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# The hydrology of Piermont Marsh, a reference for tidal marsh restoration in the Hudson river estuary, New York

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**Abstract**

The topography, hydroperiod, water table, and selected edaphic characteristics are described for Piermont Marsh, an irregularly flooded tidal marsh in the Hudson River Estuary, New York, USA. Despite variations in microtopography, overall the marsh is flat, and although the observations were conducted at a high point in the Estuary's 18.6 year metonic cycle, its surface was only inundated 10–12 times a month. Observations of spatial differences in the saturated hydraulic conductivity and surface infiltration rates are also discussed. 'Edge' portions of the marsh are characterized by a slightly higher, more uniform, more structured, less organic, and less hydrologically conductive substrate than found in the marsh interior. Preferential flow is facilitated by macropores in the creekbank wall. The water table is close to the marsh surface for a lesser percentage of the lunar month in the marsh 'edge' when compared to the interior, where it is almost always within 10 cm of the surface. The extent to which the spatial variability of these hydrologic characteristics determines the marsh's ability to provide various ecosystem services is also discussed and the implications of these observations on tidal marsh restoration efforts briefly presented.


*Keywords:* Tidal wetlands; Hudson River; Ecological restoration; Hydrology

## 1. Introduction

Ecosystems benefit humans both by the suite of marketable goods that can be extracted from them, and also by the ecosystem services they provide (Balmford et al., 2002). Coastal wetlands are among the most biologically productive ecosystems in the world and yet, because more than two-thirds of the world's population lives along the coast, they are also under heavy pressure to be drained and filled for urban and industrial development (Mitsch and Gosselink, 2000). As a result, in recent decades, wetlands have become the subject of much research, both by scientists and also increasingly by natural resource managers, whose goal it is to preserve existing wetland ecosystem functions and to attempt to restore those that have been already lost.

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Tidal wetlands provide a wide range of ecosystem services. As transitional zones between uplands and estuaries, they mediate the exchange of sediments, nutrients, organic matter, and pollutants between terrestrial and aquatic ecosystems and are important factors in determining the quality of surface waters and the viability of local fisheries. They filter contaminants out of surface waters, stabilize shorelines, and attenuate tidal surges, protecting coastal settlements. Wetlands are also important to wildlife. They are feeding, breeding, and resting grounds for resident and migratory nekton and waterfowl, and host unique vegetative and microbial communities. In terms of primary productivity, the rate at which sunlight is converted into organic matter, tidal wetlands are among the most prolific ecosystems in the world.

There is an intimate relationship between hydrology and the ability of coastal tidal marshes to provide ecosystem services (Odum et al., 1995). The wetland hydroperiod, a function of the relationship between the elevation of the marsh surface and local tidal elevations, determines the frequency and duration of inundation of its surface. Hydraulic properties of the marsh substrate determine the rate at which pore water drains out of the marsh to the estuary. Drainage patterns across the marsh surface, in turn, influence the oxidation state of the substrate, determining, in part, the chemical form of soil and pore water constituents present, the microbial and vegetative communities supported, and the rates of degradation, mineralization, and subsidence found in these systems.

Hydrologic research in the tidal wetlands of the Hudson River Estuary, NY is lacking, as shown in a review by Montalto and Steenhuis (2004). Historical hydrologic investigations conducted in the Estuary were primarily driven by the need to improve navigation and to understand the circulation of sewage and industrial waste in surface waters. These studies focused on tidal characteristics, salinity gradients, sediment characteristics, effluent discharges, and overall circulation patterns in the Estuary (Marmer, 1927; Schureman, 1934; McCrone, 1966; Giese and Barr, 1967; Howells, 1972; Abood, 1974; Jay and Bowman, 1975; Darmer, 1987; Cooper et al., 1988). The only hydrologic wetland studies conducted in the region attempted to characterize the hydroperiod and salinity levels experienced by various species of salt marsh vegetation (Harshberger, 1909; Johnson and York, 1915; Conard, 1935), and to document the hydrogeology, overall water budget, and surface water fluxes in and out of freshwater tidal marshes on the Hudson River Goldhammer and Findlay, 1988; Lickus and Barten, 1991). The present study adds to this modest body of knowledge about the hydrologic characteristics of Hudson River Estuary tidal marshes, by describing finer scale, spatial and temporal differences within Piermont Marsh.

The purpose of this paper is to document the hydrological characteristics of a brackish tidal marsh in the Hudson River Estuary, so that it may serve as a much needed reference marsh in this region. The long-term persistence, or success, of wetland restoration efforts depends on how successful the designers are in establishing new, engineered systems capable of sustaining natural fluctuations in local environmental conditions. The best models for how to do this are existing and relatively undisturbed local wetlands (Shisler, 1990; Middleton, 1999; Zedler, 2001). Although many resources have been directed towards restoration of brackish tidal wetlands in the New York/New Jersey Harbor Estuary, these initiatives can be much more successful if they are based on a sound understanding of local reference marsh hydrology and to a lesser extent on trial and error (Montalto and Steenhuis, 2004).

Piermont Marsh is an ideal reference site for study of the local tidal marsh hydrology. As one of four tidal marshes that together constitute the Hudson River National Estuarine Research Reserve, it has already been the subject of considerable ecological research. Its hydrology has been one notable omission. Information about the hydrology of Piermont Marsh can be coupled with other data already collected on site, improving overall understanding of this site and others like it in the Hudson River Estuary. Together this information can help to develop valuable bio-benchmarks to inform specification of marsh plain elevations, channel cross sections, vegetation planting plans, micro-topographical relief, and other parameters of restoration designs. Moreover, this information can be used to better document how tidal wetlands provide ecosystem services so that their true value, both to humans and to wildlife, can be better evaluated.

## 2. Site description

Piermont Marsh is located approximately 40 km north of New York City along the western bank of the Hudson River (Fig. 1) with a total surface area of approximately 115 hectares. The substrate of Piermont Marsh soil is an Ipswitch mucky peat and its lithography can be described as peats and clays varying in color and texture down to a depth of at least 11 m, with no basal sediments encountered at that depth (Wong and Peteet, 1998). This span of the Hudson River undergoes diurnal, sinusoidal, tidal fluctuations and salinities are in the mesohaline range of 5–18 ppt. The majority of Piermont Marsh is irregularly flooded, tidal creeks overflowing their banks and inundating the vast high marsh only during spring tides and storm surges.

About three-quarters of the surface of Piermont Marsh is dominated by *Phragmites australis*, ((Cav.) Trin ex Steudel). The vegetation of the interior, however, is still diverse. Tall form saltmarsh cordgrass (*Spartina alterniflora* (Loisel)) sit on a ridge of dark roots and peat along the Hudson River banks. Behind the cordgrass is a stubbly and uneven mudflat, which abruptly gives way to the tall reeds that dominate the western and eastern fringes, as well as the entire tapered southern end of the marsh. Blooming rose mallow (*Hibiscus palustris L.*) are scattered throughout Piermont Marsh and stand out brightly against the dark, dense green backdrop of the *Phragmites* monoculture. The *Phragmites* stalks gradually decrease in height with increasing distance from any of the creek or river banks. The interior of the marsh is a panoramic high marsh of salt hay (*Spartina patens* (Muhl.)) and spike grass (*Distichlis spicata* (Greene)) fields, three square bulrush (*Scirpus americanus* (Pers)), salt marsh bulrush (*Scirpus robustus* (Pursh)), narrow-leaved cattails (*Typha angustifolia* (Dudley)), occasional patches of big cordgrass (*Spartina cynosuroides* (Roth)) and short form saltwater cordgrass (*Spartina alterniflora* (Loisel)), and salt pannes (both large and small) with areas of purple saltmarsh fleabane (*Pluchea purpurascens* (Cass)) and dwarf spike rush (*Eleocharis pavula*. (Roem. and Schult) Bluff, Nees and Sch.) inside them. Isolated vines of morning glory (*Convolvus* sp.) can be found along creek and river banks.

## 3. Methodology

A variety of information was gathered throughout Piermont Marsh between June1998 and December 2000. Other than precipitation, which was measured on site, climatological data were obtained from the Northeast Regional Climate Center (NRCC). Daily potential evapotranspiration (PET) rates were estimated using MORECS, a model adapted from the Penman Monteith Equation, from meteorological data measured at White Plains, NY.

A laser plane unit and two Ashtech Z-surveyor units, (i.e., a stationary base station and a rover, linked in a real time kinematic (RTK) configuration) were used to survey site topography relative to the National Geodetic Survey Datum. National Geodetic Survey benchmarks at Dobb's Ferry and Mt. Nibo were used for vertical and horizontal control, respectively.

The saturated hydraulic conductivity was measured at 17 different locations, (labeled k1–k17 in Fig. 1,) over a period of months at various phases of the lunar and tidal cycles using the auger hole method. Holes were augered 1.2 m into the marsh substrate and one day later, after equilibrium was reached with the surrounding water table, water was removed from the hole with a bailer. The rate at which the water then rose in the hole was measured with a graduated tape and recorded. Because errors of up to 10% are common on consecutive measurements made in the same hole using this technique (van Beers, 1958), three trial tests were performed on each hole, and the values averaged. Standard in-situ hydraulic extraction formulae were used to convert this data into estimates of saturated hydraulic conductivity.

Infiltration rates were measured at seven different locations, (labeled i1–i7 in Fig. 1) by determining the steady state rate of drop of water inside a ring infiltrometer. Two trials were conducted at each location, once on August 4, 1999 (as the tide was coming in) and once on August 18, 1999 (as the tide was going out). For each trial, a regression line was used to fit the linear portion of the water level versus time graph data collected from each trial to an $r^2$ value above 0.9.

