DESIGN AND CONSTRUCTION CONSIDERATIONS FOR WETLAND RESTORATION USING DREDGED MATERIAL

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ABSTRACT

Restoration of wetlands using dredged material has received a lot of attention during the last three decades. There have been many projects implemented around the Country in the Mid-Atlantic, Gulf and West coast regions of the country, in particular. While projects have ranged from large scale projects (on the order of greater than 1000 acres of restoration), smaller projects (less than 250 acres) are being implemented in several regions as well. The success criteria for these projects have varied widely, with success in some cases, defined as establishment of vegetation, while in others success is gauged more in terms of the "end user" - the various biological species that would eventually use the fully functioning system.

This paper presents guidelines for designing a successful wetland restoration project – from an engineering, as well as ecosystem perspective. Tools for design and planning evaluations, as well as construction monitoring and maintenance are presented. Finally, considerations for adaptive management of the wetland system are discussed.

Keywords: Dredging, wetlands, beneficial use, marsh, sediment, restoration.

INTRODUCTION

Beneficial reuse of dredged material from ports and harbors has received increasing consideration since the 1970s as a way to offset wetland losses (Landin, 1991; Landin et al, 1990; Mohan and Palermo, 1998; USACE, 1986; Woodhouse 1979; Woodhouse et al 1972). Recently the restoration of eroding islands and creation of new islands with wetland habitats has been considered and demonstrated in a number of places in the U.S. Large scale projects have included the Poplar Island Restoration Project in Maryland (USACE, 1997 & 2000) and the Houston Ship Channel Marshes (Eiedensticker 2006), to name a few. To date, however, there has not been well documented, generally applicable guidance that the engineering community can use to develop future projects. This paper strives to provide common guidance for such applications.

Wetland Restoration/Creation Approaches

The overarching question has been "Can we successfully restore wetlands?" The answer appears to go both ways. A critical element to "success" is to first understand the complexity and functions of the wetland system to be created or restored. For example, factors such as site location (salt marsh versus tidal freshwater marsh), target species for revegetation (cattail versus endangered species), and project timeline (wet meadow versus forest) – all affect the design, construction and public outreach aspects of the project. Often, projects perceived as "failures" are, in fact, successes that are inadequately or incompletely documented in public forums. The degree of difficulty associated with creation of wetlands also varies widely with respect to the type of system to be created, as illustrated in Figure 1.

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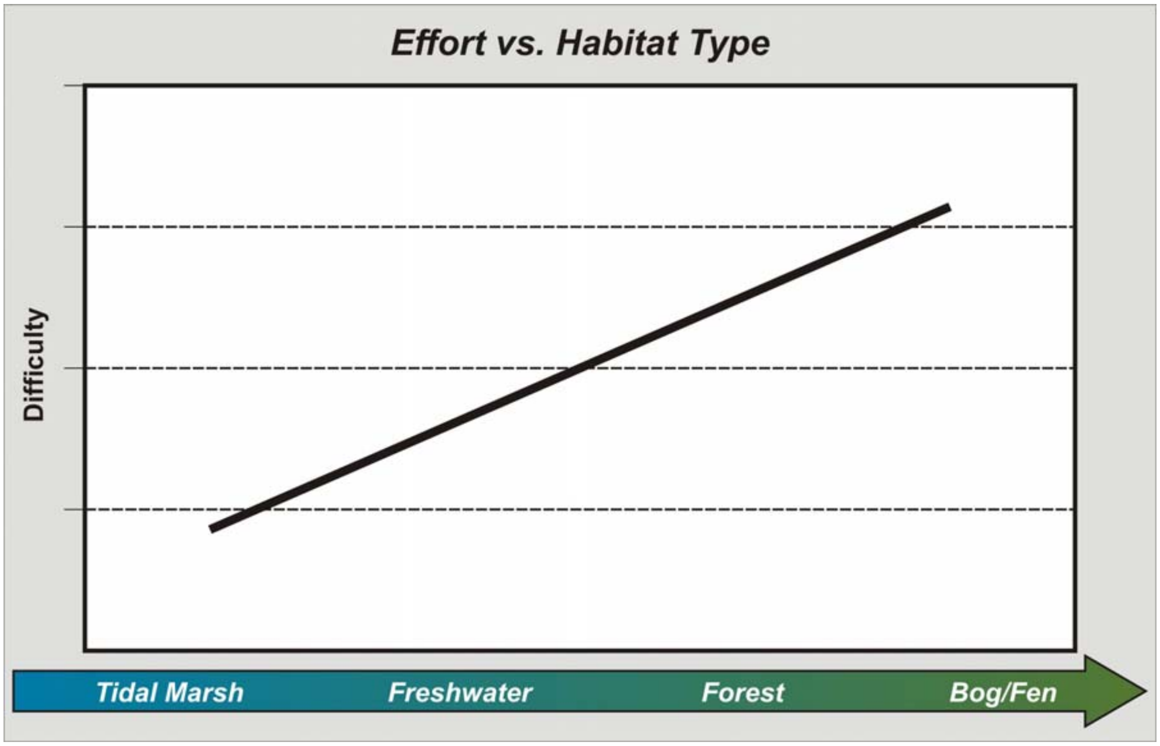

