Review

Guidelines, processes and tools for coastal ecosystem restoration, with examples from the United States

RONALD M THOM[1],*, HEIDA L DIEFENDERFER[1], JEFFERY E ADKINS[2], CHAELI JUDD[1], MICHAEL G ANDERSON[1], KATE E BUENAU[1], AMY B BORDE[1] & GARY E JOHNSON[1]

[1] *Marine Sciences Laboratory, Pacific Northwest National Laboratory, Sequim, Washington, USA*
[2] *NOAA Coastal Services Center, Charleston, South Carolina, USA*

Abstract: This paper presents a systematic approach to coastal restoration projects with five components: planning, implementation, performance assessment, adaptive management, and dissemination of results. Typical features of the iterative planning process are synthesized, beginning with a vision, a description of the ecosystem and landscape, and goals. The conceptual model and planning objectives are developed, prioritization techniques are used for site selection, and numerical models contribute to preliminary designs as needed. Within the planning process, cost analysis involves budgeting, scheduling, and financing. Performance criteria and reference sites are selected during design of the monitoring program. Particular emphasis is given to the monitoring program, used as a tool to assess project performance and identify problems affecting progression toward project goals, within an adaptive management framework. Key approaches to aspects of the monitoring program are reviewed and detailed with project examples. Another important means of strengthening the restoration project or program is documentation, peer review, and the distribution of information outside the planning team prior to finalizing construction plans, during implementation, and throughout monitoring and adaptive management.

Key words: adaptive management, coastal restoration, monitoring, performance assessment, planning, wetlands

Introduction

Background

In the two decades since an early volume of ecological restoration approaches was published (Cairns 1988), recognition of systematic features that are important to achieving restoration project and program goals has emerged. Because of the failures of many early restoration projects, the growing emphasis on restoring coastal systems (NRC 1992), and our own involvement in restoration projects, we and others began developing a systematic approach to coastal and estuarine restoration projects. In our view, enough convergence in thought has occurred to warrant a synthesis of these features specific to coastal restoration under five sequential and iterative components: planning, implementation, performance assessment, adaptive management, and dissemination of results. These features are evident in the guidelines of the Society for Ecological Restoration International (Clewell et al. 2000) and national

coastal restoration strategies (RAE & NOAA 2002) and techniques (Sea Grant Oregon 2002) in the U.S.A., and in major coastal restoration efforts across the U.S.A.: e.g., Rhode Island (University of Rhode Island 2003), Chesapeake Bay (Batiuk et al. 1992, 2000), Louisiana coastal wetlands (Louisiana Coastal Wetlands Conservation and Restoration Task Force 2001), Tijuana Estuary (Zedler 2001), San Francisco Bay Delta (Josselyn & Buchholz 1984), the Columbia River estuary (Johnson et al. 2003), and the Puget Sound nearshore ecosystem (Fresh et al. 2003). These features have been applied to projects and large regional programs as well as more isolated projects such as eelgrass restoration at the Clinton ferry terminal in Puget Sound (Thom et al. 2005b).

In this paper, adapted from a report to the National Oceanic and Atmospheric Administration (Diefenderfer et al. 2001), we endeavor to synthesize features of the iterative process typically used in the implementation of coastal restoration in the U.S.A., under the rubric of five components or categories (Fig. 1). While these are relatively standard aspects of the process, inevitably variation does occur

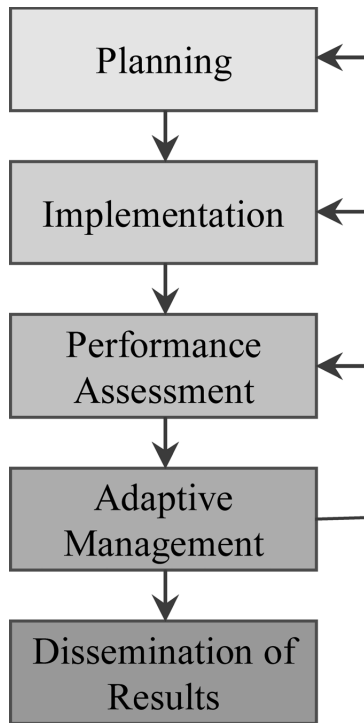* Corresponding author: Ronald M Thom; E-mail, ron.thom@pnl.gov

Fig. 1. Five components of a coastal restoration project.

in every project or program. Thus, we draw from many ecological restoration examples to illustrate the types of specifications that have been developed for certain purposes or regional conditions.

Introduction to the Restoration Project Components

In planning a coastal restoration project, sound ecological science and engineering and rigorous planning procedures are equally important. A failure in any area can lead to costly retrofitting during or after project implementation (Noble et al. 2000). A range of planning methods and theories may be used, including, for example, rational, incremental, adaptive, and consensual approaches.

Implementation may include many forms of construction "actions". Shreffler et al. (1995) list common actions including ground enhancement, rip rap installation, culvert installation, culvert cleanout and removal, channel cleaning, erosion control, vegetation planting, dike removal, dike/dam/levee building, and cattle fencing. In a national review of coastal restoration methods, Borde et al. (2003) describe innovative restoration methods in habitats including coral reefs, mangroves, salt marshes, and intertidal zones (seagrasses), including the placement of reef balls and other underwater structures.

A monitoring program for performance assessment does not need to be complex and expensive to be effective (Kentula et al. 1992a). The National Research Council (1992) recommended that to assess the equivalency of the restored system to the antecedent one, wetland restoration monitoring programs should observe ten conditions. In developing monitoring protocols for assessment of two large estuaries

on the West Coast U.S.A. (Simenstad et al. 1991, Roegner et al. 2009), we have found that these ten conditions are generally applicable to coastal restoration projects: (1) assessment criteria should include structural and functional attributes; (2) criteria should be based on known antecedent conditions of the target or reference ecosystem; (3) criteria should be established before the assessment takes place, with an indication of the expected degree of similarity between restored and reference sites; (4) criteria should be linked to the objectives of the project; (5) measurements should account for temporal variation and spatial heterogeneity; (6) multiple criteria should be used for evaluation; (7) a range of reference sites and long-term data sets should be available; (8) criteria may need to be regionally specific; (9) the time frame for reaching the criteria should be established a priori and the site should be monitored for this period; and, (10) assessment criteria and methods should stand up to peer review.

Perhaps one of the most significant developments in aquatic system restoration has been the trend toward the use of adaptive management principles in managing projects (e.g., Boesch et al. 1994). Recently, the U.S. Department of Interior released guidance on adaptive management for restoration projects (Williams et al. 2007) now used for many programs in the U.S.A. Ecosystem monitoring is at the heart of adaptive management (USACE 2000). Simply put, in adaptive management, the restored system is monitored, the data are assessed against existing knowledge and, if necessary, a remedy is prescribed based on predictions of success. Monitoring helps determine the remedy, evaluate its effectiveness, and prescribe new actions if needed. Goals may be revised based on monitoring, new knowledge, inventories, research, and new technologies. The adaptive approach provides a method to reduce project failures through cause-and-effect input to the management process, and a means to make decisions despite the existence of uncertainty (Thom 1997, 2000).

The NRC (1990) emphasized recognizing the audience for a restoration project. The dissemination of project results may serve a variety of purposes depending on the interests of these individuals. It is important for complete information about the project to be disseminated as widely as possible (Hackney 2000). Yet, our national review of restoration projects (Shreffler et al. 1995) and a more recent review of wetland mitigation projects in New England (Minkin 2003) indicated that record-keeping often was given low priority.

Though the five components occur somewhat sequentially, in practice, coastal restoration is an iterative process, as represented by the arrows in Fig. 1. Beginning in the planning phase, as new information is generated it is incorporated into the conceptual model and plans are revised accordingly. Then during implementation, conditions on the ground may dictate reevaluation and possible alterations of plans. Management goals for the system may evolve based on information generated at the site or on the evolving state

of the science. The dissemination of results facilitates information sharing by practitioners, which enables restoration practices to advance, makes restoration science more robust, and improves the chances of success at future projects.

This systematic approach is somewhat idealized in Fig. 1, in that according to national and regional reviews (Shreffler et al. 1995, Minkin 2003), many restoration projects overly emphasize implementation. Alternatively, the Louisiana coastal wetlands (Boesch et al. 1994) and Clinton ferry terminal are a large program and a relatively small project, respectively, in which all five components were included from early in development. The eelgrass transplantation at Clinton, Washington, for example, was coordinated with ferry system operations and expansions, which provides opportunities for directed experimentation within a robust monitoring and management program (Thom et al. 2005b). This paper synthesizes experiences from numerous projects and programs, which collectively demonstrate that to achieve project goals, a robust monitoring program with performance criteria is required to quantify outcomes and if necessary adjust restoration actions on the ground.

Systematic Approach to Restoration Planning

Planning includes the establishment of goals, objectives, and performance criteria for the project. Factors to consider in setting goals and performance criteria include time scale, spatial scale, structural conditions, functional conditions, self-maintenance, and the potential resilience of the system to disturbance. The type of system to be restored is determined, and the site is selected. Site selection involves examination of historical or predisturbance conditions, degree of present alteration, present ecological conditions, and other factors. Determining the level of physical effort, producing engineering designs, and cost estimates, scheduling, and producing contingency plans are all part of project planning. Stakeholders and the interested public should be identified and included in project planning. Federal agencies have developed detailed project planning and engineering processes and have used them for decades. It is critical that tools and concepts from the science of ecological restoration be integrated with proven methods such as these (Harrington & Feather 1996, Diefenderfer et al. 2005).

