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THE LINK BETWEEN HYDROLOGY AND RESTORATION OF TIDAL MARSHES IN THE NEW YORK/NEW JERSEY ESTUARY

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Abstract: The objectives of this paper are to summarize existing knowledge on the hydrologic characteristics of tidal marshes in the New York/New Jersey (NY/NJ) Estuary, to document the extensive linkages between hydrology and tidal marsh function, to underline their importance in designing restoration projects, and to identify research needs in this area. Hydrologic processes are responsible for the evolution, inter- and intra- marsh variability, and functional value of tidal marshes. Hydrology also controls the movement of materials and organisms between estuaries, wetlands, uplands, and the atmosphere. The importance of hydrology to tidal marsh function is widely recognized by the scientific community. Hydrologic research in tidal wetlands of the NY/NJ Estuary, however, is lacking. Anthropogenic development activities have resulted in drastic losses of tidal wetland value, and restoration is now finally a priority in many of the region's natural resource management plans. The success of tidal marsh restoration efforts depends on how appropriately hydrologic factors and their interdependencies are recognized and incorporated into design; yet, little guidance about how best to restore tidal marsh hydrology is available. There is a need to document better the hydrologic characteristics of existing and historical tidal wetlands, to improve hydrologic modeling capabilities, and to accompany other ecological investigations in tidal marshes with hydrologic documentation.

Key Words: Tidal wetlands, wetlands hydrology, New York/New Jersey Estuary

INTRODUCTION

Tidal wetlands and shallow water flats that historically lined the coastlines of the New York/New Jersey (NY/NJ) Estuary have been impacted heavily since the arrival of European colonists. The NY/NJ Estuary (Estuary) consists of the core harbor area and the tidal water bodies and tributaries surrounding and feeding it in New York, New Jersey, and Connecticut, USA. It also includes the south shore of Connecticut, the north and south shores of Long Island, the creeks and inlets of northern coastal New Jerey, and the entire tidal portion of the Hudson River, which extends up to the Troy Dam. Figure 1 delineates the approximate area where tidal wetlands can be found.

A lack of understanding of the value of these wetland ecosystems led to extensive impairment and destruction of local tidal wetlands. Beginning in the 17th century, huge portions of shoreline were modified, channels dredged, and wetlands disrupted or filled to accommodate increases in trade, population growth, urbanization, and traffic. Dredge and fill activities associated with residential development were responsible for the greatest losses. However, filling also occurred during the construction of transportation infrastructure and as a means of mosquito control (Squires 1990). Well-known locations in the New York metropolitan area, such as LaGuardia, Newark, and Kennedy Airports, Shea Stadium, the World's Fair Grounds, Co-op City, Fresh Kills Landfill, the Meadowlands Sports Complex, Port Elizabeth, and Port Newark, were all built on top of former marshlands (Barlow 1971, Squires 1990).

Of the wetlands that were not filled, many were functionally impaired through hydrologic alteration. Extensive hydrologic alterations likely caused extensive vegetation change in the Hackensack Meadowlands. Ditching and diking activities and the comple-