Figure 1. Level of difficulty in creating/restoring wetland systems.

In general, two approaches are utilized in wetland restoration/creation projects. The first is a, "cookbook" approach, where the design is based on generalized concepts and standard plans and specifications and target generally appropriate plant species. The second is a, "site-specific" approach, where design is tailored based on detailed site information (e.g., hydraulics, sediment types, physical aspects, etc), and the species composition is targeted on the basis of ecological surveys and benchmarks. The latter approach is often implemented in an adaptive management context in order to develop attainable project goals.

Regardless of the overall approaches, well conceived projects share common features. These are illustrated in Figure 2 and include:

- Site assessment, for planning and goal setting
- Development of detailed plans and specifications with appropriate review and stakeholder participation
- Project implementation, including construction and operations and maintenance
- Post-construction monitoring and evaluation

Figure 2. Components of a wetland restoration/creation project.

BASIC CONCEPTS

Wetland design is best conceived as an iterative process involving sealing or sizing of the wetland (shape and dimensions), specifying contours and water depths (for channels and inundated marsh systems), projected time-rate of consolidation settlement in the system following construction, and configuration of dikes, drains, weirs, and shorelines. These factors are somewhat interdependent and hence it is critical to undertake the feasibility analysis in an iterative mode to help assure that feedbacks among project parameters are adequately accounted for.

Regardless of project specifics, certain basic planning and engineering aspects apply to the entire domain of wetland restoration/creation projects. These include the project alternatives analysis phase (Figure 3) and the project design phase (Figure 4). While the level of detail in the analysis may vary from project to project – these stages – alternative analysis, hydraulic/hydrologic evaluation and design evaluations are quite fundamental and can benefit projects that might not require them by regulation or guidance.