The planning approach that follows includes elements of rational and adaptive planning, e.g. a stepwise process like rational planning (WRC 1983) as well as the adaptive ability to revise plans during implementation and monitoring (Diefenderfer et al. 2003). The process and major components of this approach are illustrated in Fig. 2 and detailed in the following sections, which correspond to the boxes in Fig. 2. New information generated at any stage of the process may necessitate returning to an earlier stage or even to the beginning of the process. While the planning steps identified in Fig. 2 may not always occur in the order pre-
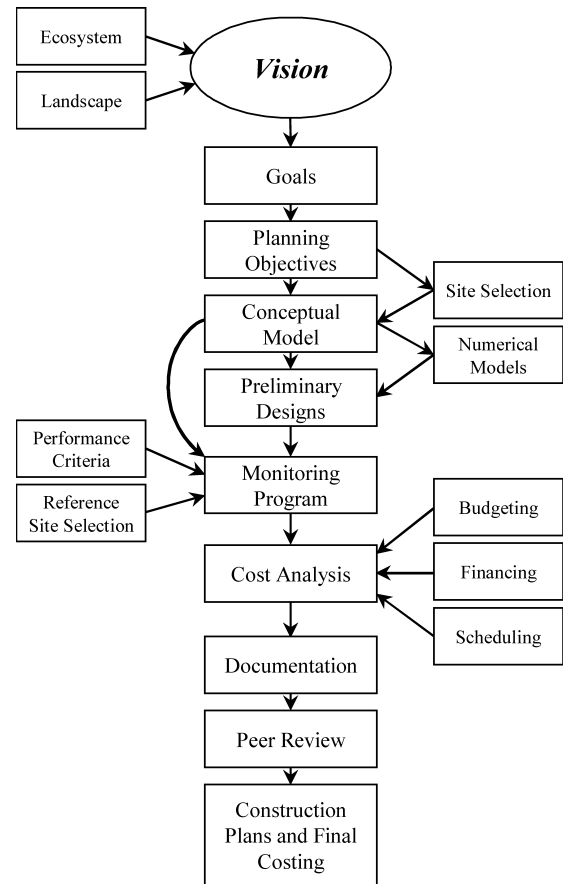

Fig. 2. A coastal restoration project planning process.

sented, it is important that they all be incorporated in the decision process in order to develop sound recommendations in the final plan.

The Vision

A vision is the overarching idea from which a restored ecosystem is developed. A picture is refined and strengthened through interaction with individuals representing a variety of disciplines. At its core is an ecological or biological target with associated social, environmental, and planning contexts. For example, how will the restored site function within the landscape? Will it complement other preservation or restoration efforts? How can the monitoring program support the project and further regional conservation goals? Examples of features that might form the heart of the vision include a mangrove forest, a fishery, a specific reef or estuary, or a single imperiled species.

Ecosystem

The vision statement highlights features at one or more scales, but if the scale of the threatened features does not encompass the ecosystem, then the ecosystem required to sustain the features is also identified (e.g., Simenstad et al. 2000). For example, if the vision includes specific benefits for one or more species, whether plant or animal, then the habitats required by these species are also included. The

ecological links and controlling factors that are critical to maintenance of the threatened structure or function, such as hydrology, must be identified to help scale the project. The conceptual model is critical to this task and to documenting any impairment to the controlling factors (Diefenderfer et al. 2009).

Landscape

The net contribution of a restoration project to conservation goals is directly related to its landscape context; therefore, the landscape is considered early in the planning phase when deciding whether a project is worthy of pursuit (Diefenderfer et al. 2005). Watershed-based or estuary-wide planning helps to prioritize projects (e.g. Johnson et al. 2003) and has been widely discussed and recommended (Lewis et al. 1999, RAE-ERF 1999, Lewis 2000, Foote-Smith 2002, Gersib 2002, Boesch 2006, Thrush & Dayton 2010). The restoration project manager must also research the potential effects on system performance of countless factors such as adjacent land use, roads, off-road vehicles, boats, water diversion, air pollution, water-borne contamination, sewage discharge, dredging, trampling by humans (including diving), cyclic disturbances, wildlife, dogs, and grazing animals. These factors help to define the spatial extent of the landscape within which the project is evaluated, because they have the capacity to affect project performance. Whether a landscape element is included in the monitoring program depends on its potential effects relative to project goals.

Goals

The vision is formally stated as a goal or set of goals for the restoration project. These goals are most useful if they translate directly into measurable conditions. In this way, the goal leads to testable null hypotheses that are evaluated in the monitoring program. Above all, it is important to 1) connect goals directly to the vision for the project; 2) make goals as simple and unambiguous as possible; and 3) set goals that can be measured in the monitoring program (Thom & Wellman 1996).

Planning Objectives

Once goals are stated and agreed to, specific planning objectives can be formulated that define more clearly what will be done to reach the goals. The identification and inclusion of stakeholders will strengthen the process by incorporating local knowledge, reducing challenges to the project, and increasing its value to the public interest (Harrington & Feather 1996). Examples of project objectives include the following:

1. increase the total spatial extent of wetlands;
2. increase habitat heterogeneity;
3. restore hydrologic structure and function;
4. restore water quality conditions;
5. improve the availability of water;
6. reduce flood damages.

Site Selection

In cases where the site has not been predetermined for other reasons, the primary factors in site selection should be potential biological importance and likelihood of restoration success (Diefenderfer et al. 2009). Generally, consideration of these factors is closely followed by an assessment of the complexity of the task and the investment required to achieve restoration success at a variety of sites using a variety of means. In particular, the feasibility of returning elements of the ecosystem to a condition that is conducive to meeting the project goals is assessed through a multi-scale, systematic prioritization process (Diefenderfer et al. 2009). Such controlling factors may include sediment deposition patterns, hydrology, soil or sediment types, temperature, or any other parameter controlling the establishment of desired vegetation, fish or wildlife. Systematic assessment enables the stressors on the controlling factors at site and landscape scales to be quantified in order to estimate relative probability of successful restoration of ecosystem function. Three general steps in site selection and prioritization are described in Borde et al. (2003): assessment and characterization of the study area, development of site selection criteria, and prioritization of potential sites.

Potential sites for restoration can be prioritized by assigning scores based upon three factors: (1) the magnitude of change in ecological function; (2) expected change in area producing that function; and, (3) probability that the restoration project will produce the predicted functions (Thom et al. in press). These three factors can be combined (multiplied together) to produce an index score for each site under consideration to rank the sites from highest to lowest index score.

Conceptual Models

Conceptual models are used to develop performance criteria from goals and objectives. The principal factors that control the development and maintenance of the habitat structure, the important habitat characteristics, and the functions for which the habitat is restored are identified in the model. The Chesapeake Bay Program restoration plan for submerged aquatic vegetation provides an excellent, comprehensive example of how to relate performance criteria to goals through a conceptual model (Batiuk et al. 1992, 2000). Conceptual models (Fig. 3) illustrate the direct and indirect connections (represented as arrows) among the physical, chemical, and biological components (represented as boxes) of the ecosystem. In this way, they highlight the specific requirements of target components. If a review of existing models and data finds important information gaps, baseline studies may be required to develop data on which to build the conceptual model. Conceptual models help to forecast the effects of restoration actions compared to expected changes if no action is taken.
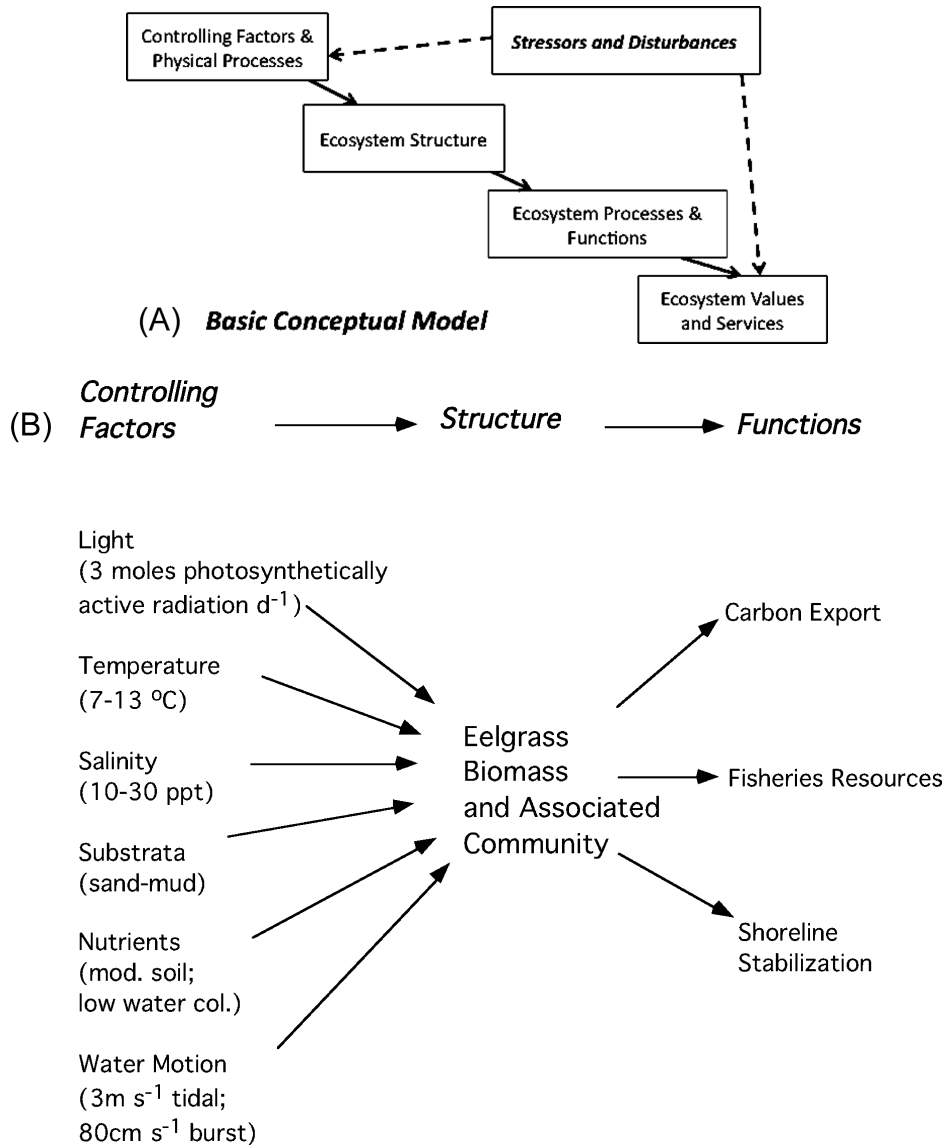
Fig. 3. (A) Structure of a conceptual model for ecosystem restoration. First, the 'problem' (i.e., stressors) must be understood, and then solutions can be developed. (B) Conceptual model of an eelgrass system (from Thom et al. (2005b)) used to quantify where stressors are affecting eelgrass survival (e.g., how shade from a dock would reduce light).

