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Mapping Elevations of Tidal Wetland Restoration Sites in San Francisco Bay: Comparing Accuracy of Aerial Lidar with a Singlebeam Echosounder

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ABSTRACT

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The southern edge of San Francisco Bay is surrounded by former salt evaporation ponds, where tidal flow has been restricted since the mid to late 1890s. These ponds are now the focus of a large wetland restoration project, and accurate measurement of current pond bathymetry and adjacent mud flats has been critical to restoration planning. Aerial light detection and ranging (lidar) has become a tool for mapping surface elevations, but its accuracy had rarely been assessed for wetland habitats. We used a singlebeam echosounder system we developed for surveying shallow wetlands to map submerged pond bathymetry in January of 2004 and compared those results with aerial lidar surveys in two ponds that were dry in May of 2004. From those data sets, we compared elevations for 5164 (Pond E9, 154 ha) and 2628 (Pond E14, 69 ha) echosounder and lidar points within a 0.375-m radius of each other (0.750-m diameter lidar spot size). We found that mean elevations of the lidar points were lower than the echosounder results by 5 ± 0.1 cm in Pond E9 and 2 ± 0.2 cm in Pond E14. Only a few points (5% in Pond E9, 2% in Pond E14) differed by more than 20 cm, and some of these values may be explained by residual water in the ponds during the lidar survey or elevation changes that occurred between surveys. Our results suggest that aerial lidar may be a very accurate and rapid way to assess terrain elevations for wetland restoration projects.

ADDITIONAL INDEX WORDS: *Tidal wetlands, sediment accretion, geomorphology, elevation, salt ponds.*

INTRODUCTION

The key factor for restoring wetlands is to restore the hydrologic conditions that drive the structure and function of the wetland (Mitsch and Gosselink, 2007; Odum, Odum, and Odum, 1995). In tidal salt marshes, wetland hydrology is largely a function of the frequency and duration of tidal inundation, which is determined by the elevation of the site relative to tidal fluctuations (Montalto and Steenhuis, 2004). Not only must the restoration site be intertidal, but the relative position within the intertidal zone can also affect restoration success; if the site is low, the time to attain desired elevation may be slower than desired, whereas a higher elevation site may not develop tidal channels as well as a mid-elevation site would (Cornu and Sadro, 2002). Furthermore, more detailed parameters such as the width-to-depth ratio of tidal channels can further inform restoration design and predict success (Zeff, 1999). For these reasons, vertical accuracy should be a primary concern when measuring elevation at tidal restoration sites.

Wetland restoration has recently become a focus of conservation efforts in the San Francisco Bay estuary. An important goal is to protect endemic salt marsh–dependent species by reversing the loss of nearly 79% of historic salt marsh habitats that occurred since the 1850s (Goals Project, 1999; Takekawa *et al.,* 2006). Success of restoration planning efforts is largely dependent on accurate site elevation measurements. Tidal restoration projects present unique engineering dilemmas, because it is often difficult to obtain accurate elevation maps of areas for modeling and restoration activities. Wetland restoration sites are often poor candidates for conventional ground surveying methods, because ground access may be difficult, areas are often inundated, and wet soils are unstable substrates for using levels. Historically, hydrographic techniques have been used to map navigational obstructions (Populus *et al.,* 2001), and currently available digital elevation data sets are of insufficient resolution to distinguish topographical features in estuarine marsh areas (Yang, 2005). A much finer level of topographic detail is needed for hydrological modeling, restoration evaluation, and planning (Populus *et al.,* 2001).

