Wetlands Ecology and Management **9:** 387–407, 2001.
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Restoration principles emerging from one of the world's largest tidal marsh restoration projects

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Received 10 October 1999; accepted in revised form 15 April 2000

Key words: fisheries, mitigation, restoration, salt marsh, wetlands

Abstract

One of the world's largest tidal wetland restoration projects was conceived to offset the loss of nekton to once-through cooling at a power plant on Delaware Bay, USA. An aggregated food chain model was employed to estimate the area of tidal salt marsh required to replace these losses. The 5040 ha was comprised of two degraded marsh types – *Phragmites*-dominated marshes and diked salt hay farms – at eleven locations in oligo-mesohaline and polyhaline reaches of the estuary. At a series of 'summits' convened with noted experts in the field, it was decided to apply an ecological engineering approach (i.e., 'self design', and minimal intrusion) in a landscape ecology framework to the restoration designs while at the same time monitoring long-term success of the project in the context of a 'bound of expectation'. The latter encompassed a range of reference marsh planforms and acceptable end-points established interactively with two advisory committees, numerous resource agencies, the permitting agency and multiple-stakeholder groups. In addition to the technical recommendations provided by the project's advisors, public health and safety, property protection and public access to the restored sites were a constant part of the dialogue between the utility, its consulting scientists and the resource/permitting agencies. Adaptive management was used to maintain the restoration trajectories, ensure that success criteria were met in a timely fashion, and to protect the public against potential effects of salt intrusion into wells and septic systems, and against upland flooding. Herbicide spray, followed by prescribed burns and altered microtopography were used at *Phragmites*-dominated sites, and excavation of higher order channels and dike breaching were the methods used to initiate the restorations at the diked salt hay farms. Monitoring consisted of evaluating the rate of re-vegetation and redevelopment of natural drainage networks, nekton response to the restorations, and focused research on nutrient flux, nekton movements, condition factors, trophic linkages, and other specific topics. Because of its size and uniqueness, the Estuary Enhancement Program as this project is known, has become an important case study for scientists engaged in restoration ecology and the application of ecological engineering principles. The history of this project, and ultimately the Restoration Principles that emerged from it, are the subjects of this paper. By documenting the pathways to success, it is hoped that other restoration ecologists and practitioners will benefit from the experiences we have gained.

Introduction

One of the world's largest wetland restoration projects is not a traditional compensatory response for a dredge and fill action (Section 404, Clean Water Act). Rather, it is a voluntary effort by the Public Service Electric and Gas Company to offset the operational effects of a power plant located on Delaware Bay. Once-through cooling at the Salem Generating Station (Figure 1) results in annual mortality of up to 10^9 eggs, larvae and juveniles of estuarine resident and marine transient taxa (Weinstein et al., 1997). The loss of young-of-year finfish was a volatile issue that culminated in a Draft New Jersey Pollutant Discharge Elimination

Figure 1. Location of the Salem Generating Station, marsh restoration and reference sites.

System permit requiring construction of two natural draft cooling towers, one for each of the generating units.

The Public Service Electric and Gas Company challenged this permit. The company proposed salt marsh restoration to replace young of the species of concern (weakfish, *Cynoscion regalis*; spot, *Leiostomus xanthurus*; white perch, *Morone americana*; and bay anchovy, *Anchoa mitchilli*) lost in the cooling system. Their proposal was based upon the positive correlation between the primary production of salt marshes and the secondary production of nekton. Extensive negotiations with stakeholders over four years resulted in a settlement that included restoration, enhancement and preservation of more than 5040 ha of diked salt hay farms and *Phragmites australis* degraded brackish marsh (Figure 1, Table 1) (Weinstein et al., 1997; Weinstein and Balletto, 1999).

Because of its size and uniqueness, the Estuary Enhancement Program (EEP), as this project is known, has become a focal point for scientists engaged in restoration ecology and application of ecological engineering principles. It is a challenge on a grand scale for these scientists and is an opportunity to advance knowledge of salt marsh function and replication of those functions through restoration practices. More than 50 specialists in ecology, design and construction of coastal wetlands have participated in implementing and/or evaluating the EEP.

Starting in 1994, a multidisciplinary team participated in several 'summits' to develop conceptual and engineering designs for the restorations, establish performance criteria, and implement adaptive management procedures to ensure project success on appropriate temporal and spatial scales. The project permit established a Monitoring Advisory Committee and a Management Plan Advisory Committee. Members of resource agencies at the federal, state and municipal levels and wetland ecologists comprised both committees. The Monitoring Advisory

Table 1. Location, type and restoration approach for sites comprising the Estuary Enhancement Program. 1 = Dike breaching, higher order channel excavation; 2 = Herbicide application, prescribed burns, long term control techniques.

Site	Type	Location	Restored area (Ha)	Dominant vegetation	Restoration approach
Dennis Township	Diked Salt Hay Farm	Cape May County, NJ	149	*Spartina patens*	1
Maurice River Township	Diked Salt Hay Farm	Cumberland County, NJ	459	*S. patens*	1
Commercial Township	Diked Salt Hay Farm	Cumberland County, NJ	1171	*S. patens/ Phragmites australis*	1
Cohansey River	*Phragmites* Degraded	Cumberland County, NJ	368	*P. australis*	2
Alloways Creek	*Phragmites* Degraded	Salem County, NJ	1138	*P. australis*	2
Cedar Swamp	*Phragmites* Degraded	New Castle County, DE	754	*P. australis*	2
The Rocks	*Phragmites* Degraded	New Castle County, DE	298	*P. australis*	2

Committee also included fisheries ecologists, while the Management Plan Advisory Committee included specialists in coastal engineering, wetland restoration science, and representatives from local communities. The latter was also tasked with consideration of property, cultural and heritage values, and public safety; and safeguarding these from any potential negative effects of the restorations. Together, the committees guided the technical and regulatory compliance work of EEP.

The history of this project and the restoration principles that emerged from it are the subjects of this paper. The history describes how the area to be restored was determined; how restoration and reference sites were chosen; and how goals, objectives, performance criteria and management plans were developed. Restoration principles were derived from common experiences, and the unifying themes that emerged from this project. We hope that future large-scale projects will benefit from our experiences and endeavors.

Why were 5,040 ha required?

The Estuary Enhancement Program is founded on the premise that primary production of salt marshes is linked to the production of marine transient taxa (Hall and Day, 1977; Weinstein, 1979, 1983; Weigert and Pomeroy, 1981; Bahr et al., 1982; Boesch and Turner, 1984; Nixon, 1988; Weinstein et al., 2000). Two calculations were required to estimate the area of marsh needed to produce fish to offset losses at the power plant: 1) annual fish biomass produced from Delaware Bay marsh primary production, and 2) annual fish biomass lost in once-through cooling at the plant.

A simple ‘aggregated food chain model’ was used to calculate marsh secondary production based on published accounts (Teal and Weinstein, 2000). The model simplified complex food web interactions by aggregating species across trophic levels (Weigert, 1979; Peters and Schaff, 1991). Most taxa were assigned to a single level, and all species on any one level were aggregated for the production estimates. The proportion of the production of each species of concern was determined by comparing the relative abundance of species at the same trophic level determined from previous monitoring surveys (Seagraves, 1981–1988, Seagraves and Cole, 1989, 1990; Michels, 1992).

The model calculations suggested that 981 ha of restored marsh were required to replace the biomass of bay anchovy, the species with the greatest losses at the plant. However, in light of the uncertainties and variability surrounding the assumptions and estimates used to construct the model, a ‘safety factor’ of about four was used to achieve consensus among stakeholders. Thus, the regulatory agencies required that up to 4047 ha be restored to meet the conditions of the project permit. A final challenge to the permit by the State of Delaware was resolved and the utility agreed to fund restoration, preservation and enhancement of a total of 5040 ha.