The moisture content and the organic content of the substrate were measured at each well location along Transects 2 and 3 and from the marsh interior, (locations labeled s1–s17 in Fig. 1). Samples were taken by

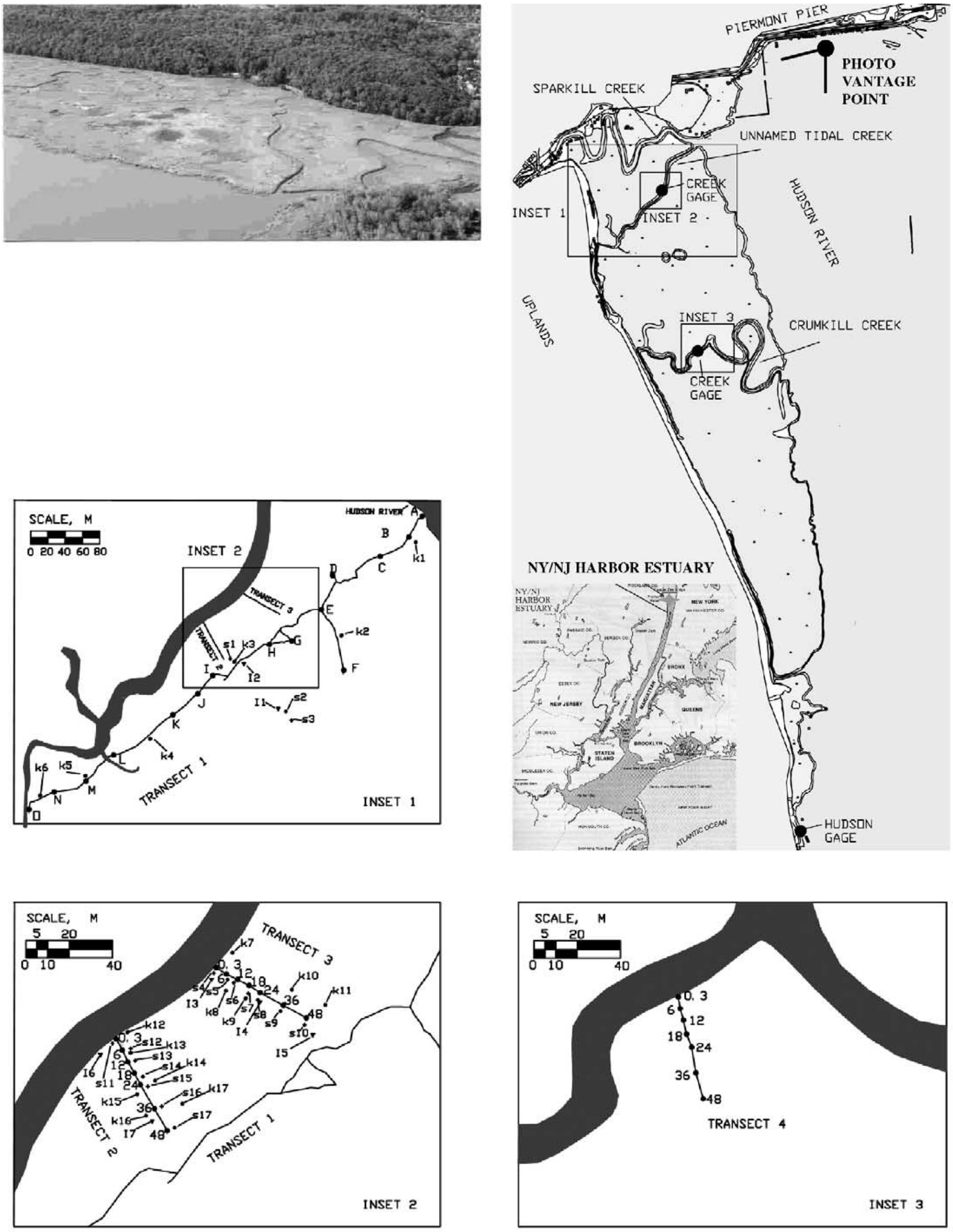



Fig. 1. Piermont Marsh is located approximately 40 km north of New York City along the western bank of the Hudson River. The insets show the locations of all wells, hydraulic conductivity measurements, infiltration measurements, and soil sampling conducted along Transects 1–4.

pushing a cylinder (approximately 10 cm in diameter by 10 cm deep) into the marsh surface and then digging around it to remove it. Wet weights were recorded immediately. Dry weights were recorded after the samples had been left in a drying oven (50–55 °C) long enough for their weight to stop decreasing. The ash weight was determined by weighing the samples after two hours in a muffle furnace (500 °C). The moisture content and percent loss on ignition were then calculated using standard formulas. The percent loss on ignition (% LOI) values reported are the averages of two replicates processed from each soil sample.

Three tide gages were installed on-site (Fig. 1) and consisted of 0.3 bar Druck pressure transducers suspended inside perforated PVC pipes mounted on bulkheads in the water. The transducer sensors were vented to correct for errors that could result from changes in atmospheric pressure, and were programmed to record the average water surface elevation every 10 min on a Telog 2100 Data Logger unit. To account for tidally induced variation in water temperature and salinity, calibration of the tide gages was accomplished by manually surveying the creek/river stage, while simultaneously noting the instantaneous pressure transducer reading, at various phases of the tide. The pressure transducer readings and manually measured stage elevations were modeled by linear regression, which was then used to convert the entire set of pressure readings into stage elevations. An average standard error and 95% zone of confidence was calculated for each installation.

Wells, constructed of 7.5 cm diameter PVC pipes amply perforated along their entire length and circumference, were used to observe spatial and temporal fluctuations of the water table. Screening was secured around the bottom and outside of each well to prevent fine materials from entering through the perforations. Along Transects 1–4 (Fig. 1), wells were installed in augered holes, backfilled first with sand and then with indigenous peat, and the surface sealed with a waterproof concrete mix to prevent preferential flow along the sides of the well. Pressure transducers, calibrated using the same procedure as for the tide gages, were used to measure and record water table fluctuations in the wells along Transects 2–4 at 10 min intervals. A detailed error analysis identical to that performed for the tide gages was conducted for each of these wells.

## 4. Results

### 4.1. General physical characteristics

The average marsh surface elevation based on the mean of approximately 80 survey points collected along Transect 1 at the marsh's northern end is 0.95 ± 0.05 m NGVD-29 (Table 1). The average of 20 spot elevations taken in the vicinity of Transect 4 at the southern end of the marsh was 0.92 m ± 0.05 m NGVD-29. Variation in microtopography across the marsh plane is a result of frequently occurring, localized depressions found where muskrat rhizomatic feeding and burrowing activities have taken place, between hummocks, and in un-vegetated salt pannes of different sizes. These depressions are usually full of water and are absent from areas of the marsh immediately adjacent to creekbanks. Overall, Piermont Marsh is flat, however, and the surface of both the southern and northern ends of the marsh are at approximately the same elevation.

Fig. 2 shows the cross-sections of the marsh surface along Transects 2–4. Creekbanks are, in general, steep throughout the marsh with slopes approaching vertical near the marsh surface and becoming parabolic deeper in the creek. Muskrat (*Ondatra zibethicus*) tunnels and fiddler crab (*Uca pugnax*) holes are evident in the sides of creekbanks during low tide.

The moisture content of the top 10 cm of substrate increased with distance from the creek, (Fig. 3), varying from about 52% in the levee to near 90% in the marsh interior. Because the samples were taken on a rainy day just after an inundation event, the moisture contents reported represent wet conditions in the marsh.

The organic content also increased with distance from the creek (Fig. 3), from 10 to 15% in the levee to nearly 60% in the marsh interior. The values measured (Fig. 3), especially in the marsh interior, were higher than those reported at other sites (see Carr and Blackley, 1986; Harvey et al., 1987; Harvey and Nuttle, 1995; Hemond and Chen, 1990; Yelverton and Hackney, 1986).

An estimate of the sediment accretion rate at Piermont Marsh was obtained by comparing present and historical marsh surface elevations. The Rockland County Department of Planning (RCDP) surveyed the

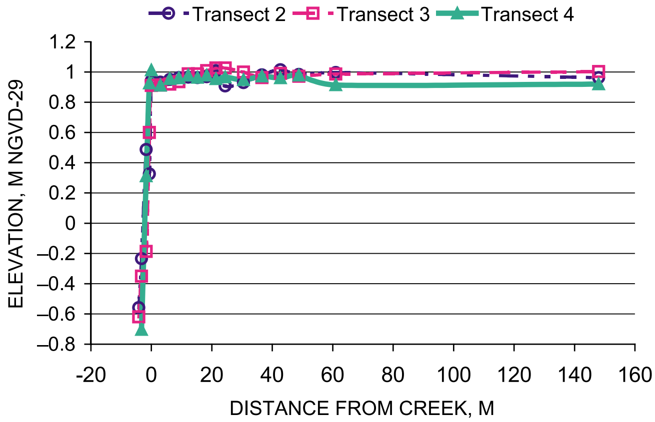
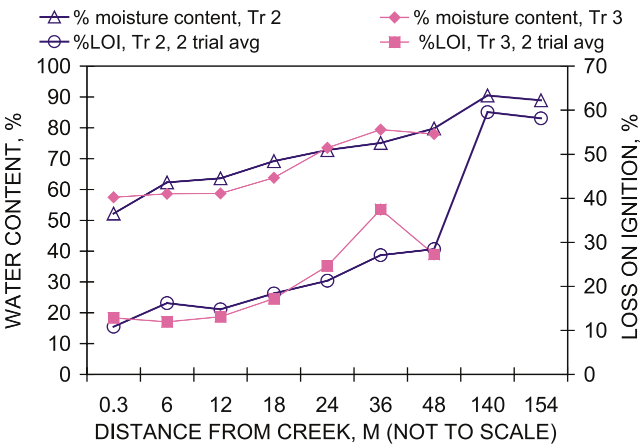



Fig. 2. Marsh surface elevation versus distance from creek.

surface of Piermont Marsh using aerial photography in 1986. The mean of the 11 RCDP grid elevations that fall within the vicinity of Transect 1 was 0.76 m. The mean of 13 RCDP grid elevations in the southern end of the marsh was 0.90 m. These data suggest a marsh accretion rate at Piermont Marsh of between 0.15 and 1.5 cm/yr over the past 14 years. This rough estimate brackets the deposition rate of 0.26 cm/yr reported by Wong and Peteet (1998) from AMS carbon-14 dating of a soil core extracted from the same study area.

During topographic surveying of the site, observations were made of the dominant vegetation type at each survey spot. Fig. 4 graphically shows the topographic ranges of various species of vegetation at Piermont Marsh. Also indicated in the figure are the ecological community classifications for the various elevations (as developed by the NYSDEC, National Heritage Program), and some tidal data (to be discussed below). As is typical of high salt marshes along the East Coast of the US, a variety of species are found above the mean high water (MHW) line at Piermont Marsh. Vegetation in the low salt marsh (below MHW) is primarily *Spartina alterniflora* and *Phragmites*.

