both the potential for the drowning of existing habitats or proposed restoration sites and for habitat migration.

Limitations of this method center on the timing of LiDAR data collection. Water-penetrating bathymetric LiDAR data flown at a consistent low-tide level during winter (when leaves have fallen) is the most ideal for coastal applications. However, even with less-ideal conditions, much can still be learned from available LiDAR data sets. By linking LiDAR data to an accurate tidal datum, our ability to understand tidal-inundation patterns relative to upslope topography is enhanced.

Conservation planning for restoration of ecosystem and social-ecological resilience has been identified as a critical issue for coastal systems (Adger et al. 2005) and fisheries managers (Bottom et al. 2009), particularly in light of climate change. Resilience of native ecosystems is thought to be linked to the diversity of phenology expressed by native species, and to the relatively wide range of environmental conditions that they are capable of tolerating (Bisson et al. 2009; Bottom et al. 2009; Naiman and Décamps 1997). Anthropogenic actions, including the filling and diking of estuary and floodplain areas and the intensive land management associated with timber harvest, have altered disturbance processes throughout the region (Waples et al. 2009). Restoring the capacity of systems to absorb environmental change has been identified as a key mechanism to enhance

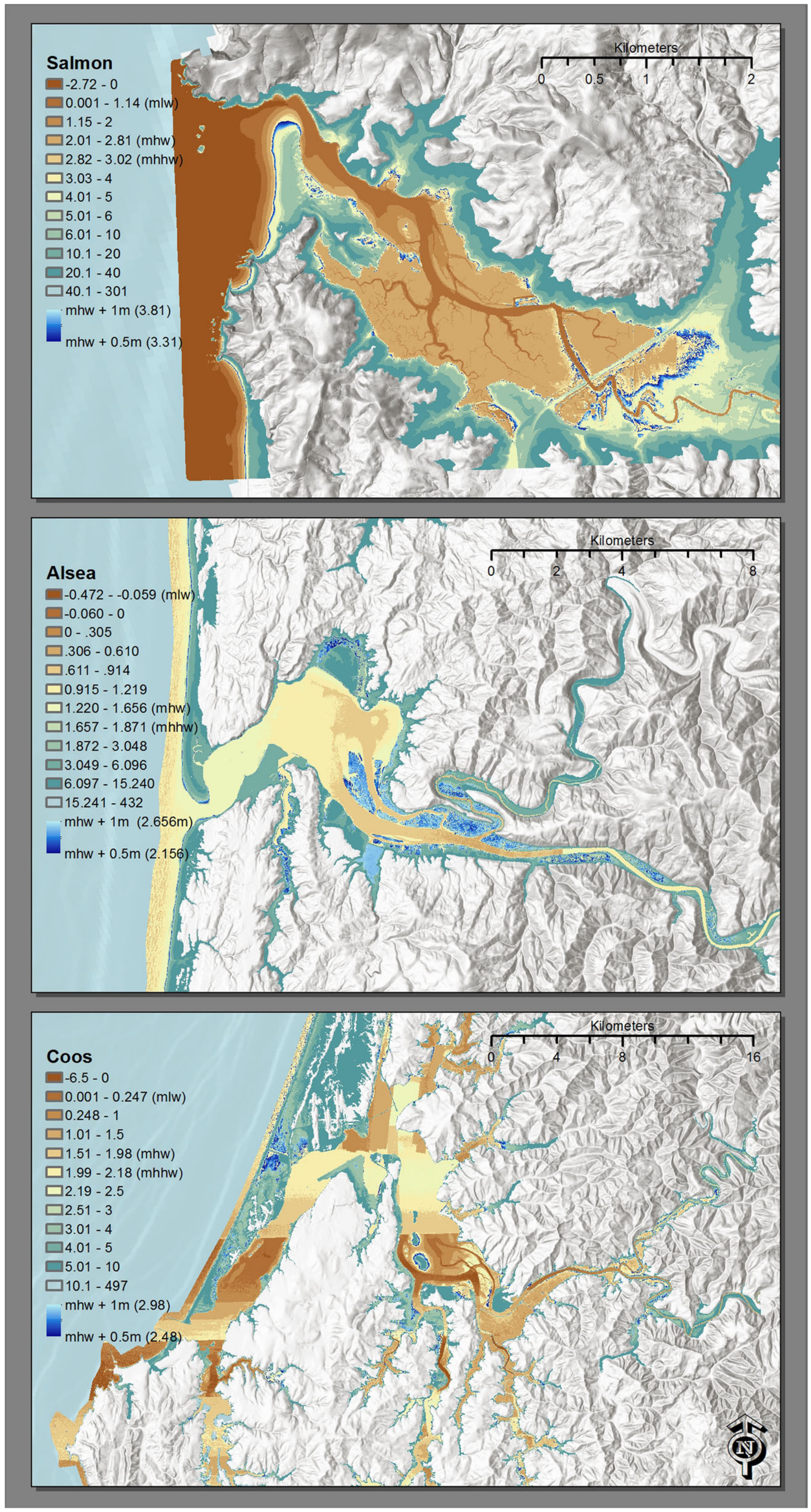

Fig. 5 Tidal elevations were referenced to benchmarks to create an adjustment to LiDAR data so that tidal heights could be mapped on upslope topography. To explore tidal inundation patterns, we mapped 0.5–1.0 m above mean high water at: **a** Salmon River, Oregon, USA; **b** Alsea Bay, Oregon, USA; and (**c**) Coos Bay, Oregon, USA

resilience (Ebersole et al. 1997) and mediate the anticipated effects of climate change (Crooks et al. 2011). Research that models future conditions demonstrates the potential for management to mediate some aspects of climate change (Battin et al. 2007; Falke et al. 2015). Restoration that works toward this goal requires comprehensive, site-specific, and detailed information. This method of linking LiDAR to tidal datums offers a simple, cost-effective tool for local managers to inform the siting and planning of restoration activities in estuaries and the estuary-freshwater ecotone.

Table 2 Each study estuary had a different adjustment factor determined by comparison between NOAA tidal benchmark tidal elevations and LiDAR elevations

Estuary		MLW	MHW	MHHW
Salmon River	Tidal Datum	0.296	1.964	2.174
	LiDAR adjustment (0.846)	1.142	2.810	3.020
Alsea Bay	Tidal Datum	0.381	2.096	2.313
	LiDAR adjustment (−0.440)	−0.059	1.656	1.873
Coos Bay	Tidal Datum	0.387	2.120	2.323
	LiDAR adjustment (−0.140)	0.247	1.980	2.183

For each estuary, the adjustment factor was used to translate LiDAR elevations into tidal elevations. These measurements were then used to map tidal elevations for each estuary

Acknowledgements The authors extend their appreciation to partner organizations and others working to develop restoration strategies for Oregon Estuaries. We would also like to thank Justin Saarinen for his thorough and thoughtful review of the manuscript prior to submission. Salary support for this research was provided by the United States Department of Agriculture, Forest Service Pacific, Northwest Research Station and the United States Environmental Protection Agency.

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