Restoration design objectives

With the challenge laid out, i.e., restore degraded salt marshes with attributes of natural function on a scale never before attempted, the project team commenced its daunting task. Because the goal was to increase secondary production through restoration efforts, the following landscape features were identified as desirable components of the restoration designs:

- Tidal creek drainage characterized by fourth or fifth order stream systems, high drainage density, bifurcation ratios, sinuosity and stream length;
- Subtidal refugia for nekton in the highest order streams;
- A wetting/drying cycle characterized by sufficient intertidal periods to aerate surficial sediments on the marsh plain, especially stream bank locations;
- Natural stream bank slopes; and
- Vegetation:open water ratios of about four to one.

Which marshes to restore?

Of the tens of thousands of hectares of degraded salt marsh around Delaware Bay, it was necessary to identify those sites that were most likely to be restored successfully and that were available for permanent conservation restrictions. Lands were acquired with *a priori* conditions that favored successful restoration: 1) appropriate marsh plain elevations, groundwater and tidal relationships; 2) the presence of plant propagules (seeds, rhizomes, larvae, etc.) in the restored marshes or neighboring marshes; 3) fauna that would populate the marshes from nearby populations; and 4) sediments of appropriate organic and nutrient content in tidal waters inundating the sites. Nine sites were chosen in New Jersey: *Phragmites*-dominated sites in Alloway Creek and the Cohansey River watershed and formerly diked salt hay farms in Commercial Township, Maurice River Township, and Dennis Township (Figure 1, Table 1). The two sites in Delaware are *Phragmites*-dominated (Figure 1, Table 1).

The selection of reference marshes

Selecting appropriate reference sites is critical to the proper design and evaluation of wetland restoration efforts (Kusler and Kentula, 1989a, b; Aronson et al., 1995, 1996; Hobbs and Norton, 1996). Tobler (1970) suggests that the similarity between two sites will decrease or decay with the distance between them. Thus, not only will the value of reference sites vary directly with distance to the restored area, but regional variation also suggests that no one site can function as a 'perfect match' for the site to be restored (Pickett and Parker, 1984; White and Walker, 1997). White and Walker (1997) comment that 'our conceptual model should be one of interpolation among multiple sites and sources of information', and that because of the unique history of ecosystems, no one reference site observed at an arbitrary time should be used to determine goals for a restoration project. Thus, the selection of reference sites should be regionally specific and should span the range of conditions anticipated at the proposed restoration tracts (Kentula et al., 1993). In Delaware Bay, this range includes relatively undisturbed systems, and systems that have experienced various degrees of human perturbation, but which have been restored to new equilibrium.

At least two reference categories were required: 1) those that established the time-trajectory for project success (at a minimum, defined by permit conditions, but including ecological success criteria recommended by the scientific community); and 2) the range of marsh types that defined acceptable endpoints for the restorations (Weinstein et al., 1997). Progress along the restoration trajectories was measured via a monitoring program with interim benchmarks for success (see below).

Most of the salt marshes along Delaware Bay show signs of human perturbation, some dating back to colonial times (Weinstein et al., 2000). Isolated from tidal exchange, the surface of diked salt marshes subsided due to sediment starvation, oxidation and compaction, and relative sea level rise. When storms or human activities consequently breached dikes, the wide range of difference in tidal elevation versus marsh surface elevation resulted in an equally large range of marsh planforms that respond to new tidal inundation (Weinstein et al., 2000). To account for the wide range of anticipated restoration endpoints, five reference marshes were selected based upon reviews of historical records, evaluation of tidal creek morphology, marsh history, and extant marsh condi-

Figure 2. Fishing Creek marsh, a relatively undisturbed 910 ha reference site in the polyhaline reach of the Delaware Bay estuary.

tions (Figures 2 through 6). Two sites, Fishing Creek (Figure 2) and Mad Horse Creek (Figure 3) represent the undisturbed condition with high stream order, high bifurcation ratios, long stream lengths, high sinuosity and larger subtidal streams. Three 'self-restored' marshes – Oranoken Creek (Figure 4), Moore's Beach (Figure 5) and Wheeler Farm (Figure 6), former salt hay farms whose dikes were breached by storm events in the 1970s and early 1980s, were chosen because they had the characteristics anticipated for the EEP sites 10+ years after restoration was completed. All five reference marshes had vegetated marsh plain to open water ratios of about four (80% vegetated marsh: 20% open water).

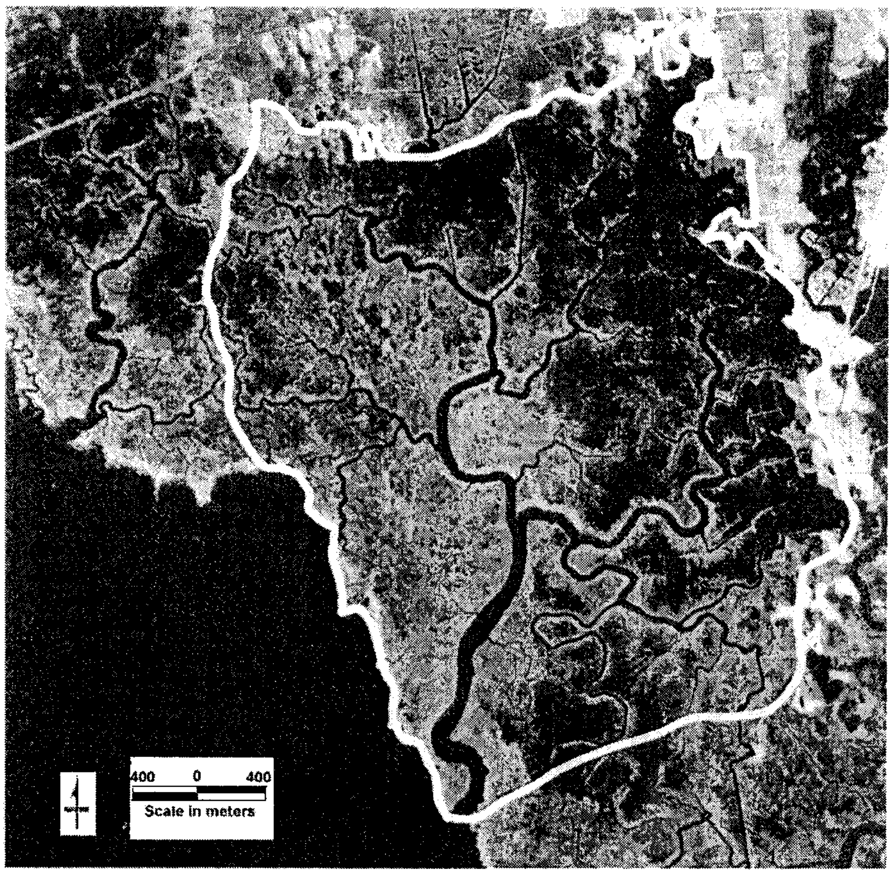

Figure 3. Mad Horse Creek marsh, a relatively undisturbed 1709 ha reference site located in the meso-oligohaline reach of the Delaware Bay estuary.

Mad Horse Creek and Moore's Beach were selected for annual monitoring to establish a baseline against which the progress of the Estuary Enhancement Program could be measured. Mad Horse Creek is oligo-mesohaline, has less than 4% coverage by *Phragmites australis,* and is representative of lower salinity *Phragmites* degraded sites in Alloway Creek (Figure 1). Moores Beach is a meso-polyhaline 'self-restored' system whose dikes were breached beginning in 1972 by storm events and activities of the New Jersey Mosquito Control Commission (Weinstein et al., 1997). *Phragmites* coverage at Moore's Beach is about 1% of the marsh plain.