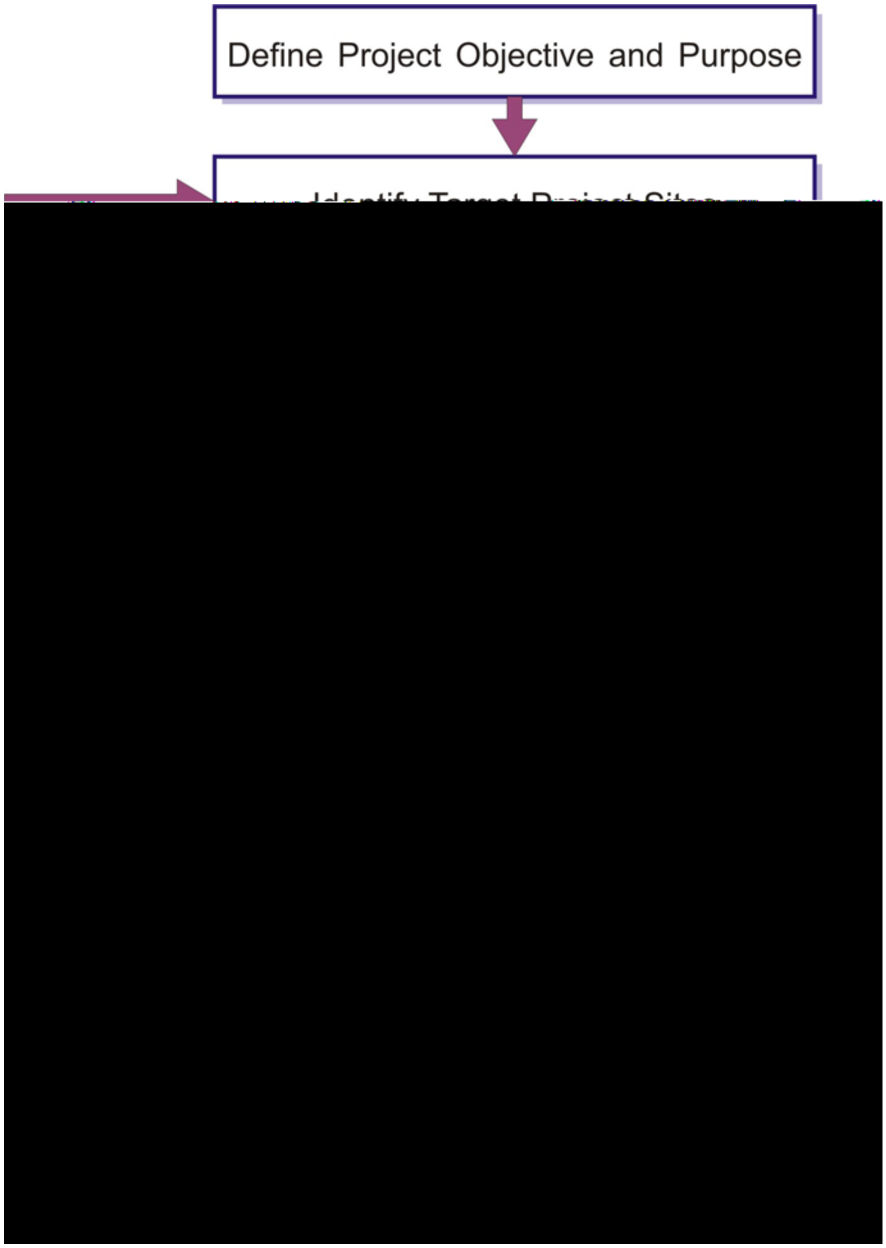

Figure 3. Alternatives analysis flow chart.

A key consideration is the determination of the volume and type of dredged material and the rate at which it will be produced. A material balance has to be worked out between the dredging site, and potential placement sites, to identify the required minimal size of the wetland [i.e., combination of acreage and dike heights, considering potential for bulking (initial expansion) and shrinkage (subsequent consolidation) of the dredged material].

The alternatives analysis phase includes defining the project objective and scope, identifying target sites that meet the basic criteria, perform logistical analysis (of space and land availability, fill material availability and transport distances), site screening, gathering planning/screening level data for the short listed sites (hydraulics, vegetation and geotechnical data on a coarse scale grid basis to compare sites from a feasibility perspective), preliminary sizing and cost analysis for the wetlands, and selection of preferred alternative.

Yet another important step is the selection of the desired biological endpoint conditions of the site. In many cases, the dominant plant community will provide project success criteria and management objectives, and will determine associated aspects of the biota, including invertebrate, fish, amphibian, reptile, bird and mammal communities. More generally, the relationship between the design conformation of the substrate and the potential biological community components plays an important role and often has a controlling influence on what habitats persist. Tidal mudflats, low salt marshes subject to twice daily tidal inundation, higher marshes inundated once daily or less, and fresh water wetlands, tidal or not as determined by the site and substrate design all support specific and consistent biota. The most efficient and effective techniques for determining final site biotic community structure are those that emphasize natural processes over hard engineering. “Natural engineering”, incorporated integrally in design, implementation, and monitoring phases of a project, reduces or eliminates inherent difficulties that can arise when human engineering ends up struggling against natural site conditions. Natural engineering reduces costs and increases opportunities for success, and should be considered for any wetland creation or restoration project involving dredged material resources.

ENGINEERING DESIGN OF THE WETLAND SYSTEM

Wetland design is a function of environmental conditions including hydrology (water budget, tidal range, wave forces), geomorphology (soil types, sedimentation rate), and dominant plant communities (Landin, 1991; Landin et al, 1990; Mohan, 1999; USACE, 1978; Woodhouse 1979; Woodhouse et al 1972). The design process involves several steps, as illustrated in Figure 4, and summarized briefly below. A detailed discussion of these aspects can be found in Mohan (2001).

