Wetlands Ecol Manage
DOI 10.1007/s11273-009-9170-6

ORIGINAL PAPER

Measuring sediment accretion in early tidal marsh restoration

John Y. Takekawa · Isa Woo · Nicole D. Athearn · Scott Demers · Rachel J. Gardiner · William M. Perry · Neil K. Ganju · Gregory G. Shellenbarger · David H. Schoellhamer

Received: 18 April 2008 / Accepted: 16 December 2009

Abstract Sediment accretion is a critical indicator of initial progress in tidal marsh restoration. However, it is often difficult to measure early deposition rates, because the bottom surface is usually obscured under turbid, tidally-influenced waters. To accurately measure early sediment deposition in marshes, we developed an echosounder system consisting of a specialized acoustic profiler, differential global positioning system unit, and laptop computer mounted on a shallow-draft boat. We conducted a bathymetry survey at the Tubbs Setback tidal restoration site on San Pablo Bay, California, along north–south transects at 25-m intervals. Horizontal position was recorded within 1 m each second and water depth to 1 cm every 0.05 s. Bottom elevations were adjusted for tidal height with surveyed tide gages. We created detailed bathymetric maps (grid cell size: 12.5 m × 12.5 m) by interpolation with inverse distance weighting. During the third year after restoration, sediment accretion averaged 57.1 ± 1.1 cm and the estimated sediment gain was 132,900 m^3. The mean difference between the elevations from the bathymetry system and the 9 sediment pins was 2.0 ± 1.0 cm. The mean difference of the intersection

J. Y. Takekawa (✉) · I. Woo · N. D. Athearn · S. Demers · R. J. Gardiner
US Geological Survey, Western Ecological Research Center, San Francisco Bay Estuary Station, 505 Azuar Drive, Vallejo, CA 94592, USA
e-mail: john_takekawa@usgs.gov

Present Address:
N. D. Athearn
U.S. Fish and Wildlife Service, Arcata Fish and Wildlife Office, 1655 Heindon Road, Arcata, CA 95521, USA

Present Address:
S. Demers
H. T. Harvey & Associates, 983 University Ave., Bldg D, Los Gatos, CA 95032, USA

Present Address:
R. J. Gardiner
Centre for Wildlife Ecology, Department of Biological Sciences, Simon Fraser University, 8888 University Drive, Burnaby, BC V5A 1S6, Canada

W. M. Perry
US Geological Survey, Western Ecological Research Center, Dixon Field Station, 6924 Tremont Road, Dixon, CA 95620, USA

N. K. Ganju · G. G. Shellenbarger · D. H. Schoellhamer
US Geological Survey, California Water Science Center, 6000 J Street, Placer Hall, Sacramento, CA 95819, USA

Present Address:
N. K. Ganju
US Geological Survey, Woods Hole Coastal and Marine Science Center, 384 Woods Hole Road, Woods Hole, MA 02543, USA

Published online: 11 February 2010

points of east–west and north–south survey transects was 2.1 ± 0.2 cm, which provided a measure of repeatability with changing water levels. Our echosounder system provided accurate and repeatable measurements of sediment accretion of a recently restored tidal wetland, and this system proved to be a viable tool for determining sediment deposition in marshes and assessing early restoration progress.

Keywords Acoustic profiler · Bathymetry · Echosounder · Monitoring · San Francisco Bay · Sedimentation · Tidal marsh restoration

Introduction

In the past decade, a large number of tidal marsh restoration projects have been initiated in the San Francisco Bay estuary (San Francisco Bay Joint Venture 2008). While 79% of historic tidal marshes have been lost to diking and development (Goals Project 1999), bayland areas are now being returned to tidal flow. Many of these restoration sites have been diked or drained for agriculture or other development, and most are subsided or below marsh plain elevations. In tidal salt marshes, hydrological processes depend on the frequency and duration of tidal inundation and the elevation of the bottom surface (Odum et al. 1995). Sediment accretion is a critical measure of restoration progress (Simenstad and Thom 1996; Montalto and Steenhuis 2004), especially in young sites that may experience rapid sediment accumulation (Williams and Orr 2002), but estimating changes in bottom elevations of newly restored tidal marshes may be very difficult because bottom surfaces are submerged and obscured much or all of the time.