What data were needed?

A biological monitoring program, developed with and reviewed by the Monitoring Advisory Committee, was implemented in 1995 to provide supplementary data for judging the ecological (not simply the regulatory) success of the program. The program includes extensive, estuary-wide studies and on-site studies at the Salem Station that provide consistent, long-term data about the Delaware Estuary and the impacts of Salem Station on it. Under guidance from the New Jersey Department of Environmental Protection, the estuary monitoring program includes ongoing sampling in shallow water areas; marsh detrital production monitoring; and monitoring of fish production and food habits in the restored marsh areas. Monitoring at the Salem Station includes abundance and survival rates of fish and other organisms impinged or entrained at Salem's water intake structures as well as studies related to the discharge of cooling water.

Project goals and performance criteria

'Special conditions' in the project permit set forth three goals for the wetland restoration program: 1) re-

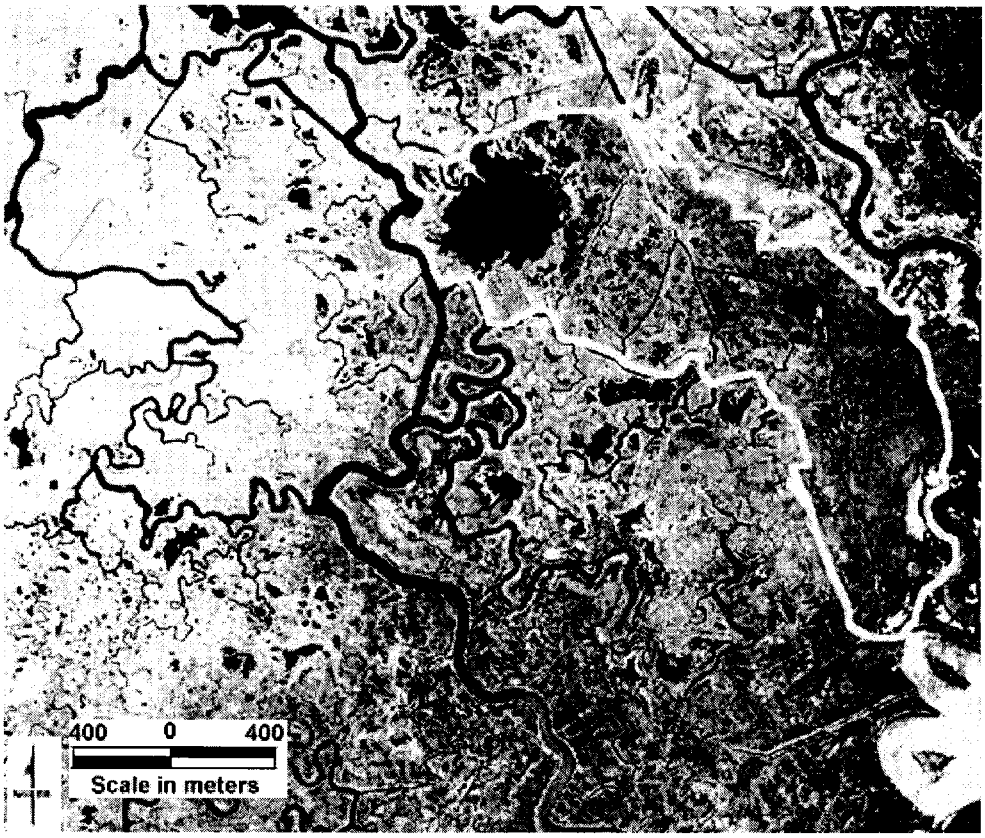

Figure 4. Oranoaken Creek marsh, a 197 ha formerly diked site restored in the early 1970s.

turn of 'normal daily tidal inundation' to impounded salt hay farms; 2) restoration of degraded wetlands 'so as to become functional salt marsh'; and 3) establishment of an 'anticipated schedule for natural revegetation' (Weinstein et al., 1997). To judge whether the restoration effort was successful at a specific site; i.e., to satisfy the permit conditions, performance criteria were developed to assess the progress of the restorations from pre-restoration conditions to fully functional salt marsh (Weinstein et al., 1997): 1) no less than 95% of the marsh plain will be colonized by desirable vegetation; 2) *Phragmites australis* coverage will be reduced to less than 5 percent of the total vegetated area of the marsh plain; and 3) open water and associated intertidal flats of the restored sites will be less than 20% of the total marsh area. 'Interim' success criteria were developed to monitor and document progress toward restoration end-points and to ensure that conditions during and immediately following restoration were on a path toward successful restoration (Weinstein et al., 1997).

Management plans

Management Plans were written for each restoration site. Restoration goals were cited followed by a description of each site, including location, area, geology and soils, surface and groundwater hydrology, vegetative cover, wildlife, aquatic fauna, rare, threatened and endangered species/significant natural communities, and cultural and historic resources. The management provisions included a summary of pre-restoration conditions, wetland restoration design and construction, public use provisions, an implementation schedule, the public notification process, and an operations and maintenance schedule. Each plan ended with a discussion of performance criteria, Adaptive Management and monitoring programs. The approved plans were incorporated as conditions of the project permit.

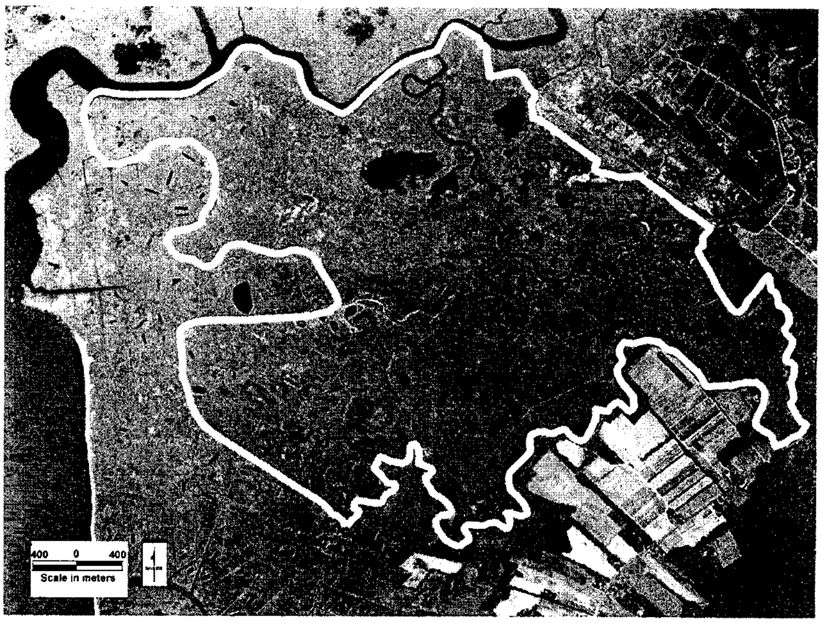

Figure 5. Moores Beach marsh, a 383 ha formerly diked reference site where restoration was initiated in 1975, and a major storm in 1980 appears to have fully compromised the perimeter dikes.

Design and construction

Salt hay farms

The restoration designs for salt hay farms optimized the use of natural site factors including channel size and configuration, drainage patterns, and ratio of marsh plain to open water to encourage natural engineering of the site. Suitable tidal exchange was achieved by excavating larger order tidal channels, construction of flood protection dikes at the marsh-upland interface, and breaching perimeter dikes. Areas for colonization by high marsh species were also created by selective placement of material excavated from the large channels.

