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Determining Ground Surface Topography in Tidal Marshes Using Watermarks

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ABSTRACT

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The structure and function of intertidal communities are intimately linked with hydrologic regime, which itself is defined by elevation gradients relative to sea level. Water surfaces have long been used as a reference plane for determining topographic profiles of the underlying ground surface. Although relatively straightforward in static systems such as lakes or ponds, this method is more complicated in the intertidal zone where the water surface is in vertical motion. Here we evaluate a technique using water marks to indicate maximum tide heights from which ground elevations relative to a tidal datum can be calculated. Comparisons of data using this technique to optical-leveling surveys in several salt marshes of Connecticut and Massachusetts showed that the water surface conformed to a horizontal plane at high, slack tide and that watermarks could be used as a reliable reference plane for determining ground elevations from flooding depth.

ADDITIONAL INDEX WORDS: *Tide sticks, salt marsh, elevations, flooding depth.*

INTRODUCTION

Ground surface elevation, thus the temporal pattern of flooding, is one of the most important factors influencing tidal marsh hydrology, biogeochemistry, and biology (BOCKELMANN *et al.*, 2002; DAY *et al.*, 1987). Although elevations in tidal marshes can be determined using optical- or laser-leveling systems, these approaches can be fraught with a number of difficulties. For example, vegetation may interfere with sight lines and instrument stability can be problematic when set on marsh peat. From a logistical standpoint, optical leveling is limited to relatively short distances between survey points, which means that multiple turning point level loops (with potential errors accumulating at each instrument setup) are needed for large study areas. With laser leveling, dust, fog, wind, and temperature variations can interfere with measurements and the instruments themselves are heavy, delicate, and expensive. Real time kinematic differential global positioning system is an effective system but still cost prohibitive. Finally, many people simply lack these kinds of surveying equipment or staff that are properly trained to use it.

In this study, we describe a rapid and inexpensive method to obtain ground elevations (relative to a single point designated as hydrographic zero) in tidal marshes using watermarks that show maximum high-tide water surface elevations. The watermarks serve as reference points delineating a horizontal plane above the marsh surface from which relative ground elevations are then calculated. Although watermarks have long been used as a simple way to collect topographic data in static aquatic systems (*i.e.,* freshwater lakes, ponds, *etc.*), there are only scattered references to their use in intertidal habitats (COLLINS, 2002; FELL *et al.*, 2003). Moreover, we could find no rigorous evaluation of the underlying assumption that the water surface over particular study areas approximates a horizontal plane during high, slack tide. Here, we directly compare relative elevations calculated from watermark data with those obtained by differential leveling using optical surveying equipment. Given the level of effort being invested in assessing and monitoring coastal ecosystems worldwide, we felt that such an evaluation would be of interest to those who study and manage such ecosystems.