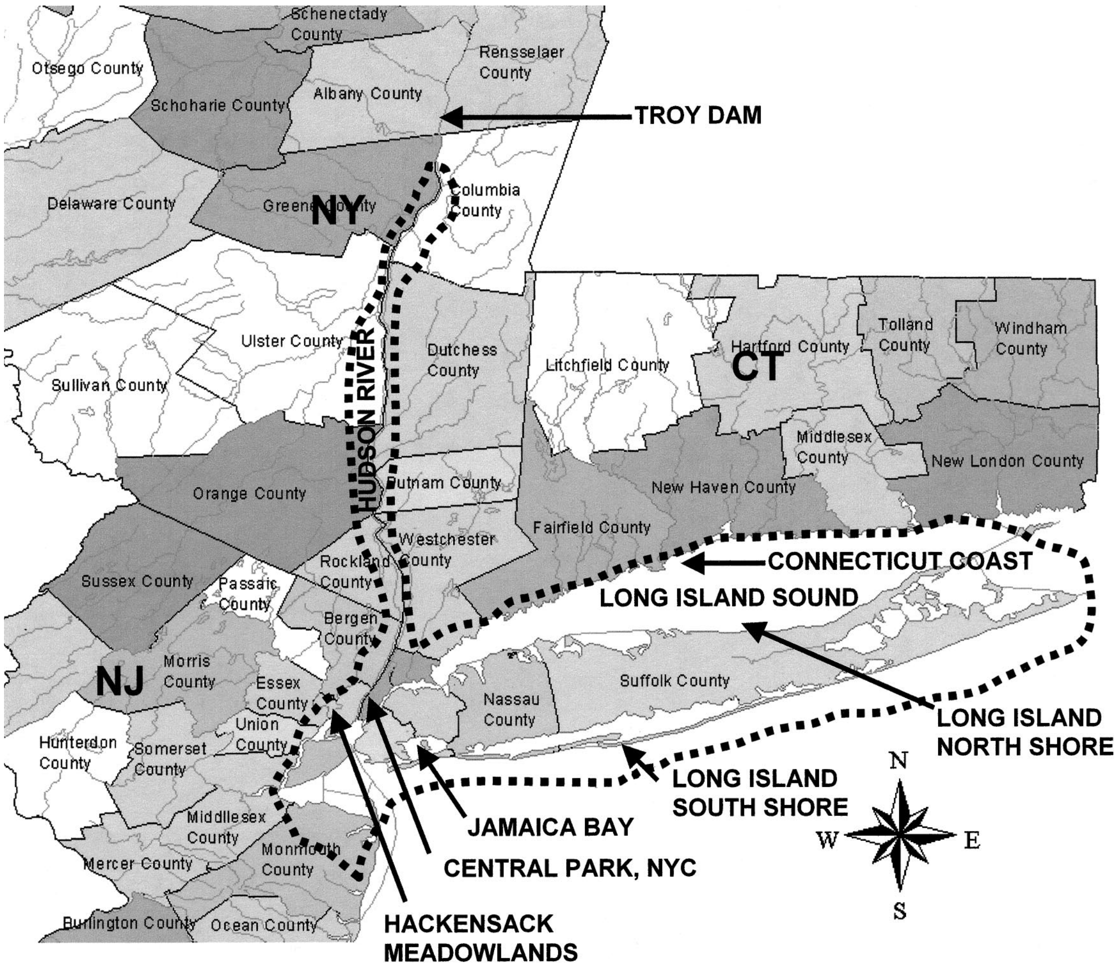

Figure 1. Map of The New York/New Jersey Estuary (adapted from National Atlas of the United States, 2000).

tion of the Oradell Dam in 1922 lowered the water table, facilitated peat decomposition and subsidence, and facilitated saltwater penetration into the area (Sipple 1971). Along the Connecticut shore, the connection of New York to Boston by railroad hydrologically isolated many wetlands from the Long Island Sound (Squires 1990). The installation of tide gates and other hydrologic restrictions has been deemed responsible for the conversion of several Connecticut Long Island Sound salt marshes to near monotypic stands of the common reed, *Phragmites australis* ((Cav.) Trin ex Steudel) (Roman et al. 1984). Historic changes to the Hudson River shoreline, including the barricading of approximately 54 and 63% of the eastern and western shorelines, respectively, for railroad construction (Young and Squires 1990), have also had detrimental hydrologic impacts on wetlands (Hudson River Estuary Action Plan Draft: 2000–2002 2000). Gross (1974) reported that deep channel dredging in the Hudson River between the Town of Hudson and Albany almost doubled the tidal range in that portion of the river. This hydrologic change would have significantly altered the hydroperiod (or pattern of marsh flooding) of wetlands in that span of the river. In addition, aerial photography taken at Stockport Flats, a tidal wetland complex in the area, soon after the dredging indicates that spoil material from the project, placed in local wetlands, resulted in sparse vegetation (Carey and Waines 1987).

Detailed quantification of the area of tidal wetlands lost to date in the NY/NJ Estuary has not been published. This is due to a difficulty in assessing the extent of pre-colonial coverage, a lack of consistency in ecotone definition, and the prevalence of many different political and geographic boundaries in the region. While it has been estimated that only 53% of the historical wetlands area in the contiguous United States in the 1780s remained in the 1980s (Dahl 1990), it has been estimated that 75% of historical wetlands in the NY/NJ Harbor Estuary have disappeared in the last century alone (New York/New Jersey Harbor Estuary Program 1996). In 1997, the U.S. Fish and Wildlife Service estimated that approximately 121,410 ha of tidal wetlands and underwater lands had been filled and that only about 20% or 6,270 ha of the historical

Table 1. Current estimates of tidal wetland coverage in and around the NY/NJ Estuary.

Geographic Description	Area (ha)	Source
Salt marsh in New York City	1,538	M. Matsil, pers. comm.
Tidal wetlands in Hackensack Meadowlands District	2,630	K. Scarlatelli, pers. comm.
Tidal wetlands in Hudson River between New York City and Troy Dam (preliminary data mapping in progress)	2,034	F. Mushake, pers. comm.
Tidal wetland islands in Jamaica Bay (included in NYC estimate above)	445	F. Mushake, pers. comm.
Tidal wetlands in all of Long Island Sound (CT and NY combined)	8,456	Rozsa 1997
Tidal salt marsh in northern NJ (Hudson, Bergen, Union, Passaic, Monmouth, Middlesex, and Essex Counties, including Meadowlands District)	4,502	NJDEP/OIRM/BGIA 1996
Tidal freshwater marsh in northern NJ (Hudson, Bergen, Union, Passaic, Monmouth, Middlesex, and Essex Counties, including HMDC District)	199	NJDEP/OIRM/BGIA 1996
Vegetated tidal wetlands along south shore of Long Island in South Shore Estuary Reserve	8,094	J. Zappieri, pers. comm.
	Total: 27,898	

tidal wetlands located within a 40 km radius of Central Park, Manhattan remained (US Fish and Wildlife Service, Coastal Ecosystem Program 1997).