Wetland restoration sites are often poor candidates for conventional ground surveys (Wilcox and Los Huertos 2005) because access may be difficult, areas are inundated, and substrates are unsuitable for operating transit levels. Other methods for measuring tidal marsh restoration sediment deposition vary widely from use of sediment pins, marker horizons, stereophotogrammetry, surface elevation tables (SET), and light detection and ranging (LiDAR) systems, all of which have major drawbacks for use in early tidal wetland restoration monitoring. Sediment pins or plastic poles pounded into the substrate are an inexpensive method to estimate accretion (Siegel 1998; Takekawa et al. 2003, The Tubbs Setback Restoration Project: Assessing Early Tidal Marsh Development, unpublished report). However, sediment pins provide limited sample points, areas of accretion or erosion distant from sediment pins may be missed, and the pins may cause altered local flows and create erosion pockets. Similarly, marker horizons may provide accretion rates at specific sampling locations; however, markers are typically few in number, can be resuspended or eroded by waves and currents, can be substantially affected by invertebrate bioturbation, and can be difficult to establish in areas of deeper water or with large tidal gradients (Cahoon and Turner 1989).

SETs provide very precise (<1.5 mm) estimates of accretion (Boumans and Day 1993; Cahoon et al. 1995), but they require fixed stations and do not work well in deeper water (>0.5 m). Stereophotogrammetry and LiDAR systems may be used to complete maps of entire restoration sites, but their costs are typically high and elevations may be obscured by vegetation or cloudy water (Gilvear et al. 2004). Currently available digital elevation datasets are of insufficient resolution to distinguish topographical features in estuarine marsh areas (Byrnes et al. 2002; Doyle et al. 2002; Yang 2005). To overcome difficulties of established methods, we developed an echosounder system to measure the shallow water bathymetry and sediment accretion in early tidal marsh restoration. We assessed the precision and accuracy of the echosounder system, and we discuss findings from its use in a recent tidal marsh restoration project.

Methods

We measured sediment accretion in the Tubbs Setback tidal restoration site (38°7.5′N, 122°26.0′W), a 29-ha wetland located in the San Pablo Bay National Wildlife Refuge (SPBNWR) in the northern reach of the San Francisco Bay estuary. The area was diked for reclamation in the early 1900s and farmed for oat hay until 1983. The restoration plan (SPBNWR 1998) involved grading the interior, reinforcing a landward levee, and breaching the outer levee to San Pablo Bay which occurred on 8 March 2002 (Woo et al. 2007). After the breach, the interior of the project formed a large, open water area that depended on natural sedimentation dynamics for mud flat and tidal marsh development.

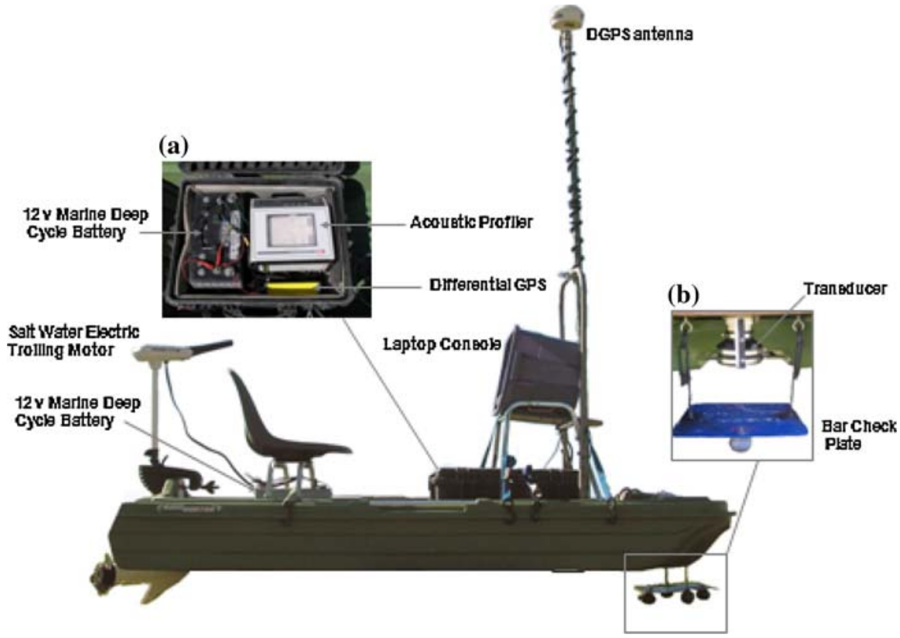

Fig. 1 Components of the single beam echosounder system for shallow water including (**a**) the differential geographic positioning system unit and antenna, and laptop and (**b**) the transducer and bar check plate

We conducted bathymetry surveys at Tubbs Setback in January 2004 with 20 north–south transects approximately at 25-m intervals and 3 east–west transects. We repeated the bathymetry survey in September 2005 with 25 north–south transects and 22 east–west transects at 25-m intervals. Aerial photographs were taken in September 2004 and September 2005 and were georeferenced to UTM NAD83 datum from surveyed control points in ArcGIS to provide a spatially referenced base layer for our bathymetry map.