Geographic Information System (GIS) Models

At the heart of GIS-based models is the concept of space and place, the principle that knowledge of the spatial variability of factors that drive or limit species distribution, habitat quality or ecosystem services is important for making restoration decisions. It is not surprising that in coastal restoration, GIS based models and applications are generally employed during the planning phase of a project to assist with site selection. However, approaches, models and applications vary widely. Process-based GIS models, such as Malhotra & Fonseca's (2007) Wave Energy Model (WEMo), calculate quantitative physical parameters, and outputs can be used to identify zones that meet thresholds or ranges of suitable values. On the other hand, optimization routines, as within Marxan, examine different clusters

of potential conservation areas to meet targets and minimize costs (Airame et al. 2003, Ball et al. 2009).

Other models use expert knowledge and ranked quantitative assessments of environmental stressors and functions to prioritize restoration areas (Diefenderfer et al. 2009) while participatory GIS approaches, like NOAA's Habitat Priority Planner, use stakeholder criteria to visualize alternative scenarios (Bamford et al. 2009). In recent years, integration with other software has expanded visualization and analytical capabilities. The Marine Geospatial Ecology Tools (MGET, Roberts et al. 2010), links ArcGIS with the statistical software R to enable researchers to explore and predict spatial occurrences of sites and environmental conditions. The Gulf of Mexico Regional Collaborative integrates web models with conceptual model creation software (Judel et

al. 2007) in Envision, where plug-ins enable development of future land-use scenarios which feed into habitat assessment models (Hulse et al. 2008). NatureServe's Ecosystem Based Management Tools Network currently provides one of the most comprehensive interfaces to learn about and access spatially aware toolsets (www.natureserve.org).

Physical Models

Because hydrology is of critical importance to water resource projects and the science is well developed, hydrologic modeling is frequently conducted during restoration project planning, e.g.,the restoration of the Florida Everglades (Fitz et al. 1996). Numerical models can help in the planning process by facilitating sensitivity analysis of aspects of the system such as basin morphology and prediction of conditions such as hydroperiod (e.g., Burdick 2000, Yang et al. 2010). They can also be used to help select performance criteria. Numerical ecological models are much less frequently employed because the relationships among ecological parameters and the physical-chemical environment often are not well understood. In some systems, however, ecological models have provided tools to describe predicted trajectories of ecosystem development under variable conditions. Improving the understanding of the relative effects of processes operating at different scales through modeling complements field studies and helps to improve project design, implementation and adaptive management (Twilley et al. 1998)

Population Models

Population models of focal plant or animal species have several vital roles in project planning as part of an adaptive management process. First, the process of model development requires decisions about which processes are critical to explaining population and community dynamics, what form those processes take, and the value of parameters such as reproductive and survival rates. When data are not available, assumptions must be made about these mechanisms and parameters. Thus, the process of developing a numerical model serves to formalize the current state of knowledge about the system, including gap analysis, which is updated as learning occurs. Once developed, the model can predict the outcomes of management actions and support decisions. The predictions of a well-designed model will reflect the amount of uncertainty inherent in the current knowledge about the system. When uncertainty is high, it may reduce the ability of the model to distinguish between the outcomes of different actions. The sensitivity of models to uncertainty can, however, be used to determine which types of information would lead to the greatest improvements in model predictions. Thus, in addition to formalizing knowledge and assumptions and predicting the outcome of management actions, numerical models provide a mechanism for prioritizing research according to what will most improve the understanding of the system and the strength of the decision making process.

Preliminary Designs

The conceptual model, GIS model and numerical models are used to develop a preliminary series of alternative restoration designs, each of which would implement a different set of management actions with different associated costs to meet the objectives. One alternative is "no action". It is critical that landscape-level variables such as size, shape, connectivity and configuration be considered in the development of these designs (Shreffler & Thom 1993, Diefenderfer et al. 2009). Designs may be weighted for comparison, but value judgments are made as well (Harrington & Feather 1996, Thom et al. in press). By developing the designs iteratively, those that don't meet relevant ecological, engineering and economic criteria can be dismissed early in the process, while those with more merit receive detailed analysis, forecasting and comparison (Thom et al. in press).

Monitoring Program

It is best to develop the monitoring program during the planning phase, so that early discussion of project goals considers the types of information required to evaluate whether the goals are met. Evaluating the progress of a restored system through monitoring is critical to adaptive management, yet it is rare that adequate monitoring is carried out to support the decision framework. Development of the monitoring program is detailed in the section on Performance Assessment.

Performance Criteria

Performance criteria are measurable or otherwise observable aspects of the restored system that indicate the progress of the system toward meeting the goals (Thom & Wellman 1996). They are more specific than the planning objectives. Most performance criteria are either controlling factors or ecological response parameters. Acceptable bounds or limit values for the criteria are specified, and may be quantitative or qualitative. Criteria are usually developed through an iterative process to determine the most efficient and relevant set of performance measures relative to goals.

Reference Site Selection

Although comparisons of the system pre- and post-implementation are useful in documenting the effect of the project, the level of performance can best be judged relative to reference systems or using a before-after-restoration-reference method that integrates both (Diefenderfer et al. in press). Monitoring sites established in reference systems serve three primary functions: 1) they can be used as models for developing restoration actions; 2) they provide a target from which performance goals can be derived and against which progress toward these goals can be compared; and 3) they provide a control system by which environmental fluctuations unrelated to the restoration action can be assessed. Alternatively, degraded reference sites can be used to show progress of the restored system away from the degraded condition (NRC 1992).

Cost Analysis

Although researchers and federal agencies have made advances in the evaluation of alternative restoration project plans using cost effectiveness and incremental cost, while most restoration projects often lack rigorous economics analysis and documentation (Shreffler et al. 1995, Brandreth & Skaggs 2002, Thom et al. in press). Even after economic analysis, actual project costs often differ substantially from estimated costs because the costs of coastal restoration projects vary widely both within and between ecosystem types and uncertainties about the site condition and implementation (Spurgeon 1998, Noble et al. 2000). According to Gunion (1989), factors affecting final wetland restoration costs are 1) economies of scale, 2) type of restoration; 3) restoration design; 4) restoration site quality; 5) adjacent site quality; 6) appropriate technology; 7) simultaneous construction/multiple use; and 8) project management. The comparison of project costs is challenging because costs are summarized and reported by different methods, e.g., categorizing cost by acre; specific restoration task; construction stage; restoration phase (e.g., design, construction, monitoring); input (e.g., labor, equipment, materials); or funding source (Guinon 1989, US DOI 1991, NOAA 1992, Shreffler et al. 1995). The costs of every restoration project are significantly influenced by unique factors such as site access, preparation requirements, controlling factors, and weather.

Budgeting

The economic issues of importance to the systematic approach to coastal restoration are pragmatic: cost analysis, financing, and budgeting. All five components (see Fig. 1) of a restoration project are critical to success, but construction or planting activities often receive the most attention, while a complete planning process, post-restoration monitoring and the dissemination of results are frequently underfunded (NRC 2001). Contingency funds should be available in case the evaluation of monitoring data determines that additional steps are required for the ecosystem to develop as planned. Funding for annual reports during the adaptive management phase supports decision-makers and provides the basis for publishing results. The budget integrates the project schedule, including seasonal requirements, with the availability of funds on unrelated cycles such as the fiscal year.

Financing

In many cases, coastal restoration projects are creatively financed through partnerships that secure funds from multiple sources and involve community volunteer time. Funding is often difficult to secure for long-term monitoring, particularly in light of institutional barriers such as annual or biennial funding cycles, but funding for monitoring and adaptive management is critical to the success of the project.

Scheduling

The four major considerations in scheduling a project are biological, engineering, funding, and legal. Ideally, scheduling would be based on a combination of biological considerations such as germination, and engineering feasibility factors like flood regimes. Optimal timing may minimize adverse effects during construction, for instance, downstream sedimentation in the case of a dike breach for estuarine restoration. The schedule of many restoration projects is largely dictated by the availability of funding and the procurement of required permits, e.g., prohibiting in-water construction activities in certain seasons to avoid adverse impacts to fish.

Documentation

Shreffler et al. (1995) found that the best-documented restoration projects provided sufficient information for both project-specific and broader purposes. Three simple concepts were common among the best-documented projects: 1) a single file was developed that was the repository of all project information; 2) project events were recorded chronologically in a systematic manner; and 3) well-written documents such as engineering plans, legal documents and monitoring reports were produced and distributed widely enough to influence regional or national awareness. Independent reviews have found it difficult to access information and shown that the quality of documentation was inadequate to allow reliable descriptions of trends in the status of the wetland or to evaluate the success of mitigation or management strategies (Kentula et al. 1992b, Shreffler et al. 1995). A simple, systematic documentation and reporting protocol containing minimum requirements for the project would remedy the problems encountered in these reviews.

Peer Review

In large restoration projects, a team of experts should be hired to review the plan. Required expertise includes engineering, ecological, funding, management, and in some cases, numerical modeling or the biology of a target species. When agencies or large organizations are involved in the project, such expertise may be found on staff. Ideally, the project team that develops plans and selects the best alternative is itself interdisciplinary, but a review by outside experts helps to strengthen the plan and ensure success.

Construction Plans and Final Costing

Projects of any complexity generally require a formal set of construction plans and specifications for implementation by the contractor (Shreffler et al. 1995, Hammer 1996). This is especially true for projects involving manipulations of land, water, or underwater structures. Conceptual plans precede detailed plans. Often the design will be refined through several iterations, and if planned features are infeasible, they are dropped or modified. The engineering drawings of the site are a useful tool to visualize the physical structure of the project and locate features such as species plantings and monitoring stations. Specifications include details such as elevation, slope, erosion protection, substrata composition, and schedule. Design engineers must

understand critical features such as tolerances for elevation and hydrology, which, if not met, would jeopardize the development of the system with an inappropriate duration of flooding for the selected plant community. Following construction, the drawings can be compared with post-construction "as built" drawings to evaluate how closely the construction followed the design. In the course of most construction projects, adjustments must be made to deal with unknown features, such as previously-unknown cables or sources of contamination, which also may require modifications to the plans. These changes can be recorded in the field and documented on the as-built surveys. Finally, the construction plans provide the basis for determining the costs and schedule of project implementation.

Implementation: From the Vision to a Project

The implementation phase begins with any required assessments, such as an assessment of on-site contamination, though these may also be conducted in the planning phase. To avoid commonplace mistakes during construction, the operation must be monitored by someone who is aware of the project goals, often the project manager. As partners in the success of the project, engineers and contractors play a key role in ensuring that decisions during construction result in improvement of the system toward the goals, and are responsible for communicating new findings that might necessitate a revision of goals or performance criteria.