Today, approximately 27,452 ha of tidal marshes remain, distributed on both shores of Long Island, throughout the Long Island Sound, in various locations throughout New York City, in the Hudson River at various points north to the Federal Dam at Troy and in the Hackensack Meadowlands and other embayments of northern New Jersey (Table 1). Most (approximately 90%) of these are tidal salt marshes. The remaining are freshwater tidal marshes (Shisler 1990)

Despite their greatly diminished extent and relative obscurity, the remaining wetlands continue to provide many important ecological functions. Located at a critical point along the Atlantic flyway, they provide critical habitat for resident and migratory wildlife. For example, despite the preponderance of sewage treatment plants, combined sewer outfalls, and major shipping and industrial operations in the area, the Arthur Kill still supports one of the largest heron rookeries in the entire northeastern United States (Yaro and Hiss 1996), not to mention another 37 fish and 128 bird species of special emphasis (NY/NJ Estuary Program 2001). Over 6,677 ha of the Hudson River Estuary have been designated ‘‘significant coastal fish and wildlife habitat’’ by the New York State Department of Environmental Conservation and Department of State. Along with other migratory bird species, bald eagles can be spotted resting and feeding up and down its banks each winter (Yaro and Hiss 1996). The Hackensack Meadowlands, its orphan landfills, superfund sites, complex railroad and highway systems notwithstanding, supports important seasonal and year round populations of over 29 fish and 55 bird species (New York/New Jersey Harbor Estuary Program 2001). The remaining NY/NJ Estuary tidal wetlands are also a natural means of flood control and water quality improvement, as well as a source of aesthetic and recreational value for the human population of the region.

Even though some wetlands in the Estuary are performing remarkably well in their heavily impacted state, wildlife populations, and the area of breeding and nursery habitats available to resident and migratory species are all greatly reduced when compared to historical baselines. These reductions have resulted in a great loss of local and regional biodiversity (New York/New Jersey Harbor Estuary Program 1996). As a result, restoration and conservation of current wetland resources was and is a top priority in many of the region’s management plans: NY/NJ Harbor Estuary Program Comprehensive Conservation and Management Plan, Hudson River Estuary Management Plan, the Long Island Sound Study Comprehensive Conservation and Management Plan, the New Jersey Meadowlands Commission’s Environmental Improvement Program, Long Island South Shore Estuary Reserve Management Plan, to name a few. Planning, design, and implementation of tidal marsh restoration projects is also rapidly increasing throughout the northeastern United States (Niedowski 2000). Estimates of the total area of tidal wetlands restored to date in the NY/NJ Estuary are summarized in Table 2.

Incentives to conserve and restore wetlands have

Table 2. Estimates of total area of local tidal marshes restored.

Geographic Location	Approximate Area Restored (ha)	Notes	Source
Long Island Sound	607 in CT 26.3 in NY	Since the early '70's	LISS 2001
Northern Coastal NJ	222.5	Mostly by NYC-NRG. Individual permits issued for wetlands restored for mitigation not included in estimate.	M. Matsil, pers. comm.
Hudson River	0		C. Nieder, pers. comm.
South Shore of Long Island	809.4	Since 1996	J. Zappieri, pers. comm.

been generated through voluntary participatory programs like the United States Fish and Wildlife Service Partners for Fish and Wildlife Program and the National Resources Conservation Service Wetlands Reserve Program, as well as through grants programs similar to those administered through the Intermodal Surface Transportation Efficiency Act (ISTEA, 23U.S.C §§ 130 and 133), the North American Wetlands Conservation Act (16 U.S.C. §§ 4401–4412), and the North American Waterfowl Management Plan. Wetland restoration is also required by law under Section 404 of the 1972 Federal Water Pollution Control Act (The Clean Water Act, 33 U.S.C. § 1344) to compensate for wetland functional losses incurred by developers. As the first significant piece of national wetland protection legislation, this Act authorized the Secretary of the Army, acting through the Corps of Engineers, to issue permits ''for discharge of dredged or fill material into the navigable waters at specified disposal sites'' (Hey and Philippi 1999). In 1977, the Army Corps declared that all wetland areas should be included under its Section 404 jurisdiction. In 1990, the Army Corps officially adopted compensatory wetland mitigation (defined as the restoration, creation, or enhancement of wetlands to compensate for wetland losses), as part of the Section 404 permit process (Hey and Philippi 1999).

Because of the intimate relationship between hydrology and the ability of a wetland to perform important ecological functions (Odum et al. 1995), an in-depth understanding of the hydrology of local wetlands is critical if efforts to conserve and restore these systems are to be effective. Yet, published research in this area is lacking. The objective of this paper is to summarize what is known about the hydrologic characteristics of tidal marshes remaining in the NY/NJ Estuary. This objective will be accomplished by reviewing literature documenting the importance of hydrologic factors in tidal marsh function and in their restoration. First, the specific ways by which hydrology controls tidal marsh development, variability, estuarine interaction, and function are discussed. Next, the impetus for and techniques employed in restoring tidal marsh function, specifically as pertains to hydrology, are described. Wherever possible, local research is highlighted. Finally, some areas of future research are suggested briefly at the end of the paper.

