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RESEARCH

Facilitating Adaptive Management in California's Sacramento–San Joaquin Delta[1]

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ABSTRACT

Uncertainties in understanding ecosystems increase the risk that management will fail to achieve desired results. Adaptive management is a structured, iterative application of science-based knowledge to reduce uncertainties and build flexibility into decision-making. However, adaptive management is more easily planned than implemented, and it is only beginning to be applied in the California's Sacramento–San Joaquin Delta. We draw from two assessments of adaptive management in the Delta and examples of its use elsewhere to suggest how the process can be facilitated. Although a highly structured adaptive-management process may not always be needed, several elements are essential. Adaptive management should begin by clearly identifying the problem, goals, and objectives; recognizing uncertainties; identifying decision points and alternative approaches; recognizing when adjustments are needed and having the flexibility to make them; and considering societal and political constraints. Model complexity should be matched to that of the system and management needs; experiments can help unravel causal relationships. Monitoring, analyses, and syntheses require comprehensive data-management systems. More frequent and organized communications among scientists, managers, stakeholders, and decision-makers are necessary. We propose the establishment of an "Adaptive Management Team" to coordinate efforts across the management spectrum of the Delta and to provide guidance and link individual projects to shared approaches and experiences. Reliable long-term support will be needed to assess results of management actions, adjust approaches where improvement is likely, and strive toward the legislated goals of enhancing the Delta ecosystem while also providing reliable water supplies to much of California, and doing both these things in a manner that protects values of the Delta as a place where people live and work.

1. This paper was written by JW, JZ, VR, TC, and SB. All authors contributed to the Delta Independent Science Board report from which this paper is based.

KEY WORDS

Adaptive management, ecosystem management, experimentation, Delta Plan, monitoring, restoration, Sacramento-San Joaquin Delta, uncertainty.

INTRODUCTION

Adaptive management is widely considered to be an effective and agile way to improve management of complex systems that have inherent uncertainties. Such systems often defy simple management solutions (Churchman 1967; Rittel and Webber 1973). The iterative and progressive process of adaptive management is often seen as a way to test and evaluate the effectiveness of management decisions, gain new knowledge about the system, and refine management actions. When well designed and implemented, adaptive management provides a roadmap to avoid dead-end or unproductive actions that aren't achieving project goals and assists in dealing with the uncertainty of complex and changing systems (Holling 2001). Ideally, adaptive management incorporates an experimental approach to confirm factors that caused a system to respond (or not respond) to management actions.

Adaptive management is embodied in the guidelines and directives of several federal agencies (e.g., the U.S. Department of Interior, Williams et al. 2007; Williams and Brown 2012; U.S. Army Corps of Engineers, Fischenich et al. 2012; USFS 2013). Furthermore, an adaptive-management approach is included in plans to restore several large-scale, complex ecosystems, including the Everglades (LoSchiavo et al. 2013; NRC 2016), Glen Canyon (NRC 2004; Melis et al. 2015), Kissimmee River (Spencer and Bousquin 2014), and sites included in the National Estuary Program (Imperial 1993) and the National Estuarine Research Reserves (*https://coast.noaa.gov/nerrs/*).

Adaptive management is also central to management of the Sacramento-San Joaquin Delta (hereafter, "the Delta"). The Sacramento-San Joaquin Delta Reform Act of 2009 (SBX7 1) stipulates that the Delta Plan prepared by the Delta Stewardship Council must include "a science-based, transparent, and formal adaptive management strategy for ongoing ecosystem restoration and water management decisions" [California Water Code section 85308(f)]. Given this requirement and the charge to the Delta Independent Science Board (hereafter "Delta ISB" or "we") to "provide oversight of the scientific research, monitoring, and assessment programs that support adaptive management of the Delta" [Water Code section 85280(a)(3)], we reviewed how adaptive management is currently being used in the Delta and how it might be improved. Our review was based on questionnaires and interviews with personnel involved in a broad range of research and management activities in the Delta and built on a previous review of adaptive management conducted by the Bay Delta Conservation Plan Independent Science Advisors on Adaptive Management (DiGennaro 2009). Details of the Delta ISB review, including methods and recommendations, are contained in our report (Delta ISB 2016) and are not repeated here.

Here we draw from those reviews and other studies to highlight several important features of adaptive management, consider why implementation has proven difficult in the Delta, use examples to illustrate how some elements of the process have been addressed in other ecosystems, and offer suggestions for making adaptive management more effective and efficient in the Sacramento-San Joaquin Delta and elsewhere.

WHAT IS ADAPTIVE MANAGEMENT?

There is considerable ambiguity about what adaptive management is and what it entails. The term is used effortlessly by politicians, administrators, managers and scientists, often with different meanings in mind. To some, adaptive management is the ability to change directions and try something else when an initial action does not achieve the desired outcomes. This is simply managing adaptively, an extreme version of which is managing by trial and error. Others perceive adaptive management as a complex and rigid process involving many steps that may demand substantial resources and time and potentially distract or delay management efforts. Scientists may view adaptive management as a way to conduct research on ecosystems, while managers might regard the process as a way to obtain

information that enables them to take action when outcomes differ from expectations (Melis et al. 2015).