Our echosounder system (Fig. 1) was comprised of a single beam, variable-frequency acoustic profiler (Navisound 210, Reson, Inc.; Slangerup, Denmark), differential global positioning system unit (DGPS; Ag132, Trimble Corporation, Sunnyvale, California, USA), and laptop computer in a water-resistant case (Fig. 1a) mounted on a shallow-draft kayak (Kiwi Kayaks; North Bay, ON) or portable flat-bottom boat (Bass Hunter, Bass Hunter Company, Colbert, GA) powered by a salt water trolling motor. The variable frequency transducer provided water depth soundings every 0.05 s with 1 cm accuracy and can record depths as shallow as 10 cm. The transducer was aligned with the bottom surface of the front of the boat. The DGPS unit provided a horizontal position each second with 1-m accuracy and was connected to the transducer through a serial cable and to an antenna. The antenna was situated on a 2-m pole to prevent loss of signal in areas adjacent to levee edges. The electronics and trolling motor were powered by 12 volt marine deep-cycle batteries. The boat and echosounder needed about 10 cm of water depth to function properly. We calibrated the echosounder system before each survey by conducting a bar check. The sound velocity was adjusted for salinity and temperature differences so that the transducer water depth readings were equal to that of a known distance to a flat plate (Fig. 1b). We also used a graduated pole to compare readings at the beginning and end of each survey to ensure depth readings remained accurate.

At a tidally-influenced site such as Tubbs Setback, it was necessary to measure the fluctuating water levels with staff gages, which were read at 15 min intervals (<1 cm accuracy; Fig. 2). Staff gages were surveyed to NAVD88 m so that the water level readings from the echosounder could be converted to an established vertical datum (NAVD88) used hereafter. Data processing included several steps (Fig. 3). Transects were established; the system was calibrated with the bar-check plate; time, echosounder water depth, and DGPS position were recorded in a text file on the laptop; linear regression was used to interpolate water surface elevation from staff gage readings taken at 15-min intervals; and data records were

Fig. 2 Field data collection with a shallow-water bathymetry system adjusting bottom elevations to NAVD88 datum by reading an adjacent surveyed staff gage

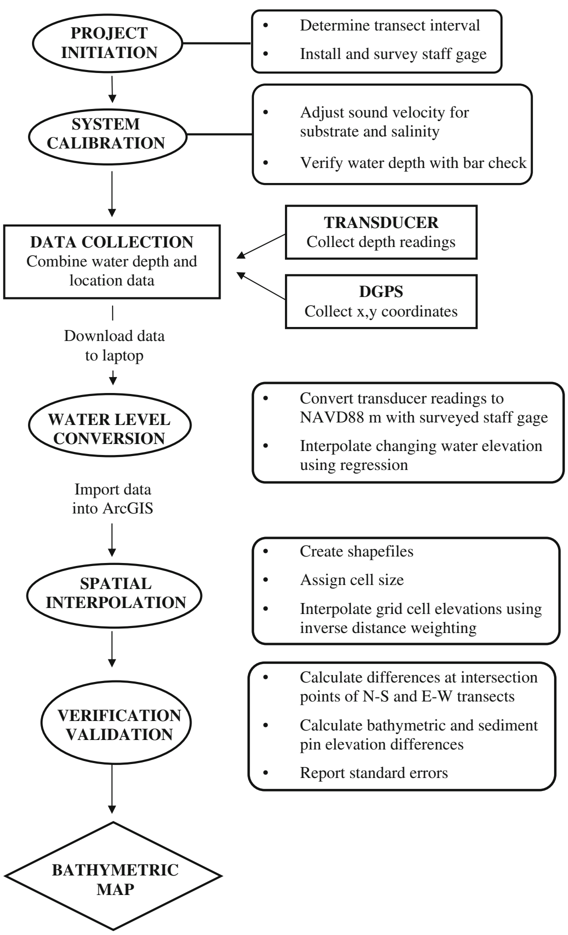

Fig. 3 Flow chart representing bathymetric data collection, processing, and the final bathymetry map product

converted to latitude, longitude, and average elevation in a custom program written in SAS 9.1 (SAS software 2003).