HYDROLOGY AND TIDAL WETLAND FUNCTION

Hydrologic processes are responsible for the evolution, inter- and intra-marsh variability, and functional value of tidal marshes and, thus, must be considered carefully in restoration. Tidal wetlands are also the link between the upland and the estuary. As such, their vitality is intimately tied to estuarine hydrodynamics. The interdependencies of the hydrologic factors on tidal marsh restoration efforts are explored below.

The development of tidal wetlands in the NY/NJ Estuary is the result of the interplay of several key hydrologic processes. Beginning about 9,000 years ago, rising sea levels began depositing fine-grained marine sediments in drowned coastal stream and river valleys of the North Atlantic Coast of the United States, a process known as marine transgression. Between 5,000 and 3,000 years ago, the rate of sea-level rise slowed, and a dynamic equilibrium was reached in these areas between the rates of coastal submergence and accretion (Warren 1997). The combined rate of sea-level rise and marsh-surface subsidence, on the one hand, matched the rates of detritus accumulation and sedimentation on the other. The relative rates of these processes were fundamental in the development of tidal marshes in this area (Mitsch and Gosselink 2000). By using accelerator mass spectrometry radiocarbon dating, sediments found at the bottom of an approximately 11-m core extracted in a Hudson River tidal marsh were found to be 4,190 years old (Wong and Peteet 1999), indicating the time span of the most recent marsh formation in the NY/NJ Estuary.

The wetland hydroperiod, or pattern of marsh flooding, is what drives wetland function and structure (Odum et al. 1995). Factors influencing the hydroper-

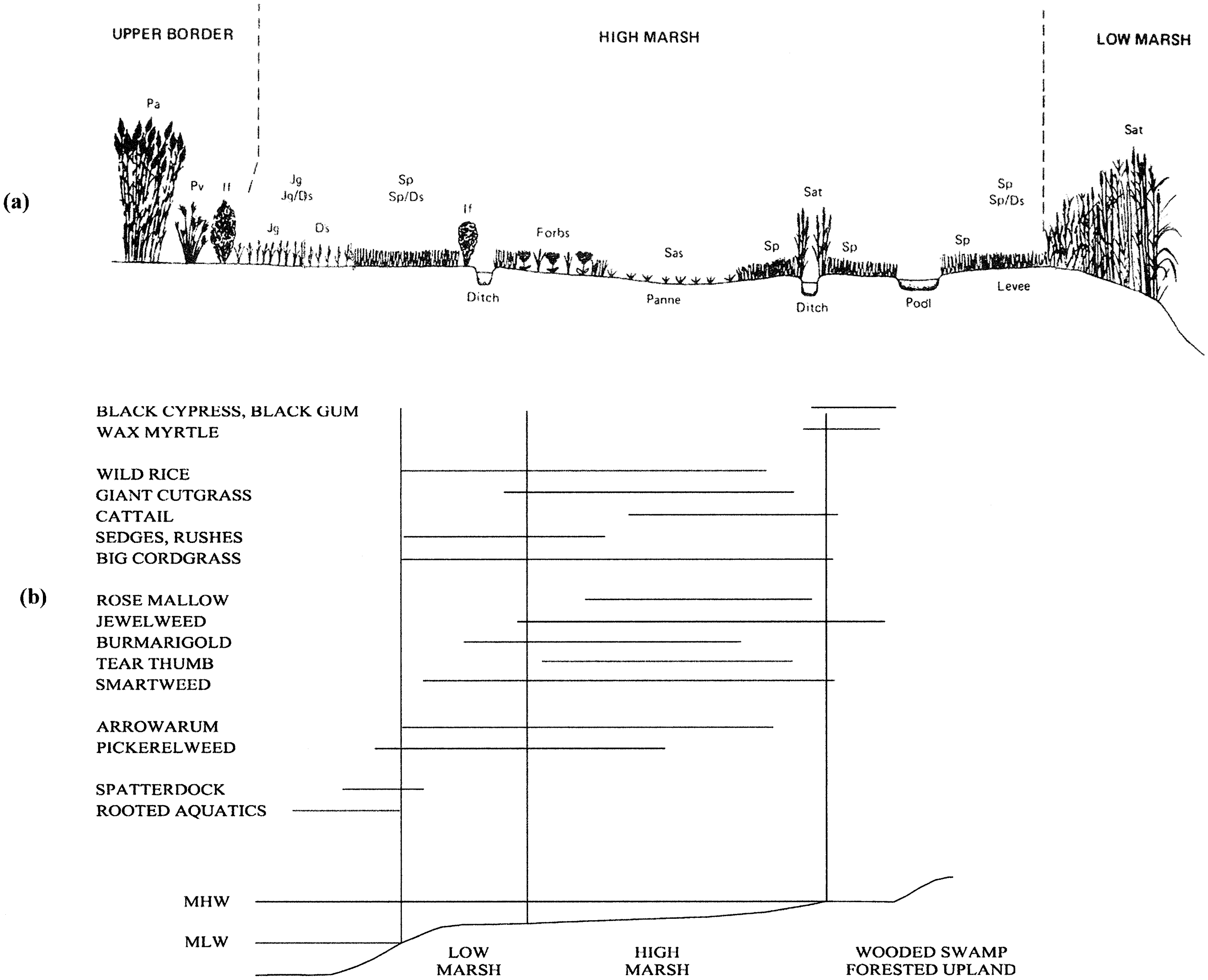

Figure 2. Typical vegetation zonation in a) Tidal salt marsh (adapted from Niering and Warren 1980); b) Tidal freshwater marsh (adapted from Odum et al. 1984).

