science for a changing world

Prepared in cooperation with the
Connecticut Department of Energy and Environmental Protection

A One-Dimensional Diffusion Analogy Model for Estimation of Tide Heights in Selected Tidal Marshes in Connecticut

Scientific Investigations Report 2013–5076

U.S. Department of the Interior
U.S. Geological Survey

Cover. Oblique photograph of Sybil Creek Marsh, Connecticut, looking eastward from the mouth of Sybil Creek where it enters Branford Harbor, 2003. Courtesy of the Department of Energy and Environmental Protection, Bureau of Water Protection and Land Reuse, and the Office of Long Island Sound Programs.

A One-Dimensional Diffusion Analogy Model for Estimation of Tide Heights in Selected Tidal Marshes in Connecticut

By David M. Bjerklie, Kevin O'Brien, and Ron Rozsa

Prepared in cooperation with the
Connecticut Department of Energy and Environmental Protection

Scientific Investigations Report 2013–5076

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Bjerklie, D.M., O'Brien, Kevin, and Rozsa, Ron, 2013, A one-dimensional diffusion analogy model for estimation of tide heights in selected tidal marshes in Connecticut: U.S. Geological Survey Scientific Investigations Report 2013–5076, 17 p., http://pubs.usgs.gov/sir/2013/5076/.

Contents

Figures

Tables

Conversion Factors and Datum

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
section (640 acres or 1 square mile)	259.0	square hectometer (hm^2)
square mile (mi^2)	2.590	square kilometer (km^2)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) and the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

A One-Dimensional Diffusion Analogy Model for Estimation of Tide Heights in Selected Tidal Marshes in Connecticut

By David M. Bjerklie, Kevin O'Brien, and Ron Rozsa

Abstract

A one-dimensional diffusion analogy model for estimating tide heights in coastal marshes was developed and calibrated by using data from previous tidal-marsh studies. The method is simpler to use than other one- and two-dimensional hydrodynamic models because it does not require marsh depth and tidal prism information; however, the one-dimensional diffusion analogy model cannot be used to estimate tide heights, flow velocities, and tide arrival times for tide conditions other than the highest tide for which it is calibrated. Limited validation of the method indicates that it has an accuracy within 0.3 feet. The method can be applied with limited calibration information that is based entirely on remote sensing or geographic information system data layers. The method can be used to estimate high-tide heights in tidal wetlands drained by tide gates where tide levels cannot be observed directly by opening the gates without risk of flooding properties and structures. A geographic information system application of the method is demonstrated for Sybil Creek marsh in Branford, Connecticut. The tidal flux into this marsh is controlled by two tide gates that prevent full tidal inundation of the marsh. The method application shows reasonable tide heights for the gates-closed condition (the normal condition) and the one-gate-open condition on the basis of comparison with observed heights. The condition with all tide gates open (two gates) was simulated with the model; results indicate where several structures would be flooded if the gates were removed as part of restoration efforts or if the tide gates were to fail.

Introduction

Tide gates and ditching are known to affect marine estuaries and estuarine habitats by reducing the tidal range, decreasing the number of pools, and changing the volume of the tidal prism and the inflow and outflow rates (Roman and others, 1984; Coats and others, 1989; Roman and others, 1995; Giannico and Souder, 2004; Adamowicz and Roman, 2005). Decreased flow rates in turn reduce the scouring ability of the tidal channel which can hasten sedimentation (Coats and others, 1989; Giannico and Souder, 2004). Predicting the tide heights inland of tide gates and other hydromodifications (for example, constrictions, culverts, and bridges) is an important element of planning estuary and marsh restoration, especially because dwellings and recreational facilities are often located immediately next to the estuary boundary and may be within the unobstructed tidal prism with foundations below the unobstructed tide height.

In this study, a method was developed for estimating tide heights by using a one-dimensional diffusion model. The Connecticut Department of Energy and Environmental Protection (CTDEEP) has identified nine priority wetlands as being substantially affected by tide gates; therefore, an investigation of improved methods for understanding the effects of hydromodifications was undertaken. For this study, conducted by the U.S. Geological Survey (USGS) in cooperation with the CTDEEP, two of those sites were included in the analysis (Sybil and Pine Creeks), along with two non-priority sites that have sufficient data for the analysis. The locations of the four sites are shown in figure 1. The method developed during the study uses observed tide heights downstream and upstream from the tide gates, tide height within the marsh, and hydraulic modeling to estimate the high-tide height for any given design or regulatory tidal range. Readily available geospatial source information (at a minimum, orthophotography) and limited calibration data were used. The method does not require detailed information about the depth of the tidal marsh or extensive field data collection, and estimates can be made from available geographic information system (GIS) data with minimal expense.

The method can be used as a guide to assist in land-use planning and wetland restoration, or to identify and quantify risks to development in or adjacent to the coastal floodplain from future tidal floods or gate failures. The method could lead to a more accurate and consistent estimation of the limits of extreme high water for use by managers, engineers, and other interested parties.

Estimates developed from the method can be used as a guide to determining when changes, impingement, and alterations to the marsh upstream from tide gates require state permits and to help property owners realize that they are proposing development in the coastal floodplain that could be damaged by future spring tidal floods or gate failure.

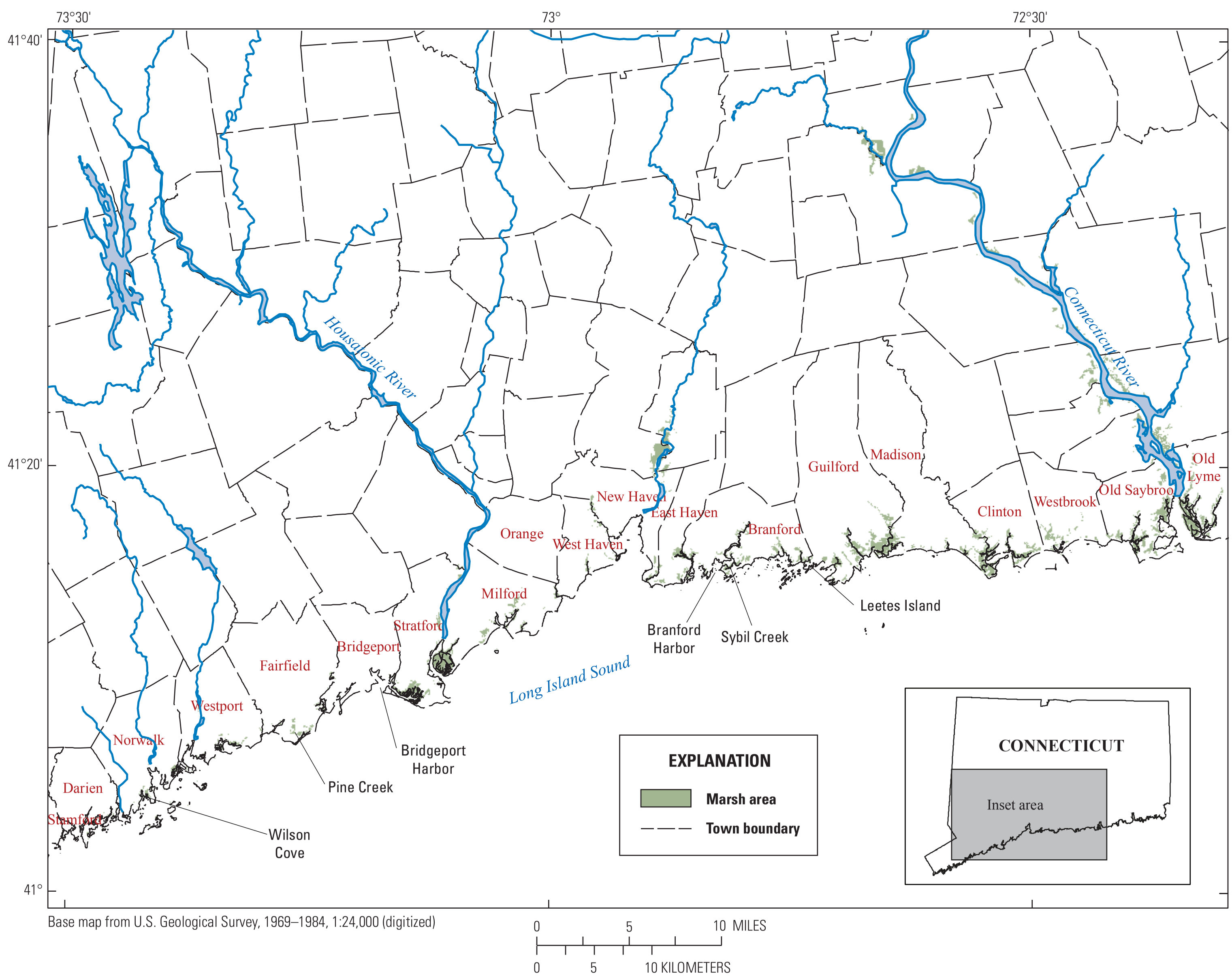


Figure 1. Locations of Pine Creek, Sybil Creek, Leetes Island, and Wilson Cove marshes in Connecticut used for calibration and validation of a one-dimensional diffusion analogy model.