Computer hydraulic models were used to develop the restoration designs to confirm adequate tidal inundation/drainage at each site. Data from local tide gauges, detailed topographic surveys (including mapping the density and cross-sectional areas of tidal channels in undisturbed marshes adjacent to the sites), and the locations of historic sluice gates and drainage ditches were incorporated into the models as baseline conditions. The computer simulations were used to estimate channel locations and cross sectional dimensions, and the number of inlets required to fully inundate and drain the sites. The goal was to create hydroperiods that would result in conditions suitable for colonization by *Spartina* spp. and other naturally occurring vegetation. Construction activities at individual sites ranged from six to sixteen months. During the construction period, revisions to engineering designs were implemented when unexpected or evolving field conditions occurred, or when threatened/endangered species were expected to be present.

Phragmites australis *– dominated sites*

A goal of the restoration program was to 'break up' the dense monocultures of *Phragmites*, reduce its coverage consistent with permit requirements, and prevent further excursion into unaffected areas (Weinstein et al., 1997; Weinstein and Balletto, 1999). The restoration design and implementation began with collection and interpretation of baseline field data, followed by application of the herbicide Rodeo® (active ingredient glyphosate, N-phosphonomethyl glycine), and prescribed burning.

Preliminary data collected on surface and groundwater hydrology, tidal elevation, tidal range, drainage channel cross-sections, and drainage channel density suggested that, for the most part, no appreciable tidal restrictions existed at the restoration sites, and that they experienced a natural hydroperiod. However, the dense canopy precluded any meaningful use

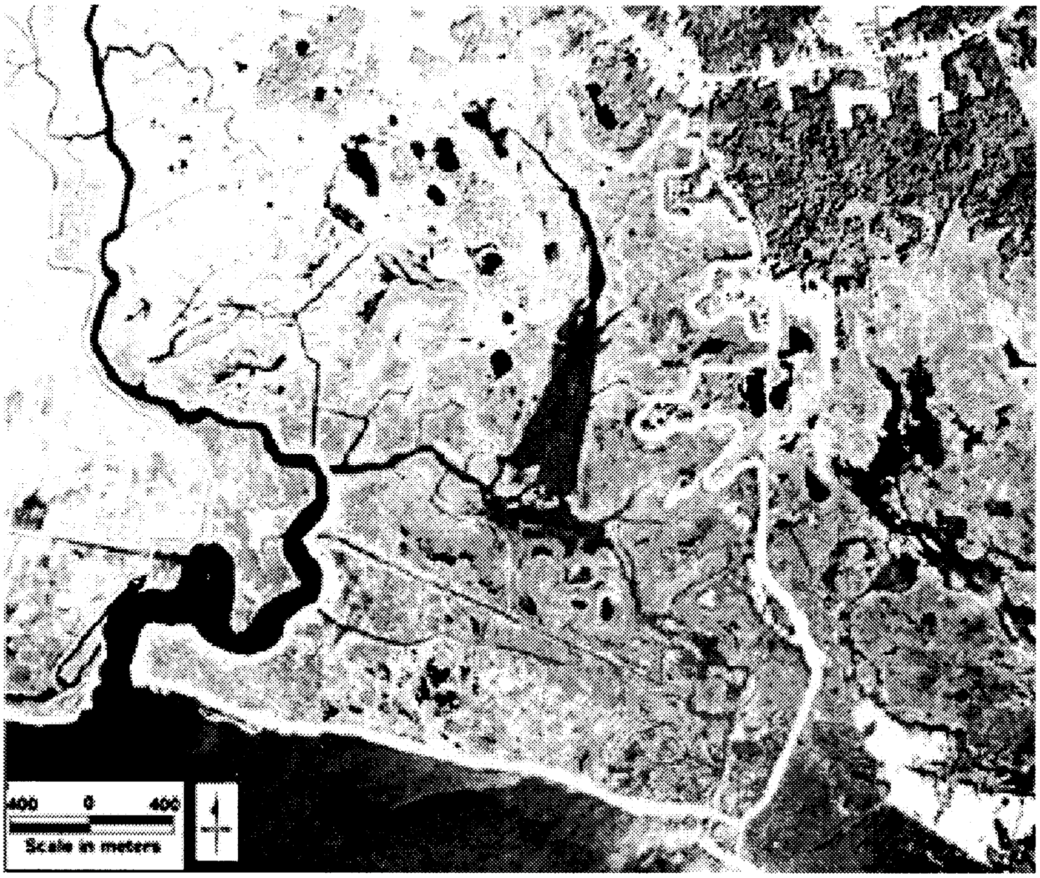

Figure 6. Wheeler Farm marsh, a 569 ha formerly diked reference site where restoration was initiated in 1972.

of aerial photography until burning took place and the marsh plain was exposed. Aerial overflights and photo-interpretation following the removal of dead *Phragmites* indicated that few rivulets or small (first order) channels were present on site (Weinstein and Balletto, 1999), and that the reticulations typical of *Spartina*-dominated marshes were absent.

Techniques to control *Phragmites* sources and re-establish the rivulets, small channels, and microtopography of the marsh plain were needed. In consultation with the Management Plan Advisory Committee, a test plot program was developed to determine the relative efficacy of different technologies for long-term control of *Phragmites.* This ongoing program seeks to provide a sound scientific basis upon which to base a program using marsh plain disturbance, sulfate addition, and supplemental seeding with *Spartina alterniflora* to control re-growth of *Phragmites* at the sites.

Emergent restoration principles

Along with adherence to the practice of restoration by many advocacy groups, the emerging science of restoration ecology has been embraced by some as a panacea for biological conservation (Jordan, 1994; Turner, 1994). However, even a casual glance at the literature indicates we continue to struggle with reference standards, quality of monitoring programs, measuring function (or 'functional equivalency', Zedler and Lindig-Cisneros, 2000), measuring success, landscape considerations, sea-level rise, and a host of other complexities that mask our ability to say that we have done the 'right thing'. Because so many restoration efforts are *ad hoc*, and mainly responsive to regulatory compliance and not necessarily to sound science, there has been little development of theory or principles that would allow transfer of methodologies from one situation to another (Aronson et al., 1996). In their editorial commentary in *Restoration Ecology*, Aronson et al. stated: 'we feel that it is essential that generalities be sought and principles be generated so that restoration efforts can be guided effectively.' The authors have reflected upon the EEP experience and extracted 'restoration principles' that are described below.

Principle 1 – State project goals clearly, as agreed to by the stakeholders; make the goals site-specific and realistic

Realistic goals, those that recognize both the ecological limits to restoration and the social, economic or cultural barriers to restoration, are key to re-establishing species and ecosystem functions (Hobbs and Norton, 1996). Because of unrealistic expectations, many projects are doomed to failure. Moreover, we often cannot or do not adequately measure progress towards meaningful project goals. Because methodologies are often developed *ad hoc*, there are limited case histories that generalize from one site or system to another (Berger, 1990). Aronson et al. (1996) advise that complete restoration is an unattainable goal.

For each restoration site, a concise set of goals, objectives and a schedule were developed in the Management Plan. Conditions in the sites are compared to the reference marshes annually. Goals of the Estuary Enhancement Program are to increase detrital production of wetland areas to the marsh/estuary food web and to provide refuge, feeding habitat, and nursery grounds for marine transient and resident nekton. These goals are being accomplished by restoring natural hydroperiods to formerly diked salt hay farms, the restoration of *Phragmites*-dominated wetlands, the protection of upland buffers, and the long-term preservation of ecological resources of the Delaware Bay.

Principle 2 – Restore degraded sites rather than create new wetlands

Unlike wetland restoration, wetlands creation requires elaborate construction efforts to produce physical, chemical and biological conditions needed by wetlands (Kusler and Kentula, 1989a, b). Creating wetlands where none existed before is a difficult process, and success rates are generally far lower than for restoration of formerly functional sites. Presence of wetland plants does not ensure that wetland functions or other desirable qualities will be present. Articles by Roberts (1993), Zedler (1988) and Zedler (1992) nominally about unsuccessful wetland restoration were, for the most part, discussions of wetland creation rather than wetland restoration.