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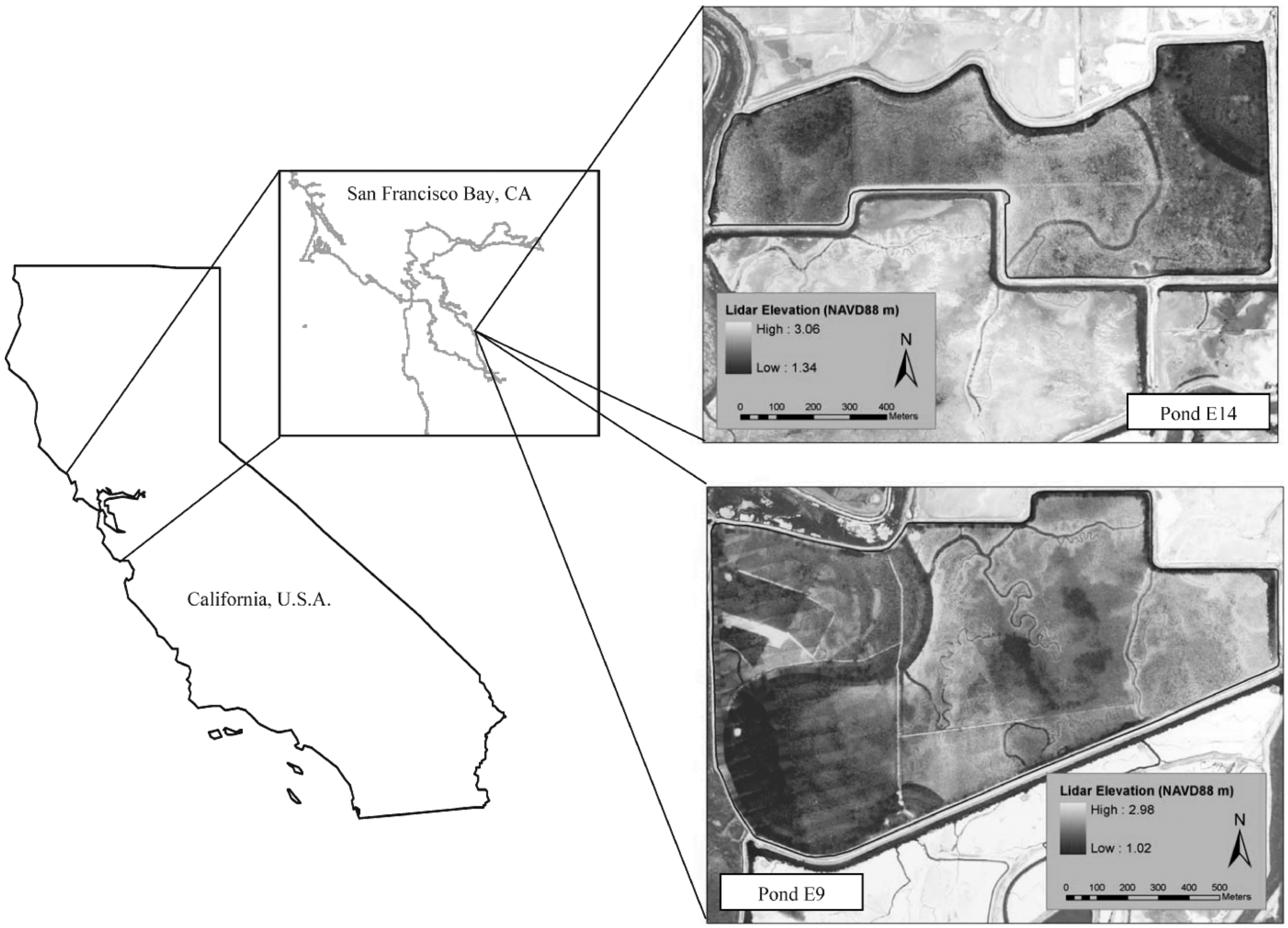

Figure 1. San Francisco Bay; the California Department of Fish and Game Eden Landing Ecological Reserve; and location of Ponds E9 and E14, former salt ponds where aerial lidar and echosounder surveys were conducted. Pond images are 1-m resolution lidar elevation grids superimposed upon aerial photographs.

Boat-based, shallow-water bathymetric sounding systems may be used to obtain highly accurate data in inundated areas (Takekawa *et al.,* 2005; J.Y. Takekawa *et al.,* unpublished data), but it cannot be used where there is not sufficient water depth for navigation or for proper functioning of depth-recording instrumentation (typically about 0.25 to 0.50 m). Aerial light detection and ranging (lidar) systems enable creation of high-resolution digital elevation models (DEMs) spanning a variety of habitats in tidal flats, marsh plains, and drained ponds. Although they may cover a more diverse area, the accuracy of lidar systems for determining bottom elevations of wetlands has not been fully evaluated. Inadequate accuracy may limit the usefulness of lidar systems for wetland restoration planning, where accurate measurements may be critical to the success of the project.

In this study, we mapped the bathymetry of two former San Francisco Bay salt evaporation ponds with airborne topographic lidar during the dry season and compared results to bathymetric data collected by a very-accurate singlebeam echosounder system on a shallow-draft boat during the wet season (Takekawa *et al.,* 2005). We examined differences for locations where elevation was calculated from both aerial lidar and singlebeam echosounder systems to compare the accuracy of airborne lidar relative to the echosounder at these locations and to evaluate its general usefulness for measuring elevation at tidal wetland restoration sites.