The elevation dataset was interpolated with inverse distance weighting (ArcGIS Geostatistical Analyst, ESRI, Redlands, California) to generate bathymetric grid maps (grid cell size: 12.5 × 12.5 m). We used the cut-fill feature in Spatial Analyst (ArcGIS, ESRI, Redlands, California) to determine volumetric difference between the 2004 and 2005 bathymetry maps (Price 2002). The cut-fill feature is a raster calculator that analyzes the difference in elevation for each grid cell, calculates volume by multiplying the elevation difference by grid cell area, and spatially identifies the areas and volume of the surfaces that have been modified. To determine how a 50% reduced sampling effort would affect the bathymetry product, we subsampled the 2005 survey such that only data from transects at 50 m intervals were represented.

We verified our bathymetry system and data processing procedure by conducting 22 east–west transects as well as the 25 north–south transects in 2005 and analyzing the mean and standard errors of the intersection points that were within a 1-m radius. Since the surveys were conducted at different times and tides, the intersection points represent the repeatability of elevation values with changing water levels. We validated our data by comparing elevations derived from the bathymetry grids with elevations measured with sediment pins (Woo et al. 2007). Twenty-four sediment pins (5 cm diameter, schedule-40 PVC) were installed prior to the levee breach, but we used the 9 pins in the interior that remained inundated during low tides for validation. The top of the sediment pins were surveyed to NAVD88 to establish their elevation. The length of the pin was measured with a graduated pole fitted with a flat disk to minimize sinking in soft substrates. We averaged two readings taken at opposite sides of the sediment pin 1 month after the bathymetry surveys were conducted. The surface elevation was calculated by subtracting the length of the pole from the elevation at the top of the pole. The sediment pin elevations were compared to the closest bathymetry elevation data from which means and standard errors were generated. Sediment volume from the nine sediment pins was calculated using the mean value of sediment accumulation from February 2004 and October 2005 and multiplying by the area of project interior (23.3 ha), excluding upland areas.

Results

The bathymetry survey grid covered 23.3 ha of the 29-ha site excluding the levees and upland areas and consisted of 1,489 grid cells (Fig. 4). We completed 20 north–south transects in 2004 and 25 in 2005, as well as 3 east–west transects in 2004 and 22 in 2005 to verify our results. We obtained 12,713 discrete measurements during 4 h of fieldwork in 2004 and 18,631 locations during 7 h in 2005. We verified the repeatability of elevation measurements with 810 intersection points from north–south and east–west transects and obtained a mean difference of 2.1 ± 0.2 cm (Table 1).

In 2004 (Fig. 5a–b), the main channel extended from the breach of the site northwest 296 m with channel depths ranging from −1.52 m near the breach to −0.57 m farther from the breach. A mud flat formed in the center of the site, ranging from −0.06 to 0.33 m. In 2005 (Fig. 5c–d), a sill (0.10 ± 0.00 m) formed at the breach, and as sediment filled the channel, its depth decreased from the mouth to the upper end (0.31–0.49 m) and the channel length decreased by 50%. The center of the mud flat had the highest elevation, ranging from 1.01 to 1.30 m. From 2004 to 2005, sediment accreted throughout the site (Fig. 5e) and was at a mean elevation of 0.62 m and the elevation ranged from −1.52 m in the channel to 1.84 m at the marsh edge (Fig. 5d). The bathymetry method generated a sediment volume increase of 132,900 m^3 and sediment accretion averaged 57.1 ± 1.1 cm over the grid cells. The greatest elevation gain (2.0 m) was at the northern section of the channel, while the greatest erosion (0.60 m) was in the main channel near the breach.

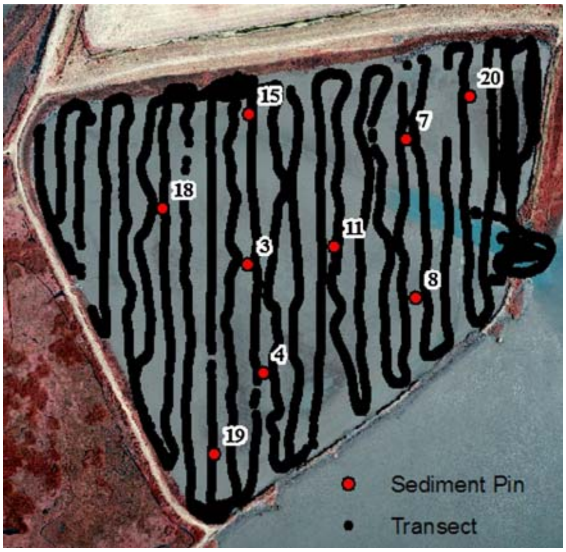

Fig. 4 Location of bathymetry survey transects and sediment pins

Table 1 Comparison of mean spot elevations (cm) at overlapping north–south and east–west transects at the Tubbs Setback tidal marsh restoration on San Pablo Bay