Observations of substrate quality were recorded during well hole augering. The uppermost substrate in the creekbank zone, as in some *Phragmites* patches of the marsh interior, is an approximately 30 cm thick, dense, root mat that vibrates under pressure. A mucky layer was found below the root mat, extending from about 30 to 60 cm below the surface everywhere




| IDENTIFIER | LOI (%) | MOISTURE CONTENT (%) |
|---|---|---|
| s1 | 28.4 | 79.8 |
| s2 | 59.6 | 90.5 |
| s3 | 58.2 | 88.9 |
| s4 | 12.8 | 57.5 |
| s5 | 11.9 | 58.6 |
| s6 | 13.0 | 58.7 |
| s7 | 17.2 | 63.8 |
| s8 | 24.6 | 73.5 |
| s9 | 37.4 | 79.4 |
| s10 | 27.2 | 78.0 |
| s11 | 18.4 | 69.2 |
| s12 | 16.2 | 62.3 |
| s13 | 14.8 | 63.6 |
| s14 | 18.4 | 69.2 |
| s15 | 21.3 | 72.8 |
| s16 | 27.1 | 75.1 |
| s17 | 28.4 | 79.8 |

Fig. 3. Percent moisture and percent loss on ignition versus distance from creek.

Table 1
Summary of tidal data as observed at Piermont Marsh

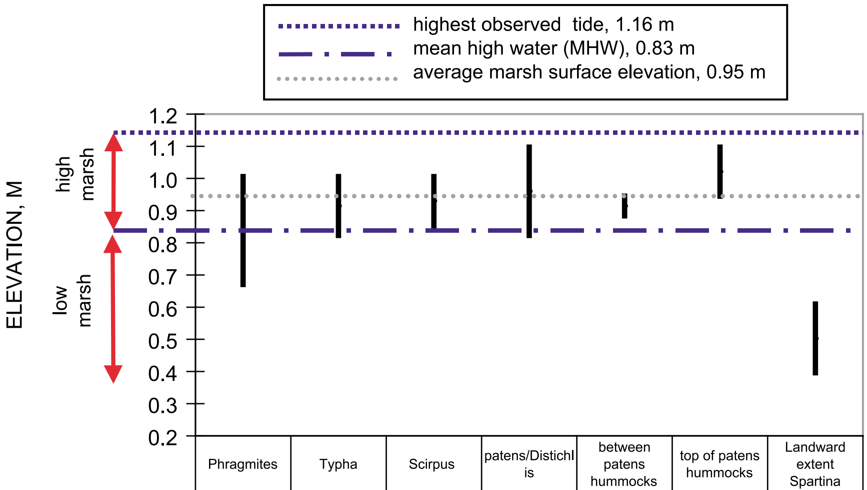
| Parameter | Elevation (NGVD-29) (m) |
|---|---|
| Highest observed water | 1.17 |
| Mean high water (MHW) | 0.83 |
| Approximate mean low water (MLW) | −0.28 |
| Average marsh surface (E/W transect) | 0.95 |

except immediately adjacent to the creekbank. Aside from the interior *Phragmites* patches, the rootzone in the marsh interior is shallower and less dense than in creekbank zones. The top meter of substrate is generally densest in areas dominated by cattails, and is completely mucky in bulrush and *S. patens*/*D. spicata* areas. Throughout the marsh, depth probing reveals a more solid substrate at depths greater than 1 m below the surface.

### 4.2. Saturated hydraulic conductivity and infiltration rates

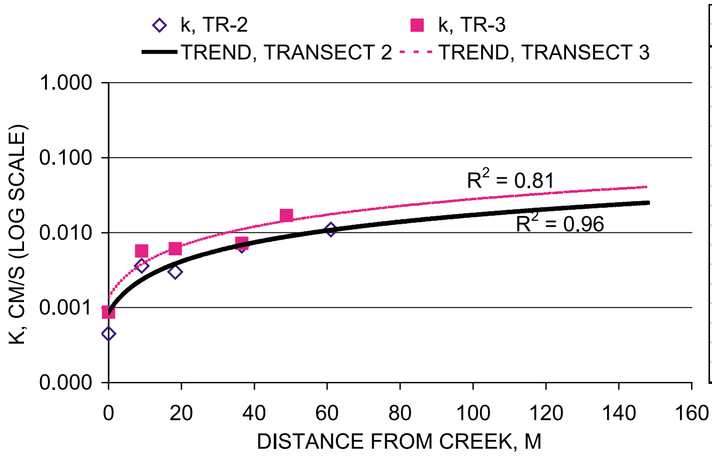
Overall, the mean saturated hydraulic conductivity of Piermont Marsh sediments was $7.75\times10^{-3}$ cm/s (st. dev. $=0.011$, $n=80$), but individual measurements varied spatially. The saturated hydraulic conductivity values measured along Transects 2 and 3 varied linearly with distance to the nearest tidal creek. (No conductivity measurements were made along Transect 4.) As shown in Fig. 5, the saturated hydraulic conductivity values measured in the creekbanks along both Transects 2 (k12) and 3 (k7) were in the range of a silty clay. The saturated hydraulic conductivity measured at the western end of Transect 1 (k6) was also in this range, and these values were similar to those reported at other tidal marshes (See Jordan and Correll, 1985; Hemond and Fifield, 1982; Harvey et al., 1987; Yelverton and Hackney, 1986; Harvey and Odum, 1990; Hemond and Chen, 1990; Nuttle and Hemond, 1988; and Nichols, 1985). Further towards the interior, saturated conductivity values measured were one to two orders of magnitude higher, similar to those of a coarse sand.

The mean infiltration rate measured at Piermont Marsh was $1.4\times10^{-2}$ cm/s (st. dev. $=0.009$, $n=15$). Individual infiltration rates along Transects 1 and 2, while spatially differentiated, did not display a consistent correlation with distance to the nearest tidal creek (Fig. 6). Although the mean infiltration rate was an order of magnitude higher than the mean saturated hydraulic conductivity, all infiltration rates measured were within the range of conductivity values found at Piermont Marsh. However, because




| | Phragmites | Typha | Scirpus | patens/Distichlis | between patens hummocks | top of patens hummocks | Landward extent Spartina |
|---|---|---|---|---|---|---|---|
| LOWEST FOUND, m | 0.7 | 0.8 | 0.9 | 0.8 | 0.9 | 0.9 | 0.4 |
| HIGHEST FOUND, m | 1.0 | 1.0 | 1.0 | 1.1 | 0.9 | 1.1 | 0.6 |
| - AVERAGE ELEVATION, m | 0.8 | 0.9 | 0.9 | 1.0 | 0.9 | 1.0 | 0.5 |

Fig. 4. Elevation range of selected vegetation zones at Piermont Marsh. The highest, lowest, and average elevation surveyed for each community are shown. (Elevations shown are relative to the NGVD-29 datum.



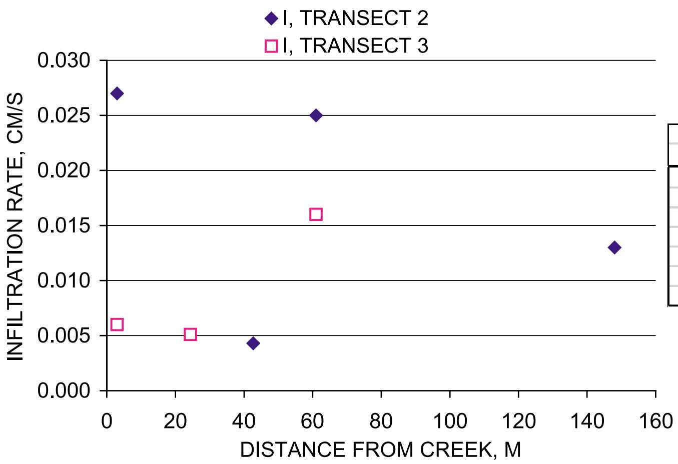

| IDENTIFIER | MEAN (x $10^{-3}$) cm/s | ST. DEVIATION (x $10^{-3}$) cm/s | N |
|---|---|---|---|
| k1 | 6.60 | – | 1 |
| k2 | 90.00 | – | 1 |
| k3 | 11.60 | 5.60 | 11 |
| k4 | 3.20 | – | 1 |
| k5 | 3.60 | – | 1 |
| k6 | 0.65 | – | 1 |
| k7 | 0.87 | 0.72 | 5 |
| k8 | 5.66 | 2.40 | 5 |
| k9 | 6.07 | 1.60 | 7 |
| k10 | 7.25 | 1.67 | 6 |
| k11 | 16.60 | 5.12 | 9 |
| k12 | 0.46 | 0.28 | 7 |
| k13 | 3.60 | 2.65 | 6 |
| k14 | 3.14 | 0.78 | 5 |
| k15 | 2.08 | 1.00 | 6 |
| k16 | 9.10 | 1.90 | 4 |
| k17 | 3.50 | 0.28 | 3 |

Fig. 5. Saturated hydraulic conductivity versus distance from creek.

the infiltration measurements were made several days after inundation of the surface by tidal waters, the values reported may actually be lower than those that might be found when the substrate is more desiccated. It appears that, on average, the rate at which water can enter the substrate through the surface is greater than the rate at which it can move horizontally through it. The spatial variability of measured infiltration rates is more likely due to factors other than distance from a tidal creek that have not been investigated here.

### 4.3. Tidal data

The Hudson River stage was monitored regularly between 9/98 to 12/98 and between 4/99 to 7/99. The creek stage was monitored between 4/99 and 8/99 in the northern unnamed tidal creek and between 11/00 and 12/00 along Crumkill Creek. This span of the Hudson River undergoes diurnal tidal fluctuations that are transmitted back into the tidal creeks at Piermont Marsh with variable time lag. A diurnal inequality, or difference in the amplitude of consecutive tides, was observed, a result of variation in the angle of declination of the moon with respect to the Earth. Asymmetry in consecutive tides has been reported in other wetlands of the Hudson River (Goldhammer and Findlay, 1987; Lickus and Barten, 1990). The tidal functions were essentially symmetric and sinusoidal in form in both the River and the creeks.




| IDENTIFIER | MEAN (x $10^{-2}$) cm/s | ST. DEVIATION (x $10^{-2}$) cm/s | N |
|---|---|---|---|
| I1 | 1.33 | 0.19 | 3 |
| I2 | 2.50 | 0.20 | 2 |
| I3 | 0.60 | 0.65 | 2 |
| I4 | 0.50 | 0.50 | 2 |
| I5 | 1.60 | 0.99 | 2 |
| I6 | 2.70 | 0.13 | 2 |
| I7 | 0.43 | 0.16 | 2 |

Fig. 6. Infiltration rates versus distance from creek.