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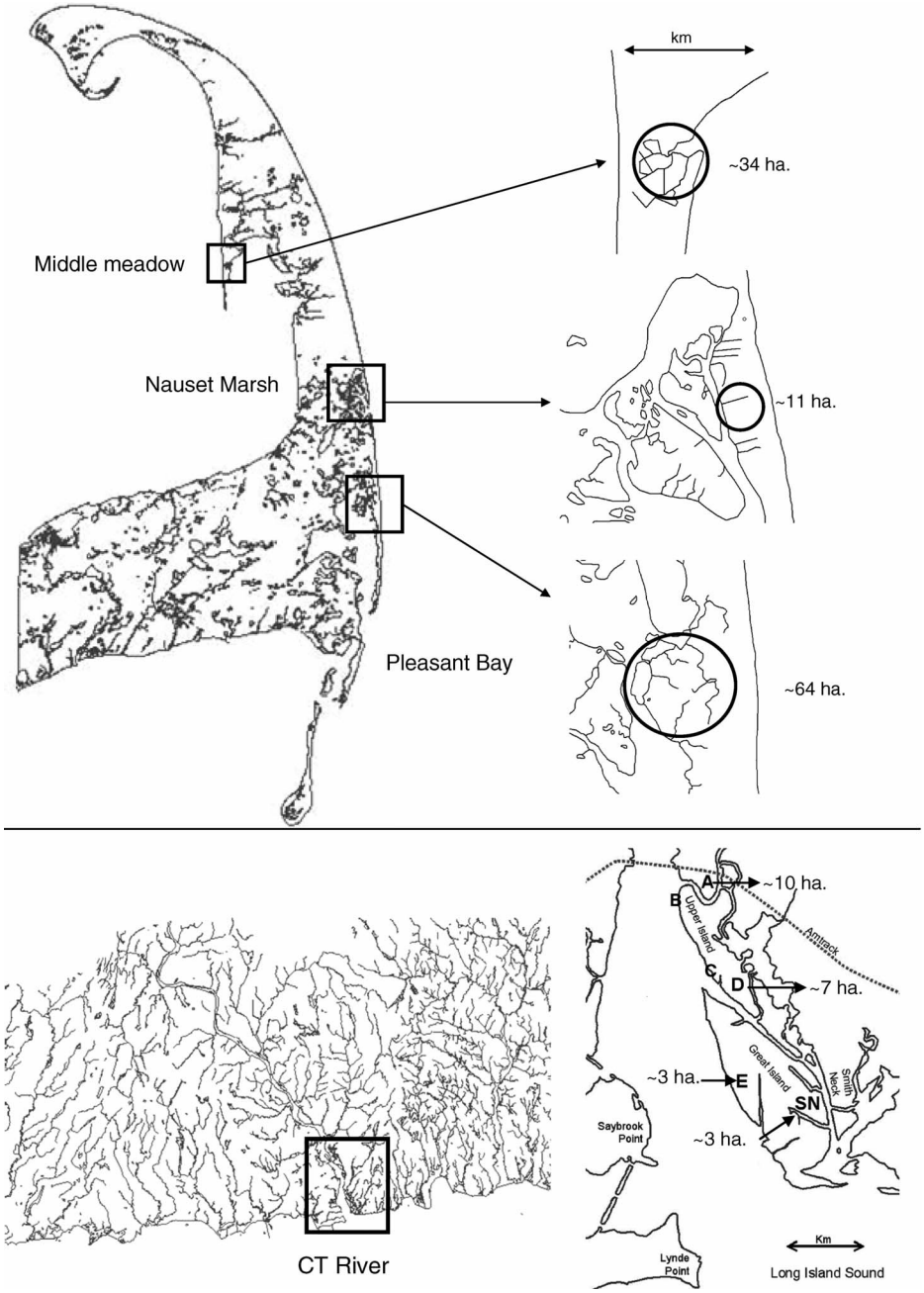

Figure 1. Map of Cape Cod (top) and Connecticut River (bottom) study areas (boxes enclose the larger marsh systems; circles enclose the approximate study area within each marsh).

METHODS

Study Sites

Data were collected from parts of three different salt marshes within Cape Cod National Seashore (CCNS) (Massachusetts) and from four areas at the mouth of the Connecticut River (CT River) (Connecticut). Two of the CCNS marshes, Nauset and Pleasant Bay, are back-barrier marshes on the Atlantic side of the outer Cape Cod peninsula. The third CCNS marsh, Middle Meadow, is an embayment within Great Island that lies between Wellfleet Bay and Cape Cod Bay (Figure 1). The CT River sites, areas A, D, E, and Smith Neck, are located where the CT River meets Long Island Sound (Figure 1). Benchmarks at all the CCNS sites and in area A of the CT River were previously surveyed by optical leveling where arrays of permanent plot markers (polyvinyl chloride [PVC] pipe) had been previously surveyed by differential leveling (automatic level with 32× telescope).