iod of a tidal marsh include astronomical tides, meteorological/climatological events, vertical movements of the land surface, and coastal geomorphology (Rozas 1995). Astronomical tidal forcing is the primary determinant of the hydroperiod in Atlantic Coast marshes (Rozas 1995), where the amplitude of tidal fluctuation is primarily a function of lunar phase, declination, and position, and varies according to the 18.6-year metonic cycle. The frequency and duration of tidal inundation, however, is determined by the relationship between the elevation of the marsh surface and local surface-water fluctuations.

The importance of hydrology as a determinant in the establishment and maintenance of specific wetland types and processes is well known (Mitsch and Gosselink 2000). In the NY/NJ Estuary, spatial estuarine salinity patterns helped to determine where the two main types of tidal wetlands (consisting of salt and freshwater marshes) developed in the estuary. In the tidal salt marshes of the brackish portions of the estuary, regularly flooded and gently sloping mudflats formed at the lowest elevations (Figure 2). Directly upland from the mudflats was the intertidal zone, inundated diurnally, and typically dominated by a pure stand of salt marsh cordgrass *Spartina alterniflora* (Loisel). The most upland portion of the tidal salt marsh, known as the high marsh or salt meadow, was flooded only during the new moon and full moon spring tides. Vegetation in the undisturbed high marsh was usually a mix of perennials, dominated by salt meadow cordgrass *Spartina patens* (Muhl.), also known as salt hay, which was widely harvested. Without the salt stress, freshwater tidal marshes that formed in the upper portions of the estuary saw the development of a greater diversity of vegetation than the salt marshes. The intertidal zone of freshwater tidal marshes was populated by a number of species of emergent macrophytes, sedges, and rushes, while a combination of annual and perennial grasses, herbaceous plants, and shrub-like thickets were distributed about the high marsh (Odum et al. 1984) (Figure 2). In general, the hydrology of tidal freshwater marshes has received less attention by researchers than the hydrology of the salt marsh.

Hydrologic factors play a strong role in determining vegetation zonation in tidal marsh environments. Johnson and York (1915), working in Cold Spring Harbor, NY believed that the vertical range of tidal salt marsh plants was ''exactly proportional to the range of the tide.'' Adams (1963) also concluded that ''tide-elevation influences'' are the most important factor in determining the vertical distribution of salt marsh species. Harshberger (1909) used the mean high water (MHW) line to distinguish between three main types of salt marsh in northern coastal New Jersey: those occurring at elevations significantly lower than the MHW, those occurring just at or slightly above the MHW, and those found at elevations significantly above the MHW, which later researchers found correspond to young, mature, and old tidal marshes, respectively (Odum et al. 1984). More recent research suggests that it is more likely the combination of a variety of factors, including salinity, microtopographical relief, substrate, nutrient and oxygen availability, natural and historical disturbance history (Niering and Warren 1980), interspecific competition, and individual species' ability to tolerate harsh environmental conditions (Bertness 1991), that together with the hydroperiod, determine vegetation zonation in tidal marshes, especially in the high marsh. In the lower elevations of the salt marsh, a positive correlation between the local, mean tidal range and the elevational growth range of *Spartina alterniflora* has been shown consistently in the literature (McKee and Patrick 1988). In the tidal freshwater marsh, there is a general consensus among researchers that the hydroperiod is the primary factor determining species distribution (Odum et al. 1984).

Research also indicates that hydrology plays a critical role in the establishment and colonization of one of this area's most prominent invasive species, *Phragmites australis* ((cav.) Trin. ex Steudel), the common reed. Although research suggests that *Phragmites* marshes provide nekton habitat (Hanson et al. 2002), nutritious leaf litter (Weis et al. 2002), flow regimes, and patterns of sediment transport and deposition similar to those of *Spartina* marshes (Leonard et al. 2002), of concern is the loss of biodiversity and associated specific habitat types as *Phragmites* crowds out other native species and develops monotypic stands (Chambers et al. 1999). Emergence of the plant is found first in well-drained areas of marshes where rhizomes have been dispersed and buried (Bart and Hartman 2002). After reviewing the existing literature on *Phragmites* in North American freshwater and brackish marsh environments, Meyerson et al. (2000) specifically recommend that more research be conducted into how environmental factors such as salinity and hydrology facilitate or inhibit invasion and spread of *Phragmites* in different wetland settings. Establishment of *Phragmites* in tidal marshes is often attributed to a lowered water table and a reduction in soil water salinity occurring as a result of hydrologic isolation of the marsh from open tidal waters (Roman et al. 1984). *Phragmites* establishment also occurs on portions of the marsh elevated slightly above the MHW line. These sites may include the upper portions of the high marsh or areas that have been created as a result of human disturbances, such as diking or spoil deposition (Odum et al. 1984, Roman et al. 1984), or by way of natural disturbances such as creekbank levee formation or shoreline processes of coastal submergence (Phillips 1987). A ''window of opportunity'' for *Phragmites* invasion might also open up during low points in the 18.6 year metonic cycle (Chambers et al. 2002), during which high tides are less high, inundation of the marsh surface is less frequent, and the loss of pore water from the marsh to evapotranspiration and creekward drainage is prolonged.