Preparation for Construction

The planner should seek advice from knowledgeable individuals in regulatory agencies regarding required permits. Although the intent of restoration projects is to have a net benefit on the ecosystem, regulators may request specific changes in the project design to minimize environmental impacts during or after construction. All details defining the site, including the elevations, slopes, substrata requirements, seeding and planting requirements, and hydrology, must be communicated to the contractor. It is particularly important to convey features of the restoration plans and specifications that may be unusual in a contractor's experience, such as the limited hydrological tolerances associated with wetlands.

Construction

Several excellent references on constructing projects are available (e.g., Galatowitsch & van deer Valk 1994, Hammer 1996). In all but the simplest projects, an engineer needs to be involved from the planning phase onward, particularly when physical alterations such as dike removal, grading, altering hydrology, or sealing of the site are required. The implementation may or may not involve the introduction of plants and/or animals into the system, but in a majority of wetland restoration projects plantings enhance the rate of development of the desired habitat. Sullivan (2001) provides a primer on the establishment of vegetation

in coastal wetlands, and Fonseca et al. (1998) provide guidelines for seagrasses. The use of transplantation methods versus natural recovery is debated for mangroves and coral reefs, and methods and species have been widely discussed (e.g. Rinkevich 1995, Field 1998, Lugo 1998, Epstein et al. 2001, Lewis & Streever 2000, Gilliam et al. 2003, Glynn et al. 2003, Quinn et al. 2003). A common cause of plant loss is grazing: for example by waterfowl in wetland projects (Calloway & Sullivan 2001), and by sea urchins in young kelp (North et al. 1986). Fencing and other techniques have been used effectively to exclude grazers during the period of initial development of plants.

Monitoring Construction

The primary goals of monitoring during construction are to ensure that the restoration plans are correctly implemented, and that the natural habitats and other properties surrounding the site are not unduly damaged. In wetland systems, for example, where a few centimeters may mean the difference in success or failure of the project, site inspections are essential for ensuring that the site is constructed to specifications (Raynie & Visser 2002). Any variations or unusual occurrences or findings should be documented as part of the overall monitoring program. Problems frequently arise during implementation of large and complex projects. During construction of the Gog-Le-Hi-Te wetland in Washington State, for example, a pipeline used for oil transport was uncovered during excavation and rerouted, and before final breaching of the river dike that would open the new system to tidal inundation, an oily material containing polychlorinated biphenyls (PCBs) was discovered near the breach site and cleanup further delayed construction. Years after construction, it was also discovered that the system was excavated to incorrect depths; although the system functioned acceptably, correct depths may have improved wetland functions (Simenstad & Thom 1996).

Immediately following construction, surveys of elevation and other relevant data should be collected to verify that the construction met the specifications for the project. These as-built surveys provide the best indicator of the starting conditions for fundamental aspects of the systems such as elevation and soil type. As-built surveys may reveal that the conceptual design produced by the restoration planners was imperfectly built.

Performance Assessment: Development of the Monitoring Program

A monitoring program does not need to be complex and expensive to be effective (Kentula et al. 1992a, Thayer et al. 2003). A well-designed, systematic program that targets key parameters tied to goals, objectives and performance criteria should be sufficient to produce concise and informative results. The NRC (1992, 2001) recommended that to assess change in a restored system over time, wetland restoration

monitoring programs should use science-based procedures and apply the following guidelines:

- link assessment criteria to the goals and objectives of the project
- assess important wetland processes and functions, or scientifically established structural surrogates
- base criteria on known conditions of the target or reference ecosystem
- establish assessment criteria before monitoring takes place, with an indication of the expected degree of similarity between restored and reference sites
- incorporate effects of position in landscape
- choose criteria that are sensitive to temporal variation and spatial heterogeneity
- compare assessment results to reference sites and long-term data sets
- generate parametric and dimensioned units, rather than non-parametric rank
- determine the monitoring period for reaching performance criteria a *priori*
- and seek peer review for assessment criteria and methods.

Approaches to Establishing Performance Criteria

Performance criteria describe the expected structure and function of the system. Reference to the conceptual model identifies the linkages among critical physical, chemical, biological, and sociological aspects of the system and can be used to determine appropriate performance criteria (e.g., Ogden et al. 2005). Monitoring parameters are measured to assess the system's structure and function relative to the performance criteria. Erwin (1990) stated that criteria for performance must be established prior to the evaluation effort and must be "fundamental to the existence, functions, and contributions of the wetland system and its surrounding landscape". A special issue of *Ecological Engineering* was devoted to "Goal Setting and Success Criteria for Coastal Habitat Restoration" (Hackney 2000) and provides proven techniques and examples of performance criteria establishment and application.

A target time frame for meeting functional performance criteria should be a prescribed criterion. True functional equivalency with a reference system may take decades or longer (Zedler & Callaway 1999). For example, a program begun in 1980 to restore tidal action to marshes off Long Island Sound in Connecticut and evaluated 20 years later by comparing restoration and reference sites found highly variable rates of recovery within and among marshes and that recovery of animal populations took up to two decades or more (Brawley et al. 1998, Swamy et al. 2002, Warren et al. 2002). Therefore, to make time-frame criteria more meaningful, performance criteria should be stated in terms of trends as well as target ranges.

Trends can indicate whether the system is on its way to meeting restoration goals and the rate at which this is occurring. Identification of trends is a powerful tool in assess-

ing the need for midcourse corrections. The trends analysis can be plotted as performance curves (Kentula et al. 1992a); shapes of these curves are often referred to as trajectories of development (Simenstad & Thom 1996). The development of sites with characteristics such as high levels of environmental pulsing may not smoothly follow predicted trajectories (Zedler & Callaway 1999, Diefenderfer et al. in press), and many restoration sites have been shown to follow nonlinear trajectories, eventually reaching reference conditions (Morgan & Short 2002). The duration of expected performance once goals are met should also be stated in the planning phase (Zedler 2000).

Performance criteria are distinctive to a region and a system and as such, specific parameters have been developed for restoration programs such as the southern California coastal wetlands (PERL 1990), estuarine habitats in the Pacific Northwest (Simenstad et al. 1991, Roegner et al. 2009), Louisiana coastal marshes (Steyer & Stewart 1992), the Everglades (Ogden et al. 2003, RECOVER 2007), Florida salt marshes and mangroves (Redmond 2000), and seagrass systems (Fonseca et al. 1998). In addition to regional or system-specific performance criteria, various efforts to assess or index ecological systems may also provide valuable references for restoration efforts. Examples include the EPA Environmental Monitoring and Assessment Program (EMAP) (Hunsaker & Carpenter 1990) and the EPA biological criteria for water quality assessments (EPA 1991a, 1991b).

Identifying Reference Sites

Appropriate reference sites are often as critical to a restoration monitoring program as they are difficult to find. This is particularly true in urban settings and rural areas with high levels of resource extraction, where restoration actions are most frequent. The inclusion of several reference sites in the monitoring program provides information about the natural range of values for the parameters used in the monitoring program, and shows the annual variation in these parameters. Boesch et al. (1994) demonstrated that it is often difficult or impossible to find appropriate reference sites, especially for large-scale restoration projects in landscapes as complex as coastal Louisiana, and recommended a two-tiered approach in which a limited number of restoration sites are monitored intensively as a representative "class". Horner & Radaeke (1989) identified the following features that should be assessed for degree of similarity between the reference site and the potential conditions at the mitigation site:

- functional similarity
- climatological and hydrological similarity
- similarity in influences of human access, habitation, and economic activities, and in the quantity and quality of water runoff from these activities to the wetland
- similarity in the history of and potential for such activities as grazing, mowing, and burning
- similarity in size, morphology, water depth, wetland

zones and their proportions, and general vegetation types
- similarity in soils and nonsoil substrates
- and similarity in access by fish and wildlife.

A coast-wide reference monitoring system being implemented to evaluate wetland restoration trajectories in Louisiana addresses the problem of identifying paired reference and restoration areas by providing an array of reference sites, which will be used to evaluate project effectiveness as well as the cumulative effects of multiple restoration projects (Steyer et al. 2003).

Selection of Monitoring Parameters

A scientifically-based and relatively easily measured set of monitoring parameters is selected to provide direct feedback on the performance of a system with respect to the goals. The NRC (1992) recommended that for aquatic systems, at least three parameters be selected representing physical, hydrological, and ecological features; too few parameters may provide insufficient information to evaluate performance or information that is difficult to interpret. The most specific guidance in the USA on the selection of restored wetland monitoring parameters comes from NOAA (Thayer et al. 2005) the NRC (1992, 2001), and EPA (Kusler & Kentula 1990, Kentula et al. 1992a). The NRC developed a list of seven wetland functions that should be considered in assessing equivalency between natural and constructed wetland systems based upon experiences in coastal salt marshes. Kentula et al. (1992a) presented a list of 26 wetland system variables with justification for selection, suggested uses, and general procedures. The variables are divided into categories of general information, morphometry, hydrology, substrate, vegetation, fauna, water quality, and additional information. Structural attributes are measurable features that comprise a tidal marsh, including vegetation cover and composition, hydrology, water quality, marsh plain elevation, slope, channel network, channel shape, and substrate composition (Thayer et al. 2005). Batiuk et al. (2000) have analyzed monitoring data to refine the habitat requirements for submerged aquatic vegetation (SAV) on the Chesapeake Bay. This effort provided an improved approach for testing the suitability of shallow water sites for SAV restoration. It incorporates an indicator that had previously not been addressed, the availability of light at the leaf surface, by developing an algorithm integrating the previous water quality habitat requirements: dissolved inorganic nitrogen, dissolved inorganic phosphorus, water-column light attenuation coefficient, chlorophyll a and total suspended solids.