Variable	Value
Number of comparable elevation points	810
Mean number of spot elevation points at each location	1.60
Mean difference	2.08
Standard error of mean difference	0.20
Minimum difference	0.00
Maximum difference	30.20
Grid elevations from transects separated by 25 m	0.62
Grid elevations from transects separated by 50 m	0.62

Differences in mean grid elevations from transects separated by 25 and 50-m are reported

We validated the bathymetry method by comparing surface elevations from sediment pins and the echosounder system interpolation grid. The difference in elevation at the sediment pin locations between the two methods was 2.0 ± 1.0 cm in 2004, and 2.1 ± 0.2 cm in 2005. Sediment pin data (Table 2) corroborated the sedimentation patterns detected with the echosounder system. The mean accumulation at sediment pins (Fig. 4) was 33% greater than that of the bathymetry grids at 76.1 ± 2.5 cm. The estimated change in sediment volume from the 9 sediment pins was 177,050 m^3 or 44,150 m^3 more than the estimated accretion from the echosounder system. For the 12.5 × 12.5 m grid cells, the mean elevation (0.62 m) did not differ whether we used north–south transects separated by 25 m or half as many transects separated by 50 m.

Discussion

Callaway et al. (2001) identified hydrologic and topographic surveys as essential elements of tidal marsh restoration monitoring. In the San Francisco