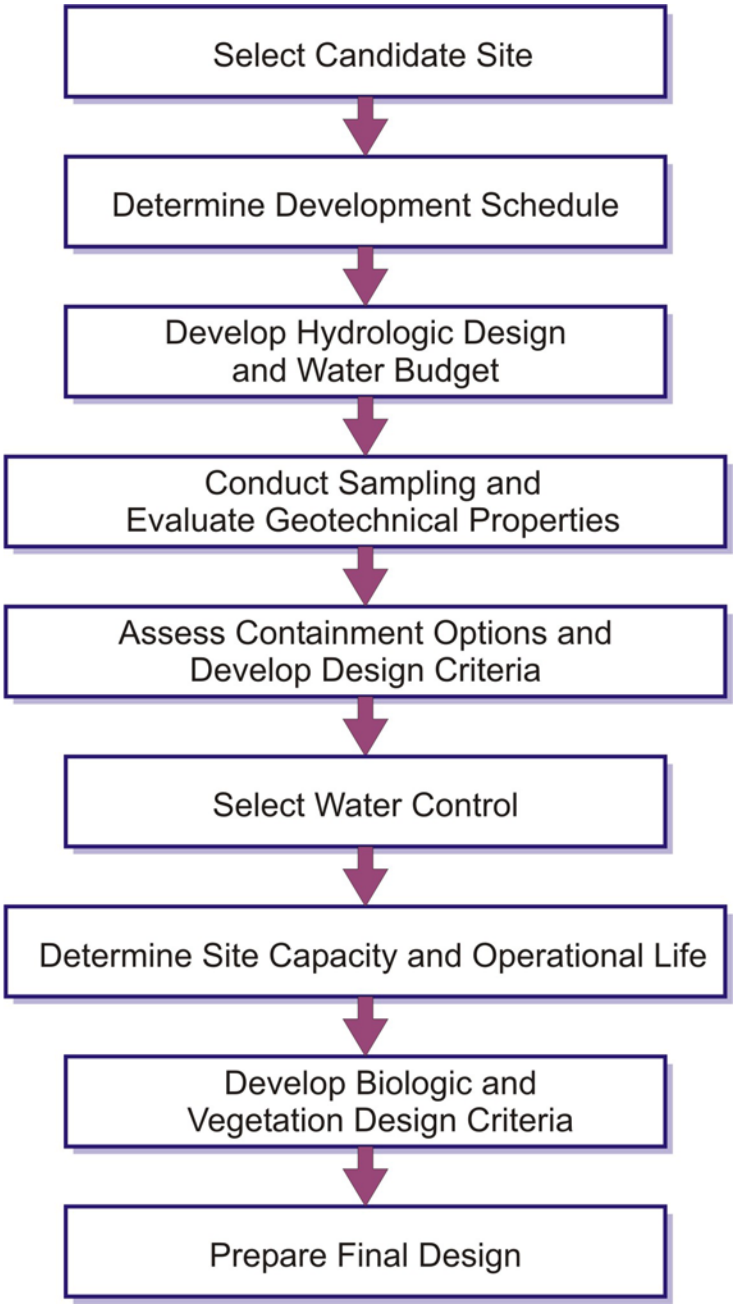

Figure 4. Detailed design flow chart .

Site Selection Criteria

The major site selection criteria are:

- geographical considerations (i.e., distance of the site from the dredging area, and the geometry of the site);
- physical considerations (i.e., water depth at the site, tidal range, wave characteristics, magnitude of storm surges, and velocity and direction of currents);
- hydrodynamic aspects (i.e., circulation and sedimentation);
- biological considerations (i.e., potential impacts on benthos, fish, and other sensitive species);
- environmental considerations (i.e., potential impacts on water quality, presence of contaminants at the site, and previously impacted areas);

- geotechnical considerations (i.e., sediment type and characteristics and potential for consolidation and instability); and
- other considerations (including cultural/archeological resources, aesthetics, jurisdiction issues, and other factors).

Site Development Schedule

The site construction/management schedule should be developed:

- considering production demand (i.e., local dredging requirement and the availability of placement sites);
- construction limitations (depends on the number of available construction equipment near the project site and their production capabilities);
- site capacity (influenced by material placement rate, crust management operations and project schedule);
- retaining structure [refers to the availability of suitable material for construction of retaining dikes (rip-rap, quarry run, etc) in the project vicinity];
- economics (denotes the allocated funding for the project and the sequencing of such funds); and
- other aspects (e.g., considerations such as efficient release of site water, site availability prior to nesting season, gentle dike slopes, etc., for sites planned for final wildlife).

Hydrologic Regimes

A good understanding of the hydrologic regime is critical for establishment for vegetation in the short and long term. Factors such as rainfall/runoff, storm/flood, surface water and groundwater infiltration and exchange rates are integral to understanding the water balance at the site of interest. If such factors are in agreement with project objectives, additional design steps can be taken.