Monitoring Methods

Monitoring methods include sampling design, sampling methods, and sample handling and processing. Monitoring methods used on restoration projects in the United States have been extremely varied (Shreffler et al. 1995). Calloway et al. (2001) provide excellent guidance on monitoring methods. Three basic questions to ask when selecting methods for monitoring are: 1) does the method efficiently pro-vide accurate data on physical and biological parameters; 2) is the method repeatable; and 3) is the method feasible within time and cost constraints? Any method used for sampling a parameter should have a documented protocol. It is highly desirable to choose sampling methods that provide for collection of data on more than one parameter. For example, a sediment core sample can provide information on rhizome development, hydrology, and invertebrate communities. Ongoing monitoring programs provide useful data, e.g., state hunting and fishing reports, U.S. Geological Survey hydrological data and topographic maps, Audubon Society bird counts, NRCS soils maps, U.S. Weather Service data, and air quality data. Many agencies and volunteer groups want to see their data used and are willing to cooperate with restoration programs, but a systematic and equitable method of data transfer should be planned. Methods have been developed to rank the performance of habitats for certain functions, using scores of system features to arrive at a numeric value for each function, e.g., the Habitat Evaluation Procedure (HEP) (USFWS 1980), the Wetland Evaluation Technique (WET) (Adamus 1983), and the Hydrogeomorphic (HGM) Approach (Brinson 1993, Shafer & Yozzo 1998).

Timing, Frequency, and Duration

Timing, frequency, and duration are dependent on system type, complexity, and uncertainty. The monitoring program should be carried out according to a schedule including the program start and end date, the time of the year during which field studies take place, and the frequency of field studies. Controversy over a project can force a higher degree of scrutiny and may necessarily increase the level of monitoring effort.

Timing. The monitoring program should be designed prior to conducting baseline studies so that the pre- and post-construction sampling and analysis methods are the same. Baseline studies complete the initial database and are important to understanding existing conditions, planning restoration, and analyzing the effects of restoration activities. Post-construction implementation, compliance, and performance monitoring should commence as soon as the major restorative actions have taken place and the system is left to develop more or less on its own. Post-construction data are compared with baseline data to assess the effect of the construction. Seasonality is often a concern, and data from the ecoregion can help, e.g., migratory bird and fish populations can be economically studied during seasons of greatest abundance; water temperatures at peak or minimum levels; and wetland hydrology during the growing season. Because weather varies from year to year, it is wise to "bracket" the season, e.g., sampling temperature four times during the midsummer. The monitoring protocols for tidal wetland restoration in the Gulf of Maine call for monitoring up to three spring and three neap tides to track the pattern of water level change (Neckles et al. 2002).

Frequency. Frequency of sampling can vary within a

year as well as among years. In general, "new" systems change rapidly and should be monitored more often than older systems. As the system becomes established, it is generally less vulnerable to disturbances. Hence, monitoring can be less frequent. Frequent monitoring in the early stages also is necessary to understand major processes that can affect the system. A simple visit to a new site after a major storm event may be useful in documenting the exact cause of loss or malfunction in the system seen the next summer. Often the most efficient documentation in these cases is photographs, videotapes, and field notes.

Duration. The monitoring program should extend long enough to provide reasonable assurance that the system has met its performance criteria, will meet them, or will not likely meet them. A growing body of evidence on constructed systems shows that most aquatic systems do not reach stability in less than 5 years (e.g., Simenstad & Thom 1996, Kentula 2000). Ecosystems of the size of most restoration projects take decades or centuries to develop (Frenkel & Morlan 1990, Boumans et al. 2002, Crooks et al. 2002, Thom et al. 2002). Hence, we cannot expect restored systems to be stable in a year. The period of development is dependent on the initial conditions and the type of habitat being restored. If the system is what Cairns (1989) terms a "new ecosystem" (i.e., a system constructed that is new for the site, also called "creation"), development may take a long time because hydrologic processes and vegetation must be established. In contrast, systems that are minor adjustments of existing aquatic habitats will require less time.

Statistical Framework

The monitoring study design needs to include statistical considerations such as sample location and number of replicates. These decisions should be made based on an understanding of the accuracy and precision required for the data as identified in the protocol. Many scientists view restoration projects fundamentally as experiments that can be set up to test hypotheses. Performance goals and criteria could be considered informal statements of testable hypotheses (Diefenderfer et al. in press). The NRC (1992) recommended that at least some part of the restoration action incorporate experiments that will evaluate aspects of restoration actions. The result of these experiments can improve the technology of restoring ecosystems. In contrast, the goal of a restoration action is generally to improve the system function. Although accurate quantification of some functions of aquatic systems is possible, overall ecosystem "performance" is much more complex and difficult to evaluate. A rigorous experimental design that evaluates one or more null hypotheses is appropriate on a limited basis for most restoration efforts, but less rigorous analyses are more appropriate for supplying evidence for the development of the ecosystem. Yoccuz (1991) argued that ecological studies often use statistical "overkill", when simple bar graphs with error bars are sufficient to interpret trends. The analy-

sis of the results should be driven by an understanding of the ecosystem rather than by statistics. Although rigorous statistical testing documents statistical significance at an a priori level of confidence, this type of study requires intensive sampling, and many of the assumptions of true replication and appropriate controls are not easily met (Hurlbert 1984, Boesch et al. 1994). An example of a study in which useful results were attained without a rigorous experimental design is the examination by Short et al. (1995) of the effectiveness of reducing the number of eelgrass shoots during restoration planting.

Adaptive Management AM and the Dissemination of Results

The monitoring program is used as a tool to assess project success and identify any problems that might affect progression toward the project goals. Broadly speaking, the options available to the manager are no action, maintenance of the system, and modification of the project goals. If the monitoring program identifies deviation from the predicted trajectory of ecosystem development, adjustments can and should be made. Adaptive management of this kind has been recommended at a national level and is in use on major restoration projects (Williams et al. 2007). To ensure success, restored systems often require midcourse corrections and management. The NRC (1992) states that rather than relying on a fixed goal for restoration and an inflexible plan to achieve the goal, adaptive management recognizes the imperfect knowledge of interdependencies within and among natural and social systems. This uncertainty requires that plans be modified as technical knowledge improves and social preferences change.

Clear goals and objectives are the foundation of the AM process (e.g., Thom 1997, 2000, Thom et al. 2005a). Monitoring parameters used to assess progress relative to performance criteria dictate how the data will be collected for each metric (e.g., aerial or satellite imagery, census counts) and whether an objective is being met (e.g., area of habitat, population size). The performance criterion is the desired value of the metric (e.g., number of acres, number of adults in a population). The performance criteria become the focus of the monitoring effort. Monitoring assesses system status and provides calibration and validation to support the process of refining models, conceptual and numerical, to predict the consequences of actions for program objectives.

The assessment step consists of deciding whether the metrics are on target or are on track to meet the target and whether the objectives and actions are appropriate. The assessment informs decisions about which set of actions to take, where the efforts will be targeted and how they will be accomplished. The assessment and decision steps are reviewed on an annual basis and the objectives are reviewed when necessary. It is this iterative decision-making process whereby managers plan, implement, monitor, assess, make decisions, and change where necessary to continually im-

prove predictions about which management actions will best support the ecosystem (Fig. 4). Specifics on development of adaptive management for Corps of Engineers restoration projects are provided in Yozzo et al. (1996), which recommends annual assessments of system progress, at which time decisions regarding midcourse corrections or goal modifications are made.

Using a system development matrix to characterize outcomes (Thom 1997) can help organize the performance criteria for target resources (Fig. 5), and frame adaptive management for a restoration project. The matrix acknowledges that structure and function are correlated, and that by dividing each axis into three sections one can quantify this relationship only within wide ranges of variation. Establishing high, moderate and low categories acknowledges the uncertainties about the system and system development predictions. Each of the system states is described by an explanation of why the system may be in that state. Considerations in regard to disseminating the results of a coastal restoration project include the purpose, audience, timing, and appropriate venues. The coastal restoration and scientific communities learn by sharing information and methods im-

proved on that basis. Coastal restoration projects also affect the interests of various stakeholders who need to understand the outcomes. Good reporting is also critical to informed long-term adaptive management of the project itself. It is strongly recommended that the results of the monitoring program be published in a peer-reviewed journal, and that the restoration project be presented at technical meetings and workshops where the project manager can discuss problematic aspects with colleagues. The sharing of fundamental information is integral to developing the technology of coastal ecosystem restoration. Although large, complex, and controversial projects are always of interest, small, well-conceived and well-implemented projects can also be worthy of publication. Publication is often reserved for completed projects, but for projects with longer monitoring programs, a report summarizing early results may be appropriate. Preliminary results and project descriptions are often welcome at conferences and workshops. The results of the monitoring program can be of great use to others in the field. Once a project has been presented to a professional audience, the members look forward to periodic updates on its progress. Professional societies that feature aquatic habitat restoration in meetings include the American Fisheries Society, Estuarine Research Federation, Ecological Society of America, Society for Ecological Restoration International, Society of Wetland Scientists, and American Society of Civil Engineers.
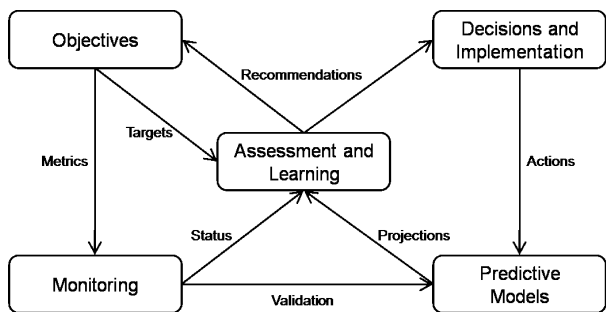
Conclusion: Keys to Successful Restoration

The five key components of a complete and successful restoration project covered in this paper are planning, implementation, performance assessment, adaptive management, and the dissemination of results (Fig. 1). In the past, implementation has typically received the most investment. However, the examples discussed here and in a National Review of Innovative and Successful Coastal Habitat Restoration (Borde et al. 2003), show that the other four components are now being integrated in programs throughout the country. The monitoring program is central to project success as a tool to assess project performance and identify problems affecting progression toward project goals, in an adaptive management framework.

Features of the iterative planning process applicable in a variety of coastal habitats were synthesized from restoration project experience and the literature (Fig. 2). The planning process starts with a vision, a description of the ecosystem and landscape, and goals. A conceptual model and planning objectives are developed, a site is selected, and numerical models contribute to preliminary designs as needed. Performance criteria and reference sites are selected and the monitoring program is designed. Cost analysis involves economic analysis, budgeting, scheduling, and financing. Finally, documentation is peer reviewed prior to making construction plans and final analysis.