In the Delta Reform Act, adaptive management is defined as "a framework and flexible decision-making process for ongoing knowledge acquisition, monitoring, and evaluation leading to continuous improvements in management planning and implementation of a project to achieve specified objectives" (Water Code section 85052). Following the Delta ISB report (2016), we define adaptive management as "*a structured approach to management and decision-making that accumulates and incorporates knowledge to reduce uncertainty*."

This definition of adaptive management emphasizes three essential elements: it is a *structured* process, it *accumulates and incorporates knowledge*, and it *reduces uncertainty*. To understand what makes adaptive management distinctive and difficult to do, it is useful to consider these themes in more detail. Comprehensive treatments of the process and practice of adaptive management are provided by Holling (1978), Walters (1986), Williams et al. (2007), Williams and Brown (2012, 2014), and Zedler (2017).

To begin with structure, adaptive management is an iterative, systematic, decision-making process that involves well-defined steps, usually depicted as a circle that feeds back on itself. There are dozens of such diagrams; for consistency, we use the one included in the Delta Plan (DSC 2013; Figure 1). The process begins by clearly defining the problem to be addressed (Step 1) and then engaging stakeholders to help managers develop goals and objectives and identify social, political, and economical constraints (Step 2). To achieve site- or project-specific goals, scientific understanding of the system and models are used to help managers develop proposed management actions and predict the outcomes of various alternative actions (Step 3). Pilot studies and additional research may be used to help decide among alternatives (Step 4). Implementing management actions as designed experiments (incorporating controls and replication) can help to demonstrate whether an action is really having the desired effects and to disentangle causes from confounding factors (Step 5). Responses to actions are then monitored to assess progress (Step 6).

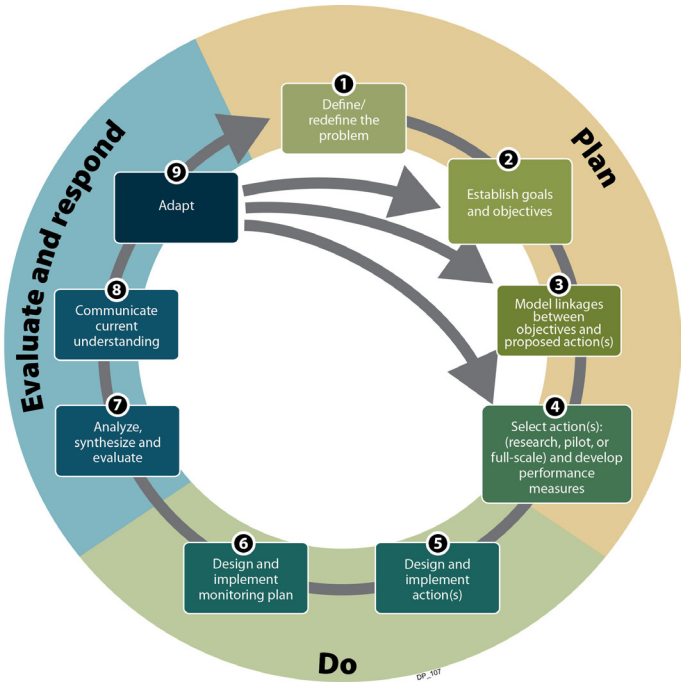

Figure 1 A nine-step framework for adaptive management. Boxes represent process steps and the circular arrow represents the general sequence of steps. Additional arrows show possible next steps to address the problem or revise the selected action based on what has been learned. From the Delta Plan (Delta Stewardship Council 2013).

Step 7 is the point at which knowledge is accumulated, incorporated, and used to help evaluate responses to management actions. Is the system responding as intended? Do the initial assumptions still hold? Have there been surprises or unexpected events (e.g., droughts, invasive species, earthquakes) that require a rethinking of initial expectations? This information can then be synthesized and shared with practitioners, stakeholders, and decision-makers (Step 8). By evaluating the findings to assess whether the actions are performing as expected, decisions can then be made to continue the actions, make modifications, undertake additional modeling, revisit the initial goals and objectives, or reconsider the problem being addressed (Step 9). Often a trigger point is established to specify when such a decision is warranted. This is the "adapt" part of adaptive management.