Purpose and Scope

This report describes the one-dimensional diffusion analogy model used to estimate tide heights in marshes with tide gates. Calibration and validation are described, and the data used for calibration and validation of the model are presented in tables. An example application of the method is presented.

Study Sites

This study used data from four previously studied tidal marshes to develop and calibrate the model. The sites are located on the Connecticut shoreline along Long Island Sound and include Pine Creek in Fairfield, Sybil Creek in Branford, Wilson Cove in Norwalk, and Leetes Island Cove in Guilford. Pine Creek and Sybil Creek (fig. 1) are two of the CTDEEP priority marshes; both contain more than one constricted opening, including tide gates, channelization, culverts, and bridges. The two other marshes used in this study, Leetes Island and Wilson Cove, do not have developed areas in the floodplain but provided a range of values that could be used to develop calibration relations between the size of the opening and the attenuation of the tidal surge.

Three of the marshes were studied by the consulting firm Milone and MacBroom: Sybil Creek in 1987, Leetes Island in 1999, and Wilson Cove in 1999 (Milone and MacBroom Consulting Engineers, 1987, 1999a, 1999b, respectively). These studies included tidal monitoring and mapping of the marsh; the Leetes Island study also included a two-dimensional modeling application as part of a marsh restoration study. Pine Creek marsh was studied by the USGS (Larry Weiss, U.S. Geological Survey, written commun., 1992); tidal monitoring and assessment of the marsh response to the tide were part of a preliminary study for the Town of Fairfield, Conn. The preliminary study was designed to assess the feasibility of developing a hydrodynamic model of the marsh.

Each of the study marshes had available tide-height information and mapping that was used to characterize the hydraulic conditions in the main tidal channels and in the vegetated marsh areas. The four marshes were visited by USGS personnel for the current study, and the hydromodifications (in the form of constrictions to flow at culverts) were observed and measured for opening size and general hydraulic conditions.

All of the marshes, except Wilson Cove, have tide gates that operate with varying levels of efficiency. Pine Creek and Sybil Creek each have more than one hydromodification—constricted bridge openings and open culverts—in addition to the tide gates. The tide gates at Sybil Creek consist of two approximately 4-foot by 4-foot openings. Under normal operating conditions with the gates closed, ponds and salt pannes in the Sybil Creek marsh show small or negligible tidal flux, indicating that they are isolated or above the height of the tidal flux. The leakage through the gates is greatly reduced (as of 2010) compared to leakage when Milone and MacBroom (1987) did their study. However, during the Milone and MacBroom study (1987), one of the gates was opened to allow for observation of tidal flux at various points in the marsh. Both gates could not be opened because the resulting tidal flood threatened to inundate adjacent properties. The other three marshes all show tidal flux within the marsh. The tide gates at Pine Creek consist of two 4-foot-diameter circular gated culverts that were open at the time of the earlier USGS study (Larry Weiss, U.S. Geological Survey, written commun., 1992). Leetes Island has a single, gated 3.5-foot-diameter culvert that was open at the time of the Milone and MacBroom study (1999a). Wilson Cove marsh is connected to Long Island Sound by twin 6-foot-diameter corrugated metal pipes with no gates.

Modeling Method and Calibration

A relatively simple method to estimate tide heights in marshes has been developed that can be used in regions and with scenarios in which tide heights cannot be directly measured. The objectives are to use readily available data and apply the method to any marsh with relatively small effort. This simplified, one-dimensional diffusion model was developed, tested, and used to derive tide heights at the boundary of a marsh. The method was designed to be easily adaptable to other regions of the coast, and it requires only planimetric marsh geometry and the size of the gate opening (leakage) to define the relation between downstream and upstream tidal events. Because this approach does not consider the tidal prism (volume) explicitly, the flood height is transferred inland without attenuation resulting from storage, except as a consequence of a calibration of the diffusion coefficient. Therefore, the method is considered to provide a conservative estimate (the highest potential height).

Other modeling methods that have been used to estimate tide heights in estuaries include one and two dimensional analytical and numerical solutions to unsteady flow equations that are based on flow resistance (momentum) and conservation of mass (Roman and others, 1995; Coats and others, 1989). These models require channel and marsh depth and calibrated flow resistance coefficients. In comparison, the method developed in this report requires a calibrated diffusivity coefficient but does not require measured or estimated flow depth as input to the model. In effect, the diffusivity coefficient incorporates flow resistance and depth into a single calibration. Because of this, the model presented here can be calibrated and applied by using only planimetric information available from maps and readily available geospatial data (orthophotography, GIS data layers) However, the diffusion model presented here is not a complete representation of the marsh geometry; it provides a potential height value as a function of distance, tidal range, and diffusive characteristics.

The model employs a one-dimensional harmonic function using a diffusion analogy adapted from a method to estimate the effect of tides on groundwater levels (Turner and others, 1996; Todd, 1980, p. 242–247; Ferris, 1951). This method was used to estimate the attenuation of a periodic wave (tide) with distance and over time within a marsh. For this method, which incorporates Darcy's Law (Todd, 1980, p. 242–247), it is assumed that flow conditions are laminar, velocity head is minimal (low Reynolds number), and there is a linear proportionality between flow resistance and head loss and an inverse proportionality between flow and length of the flow path. These assumptions are reasonable for the marsh because the flow is contained within the spaces between the marsh vegetation (analogous to flow in porous media), but flow may not be contained in the open channels and constricted openings to the marsh, such as inlet culverts.

Some of the hydraulic issues that may arise as a result of flow in the channels and culverts include change in flow resistance as flow depth changes and head differences upstream and downstream from constrictions. Because of these hydraulic issues, the model is calibrated only for the high-tide level of interest. Predictions for tidal conditions at less than high tide are not considered calibrated and may not be reasonable.

The basic diffusion equation is

$$\frac{\partial^2 h}{\partial x^2} = D_f \frac{\partial h}{\partial t}, \tag{1}$$

where

- D_f is the diffusion coefficient (hereafter referred to as the diffusivity with units of time divided by length squared, T/L^2);
- h is the volumetric height (L);
- t is time (T); and
- x is volumetric length (L).

This equation can be readily developed from the one-dimensional transient equation of continuity and a one-dimensional equation of motion. The transient equation for continuity (Turner and others, 1996) is

$$\frac{\partial h}{\partial t} = \frac{1}{S_x} \frac{\partial (hv)}{\partial x}, \tag{2}$$

where

- S_x is the storativity of the volume (the available storage in the volume, dimensionless); and
- v is the net flow velocity out of the volume (L/T).

An equation of motion for laminar flow, provided by Darcy's law (Turner and others, 1996; Todd, 1980, p. 242–247), is

$$v = K \frac{dh}{dx}, \tag{3}$$

where

- K is the conductance coefficient (hydraulic conductivity, L/T).

Darcy's law is a simple representation of a flow resistance equation that assumes a linear response to changes in head (depth). Fick's Law (Fisher and others, 1979) is identical in form to Darcy's Law and results in the classic one-dimensional diffusion equation (eq. 1). As such, the method used here is a mass diffusion equation for movement of water into the marsh.

Substituting Darcy's law (eq. 3) into equation 2 results in

$$\frac{\partial h}{\partial t} = \frac{1}{S_x} \frac{\partial (Kh \frac{dh}{dx})}{\partial x}. \tag{4}$$

Simplifying with Kh equal to the transmissivity, T (L^2/T),

$$\frac{\partial h}{\partial t} = \frac{T}{S_x} \frac{\partial^2 h}{\partial x^2}. \tag{5}$$

A comparison of equations 1 and 5 shows that, in this application, the diffusivity (as defined for eq. 1) for the marsh is equivalent to the inverse of the ratio of transmissivity to storativity. The transmissivity values are assumed to be very high for open water and much smaller for the vegetated marsh; similarly, the storativity is assumed to range from 1 for open water to a fraction for the vegetated marsh. Relating the diffusivity to the transmissivity and storativity provides a means to estimate the diffusivity from estimated hydraulic properties of the marsh characteristics.

Assuming the boundary conditions of a periodic change in head at the outlet of the marsh are represented by a sine function for the daily tidal flux and that at $h = 0$, $x = \infty$, the solution to equation 5 is (Ferris, 1951; Todd, 1980, p. 242–247; and Turner and others, 1996)

$$h_x = h_0 e^{-x} \sqrt{\frac{\pi D_f}{t_0}} \tag{6}$$

and

$$t_L = x \sqrt{\frac{t_0 D_f}{4\pi}}, \tag{7}$$

where

- h_x is one-half the maximum tidal amplitude at distance x from the source, in feet;
- h_0 is one-half the maximum tidal amplitude at source, in feet;
- x is distance from tidal source, in feet;
- t_0 is tidal period, per day;
- t_L is the time (lag time) required for h_x to be reached relative to the source, per day;
- D_f is diffusivity, per day per square feet; and
- π is the ratio of the circumference to the diameter of a circle.