High tides were higher and low tides were lower during the full and new moon spring tides than during intermediate (or neap) tidal conditions, when the gravitational pulls of the sun and the moon on the earth are opposed to each other. The new moon spring tides always began during the end of the fourth lunar quarter and ended during the beginning of the first. The latter half of the first quarter and most of the second quarter was characterized by neap tides, after which the full moon spring tides took place during the third quarter.

An average neap high tide did not inundate the marsh surface. However, the entire marsh surface was inundated by spring high tides on average about 10–12 times a month. Depths of inundation varied from between 1 and 22 cm of water above the average marsh surface elevation and usually lasted between 3 and 4 h per high tide. Storm surges brought on by wind or other extreme meteorological events were observed to cause additional marsh surface flooding, unrelated to the spring tide events. This irregular flooding pattern distinguishes irregularly flooded wetlands like Piermont Marsh from other wetlands in the Estuary that are flooded by every high tide.

The average of 175 high water observations made between 10/2/98 and 12/31/98 in the Hudson River was 0.84 m NGVD-29. The highest observed water level during this time period was 1.17 m NGVD-29. The MHW can be calculated by correcting measurements made over a short period of observation for long-term fluctuations in the metonic cycle and for the meteorological conditions experienced during the observation period. Correcting three months of high water observations according to the methodology outlined by Marmer (1927) yielded a MHW of 0.83 m NGVD-29 for Piermont Marsh.

Low water observations could not be consistently recorded due to limitations in the range of the pressure transducers and the fact that the plane of low water often was too low to measure at either the river or creek gage locations. Mean low water could, therefore, not be calculated. An estimate was made, however, by averaging 25 low water observations made at the USGS Hastings-on-Hudson tide gage located across the River from Piermont Marsh. This value was B0.28 m NGVD-29, and is listed with the other tidal datum values in Table 1. The average tidal variation in this span of the Hudson River is therefore estimated at approximately 1.11 m, which interestingly is the same range reported about 130 km further upriver at Tivoli North Bay (Lickus and Barten, 1990).

### 4.4. Water table observations

Figs. 7 and 8 depict the elevation of the water table versus time at all well locations monitored along

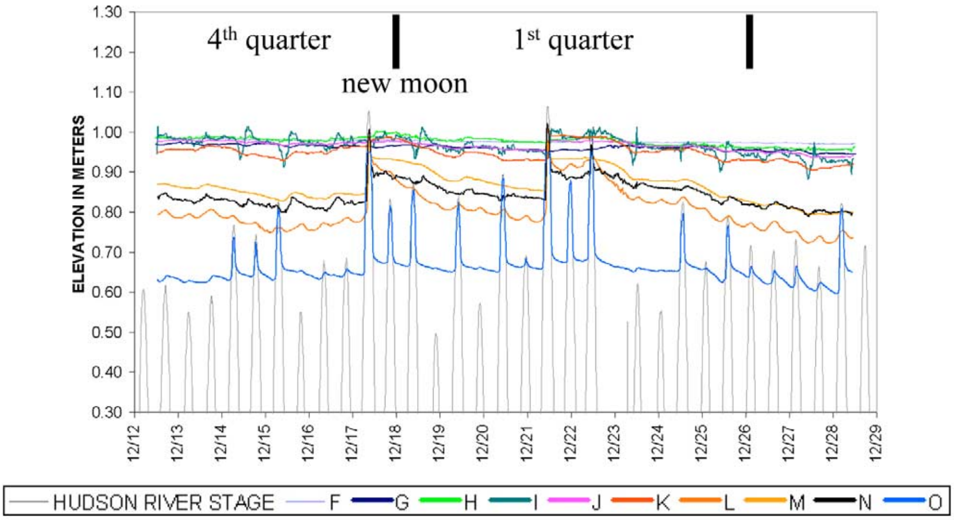
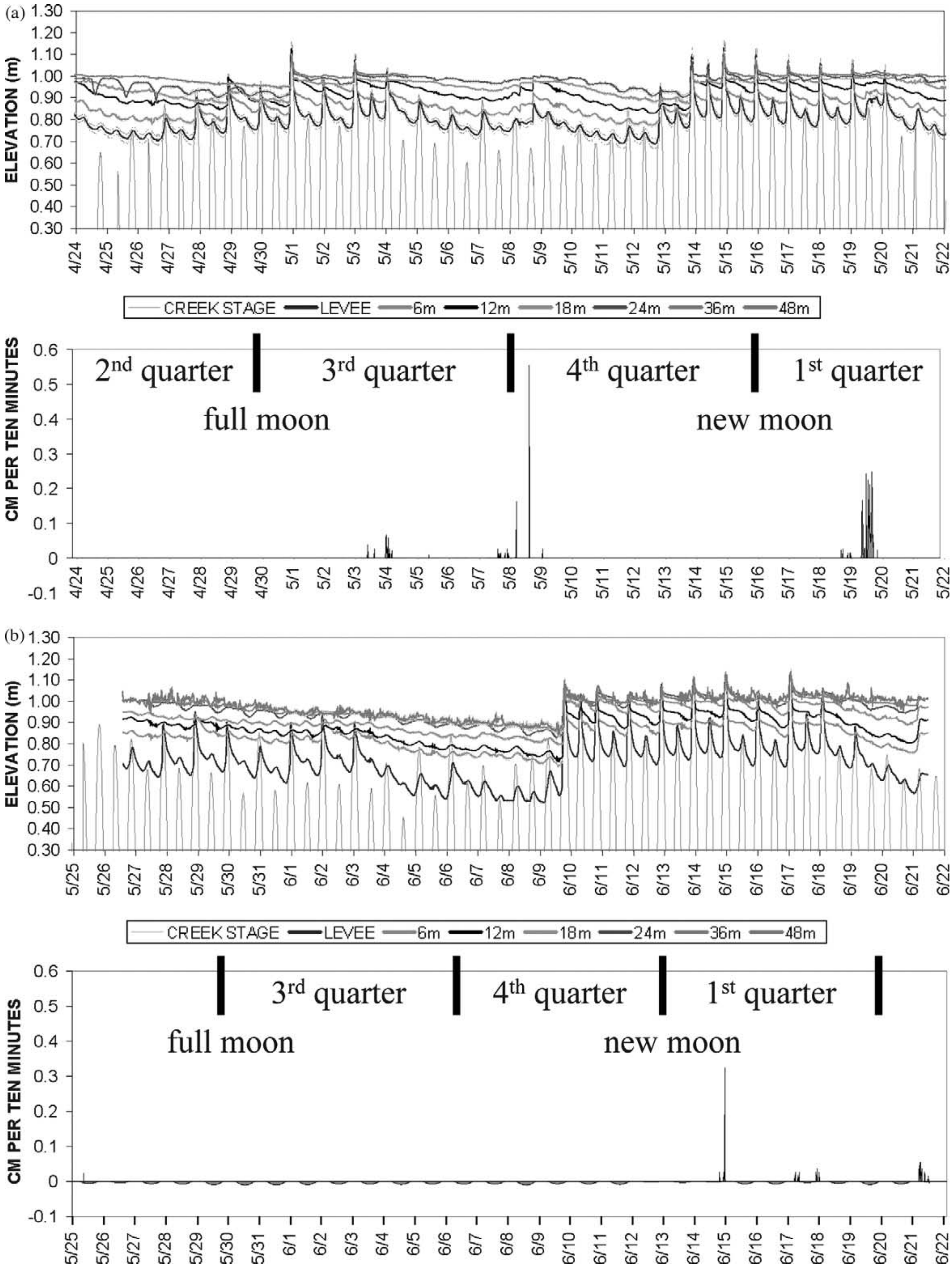



Fig. 7. Water table observations made in selected wells along Transect 1. Note that the marsh surface elevation along transect 1 is 0.95 m. Letters in the legend refer to the locations shown in transect in Fig. 1.


(a)
ELEVATION (m)
CREEK STAGE
LEVEE
6m
12m
18m
24m
36m
48m
CM PER TEN MINUTES
2nd quarter
3rd quarter
4th quarter
1st quarter
full moon
new moon
(b)
ELEVATION (m)
CREEK STAGE
LEVEE
6m
12m
18m
24m
36m
48m
CM PER TEN MINUTES
3rd quarter
4th quarter
1st quarter
full moon
new moon