The third element of the definition of adaptive management is uncertainty. Uncertainty is the bane

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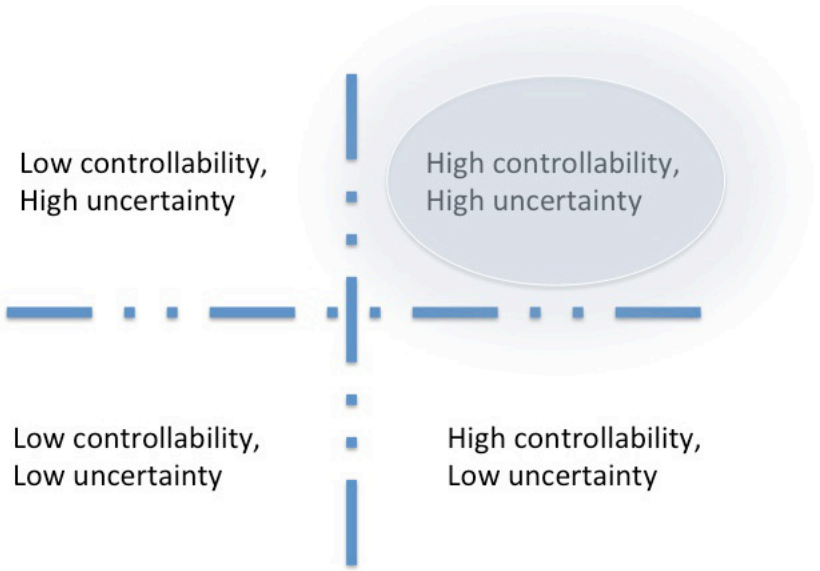

Figure 2 Relations between system controllability (the influence management actions can have on the system) and uncertainty in the outcomes of the actions. Adaptive management is most useful when controllability and uncertainty are both high (shaded area in upper right); in other situations, other approaches (e.g., scenario planning, deterministic optimal control) may be more appropriate. Sources: Peterson et al. (2003) and Williams et al. (2007).

of managers—if uncertainty is extreme, it becomes impossible to predict an outcome of a management decision and formal adaptive management could not be used. For adaptive management, the science must be 'good enough' to take the risk and 'good enough' to make reasonable predictions of outcomes and to realize when decision points have been reached.

"Uncertainty" has multiple meanings. There is uncertainty in information—a lack of knowledge of basic facts, understanding of cause-effect relationships, and how a system will respond to management actions. There is also uncertainty in how information is communicated, due to vagueness, ambiguity, or different perceptions of what words mean.[2] Adaptive management deals with both types of uncertainty. It aims to reduce uncertainty in information and understanding by designing actions with predicted outcomes while recognizing that outcomes may be wrong; applying science to reduce sources of error; addressing environmental variation; and using rigorous analytical tools (Steps 3-7 in Figure 1). Uncertainty in communication can be reduced by using clear, concise language to frame the management problem and objectives and by scientists and researchers communicating their findings in readily understandable terms to those who must act upon the information (Steps 1-2 and 8-9).

The level of uncertainty is an important determinant of whether and when adaptive management is the best approach to a management problem. Adaptive management is most useful when a manager can control how management actions may influence a system (controllability) but there is considerable uncertainty about the outcomes of those actions (Peterson et al. 2003; Williams et al. 2007; Figure 2). For example, when dam operators release water from a dam, downstream flow rates are controlled but effects on fish spawning downstream are uncertain because a multiplicity of other factors also comes into play. In other situations (e.g., when system controllability is high and the impacts are predictable, or when it is difficult to control how an action may influence a system; Figure 2), adaptive management may be unnecessary or other approaches may be better. Thus, although the Delta Reform Act mandates the use of adaptive management in the Delta, it may not always be appropriate. We will return to this issue later.

2 Regan et al. (2002) call the former "epistemic" uncertainty and the latter "linguistic" uncertainty.

Adaptive management is a science-based process, but management decisions are not made on the basis of science alone. Monitoring and scientific research provide information to evaluate the consequences of management options, but multiple constraints and priorities that fall outside the adaptive management process also influence decisions (Gregory et al. 2006; Lund and Moyle 2013; Williams and Brown 2014). These may be legal (e.g., regulatory restrictions, permitting for proposed actions), social and/or political (e.g., stakeholder resistance, political agendas), psychological (e.g., a reluctance of managers to take risks in the face of uncertainty), organizational (e.g., conflicting agency responsibilities, lack of collaboration, delays in processing what is learned), and/or financial (i.e., funding). These realities also must be considered when determining whether adaptive management is an appropriate course of action to take.

ADAPTIVE MANAGEMENT IN THE DELTA

Comprehensive adaptive management is challenging and demanding. How has it been done for the Sacramento-San Joaquin Delta? To address this question, we solicited input from practitioners and managers in the Delta (Delta ISB 2016).

Respondents generally agreed that the use of adaptive management in the Delta requires a high degree of collaboration; that conceptual models should include both sociopolitical and ecological factors; and that the results must be communicated to Delta stakeholders. However, there was less agreement about whether baseline information about the Delta is sufficient; whether conceptual models are usually built before actions are taken; the degree to which monitoring and assessment results are used in decision-making; and whether adaptive management actually leads to changes in management. There was even less agreement about whether particular agencies did or did not use adaptive management; whether management was flexible enough to do adaptive management; and whether laws and regulations restricted management options or could be changed to make adaptive management more successful. The overall results (Table 1) clearly indicate that implementing comprehensive adaptive management in the Delta is far from routine.