A value for D_f was calibrated for channel and marsh distances between known points of tide height with equation 2 by matching the tide-height observations. The approach used here is to measure the travel length (distance) on a map along the open channel; then, to estimate a travel length through the marsh, draw a straight line perpendicular to the flow path from the channel out into the marsh. The calibration of the model was achieved by fitting the best value for diffusivity, given the measured lengths that result in the observed tide heights. Through this procedure, values of diffusivity for the vegetated marsh and channel environments were determined. On the basis of the calibration, the range of diffusivity values for the open channel and the marsh tended to be similar at the different sites (see tables 1 and 2), low for the vegetated marsh and very low for the open water.

The assumption of a linear response between head change and flow resistance requires that flow resistance does not change with head, implying that friction is uniform. Considering tidal flow into the marsh through the marsh vegetation, this assumption may be reasonable; however, it is not necessarily reasonable for flow in the open channels of the marsh and through the constricted opening to the marsh, such as a culvert. These issues are addressed through calibration of the diffusivity, but the calibration, therefore, applies only to a specific flow condition; in this study, that flow condition is the high tide. Lower tide heights cannot be relied upon; therefore, the time of arrival may have substantial errors as a result of improper accounting for the time of travel at lower tide levels.

Similarly, D_f was calibrated for channel sections with constrictions, including tide gates, bridges, and culverts. The diffusivity estimated for the constrictions was determined as described above for the channel and marsh. Where the marsh is broken into different regions by in-line structures, a model was derived for each region, and models were used in series (a link-node type model). For locations with more than one structure at a constriction, all of the structures were modeled with a constant diffusivity.

A relation was derived between the size of the opening at each constriction and the calibrated diffusivity through the constriction for all four study sites (fig. 2). The cross-sectional areas shown in figure 2 reflect the hydromodification caused by the opening size of the constriction; however, the diffusivity value accounts for the effects of the length of the culvert and channel positioned between the calibration points. These effects are assumed to be small relative to the effect of the opening. Thus, the curve shown is applicable to the data in this study but is not a general relation, and provides a means to estimate a change in diffusivity given alternative or hypothetical opening sizes (for example, gates fully open, gates closed, gates half open). In the future, a more general relation between dimensionless scalars could be developed to characterize openings and diffusivity, such as opening diameter divided by culvert length and opening area divided by area of the inflow channel. The small data set available here precluded a more in-depth analysis.

Recognizing the limited data used to develop the relation between the diffusivity (D_f) and the constricted opening, the sensitivity of the model to different values for the D_f and travel length (x) was assessed. Doubling of D_f results in a 12-percent increase in the simulated tidal height (h_x); halving D_f results in a -15-percent change in h_x (it is a log function such that the larger the change in D_f the less change in h_x). The h_x is also sensitive to the travel length (x) over which D_f is applied; the shorter the x, the less error is introduced by a different D_f.

The high-tide height is based on the simulated attenuation of the tidal amplitude determined using equation 6. The height of the high tide is determined from the estimated height relative to the tidal datum. The length of time for the arrival of the high tide (lag time, calculated from eq. 7) was not used as a calibration criterion but serves as a verification of the method.

The results of the calibration for all four marshes are shown in table 1. Approximate locations of the observed and estimated tide heights and the location of structures for Sybil Creek marsh, a typical marsh, are shown in figure 3. The tide heights were fit by adjusting the diffusivity and thus are in good agreement with the observed heights. This method can be used to estimate tidal range, peak tide height, and lag times to the peak height.

The lag times were not used in the calibration and thus serve as a qualitative validation of the method. The lag-time estimates are not considered to be as accurate as the tide-height estimates because (1) the actual flow path is unknown (and not simulated) and thus may differ from the assumed path as represented by the flow length in the simulation and (2) the calibration is for the high tide only with no representation of the time needed for water to move into the marsh at intermediate tide heights. Where lag times are available for comparison, the method provides reasonable values for the sites, with the exception of Wilson Cove, where the estimated lag times and observed lag times are an order of magnitude different. The reason for this may be that there are large storage effects in this marsh; however, it does not seem reasonable that the observed lag time at station 2c (fig. 3), which is only 25 feet (ft) from the edge of the channel, requires an observed time of 34 minutes for the tide to travel from the source 280 ft downstream. This indicates that there may be an issue with the time stamp for the observed values relative to the timing of the tidal cycle. Alternatively, the model may not appropriately represent the travel path or physical characteristics associated with this marsh.

The lag time is a function of distance, diffusivity, and the tidal period but not the tidal range or height (eq. 7). Thus, for a given point in the marsh, given the same geometric conditions governing diffusivity and distance, the lag time should be the same for a given tidal period. The model shows this result, although it is best to keep in mind that the lag time does not reflect time on a clock, and it is assumed that the tidal period remains constant. Because the timing and height estimates are derived from the length and diffusivity values, the tide heights can be mapped in two dimensions given an appropriate scheme for assigning the diffusivity and travel length to any point of interest within the marsh.

Table 1. Calibration results based on data from Sybil Creek, Pine Creek, Lettes Island, and Wilson Cove, Connecticut.

[The observation station designations are taken from the site studies (Milone and MacBroom, 1987; Larry Weiss, U.S. Geological Survey, written commun., 1992; Milone and MacBroom, 1999a; Milone and MacBroom, 1999b). The letter c denotes that the station is in a channel, and the letter m denotes that the station is in the marsh. Elevations are in feet above the National Geodetic Vertical Datum of 1929; ft, feet; min, minutes; --, no data; t_0, tidal period; D_f, diffusivity; ft^2, square feet; h_0, ½ the tidal amplitude; h_x, ½ the tidal amplitude at distance x from the tidal source; t_L, the time lag required for h_x to be reached. Variables correspond to equations 6 and 7]

Observation station	Distance of segment x (ft)	t_0 (day)	D_f (day/ft²)	Variables						
				h_0 (ft)	h_x (ft)	Estimated height (ft)	Observed height (ft)	Difference between estimated and observed heights (ft)	t_L estimated (min)	t_L observed (min)
Sybil Creek			14-July, 1987							
P2	700	0.5	5.26E-08	7	4.68	3.01	3.02	-0.01	46.13	45
P3	875	0.5	2.63E-08	4.68	3.28	2.11	2.11	0	86.9	60
S1c	800	0.5	5.00E-12	4.68	4.66	3	--	--	46.64	--
S1m	400	0.5	1.25E-07	4.66	3.27	2.1	2.1	0	86.75	--
S2c	1,350	0.5	5.00E-12	3.28	3.25	2.09	--	--	87.77	71
S2m	150	0.5	5.00E-07	3.25	2.49	1.6	1.61	--	118.23	90
Pine Creek			22-June, 1992							
Dam Road	1,750	0.5	3.33E-14	5.6	5.6	4.1	4.1	0	--	--
Salt Meadow	6,550	0.5	8.33E-12	5.6	5.34	3.91	3.9	0.01	--	--
Old Field	2,000	0.5	4.76E-10	5.34	4.78	3.5	3.5	0	--	--
Leetes Island			19-Mar., 1999							
Sta2	170	0.5	5.43E-06	6	2.22	1.63	1.63	0	113.84	140
Sta3	1,200	0.5	1.00E-10	2.22	2.16	1.58	1.58	0	117.28	--
Sta4c	1,930	0.5	10.00E-12	2.22	2.19	1.6	--	--	119.04	--
Sta4m	150	0.5	8.33E-09	2.19	2.11	1.55	1.55	0	122.97	180
Sta5c	1,430	0.5	10.00E-12	2.22	2.2	1.61	--	--	120.34	--
Sta5m	300	0.5	5.00E-09	2.2	2.08	1.53	1.53	0	126.43	--
Wilson Cove			7-Oct., 1999							
Sta2c	240	0.5	3.33E-09	8.99	8.68	5.79	5.78	0.01	3.98	--
Sta2m	25	0.5	2.50E-08	8.68	8.6	5.73	5.72	0.01	5.12	34
Sta3 (at culvert)	530	0.5	3.33E-12	8.68	8.66	5.77	5.77	0	4.26	55
Sta5	450	0.5	5.00E-11	8.66	8.59	5.73	5.72	0.01	5.17	59
Sta6	65	0.5	3.33E-09	8.59	8.51	5.67	5.67	0	6.25	50
Sta7 (at culvert)	1,320	0.5	1.67E-11	8.66	8.55	5.69	5.69	0	6.72	62

Table 2. Validation results based on data from Pine Creek, Lettes Island, and Wilson Cove, Connecticut.