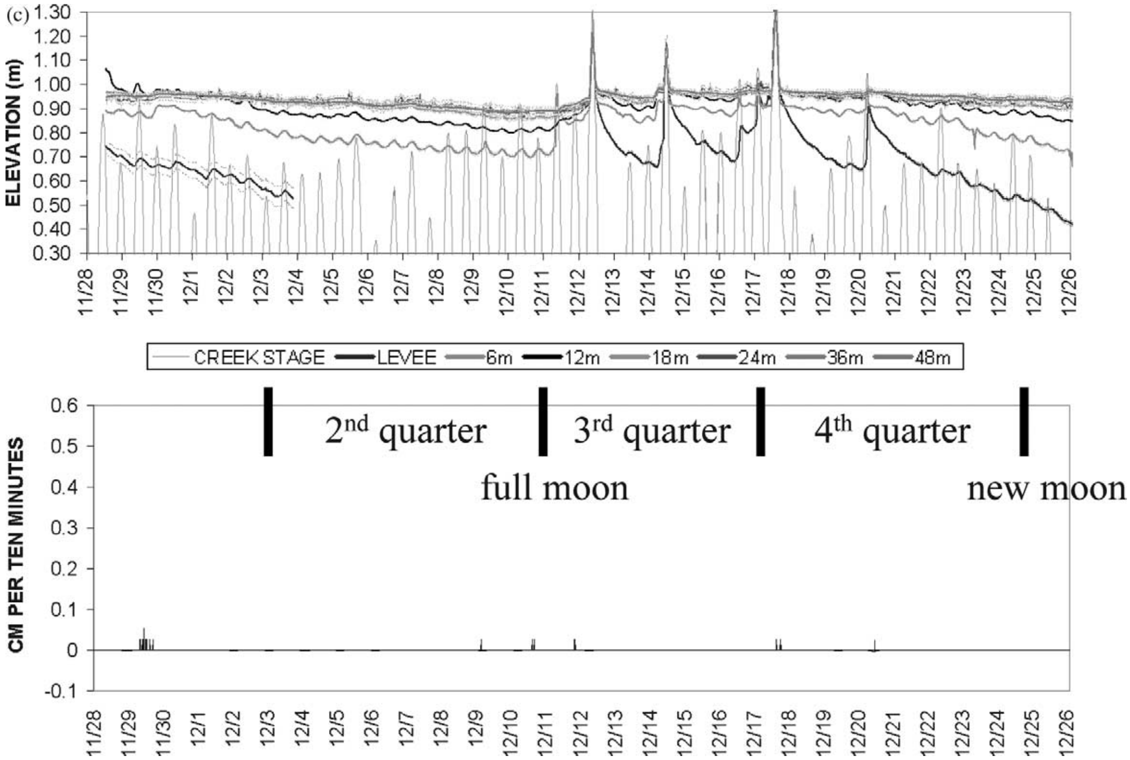



Fig. 8 (*continued*)

Transects 1–4. The simultaneously monitored creek or river stage elevations are shown in gray in the figures and the highest marsh surface elevation along the transect is listed in the figure caption. Different colors are used to depict the water table at different well locations. In Fig. 8, the zone of 95% confidence above and below the water table lines, as determined from the regression analysis performed on the transducer calibrations, is outlined. For most installations, this region was $\pm 1$ cm and is barely visible in the figure. The lowest confidence values were calculated in the levee wells along all three transects. Pressure transducer malfunction is responsible for the gap in 36 m well observations along Transect 2 between 5/5 and 5/14, the noise in the 48 m observations along Transect 3 in Fig. 7b, and the gap in levee well data along Transect 4 between 12/4 and 12/12. Transducer malfunction is also the reason that no 48 m observations are shown along Transect 2 in Fig. 7a. No confidence levels were determined for the data shown in Fig. 7.

### 4.4.1. Water table observations along Transect 1

December 1988 observations of the water table elevation along Transect 1, which extended from the western end of the northern creek to the Hudson River, are shown in Fig. 7. Observations of the water table in other Transect 1 wells shown in Fig. 1 are not shown here because insufficient calibration points prevented accurate conversion of the transducer readings into water table elevations.

Fig. 8. Water table observations along: (a) Transect 2 with surface elevation of 1.02m NGVD-29; (b) transect 3 with surface elevation 1.03 m, NGVD-29; (c) transect 4 with surface elevation 1.01 m NGVD-29. The lower graphics of (a), (b), and (c) depict the net meteorological fluxes (precipitation - potential evapotranspiration) in centimeters per ten minutes (the time step over which the well measurements were made) for the observation periods along each of the three transects.

Despite problems with the transducer calibrations in Wells A–D, manual observations made at these locations, together with the transducer measurements in Wells E–O, were useful in developing some insight into the behavior of the Piermont Marsh water table. The water table was within 10 cm of the local marsh surface elevation for nearly 100% of the periods of observation in Wells D–K, and N. The water table was within 10 cm of the marsh surface for only about half of the observation period in Wells A–C, L, M, and O. These latter wells have, in common, the fact that they are all close to a tidal water body: Wells A–C are close to the Hudson River, with Well A actually positioned in the mudflat, Wells L and M are on opposite sides of a small tidal branch of the northern creek, and Well O is immediately adjacent to the northern creek at its western end. Wells E–K and N, on the other hand, are all located at least 30 m from the nearest tidal water body. (All well locations are shown in Fig. 1).

The December monitoring revealed that the water table elevation across the marsh was identical to within 8 cm in all wells except Wells A and L–O, where it was deeper. Considering the cumulative errors associated with the topographic surveying (vertical errors of 0.5–2 cm are typical for RTK GPS surveying), and the pressure transducer calibrations, these observations suggest that the water table is nearly flat across the majority of the marsh interior, while a gradient is established in those wells located closest to the tidal water bodies.

Only wells located in the marsh 'edge' responded to non-inundating tidal fluctuations in the creek. The water table in Well L rose and fell several centimeters twice a day in response to all tides, even to those that never superceded the elevation of the water table at that well location (Fig. 7). Well O responded to creek stage fluctuations when they superceded its water table elevation only (see, for example, Fig. 7, 12/14–12/15). The sequence was as follows: As the creek stage exceeded the well water table elevation, the latter began to rise with the former. Then, as the tide ebbed, the water table in the well dropped until it reached an elevation very close to where it was before the tide rose. Manual observations in Well A suggest a water table signature similar to that of Well O. All three of these wells were located within several meters of tidal water bodies.

On 12/17, 12/21, and 12/22 the entire marsh was inundated by spring tides. Because the water table was already near the surface in interior Wells F–K, the post inundation water table elevation at these locations was only a few centimeters higher than prior to tidal inundation of the marsh. Manual observations made in Wells D and E suggest a similar result at those locations. The post-inundation water table in Wells L–N, on the other hand, was between 6 and 12 cm higher than immediately prior to inundation (see Fig. 7, 12/17–12/18). It then took approximately three days for the water table to fall to its pre-inundation elevation.

Because of the differences in depth, gradient, and response to diurnal and spring tides, the water table signature of the wells along Transect 1 can be grouped into categories. Wells A, L, and O are called Category 1 because of the extent to which the water table at these locations is affected by the creekbanks. Wells C, M, and N are transitional in nature and are, therefore, labeled Category 2. Category 3 includes Wells D–K, all of which respond similarly to one another and are typical of the marsh interior.

*4.4.2. Water table observations along Transects 2–4*

Fig. 8a–c show approximately one full lunar month of water table observations along Transects 2–4. Along each of these transects, wells were installed at 30 cm, 6, 12, 18, 24, 36, and 48 m from the creekbank. (The 30 cm well is referred to alternatively as the 'levee well' in this paper.) Observations were made along Transects 2–3 in spring and summer conditions between March and August of 1999. Observations were made in autumn and winter conditions during November and December 2000 along Transect 4. The well observations shown, while equivalent in length, began and ended at different points in the lunar cycle along each transect. Also shown on the secondary ordinate axis of Fig. 8a–c are the net meteorological conditions during the observation period. Positive values indicate time intervals during which precipitation exceeded evapotranspiration.

Spring high tides during the first and third lunar quarters periodically inundated the surface of Piermont Marsh, saturating the entire substrate. Manual measurements (not shown) of the water table in all wells along Transects 2–3 were made before, during, and after an inundation event to verify the sequence. Immediately after the inundating tidal waters receded, a surface of seepage was evident

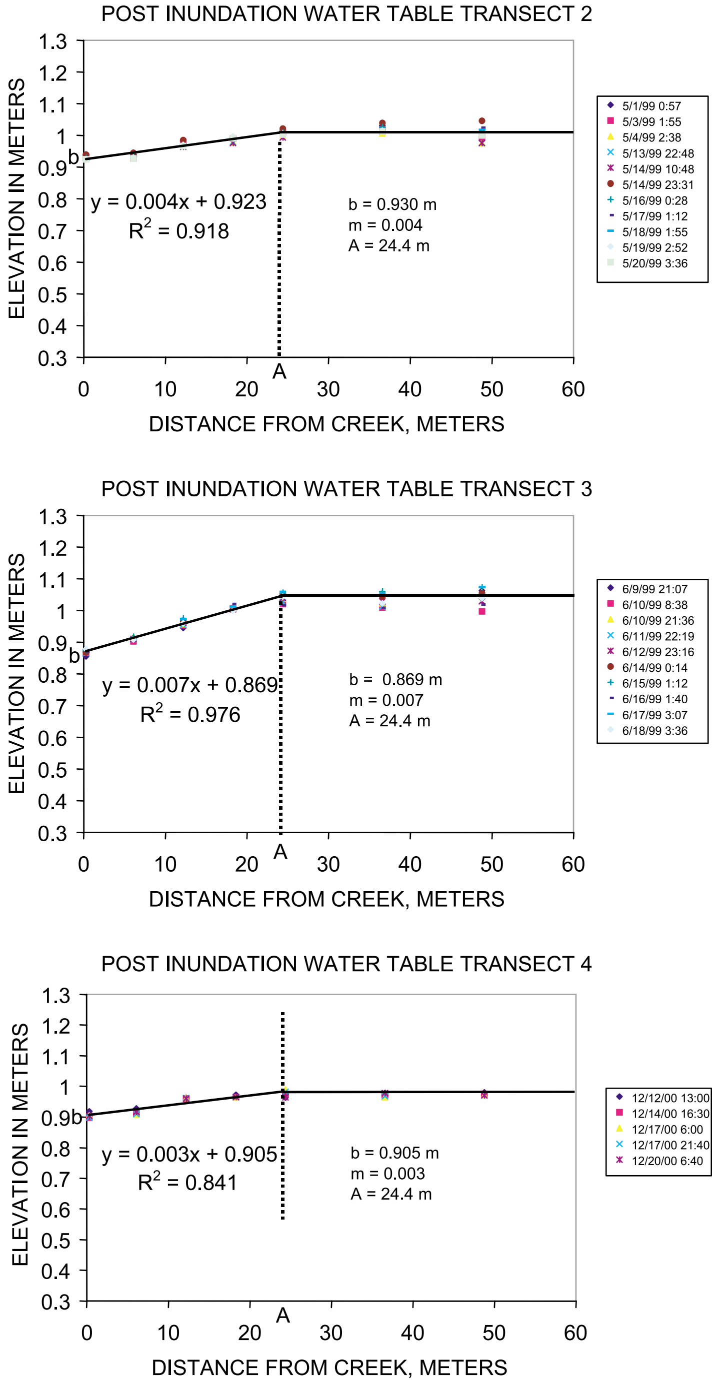



Fig. 9. The water table observed along Transects 2–4 during the first time step for which the creek stage was 5 cm below the water level in the levee well.

along the vertical portion of the creekbank, as has been observed at other sites (Gardner, 1975). A gradient was established in the water table profile of the creekbank region. At distances in excess of 25 m from the creekbank, the post-inundation water table was level and close to the marsh surface. In Fig. 9, the water table observed along Transects 2–4 at the first time step for which the creek stage was 5 cm below the water level in the levee well is shown. Once this initial post-inundation profile was established, the water table across the transects began to drop slowly and steadily throughout the subsequent period of marsh surface exposure. However, the water table only dropped to below the creek half-tide elevation (0.55 m) in the levee well along Transects 3 and 4. At the 36 and 48 m well locations along all three transects, the water table elevation, even after a long period of marsh surface exposure during summer conditions (see elevations along Transect 2 on 6/9 for example), remained very close to the marsh surface.