METHODS

Study Area

We examined two former salt ponds in the South Bay subregion (37°25′ N to 37°37′ N; 121°56′ W to 122°16′ W) of the San Francisco Bay estuary (Figure 1). Ponds E9 and E14 were located about 4 km west of Union City, California (37°35′ N, 122°3′ W) and comprise about 154 ha (1.5 km^2) and 69 ha (0.7 km^2), respectively. Ponds within this area were acquired in 2003 by the California Department of Fish and Game as part of the Eden Landing Ecological Reserve. These ponds were inundated during the winter and surveyed by boat with a singlebeam echosounder system, and they were predominantly dry by the early spring when they were surveyed by aerial lidar.

Singlebeam Echosounder System

We used a shallow-water sounding system comprised of a singlebeam echosounder (Navisound 210, Reson Corporation, Slangerup, Denmark), a differential global positioning system unit (DGPS; Trimble Corporation, Sunnyvale, California), and a laptop computer in a water-resistant case mounted on a shallow-draft boat (Bass Hunter, Bass Hunter Company, Colbert, Georgia) powered by a saltwater trolling motor (Takekawa *et al.,* 2005). This system has proven effective in measuring water depths >0.3 m with a precision of 1 cm (Takekawa *et al.,* 2005; J.Y. Takekawa *et al.,* unpublished data). Twenty depth readings and one DGPS location were recorded each second; we obtained the average depth value per location during postcollection analysis (SAS Institute, 2004). Pond E9 was surveyed on 26 and 29 January 2004, and Pond E14 was surveyed on 15 January 2004. We obtained water surface elevation from staff gages surveyed in National Geodetic Vertical Datum of 1929 (NGVD29) converted to North American Vertical Datum of 1988 (NAVD88) (Program Corpscon v. 5.0, U.S. Army Corps of Engineers) and estimated elevation at the bottom by subtracting the water depth from the surface elevation. We conducted sample transects spaced 100 m apart and recorded staff gage readings at 15–20 minute intervals to account for any changes in surface water level. We calibrated the system before each survey by performing a physical measurement of depth (with a bar check system or measuring pole) and compared it to the transducer reading while the boat operator was in the boat. Raw data were compiled, reformatted, and converted to latitude, longitude, and depth measurements (SAS 9.1; SAS Institute Inc., 2004).

Airborne Lidar

Hydrographic lidar systems that measure bathymetry through water would not work well in the turbid waters of San Francisco Bay because they are limited by water clarity (Gilvear, Tyler, and Davids, 2004). Furthermore, airborne lidar bathymetry systems are capable of measuring water from 1.5–60 m in depth (Wang and Philpot, 2007), and many tidal restoration sites such as salt evaporation ponds are too shallowly inundated (<1.5 m) for such systems. In these cases, it may be more appropriate to temporarily drain shallowly inundated areas and use conventional aerial lidar for maximum accuracy. The south San Francisco Bay lidar survey was conducted from 5–21 May 2004 by TerraPoint Corporation (The Woodlands, Texas) with ALMIS (Airborne Laser Mapping Imaging System) that includes a 60° full-angle Riegel laser with a rotation polygon mirror, a Novatel global positioning system (GPS) receiver, and a Honeywell initial measurement unit.

The ALMIS was mounted in a Partenavia P68 twin-engine aircraft flown at an altitude of 245 m above ground level during the survey. The size of the surface illuminated by the Riegel laser, referred to as the footprint or spot size, was 0.75 m in diameter. The extent included 334 km² and extended south of the San Francisco and Oakland airports, covering tidal flats, marsh, levees, and surrounding areas within the 100-year floodplain. The scan pattern produces parallel lines that are perpendicular to the flight line and have a spacing of 1.4 m in the across-swath direction and 1.1 m in the along-swath direction. Nominal flightline spacing was 99 m with 51% overlap between adjacent lines, resulting in data density greater than 1 point/m² (Foxgrover and Jaffe, 2005). Data from onboard instruments were compared with GPS base stations in postprocessing to determine surface elevations. An additional processing step was required to correct for a roll error introduced as a result of a loose component within the ALMIS.