[The observation station designations are taken from the site studies (Milone and MacBroom, 1987; Larry Weiss, U.S. Geological Survey, written commun., 1992; Milone and MacBroom, 1999a; Milone and MacBroom, 1999b). The letter c denotes that the station is in a channel, and the letter m denotes that the station is in the marsh. Elevations are in feet above the National Geodetic Vertical Datum of 1929; ft, feet; min, minutes; --, no data; t_0, tidal period; D_f, diffusivity; ft^2, square feet; h_0, ½ the tidal amplitude; h_x, ½ the tidal amplitude at distance x from the tidal source; t_L, the time lag required for h_x to be reached. Variables correspond to equations 6 and 7]

Observation station	Distance of segment x (ft)	t_0 (day)	D_f (day/ft^2)	Variables						
				h_0 (ft)	h_x (ft)	Estimated height (ft)	Observed height (ft)	Difference between estimated and observed heights (ft)	t_L estimated (min)	t_L observed (min)
Leetes Island			7-Apr., 1999							
Sta2	170	0.5	5.43E-06	5	1.85	1.26	1.55	-0.29	113.84	95
Sta3	1,200	0.5	1.00E-10	1.85	1.8	1.22	1.5	-0.28	117.28	--
Sta4c	1,930	0.5	10.00E-12	1.85	1.82	1.24	--	--	119.04	--
Sta4m	150	0.5	8.33E-09	1.82	1.76	1.2	1.4	-0.2	122.97	180
Sta5c	1,430	0.5	10.00E-12	1.85	1.83	1.24	--	--	120.34	--
Sta5m	300	0.5	5.00E-09	1.83	1.74	1.18	1.45	-0.27	126.43	--
Leetes Island			16-Apr., 1999							
Sta2	170	0.5	5.43E-06	4.45	1.65	1.28	1.5	-0.22	113.84	55
Sta3	1,200	0.5	1.00E-10	1.65	1.6	1.24	1.33	-0.09	117.28	--
Sta4c	1,930	0.5	10.00E-12	1.65	1.62	1.26	--	--	119.04	--
Sta4m	150	0.5	8.33E-09	1.62	1.57	1.22	1.25	-0.03	122.97	115
Sta5c	1,430	0.5	10.00E-12	1.65	1.63	1.26	--	--	120.34	--
Sta5m	300	0.5	5.00E-09	1.63	1.54	1.2	1.3	-0.1	126.43	--
Wilson Cove			23-Sep., 1999							
Sta2c	240	0.5	3.33E-09	5.5	5.31	4.67	--	--	3.98	--
Sta2m	25	0.5	2.50E-08	5.31	5.26	4.63	--	--	5.12	--
Sta3 (at culvert)	530	0.5	3.33E-12	5.31	5.3	4.66	4.73	-0.07	4.26	35
Sta5	450	0.5	5.00E-11	5.3	5.26	4.63	4.66	-0.03	5.17	71
Sta6	65	0.5	3.33E-09	5.26	5.21	4.58	4.67	-0.09	6.25	45
Sta7 (at culvert)	1,320	0.5	1.67E-11	5.3	5.23	4.6	4.67	-0.07	6.72	58
Pine Creek			21-June, 1992							
Dam Road	1,750	0.5	3.33E-14	5.4	5.4	4.1	4.05	0.05	--	--
Salt Meadow	6,550	0.5	8.33E-12	5.4	5.15	3.91	3.7	0.21	--	--
Old Field	2,000	0.5	4.76E-10	5.15	4.61	3.5	3.45	0.05	--	--

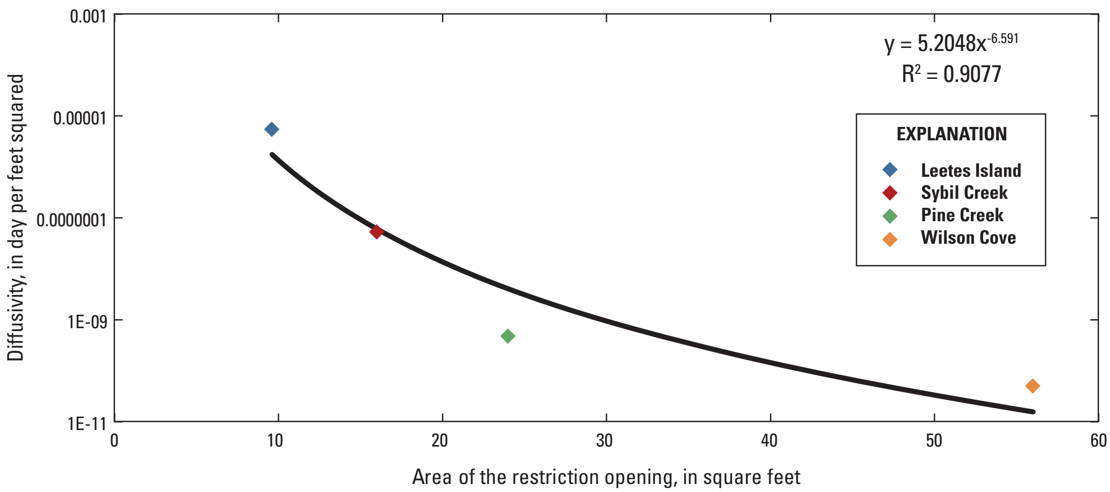


Figure 2. The area of the constriction opening that forms the hydromodification to the effective diffusivity of the opening for Pine Creek, Sybil Creek, Leetes Island, and Wilson Cove marshes, Connecticut.

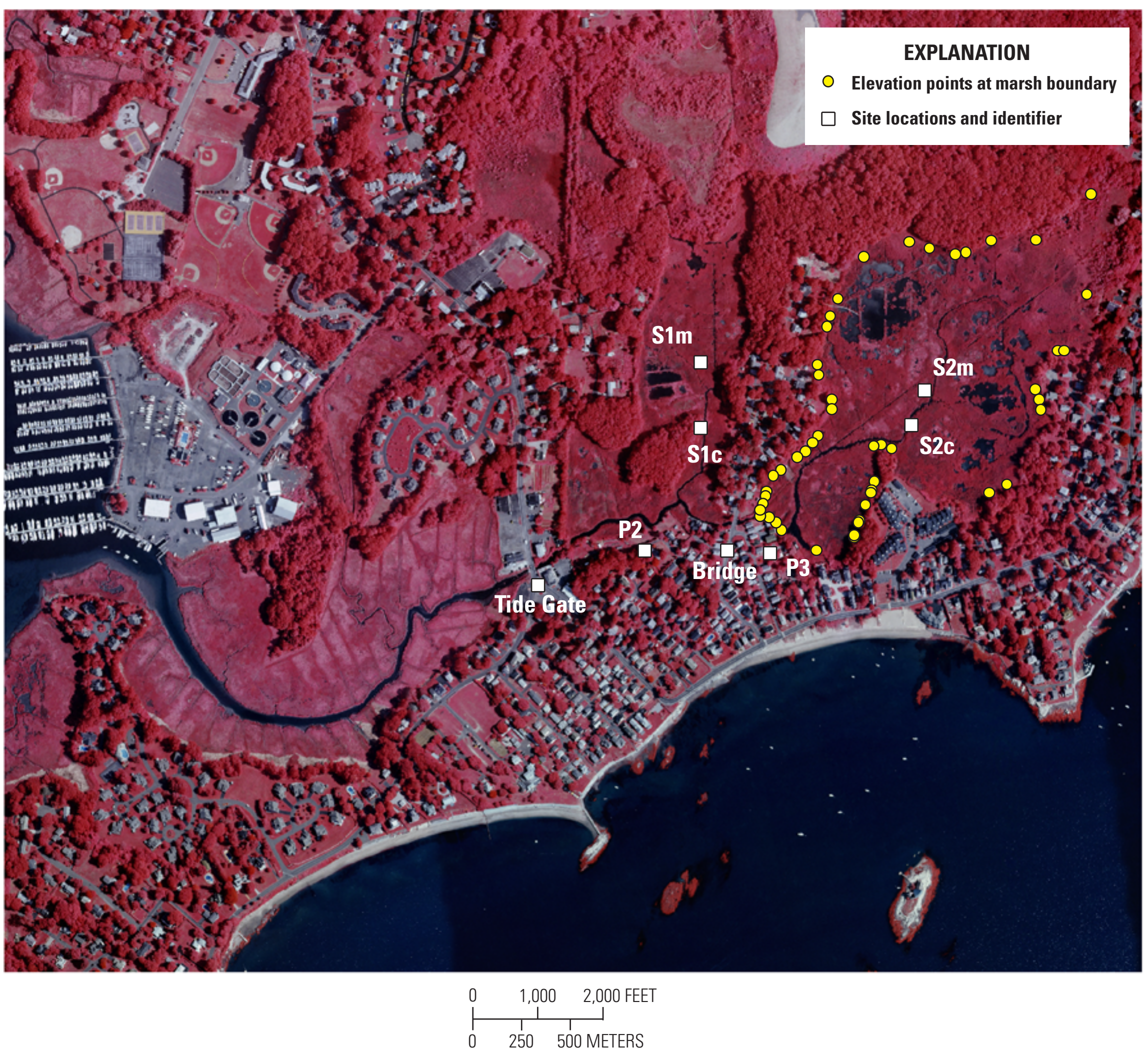


Figure 3. Approximate locations of observed and estimated elevation points at the boundary of Sybil Creek marsh, Connecticut.