A diurnal tidal response to non-inundating creek stage fluctuations was observed in the water table observations made along all transects at distances of up to 12 m from the bank, with some tidal behavior evident even at 18 m along Transect 2. This distance is greater than that reported at other sites. Nuttle and Hemond (1988) observed tidal influence only within the first 3 m of creekbanks at Belle Isle Marsh which has substrate characteristics similar to Piermont. Hemond et al. (1984) report that the effects of tidally induced pore water exchange across the creekbanks of the Great Sippewissett Marsh in Massachusetts were attenuated within 4 m from the creek.

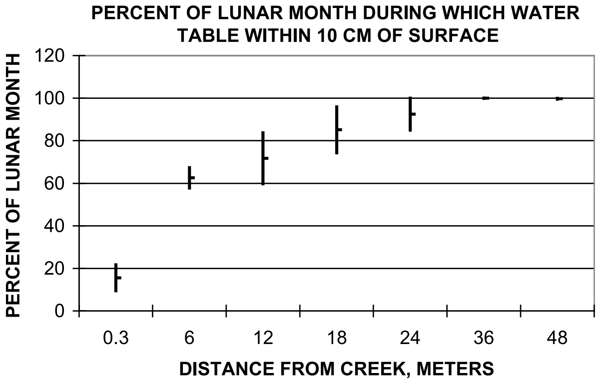
The levee water table oscillated diurnally about a plane that, like the water table in the more internal wells, gradually decayed during periods of marsh surface exposure (see, for example, 4/24–4/27 along Transect 2, 6/18–6/21 along Transect 3, and 12/22–12/25 along Transect 4). Rainfall (see 5/8–5/9 along Transect 2), some non-inundating high tides (see 4/26–4/30 along Transect 2 and 6/5–6/7 along Transect 3), as well as the inundating spring high tides could all potentially raise the elevation of this plane at any point during the lunar month, through a process of hysteresis (the increase occurs much faster than the subsequent decrease).

Finally, rainfall occurring at random with respect to the spring/neap cycle had the greatest effect where the water table was furthest below the surface. For example, during rainfall occurring between 5/7 and 5/10, the water table was nearly 'reset' along Transect 1 to the profile usually observed immediately after tidal inundation. Rainfall occurring on 4/23 raised the water table in the levee, 6 and 12 m wells, and had a minimal effect on the water table further toward the interior. These observations concur with those of Carr and Blackley (1986) who found that rainfall had the greatest effect on pore water pressures, water circulation, and water levels of an irregularly flooded tidal marsh in Cumbria, England, when it fell during low water neap tides.

## 5. Discussion

The hydrology of Piermont Marsh is determined by a delicately balanced relationship between morphological parameters like the surface elevation and the substrate hydraulic conductivity, local meteorological conditions, and local tidal datum. The relationship between the marsh surface elevation and the local tidal datum, not to mention the frequency with which high winds and other meteorological events raise local surface water levels, together determine the marsh's overall hydroperiod. The substrate properties and local precipitation and evapotranspiration rates determine the rate at which water infiltrates into the substrate through the surface and is then lost either to the atmosphere or to creeks during low tide throughout the subsequent period of marsh surface exposure.

To illustrate the dynamic balance between these factors that is achieved at Piermont Marsh, the inter-transect percentage of the lunar month, during which the water surface was within 10 and 20 cm of the marsh surface elevation, was calculated and is shown in Fig. 10. These values were obtained by calculating first the percentages of all observations made along Transects 2–4, during *each* of the four lunar quarters when the 10 or 20 cm condition was met, and then by calculating the weighted average over *all four* quarters to determine the monthly averages. Note that the averages were based on all observations in the wells, including some outside the time interval shown in Fig. 8. The vertical bars show the inter-transect standard deviation between observations made at each distance from the creekbank.



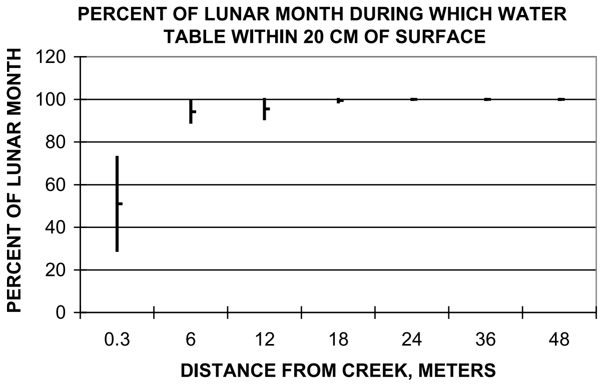




Fig. 10. The percent of the lunar month during which the water table was within 10 and 20 cm of the average marsh surface along Transects 2–4. The vertical error bars show the inter-transect standard deviation for all wells located at each distance back from the creekbank. At distances of equal to and greater than 36 m from the creek, the water table was nearly always within 10 cm of the marsh surface along all three transects. The water table was nearly always within 20 cm of the marsh surface along all three transects for all distances 18 m and greater from the creek. Closer to the creek, the water table is deeper for a greater percentage of the month.

The water table was close to the surface of Piermont Marsh for a longer percentage of the lunar month at the marsh interior than in wells located closer to the creeks. The same observation has been made at other tidal marsh sites (Jordan and Correll, 1985; Nuttle, 1988a,b; Nuttle and Hemond, 1988; Warren et al., 2001). At distances of equal to and greater than 36 m from the creek, the water table was nearly always within 10 cm of the marsh surface along all three transects. Even during the observations made along Transect 3 characterized by very hot daytime temperatures approaching 38 °C, the water table was always very close to the marsh surface (see Fig. 8b, 6/7). The water table was nearly always within 20 cm of the marsh surface along all three transects for all distances 18 m and greater from the creek. At distances of less than 18 m from the creek, the percentage of the lunar month during which the water table was close to the marsh surface decreased. In the levee, for example, the water table was never within 10 cm of the marsh surface for more than about one quarter of the lunar month. From these observations, it appears reasonable to assume that the 36 and 48 m wells along Transects 2–4 behave similar to the Category 3 wells along Transect 1, and represent the behavior of the water table under the vast majority of the interior marsh plane.

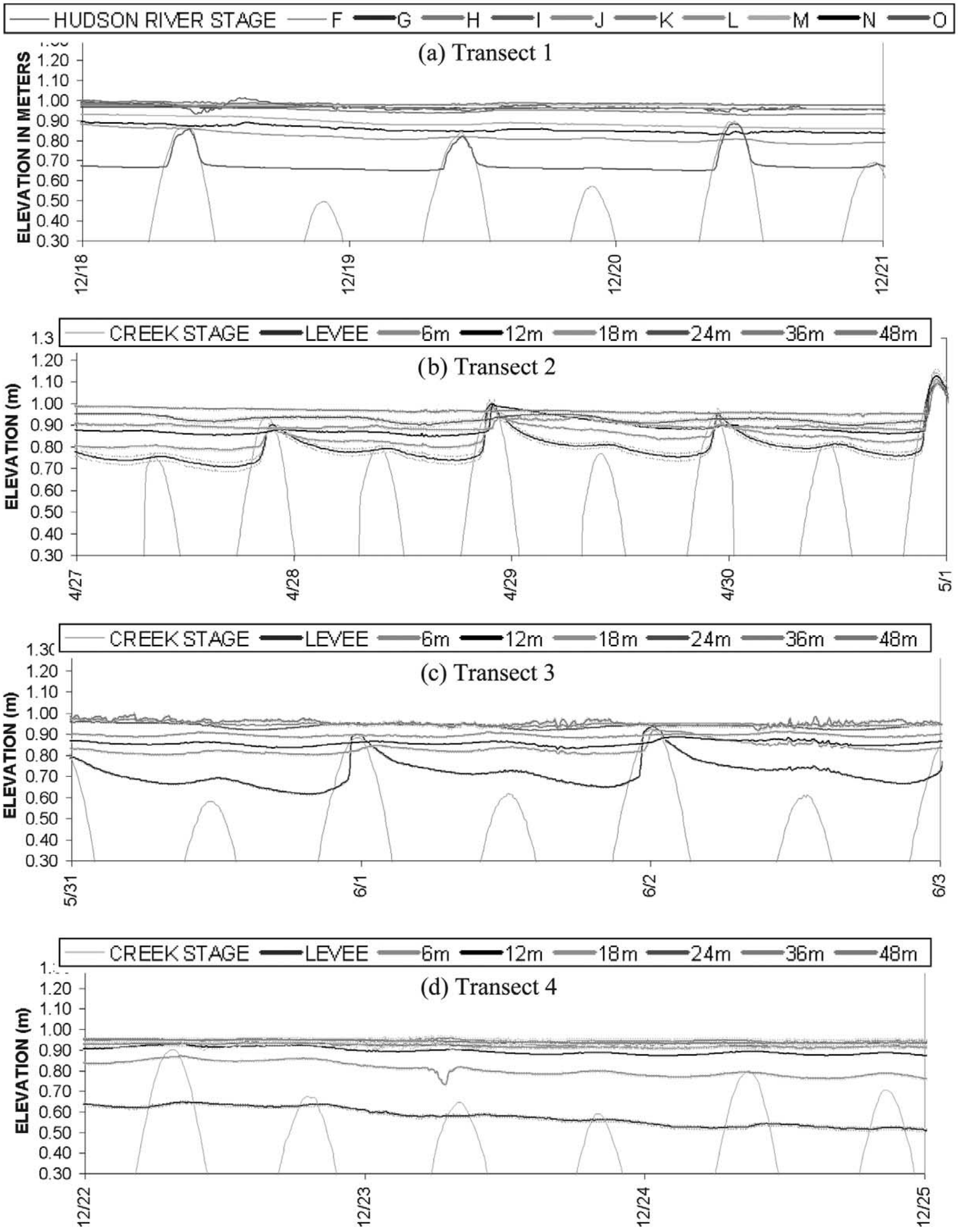
The water table position does not necessarily correspond to the upper limit of substrate saturation. Substrate desaturation and air entry only occurs when the pore water pressures above the water table have fallen low enough for atmospheric pressure to overcome the surface tension of the meniscus at the pore water/atmosphere interface. Less frequent inundation of the marsh surface, a more highly conductive substrate, or higher evapotranspiration rates would result in a lower water table and more frequent substrate desaturation, all other factors being equal in a given marsh. The fact that the water table across the majority of the marsh interior almost always remained within 10 cm of the marsh surface could be significant, considering that Nuttle and Hemond (1988) report the onset of desaturation at Belle Island Marsh, in Boston, MA, at the point when the water table dropped below approximately 10 cm from the marsh surface. The extent and frequency of desaturation and air entry into the marsh substrate is important in determining rates of sediment metabolism and soil toxicity which, in turn, are factors in determining the microbial and vegetative species present and the solubility and, therefore, the rate of export of various inorganic substances to the estuary (Hemond and Chen, 1990).