Sampling and Testing

Sampling and testing that should be conducted to aid in determining the key parameters that affect the site design include:

- physical investigations (measurement of water depth, tidal range, wind/wave characteristics, and velocity/direction of currents);
- biological investigations (includes sampling/mapping of benthos, fish, and other sensitive species to evaluate total abundance, species diversity, relative degree of productivity, and presence/aerial extent of submerged aquatic vegetation);
- environmental investigations (includes sampling/testing of the water column and in-place sediments for the target list of contaminants expected at the site); and
- geotechnical investigations [includes index property tests (water content, Atterberg limits, specific gravity, and grain size distribution), probing/borings, in-situ vane shear tests, column settling tests, cone penetrometer tests, and consolidation (column settling, self-weight and one-dimensional tests), permeability, and shear strength tests].

It is important to conduct detailed sampling not only in the area to be dredged (to understand the nature and characteristics of the dredged material), but also at the placement site (for evaluating site conditions for dike design and estimating any post construction consolidation and settlement of native sediments). Samples should include borings to understand basic soil index properties, as well as soil stratigraphy, and testing for strength and consolidation. For the dredged material, consolidation testing should include bulking and column settling tests, as well as self weight consolidation, while for the native soils, one dimensional consolidation testing is more important. Prior dredging records are also a good source of information to understand the general characteristics of the dredged material – however, it is often advisable to supplement historic data with more current information. Finally, bathymetric surveys should be conducted both for the dredging as well as for the wetland sites.

Lateral Containment and Water Control Structures

Wetlands created or restored using dredged material are often confined by lateral earthen dikes. However, in certain cases, geobags filled with dredged material or bulkheads are also used in the berm construction. Once the perimeter dikes/structures have been designed, the various forces to which they would be subjected should be determined. These include wind effects, design wave and storm criteria, current velocities, and evaluation of ice thrusts, if applicable. For a high degree of protection, an armor layer with a net height greater than the maximum level of wave runup (during storm surges) should be provided. In some cases, a berm is provided to breakup the wave energy.

Assessment of water control structures are often site specific, and generally consist of evaluation of structures such as box weir spillways, or half round riser spillways, or in certain cases, telescoping weir spillways. The most commonly used outlet structures are spillways, which are used to provide ponding for clarification of cell water to meet effluent quality standards (Mohan and Urso, 1997; Palermo, 1995; Palermo et al, 1978). In general, cell water levels should be kept as low as possible in accordance with applicable effluent water quality requirements. Cell water levels are typically raised by the installation of weir boards and lowered by the removal of weir boards at the spillway structure. The spillways are fitted with slide gates which allow complete shutdown, should the water quality needs require such an action. Another function of spillways is to control the release of cell water during crust management and during periods of no dredged material placement. The spillway crest elevations should be as low as possible to provide efficient removal of surface water and rainwater, and to allow material drying. Spillway boards may also need to be removed if the cell elevations drop considerably due to consolidation and desiccation.

Short-circuiting can be a major issue affecting the overall efficiency and operation of the site. Short-circuiting occurs when the dredged material slurry follows a preferential short-distance flow path thereby effectively isolating the remaining surface area of the site from acting as a sedimentation basin. The net result would be the creation of “dead zones” at the bypassed locations causing a dramatic decrease in the overall sedimentation efficiency. Curves of retention time versus pond area should be generated for each inflow scenario in order to evaluate the hydraulic efficiency of the site. Basically, the computed retention times should be sufficient to permit adequate settling of the suspended particles in the dredged slurry. Retention times may be increased by artificial methods such as baffles, training dikes or deflection barriers. It should be noted that although larger pond areas provide more retention times for the slurry; they also increase the potential for wind generated water column turbidity and sediment resuspension. Therefore, it is important to maintain an optimal pond area at the site in order to provide necessary settling times for the slurry while keeping the wind generated turbidity and resuspension to a minimum.

Site Capacity and Operating Life

Once the engineering design considerations are finalized, estimates of site capacity and operating life of the system can be determined – the former determines the amount of dredged material that the site can accommodate accounting for factors such as bulking and eventual (post-placement) shrinkage of the material, while the latter refers to the number of years it will take to completely fill the site with dredged material.

Predicting the behavior of fine-grained dredged material is difficult due to the high water contents. The physical characteristics of the dredged material are important because of their effect on the following (Herbich, 1992b; Mohan, 2001; Mohan and Urso, 1997; Palermo, 1995):

- *Material bulking* - During the dredging and placement process, the in-situ material will “bulk” or expand due to the addition of water and the handling of the material. The term Bulking Factor (BF), describes the volume change between original in-situ cut (in channel) volume and the volume at the placement site, as described below:

  $$BF = V_{od}/V_{id} = 1+[(e_o-e_i)/(1+e_i)]$$

  where, V_{od} is the volume of dredged material measured at placement site, V_{id} is the initial in-channel or in-situ volume of dredged material, e_o is the void ratio of the dredged material measured at placement site, and e_i is the initial in-channel or in-situ void ratio of the dredged material.

