

What's New in Adaptive Management and Restoration of Coasts and Estuaries?

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Received: 19 August 2016 / Accepted: 30 August 2016
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Abstract Adaptive learning about nature, based on observations and continual rethinking, dates back to Native Americans in what we call Traditional Ecological Knowledge. Fast forward to 1950+, when Eugene, Howard, and William Odum promoted sound science and its use in managing ecosystems—called adaptive management (AM). What began as an instinctive way of thinking and deciding how to obtain resources using accumulated information became a structured, science-based process that improves over time, given continual critiques of projects, clarification of definitions, and analyses of outcomes. The basic need is still to sustain ecosystem services despite uncertainties, such as climate change. I report recent innovations in the AM of estuaries and coasts that can add knowledge and improve future efforts. Innovations include new guidelines and approaches to confront uncertainty, engage stakeholders, improve governance, prioritize actions, centralize the role of science, and manage holistically. AM has been effective along the coast of Denmark and in several estuaries, and it is evolving elsewhere. In The Netherlands, Spain, California, and Oregon, large field experiments are generating “learning while restoring” (adaptive *restoration*, AR). AM and AR can help managers of coastal ecosystems and watersheds mitigate the impacts of rising sea levels, sea storms, and human disturbances. Science-based decision-making will become

more nimble and protection/restoration more effective as innovations and model approaches are tailored to individual estuaries and coasts.

Keywords Adaptive management · Adaptive restoration · Experimentation · Science-based decisions · Holistic watershed approaches · Odum legacies

Introduction

This overview highlights recent innovations for managing and restoring estuaries and coasts. New approaches counter the characterization that adaptive management (AM) is “...at best uninformative and at worst a smokescreen...” (Doremus et al. 2011, p. 3). First, I explore the roots of AM and the special needs of coasts and estuaries, followed by recent innovations, examples of effective estuarine and coastal AM, and opportunities for holistic approaches, ending with adaptive restoration (AR). I emphasize the latest papers from a rapidly expanding literature. Background information and more examples are in >200 references cited here and in electronic supplementary material (ESM-1.5).

AM *at its best* reduces critical uncertainties and points the way to selecting an effective suite of management actions for whole systems (estuary + river + watershed). An outstanding example is the Denmark Model (ESM-1.1). Several large field experiments also demonstrate the feasibility and value of AR, which is *at its best* when field experiments are phased, so that early tests can inform later tests, and when hypothesis-based treatments indicate *why* one approach is superior to others (Zedler 1997, 2005; Zedler and Callaway 2003; Larkin et al. 2008, 2009; Doherty et al. 2011; ESM-1.2). Successive experimentation can progress from testing alternative plantings and topographic contours to restoring resilience of ecosystems and landscapes.

Communicated by Iris C. Anderson

Electronic supplementary material The online version of this article (doi:10.1007/s12237-016-0162-5) contains supplementary material, which is available to authorized users.

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Roots of Adaptive Management

Traditional Ecological Knowledge

Adaptive management (AM) has its roots in Traditional Ecological Knowledge and the practice of Traditional Resource Management, which foster learning while managing and restoring land. Indigenous peoples have tended natural resources for centuries using information accumulated over generations (Berkes et al. 2000, Mistry and Berardi 2016, Brondizio and LeTourneau 2016). Gatherers and hunters experienced uncertainty daily, seasonally, and over years of dealing with variable weather and resource availability. Advice from elders and individual experiences led to learning as people repeated old ways and tried new ways to obtain resources. I defer to Native American colleagues and writings for deeper understanding (Berkes et al. 2000, Pierotti and Wildcat, 2000, Stevens 2003, 2004, Anderson 2005, Mistry and Berardi 2016), while reiterating that AM has strong roots in Traditional Resource Management. Both aim to reduce uncertainty, improve skills, and sustain resources. In Canada, expert judgment is drawn from Aboriginal communities to improve the AM of salmon (Failing et al. 2013). In the Iraqi (Mesopotamian) Marshlands, experienced fishers have the understanding needed to allocate limited water supplies to sustain fisheries, and Marsh Arabs know how to construct buildings using *Phragmites* and how to use other native plants for crafts and medicines (Fawzi et al. 2016). Native people might be able to adapt to a salinizing landscape (Zedler 2016) because traditional approaches are not immutable. “Each generation...makes observations, compares their experiences with what they have been taught, and conducts experiments to test the reliability of their knowledge” (Pierotti and Wildcat, 2000, p. 1338). In the Amazon Delta, a “tradition of change” helps indigenous people adapt to a broad range of flood conditions. A 30-year study by Vogt et al. (2016) found that Traditional Ecological Knowledge helped expert farmer-fishers adapt to both gradual and unpredictable changes in inundation and to cope with increasingly modified flood patterns. They also adapted to changes in markets by planting açai palms to meet rising demand for açai fruit. As water levels and/or salinities changed, local experts adaptively shifted food crops and planted shrub and trees to stabilize shorelines and provide habitat for shrimp and fish.