Wetland restoration is the process of *re-establishing* the physical, chemical and biological conditions at degraded wetland sites that still possess some of the characteristic features of original wetlands. Wetland restoration is accomplished most effectively by removing or altering the features that prevent the degraded lands from functioning at full value.

Restoration is technically feasible and has a high rate of success when proper attention is given to the specifics of the process (Mitsch and Gosselink 1993, Simenstad and Thom 1992). One must observe whether the primary processes delimiting the habitat type are still effective at the site, e.g., salinity intrusion, sedimentation sources and processes, and corridors to other natural estuarine and upland habitats.

Factors favoring successful restoration

The physical, chemical, and biological factors favoring successful restoration are summarized here.

Historical ecosystem types – Ecosystems that were historically present at the site indicate potential suitability for re-establishing a similar ecosystem. The lands targeted for restoration by EEP were, until disturbed by human intervention, functional tidal salt marshes connected by tidal flow to the Delaware Estuary ecosystem;

Hydrology and topography – Wetlands require a certain level of inundation and water flow (Hellings and Gallagher, 1992). Tidal relationships in the diked salt hay farms targeted for restoration had suitable elevations and would have appropriate salinities for replacement of *Phragmites* and high marsh vegetation by *Spartina alterniflora.*

Creeks and channels – Most of the larger marsh creeks at the salt hay farms had been filled by farmers. They had to be dredged or excavated anew. They were designed to look like those in the reference marshes and their function was modeled to ensure they would function properly (Teal and Weinstein, 2000). 'Properly' means they would allow the marsh to flood and drain with wetting/drying cycles long enough to aerate surface sediments by drainage or evapotranspiration (Dacey and Howes, 1989).

Sediment organic content – Relatively high sediment organic content contributes to successful marsh restoration by supporting active nutrient cycling and energy flow processes, by providing a favorable substrate for seed germination and plant growth, and by supporting development of productive benthic animal communities. Measured total organic carbon contents in sediments of diked marshes chosen for restoration range from 0.5% to 46.1%. The latter value likely represents peat or other high-carbon material in the sample, the former relatively pure sand. Overall, the average organic carbon content of the diked marshes is relatively high, indicating that all necessary exchanges and transformations of matter and energy will accompany the development of a functional *Spartina* marsh on these lands.

Colonizer presence and proximity – The wetlands adjacent to proposed restoration sites provide a source of propagules and colonists to help achieve rapid invasion of appropriate organisms at the restoration sites. The EEP restoration sites are part of a larger estuarine wetland system, with fully functional *Spartina* marshes located throughout the estuary (Weinstein et al., 1997). Restoration of tidal flow to formerly diked areas is accompanied by rapid biotic community structure changes, with the system shifting rapidly to functional tidal salt marsh.

Salinity – Salinity plays a large role in determining the vegetation and faunal communities of salt marshes. Diked areas support communities that are characteristic of lower salinity levels and include *Phragmites* as a prominent component. Restoration of tidal flow returns marshes to more natural salinity conditions.

Sediment accretion – Undiked salt marshes around Delaware Bay receive a constant supply of sediment that maintains marsh surface in equilibrium with local sea level rise.

Principle 3 – Select sites in a landscape ecology framework

Landscape ecology deals explicitly with the effect of pattern on ecological processes (Turner, 1989). The marsh mosaic is characterized by emergent vegetation at different elevations, all influenced by different hydroperiods (area, depth, frequency and duration of inundation). Undisturbed marshes in the Delaware Bay generally have vegetated marsh plain to open water ratios of about four (Rubino, 1991; Weinstein et al., 1997; Weinstein, unpublished data). However, where the interface between the marsh plain and tidal creeks is extensive, 'edge' is greater, and consequently, the exchange of marsh products is greater. Edge has been equated with efficient access to the marsh by nekton, and is enhanced by several landscape features: high drainage density, 4th or 5th order stream systems, high bifurcation ratios, long stream lengths, and extensive marsh plain reticulation (Zimmerman and Minello, 1984). Ponded water on the marsh plain, and optimal ratios of high marsh to low marsh also contribute to edge. Nekton respond favorably to these geomorphological and biological features of salt marshes.

Both the marsh surface and marsh fringe are used extensively at high tide, and there may be ontogenetic shifts in species use patterns with life stage (Rountree and Able, 1992). Subtidal channels provide refuge and 'staging' areas for nekton at low tide (Cain and Dean, 1976; Hodson et al., 1981; McIvor and Odum, 1988; Rozas et al., 1988; Hettler, 1989; Kneib, 1997). The tidal creeks act as conduits between the estuary and the primary production that takes place on the marsh plain in the form of nutrient export, trophic relays and the ingress and egress of fauna (Kneib, 1997; Weinstein, 1981; Deegan, 1993).

To the extent practicable, desirable geomorphological landscape features were 'built' into the EEP by allowing natural processes guide the restoration trajectories.

Principle 4 – Ecological engineering practices should apply

Odum (1989) described ecological engineering as developing restoration designs that can compete and survive so humans become partners with their environment. Odum believed that the essence of ecological engineering is managing self-organization, i.e., providing optimum designs that take advantage of environmental structures and processes. Ecologically engineered designs use an optimum mix of man-made and ecological components, 'lightly' manage self-organization processes, and minimize human intrusion. Simply stated, ecological engineering is a restoration approach that uses human intervention to initiate a predictable process to be completed by nature.

Restoration approaches that specify organisms, usually plants, whose survival and areal coverage are the metrics for success, are less successful than restoration that relies upon ecological engineering. Mitsch et al. (1998) and Mitsch and Wilson (1996) stated that much of the apparent failure in creating and restoring wetlands can be 'corrected' through proper training, giving the system time, and appreciating the concept of self-design. The latter, in turn, relies on the self-organizing traits of ecosystems in which natural processes contribute to species introduction and selection (Mitsch et al., 1998).

Self-design is the essence of succession and development of an ecosystem where many species are introduced but few are chosen. After the initial period of competitive colonization, the species prevailing are those that reinforce other species through nutrient cycles, aids to reproduction, control of spatial diversity, and population regulation (Odum, 1989).

Restoration of 'functional', self-sustaining wetlands at the scale of the Estuary Enhancement Program is achieved by applying sound ecological engineering principles under conditions where the marsh plain elevations, groundwater and tidal relations are appropriately interrelated. With the right hydrology, potential colonists from nearby undisturbed sites or those recruited from outside the system (e.g., marine transient finfishes that may be spawned hundreds of kilometers or more offshore) will gain access to the sites. Ecologically engineered salt marshes should be self-perpetuating and require minimal management (Burdick et al., 1997).

Principle 5 – Restored sites should be self-sustaining, but should be 'guided' by adaptive management toward desired endpoints

Adaptive management is a framework for identifying and meeting environmental management goals through an iterative process of monitoring and intervention (Holling, 1978). Expectations for how a restored area will recover its structure and function are derived from an understanding of basic ecology and site specific conditions. If expectations are met, actions are not needed; if expectations are not met, information is gathered and the restoration is corrected, if necessary, by active management response (National Research Council, 1992). In the EEP, the expectations and the thresholds indicating a need for possible action were identified and agreed to (Weinstein et al., 1997). The stakeholders and independent scientists involved in the Estuary Enhancement Program, including members of advisory committees, provide ongoing advice and direction to the restoration program. Details of the adaptive management approach have been published (Weinstein et al., 1997; Teal and Weinstein, 2000).

There are two components of the Adaptive Management Program developed for this project: Restoration Management and Management Plan Required Adaptive Management. They both use a team of experts consisting of wetland and ecological engineering experts along with restoration managers who make regular visits to the restoration sites.