Table 1 A comparison of features of adaptive management among a broad range of management projects in the Delta (as reported by Delta ISB 2016) and among eight tidal-marsh restoration plans in the Delta and San Francisco Bay (as tabulated by Nagarkar and Raulund–Rasmussen 2016).

Adaptive management element	Delta ISB (2016)	Nagarkar and Raulund–Rasmussen (2016) *(No. of instances / 8 projects)*
Goals and objectives defined	Always	8/8
Uncertainties considered	Inconsistent	5/8
Formal hypotheses generated	Infrequent	4/8
Conceptual models used	Usual	5/8
Quantitative models used	Infrequent	8/8
Alternative actions included in plan	Infrequent	3/8
Future changes (e.g. climate change) considered	Infrequent	Not considered by the authors
Trigger points for decisions identified	Infrequent	3/8
Performance measured specified	Inconsistent	7/8
Scientific research, experiments, or pilot studies included	Uncommon	2/8
Monitoring designed and implemented	Usual, but not maintained	6/8
Data managed, analyzed, and synthesized	Inconsistent	2/8
Systematic communication of results	Inconsistent	5/8
Adaptive management influences decisions	Sometimes	Not considered by the authors
Collaboration among multiple parties	Usual but limited	Not considered by the authors

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A concurrent study reached similar conclusions after analyzing planning documents for eight tidal-marsh restoration projects in the Delta and San Francisco Bay and interviewing associated practitioners (Nagarkar and Raulund-Rasmussen 2016). Participants in both studies acknowledged the importance of adaptive management, and most referenced it in their project plans (Table 1). However, neither study revealed much support for scientific research or experiments as part of the process, perhaps because they were perceived as time consuming and detracting from management objectives.

Modeling is one way to explore potential outcomes and identify risks of management decisions and to identify key factors to monitor project effectiveness. Opinions of Delta practitioners about modeling also differed. All eight marsh-restoration cases reviewed by Nagarkar and Raulund-Rasmussen (2016) incorporated quantitative models, although fewer explicitly included conceptual models (even though conceptual models are often the foundation for quantitative models). In contrast, many managers and practitioners surveyed by the Delta ISB considered quantitative models too demanding and expensive for many projects, although conceptual models were common.

Most of the marsh-restoration projects included performance measures to gauge outcomes. However, few projects included alternative actions (i.e., a "Plan B" if expectations were not being met) or trigger points that might prompt reconsideration of current actions. Effects of future changes in the ecosystem (such as climate change, sea level rise, or shifting societal, political, or economic priorities) or surprises (e.g., new invasive species, drought, floods), were rarely mentioned by participants in the Delta ISB survey and were not addressed by Nagarkar and Raulund-Rasmussen (2016).

Although the power of adaptive management lies in recognizing uncertainties and using science to reduce them, there were few indications that hypotheses or studies were designed to address uncertainties. Participants generally began with a clear statement of the problem and goals, and most projects included planning, some form of modeling, implementing actions, and monitoring to track progress (i.e., Steps 1-6 in Figure 1; Table 1). The process of adaptive management began to break down when the data needed to be managed, analyzed, and synthesized (Step 7). Without this, adaptive management is incomplete and critical information needed to inform management decisions is not available. Nonetheless, most practitioners recognized that communicating the results of the process to managers, decision-makers, and stakeholders (Step 8) is essential, although most did not have a systematic plan for doing so.

So why is adaptive management so infrequently implemented as a complete, organized process in the Delta, despite the widely acknowledged mandate that Delta projects follow adaptive management? There is little doubt that implementing adaptive management is difficult in this ecosystem because of its large size and complexity, highly altered physical and biological systems, the presence of endangered species, numerous stakeholders, multiple agencies with different responsibilities and mandates, increasing (and often conflicting) demands for water, and growing impacts of climate change and invasive species (Healey et al. 2016). Still, participants in the Delta ISB (2016) review did not consider complexity to be the greatest single impediment to undertaking adaptive management in the Delta; rather, they attributed difficulties to the lack of reliable, long-term funding. Similarly, costs and delays resulting from environmental reviews, permitting, and re-permitting if changes were needed once permitted actions were underway were most often mentioned as difficulties by the restoration practitioners surveyed by Nagarkar and Raulund-Rasmussen (2016). While funds might be available for planning, monitoring, analyses, and even experiments, it becomes increasingly difficult to obtain support for changes and follow-up or long-term monitoring as a project nears completion.