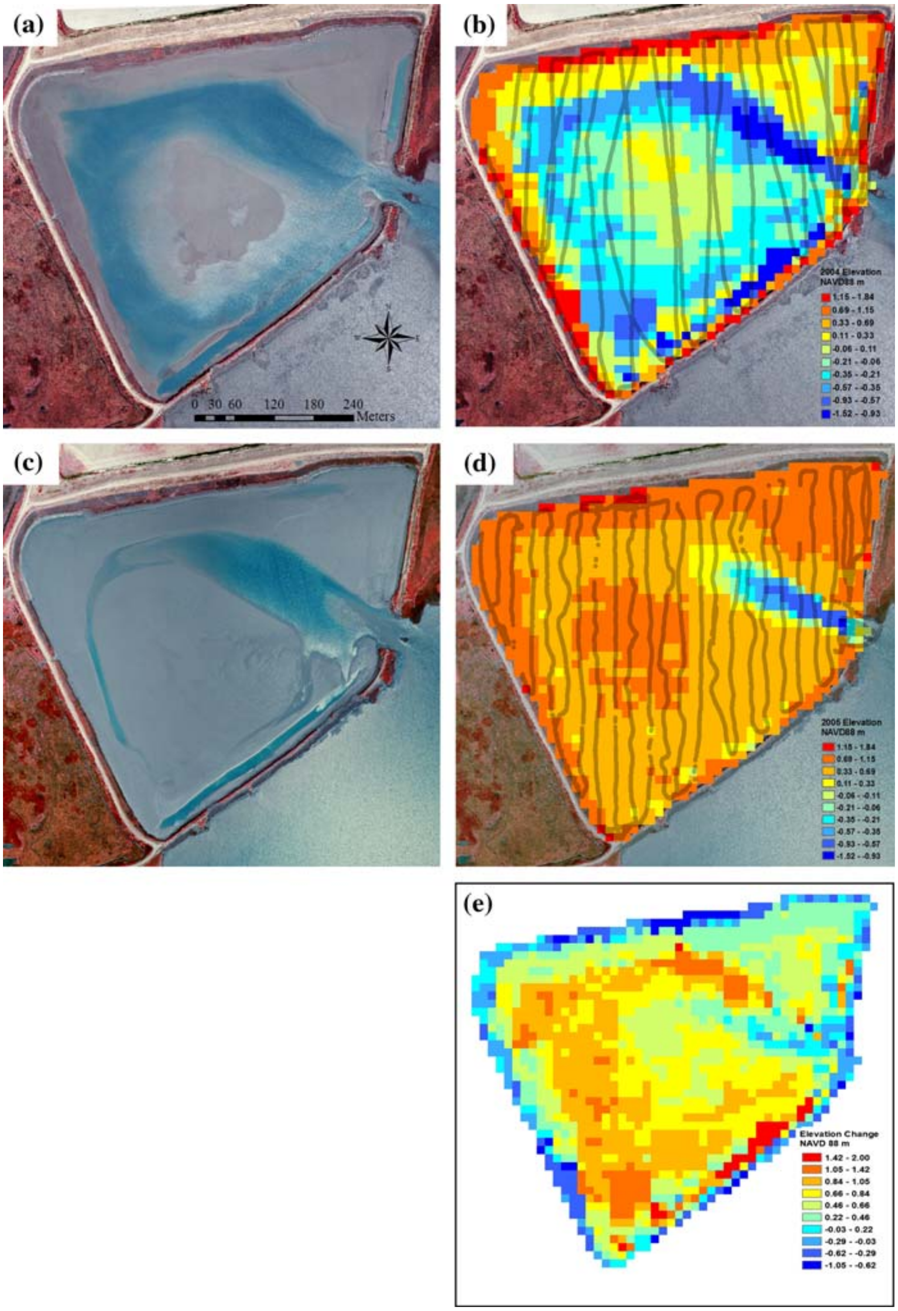

Fig. 5 Tubbs Setback tidal marsh restoration site in the North San Francisco Bay, California including: (**a**) 2004 aerial photograph, (**b**) 2004 bathymetry map (NAVD88 m), (**c**) 2005 aerial photograph, (**d**) 2005 bathymetry map (NAVD88 m), (**e**) bathymetry map of change in surface elevation between 2004 and 2005

Bay estuary, planning for tidal marsh restoration projects have typically included detailed models of sediment accretion and site evolution, but few projects have conducted detailed monitoring of the site following the breach. Our shallow-water echo-sounder system proved effective at estimating topographic change in early restoration. In San Pablo Bay where there is a large supply of sediment (Jaffe et al. 1998), we measured sediment accretion of 57.1 cm/year in the second year of the Tubbs Setback restoration. Sediment accretion was higher at this site compared to other San Pablo Bay restoration sites that ranged from 15.0 cm/year (Tolay Creek: author's unpublished data) to 32.2 cm/year (Guadalcanal: Woo et al. 2008). However, sedimentation may differ by site because of unique sediment loads, wind

Table 2 Comparison of bottom elevations (NAVD88) estimated within elevation grids (12.5 × 12.5 m squares) and 9 sediment pins at the 29-ha Tubbs Setback tidal marsh restoration on San Pablo Bay

			Elevation (m)		
Pin#	Northing	Easting	Grid	Pin	Difference
3	4219789	549663	0.74	0.70	0.04
4	4219661	549681	0.65	0.64	0.01
7	4219937	549849	0.70	0.65	0.05
8	4219750	549860	0.53	0.52	0.01
11	4219810	549764	0.65	0.66	−0.01
15	4219967	549665	0.71	0.65	0.06
18	4219855	549563	0.70	0.65	0.05
19	4219566	549624	0.52	0.49	0.03
20	4219988	549923	0.77	0.79	−0.02

The grid map was interpolated from north–south transects separated by 25 m with a shallow-water, single beam-echosounder system

and wave resuspension (McKee et al. 2006), salinity, bottom topography (Schoellhamer 2001), and hydrogeomorphology (Steiger and Gurnell 2002), and Tubbs Setback was highly subsided with a direct breach to San Pablo Bay.

At the Tubbs Setback restoration, we obtained systematic samples along north–south transects separated by 25 m to create a bathymetric map with 12.5 × 12.5 m grid cells. However, we found that the overall estimate of sedimentation was the same with transects separated by 50 m, probably because the mud flat elevation in this site was relatively uniform. Although we could have selected smaller grid cells, each would have been based on fewer points and interpolation may have been less accurate. Typically, a more accurate bathymetric map could be developed by increasing the number of transects and decreasing their separation, but this may not provide additional information if the site is relatively uniform, such as at Tubbs Setback, and may increase the time needed for the surveys, which may not be practical. The transect interval can be adjusted accordingly depending on the spatial scale and the desired resolution. For example, at a 529-ha restoration site, we used transects separated by 125 m (Takekawa et al. 2006). On such large sites, it can be difficult to navigate more closely aligned transects, the fieldwork time may be prohibitive, and additional staff gages would be needed to relate water levels to an established elevation datum.

Our procedure was designed to increase the spatial coverage of sedimentation patterns and map developing marsh plain, not necessarily to map smaller features such as channels. Since channels may be <1 m wide, they may not be captured on survey transects and it would be difficult to conduct enough systematic transects to document their development, unless efforts were made to target these features of interest at known locations. On the other hand, data points along linear features like deep borrow ditches will equally influence neighboring cells within and outside of the ditch, potentially distorting mud flat areas. To prevent ditches or channels from distorting the mud flat, it is possible to use barrier lines to isolate them during the interpolation process in GIS. Aerial photographs taken at low tide may be used to identify developing channels, linear surveys could be conducted to measure their depth, and barrier lines could be used to retain them in the map during interpolation.