Hydrologic processes allow tidal marshes to respond and interact with the estuaries in which they reside. Physically, they dissipate wave energy and buffer storm surges, thereby preventing coastal flooding and accelerated erosion of sediments. Qualitatively, the frequency of tidal inundation, and rates of runoff, infiltration, and pore-water drainage from tidal marshes to the estuary are important in determining the magnitude of exchange of nutrients, organic matter, toxins, pollutants, and other particulates between tidal marshes and their surrounding estuaries (Gardner 1975, Heinle and Flemer 1976, Valiela et al. 1978, Luther, III et al. 1982, Hemond et al. 1984, Jordan and Correll 1985, Yelverton and Hackney 1986). There is evidence that small variation in the depth and duration of flooding can have a significant effect on the rate of accumulation and allocation of nutrients and biomass in different emergent macrophytes (Rea and Ganf 1994). Small increases in the frequency and duration of inundation will reduce the diversity of plant communities present in freshwater tidal marshes (Baldwin et al. 2001). Periodic wetting and drying also modulates gas emissions (Nuttle and Hemond 1988) and air entry (Hemond and Chen 1990) into tidal marsh sediments, particularly significant today given evidence of increasing concentrations of greenhouse gases in the atmosphere.

The ''openness'' of a wetland to hydrologic fluxes is considered an important determinant of its potential rate of primary productivity (i.e., the rate at which organic carbon compounds are produced from inorganic materials usually through photosynthesis). Generally speaking, the more frequently inundated a tidal marsh, the more productive it is (Mitsch and Gosselink 2000). Primary productivity is regulated vis-à-vis hydrologic control of substrate sulfide concentrations (King et al. 1982), redox potential (Howes et al. 1981), and creekbank pore-water chemistry (Agosta 1985).

Finally, a marsh's pulsing hydroperiod determines its habitat value. Inundation events allow access to its surface by natant marine life (nekton) (Rozas 1995) and the higher trophic species that feed on them. Emergence opens up the marsh surface to birds and other terrestrial organisms.

HYDROLOGIC RESTORATION OF THE TIDAL MARSH

Wetland restoration efforts ideally aim to re-establish a self-perpetuating ecosystem with a hydrologic regime typical of the surrounding region (Middleton 1999). Because of the intimate relationship between hydrology and wetland function, a sound hydrologic understanding of the site is critical in the planning and design of tidal wetland restoration projects (Haltiner and Williams 1987, Coats and Williams 1990, Shisler 1990, Niedowski 2000). A conservative design approach is to attempt to create systems that mimic, as closely as possible, the hydrologic and ecological conditions of nearby reference marshes. Alteration of the existing hydroperiod may be all that is required for successful restoration of some sites (Shisler 1990) because, under the ''correct'' hydrologic conditions, there is a good chance that all other wetland characteristics and functions will develop with time (Interagency Workgroup on Wetland Restoration 1999). This may be accomplished, for example, by removing a tide gate, adding a culvert, or deepening a channel to re-establish a more open tidal connection. The importance of the marsh hydroperiod, in determining patterns of fish use, abundance, and diversity on the marsh surface, a critical habitat for fish reproduction and larval growth (Talbot and Able 1984), and in formerly impounded areas has also been shown (Rey et al. 1990, Poulakis et al. 2002). Re-introduction of tidal flow to the marsh plain has also been shown to improve avian abundance, species richness, and frequency of occurrence (Brawly et al. 1998).

This type of restoration may not always be sufficient or appropriate, however. In some cases, a marsh that has been artificially restricted from open tidal waters may be providing important nursery, breeding, and overwintering habitat that would be lost by restoring the ''historic'' hydroperiod (Raposa and Roman 2001). The surface elevation of tidal marshes that have been diked, ditched, or otherwise restricted from tidal flow for a period of years may have subsided significantly in elevation. Hydrologic restriction limits sedimentation on the surface, dries out and shrinks the existing substrate, and may also cause a drop in the marsh water table, which in turn could result in enhanced peat decomposition and wetland subsidence (Roman et al. 1984, Roman et al. 1995, Portnoy 1996, Rozsa 1997) or fires (Heusser 1949). In these cases, merely re-establishing the tidal connection without raising the marsh surface could result in over-flooding and limited improvement in wetland function.

In other cases, prior hydrologic alterations may have radically changed the biogeochemical composition of the substrate of some candidate restoration sites (Portnoy 1999), increasing the complexity of restoration techniques required. If ignored, sulfide toxicity in the soils of previously diked/waterlogged marshes could result in poor vegetative regrowth (Portnoy 1999). Re-introducing seawater to previously drained marshes could lead to nutrient loading of surrounding surface waters (Portnoy 1999). Altered management of flow in and out of tidal wetlands through water-control structures can have significant effects on the salinity of the outlying estuary, with simultaneous repercussions on its vegetation communities (Pearlstine et al. 1993). In the case of contaminated tidal marshes, alteration of the hydroperiod and, as a direct consequence, the relative magnitude of oxidation and reduction processes taking place in its substrate, can lead to the mobilization of metals into surface waters (Luther et al. 1982).