The availability of adequate funding is a challenge that lies outside the adaptive management framework (Figure 1), but it is not the only challenge (Rist et al. 2013). Other examples are the lack of a clear, quick process for coordinating among multiple agencies with different priorities and cultures; the lack of organized, two-way communication between scientists and managers; and a failure to use formal decision-support tools. There is also a perception that adaptive management is ponderously slow. Regulations, gaining public support for restoration,

obtaining land, and permitting can all cause delays, but so do generating and testing hypotheses, using quantitative models, establishing long-term monitoring, and conducting data analyses, all of which are central to adaptive management. Such delays can frustrate managers, who want to complete a project and move on (what one practitioner termed "the curse of the immediate").

LESSONS FROM OTHER ECOSYSTEMS

Difficulties in implementing comprehensive adaptive management, following all the steps of Figure 1 (or an equivalent structure), are not unique to the Delta. Westgate et al. (2013), for example, reviewed 1,336 papers dealing with adaptive management of biological systems; fewer than 5% explicitly claimed to do adaptive management, and of these less than a dozen actually met strict criteria for the process. Adaptive management is something that is more often talked about than actually done, at least as the structured, systematic, science-based process we have described.

Here we use several examples to illustrate the variety, nuances, and difficulties of applying adaptive management in complex ecosystems, relatng the approaches to steps in the adaptive management framework (Figure 1). We note additional examples in the Appendix (Zedler 2017). None of these examples embodies the complete process of adaptive management, and in some cases the practitioners realized that they were trying to do adaptive management only after the project was well along. Nonetheless, the examples provide insights into some elements of the process and, in particular, how the need for flexibility to change directions is prompted by the results of scientific research. In these examples, progress was made because changes could be made in management actions, plans, or overall goals.

An example using Steps 2→3→4→8: Establish goals, model, select, communicate. The construction of Glen Canyon Dam in 1963 altered the downstream hydrology and ecology of the Colorado River and sandbar formation in the Grand Canyon. An adaptive management program related to dam operations was established in 1997 to restore sandbar habitat in the Grand Canyon and protect endangered fish (especially the Humpback Chub, *Gila cypha*; Melis et al. 2015). Collaborative modeling identified experimental water releases from the dam that would simulate natural-flow (flood) events. Managers hypothesized that occasional high flows would release accumulated sediments and create stable sandbars downstream. However, the initial high-flow release did not cause sediment to accumulate; instead of creating sandbars, subsequent high-flow releases rapidly eroded them. Monitoring data led to the decision to release water over shorter periods of high flows, which allowed sediments to accumulate, followed by low flows to reduce sandbar erosion and control water temperature for fish. New research has addressed cause-effect relationships (Kennedy et al. 2016; Poff and Schmidt 2016), leading to continual adjustment of management actions. Communication was facilitated by involving stakeholders and multiple agencies from the outset.

An example using Steps 6→7→8. Design and implement monitoring; analyze results; communicate new understanding. In San Diego Bay's Sweetwater Marsh, monitoring coupled with field experiments identified flaws in a plan to compensate impacts of freeway widening on an endangered bird's nesting habitat (Light-footed Ridgway's Rail, *Rallus obsoletus levipes*). A mitigation mandate had required that cordgrass (*Spartina foliosa*) be monitored to assess nesting habitat for rails, and a specific criterion (that tall plants be self-sustaining) was evaluated for seven 1-ha home ranges along channels built in sandy dredge-spoil deposits. Researchers monitored the vegetation and alerted mitigators and regulators that cordgrass planted in sandy substrates was stunted relative to that in natural populations. A short-term experiment was authorized to test the hypothesis that nitrogen limited growth height in sandy substrates. The experiment supported the hypothesis, but it was still uncertain if the sandy substrate would supply adequate nitrogen given more time. The Adaptive Management Team authorized a long-term experiment, which also showed that sandy dredge spoils could not provide rail nesting habitat even after 5 years of nitrogen addition (Lindig–Cisneros et al. 2003). The U.S. Fish and Wildlife Service concluded that the site was unlikely to compensate for lost habitat and required an alternative mitigation plan. The scientific prediction has withstood the test

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of time; cordgrass still appeared to be stunted even after 20 years (J. Zedler, personal observation, June 2016).

An example using Steps 7→8→9→1: Synthesize results, communicate, adapt, reset goals iteratively. Tampa Bay, Florida, is a large (1036 km^2) estuary with a diverse flora and fauna that supported extensive recreation and fisheries activities in the 1950s. By the 1970s, however, turbid water impaired swimming and fishing and diminished seagrass (*Halodule wrightii*) beds (Greening et al. 2014). When scientific studies confirmed that nitrogen was causing the algal blooms, regulations were developed to control point-source inputs from wastewater and electrical power generating plants. Still, water quality remained impaired. Monitoring data helped regulators and citizen representatives set new targets and numerical standards for clean water, even expanding regulations to reduce use of lawn fertilizers by a rapidly growing urban population (Greening et al. 2014). Tampa Bay eventually achieved clear water.