Method Validation and Application for Sybil Creek

The method was validated by applying it to the four marshes by using different dates for which observed tide heights were available. The method was applied to the Sybil Creek marsh to estimate the high-tide elevation around the perimeter of the marsh.

Validation

The method was validated by using the calibrated values for diffusivity to estimate tide heights in Leetes Island marsh, Wilson Cove marsh, and Pine Creek marsh for days not used in the calibration and comparing the estimates against observed heights. In most cases, the data used for validation were separated by more than a few weeks from the data used for calibration. This could not be done with the Sybil Creek marsh because observations were made on 1 day only during the study period. The results of the validation test are provided in table 2. On the basis of this validation, the method accuracy averages about ±0.1 to 0.2 foot with a maximum error of 0.3 foot (the largest error between simulated and observed tide heights). The model had a tendency to under predict tide heights at all sites, except Pine Creek. Given the small number of sites and the consistent range of error (positive or negative), it was not feasible to evaluate whether there is any relation between marsh characteristics and error.

Example Application

The method was tested for Sybil Creek in Branford, Conn., by using a GIS application to estimate tide heights at the upland edge of the eastern portion of the Sybil Creek marsh, which is shown on figure 4. The application extended the estimates across the marsh to the boundaries on the basis of travel distances along the marsh and in the open channels. Figure 3 shows the relation of the marsh boundary to the tide gate. This test was designed to model the height of a high tide at the boundary of the marsh with the tide gates open. Sybil Creek has two tide gates and one bridge constriction (fig. 5). The locations of these structures are shown on the infra-red photograph of the marsh (fig. 3), along with points of observed tide height (tables 1 and 2), and on figure 4.

In order to apply the model to any point in the marsh (and specifically to the boundary), a GIS method was developed to measure flow-path lengths and to estimate the amount of open water in the marsh. The open-water fraction along the flow paths was required so that the diffusive properties of the channel and open water could be considered separately from those in the marsh-grass regions of the marsh. The open-water fraction was estimated from three-band false color infrared orthophotography taken in the summer of 2005, which was provided by CTDEEP, using an image analysis software package MultiSpec (Landgrebe and Biehl, 2011). The software was used to distinguish between water and non-water (fig. 6) and was calibrated visually from selected representative areas of the orthophotography for classification. Areas of shadows appearing in the orthophotography were consistently identified as water by the program; these were removed manually.

The GIS was used to determine the marsh geometry and flow paths by first digitizing the centerline of the main channel within the marsh and then using a pre-existing geospatial dataset that defines the upland marsh boundary. From the channel centerline, perpendicular lines were constructed to the marsh boundary. The channel centerline was designed to allow perpendicular flow paths every 50 ft; however, the nature of the channel's orientation precluded the use of every flow path. In instances where multiple paths intersected or where multiple paths of varying length converged to the same region of the upland boundary, the shortest-length path was retained.

The channel was assumed to be the primary flow path into the marsh, and the perpendicular lines were assumed to represent the idealized flow path from the channel to the marsh boundary, along which the tidal wave was propagated. Figure 6 illustrates the water-surface area determined by using MultiSpec analysis of the infrared orthophotography. Figure 7 illustrates the flow paths, defined for the analysis, including the channel and perpendicular flow paths, as well as polygons that extend 25 ft on each side of the perpendicular lines. In order to classify the physical characteristics of the marsh in the region of the flow paths, the percentages of marsh and open water were determined for each of these polygons.

A spreadsheet was developed to compute (1) the estimated tide heights within the channel, as a function of distance from the tidal source and an assumed channel diffusivity, and (2) the estimated tide heights at the marsh boundary, as a function of the tide height at each channel node, the flow length through the marsh, and an assumed marsh diffusivity. The attenuation of the tide through the constriction was estimated by using the calibrated diffusivity for the tide gates and the bridge. The channel and marsh diffusivities were assumed to be constant with values of 5.00E-12 and 5.00E-09 day per square foot (day/ft^2), respectively. These are representative values determined from the calibration for all of the marshes.

The highest spring tides typically occur in October, and these are often used to determine the limits of extreme high water. In tidal marshes, this boundary can be located in the field through careful interpretation of wracklines deposited beyond upland borders by high spring tides. It is important to use the most recent high-tide values rather than an average of the highest tides over the lunar nodal cycle because the high-tide-line changes annually due to the metonic cycle and sea-level change. For this reason, the highest October spring tide for the three year period 2005 to 2007 was used for this study.

Figure 4. Oblique photograph of Sybil Creek marsh, Connecticut, looking eastward from the mouth of Sybil Creek where it enters Branford Harbor, 2003. Courtesy of the Department of Energy and Environmental Protection, Bureau of Water Protection and Land Reuse, and the Office of Long Island Sound Programs.

Figure 5. The tide gate in closed position (left) and the bridge constriction (right) on Sybil Creek, Connecticut.

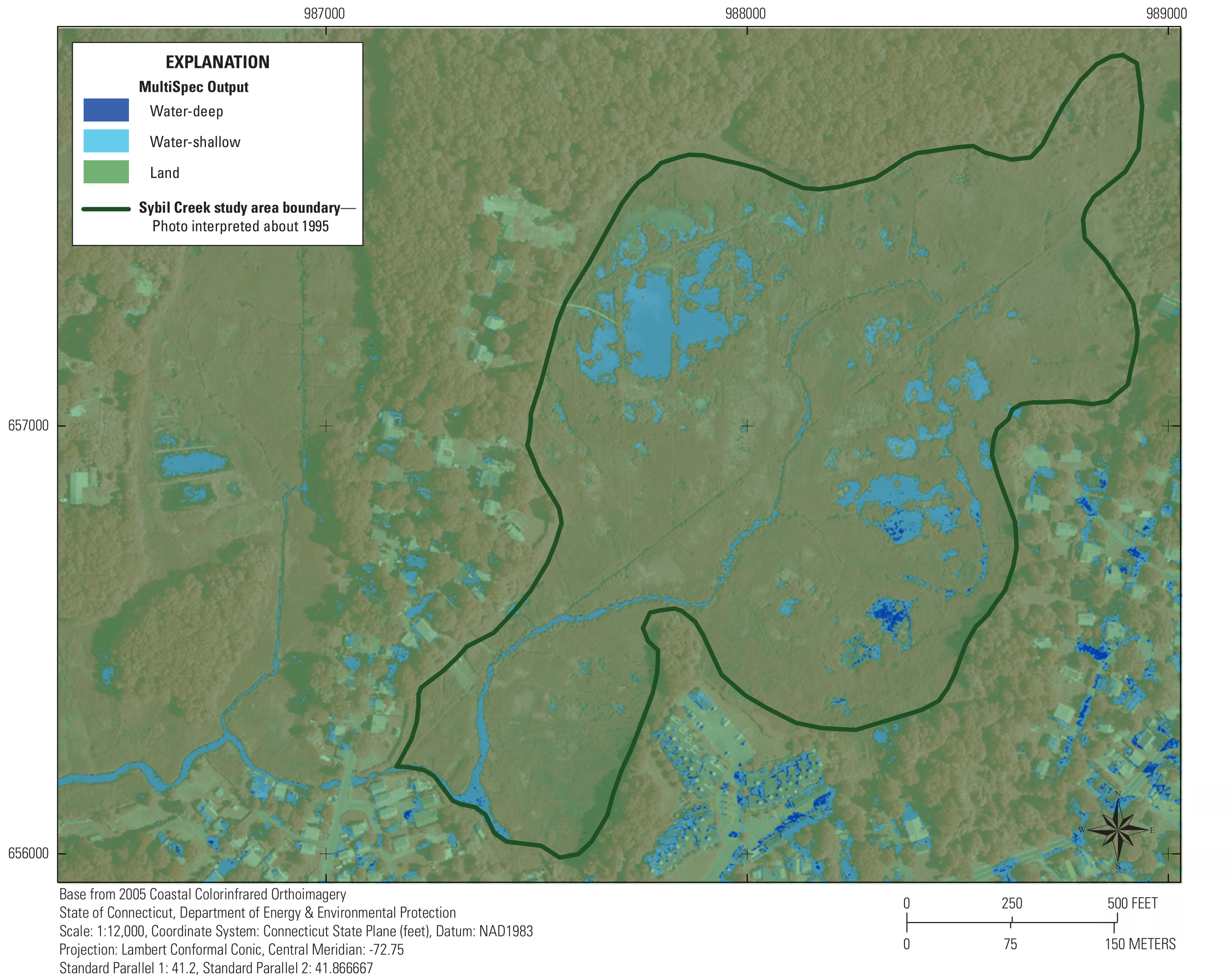
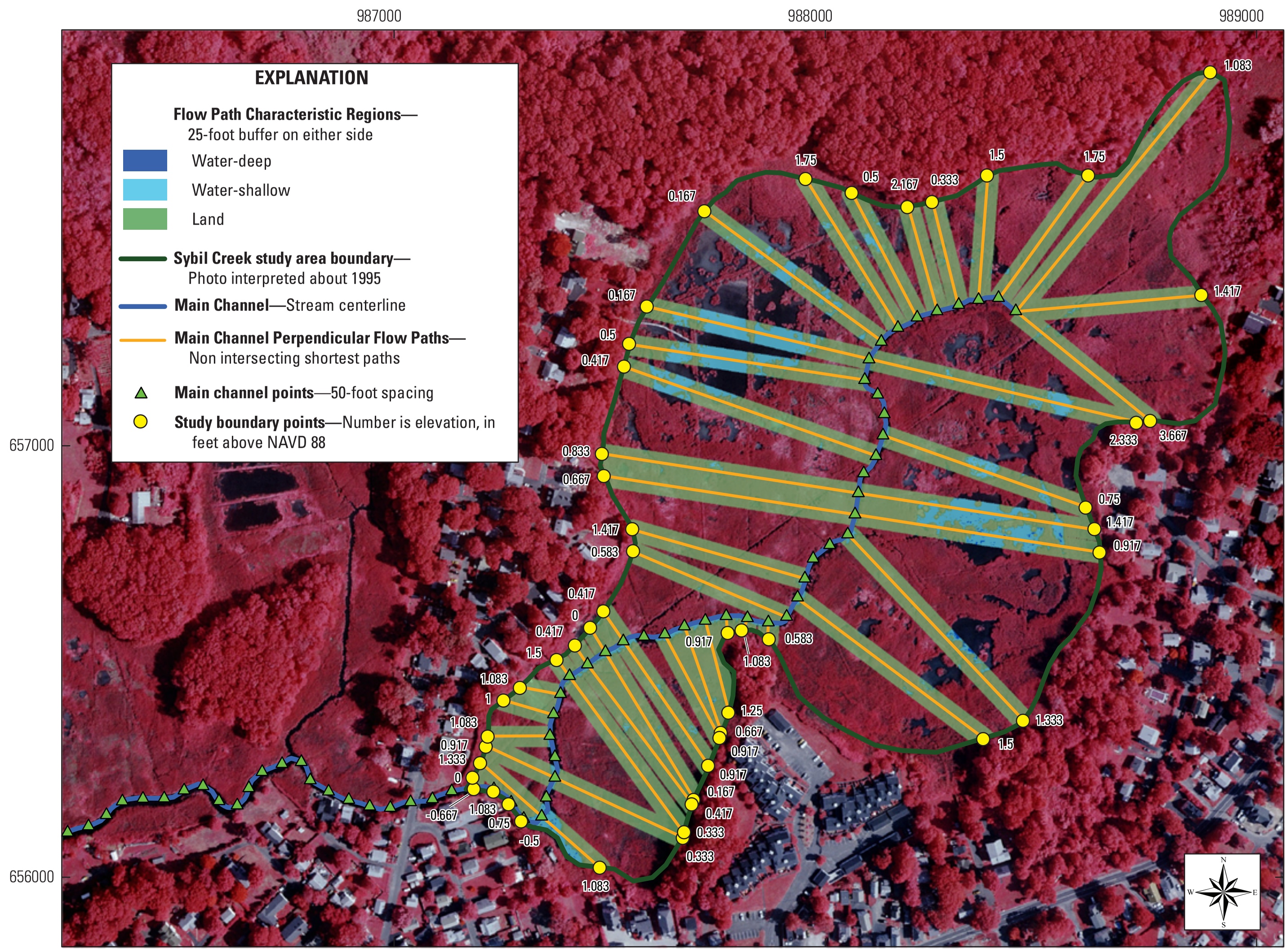