For restoration projects that call for more than simply re-introducing tidal flow to a site, restoration should involve geomorphological designs that respond appropriately to the local tidal signal. Documentation of the hydrology and other ecological characteristics of local reference marsh sites can help in conceptualizing, prioritizing, and refining local restoration designs (Shisler 1990, Zedler 2001). Historical areas, proportions, and/or spatial distributions of parameters can be used to prioritize restoration efforts in a given region (Niedowski 2000) by helping wetland managers identify which sites could be restored most easily, (i.e., with the least amount of required earthwork and disruption of native soils). The essential features (including the hydroperiod) of the closest, least disturbed wetlands can and should be incorporated into restoration plans (Interagency Workgroup on Wetland Restoration 1999, National Research Council 2001).

Despite the importance of hydrology in the functioning of existing and restored tidal wetlands and the extent of restoration activities already undertaken, very limited information has been published regarding the hydrologic characteristics of the historical or present-day tidal wetlands in the NY/NJ Estuary. The objectives of historical hydrology investigations in the region included the production of tide and current tables to improve navigation, the planning of dredging projects, and the desire to understand the circulation of sewage and industrial wastes in the Estuary (Jay and Bowman 1975). These investigations focused on tidal characteristics, salinity gradients, sediment characteristics, effluent discharges, and overall circulation patterns in the surface waters of 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). Several early researchers also attempted to correlate local salt marsh vegetation zones with tide levels and or salinity (several locations in northern coastal New Jersey by Harshberger (1909) Cold Spring Harbor, Long Island by Johnson and York (1915), and the salt marshes of Central Long Island by Conard (1935)).

More recently, the research community, in general, has given more attention to tidal wetlands. Often, however, investigations into the physical, chemical, and biological characteristics of local tidal marshes are not accompanied by thorough documentation of the hydrology of the sites considered. The implications of this research for planned restoration activities or for the overall health of the estuary are difficult to ascertain without an understanding of how they are linked through hydrology. Four reports funded by the Hudson River Foundation Tibor T. Polgar Program do address, very generally, the hydrology of some Hudson River tidal marshes. Without collecting any new data, Carey and Waines (1987) described the general hydrogeological setting of two Hudson River freshwater tidal marshes: Tivoli Bays and Stockport Flats. Goldhammer and Findlay (1988) measured the flux of organic and inorganic particles between the Hudson River and Tivoli South Bay. Lickus and Barten (1991) attempted to estimate the surface-water budget of Tivoli North Bay. Albertson and Barten (1993) developed a theoretical model of ground-water flow into the Tivoli Bays. A few other researchers have recently attempted to correlate hydrologic patterns with nekton use of a *Phragmites*-dominated portion of Piermont Marsh (Hanson et al. 2002) and the loss of salt marsh islands in Jamaica Bay (Hartig et al. 2002). None of these studies, however, are extensive enough hydrologically to be of help in the planning or design of restoration initiatives.

We are currently investigating subsurface hydrology patterns in Piermont Marsh, another Hudson River wetland, and developing an analytical model to describe these observations. The model is being validated at this and other sites in the NY/NJ Estuary, and the results are being used to help devise guidelines for the hydrologic restoration of tidal marshes (Montalto et al. 2002) and improve understanding of how hydrologic factors may be facilitating *Phragmites* invasion in these systems (Bart and Montalto 2002).

Recently, a committee established by the National Research Council to evaluate the success of wetland restoration projects, initiated as part of the Section 404 Program, found that wetlands restored through this Program often failed to replace the ecological functions of the wetlands they were designed to replace. One of the primary reasons for the failure of attempts to restore or create wetland values is inappropriate hydrology (Mitsch and Gosselink 2000, National Research Council 2001). Other important factors include the lack of a proper watershed or landscape approach in design, insufficient post-construction maintenance, management, and regulatory monitoring, the technical difficulty or impossibility of compensating for the functions of certain rare wetland types, underestimation of the functional value of lost wetlands, a lack of economic incentives for high quality versus low cost mitigation projects, and poor accountability—the fact that many required mitigation projects simply are never actually undertaken (Hey and Philippi 1999, Mitsch and Gosselink 2000, National Research Council 2001).

While the importance of hydrologic parameters in tidal marsh function and restoration is universally recognized by both the regulators and the scientific community, few detailed guidelines on how best to restore the hydrology of tidal wetlands are available to those working in the field. None of the estuary's wetland management plans describe specific methods of restoration. The Hudson River Estuary Action plan calls for the development of a manual to support small-scale restoration projects by municipalities, but at present, the only local technical guidelines are included in the New York State Salt Marsh Restoration and Monitoring Guidelines, produced by the New York State Department of State, Division of Coastal Resources. The need for more detailed wetland restoration guidance nationwide was recognized by the National Research Council Committee, who recommended that the Army Corps of Engineers develop regional reference manuals on the creation or restoration of individual wetland types, hydrologic conditions, and functions.