An example of Steps 7→8→9→1. Evaluate, communicate, adapt, reset goals iteratively. Like Tampa Bay, Danish shallow coastal waters became eutrophic, causing turbid water and loss of eelgrass (*Zostera marina*). In Denmark, however, the persistent source of nutrients was from agriculture and the threatened fishery was lobster (*Homarus gammarus*). The approach for restoring water quality of coastal waters began in 1985 with an action plan to cut both nitrogen and phosphorus runoff from agricultural fields. The 1987 aims were specific—to cut N runoff by 50% and P runoff by 80%. By establishing and monitoring 180 stream-sampling stations, researchers separated point loads (wastewater and industry) from loads originating in agricultural fields. Point sources of P were reduced by improving wastewater treatment, but coastal waters were still eutrophic. Subsequent action plans increasingly restricted nutrient inputs, as in the European Union's call for major cuts in N and P by 2015. Reducing nutrient inputs from the land lowered concentrations in coastal waters and sediments, and monitoring of 14 ecosystem response variables confirmed that coastal ecosystems were recovering (Kronvang et al. 2008; Reimann et al. 2016).

An example of Steps 9→4→5. Adapt, select action, scale up, implement. At Tijuana Estuary in southern California, experimental plantings at a small restoration site in 1997 showed which and how many salt-marsh species would self-recruit and which would require planting in later restoration sites. Eight native species, alone and in random combinations, simultaneously vegetated the bare site and showed that three species could self-recruit adequately (Lindig–Cisneros and Zedler 2002). Consequently, the other five species were planted in a larger, 8-ha site excavated in 2000 to test effects of creating tidal creeks (Larkin et al. 2008). Monitoring was streamlined over time by eliminating measures of productivity and nitrogen accumulation after it became clear that species-rich plantings increased ecosystem services only in the short term (Callaway et al. 2003). After a decade, perennial pickleweed (*Salicornia pacifica*) had excluded most of its neighbors, and less costly measures (cover, canopy height) were adequate to show how ecosystem services were shifting (Doherty et al. 2011).

An example of Step 9. Adapt goals when outcomes are unexpected. In Chile's Tierra del Fuego, the Rio Condor Project (a 272,000-ha land purchase) was intended to integrate sustainable forestry with conservation and ecotourism (Lindenmayer and Franklin 2002). Adaptive management was planned, and monitoring and research began in 1999. Then, a shortfall in funding led Goldman Sachs to purchase loans and donate the land to the Wildlife Conservation Society—an adaptive shift omitting forestry objectives and revising conservation goals to include carbon-sequestration, ecotourism, and endangered species protection (e.g., the guanaco, *Lama guanicoe*, an iconic animal of Patagonia).

The above examples (and those in Appendix A) illustrate how social, economic, and political realities can constrain or guide the adaptive-management process; tradeoffs may be necessary. In the Glen Canyon Dam case, tradeoffs were anticipated, and decision-makers considered how experimental releases would affect hydroelectric generation from the dam, recreational uses of the river, and legal water-transfer obligations. In some other cases tradeoffs might emerge after a project is underway. For example, the funding shortfall for the Rio Condor project led to a complete change in objectives and

redesign of the project. The results of targeted monitoring and evaluation may indicate a need to evaluate modifications or change course. All of these examples emphasize the importance of flexibility in adaptive management.

MAKING ADAPTIVE MANAGEMENT MORE EFFECTIVE AND EFFICIENT IN THE DELTA

Several issues underscore the need for a clear, organized approach to project planning and implementation in the Delta, including the myriad challenges and management issues facing this complex and highly modified system (Luoma et al. 2015); the need for collaborative efforts in science, management, and policy (Cloern and Hanak 2013; Meyer 2013); and the legislative mandates of the Delta Reform Act and the Delta Plan. By using science to improve management, adaptive management can reduce critical uncertainties (and thereby risks) that challenge restoration and other land- and water-management activities in the Delta. We see several ways to smooth the path to more comprehensive adaptive management in the Delta.

Support adaptive management. Including science in Delta adaptive management requires flexibility. Money, personnel, facilities, and time are usually insufficient, and adaptive management will falter unless these resources are available when a new approach is called for (Delta ISB 2016). Management agencies must recognize the importance of adaptive management and be willing to assign staff to the necessary planning, synthesis, and communication. Doing this may require a resetting of priorities for staff time rather than additional funding (although that helps). There also should be sufficient funding for monitoring of actions and outcomes and to support the science needed to refine models and test key assumptions. Innovative funding might include a line-item allocation of a fixed proportion (e.g., 10%) in project budgets to support adaptive management, above and beyond the funds required for monitoring. The possibility of establishing an endowment to support adaptive management (as well as other long-term needs of stewardship of Delta resources) should be explored.