Restoration may require a multitude of strategies devel-

Fig. 4. The linked components of an applied adaptive management program for ecosystem restoration.
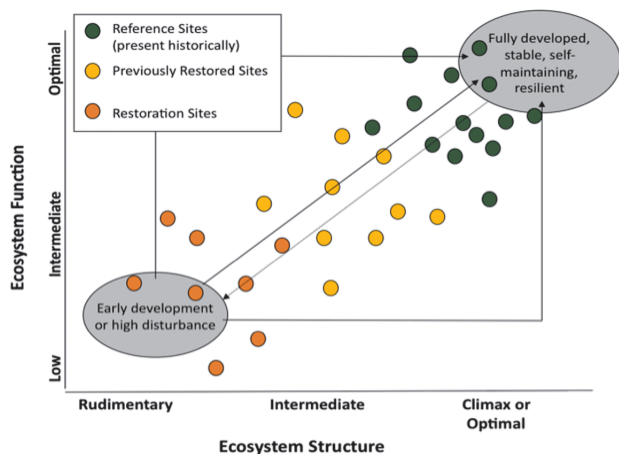

Fig. 5. System development matrix. This type of matrix can be useful in tracking the progress of a project toward its goal, as well as determining the basic actions associated with each of the system 'states'.

oped from several scientific and technical disciplines. For example, restoring seagrasses or mangroves may help enhance a fish population. Full restoration of the population, however, may require protection of the adjacent coral reef upon which the fish also depend (e.g., Nagelkerken et al. 2002). This example demonstrates the synthesis of at least three distinct scientific disciplines: restoration ecology, landscape ecology, and fisheries biology. Other highly specialized disciplines that can serve to influence and assist in restoration and restoration monitoring include plant and animal community ecology, reproductive biology, biodiversity ecology, population genetics, soils science, hydrology, ecotoxicology, island biogeography, disturbance ecology, geospatial analysis, remote sensing, and ecological modeling. The challenge for the restoration planner is the effective synthesis of relevant information from multiple disciplines and application to the practical problem of project design. To accomplish this task, the planner should first seek help from knowledgeable experts; second, think of restoration from the landscape to the site scale; third, keep the goals of the project paramount; and fourth, during and following implementation, evaluate the results against the theoretical basis by using monitoring to determine whether the design is working as predicted. When a project does not develop according to the theoretical basis, improvements may be made to the design, the monitoring program, or the theory. Regardless, the discovery of information can be used to improve project success through adaptive management and to strengthen the science of restoration ecology.

New Guidance in the United States

Over its relatively short history, the United States has suffered a dramatic loss of coastal ecosystems and the benefits they provide; regulations have, at best, slowed the rate of loss. More than half of the coastal wetlands in the contiguous U.S. have been lost in the past 200 years—wetlands that help protect water quality, buffer storm surge and flooding, and provide habitat for a wide variety of species. Since 1990, the Pacific coast of the U.S.A. has lost an estimated 60 percent of its natural, non-armored shorelines (NOAA 2010). To recover from such losses, it is important to restore impaired ecological systems and functions while preserving those that remain (Interagency Workgroup on Wetland Restoration 2003).

Proposed new guidance from the President's Council on Environmental Quality (CEQ) for conducting water resources development studies illustrates the increasing national priority of protecting and restoring ecosystems (CEQ 2010). The proposal states that "federal water resources planning and development should both protect and restore the environment and improve the economic well-being of the nation for present and future generations", placing the economic well-being of the nation and environmental protection and restoration on equal footing. This would apply to all federal studies of site-specific projects and project modifications that include "significant structures or landform changes". Currently under review by the National Academy of Sciences, the CEQ proposal explicitly calls for consideration of non-monetary benefits in water resource management, e.g., those ecological services and functions associated with improved habitat for fish and wildlife or biodiversity. If approved, the updated "Principles and Guidelines for Water and Land Related Resources Implementation Studies" will significantly change the process for water resource planning that has been in place for more than 25 years.

References

Adamus PR (1983) A method for wetland functional assessment. Volume II. The method. No. GHWA-IP-82-24. U.S. Department of Transportation, Federal Highway Administration, Office of Research, Environmental Division, Washington, DC.

Airame, S, JE Dugan, KD Lafferty, H Leslie, DA McArdle, RR Warner (2003) Applying ecological criteria to marine reserve design: A case study from the California Channel Islands. Ecol Appl 13 Supplement: S170–S184.

Ball IR, Possingham HP, Watts M (2009) Chapter 14 Marxan and relatives: Software for spatial conservation prioritization. In: Spatial Conservation Prioritization: Quantitative methods and computational tools (eds Moilanen A, Wilson KA, Possingham HP), Oxford University Press, Oxford, pp. 185–195.

Bamford D Y Ye, McGuinn R, Stroh C, Beard S, Burkhalter S, Hadley B, Love R (2009) Habitat Priority Planner, Version 2: Help Document. NOAA CSC, 101 pp. (http://csc.noaa.gov/digitalcoast/tools/hpp/files/HPP_Help_Version%202.0.pdf)

Batiuk RA, Bergstrom P, Kemp M, Koch E, Murray L, Stevenson JC, Bartleson R, Carter V, Rybicki NB, Landwehr JM, Gallegos C, Karrh L, Naylor M, Wilcox D, Moore KA, Ailstock S, Teichberg M (2000) Chesapeake Bay submerged aquatic vegetation water quality and habitat-based requirements and restoration targets: a second technical synthesis. Chesapeake Bay Program, Annapolis, Maryland.

Batiuk RA, Orth RJ, Moore KA, Dennison WC, Stevenson JC, Staver LW, Carter V, Rybicki NB, Hickman RE, Kollar S, Bieber S, Heasley P (1992) Chesapeake Bay submerged aquatic vegetation habitat requirements and restoration targets: a tech-

nical synthesis. Chesapeake Bay Program, Annapolis, Maryland.

Boesch DF (2006) Scientific requirements for ecosystem-based management in the restoration of Chesapeake Bay and Coastal Louisiana. Ecol Eng 26: 6–26.

Boesch DF, Josselyn MN, Mehta AJ, Morris JT, Nuttle CA, Simenstad CA, Swift DJP (1994) Scientific Assessment of Coastal Wetland Loss, Restoration and Management in Louisiana. J Coast Res Special Issue 20: 103 pp.

Borde AB, O'Rourke LK, Thom RM, Williams GW, Diefenderfer HL (2003) National Review of Innovative and Successful Coastal Habitat Restoration. Prepared for National Oceanic and Atmospheric Administration Coastal Services Center, Charleston, South Carolina. (http://www.csc.noaa.gov/coastal/)

Brandreth B, Skaggs LL (2002) Lessons learned from cost effectiveness and incremental cost analysis. Report 02-R-5. U.S. Army Corps of Engineers, Institute for Water Resources, Alexandria, Virginia.

Brawley AH, Warren RS, Askins RA (1998) "Bird Use of Restoration and Reference Marshes Within the Barn Island Wildlife Management Area, Stonington, Connecticut, USA. Environ Manage 22: 625–633.

Brinson MM (1993) A hydrogeomorphic classification for wetlands. Wetlands Research Program Technical Report WRP-DE-4. U.S. Army Corps of Engineers, Waterways Experimental Station, Vicksburg, Mississippi.

Burdick DM (2000) Ecosystem indicator: hydrology. In: Regional standards to identify and evaluate tidal wetland restoration in the Gulf of Maine (eds Neckles HA, Dionne E). Wells National Estuarine Research Reserve Technical Report, Wells, ME, pp. 7–9.

Cairns J Jr. (1989) Restoring Damaged Ecosystems: Is Predisturbance Condition a Viable Option? Environ Prof 11: 152.

Cairns J Jr. (ed) (1988) Rehabilitating Damaged Ecosystems. Lewis Publishers, Boca Raton, Florida, 425 pp.

Calloway JC, Sullivan G (2001) Sustaining restored wetlands: identifying and solving management problems. In: Handbook for Restoring Tidal Wetlands (ed Zedler JB), CRC Press, Boca Raton, Florida, pp. 337–362.

Calloway JC, Sullivan G, Desmond JS, Williams GD, Zedler JB (2001) Assessment and Monitoring. In: Handbook for Restoring Tidal Wetlands (ed Zedler JB). CRC Press, Boca Raton, Florida, pp. 271–335.

CEQ (U.S. Council on Environmental Quality). (2010) Updated Principles and Guidelines for Water and Land Related Resources Implementatiuon Studies. April 19, 2010. (http//www.whitehouse.gove/administration/eop/ceq/initiatives/PandG)

Clewell A, Rieger J, Munro J (2000) Guidelines for Developing and Managing Ecological Restoration Projects. A Society for Ecological Restoration Publication, June 24, 2000. (http://www.ser.org/reading)

Diefenderfer HL, Sobocinski KL, Thom RM, May CW, Borde AB, Southard SL, Vavrinec J, Sather NK (2009) Multiscale analysis of restoration priorities for marine shoreline planning. Environ Manage 44: 712–731.

Diefenderfer HL, Thom RM, Adkins JE (2003) Systematic approach to coastal ecosystem restoration. Prepared for National Oceanic and Atmospheric Administration, Coastal Services Center. Battelle, Pacific Northwest Division, PNWD-3237. (http://www.csc.noaa.gov/coastal/)

Diefenderfer HL, Thom RM, Hofseth K (2005) A framework for risk analysis in environmental investments: The U.S. Army Corps of Engineers restoration project planning process. In: Economics and ecological risk assessment: applications to watershed management (eds Bruins R, Heberling M). CRC Press, Boca Raton, Florida, pp. 57–105.

Diefenderfer HL, Thom RM, Johnson GE, Skalski JR, Vogt KA, Ebberts BD, Roegner GC, Dawley EM (in press) A levels-of-evidence approach for assessing cumulative ecosystem response to estuary and river restoration programs. Ecol Restoration 29.

EPA (1991a) Biological criteria: research and regulation. Proceedings of a Symposium. EPA-440/5-91-005, U.S. Environmental Protection Agency, Office of Water, Washington, DC.

EPA (1991b) Biological criteria: guide to technical literature. EPA-440/5-91-004, U.S. Environmental Protection Agency, Office of Water, Washington, DC.

Epstein N, Bak RPM, Rinkevich B (2001) Strategies for Gardening Denuded Coral Reef Areas: The Applicability of Using Different Types of Coral Material for Reef Restoration. Restoration Ecol 9: 432–442.