WHAT NEXT?

While the need to maintain navigation channels and understand spatial water quality patterns will undoubtedly continue to motivate hydrologic research in the NY/NJ Estuary, research priorities must be extended to include hydrologic studies in the region's tidal marshes. Specifically, more research is needed to document the hydroperiods and overall hydrologic characteristics of both natural and restored tidal marshes in the region. These reports need to be made in units of the local topographic datum systems: National Geodetic Vertical Datum of 1929 (NGVD-29) or the North American Vertical Datum of 1988 (NAVD-88), so that they can be compared to observations made at other sites and at other times. Improved tidal monitoring, especially in tidal wetland areas and not solely in deep-water navigation channels is also needed. Hydrologic modeling of both the estuary and specific ecosystems within it could also be used to help plan and design better restoration projects, and to assess their long-term ecological viability. Some numerical, hydrodynamic surface-water modeling has been conducted in the Hudson River (Abood 1974, Jay and Bowman 1975, Darmer 1987), the Hackensack River, and in other portions of the estuary. None of these studies, however, have considered the effects of tidal wetlands on flow dynamics. Moreover, models have not been previously developed to describe the subsurface hydrologic flow patterns in any of the region's tidal wetlands, nor have any studies attempted to identify design parameters that most significantly determine subsurface hydrologic conditions.

Increased hydrologic research in tidal marshes in the heavily populated NY/NJ Estuary would serve several purposes. This information could be implemented in very specific design decisions about how best to incorporate the findings of other ecological studies in restoration projects. It would also help to document the linkages between ongoing geomorphological alterations to the estuary, often justified on economic or geopolitical terms, and the conservation of its wetland and other natural resources. Better documentation of these hydrologic linkages between tidal marshes and the health of their surrounding terrestrial and aquatic resources would also contribute to bolstering further the image of wetlands in the eyes of both policy makers and the general public.

In the development of a restoration project, the question: ''restore to what condition?'' very often arises and reference sites, be they present-day or historical, are often used to attempt to answer this question. If ecological data are collected in a reference marsh without simultaneously noting the hydrologic conditions of the site, this information is of limited use for restoration designs. Hydrologic data provide the point of commonality between the reference and restoration sites and help to translate ecological studies into useful ''biological benchmarks'' that can then be incorporated into design.

More detailed characterization of the hydrologic characteristics and processes of tidal wetlands in the NY/NJ Estuary is essential if restoration efforts are to be successful. Such data were not the focus of historical research efforts, which tended instead to concentrate on collecting data to improve navigation, dredging, and the impact of wastewater discharges. Intensive measurements of other tidal systems along the coast at beaches (e.g., Baird and Horn 1996) have been made but are not helpful in informing decisions about tidal marsh restoration because the ground-water table does not intersect the land surface for these beach systems. What is required are data that will help to better specify marsh plain elevations, creek cross-sections, vegetation planting plans, imported soil properties, microtopographical relief, and other restoration design features.

Although the focus of this paper has been on how increased hydrologic research and information could improve restoration, this same hydrologic data can also foster improved conservation. Wetlands still have an image problem, especially in urban areas where the majority of the population never set foot in them. In the heavily urbanized NY/NJ Estuary, development pressure continues to threaten already reduced natural resources. Mark Matsil, chair of the NY/NJ Harbor Estuary Program wrote in the Habitat Workgroup 2001 Status Report: ''. . . despite our best efforts, bulldozers are poised to develop many of the region's natural lands . . . salt marsh, freshwater wetlands, and adjacent forests continue to be destroyed . . . '' (New York/New Jersey Harbor Estuary Program 2001). When human activities in the estuary or in coastal land areas alter hydrology patterns, there are direct impacts on the ability of tidal marshes and other natural systems to perform important ecological functions. Human activities can also have indirect impacts on wetland functions, such as those that occur when the tidal range or salinity of the estuary is altered, the currents increased, or the conditions that facilitate colonization of invasive species are created in the estuary. Some of these functions can be restored while others can not. Hydrology is the connection between tidal marsh function and anthropogenic activities. Hydrologic research in tidal marshes can be used to document, quantify, and link specific dredging or construction projects, land-use patterns, construction projects, or other initiatives with the health and vitality of natural systems. Hydrologic research can foster conservation of existing wetland resources by outlining the limits of restoration in reproducing the hydrologic conditions of natural ecosystems that developed gradually over thousands of years. It is only after these linkages have been made locally and publicized, that policy and land-use decisions can be expected to follow.

Hydrology completes the ecological story of the life of a tidal marsh. Barlow (1971) wrote: ''. . . the remnants of New York City's once luxurious mantle of marshlands are prolific laboratories for the naturalist in spite of the urbanization all around them . . . New York's forests and wetlands tell more than simply a story of nature; they tell a story of man and his power to shape and alter, to destroy and, sometimes, to remake the natural world . . . '' Hydrologic evidence can be used to recount this story by providing context to other ecological studies, by establishing and validating ''biological benchmarks,'' by documenting the true impacts of development and land use patterns on tidal wetlands and the biota that depend on them, and by helping to educate the public about the many ways that humans, even in an urban environment, are inextricably connected to nature.

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