Some observations made on-site indicate that some substrate desaturation may be occurring. Fluctuation by a few centimeters of the distance between the marsh surface and fixed marks made on long rebars installed as topographic benchmarks was indicative of the periodic shrinking and swelling of the marsh peat throughout the observation period. Shrinking of peaty soils could be the result of soil consolidation as air enters desaturated pore spaces, but could also be confounded with a decrease in bulk sediment volume that occurs as water is lost from highly elastic marsh soils (Hemond and Chen, 1990). The moisture content of the top 10 cm of substrate was found to be much lower in the creekbank than more internally. At the same time, the organic content of the creekbank region was also much lower than further inland. Together, these latter observations could indicate that less saturated conditions in the creekbank zone are causing increased rates of decomposition and mineralization in this region. However, the lower organic content in the creekbank could also be the result of higher rates of sedimentation from inundating creek waters and only further research can clarify this point.

The marsh hydroperiod, as characterized by this study, is indicative of the frequency and duration of inundation during this particular moment in the 18.6 year metonic cycle only. At The Battery, the nearest NOAA-NOS tide gage station for which the full 18.6 year tidal epoch data are available, the average water level during the three observation periods (9/98–12/98, 4/99–7/99, and 11/00–12/00) was between 2 and 6 cm higher than the 18.6 year average for that location. This observation indicates that water levels at other points in the Estuary, including the Hudson River near Piermont Marsh, were probably also above average during the present study period than at other points in the tidal epoch. Piermont Marsh was, therefore, probably inundated more frequently during this study period than it was at other periods during its 18.6 year tidal epoch.

The unique geomorphological characteristics of the creekbank region of Piermont Marsh seem to exert considerable control over the hydrology of the remainder of the marsh interior, in specific, and the overall ecology of the marsh, in general. Measurements of the saturated hydraulic conductivity made using the auger hole method have a zone of influence on the order of 10 m (Brutsaert, 2002, personal communication). This signifies that the lower saturated hydraulic conductivity values of the creekbank substrate differentiate the hydraulic characteristics of that region from those of the marsh interior. The less conductive substrate of the creekbank likely controls the rate at which water from the marsh interior drains through the creekbanks and into the estuary, and vice versa. Darcy's Law states that the rate of flow through a given area of porous media is proportional to the hydraulic conductivity and the hydraulic gradient in the media. If the saturated hydraulic conductivity of the creekbank substrate were of the same order of magnitude as that found in the marsh interior, the rate at which water is exchanged between creeks and the marsh substrate would be orders of magnitude higher in both directions, under the same hydraulic gradient. Of course, under these conditions, the hydraulic

Fig. 11. Preferential flow was observed to varying extents along each of the four transects in response to noninundating high tides: (a) The water table in Well O along Transect 1 rose and fell with the creek stage whenever the latter exceeded approximately 0.65 m. (b) and (c) On the incoming tide, the water table in the levee well along Transects 2 and 3 followed the creek stage closely. However, on the outgoing tide, the creek stage receded at a much faster rate than the water table in the levee. (d) The levee well along Transect 4 showed only a minimal response to noninundating high tides, even when they exceeded the levee water table by 20 cm or more.


HUDSON RIVER STAGE
F
G
H
I
J
K
L
M
N
O
(a) Transect 1
ELEVATION IN METERS
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
12/18
12/19
12/20
12/21
CREEK STAGE
LEVEE
6m
12m
18m
24m
36m
48m
(b) Transect 2
ELEVATION (m)
1.3
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
4/27
4/28
4/29
4/30
5/1
CREEK STAGE
LEVEE
6m
12m
18m
24m
36m
48m
(c) Transect 3
ELEVATION (m)
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
5/31
6/1
6/2
6/3
CREEK STAGE
LEVEE
6m
12m
18m
24m
36m
48m
(d) Transect 4
ELEVATION (m)
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
12/22
12/23
12/24
12/25

gradient found in the substrate would decay at a much faster rate, extending the 'edge' hydrology patterns, as observed in Category 1 wells along Transect 1 and in the levee and 6 m wells along Transects 2–4, throughout a much greater proportion of the marsh. The seepage surface might altogether disappear during low tide and tidal fluctuations in the creek would propagate much further into the marsh aquifer.

Fig. 11 is a comparison of the variable levee water table response to non-inundating high tides along Transects 1–4. Along Transects 2 and 3 (Fig. 11b,c), it appears that macropores provide a point of entry through which creek waters enter the marsh substrate preferentially, raising the water table almost immediately. On recession of the tide, however, the water table in these areas gets 'stuck' at an elevation that is higher than before the high tide. This response contrasts with those of Wells A and O along Transect 1 (Fig. 11a) where the pre- and post-high tide water table elevations were similar. A third kind of response to non-inundating high tides was observed in the levee water table along Transect 4 (Fig. 11d). Very little water table response to non-inundating high tides was observed at that location, even when creek stage elevations exceeded the levee water table by 20 cm or more.

Nuttle and Hemond (1988) speculate that the saturated hydraulic conductivity of the tidal marsh substrate is controlled by its macroporous structure, which is itself biotically controlled. At Piermont Marsh, the variable response of the levee water table to creek stage fluctuations may be the result of fiddler crab burrows, muskrat tunnels, and other macropores in the creekbank wall that are alternatively clear and open, or full and under pressure. The minimal response along Transect 4 could be due to freezing temperatures resulting in ice blockage of large openings in the creekbank wall. Alternatively, it is possible that the density of macropores in the banks of Crumkill Creek is lower than along the northern creek. Similarly, the density of macropores at Wells A and O locations could be higher than in the middle of the northern creek. Also a potential factor are seepage face phenomena occurring along the creekbank itself, and the firmer, more intact, quality of the substrate in 'edge' portions of the marsh. Nuttle (1982) observed that water movement near the creekbanks of a Massachusetts tidal marsh has a component with a period longer than the 12.5 h tidal period, suggesting that longer term spring/neap and metonic cycles may also come into play.

The substrate quality, horizontal water table gradient, and tidal oscillations in the creekbank region of Piermont Marsh are similar to observations made at other sites, and are the reason that the biota, chemistry, and fluxes in these areas differ from those of more internal portions of the marsh (Harshberger, 1909; Johnson and York, 1915; Hemond et al., 1984; Agosta, 1985; Jordan and Correll, 1985; Yelverton and Hackney, 1986; Harvey et al., 1987; Nuttle and Hemond, 1988). Higher growth of *Spartina alterniflora* along creekbanks, for example, has been widely reported in these areas (Howes et al., 1981; DeLaune et al., 1983; Dacey and Howes, 1984; Agosta, 1985; Nuttle, 1988a,b; Furbish and Albano, 1994). Creekbanks are also where invasive *Pragmites* were initially established at Piermont Marsh (Winogrond, 1996). In Belle Island Marsh, a tidal marsh with substrate characteristics, hydroperiod, water budget, and vegetation regime similar to that of Piermont Marsh, Nuttle (1988a,b) reports that creekward drainage accounts for 40% of the water lost within 10 m of the creekbank, with that percentage becoming negligible in the interior. If restored wetlands are to function similarly to natural wetlands, the specific physical characteristics of the creekbank region of the tidal marsh need to be studied more closely.

### *5.1. Practical implications for Marsh restoration*

There is a clear difference between the hydrology of the 'edge' versus 'interior' portions of Piermont Marsh. At Piermont Marsh, a low conductivity (on the order of 0.001 cm/s) in the creekbank levee probably helps to ensure that the water table throughout most of the marsh interior is near the surface. A highly conductive ($>0.01$ cm/s) substrate in the marsh interior, on the other hand, likely allows small but significant fluxes of water from the marsh interior to replenish water lost from the edge portions of the marsh to creekward drainage. Just as a less conductive marsh interior might result in a wider marsh 'edge', a more conductive creekbank might greatly increase drainage rates. The variable extent of preferential flow that takes place in the levee is likely a function of the size and density of macropores in the creekbank walls. The macroporous structure and spatial distribution of hydraulic conductivity both appear to be important, therefore, in determining the position of the water table which, in turn, determines spatial patterns of soil desaturation and oxygenation, and also the overall rate of the transport of pore water from the marsh to the estuary. The design, construction, and evolution of the marsh 'edge' will greatly determine the extent to which natural hydrologic patterns are successfully reproduced in restored marshes. The overall network of primary and secondary tidal creeks is also critical in determining the overall percentage of the marsh that has 'edge-like' hydrology. More creeks will create more edges, and the distinctly different biogeochemical conditions that accompany them.