Restoration management

Potential problems such as premature dike breaches, sediment erosion, upland flooding, standing water, salt water intrusion, poor drainage, sedimentation, or other conditions that might interfere with restoration success are addressed on an ongoing basis under restoration management.

Management plan required adaptive management

The Management Plan for each restoration site identifies success criteria in measurable terms. In particular, specifications are provided for reduction of *Phragmites australis* marsh plain coverage, increases in marsh plain coverage of other naturally occurring marsh vegetation, drainage, flooding, and erosion. These criteria were based on conditions in the reference marshes and other naturally restored marshes (Weinstein et al., 1997) and evaluated to predict how a restored ecosystem would appear at a particular point in time. This defines the expected restoration time trajectories for the restoration and the range of acceptable end-points that defined restoration success. Failure to meet these expectations by a specific time precipitates an adaptive management response, beginning with additional information gathering and ending with additional ecological engineering, if warranted.

Principle 6 – Site monitoring should be planned and implemented, and last until success is assured

A key element in any restoration approach is a determination of conditions likely to result in a self-sustaining system and, consequently, low management costs (White and Walker, 1997). Reference information helps determine the site-specific data requirements to set restoration goals and forecast the need for management that will replace or counteract natural processes. In essence, selecting reference sites and designing a sound monitoring program that addresses feasible restoration goals is an activity at the fundamental core of ecology; i.e., understanding the

Table 2. Summary of geomorphology and vegetation monitoring at restoration and reference sites.

Program element	No. areas	No. stations	Periodicity	Frequency	Parameters
Vascular plants					
Vegetation mapping (Aerial photos)	12	– –	Peak growth	Annually	Community analysis & vegetation coverage
Quantitative sampling (0.25 m^2 quadrats)	8	32 transects (sampling quadrats)	Peak growth	Annually	Species composition; height, flowering, biomass (live and dead)
Benthic algae and epiphytes	5	∼200 total	Early summer	Annually	Chorophyll *a* and 14C productivity
Geomorphology (Aerial photos)	12	–	Peak growth	Annually	Mapping channel order, density, stream length, bifurcation ratio
Tidal monitoring	12	∼17	Continuous	30 d minimum period	Surface elevation in channels; hydroperiod on marshplain; salinity

Table 3. Summary of nekton monitoring at restoration and reference sites. CPUE = catch per unit effort.

Program element	Sites	No. stations	Gear	Periodicity	Frequency	Parameters
Fish utilization						
Large Creeks	6	18	4.9 m trawl	Apr-Nov	Monthly	CPUE, composition, length, weight; 3 sta in 4 restored and 2 reference marshes
Small Creeks	6	18	Weirs (2.0m × 1.5m × 1.5m w/wings)	Apr-Nov	Monthly	CPUE, composition, length, weight; 3 sta in 4 restored and 2 reference marshes
Fish Food Habits	4	12	Bag seine; 4.9 trawl	Apr-Nov	Monthly	Gut contents; relative gut fullness; 3 sta in 2 restored and 2 reference marshes

nature, cause and function of variation in ecosystems and landscapes (White and Walker, 1997).

In addition to monitoring vegetation, geomorphological features, and nekton for permit compliance (Tables 2 and 3), an extensive series of focused studies (Table 4) were initiated to examine trophic linkages, movement patterns of nekton including large predatory species, and nursery utilization by nekton of restored and reference sites (Able et al., 2000; Teo, 1999; Smith et al., 2000; Wainright et al., 2000; Weinstein et al., 2000). Many of these studies were recommended by the Monitoring Advisory Committee, or by a panel of marsh experts convened in several workshops during the course of these projects. The efforts of researchers also benefited from a Delaware Bay wide monitoring survey to establish the distributional ecology of the species of concern. Along with focused research, monitoring studies will assure that a comprehensive, quantitative data base will be available for judging the long-term success of the project.

Monitoring program

Geomorphological features and vegetation at restored sites (Figure 1, Table 2) are monitored by annual overflights in September or October with false color infrared digital orthophotography. Images are transferred to a geographic information system (GIS) and analyzed for: 1) development and extent of drainage channels; 2) drainage channel configuration; 3) total area covered by standing water at low tide; 4) coverage of the marsh plain by *Phragmites australis*; and 5) coverage of the marsh plain by *Spartina* spp. and other desirable macrophytes. These parameters are compared to reference marshes at Mad Horse Creek and Moore's Beach.

Table 4. Summary of supplemental focused research in *Phragmites*-dominated and *Spartina alterniflora* marshes. DTSHF = Dennis Township Salt Hay Farm restoration site; MB = Moores Beach reference marsh; CTSHF = Commercial Township Salt Hay Farm restoration site; MHC = Mad Horse Creek reference marsh.

Program	Study sites	Periodicity	Frequency	Year	Parameters
Food habits of large predatory fishes in tidal creeks	DTSHF, MB	Jun–Oct	Biweekly	1998	CPUE, length, weight, gut contents, relative fullness
Utilization of tidal creeks by Atlantic croaker (*Micropogonias undulatus*)	DTSHF, MB	Jul–Oct	Variable	1998	Mark-recapture, residence time, movements, and growth
Utilization of tidal creeks by striped bass (*Morone saxatilis*)	DTSHF, MB	Jun-Sep	Variable	1998	Ultrasonic tagging, residence time, movements striped bass (*Morone saxatalis*)
Response of mummichog (*Fundulus heteroclitus*) and sheepshead minnow (*Cyprinodon variegatus)* to marsh restoration	DTSHF, MB.	May-Sep	Variable	1998	Seasonal habitat use, movements, growth, and reproduction
Response of blue crabs (*Callinectes sapidus*) to marsh restoration	DTSHF, CTSHF, MB	Apr-Nov	Monthly	1996–1998	CPUE, mean size and size frequency distribution, sex ratio, and molt stages
Effects of *Phragmites australis* invasion on marsh surface macrofauna	Hog Islands, Mullica River-Great Bay	Jun-Oct Apr-Oct	Biweekly	1997 1998	YOY mummichogs; *Spartina* vs *Phragmites*
Trophic linkages between primary producers and fishes from open water and marsh habitats	DTSHF, CTSHF, Alloways Creek lower and mid Delaware Bay; MB & MHC	Jun-Oct	Variable	1998	Multiple stable isotope ratios of C, N and S in weakfish (*Cynoscion regalis*), bay anchovy (*Anchoa mitchilli*) & white perch (*Morone americana*)
Nutritional status of selected fishes in marshes & adjacent shoal habitats	MHC, MB, Alloways Creek and shoals (<6 m) immediately adjacent to these sites	Oct	–	1998	RNA-DNA ratios in weakfish (*Cynoscion*), *regalis*), white perch (*Morone americana*) & bay anchovy (*Anchoa mitchilli*)
Neomysis americana – tidal creek utilization	DTSHF, MB	Jun-Sep	3 dates	1998	Relative abundance in epibenthic sled samples
Small pelagic fishes – tidal creek utilization	DTSHF, MB	Jun-Aug	Monthly	1998	Relative abundance in push trawl samples

Hydrologic monitoring at the restored sites is used to assess the return of 'normal daily tidal inundation" (hydroperiod) required by the permit. Tide gauges are located either in marsh channels or upon the marsh plain at all restoration locations (Table 2). Macrophytes are monitored along transects in sample quadrants in representative habitats (Table 2). During the late summer when maximum biomass is present, quadrants are selected randomly and 'peak standing crop biomass' of macrophyte vegetation was used to calculate production.

Algal production is monitored with paired core samples taken from sediments along the vegetation sampling transects (Table 2). Gross and net production is calculated from oxygen flux measurements. Algal biomass is measured as chlorophyll-a and phaeophytin concentration by solvent extraction.