Figure 6. Areas of water and non-water (land) resulting from MultiSpec analysis of the three-band false color infrared orthophotography of Sybil Creek marsh, Connecticut. Four different characteristic water spectra were found to provide the best representation of the water area in the marsh and were classified as shallow and deep. Areas of shadows identified as water by the program (visible near many of the homes) were removed manually from areas within the marsh boundary.



Base from 2005 Coastal Colorinfrared Orthoimagery
State of Connecticut, Department of Energy & Environmental Protection
Scale: 1:12,000, Coordinate System: Connecticut State Plane (feet)
Datum: NAD1983, Projection: Lambert Conformal Conic
Central Meridian: -72.75, Standard Parallel 1: 41.2
Standard Parallel 2: 41.866667

Figure 7. Geographic information system overlay of the Sybil Creek marsh, Connecticut, with the channel flow path, perpendicular flow paths from the channel to the marsh boundary, and the characteristic marsh polygons defined by buffering the perpendiculars and determined by using MutiSpec classification data.

The model simulated high-tide heights for a normal (neap) tide, as observed during the Milone and MacBroom study (1987), and a design high tide. The simulations included conditions with the gates closed (existing condition with some leakage of water past the gates which do not close completely in some cases), one gate open, and both gates open. As there is no local tide gage, the tidal data for Branford (at the mouth of Sybil Creek), used in this study, were estimated by using data from the National Oceanographic and Atmospheric Agency (NOAA) tidal station in Bridgeport with a NOAA-provided correction factor. The highest October tide for 3 years (2005–2007), estimated for Branford Harbor, was used for translation to the mouth of Sybil Creek.

The application was compared to the one-gate-open test that was conducted by Milone and MacBroom (1987) during their study. This is the only case during which a gate was opened for a sufficient length of time to yield steady water levels in the marsh. All other observations made in the marsh were made with gates closed. Only one gate was opened to avoid inundating properties. The comparison between the observed and estimated tide heights for the one-gate-open condition showed a good match at the two observation points that were available within the modeled area. The observed heights (table 1) at P3 and S2m are 2.11 and 1.60 ft, respectively, and the GIS simulated heights are 2.04 and 1.55 ft above the National Geodetic Vertical Datum of 1929 (NGVD 29). Using these values, the estimated tide heights at the observation points measured by Milone and MacBroom (1987) for the one-gate-open condition were estimated to be within ±0.1 foot of the calibrated values. This indicates that the general values used for diffusivity in the calibration and transferred to the GIS application provide accurate results for different gate scenarios. Unfortunately, few points were available to calibrate or validate the method other than the points listed in tables 1 and 2. For this reason, the estimates made at the boundary are considered to be approximate when used as a guide for regulatory action. Future work might include the development of buffer zones that are based on the approximate estimates developed by using this method, to account for uncertainty.

No validation data are available for the gates-open condition, except for those discussed above. The only validation data available for the GIS application of the method included general observations made during the pre-test existing condition with both gates closed, as reported by Milone and MacBroom (1987). To use this data for validation, a diffusivity for the gates-closed condition was estimated from the calibration data set by matching the observed tide heights at P2 and P3 (see table 1). Using this value for the gate constriction in the spreadsheet application, heights at the marsh boundary were estimated and compared with observed values for the high-tide height and tidal range from the Milone and MacBroom study (1987). These tide values are listed in table 3. The spreadsheet-estimated tide height was within 0.3 ft of the observed height at P3. This comparison is not direct because the tidal range at the source for the P3 gates-closed condition was not specified in the study and is an estimate.

The method presented here estimates a potential height relative to a datum (in this case the tide heights relative to mean sea level). Interpretation of the results requires comparison with the topographic limitations in the marsh. For example, the method may estimate a tide height at a given distance that is well below the topographic elevation at that location in the marsh. Under this circumstance, the tide is interpreted as not reaching the location, and thus for that tidal range, the marsh at that distance does not experience a tidal flux. Estimated tide heights for the gates-closed condition indicate that the tide does not extend into the marsh and is confined to the channel. This is evident from the marsh topography provided by Milone and MacBroom (1987), which shows that the heights of the marsh are greater than the estimated tide heights and also shows that the marsh ponds are isolated from the channel and the tide. On the basis of anecdotal observations (Richard Orson, Save The Sound, New Haven, Conn., personal commun., 2009), under normal operating conditions (gates closed) the tide does not leave the channel, and the ponds are isolated, qualitatively confirming the model results.

Table 3. Estimated tide heights and ranges at Sybil Creek, Connecticut, used in the model.

[NAVD 88, North American Vertical Datum of 1988; NGVD 29, National Geodetic Vertical Datum of 1929]

Tide description	Estimated high-tide height at Branford Harbor (feet)	Estimated tidal range at Branford Harbor (feet)
3-year (2005–2007) October high (NAVD 88)	4.8	8.2
Sybil Creek Study, Milone and MacBroom, 1987 (NGVD 29)	4.5	7
Sybil Creek Study, Milone and MacBroom, 1987 (NAVD 88)	3.5	7

Given the paucity of data for verification of the estimated tide heights, the existing condition estimates were compared with marsh heights derived from Light Detection And Ranging (LiDAR) data for coastal Connecticut in winter 2006 (Connecticut Department of Environmental Protection, 2008). The difference between the estimated height and the LiDAR height at the marsh boundary plotted against the distance from the tidal source is shown in figure 8. The plot shows that the heights at the marsh boundary are greater than the estimated high-tide heights along the entire boundary, except near the tidal source. This indicates that the model is estimating tide heights within the correct range near the source, but farther away from the source, the marsh height is greater than the tide height. This confirms the expected result, in that the high tide would be expected to be contained within the marsh boundaries when the gates are closed.