Unlike methods such as sediment pins or marker horizons that provide a limited set of sample points, grid maps created from the echosounder system provided a more detailed, comprehensive, and accurate view of the entire project. The echosounder system was able to reveal much more variation in sedimentation including zones of sedimentation and erosion near the mouth where sediment pins were lacking. The lack of spatial resolution using sediment pins can lead to gross distortions of overall sediment gain or loss. The sediment pin data overestimated the change in sediment volume for the site compared with the bathymetry volume calculation, largely because sediment pins were not located in the developing channel.

Though the bathymetry system verification differences were small, we acknowledge that sources of survey error may be attributed to differences in survey timing and extent, variation in reading staff gages, and differences in water level across a site. Our bathymetry system results also matched well with spot elevations at sediment pins locations, though sediment pin measurements may not be very accurate because of their local effect on water flow causing bottom surface erosion, and the measurement poles may penetrate into unconsolidated sediments.

Although the initial capital outlay for the bathymetry system exceeded $12,000 US, we have since used it to map more than 35 sites, demonstrating that the shallow-water bathymetry system can be a cost-effective tool for monitoring restoration processes. We are now using a real-time kinematic (RTK) corrected GPS survey unit (Leica Smart Rover GPS 1200, Leica Geosystems Inc., Atlanta, Georgia) and RTKMax service with total station integration (Haselbach Surveying Instruments Inc., Burlingame, California) to increase the accuracy of our system and replace two components of our system (US Geological Survey, unpublished data). The Leica GPS 1200 can accurately determine horizontal and vertical position of our boat, eliminating the need for staff gages to reference water depths to a vertical datum (Freeman et al. 2003; Thomas and Ridd 2004). This will reduce a source of measurement error by eliminating the use of staff gages to record fluctuating water elevations and simplify data processing.

Acknowledgments This study was supported by the US Geological Survey, Western Ecological Research Center (WERC) and US Geological Survey, California Water Science Center (CAWSC). Restoration monitoring support was provided by the US Fish and Wildlife Service Ecological Services, San Francisco Bay Estuary Program (R. Morat) and the San Pablo Bay National Wildlife Refuge through the United Heckathorn Trustee Council. We are grateful to M. Kolar, M. Parker, J. Bradley, and M. Stewart for administrative assistance; B. Winton, C. Smith, and G. Block for logistical support; J. Bluso, K. L. Turner, A. Rowan, H. Bohmann, A. Westhoff, D. Gaube, and L. Dembosz (WERC) for field assistance; S. Carroll and F. Reid (Ducks Unlimited), Hans Haselbach (Haselbach Surveying Instruments Inc), P. Goebel (Shoreline Engineering), and J. Kulpa (Environmental Data Solutions) for survey and design information; and J. Yee for assistance with analysis programs. We appreciate the helpful comments of J. Callaway and G. Wylie to improve the manuscript. The use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

Boumans RMJ, Day JW Jr (1993) High precision measurements of sediment elevation in shallow coastal areas using a sediment-erosion table. Estuaries 16:375–380. doi:10.2307/1352509

Byrnes MR, Baker JL, Li F (2002) Quantifying potential measurement errors associated with bathymetric change analysis. ERDC/CHL CHETN-IV-50. US Army Engineer Research and Development Center, Vicksburg

Cahoon DR, Turner RE (1989) Accretion and canal impacts in a rapidly subsiding wetland II. Feldspar marker horizon technique. Estuaries 12(4):260–268. doi:10.2307/1351905

Cahoon DR, Reed DJ, Day JW Jr (1995) Estimating shallow subsidence in microtidal salt marshes of the southeastern United States: Kaye and Barghoorn revisited. Mar Geol 128:1–9. doi:10.1016/0025-3227(95)00087-F

Callaway JC, Sullivan G, Desmond JS, Williams GD, Zedler JB (2001) Assessment and monitoring. In: Zedler JB (ed) Handbook for restoration tidal wetlands. CRC Press, Boca Raton

Doyle TW, Michot TC, Wells CJ (2002) Modeling the bathymetry of Catahoula Lake: specialized technology for wetland management. US Geological Survey. National Wetlands Research Center. Fact Sheet 098–02. Lafayette, LA

Freeman CW, Bernstein DJ, Mitasova H (2003) Rapid response 3D survey techniques for seamless topo/bathy modeling: 2003 Hatteras Breach, North Carolina. Shore Beach 72:3–7