Nekton response to the marsh restorations is evaluated by comparing faunal use of restored sites relative to that of reference marshes (Table 3). Reproduction, feeding, growth rates and production estimates of selected species are evaluated as surrogates for marsh function (Teo, 1999; Able et al., 2000; Smith et al., 2000). Species composition, life history stage, size, and growth across sub-habitats (large and small tidal creeks) are analyzed, including annual, seasonal and diel aspects of community structure. Assemblages of fish of different ages are compared. Habitat use, residency, and movements patterns are determined with mark-recapture techniques for striped bass (*Morone saxatilis*), Atlantic croaker (*Micropogonias undulatus*), sheepshead minnow (*Cyprinodon variegatus*), and mummichog (*Fundulus heteroclitus*) (Teo, 1999; Able et al., 2000).

Principle 7 – Success criteria should include functional as well as structural components (framed by a 'bound of expectation')

How closely the attributes of 'natural systems' must be reproduced in any restoration effort is an important consideration (Aronson et al., 1996). Recognizing that there may be many potential end-points influenced by prior human activities in wetland landscapes, as well as natural ones, the business of restoration must be undertaken in the context of *multiple* stable end-points. Aronson et al. (1995) warned that choosing one particular natural state against which restoration success is measured may unnecessarily constrain restoration efforts and lead to the setting of unattainable goals. Rather, they suggest that by failing to inject 'a dynamic perspective into real world restoration efforts', i.e., a range of reference *ecosystems*, that the out-come would be 'failed restorations and frustrated restorationists'.

Because nature and ecosystems are historically and *culturally* contingent ideas, Higgs (1997) suggested that there ought to be no one single, fixed, correct restoration for any particular site, although structure, composition and function criteria should still provide tight guidelines for success of the project. Yet by Higgs' standards, the definition of 'good ecological restoration' will always be rooted by 'ecological fidelity': the appropriate combination of structural replication, functional success and durability. Furthermore, Higgs states that good restoration practices benefit from an expanded context (especially, in setting goals and outcomes) by including societal values (economic efficiency, and social, historical, political, moral and aesthetic) (see below). The 'cultural' element is also critical, not only because incorporating societal values enhances public acceptance of restoration, and improves its chances of success, but also because virtually all tidal wetlands on Delaware Bay have been influenced by human presence. We suspect this is true for most coastal regions of the United States.

Thus, the fabric of wetland restoration on Delaware Bay is at once driven by ecological criteria (restore ecosystem function), as well as the likelihood that restoration end-points must be something less than pristine. We have chosen the 'upper bound' to be the least disturbed systems on Delaware Bay, but certain 'self-restored' (after human perturbation) sites also qualified (by consensus among stakeholders). The degree of function returned to these sites will be determined through monitoring assessment and focused, species specific studies on population dynamics, trophic linkages, and productivity estimates. Although some of our colleagues may disagree, we chose not to disassociate structure and function as categories (Higgs, 1997). Rather, we believe that the functional success of restored wetlands is inextricably tied to compositional and structural replication; neither one is possible over time without the other. If we get the geomorphology and hydrology 'right', the ecosystem will naturally align with the system it is designed to produce (Higgs, 1997; Weinstein et al., 1997). Thus, we have selected reference sites for their natural characteristics and disturbance history (time behind dikes, presence of ditches and canals, and degree of subsidence), and existing planform characteristics.

Principle 8 – Consider people and property, a management plan should be developed that protects offsite elements (e.g., upland flooding, salt intrusion into wells, septic systems)

Because restoration of the diked salt hay farms, in particular, would re-introduce tidal inundation closer to upland dwellings (at the Commercial Township site [Figure 1], e.g., nearly 1.3 km inland of the prior existing dikes), there were concerns raised about upland flooding, salt intrusion into potable wells and septic systems, and the effects of sea level rise. To address these concerns, management plans for the salt hay farms incorporated the means to minimize potential adverse impacts to the surrounding environment, local communities, and the region as a whole. A Deed Covenant was recorded to correct any adverse impact resulting from construction activities at the sites. Specifically, the Deed Covenant covered repair or replacement of any off-site structure on property damaged as a result of restoration practices (e.g., from off-site flooding), and restoration and replacement of wells or septic systems damaged by reintroducing tidal inundation to the marsh. Corporate surety bonds were filed with each Township to secure these promises.

The individual site Management Plans also included provisions to assure that the frequency and depth of upland flooding adjacent to the restoration sites would not exceed the frequency of pre-restoration flooding events. This protection was put in place through the construction of dikes at the upland edge of the restoration sites and through the purchase and control of properties adjoining the restoration areas. Cross drains were installed in the upland dikes to drain floodwaters originating *upland* of the dikes.

A comprehensive monitoring system at each of the restored salt hay farms was designed to detect change in groundwater quality or groundwater elevation resulting from the restoration activities. As part of a pre-construction sampling program, nearby residents were queried to determine whether they wished to have their wells tested prior to the completion of the restoration, i.e., breaching of perimeter dikes. The program included sampling of homeowners' wells as well as installed monitoring wells and piezometers to establish pre-breach baseline conditions. Both the monitoring wells and the results of the well sampling provided baseline information from which to determine the effects of restoration. Post-restoration groundwater sampling was initiated at the time of dike breaching. Monitoring data collected in the past two years do not show any adverse changes in groundwater quality or elevation resulting from the salt hay farm restorations.

Principle 9 – Where possible, sites should be developed with conservation restrictions to ensure their perpetuity and to protect adjacent property

The annual loss of estuarine habitat, particularly wetlands, has generally outstripped the rate at which we are able to restore degraded habitat. Consequently, preservation of existing habitat is a critical component for achieving a net gain in healthy functioning estuarine habitat (Waters et al., 1999). The preservation of Estuary Enhancement Program restoration sites through deeds of Conservation Restriction (New Jersey) and Declarations of Restrictions and Covenants (Delaware) provide long-term protection of continuous wetland landscapes for publicly and privately conserved open space. The restoration sites connect other large tracts of publicly owned land to create a 'greenway' of nearly uninterrupted areas of protected wetland along the Delaware Bay shoreline.

Each of the Deed Covenants provide assurance that real estate taxes will continue to be payable (based on taxes paid in 1995) and that no claim for waiver or exemption would be made by reason of the effect of restoration activities or the subsequent ownership of the properties by exempt owners. Where applicable, the Deed Covenant also includes a promise to the owner to restore or replace well or septic systems rendered unusable where such condition was found to have occurred as a result of tidal marsh restoration activities. Similarly, the Deed Covenant calls for the restoration or replacement of any off-site structures on property damaged as a result of tidal marsh restoration activities. Finally, where the restoration or preservation involved facilities and improvements (e.g., dikes, tidegates, public access facilities), the Deed Covenant provides for a maintenance covenant covering the improvements.

As security for the promises contained in the Deed Covenants, the permittee agreed to post corporate surety bonds for tax and maintenance obligations for an initial term of 30 years, but renewable by each township for good cause at ten-year intervals. Bonds covering well and septic system impacts were put in place for an initial term of five years and made renewable for good cause at five-year intervals.

Table 5. Summary of public access amenities at restoration sites. DTSHF = Dennis Township Salt Hay Farm restoration site; CTSHF = Commercial Township Salt Hay Farm restoration site; MRSHF = Maurice River Salt Hay Farm restoration site; F = fishing, C = crabbing, T = trapping, H = hunting, B = birding; TBD = To be determined; – = not applicable.