High tides in Nauset Harbor and Wellfleet Bay average 1.84 and 3.07 m above mean low water with maximum tidal amplitudes of 2.5 and 4.0 m (data from National Oceanic and Atmospheric Administration Center for Operational Oceanographic Products and Services). Pleasant Bay and the lower CT River estuary both fluctuate by 1.4 m with mean high tides reaching 0.99 and 1.06 m. Vegetation at both the CCNS and CT River sites is comprised of typical salt and brackish marsh species including *Spartina alterniflora* (smooth cordgrass), *Spartina patens* (salt meadow hay), *Salicornia* spp. (glassworts), *Sueada* spp. (sea blights), *Scirpus* spp. (bulrushes), *Typha angustifolia* (narrow-leaved cattail), and *Phragmites australis* (common reed).

Tide Sticks

High tide levels are marked as flooding removes a soluble pigment from the surface of a stick or rod (a "tide stick"). At CCNS, wooden dowels (0.5 cm diameter, 120 cm in length) were pushed approximately 20 cm into the sediment next to the plot markers. Using a small paint brush, liquid chocolate syrup was applied to the exposed portion of the dowels. In Nauset Marsh, dowels were established at 18 plots during low tide of three spring tide periods (March, May, and June, 2004). In Middle Meadow and Pleasant Bay, 12 and 24 dowels were set out on single occasions in July and November, 2004, respectively. During low tide the next day the distance from the ground surface to the watermark, which was demarcated by a sharp discontinuity in the coating caused by its dissolution in water, was measured with a meter stick and recorded. At the CT River site, tide sticks were clean dead stems of *Phragmites australis* prepainted with a mixture of one part water-soluble glue and one part food coloring. These were deployed on three occasions in areas D, E, and Smith Neck and four times in area A between June and August 2004.

For each watermark datum, relative ground elevations (RE) were calculated in relation to the site with the highest elevation (*i.e.,* the site with the shortest ground-to-watermark distance), which was designated as hydrographic zero (value of 0). The RE of all other points were then calculated as RE $= 0 - (D_x - D_{hz})$, where D_x is the distance from the ground to the watermark at plot X and D_{hz} is the distance from the ground to the watermark at hydrographic zero. To evaluate the correspondence between RE determined by high tide marks and by leveling, values for the same sets of benchmarks were compared by linear regression with trend lines forced through the origin.

RESULTS

CCNS Sites

The range of elevations in Nauset Marsh was 0.83 m (Figure 2A). Watermark patterns were very consistent among the different times during which the tests were run and the average standard deviation for any one benchmark among surveys was very low, ranging between 0 and 0.036 m with an average of 0.007 m. In Middle Meadow and Pleasant Bay, the difference between high and low points in the survey was 0.63 m and 0.73 m, respectively (Figures 2B, 2C). For all sites, there was a very close linear relation between RE determined by optical leveling and those determined by watermarks. Slope coefficients for each regression approached 1.0 and R^2 values were ≥ 0.96.

CT River Sites

In area A, minimum and maximum watermark heights differed by 0.65 m (Figure 2D). Correspondence between tide stick and benchmark data for this area resembled that observed for the CCNS sites. The linear regression explaining the relation between minimum and maximum watermark was associated with a high R^2 value and slope very close to 1.0. Temporal variability among RE among the 10 points in areas A and D was very low over four sample dates (SD $<$ 0.01 m, Table 1). By contrast, there were much larger variations among sample dates in area E and Smith Neck. Standard deviations for the CT River sites ranged between 0.005 m and 0.06 m.