- *Consolidation and desiccation* - After placement, material layers will undergo a reduction in height or shrinkage due to sedimentation, primary consolidation, secondary compression, and desiccation (Palermo; 1995; Vanoni, 1977). The sedimentation process is complete within a number of days after placement and has little or no effect on the long term settlement of the material layers. The long-term settlement due to consolidation and desiccation is the major factor in estimating the volume occupied by fine-grained dredged material. Consolidation of fine-grained dredged materials is the gradual release of excess pore-water pressure within the soil matrix, which results in settlement of material layers. Desiccation of fine-grained dredged materials is the drying and formation of crust, which results in settlement of the top portion of the layer and the subsequent consolidation of underlying layers.

- *Mathematical modeling* - Consolidation and desiccation can be simulated using the U.S. Army Engineer Research and Development Center (ERDC) computer model, Primary Consolidation, Secondary Compression, and Dessication of Dredged Fill (PSDDF) which simulates the primary consolidation, secondary compression, and desiccation processes in fine-grained soils using the finite strain theory of consolidation, the secondary compression theory and an empirical desiccation model (Stark, 1995). The model computes the total settlement of the dredged fill layer based on the consolidation characteristics of the soils above and/or below the layer, the consolidation characteristics of the dredged fill, local climatological data, and surface water management techniques within the containment facility. This settlement is then accumulated for each compressible layer within the area and a cumulative settlement for all dredged material and compressible foundation layers is calculated. New layers of dredged material can be added at any time.

The potential for material drying and consolidation is greatly dependent on the placement rates and lift thickness. Lift thickness (T_{DM}) is defined as;

$$T_{DM} = P_R / A$$

where, P_R is the placement rate per year, and A is the surface area of the site at the particular elevation. In general, lift thickness greater than about 1.3 m do not allow the lower portion of the lift to be desiccated and therefore, do not promote adequate consolidation and settlement.

Plots illustrating the variation of site surface area and site capacity with dike elevation are extremely valuable for choosing the optimum design dike elevation. Site areas can be determined for various elevations using digital terrain models and the resulting site volumes (V) and site capacities (C) determined as described below:

$$V = (A*d_e)/27$$

$$C = V / BF$$

$$d_e = d_h - d_{fb} - d_p$$

where, d_e is the maximum permissible elevation for material placement, d_h is the total required dike height, dike d_{fb} is the freeboard depth, d_p is the ponding depth, and BF is the bulking factor. Note that the dike height is also governed by the final desired range of elevation for establishment of vegetation, and the water levels at the site.

Habitat Design

During the habitat design stage of the project, it is critical to select habitats that are associated with the area that may be successful in restoration or creation. Today, projects are not just the creation of wetlands but have been directed towards more complex ecosystems. For example the bay island habitat restoration projects in the Chesapeake Bay (USACE, 1997 & 2000) and Houtson-Galveston Bay (Eiedensticker 2006) are from subtidal, tidal flats to tidal marshes and up into the mature forest. These complex habitats will require a greater understanding of succession and a more than the normal monitoring time (5 years usually) to ensure success.

An important component in the habitat selection is the plant species that will establish successfully. The most common habitat associated with the beneficial use of dredge material has been directed towards tidal marshes.

Successful plant species selection should be identified through a field survey of nearby habitats to be used as ecological benchmarks. Habitat selection is a function of a number of factors (Landin, 1991; Landin et al, 1990; USDA, 1992), including:

- project goals (must be compatible with surrounding land uses);
- water budget (including fluctuations and inundations, flooding levels and durations, tidal ranges, water volumes and quality, and inlet/outlet locations);
- substrate characteristics (including soil properties and texture, soil slope and elevation, subsurface stratigraphy and soil layering);
- water depth (directly linked to the vegetation type desired, and is affected by substrate saturation, water budget and water control structures);
- final slope [SCS (1992) recommends a final site slope of 6H:1V or milder; slopes of 10H:1V to 15H:1V are typical];
- growth season (should be sufficient to promote the full growth of the plants and generation of seeds);
- wind and waves [The plant species (or auxiliary measures such as protective dikes) should be able to withstand the wind and wave energy]; and
- costs (function of the vegetation type and working conditions at the site).