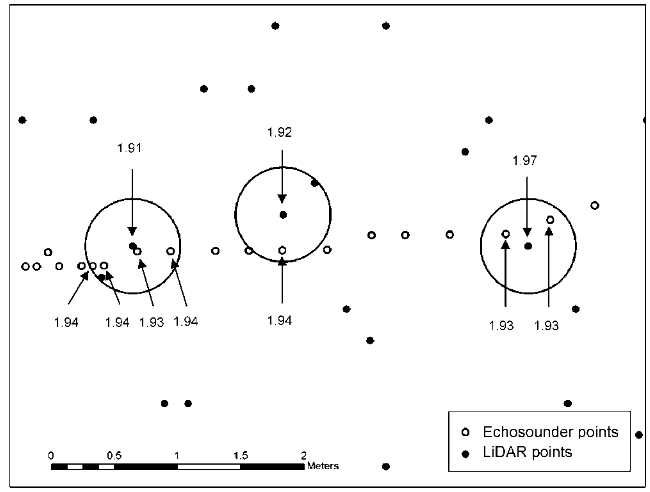

Figure 2. Comparison of aerial lidar and singlebeam echosounder elevation points in San Francisco Bay, Eden Landing Ecological Reserve Ponds E9 and E14. Spot size of 0.75-m diameter was used to obtain comparison points from echosounder surveys.

The primary factors determining vertical accuracy are uncertainty in position and orientation of the laser and differences in elevation of the illuminated surface. Errors in differential GPS solutions and uncertainty in elevations of the ground surface on steep terrain also degraded horizontal accuracy. Absolute positional (horizontal) accuracy was estimated as 20–60 cm on all but extremely hilly terrain. Ground elevations of steep slopes, such as the sides of levees, are less accurate than elevations on flat surfaces. The estimated and actual vertical accuracy of this system on low-sloping, hard surfaces was 10–15 cm at the 95% confidence level, while accuracy was estimated to be 15–25 cm for soft or vegetated surfaces on flat to rolling terrain (Foxgrover and Jaffe, 2005).

Processing

We used aerial imagery to select points from lidar and echosounder data sets that were inside pond boundaries. We selected sample points from the two data sets that were within a 0.375-m-radius circle corresponding to the 0.75-m-diameter lidar spot size (ArcMap 9.1, ESRI, Redlands, California; see Figure 2). We associated each lidar elevation with all echosounder points that fell within its spot size, and if more

Table 1. *Number, differences, standard errors, and range in comparison of aerial lidar and echosounder surveys of two former salt ponds in south San Francisco Bay.*

Variable	Pond E9	Pond E14
Number of lidar points	5164	2628
Number of echosounder points per lidar spot size	1.1	1.2
Mean difference (echosounder − lidar, cm)	5 ± 0.1	2 ± 0.2
Mean difference (echosounder − lidar, absolute value, cm)	8 ± 0.1	6 ± 0.1
Absolute differences (min, max; cm)	0, 54	0, 68

than one point existed, we obtained an average value from all associated echosounder points (SAS 9.1; SAS Institute Inc., 2004) and calculated difference statistics. Mean differences and standard errors of the mean differences are presented to allow assessment of the two difference measurement techniques.

Elevation measurements are discrete samples of a continuous surface, and interpolation methods are often used to translate sample points into a continuous grid that can then be used for analyses or decision making. If a continuous surface data set is the intended final result of elevation measurements, then the desired grid cell size can direct the frequency at which data are collected across a landscape. We examined continuous surface results at three different resolutions to determine the extent to which increased field data collection effort would result in more accurate elevations across the study area; larger grid cell sizes were used to represent lower data collection effort because fewer data were needed to estimate their values. We used the inverse distance weighting method (Spatial Analyst, ArcMap 9.1, ESRI) to create an elevation grid for each pond from source data sets at three cell sizes (5 m, 10 m, and 25 m) and compared the resulting grid cell coverages developed from data collected from lidar and sounding methods. We digitized barrier polylines from low tide aerial imagery (National Agriculture Imagery Program, U.S. Department of Agriculture) to aid interpolation around known topographic features such as borrow ditches and channels. Difference grids were obtained by subtracting the lidar grids from the echosounder-based grids (Spatial Analyst, ArcMap 9.1, ESRI).