The implementation of adaptive management also needs to be efficient. The process itself should be continually honed. For example, multiple factors could be monitored initially, retaining only those that are most useful. Another possibility is hierarchical sampling, applying less expensive and demanding measurements widely and more resource-intensive measurements on a limited basis in a hypothesis-testing framework. This can reduce costs and provide an opportunity to test for relationships between measurements. Or an array of sampling stations could be monitored and then refined to a (randomized) subset, or all stations could be sampled less frequently. The aim should be to focus monitoring on obtaining the most critical information needed to make informed decisions with defined thresholds or trigger points. Potential constraints also need to be considered during initial project planning. Budgetary, legal, political, social, and other forces may dictate what is feasible. To minimize disruptions once adaptive management is underway, the management options being considered should first be vetted among stakeholders, practitioners, and the concerned public, even before research and monitoring begin. In the end, generating reliable long-term stakeholder and financial support for adaptive management and developing ways to organize and guide it will help to make the approach more consistently and widely used in the Delta.

Create a team to guide adaptive management in the Delta. Adaptive management and the science that is its foundation are currently fragmented among agencies and disciplines, thwarting effective use of the process (Lund and Moyle 2013). Moreover, management actions in one sector (e.g., water use, diversions) have outcomes that cut across other sectors (e.g., land use, fish). Holistic and integrated approaches are needed to face both current and future challenges. We suggest that a dedicated body—a Delta-wide "Adaptive Management Team"—could provide leadership to this end. The Team would be expected to foster collaboration among agencies, accelerate the adaptive-management process, help practitioners incorporate adaptive management into project plans, invite stakeholders to participate, integrate projects within landscapes and ecosystems, and provide guidance in implementing our recommendations. Similar suggestions have been made before (Zedler and Callaway 2003; Lund and Moyle 2013). Creating such a team will require

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addressing issues about authority and independence and dispelling a perception (expressed by some of those interviewed by the Delta ISB) that this would be just another bureaucratic hurdle to be overcome.

Include alternatives, decision points, and identified uncertainties in project plans. In the planning phase, incorporate decision points and timelines so that when a mismatch between outcomes and expectations occurs, management actions (or even goals and objectives) can be re-examined. Measures should be developed to ensure that the decision points are statistically valid. Uncertainties should be identified and prioritized in plans, with urgent and basic information needs given highest priority for research funding. Monitoring and research can then focus on reducing critical uncertainties.

Be strategic about modeling. Modeling should be tuned to meet immediate and long-term management needs. Both conceptual and quantitative models are useful tools, and both are efficient for predicting the range of likely outcomes for alternative management actions in "what if" scenarios, delving into the effects of uncertainties, and revealing where threshold conditions require new actions. Useful models need to consider the range of possible surprises that exceed normal expectations. Surprises (droughts, invasive species, levee failures, other extreme events), can be viewed as learning opportunities and will likely create a need for recalibration of model expectations. A large, complex system such as the Delta might seem to require large, complex models, but their development can make unreasonable demands for expertise, time, and costs. For example, the initial, complex Grand Canyon Ecosystem Model (Walters et al. 2000) often failed to predict the effects of altered river flows, while later submodels could deal with specific management needs (Melis et al. 2015).

Use experiments where possible. Some of the most effective implementations of adaptive management incorporated field experiments into project design (e.g, replicated field-plot design at Tijuana Estuary and sequential tests of large flows from Glen Canyon Dam). Although each project has unique features, subareas can be used to test some hypotheses, and larger areas can be restored in phases of increasing spatial scale, in a before-after-control-impact (BACI) design (Osenberg et al. 2006). In the Delta, habitat restoration is underway for 26 projects encompassing more than 12,000 ha as part of California EcoRestore (*http://resources.ca.gov/ecorestore/*), and all are required to follow an adaptive-management process. Individually and collectively, these projects present extraordinary opportunities to incorporate field experiments. Conducting restoration as field experiments (i.e., adaptive restoration; Zedler 2017) reduces critical uncertainties and could well save money in the long term.

Integrate monitoring, analyses, and synthesis into a comprehensive data-management system. Monitoring is essential to evaluate the outcomes of actions, but the scope and intensity of monitoring can be tuned to management needs (and detect surprises, opportunities, or faults in underlying assumptions). Data from monitoring need to be distilled, stored, and synthesized so that findings, causes, and impediments to progress can be communicated to practitioners, decision-makers, stakeholders, and scientists. While the details are often situation-specific, general methods of measurement and analysis may apply broadly and across a range of projects. Consolidating some of these functions into an informatics group shared among agencies could achieve economies of scale, improve transparency, and reduce overall costs. One step in this direction is the shared data-management system proposed by the DSC (2015).

Facilitate collaboration among scientists and managers. Effective communication and collaboration among scientists and managers are key assets to adaptive management (Cloern and Hanak 2013; Meyer 2013). Monitoring and research provide information to reduce risk and increase the reliability of outcome predictions for management options. At the same time, the questions managers ask can suggest studies that will meet their needs, helping to ensure that the science is realistic and relevant as well as rigorous.