Gilvear D, Tyler A, Davids C (2004) Detection of estuarine and tidal river hydromorphology using hyper-spectral and LiDAR data: Forth estuary, Scotland. Estuar Coast Shelf Sci 61:379–392. doi:10.1016/j.ecss.2004.06.007

Goals Project (1999) Baylands ecosystem habitat goals: a report of habitat recommendations prepared by the San Francisco area wetlands ecosystem goals project. US Environmental Protection Agency, San Francisco, California and San Francisco Regional Water Quality Control Board, Oakland

Jaffe BE, Smith RE, Torresan LZ (1998) Sedimentation and bathymetric change in San Pablo Bay: 1856–1983: US geological survey open-file report 98–759

McKee LJ, Ganju NK, Schoellhamer DH (2006) Estimates of suspended sediment entering San Francisco Bay from the Sacramento and San Joaquin Delta, San Francisco Bay, California. J Hydrol (Amst) 323(1–4):335–352. doi:10.1016/j.jhydrol.2005.09.006

Montalto FA, Steenhuis TS (2004) The link between hydrology and restoration of tidal marshes in the New York/New Jersey estuary. Wetlands 24:414–425. doi:10.1672/0277-5212(2004)024[0414:TLBHAR]2.0.CO;2

Odum WE, Odum EP, Odum HT (1995) Nature's pulsing paradigm. Estuaries 18:547–555. doi:10.2307/1352375

Price M (2002) Deriving volumes with ArcGIS spatial analyst. ArcUser News October–December: 52–55

San Francisco Bay Joint Venture (2008) Project database, http://www.sfbayjv.org/tools.html. Cited 19 March 2008

SAS Software (2003) SAS language, version 9.1. SAS Institute Inc, Cary

Schoellhamer DH (2001) Influence of salinity, bottom topography, and tides on locations of estuarine turbidity maxima in northern San Francisco Bay. In: McAnally WH, Mehta AJ (eds) Coastal and estuarine fine sediment transport processes. Elsevier Science B.V, Amsterdam, pp 343–357

Siegel SW (1998) Petaluma River Marsh monitoring report 1994 to 1998. Unpublished Report. Stuart Siegel wetlands and water resources. San Rafael, CA, pp 38

Simenstad CA, Thom RM (1996) Functional equivalency trajectories of the restored Gog-Le-Hi-Te estuarine wetland. Ecol Appl 6:38–56. doi:10.2307/2269551

SPBNWR (San Pablo Bay National Wildlife Refuge) (1998) Final Tubbs island restoration plan and environmental assessment Report. US Fish and Wildlife Service. Sacramento Fish and Wildlife Office, Sacramento

Steiger J, Gurnell AM (2002) Spatial hydrogeomorphology influences on sediment and nutrient deposition in riparian zones: observations from the Garonne River, France. Geomorphology 29(1–2):1–23

Takekawa JY, Miles AK, Schoellhamer DH, Athearn ND, Saiki MK, Duffy WD, Kleinschmidt S, Shellenbarger GG, Jannusch CA (2006) Trophic structure and avian communities across a salinity gradient in evaporation ponds of the San Francisco Bay estuary. Hydrobiologia 567:307–327. doi:10.1007/s10750-006-0061-z

Thomas S, Ridd PV (2004) Review of methods to measure short time scale sediment accumulation. Mar Geol 207:95–114. doi:10.1016/j.margeo.2004.03.011

Wilcox C, Los Huertos M (2005) A simple, rapid method for mapping bathymetry of small wetland basins. J Hydrol (Amst) 301:29–36. doi:10.1016/j.jhydrol.2004.06.027

Williams PB, Orr MK (2002) Physical evolution of restored breached levee salt marshes in the San Francisco Bay estuary. Restor Ecol 10:527–542. doi:10.1046/j.1526-100X.2002.02031.x

Woo I, Takekawa JY, Rowan A, Gardiner RJ, Block GT (2007) The Tubbs setback restoration project: 2006 Final report. Administrative report. US Geological Survey, Western Ecological Research Center, San Francisco Bay Estuary Field Station, Vallejo 70 pp

Woo I, Takekawa JY, Gardiner R (2008) Guadalcanal Tidal Marsh Restoration: 2007 Annual data summary report, US Geological Survey, Western Ecological Research Center, San Francisco Bay Estuary Field Station, Vallejo 62 pp

Yang X (2005) Use of LIDAR elevation data to construct a high-resolution digital terrain model for an estuarine marsh area. Int J Remote Sens 26:5163–5166. doi:10.1080/01431160500218630