RESULTS

A total of 26,781 echosounder and 864,614 lidar points were collected in Pond E9, and 16,048 echosounder and 335,270 lidar points were collected in Pond E14. We were able to create a difference data set from 5164 (E9) and 2628 (E14) lidar and echosounder pairs (within 0.375 m of each other). Frequency distributions of elevation values were similar in shape between the two methods, but the mean difference indicated that lidar elevations were 5.0 ± 0.1 cm lower than echosounder elevations in Pond E9 and 2.0 ± 0.2 cm lower in Pond E14 (Table 1). About 5% of lidar values in Pond E9 and 2% in Pond E14 were >20 cm different from paired echosounder elevations.

The distribution of differences within the ponds showed spatial patterning (Figure 3). Differences were not attributable to daily variation in echosounder surveys, because Pond

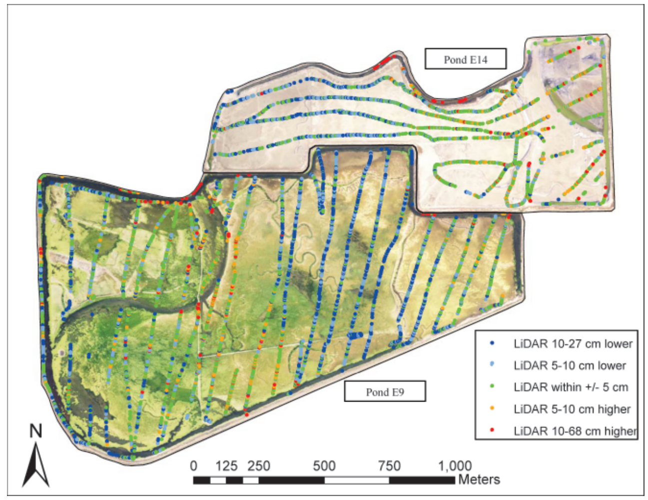

Figure 3. Spatial distribution of difference values (difference = lidar − echosounder locations) across Pond E14 and Pond E9. Point locations represent lidar locations within a 0.375-m radius of echosounder points (0.75-m diameter spot size) and echosounder transect locations, spaced 100 ± 25 m apart.

E14 was sampled in a single day, and the pattern of differences in Pond E9 was not consistent with different sample dates. Similarly, lidar data for both ponds were collected on a single date, and the pattern of differences was not consistent with the orientation of the lidar trackline. Areas where lidar was consistently ≥10 cm lower than the echosounder were relatively shallowly inundated areas that dried more quickly than other areas in the ponds. By 18 March 2004, E9 was mostly dry, whereas parts of E14 were very shallow or mostly dry by 26 April 2004. However, linear regression found a weak but significant ($p < 0.001$) relation between the difference between the two techniques and earlier echosounder elevations across ponds. The earlier elevation obtained from the echosounder explained only 10% of the variability in Pond E9 and 23% in Pond E14.

Although both survey methods covered the same area, some low and high features were not measured by both methods due to inherent limitations associated with each method. Both ponds had standing water remaining in deep borrow ditches and channels during the May 2004 lidar survey. Pond areas where lidar data showed elevations >10 cm higher than the echosounder were often located near borrow ditches or channels that contained standing water (see Figure 3). The echosounder recorded water depths in ditches and channels that remained submerged during the lidar survey, and bathymetric data sets had lower minimum elevation values than lidar (Table 2). Similarly, pond features that were not submerged (berms, islands, and wooden structures) could not detected by the echosounder, and lidar had consistently higher maximum elevations (Table 2).

Differences were interpolated into 5-, 10-, and 25-m resolution grids. Echosounder data were collected along transect lines separated by 100 m and created visual breaks in elevation grids between transects, but these breaks were not

Table 2. *Elevation differences of aerial lidar and echosounder surveys in former salt ponds in south San Francisco Bay at three cell sizes. SE = standard error.*

Pond	Cell Size (m)	Source Data	Minimum Elevation (m)	Maximum Elevation (m)	Mean Elevation Difference ± SE (m)
E9	5	echosounder	0.21	1.98	1.59 ± 0.001
		lidar	1.09	2.93	1.56 ± 0.001
	10	echosounder	0.28	1.98	1.59 ± 0.001
		lidar	1.12	2.66	1.56 ± 0.001
	25	echosounder	0.43	1.97	1.59 ± 0.003
		lidar	1.21	2.46	1.56 ± 0.003
E14	5	echosounder	0.93	2.00	1.78 ± 0.001
		lidar	1.45	2.94	1.78 ± 0.001
	10	echosounder	0.94	1.94	1.78 ± 0.001
		lidar	1.47	3.00	1.78 ± 0.001
	25	echosounder	0.94	1.94	1.78 ± 0.003
		lidar	1.51	2.32	1.78 ± 0.003

apparent in the 25-m resolution grid (Figure 4). Minimum echosounder elevations increased with grid cell size, and maximum lidar values decreased with increasing cell size, although overall mean elevations did not change (Table 2). When we compared the grids derived from the two data sets (Figure 5), lidar was on average 3 cm lower than the echosounder in Pond E9, but there was no difference in Pond E14 (Table 2). Spatial distribution of the differences (Figure 3) remained apparent in the difference grids (Figure 5).