DEFINING SUCCESS – THE ADAPTIVE MANAGEMENT APPROACH

The implementation of the factors outlined above requires an understanding their interactions in the development of the various habitats meeting their attainable goals. Routine monitoring is requiring assessing if the habitats are approaching their objectives and what methods need to be incorporated to ensure that the plan is within acceptable expectation (Figure 5). The adaptive management plan is a method that is being has been developed to include these monitoring events the development of an adaptive management plan.

Current consensus in the scientific community regarding the concept of adaptive management:

The definition of adaptive management has many different variations. However, most definitions accepted in the scientific community include:

- established attainable project objectives;
- routine monitoring to evaluate management strategy effectiveness; and
- flexible framework that allows for adjustments in current management practices.

The evaluation process is considered one of the most important, but overlooked components of the process, and is dependent on collection of data representative of project conditions relative to the project objective. As such, the selection of measurable parameters relative to the project objective is crucial to accurate evaluations of current management practices.

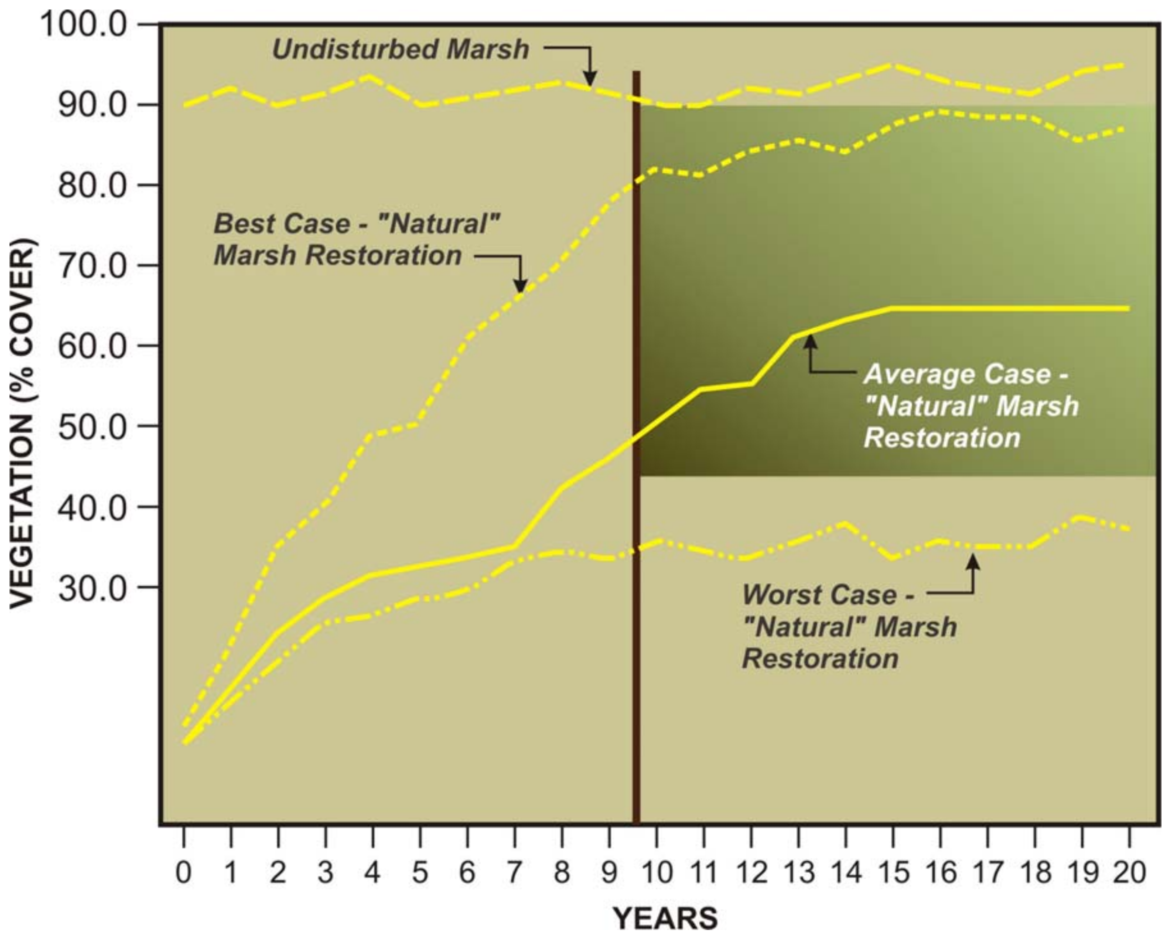

Figure 5. Illustration of adaptive management concept.