In the marsh interior, the total volume of evapotranspiration and horizontal creekward drainage occurring during periods of marsh surface exposure is not sufficient to cause the water table to drop further than about 10 cm from the marsh surface, even during very hot summer conditions. Spring tide inundation of the entire marsh surface and, to a lesser extent precipitation, replenishes any water that is lost from the marsh interior and maintains these saturated conditions. Less frequent inundation and precipitation would likely cause an expansion of the edge hydrology into the interior and cause more frequent desaturation of interior marsh sediments. More frequent inundation and precipitation would likely reduce the width of the marsh 'edge', and cause less oxygenation of the substrate there, with significant biogeochemical implications. In order to recreate the hydrologic conditions of an irregularly flooded wetland like Piermont Marsh, restoration designs need to replicate the spring/neap tidal inundation pattern and overall water budget. This involves selecting an appropriate marsh surface elevation, given both local tidal elevations and historical meteorological conditions in the area.

Finally, just as the elevation of the surface of Piermont Marsh has risen in the last decade, the initial marsh surface elevation established in a restoration site will accrete due to processes of sedimentation and deposition. It may also subside due to substrate consolidation. At the same time, the sea level is rising. Along with these factors, to establish target inundation frequencies for a restoration site, the long-term metonic cycling and meteorological conditions during the period of observations at the reference site need to be considered. A given marsh may be inundated much more frequently during high points in the 18.6 year metonic cycle than at low points. Thus, short-term observations made at a reference site need to always be considered in the context of longer-term cycles that affect them.

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## References

Abood, K.A., 1974. Circulation in the hudson estuary. In: Roels, O. A. (Ed.), Annals of the New York Academy of Sciences: Hudson River Colloquium. New York Academy of Sciences, New York, pp. 39–109.

Agosta, K., 1985. The effect of tidally induced changes in the creekbank water table on pore water chemistry. Estuarine, Coastal, Shelf Science 21, 389–400.

Balmford, A., Bruner, A., Cooper, P., Costanza, R., Farber, S., Green, R.E., Jenkins, M., Jefferiss, P., Jessamy, V., Madden, J., Munro, K., Myers, N., Naeem, S., Paavola, J., Rayment, M., Rosendo, S., Roughgarden, J., Trumper, K., Turner, R.K., 2002. Economic reasons for conserving wild nature. Science 297, 950–953.

Carr, A.P., Blackley, M.W.L., 1986. The effects and implications of tides and rainfall on the circulation of water within salt marsh sediments. Limnology and Oceanography 31, 266–276.

Conard, H.S., 1935. The plant associations of central Long Island: a study in descriptive plant sociology. American Midland Naturalist 16, 433–516.

Cooper, J.C., Cantelmo, F.R., Newton, C.E., 1988. Overview of the Hudson River Estuary. American Fisheries Society Monograph 4, 11–24.

Dacey, J.W., Howes, B.L., 1984. Water uptake by roots controls water table movement and sediment oxidation in short *Spartina* marsh. Science 224, 487–489.

Darmer, K.I., 1987. Overview of Hudson River hydrology. Final Report to the Hudson River Foundation, 174 pp.

DeLaune, RD, Smith, CJ, Patrick Jr.., W.H., 1983. Relationship of marsh elevation, redox potential, and sulfide to *Spartina alterniflora* productivity. Soil Science Society American Journal 47, 930–935.

Furbish, C.E., Albano, M., 1994. Selective herbivory and plant community structure in a mid-Atlantic salt marsh. Ecology 75, 1015–1022.

Gardner, R.G., 1975. Runoff from an intertidal mash during tidal exposure - recession curves and chemical characteristics. Limnology and Oceanography 20, 81–89.

Giese, G.L., Barr, J.W., 1967. The Hudson River Estuary: a preliminary investigation of flow and water quality characteristics, State of New York Conservation Department, vol. 61. Water Resources Commission, Bulletin. 39 pp.

Goldhammer, A., Findlay, S., 1988. Estimation of suspended material flux between a Trapa natans stand and the Hudson River Estuary. In: Blair, E.A., Waldman, J.R., (Eds.), Final Reports of the Tibor T. Polgar Fellowship Program, 1987. Hudson River Foundation, NY, 46 pp. (Section VIII).

Harshberger, J.W., 1909. The vegetation of the salt marshes and of the salt and fresh water ponds of northern coastal New Jersey. Academie Nationale Science Philadelphia Process 61, 373–400.

Harvey, J.W., Odum, W.E., 1990. The influence of tidal marshes on upland groundwater discharge to estuaries. Biogeochemistry 10, 217–236.

Harvey, J.W., Nuttle, W.K., 1995. Fluxes of water and solute in a coastal wetland sediment. 2. Effect of macropores on solute exchange with surface water. Journal of Hydrology 164, 109–125.

Harvey, J.W., Germann, P., Odum, W.E., 1987. Geomorphological control of subsurface hydrology in the creekbank zone of tidal marshes. Estuarine, Coastal, Shelf Science 25, 677–691.

Hemond, H.F., Fifield, J.L., 1982. Subsurface flow in salt marsh peat: a model and field study. Limnology and Oceanography 27, 126–136.

Hemond, H.F., Chen, D.G., 1990. Air entry in salt marsh sediments. Soil Science 150, 459–468.

Hemond, H.F., Nuttle, W.K., Burke, R.W., Stolzenbach, K.D., 1984. Surface infiltration in salt marshes: theory, measurement, and biogeochemical implications. Water Resources Research 20, 591–600.

Howells, G.P., 1972. The estuary of the Hudson River, USA. Proceedings of the Royal Society of London. Series B 180, 521–534.

Howes, B.L., Howarth, R.W., Teal, J.M., Valiela, I., 1981. OxidationBreduction potentials in a salt marsh: spatial patterns and interactions with primary production. Limnology and Oceanography 26, 350–360.

Jay, D.A., Bowman, M.J., 1975. The physical oceanography and water quality of New York Harbor and western Long Island Sound. U.S. Department of Commerce, National Technical Information Service, Springfield, VA, Technical Report #23, Reference # 75-7. 71 pp.

Johnson, D.S., York, H.H., 1915. The Relation of Plants to Tide-Levels: A Study of Factors Affecting the Distribution of Marine Plants. Carnegie Institution of Washington, Washington, DC (Pub. 206. 162 pp).

Jordan, T.E., Correll, D.L., 1985. Nutrient chemistry and hydrology of interstitial water in brackish tidal marshes of Chesapeake Bay. Estuarine, Coastal, Self Science 21, 45–55.

Lickus, M., Barten, P., 1991. Hydrology of a tidal freshwater marsh along the Hudson River. In: Blair, E.A., Waldman, J.R. (Eds.) Final Reports of the Tibor T. Polgar Fellowship Program, 1990. Hudson River Foundation, NY, 45 pp. (Section I).

Marmer, H.A., 1927. Tidal datum planes, Special Publication No. 135 of the U.S. Coast and Geodetic Survey. U.S. Government Printing Office, Washington, DC (142 pp).

McCrone, A.W., 1966. The Hudson River Estuary: hydrology, sediments, and pollution. Geographical Review 56, 175–189.

Middleton, B., 1999. Wetland Restoration: Flood Pulsing and Disturbance Dynamics. Wiley, New York (388 pp).

Mitsch, W.J., Gosselink, J.G., 2000. Wetlands, third ed. Van Nostrand Reinhold, New York.

Montalto, F.A., Steenhuis, T.S., 2004. The link between hydrology and restoration of tidal marshes in the New York/New Jersey Estuary. Wetlands 24 (2), 414–425.

Nichols, E.M., 1985. Determination of the hydrologic parameters of salt marsh peat using in-situ well tests. Masters Thesis, Massachusetts Institute of Technology, Cambridge, MA.

Nuttle, W.K., 1982. The flow of water in salt marsh peat. Masters Thesis, Massachusetts Institute of Technology, Cambridge, MA.

Nuttle, W.K., 1988. The extent of lateral water movement in the sediments of a New England salt marsh. Water Resources Research 24, 2077–2085.

Nuttle, W.K., 1988a. The extent of lateral water movement in the sediments of a New England salt marsh. Water Resources Research 24, 2077–2085.

Nuttle, W.K., 1988b. The interpretation of transient pore pressures in salt marsh sediment. Soil Science 146, 391–402.

Odum, W.E., Odum, E.P., Odum, H.T., 1995. Nature's pulsing paradigm. Estuaries 18, 547–555.

Schureman, P., 1934. Tides and currents in the Hudson River, Special Publication No. 180 of the U.S. Coast and Geodetic Survey. U.S. Government Printing Office, Washington, DC. 106 pp.

Shisler, J.K., 1990. Creation and restoration of coastal wetlands of the northeastern United States. In: Kusler, J.A., Kentula, M.E. (Eds.), Wetland Creation and Restoration: The Status of the Science. Island Press, Washington, DC, pp. 143–170.

van Beers, W.F.J., 1958. The Auger-Hole method, a field measurement of the hydraulic conductivity of soil below the water table, International Institute for Land Reclamation and Improvement, Bull. 1. Wageningen, The Netherlands.

Warren, R., Fell, P., Grimsby, J., Buck, E., Rilling, C., Fertik, R., 2001. Rates, patterns, and impacts of *Phragmites australis* expansion and effects of experimental *Phragmites* control on vegetation, macroinvertebrates, and fish within tidelands of the lower Connecticut River. Estuaries 24, 90–107.

Winogrond, H.G., E. Kiviat, 1997. Invasion of Phragmites australia in the tidal marshes of the Hudson River. Section VI. In: Nieder, W.C., Waldmon, J.R. (Eds.), Final Reports of the Tibor T. Polgar Fellowship Program, 1996. Hudson River Foundation, New York.

Wong, J., Peteet, D., 1999. Environmental history of Piermont Marsh, Hudson River, NY. Section III: 30. In: Nieder, W.C., Waldman, J.R. (Eds.), Final Reports of the Tibor T. Polgar Fellowship Program, 1998. Hudson River Foundation, NY. (Section III. 30 pp).

Yelverton, F.G., Hackney, C.T., 1986. Flux of dissolved organic carbon and pore water through the substrate of a *Spartina alterniflora* marsh in North Carolina. Estuarine, Coastal, Shelf Science 22, 255–267.

Zedler, J.B., 2001. Handbook for Restoring Tidal Wetlands. CRC Press, New York. 439 pp.