DISCUSSION

Lidar and sounding systems generally performed comparably in these former salt evaporation ponds, and our results were generally similar to earlier but less-rigorous comparisons of the two methods. Lowe (2003) compared 11 sounding transects within 1 m of lidar points and found that lidar values averaged 19 ± 12 cm lower than sounding values. However, Populus *et al.* (2001) examined 341 lidar-sounding pairs on tidal flats within 1 m of each other and found that lidar measurements were on average 2 ± 0.9 cm higher than sounding data. These values are similar to results from Pond E14, where differences were 2 ± 0.2 cm. Although differences within Pond E9 were higher (5 ± 0.1 cm), our sampling in this pond included 5164 comparison values, at least an order of magnitude higher than previous studies.

Mean elevation differences between echosounder and lidar grid elevation coverages did not change with increasing cell size. Because larger grid cells require fewer data to interpolate, this suggests that overall site elevation accuracy is not sacrificed and fewer data may be needed for projects where spatial detail is less important. Interpolation of the full echosounder and lidar data sets resulted in better agreement between lidar and echosounder grids than was observed with points alone (5 cm to 3 cm at Pond E9; 2 cm to 0 cm at Pond E14). This is probably attributable to smoothing from interpolation and increased data used per grid cell. Our imagery indicated that some lidar values clearly overlaid submerged ditches, but we did not edit the data to improve our estimates since that option may not be available in many instances. Similarly, we were aware of posts and other wooden struc-