CONSTRUCTION CONSIDERATIONS

Mitch (2006) indicated that we may be over engineering and landscaping our habitat restoration/creation projects and should allow more input from 'Mother Nature' and 'Father Time'. Ecosystem creation and restoration work best when engineering is minimized and the reliance on self-design capacity is maximized with the constraints of project goals (Mitch 2006). There are a number factors involved the construction of the habitats that have to be considered. It is of the utmost importance to utilize adjacent habitats as ecological benchmarks for species composition, elevation gradients and tidal inundation in the habitats when working in the estuarine ecosystem (Shisler 1990). The benchmark habitats should be subjected to the same environmental stress associated with proposed habitat and will be the standard by which success will be measured. During the final preparation it is imperative that a wetland consultant be on site to make the necessary corrections without delay of the operation. Personnel continuity from the design through the implementation and the application of the adaptive management is of the utmost for success. In the development of the habitat design the factors where evaluated by the habitat design team in to consideration and incorporated into the final design. The habitat team developed the extensive knowledge and experience of the project in relation with environmental stresses on the proposed system that can not be exchanged in/or expressed in reports and drawings. The adaptive management plan incorporates these possible impacts and methods ensure success but the understanding of these is developed through a depth experience of the project in the design and construction phases.

The tidal systems are considered to be the easier habitats to construct but are dependent upon the elevations of the final grade. Minor changes in the topography of the final grade are to contain micro-elevations to increase species diversity. Mother Nature takes the lead in determining the species composition and with tidal systems the seed source is brought in on the tides. New Jersey tidally restored over 6900 acres of salt hay impoundments by 1990 without planting any vegetation (Shisler 1990). A recent restoration of the Delaware salt hay impoundments with sites up to 3,000 acres were successful restored without any plantings of low or high marsh vegetation (Mitch 2006, Hickle and Teal 2006). Father Time in this project has been the development of the tidal creeks were just the first through third order tidal creeks were constructed and now these systems contain up to fourteen and fifteen order tidal creeks (Mitch 2006, Weisher 2006). Father Time is also the required component in the development of the complex systems such as forests and bogs.

The measurement of success is not the 85% survival rate to the plants planted but in the development of the functioning habitat similar to the reference site. The final habitat could be composed a different species composition than the one planted but is still a functioning habitat similar to the reference site. Any habitat effort (restoration/creation) must be directed towards a self-perpetuating system which will permit the potential for all the future biotic variations which may occur in a natural system (Niering 1990).

LESSONS LEARNED

Dredged material has been successfully used for creating and restoring wetlands and a review of completed projects yield the following observations (Coastal America, 1996; Landin et al, 1989; Mohan, 1996; Mohan et al, 1998; Mohan, 1999; Urso et al, 1999):

- The wetland development process should be coordinated with maintenance dredging schedules and locations.

- Wetland cell size should be optimized for volume of dredged material. Depending on the size of the wetland area to be constructed, larger cells would decrease construction costs, reduce the quantity of material needed for dike construction and increase the capacity of dredged material. Though larger wetland cells are more difficult to manage consolidation of dredged material as well as increased complexity of hydraulics.

- It is critical to estimate the final marsh elevation since errors in this has led to project failures and the use of adjacent ecological benchmarks.

- Planting schedule should be carefully developed so that at the time of planting, the material should have undergone most of its estimated settlement.

- Pilot demonstration projects are very helpful to gather and strengthen public support and also to field test new techniques and assumptions.

- It is essential to involve local and community groups as well as regulatory agencies and other stakeholders early on in the planning process in order to bring all interested parties to a common cause. Further, such a unique partnership will bring together a pool of multitalented individuals, thereby aiding in achieving much more than what a single agency could achieve on its own.

- The technique of adaptive management has been proven to allow multiple objectives and expectations to be realistically met.

A detailed discussion of lessons learned from a management perspective and technical perspective is provided in Mohan (2001).

CONCLUSIONS

Wetland creation/restoration projects are attractive to resource agencies due to their environmental benefits, since wetlands are prime habitats and breeding grounds for several animal species. Use of dredged material in such projects leads to a beneficial application of dredged material, thereby making harbor development projects environmentally and economically attractive. As the demand for dredged material placement sites increase in the future due to economic and environmental factors, use of such material to create/restore wetlands will become more and more attractive. The techniques presented in this paper are intended to serve as general guidelines for engineers and project managers alike involved with wetland projects.

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