Site	Platforms & boardwalks	Trails	Boat launch	Parking areas	Coastal heritage trail site	Educational signs	Osprey nesting platforms	Activity
DTSHF	2	Yes	1	1	Yes	Yes	4	F,C,T,H, B
MRSHF	1	No	2	2	Yes	Yes	4	F,C,T,H, B
CTSHF	3	Yes	1	3	Yes	Yes	4	F,C,T,H, B
Cohansey River	Outdoor classroom	Yes	1	1	Yes	Yes	4	F,C,T,H, B
Alloways Creek	3	Yes	TBD	4	Yes	Yes	4	F,C,T,H, B
Cedar Swamp Swamp	1	–	1	1	–	–	–	F,C,T,H, B
The Rocks	–	–	1	1	–	–	–	F,C,T,H, B

Principle 10 – Site plans should encourage public access for sustainable uses

The Comprehensive Conservation and Management Plan for the Delaware Estuary cites a goal to 'promote greater understanding of the Delaware Estuary and greater participation in decisions and programs affecting the estuary' (CCMP, 1994). To help improve science literacy and informed decision making, and to promote sustainability, environmental stewardship, eco-tourism and open space preservation, the plan recommends that all citizens should have within driving distance of their homes, opportunities for hands-on educational activities relating to Delaware Bay: floating classrooms, outdoor classrooms, guided walks, and opportunities for public access.

For these reasons and many others, public access improvements have been installed at all restoration sites in concert with other regional and local programs to promote public use of natural areas, and to allow visitors to traverse and explore a variety of habitats. A Citizens Advisory Committee was established in each host town that worked with the Estuary Enhancement Program to identify those public access facilities for each site.

Among the new facilities are 537 m of boardwalks for access into the restored marshes and which connect to eleven elevated observation platforms (only two of which are not compliant with the Americans with Disabilities Act). A floating dock to provide an educational platform for local school children, 6.5 km of nature trails with parking facilities, and six boat launches (for canoeists, kayakers, trappers, birders, hunters and fishermen) (Table 5). Several of the restoration sites are included in the National Park Service's New Jersey Coastal Heritage Trail as 'A Point of Interest.' Environmental education literature has been made available at the sites and through the Nature Conservancy. Permanent signs have also been installed at numerous locations to highlight the unique wildlife, wetland features, and historic and cultural resources of the sites and adjacent areas.

Summary and conclusions

Increasingly, restoration practices have included a cultural fabric in their formula for success. This makes sense for several reasons. We have already commented that aesthetic principles are important because they enhance public acceptance of restoration. If we are not careful though, public acceptance and aesthetic production could easily overwhelm the need for ecological fidelity; i.e., the combination of structural replication, functional success, and durability (self-sustainability) that we desire to achieve. Therefore, a substantial effort in restoration practice ought to seek balance between sustainable human practices and ecological function (Higgs, 1997). Without this balance, ecologists will miss an important constituency if the role of humans in ecosystems is ignored (McDonnell and Pickett, 1993).

At the core of restoration ecology is the desire to "return an ecosystem to a close approximation of its condition prior to disturbance' (NRC 1992). Although a solid foundation in knowledge of ecological systems is requisite, there is a heightened awareness among restoration ecologists to carefully build anthropocentrism into the process. In 1975, Cairns et al. (1975) distinguished between public perception of the practice and scientific knowledge:

> "The characteristics of restored ecosystems are bound by two general constraints, the publicly perceived restoration and the scientifically documented restoration. For example, *recovery* may be defined as restoration to usefulness as perceived by the 'users' of the resource. This is significantly different than restoration to either the original structure or the original function (or both) as rigorously determined by scientific methodology."

How can public perception and scientific rigor be balanced? Cairns (1995) attempted to answer this question with a proposal for 'eco-societal restoration':

> "Because of its interdisciplinary nature, ecological restoration must involve eco-societal restoration. This is the process of reexamining human society's relationship with natural systems so that repair and destruction can be balanced and, perhaps, restoration practices ultimately exceed destructive practices. Human society's practices are the best indication of its ethos or set of guiding beliefs. Ecosocietal restoration is a positive statement of cooperation with natural systems.'

Obviously, Cairns model of ecosocietal restoration forces the recognition that restoration practices manifest societal values. In our case, that restoration of 5040 ha of degraded wetland on Delaware Bay, although founded in the premise that not only do marshes 'make fish', but that they make fish of the 'right kind', is only part of the value that society will reap from the Estuary Enhancement Program. To optimize success, Cairns (1995) suggested further that:

> "Not only have nonscientists in a wide variety of fields and places undertaken ecological restoration projects, but the field *requires* [emphasis added] the input and cooperation of society to be successful. For example, if done on any significant scale, projects require approval of society or its representatives, significant funding, a long-term commitment to goals and significant allocation of human, economic, and biological resources. Therefore, communication among disciplines and between scientists, engineers and the general public and its decision-makers is crucial. Also crucial is that all participants, including the general public, have adequate environmental literacy.'

What Cairns is clearly advocating is recognition of mutual interests on the part of restoration scientists/practitioners and the public. These considerations are precisely what was incorporated into the Estuary Enhancement Program, and have made it a model for future large-scale restoration efforts. Perhaps more so than most projects, the Estuary Enhancement Program developed an *inclusive* process for making decisions about the design, implementation and management of the project. Higgs (1997) calls this inclusiveness, a 'reasonable balance' between individuals who are long-term stakeholders; e.g., recreational and commercial fishermen, environmentalists, restoration scientists, restoration consultants, amateur naturalists, landholders, corporations with vested interests (e.g., the project sponsor), and federal, state and local governments. By bringing such stakeholders with diverse interests together and by providing them with a voice in the conduct of the restorations, constructive discussion, criticism, and negotiation will ensue that can only benefit the project. The risks are minimal.

Restoration success

We have attempted ecological engineering on a grand scale in the Estuary Enhancement Program. The chosen goal (restore an increment of fish production to the estuary) was realistic for re-establishing species and functional ecosystems, having certainly recognized both the ecological limitations on restoration and the socioeconomic and cultural barriers to its implementation. We feel that the principles that we have extracted from our collective experience have broad application to similar undertakings worldwide. To let 'mother nature' and 'father time' guide the process, and to minimally intrude on a site, seems infinitely reasonable. The emphasis on restoration versus creation maximized the chances of success because many of the prerequisites for achieving this success were already in place. Similarly, the directive factors (abiotic as well as the biotic) in salt marshes are so complex and interactive that only by carefully selecting and capturing a reasonable range of natural and human influenced variation (a 'bound of expectation') could we develop acceptable success criteria, estimate the trajectories to get there, and the knowledge to determine when we had arrived. This knowledge is based upon monitoring key system variables, assessing the progress of the restorations relative to the agreed upon goals, and adjusting the trajectories as needed (or 'learning by doing' as adaptive management is sometimes called).

By developing Management Plans, a tool for tracking projects success is assured, but the Management Plans also give additional value-added, societal benefits to the restorations: providing accessibility for sustainable uses, adding amenities to facilitate these uses, and protecting people and property.

Finally, by engaging, sustaining and incorporating the expertise of top scientists, engineers, managers, and members of public institutions in the process, we have implemented a project that is shaped and directed in such a manner that it manifests both high human virtues and ecological responsibility (Higgs, 1997). It continues to be a 'win-win' situation for all involved.

Acknowledgements

The authors acknowledge Public Service Electric and Gas Company's Senior Management Team for their convictions in approving an unprecedented project of this scale; the staff of the Estuary Enhancement Program and Office of Environmental Counsel; the practitioners and scientific personnel of various consulting firms, and in particular the independent expert scientists who have shared a lifetime of knowledge with us and enabled this team to accomplish so much in so little time. The authors are also indebted to Dr Susan Peterson for her keen editorial insights for improving this paper. This is New Jersey Sea Grant Publication No. NJSG-00-438.

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