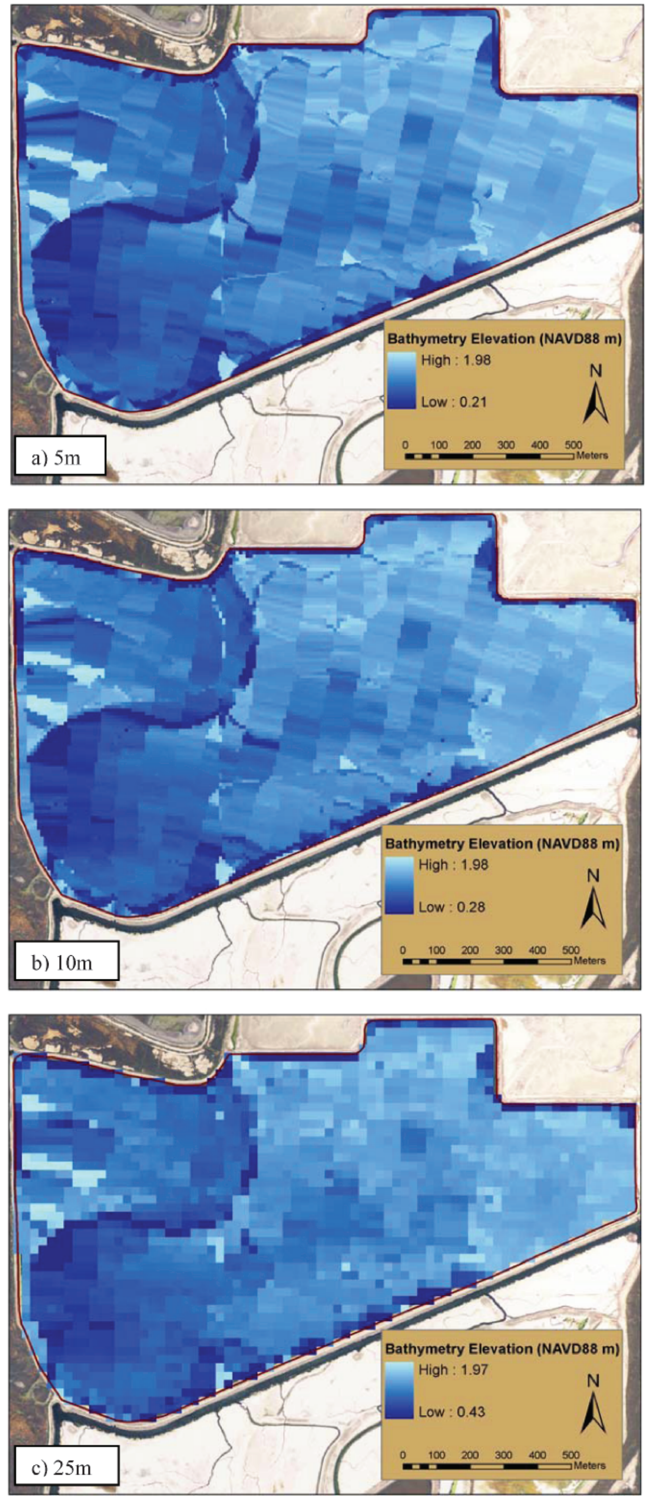

Figure 4. Interpolated Pond E9 elevation grids from echosounder points at three resolutions: (a) 5 m, (b) 10 m, and (c) 25 m. Smaller grid cell values show more details but result in more variation between echosounder track lines, whereas 25-m grid cells show less detail but increase inter-method consistency.

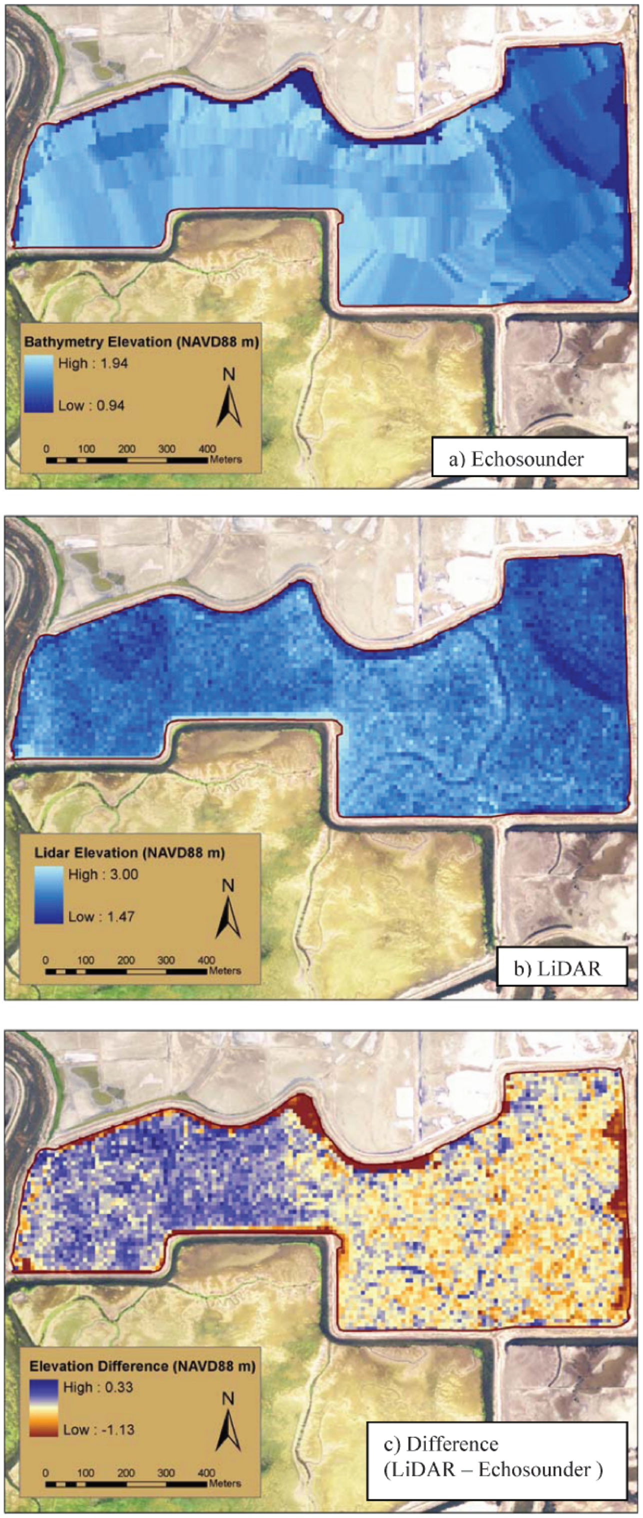

Figure 5. Interpolated 10-m-resolution elevation grids at Pond E14 from (a) echosounder, (b) lidar, and (c) a difference grid (difference = lidar − echosounder).

tures that could potentially skew results. We expected that mean differences from uncorrected data sets showed realistic differences for the two methods.