Erwin KL (1990) Wetland evaluation for wetland creation and restoration. In: Wetland creation and restoration: the status of the science (eds Kusler JA, Kentula ME). Island Press, Washington, DC, pp. 420–458.

Field CD (1998) Rehabilitation of Mangrove Ecosystems: an Overview. Mar Pollut Bull 37: 383.

Fitz HC, DeBellevue EB, Costanza R, Boumans R, Maxwell T, Wainger L, Sklar FH (1996) Development of a general ecosystem model for a range of scales and ecosystems. Ecol Modell 88: 263–295.

Fonseca MS, Kenworthy WJ, Thayer GW (1998) Guidelines for the conservation and restoration of seagrasses in the United States and adjacent waters. National Oceanic and Atmospheric Administration, Coastal Ocean Office, Silver Spring, Maryland.

Foote-Smith C (2002) Watershed wetlands restoration planning: The Massachusetts Experience. In: Watershed-based Wetland Planning and Evaluation (compiler Tiner RW), A Collection of Papers from the Wetland Millennium Event (August 6–12, 2000; Quebec City, Quebec, Canada), Distributed by the Association of State Wetland Managers, Inc., Berne, NY.

Frenkel RE, Morlan JC (1990) Restoration of the Salmon River salt marshes: retrospective and prospect. Final Report to U.S. Environmental Protection Agency, Region 10, Seattle. Oregon State University, Corvallis.

Fresh K, Brennan J, Dethier M, Gelfenbaum G, Goetz F, Logsdon M, Meyers D, Mumford T, Newton J, Shipman H, Simenstad C, Tanner C (2003) Guidance for Protection and Restoration of the Nearshore Ecosystems of Puget Sound. Draft report prepared in support of the Puget Sound Nearshore Ecosystem Restoration Program (PSNERP). (http://www.pugetsoundnearshore.org/science.htm)

Galatowitsch SM, van der Valk AG (1994) Restoring prairie wetlands. Iowa State University Press, Ames, Iowa, 344 pp.

Gersib RA (2002) The Need for Process-driven, Watershed-based Wetland Restoration: The Washington State Experience. In: Watershed-based Wetland Planning and Evaluation (compiler

Tiner RW), A Collection of Papers from the Wetland Millennium Event (August 6–12, 2000; Quebec City, Quebec, Canada), Distributed by the Association of State Wetland Managers, Inc., Berne, NY.

Gilliam DS, Dodge RE, Thornton SL, Glynn EA, Jaap W, Wheaton J (2003) Scleractinian coral reattachment success and recruitment on a shallow-water ship grounding site in southeastern Florida, USA. National Coral Reef Institute, Nova Southeastern University Oceanographic Center, Dania Beach, FL.

Glynn EA, Quinn TP, Fahy DP, Dodge RE, Gilliam DS, Spieler RE (2003) Growth and survivorship of stony coral Meandrina meandrites and Montastrea cavernosa transplants to an artificial reef environment: A work in progress. National Coral Reef Institute, Nova Southeastern University Oceanographic Center, Dania Beach, FL.

Guinon M (1989) Project elements determining comprehensive restoration costs and repercussions of hidden and inaccurate costs. Paper Presented to Society for Ecological Restoration and Management Annual Meeting, Oakland, California.

Hackney CT (2000) Restoration of coastal habitats: expectation and reality. Ecol Eng 15: 165–170.

Hammer DA (1996) Creating freshwater wetlands. Second Edition. Lewis Publishers, Boca Raton, Florida, 480 pp.

Harrington KW, Feather TD (1996) Evaluation of Environmental Investments Procedures: Interim Overview Manual. IWR Report 96-R-18, June 1996. U.S. Army Corps of Engineers Institute for Water Resources, Alexandria, Virginia.

Horner RR, Raedeke KJ (1989) Guide for wetland mitigation project monitoring. Report No. WA-RD 195.1. Washington State Department of Transportation, Olympia, Washington.

Hulse D, Branscomb A, Enright C, Bolte J (2008) Anticipating floodplain trajectories: a comparison of two alternative futures approaches. Landscape Ecol. DOI:10.1007/s10980-008-9255-2

Hunsaker CT, Carpenter DE (1990) Environmental monitoring and assessment program: ecological indicators. EPA/600/3-90/060, U.S. Environmental Protection Agency, Washington, DC.

Hurlbert SH (1984) Pseudoreplication and the Design of Ecological Field Experiments. Ecol Monogr 54: 187–211.

Interagency Workgroup on Wetland Restoration (U.S.) (2003) An Introduction and User's Guide to Wetland Restoration, Creation, and Enhancement. Washington, DC.

Johnson GE, Thom RM, Whiting AH, Sutherland GB, Berquam T, Ebberts BD, Ricci NM, Southard JA, Wilcox JD (2003) An ecosystem-based approach to habitat restoration projects with emphasis on salmonids in the Columbia River estuary. Final report prepared by the Bonneville Power Administration, Columbia River Estuary Study Taskforce, Lower Columbia River Estuary Partnership, Pacific Northwest National Laboratory and U.S. Army Corps of Engineers, Portland District, Portland, OR. Pacific Northwest National Laboratory, Richland, Washington. PNNL-14412.

Josselyn MN, Buchholz JW (1984) Marsh Restoration in San Francisco Bay: A Guide to Design and Planning. Technical Report #3 Tiburon Center for Environmental Studies, San Francisco State University, San Francisco, California.

Judd C, Woodruff DL, Thom RM, Anderson MG, Borde AB

(2007) Restoration Prioritization Toolset: Documentation and User's Guide ⟨http://www.pnl.gov/main/publications/external/technical reports/PNNL-17054.pdf⟩. PNNL-17054, Pacific Northwest National Laboratory, Sequim, WA. pp. 32. (http://www.gomrc.org/documents/UserGuide Restgoration Toolbox vs Oct2007.pdf)

Kentula ME (2000) Perspectives on setting success criteria for wetland restoration. Ecol Eng 15: 199–209.

Kentula ME, Brooks RP, Gwin S, Holland C, Sherman AD, Sifneos J (1992a) An approach to improving decision making in wetland restoration and creation. U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, Oregon.

Kentula ME, Sifneos JC, Good JW, Rylko M, Kunz K (1992b) Trends and Patterns in Section 404 Permitting Requiring Compensatory Mitigation in Oregon and Washington, USA. Environ Manage 16: 109–119.

Kusler JA, Kentula ME (1990) Wetland creation and restoration, the status of the science, Island Press, Washington, DC, 616 pp.

Lewis RR, Clark PA, Fehring WK, Greening HS, Johansson RO, Paul RT (1999) The rehabilitation of the Tampa Bay estuary, Florida, USA, as an example of successful integrated coastal management. Mar Pollut Bull 37: 468–473.

Lewis RR, Streever B (2000) Restoration of Mangrove Habitat. ERDC TN-WRP-VN-RS-3.2., U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.

Louisiana Coastal Wetlands Conservation and Restoration Task Force (2001) The 2000 evaluation report to the U.S. Congress on the effectiveness of Louisiana coastal wetland restoration projects. Baton Rouge, LA: Louisiana Department of Natural Resources.

Lugo AE (1998) Mangrove forests: A tough system to invade but an easy one to rehabilitate. Mar Pollut Bull 37: 427–430.

Malhotra A, Fonseca M (2007) WEMo (Wave Exposure Model): Formulation, Procedures and Validation. Beaufort, NC. NOAA/National Ocean Service/National Centers for Coastal Ocean Science, NOAA Technical Memorandum NOS-NCCOS, pp. 65.

Minkin P (2003) Studying Success of Federally-Required Wetland Mitigation in New England. In: Proceedings, Meeting of the Society of Wetland Scientists, June 8–13, 2003, New Orleans, LA.

Morgan PA, Short FT (2002) Using Functional Trajectories to Track Constructed Salt Marsh Development in the Great Bay Estuary, Maine/New Hampshire, U.S.A. Restoration Ecol 10: 461–473.

Nagelkerken I, Roberts CM, van der Velde G, Dorenbosch M, van Riel MC, Cocheret de la Morinière E, Niehuis PH (2002) How Important are Mangroves and Seagrass Beds for Coral-Reef Fish? The Nursery Hypothesis Tested on an Island Scale. Mar Ecol Prog Ser 244: 299–305.

National Oceanic and Atmospheric Administration (NOAA) (1992) Restoration guidance document for natural resource injury as a result of oil spills. National Oceanic and Atmospheric Administration, Washington, DC.

National Oceanic and Atmospheric Administration (NOAA) (2010) Coastal and Marine Habitat Loss. NOAA Restoration Portal. National Oceanic and Atmospheric Administration. Ac-

cessed 19 Apr 2010. (http://habitat.noaa.gov/restorationtechniques/public/about_loss.cfm)

National Research Council (NRC) (1990) Managing troubled waters: the role of marine environmental monitoring. National Academy Press, Washington, DC, 125 pp.

National Research Council (NRC) (1992) Restoration of aquatic ecosystems. National Academy Press, Washington, DC, 552 pp.

National Research Council (NRC) (2001) Compensating for wetland losses under the Clean Water Act. National Academy Press, Washington, DC, 322 pp.

Neckles, HA, M Dionne, DM Burdick, CT Roman, R Buchsbaum, and E Hutchins (2002) A monitoring protocol to assess tidal restoration of salt marshes on local and regional scales. Restoration Ecol 10: 556–563.

Noble BD, Thom RM, Green TH, Borde AB (2000) Analyzing uncertainty in the costs of ecosystem restoration. (Institute of Water Resources, U.S. Army Corps of Engineers), Alexandria, Virginia.

North WJ, Jackson GA, Manley SL (1986) Macrocystis and its environment, knowns and unknowns. Aquat Bot 26: 9–26.

Ogden JC, Davis SM, Brandt LA (2003) Science strategy for a regional ecosystem monitoring and assessment program: The Florida Everglades example. In: Monitoring Ecosystems (eds Busch DE, Trexler JC). Island Press, Washington, DC, pp. 135–163.

Ogden JC, Davis SM, Jacobs KJ, Barnes T, Fling HE (2005) The use of conceptual ecological models to guide ecosystem restoration in South Florida. Wetlands 25: 795–809.