The simulated tide heights at the marsh boundary for the existing gates-closed condition are shown in figure 8. Note that the LiDAR elevations are greater than the simulated tide heights for most of the marsh. The LiDAR-based marsh heights at the boundary are shown in figure 9. These heights do not necessarily document the water-surface height at high tide because of the time of the LiDAR data collection and interference from vegetation and irregular ground surface; however, given the attenuation of the tide through the gate and bridge, the heights are considered to be indicative of the water surface in the channel and the marsh surface at the boundary. The simulated potential tide heights at the boundary with both gates open are shown in figure 10. The heights are greater than the LiDAR elevations at the marsh boundary, indicating that if both gates were open, the entire marsh would be flooded up to 1 foot at the farthest distance from the tide gage. A comparison of the estimated heights with the 1987 topography from Milone and MacBroom (1987) indicates that a number of structures near the bridge at the western end of the study area would be flooded.

Limitations

The model presented here was designed to be a simple way to estimate tidal heights using only remote sensing or geographic information system data layers; therefore, it has several limitations. The model is not a complete representation of the marsh geometry, and because of the paucity and distribution of the data, the estimates made at the boundary of the marsh are considered to be approximate when used as a guide for regulatory actions.

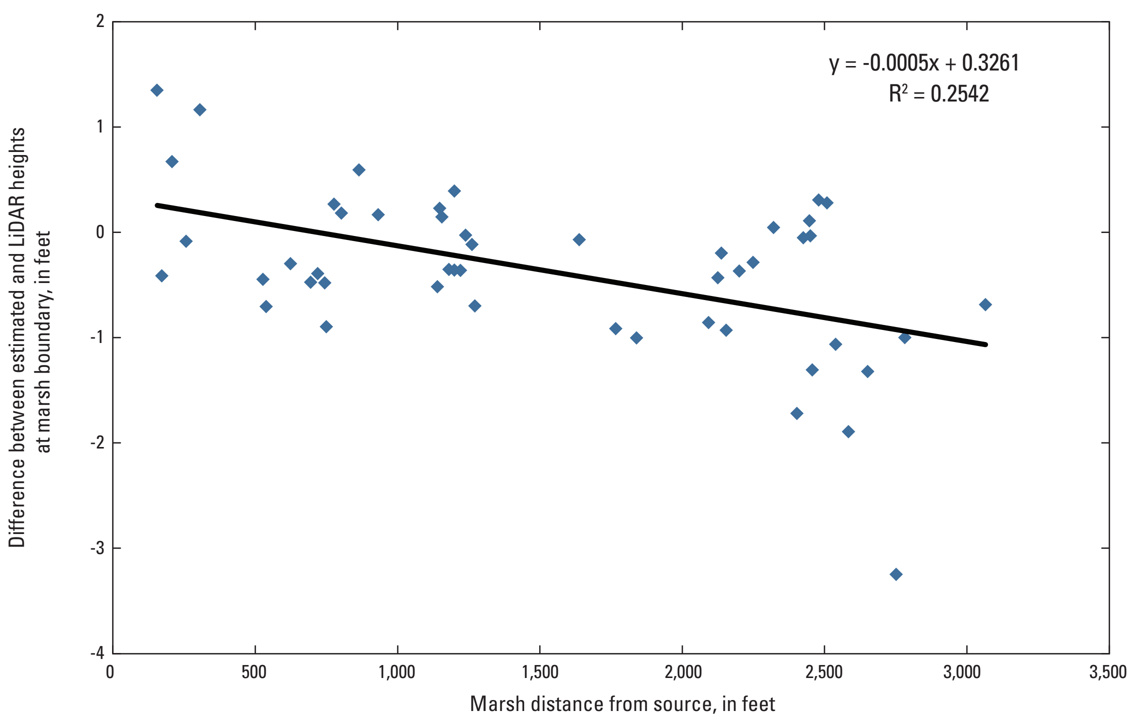
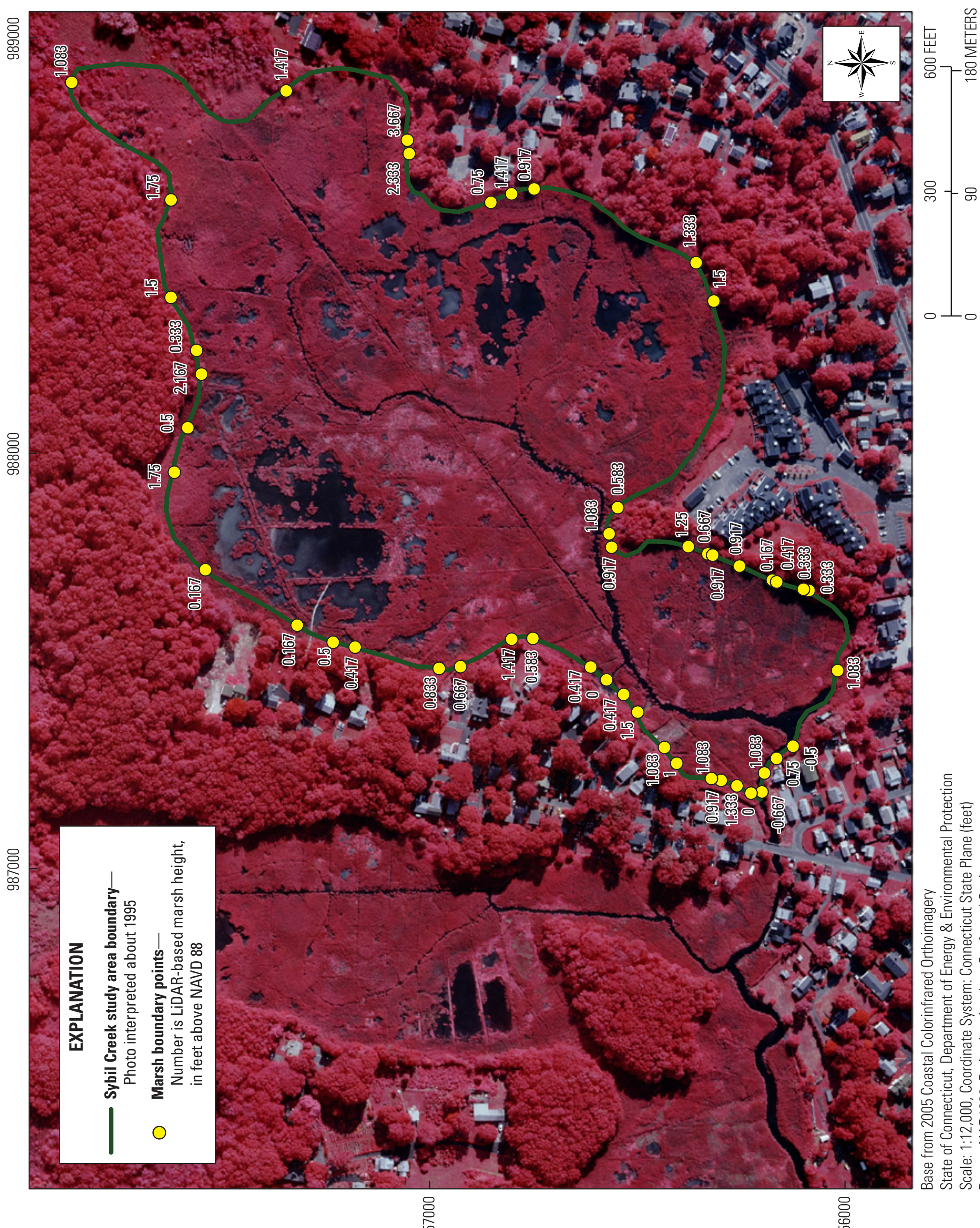


Figure 8. Difference between the estimated tide heights and LiDAR heights at Sybil Creek marsh, Connecticut, assuming gates closed and using a single point calibration, in relation to the distance from the source. The simulation with gates closed represents the existing condition that would be reflected by the LiDAR data.



Base from 2005 Coastal Colorinfrared Orthoimagery
State of Connecticut, Department of Energy & Environmental Protection
Scale: 1:12,000, Coordinate System: Connecticut State Plane (feet)
Datum: NAD1983, Projection: Lambert Conformal Conic
Central Meridian: -72.75, Standard Parallel 1: 41.2
Standard Parallel 2: 41.866667

Figure 9. LiDAR elevations at the boundary of the Sybil Creek marsh, Connecticut.