Echosounder results are considered accurate because the sources of error are well constrained. Accuracy could have been affected by signal frequency and water depth, as well as pitch and roll of the boat. Recorded depths were generally within a narrow range (0.3–1.5 m) and did not vary widely (J.Y. Takekawa *et al.,* unpublished data). Conversion of water depth to elevation depended upon accurate staff gage elevations and water level readings, but these ponds were closed and did not experience water level fluctuation during the surveys. A small proportion (5% in Pond E9, 2% in Pond E14) of comparison point pairs differed by more than 20 cm, and these differences may be partially explained by inherent differences in the methods. One important way in which the echosounder data were biased was that exposed features within the pond boundaries could not be measured. Conversely, the lidar survey was biased in the opposite direction: it measured all pond features, including some undesired features such as standing water and standing wooden structures that were present in some areas of the pond. Furthermore, the lidar spot size was 0.44 m^2, and because >1 echosounder readings could be made within that area, the variation in elevation within the spot size could be captured with the bathymetric soundings but not with lidar.

Lidar should tend to overestimate elevation relative to echosounder in areas with standing pond structures or standing water. Although we did observe this in areas of known or suspected standing water, we observed the opposite trend when elevations were compared across the whole pond. Points where lidar was >10 cm lower than the echosounder were not evenly distributed across the pond, as would be expected if it were due to measurement error. Instead, these differences were concentrated in pond areas that were observed to be shallowest and were exposed to drying for longer periods of time. The shrink-and-swell potential of these fine-textured salt pond sediments is not known, but pond substrates are regularly observed to consolidate and form large cracks during dry seasons (N.D. Athearn, unpublished data), and these portions of the pond were dry for ≥ 2 months. If measurement differences in these pond areas could be attributed to compaction of dewatered sediments or soils, *i.e.,* a change in actual elevation in the pond rather than measurement discrepancies, then lidar measurements would have been closer to echosounder measurements overall when areas of equal elevation were measured with the two methods. This would suggest that the two methods measured elevations more closely than is reported here, and this could also have important implications for measuring ground elevations in wetlands. It is the saturated elevation that is most relevant for tidal wetlands, so lidar measurements should be taken when soils are fully saturated.

The application of lidar in ecological studies is an area of great potential that is just beginning to be realized (Turner *et al.,* 2003). Airborne lidar is primarily used for obtaining elevation data for large areas, but its potential for aiding ecological studies and restoration projects extends well beyond simple ground elevation measurements. For example, vegetation and standing water (in bathymetric lidar systems) create interference that must be removed through postprocessing when measuring ground surface elevation values. However, it has recently been recognized that differential return signals from structurally complex surfaces such as vegetation canopies and substrate types are not merely noise but can be interpreted in order to remotely characterize the surface (*e.g.,* Bradbury *et al.,* 2005; Wang and Philpot, 2007).

Accurate, noninvasive elevation data are especially important for tidal wetland restoration projects, where site elevation and geomorphology may be critical to planning efforts. Such data may be used to calculate the amount of sediment needed for marsh development and may also be useful for calculating restoration timelines when local sedimentation rates are known. Boat-based echosounder methods are accurate and feasible for small areas. However, the areas must be sufficiently inundated to use this method, and transects create inconsistent spatial coverage. Transect spacing must be determined by the need for detailed spatial data. If high-resolution data are needed, more transects must be completed, which increases survey duration and costs; for very large areas, this can be prohibitive. Lidar methods offer more complete spatial coverage regardless of the level of detail, although lower flight elevations that create denser data sets also increase survey duration and costs. Aerial lidar costs are prohibitively high for many small restoration projects and often carry logistical constraints when flightlines interfere with nearby airports and populated areas. The most obvious advantages of aerial lidar methods are that large areas can be surveyed quickly and do not require inundation. However, terrestrial lidar methods may be a lower-cost, high-accuracy option for smaller wetland sites that are not inundated (Hetherington *et al.,* 2007). Surveys conducted at well-drained, unvegetated tidal restoration sites during low tides may be nearly comprehensive; if permanently inundated regions exist, a combination of echosounder and lidar methods may be used to obtain more complete elevation data. Our data suggest that lidar performed comparably to soundings in unvegetated former salt evaporation ponds, and lidar systems are suitable for evaluating and monitoring tidal wetland restoration sites.

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