PERL (Pacific Estuarine Research Laboratory) (1990) A Manual for assessing restored and natural coastal wetlands with examples from Southern California. California Sea Grant Report No. T-CSGCP-021. La Jolla, California.

Quinn TP, Glynn EA, Dodge RE, Banks K, Fisher L, Spieler RE (2003) Hypothesis-based restoration study for mitigation of a damaged southeastern Florida coral reef: A work in progress. National Coral Reef Institute, Nova Southeastern University Oceanographic Center, Dania Beach, FL.

RAE and NOAA (2002) A national strategy to restore coastal and estuarine habitat. Restore America's Estuaries, Arlington, Virginia and NOAA, Washington DC.

RAE-ERF (1999) Principles of estuarine habitat restoration: Working together to restore America's estuaries—Report on the RAE-ERF partnership year one. Restore America's Estuaries, Arlington, Virginia and the Estuarine Research Federation, Port Republic, Maryland. (http://www.estuaries.org/)

Raynie RC, Visser JM (2002) CWPPRA Adaptive Management Review Final Report. Prepared for the CWPPRA Planning and Evaluation Subcommittee, Technical Committee, and Task Force, Louisiana, December 20, 2002 revision.

RECOVER (Restoration Coordination & Verification Team) (2007) Development and Application of Comprehensive Everglades Restoration Plan System-wide Performance Measures. (http://www.evergladesplan.org/pm/recover/perf_systemwide.aspx)

Redmond AM (2000) Dredge and Fill Regulatory Constraints in Meeting the Ecological Goals of Restoration Projects. Ecol Eng 15: 181–189.

Rinkevich B (1995) Restoration Strategies for Coral Reefs Damaged by Recreational Activities: The Use of Sexual and Asexual Recruits. Restoration Ecol 3: 241–251.

Roberts, JJ, Best BD, Dunn DC, Treml EA, Halpin PN (2010) Marine Geospatial Ecology Tools: An integrated framework for ecological geoprocessing with ArcGIS, Python, R, MATLAB, and C++. Environ Model Softw 25: 1197–1207.

Roegner GC, Diefenderfer HL, Borde AB, Thom RM, Dawley EM, Whiting AH, Zimmerman SA, Johnson GE (2009) Protocols for monitoring habitat restoration projects in the lower Columbia River and estuary. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-97.

Sea Grant Oregon (2002) National Coastal Ecosystem Restoration Manual. ORESU-H-02-002, NOAA Office of Sea Grant and Extramural Programs, and Oregon State University Extension Service, Corvallis, OR.

Shafer DJ, Yozzo DJ (1998) National Guidebook for Application of Hydrogeomorphic Assessment to Tidal Fringe Wetlands. Wetlands Research Program Technical Report WRP-DE-16, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

Short FT, Davis R, Burdick DM, McHugh D, Bosworth WS (1995) Creation of eelgrass, saltmarsh and mudflat habitats in the Piscataqua River, New Hampshire. Abstracts from the Estuarine Research Federation, 13th Biennial International Conference. National Oceanic and Atmospheric Administration, Washington, DC.

Shreffler DK, Thom RM (1993) Restoration of urban estuaries; new approaches for site location and design. Prepared for Washington Department of Natural Resources, Olympia, Washington.

Shreffler DK, Thom RM, Scott MJ, Wellman KF, Walters MA, Curran M (1995) National review of non-Corps environmental restoration projects. IWR Report 95-R-12. U.S. Army Corps of Engineers and Waterways Experimental Station, Vicksburg, Mississippi.

Simenstad CA, Hood WG, Thom RM, Levy DA, Bottom DL (2000) Landscape structure and scale constraints on restoring estuarine wetlands for Pacific coast juvenile salmon. In: Concepts and controversies in tidal marsh ecology (eds Weinstein MP, Creeger DA). Kluwer Academic Publications. Dordrecht, pp. 597–630.

Simenstad CA, Tanner CD, Thom RM, Conquest L (1991) Estuarine Habitat Assessment Protocol. UW-FRI-8918/-8919. Fisheries Research Institute, University of Washington, Seattle, Washington.

Simenstad CA, Thom RM (1996) Functional Equivalency Trajectories of the Restored Gog-Le-Hi-Te Estuarine Wetland. Ecol Appl 6: 38–56.

Spurgeon J (1998) The Socio-Economic Costs and Benefits of Coastal Habitat Rehabilitation and Creation. Mar Pollut Bull 37: 373–382.

Steyer GD, Sasser CE, Visser JM, Swenson EM, Nyman JA, Raynie RC (2003) A Proposed Coast-Wide Reference Monitoring System for Evaluating Wetland Restoration Trajectories in Louisiana. Environ Monit Assess 81: 107–117.

Steyer GD, Stewart RE (1992) Monitoring program for coastal wetlands planning, protection, and restoration act projects. Open File Report 93-01. U.S. Fish and Wildlife Service, National Wetlands Research Center, Washington, DC.

Sullivan G (2001) Establishing Vegetation in Restored and Created Coastal Wetlands. In: Handbook for Restoring Tidal Wetlands (ed Zedler JB). Boca Raton, Florida, pp. 119–155.

Swamy V, Fell PE, Body M, Keaney MB, Nyaku MK, McIlvain EC, Keen AL (2002) Macroinvertebrate and Fish Populations in a Restored Impounded Salt Marsh 21 Years After the Reestablishment of Tidal Flooding. Environ Manage 29: 516–530.

Thayer GW, McTigue TA, Bellmer RJ, Burrows FM, Merkey DH, Nickens AD, Lozano SJ, Gayaldo PF, Polmateer PJ, Pinit PT (2003) Science-Based Restoration Monitoring of Coastal Habitats. Volume 1: A Framework for Monitoring Plans Under the Estuaries and Clean Waters Act of 2000 (Public Law 160-457). NOAA Coastal Ocean Program, Silver Spring, Maryland. (http://coastalscience.noaa.gov/ecosystems/estuaries/restoration_monitoring.html

Thayer GW, McTigue TA, Salz RJ, Merkey DH, Burrows FM, Gayaldo PF (2005) Science-Based Restoration Monitoring of Coastal Habitats. Volume 2: Tools for Monitoring Coastal Habitats. Decision Analysis Series. NOAA Coastal Ocean Program. Silver Spring, Maryland. (http://coastalscience.noaa.gov/ecosystems/estuaries/restoration_monitoring.html)

Thom RM (1997) System-development matrix for adaptive management of coastal ecosystem restoration projects. Ecol Eng 8: 219–232.

Thom RM (2000) Adaptive management of coastal ecosystem restoration projects. Ecol Eng 15: 365–372.

Thom RM, Haas E, Evans NR, Williams GD (in press) Lower Columbia River and estuary habitat restoration prioritization framework. Ecol Restoration 29.

Thom RM, Wellman KF (1996) Planning aquatic ecosystem restoration monitoring programs. 96-R-23, U.S. Army Corps of Engineers Institute for Water Resources and Waterways Experiment Station, Vicksburg, Mississippi.

Thom RM, Williamns G, Borde A, Southard J, Sargeant S, Woodruff D, Laufle JC, Glasoe S (2005a) Adaptively addressing uncertainty in estuarine and near coastal restoration projects. J Coast Res 40: 94–108.

Thom RM, Williams GD, Diefenderfer HL (2005b) Balancing the need to develop coastal areas with the desire for an ecologically functioning coastal environment; is net ecosystem improvement possible? Restoration Ecol 13: 193–203.

Thom RM, Zeigler R, Borde AB (2002) Floristic development patterns in a restored Elk River estuarine marsh, Grays Harbor, Washington. Restoration Ecol 10: 487–496.

Thrush SF, Dayton PK (2010) What can ecology contribute to ecosystem-based management? Annual Review of Mar Sci 2: 419–441.

Twilley RR, Rivera-Monroy VH, Chen RH, Botero L (1998) Adapting an Ecological Mangrove Model to Simulate Trajectories in Restoration Ecology. Mar Pollut Bull 37: 404–419.

University of Rhode Island (2003) Rhode Island Habitat Restoration Portal. (http://www.edc.uri.edu/restoration/)

USACE (U.S. Army Corps of Engineers) (2000) Engineer Regulation 1105-2-100, Planning Guidance Notebook, 22 April 2000. U.S. Army Corps of Engineers, Washington, DC.

US DOI (U.S. Department of Interior) (1991) Estimating the environmental costs of OCS oil and gas development and marine oil spills: A general purpose model. Report prepared by Kearney AT, Inc. for U.S. Department of Interior, Minerals Management Service, Washington, DC.

USFWS (U.S. Fish and Wildlife Service) (1980) Habitat evaluation procedures. ESM 102. U.S. Department of the Interior, Fish and Wildlife Service, Division of Ecological Services, Washington, DC.

Warren RS, Fell PE, Rozsa R, Brawley AH, Orsted AC, Olson ET, Swamy V, Niering WA (2002) Salt Marsh Restoration in Connecticut: 20 Years of Science and Management. Restoration Ecol 10: 497–513.

Water Resources Council (WRC) (1983) Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies. US Government Printing Office, Washington, DC.

Williams BK, Szaro RC, Shapiro CD (2007) Adaptive management: the U.S. Department of the Interior technical guide. Adaptive Management Working Group, U.S. Department of the Interior, Washington, DC.

Yang Z, Sobocinski KL, Heatwole D, Khangaonkar T, Thom R, Fuller R (2010) Hydrodynamic and ecological assessment of nearshore restoration: a modeling study. Ecol Model 221: 1043–1053.

Yoccuz NG (1991) Commentary: Use, Overuse, and Misuse of Significance Tests in Evolutionary Biology and Ecology. Bull Ecol Soc Am 72: 106–111.

Yozzo D, Titre J, Sexton J (1996) Planning and evaluating restoration of aquatic habitats from an ecological perspective. IWR Report 96-EL-4. Prepared for the U.S. Army Corps of Engineers, Institute for Water Resources and Waterways Experiment Station, Alexandria, Virginia.

Zedler JB (ed) (2001) Handbook for restoring tidal wetlands. CRC Press, Boca Raton, Florida, 439 pp.

Zedler JB, Callaway JC (1999) Tracking Wetland Restoration: Do Mitigation Sites Follow Desired Trajectories? Restoration Ecol 7: 69–73.

Zedler JB, Callaway JC (2000) Evaluating the Progress of Engineered Tidal Wetlands. Ecol Eng 15: 211–225.