DISCUSSION

Calculating RE from watermarks in the manner described here relies implicitly upon the assumption that the water surface is virtually flat and horizontal at high tide. At the CCNS and CT River sites, this assumption appears to be valid on the basis of the relation between elevations determined by watermarks *vs.* optical leveling. Additional support comes from tide gauge data from Nauset Harbor and Pleasant Bay (Cape Cod, Massachusetts), which indicate that high tide heights in several embayments within the larger systems vary by only 2 cm or less (Aubrey *et al.*, 1997; MEP, 2003). Two apparent exceptions to this condition occurred in area E and Smith Neck of the CT River site. Both exhibited inconsistencies in the relative heights of watermarks among dates. However, area E is an interior portion of the system that is separated from the main tidal channel by an elaborate network of mosquito ditches, each bordered by small levees. Furthermore, some of these ditches have been fully or partially plugged while others have been dredged. As such, there is likely a hydrologic disconnect between area E and the main channel. Only during a few astronomically high tides that overtop the main river-edge levee does water cover the entire site as a continuous sheet. Unfortunately, we were not able to conduct the tide stick surveys on these occasions. The Smith Neck area is anomalous in that it is close to a large (and active) breach in the nearby barrier beach. As such, waves and surges from the sound are likely affecting this location. Since it is also an area of considerable boat traffic, wakes are probably a factor here as well (the use of stilling wells may have mitigated these effects).

For all sites, it was necessary to conduct the sampling during or near the spring tide periods, when the highest elevations are completely inundated. Given that there is substantial variation among marshes, it is advisable to first establish some test markers as a way to choose optimal tides and tide stick heights for the work. It should also be noted that other kinds of coatings and substrates, such as cork dust on the inside of clear tubes, can serve in place of syrup or glue–dye