Collaboration takes time and requires staff to bring people together from different disciplines and different agencies and different perspectives. The ongoing South Bay Salt Pond Restoration Project in San Francisco Bay[3] (Delta ISB 2016) provides an encouraging example of effective collaboration. Managers, scientists, and stakeholders meet

3 *http://www.southbayrestoration.org/pdf_files/SBSP_EIR_Final/Appendix%20D%20Final%20AMP.pdf*

frequently to anticipate issues and design monitoring to address specific management questions. For example, a multi-year test of the effects of increasing tidal influence on mercury dynamics involves researchers who track mercury concentrations in sediment, water, fish, and birds, and managers who modify inflow regimes. The result is an iterative progression toward more functional tidal flows (Bourgeois 2016, unreferenced, see "Notes").

Use quantitative tools to enhance decision-making. Many steps in adaptive management are steeped in quantification and predictions—this helps make the process scientifically sound. The rigor of the final step—of making management decisions based on the results of modeling, experiments, and monitoring, followed by analysis and synthesis—can be improved by using a variety of quantitative approaches and tools (e.g., optimization algorithms, neural networks). Ecological risk analysis, for example, can provide a framework for incorporating social and scientific factors into structured decision-making (Wyant et al. 1995; Van den Brink et al. 2016). Bayesian networks and other decision-support tools (e.g., Nyberg et al. 2006; Carriger and Barron 2011; Marcot et al. 2012; Foran et al. 2015) may also provide useful structures for making the critical decisions about whether to continue a management action, make incremental modifications, or change course dramatically.

Assess costs and benefits. Generating institutional support for comprehensive adaptive management in the Delta requires that a compelling case be made that the process is, in fact, worth the effort and is valuable for a system with recognized uncertainties yet a strong scientific foundation. Making this case could benefit from better and more comprehensive assessments of costs and benefits, recognizing that the costs of conducting adaptive management may be minor relative to the costs of unanticipated outcomes or making irreversible mistakes. Because adaptive management occurs in a legal, political, economic, and social context as well as a scientific or ecological one, determination of costs and benefits can differ depending on who is doing the calculations and their own priorities (e.g., water for agriculture vs. endangered fish species). It might be instructive to examine how or whether other large-ecosystem projects (e.g., Chesapeake Bay, the Everglades, Glen Canyon) have assessed costs and benefits.

Recognize when and where adaptive management might not be appropriate. Adaptive management should be the default approach to management actions in the Delta. But adaptive management may not be appropriate for some situations, depending on the capacity of management to control or predict the outcomes of actions and the level of uncertainty (Figure 2). When actions are dictated by law or are essentially irreversible (e.g., construction of hard infrastructure), changing the action itself is rarely possible, although the results can still be monitored and improvements in operations may become evident. Limited support from federal, state, and local agencies or a lack of stakeholder buy-in also may restrict options for subsequent changes in management directions. Adaptive management may be unnecessary if the science is solid and outcomes can be predicted with near certainty.

Adaptive management is a rigorous process that involves more than monitoring the outcomes of actions or using science to support decisions. Although the details of adaptive management can vary depending on circumstances, the core element is its organized science base. Whether one follows the nine-step process depicted in Figure 1 or some other version (e.g., Gregory et al. 2006; Williams et al. 2007), the essentials of adaptive management are the same: clear management objectives; scientific evaluation of the potential outcomes of contrasting management approaches; modeling to identify causal pathways and key uncertainties and to explore expected outcomes and trigger points of interventions; clearly articulated benefits from learning; an institutional capacity to learn from management decisions and follow-up monitoring; and an effective process for translating the results of the adaptive-management process into improved management.

THE FUTURE

Today, the Delta is buffeted by the accelerating effects of climate change, invasive species, recurring droughts, floods, and social, economic, and political influences. Management in this mélange of change is challenging, not the least because of our incomplete knowledge of how these forces interact—indeed, of even how the Delta ecosystem functions when these

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major drivers are changing. Managers encounter uncertainty at every turn, and decision-makers must make hard choices, all with the intent of producing the desired results.

Adaptive management cannot address all of these forces. What adaptive management does best is to use the tools of science—hypothesis formulation, modeling, experimentation, monitoring, and data analyses and interpretation—to systematically reduce uncertainties, clarify management options, and facilitate achievement of project goals by encouraging flexibility, communication, and transparency.

Expanding the use of adaptive management in the Delta will require changes in the culture of management in the Delta. Agencies will need to be more collaborative, sharing staff and resources as challenges require. Managers and decision-makers will need to expect and prepare for uncertainty, take risks, be able to change their minds, and be rewarded for doing so. Making adaptive management an integral part of plans and actions will require effective leadership; flexibility in decision-making, regulations, and permitting; planning for future changes; and adequate and reliable funding. Science-based adaptive management should become commonplace in the Delta, not just because it is mandated, but because it can lead to more effective outcomes.

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