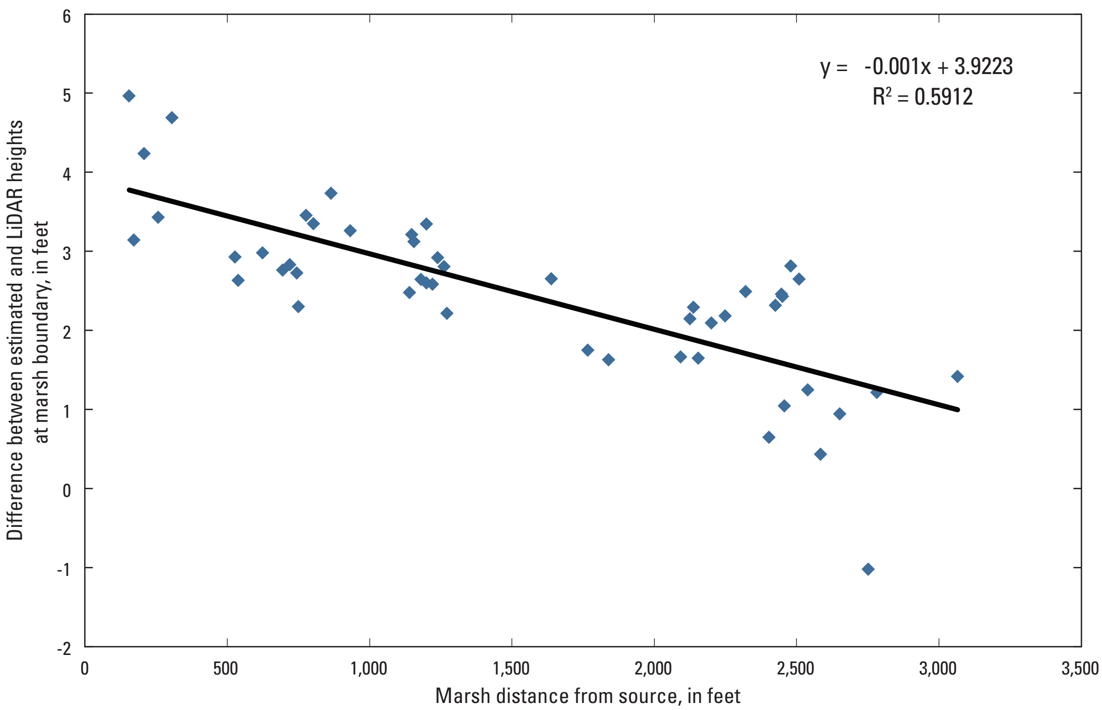


Figure 10. Difference between simulated tide heights, assuming gates-open condition, and LiDAR heights at Sybil Creek marsh, Connecticut, in relation to the distance from the source. The simulation shows that the entire Sybil Creek marsh would be inundated up to approximately 1 foot at the farthest distance from the tide gates.

The model assumes that flow resistance does not change with head, implying that friction is uniform, which may not be reasonable for the full range of flow in the open channels and through constricted openings. Therefore, the model is calibrated only for a single high-tide level of interest; arrival times at lower tide heights may have substantial errors. In addition, the small data set available precluded a more in-depth analysis that could develop a general relation to characterize openings and diffusivity.

The one-dimensional diffusion analogy model should not be used to evaluate tide heights, flow velocities, and tide arrival times for tide conditions other than the highest tide for which it is calibrated. Additionally, because the model does not include depth or water-surface slope information, flow velocity, travel time, and tidal storage cannot be estimated reliably.

Summary and Conclusions

A study was conducted to develop a one-dimensional diffusion analogy model to estimate tide heights in four coastal marshes in Connecticut. The method used to estimate maximum tide heights in coastal marshes in this study can be used for areas where the high tides under specific conditions cannot be measured directly, such as marshes with tide gates that cannot be opened without risk of flooding properties and structures. The simplicity of the method allows it to be used to evaluate the tide heights in estuaries and marshes with significantly less field and modeling effort than other methods used for modeling marsh hydrodynamics. The method can be applied with limited calibration information that is based entirely on remote sensing or geographic information system data layers. Tide heights were estimated for four coastal marshes in Connecticut—Pine Creek, Sybil Creek, Leetes Island, and Wilson Cove marshes.

The model was calibrated and validated by using data collected during previous studies. The expected accuracy of the method is in the range ±0.1 to 0.3 foot (based on the error in the calibration/validation points for the marshes studied). The method would be applicable as a survey tool for assessing conditions along the coast and could be used to indicate those marshes with greatest potential for successful restoration without increasing flooding of existing structures and properties. Additionally, the method could be used to make a first estimate of tide heights, which would indicate where more detailed modeling would be needed.

The method developed and tested in this study to estimate extreme high water limits in tidal marshes along the Connecticut coast can assist in regulatory and planning processes. The method provides a simple, consistent, and inexpensive way to estimate these boundaries where direct measurements are not possible and where direct measurements have not yet been made. The method is simpler to use than other one- and two-dimensional hydrodynamic models because it does not require marsh depth and tidal prism information; however, the one-dimensional diffusion analogy model cannot be used to evaluate tide heights, flow velocities, and tide arrival times for tide conditions other than the highest tide for which it is calibrated. Additionally, because the model does not include depth or water-surface slope information, flow velocity, travel time, and tidal storage cannot be estimated reliably.

Acknowledgments

The authors would like to thank John Warner (USGS Woods Hole) and Robert Dudley (USGS New England Water Science Center Maine Office) for their helpful and insightful technical review and comments, and Ruth Larkins (USGS Science Publishing Network) and Virginia de Lima (USGS New England Water Science Center Connecticut Office) for helpful technical and editorial review comments.

References Cited

Adamowicz, S., and Roman, C.T., 2005, New England salt marsh pools—A quantitative analysis of geomorphic and geographic features: Wetlands, v. 25, no. 2, p. 279–288.

Coats, R., Swanson, M., and Williams, P., 1989, Hydrologic analysis for coastal wetland restoration: Environmental Management, v. 13, no. 6, p. 715–727.

Connecticut Department of Environmental Protection (CTDEEP), 2008, Original 2006 coastal LiDAR data, collected and processed by Terrapoint, Inc.; project managed by Dewberry, Inc.; QA/QC reviewed by Roald Haested, Inc., for FEMA under Task/Delivery Order Proposal Request “Riverine/Coastal Flood Studies” pursuant to CONTRACT NO. EME-2003-CO-0338: Connecticut Department of Environmental Protection.

Ferris, J.G., 1951, Cyclic fluctuations of the water-level as a basis for determining aquifer transmissivity: International Association of Scientific Hydrology Publication 33, p. 148–155.

Fischer, H.B., List, J.E., Koh, C.R., Imberger, J., and Brooks, N.H., 1979, Mixing in inland and coastal waters: Academic Press, 302 p.

Giannico, Guillermo, and Souder, J.A., 2004, The effects of tide gates on estuarine habitats and migratory fish: Oregon State University ORESU-G-04-002, 9 p.

Landgrebe, D., and Biehl, L., 2011, MultiSpec version 9.2011: School of Electrical and Computer Engineering, Purdue University, Purdue Research Foundation, 189 p., accessed at https://engineering.purdue.edu/~biehl/MultiSpec/.

Milone and MacBroom Consulting Engineers, 1987, Sybil Creek salt marsh study, Branford, Conn.: Connecticut Department of Environmental Protection.

Milone and MacBroom Consulting Engineers, 1999a, Leetes Island marsh, Guilford, Conn., prepared the Connecticut Department of Environmental Protection Office of Long Island Sound.

Milone and MacBroom Consulting Engineers, 1999b, Wilson Cove tidal restoration, Norwalk, Conn.: City of Norwalk, Conn.

Roman, C.T., Garvine, R.W., and Portnoy, J.W., 1995, Hydrologic modeling as a predictive basis for ecological restoration of salt marshes: Environmental Engineering, v. 19, no. 4, p. 559–566.

Roman, C.T., Niering, W.A., and Warren, R.S., 1984, Salt marsh vegetation change in response to tidal restriction: Environmental Management, v. 8, p. 141–150.

Todd, D.K., 1980, Groundwater hydrology: New York, John Wiley and Sons, 336 p.

Turner, I.L., Coates, B.P., and Acworth, R.I., 1996, The effects of tides and waves on water-table elevations in coastal zones: Hydrogeology Journal, v. 4, no. 2, p. 51–69.

Prepared by the Pembroke and West Trenton Publishing Service Centers.

For more information concerning this report, contact:

Office Chief
U.S. Geological Survey
New England Water Science Center
Connecticut Office
101 Pitkin Street
East Hartford, CT 06108
dc_ct@usgs.gov

or visit our Web site at:
http://ct.water.usgs.gov

Bjerklie and others—**A One-Dimensional Diffusion Analogy Model for Estimation of Tide Heights in Selected Tidal Marshes in Connecticut**—SIR 2013–5076