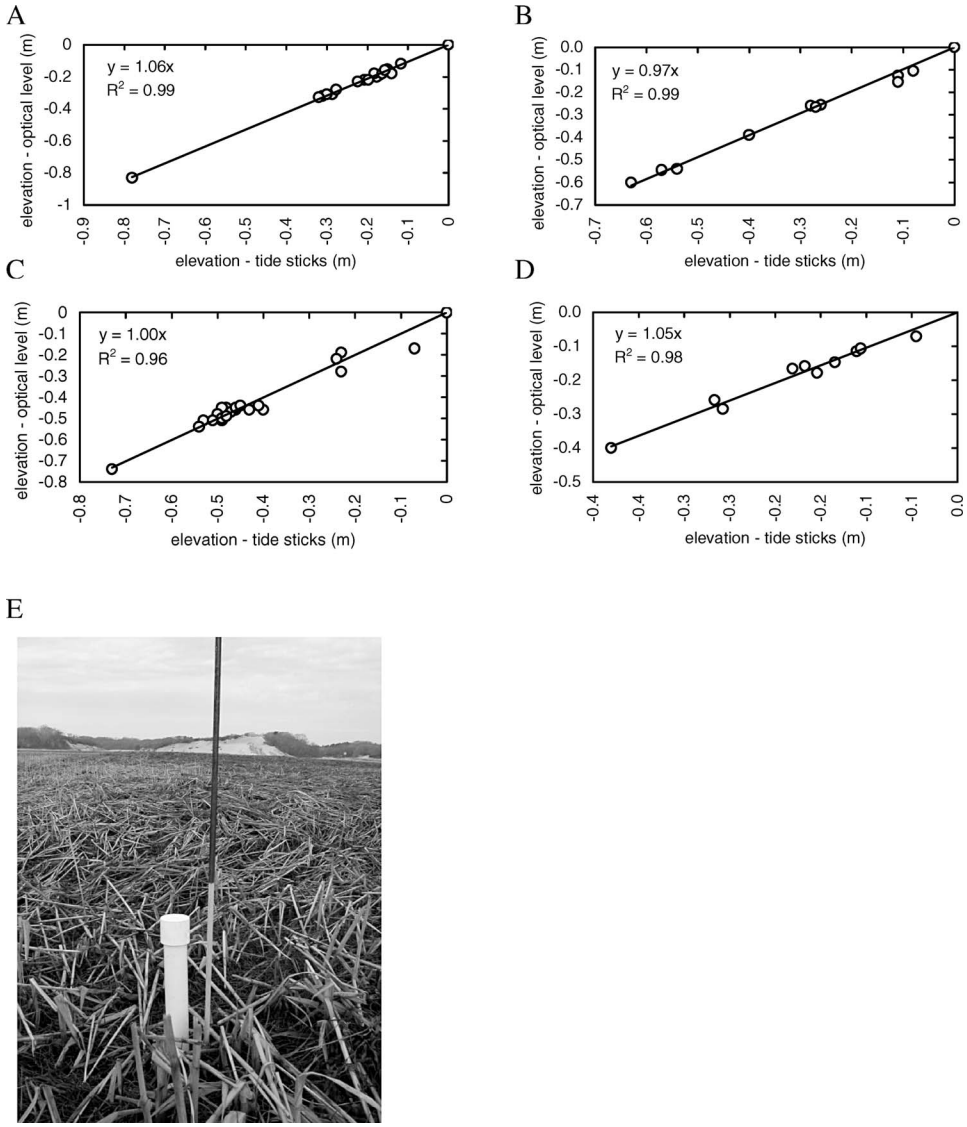

Figure 2. Linear regression of relative elevations determined by optical leveling *vs.* watermarks on tide sticks (A) Nauset Marsh, (B) Middle Meadow, (C) Pleasant Bay, (D) area A (Connecticut River), and (E) watermark left by the previous high tide in March 2004 (adjacent polyvinyl chloride pipe is the benchmark).

Table 1. *Temporal variability in water marks (SD = standard deviation of mean elevations relative to hydrographic zero,* N *= number of observations per run).*

Site	Dates (2004)	Mean SD (m)	*N*
Nauset (CCNS)	March 4, May 5, June 7	0.007	18
Area A (CT River)	June 29, July 1, July 30, August 2	0.008	5
Area D (CT River)	July 6, July 28, July 30	0.005	3
Area E (CT River)	June 29, July 6, August 2	0.034	3
Smith Neck (CT River)	June 29, July 6, August 2	0.034	3

CCNS = Cape Cod National Seashore; CT River = Connecticut River.

mixtures (R.S. WARREN, unpublished data). Regardless of the material used, it is critical that it adhere firmly to the substrate but dissolve quickly in water without capillary rise or subsequent gravity flow after a mark has been left. For obvious reasons rainfall is another potential problem, but one that can be solved by placing PVC or butyrate tubing over the dowel—provided that there are small holes drilled into the side to allow for water rise and fall and an end cap to prevent rainfall from entering through the top. This also has the desirable effect of stilling the water surface. In relatively protected back-barrier marshes, the disruption of the water surface by wind-generated waves should generally not be a problem within vegetated areas as the plants have huge dampening effect. Where marshes are more open to the

ocean, however, waves may not be a trivial concern. In larger basins, high winds also can force water to pile up on one side and cause a significant deviation of the water table from a horizontal position (Seiche effect).

In general, tide sticks provide extremely useful data in return for a relatively small investment of time, money, and manpower. A large area of marsh can be surveyed by a single person and only one plot needs be tied in to an established benchmark (preferably one in proximity to the study site) to determine actual elevations. If the benchmark itself is subject to tidal flooding, a tide stick can be established right next to it and high tide elevations calculated by measuring from the known elevation point to the watermark. If the benchmark is on dry land, optical or laser leveling can be used to determine the difference between the benchmark and the ground surface at the closest plot. Alternatively, nearby tide gauges can serve as a basis for calculating elevations (FELL *et al.*, 2003; WARREN *et al.*, 2001), simply by subtracting the watermark D_x values from the maximum tide gauge readings during the period of tide stick deployment. However, the further away a gauge is located from the study site, the greater the chance that error will be introduced because of deviations of the water table from horizontal across that distance. Notwithstanding, simply knowing flooding depths across marshes, regardless of ground elevations, is highly useful in itself. However, caution must be taken when working across extremely large areas or at sites with complex hydrodynamics. Abnormalities in water surface topography caused by such things as large freshwater discharges, dikes/levees, boat wakes, *etc.* may produce significant error. Under these circumstances, this watermark method may not be applicable.

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