Writings about Traditional Ecological Knowledge capture a key lesson for managers of estuaries and coasts, namely that decisions be evidence-based. This same message appears in the work of three early ecologists who promoted sound science and its use in managing ecosystems.

Odum Leadership

The Odums—Eugene, his brother Howard and his son William—developed and tested key hypotheses about

estuaries and wetlands, and all three left impressive research legacies. Howard (“HT”), the engineer, thought holistically about how ecosystems operate and sought ways to use but not abuse them, e.g., he and Kathy Ewel tested cypress domes for tertiary treatment of wastewater (Odum et al. 1976). Gene (E. Odum) bridged science and policy to help wetlands obtain protection under the Clean Water Act (Ruggiero 1999). Bill (W. Odum) compared wetlands along salinity and tidal gradients to figure out why they worked as hypothesized (E. Odum 1980). In a *BioScience* paper (Odum 1982, p. 728), Bill adapted an idea from economics, that “...through hundreds of little decisions and the conversion of hundreds of small tracts of marshland, a major decision in favor of extensive wetlands conversion was made without ever addressing the issue directly.” Bill advised planners and politicians to expand their perspectives beyond little decisions to holistic views. Collectively, the Odums’ research and writings provided sound science for ruling in favor of the environment. Indeed, Gene closed the third edition of his textbook (Odum 1971) by advising scientists to help decision-makers, e.g., by determining the optimum (not maximum) population size and configuration for overpopulated areas. Later, AM was formalized for fisheries management (Holling 1978). Over time, the Odums’ work spanned coastal and upstream wetlands, ecosystem structure and function, observational and experimental research, and conceptual and simulation models. Applied research was often shunned in academia (rebutted in Zedler 1997), but it was welcome along the southern California coast. By 1982, my students’ tests of Odum hypotheses (Odum 1980; Odum et al. 1995) justified naming Tijuana Estuary a National Estuarine Research Reserve (NERR).

Today, AM is seen as a key to managing ecosystems facing “the dynamics of riverine and marine processes, climate change, population growth, economic activity, and ongoing human reliance on the natural resources the coast provides” (WIG 2013, p. 1). For global wetlands, including coral reefs, annual losses in services exceed US\$20 trillion, even though the science is available to conserve these critical ecosystems and their services (Gardner et al. 2015). The Great Barrier Reef alone generates up to A\$20 billion/year (Brodie and Pearson 2016). As degradation continues, the task of restoration grows larger (Davidson 2014), along with the need for more effective tools (Moreno-Mateos 2012; Shelton and Richmond 2016) to use at much *larger spatial scales* (ESM-1.3). Large-scale efforts can arise from laws, agency policies, and citizen groups (e.g., RAE 2015). A major advocate, the United Nations Environment Program (UNEP 2016) plans to complete its assessment of global, regional, and local ecosystems in 2018 (Aronson and Alexander 2013). General policies and actions will likely follow, all of which will need site-specific science—for use in AM and AR.

Coasts and Estuaries Need AM

Science-based decision-making is essential for estuaries and coasts, which face *uncertainties on two fronts*. On the landward side, they receive altered flows and contaminants from urban and agricultural watersheds. On the seaward side, they face rising sea levels and more frequent, more intense sea storms. Important resources are at risk. “With only 13 % of the land area of the continental U.S., the estuary regions of the United States comprise a hugely disproportionate share of the national economy, with 43 % of population, 40 % of employment, and 49 % of output” (Colgan 2008, p. 63). Additional services were provided by native ecosystems that abated floods, removed nutrients, stored carbon, and supported biodiversity. Some of these services are recoverable through AM and AR, e.g., restoring 364 ha of a large river delta in Puget Sound rapidly increased salmon foraging (Ellings et al. 2016), although growth potential was lower in the warmer restored channels (David et al. 2014).

Changing climate especially threatens estuaries and coasts; it is certain that changes will occur, but uncertain when and how. A vision, which the Odums likely shared, is for coastal ecosystems to sustain both ecological and societal services in the face of change. The Pacific Decadal Oscillation (a natural variation in climate and storminess) offered a preview of major sediment inflows given more frequent and more intense storms (Zedler 2010). In the same region, some estuaries subsided due to tectonic activity, exacerbating effects of rising sea levels (Simms et al. 2016). Since tectonic activity can also elevate land, management must be based on site-specific science and involve nimble, long-term thinking to sustain resources. New tools to manage climate-change actions adaptively include a *workbook* that helps managers identify risks and prioritize actions to adapt to climate change (USEPA 2014) and an approach for *integrating monitoring and predictive modeling* to identify tradeoffs among alternative management regimes within a coastal watershed (Peterson and Freeman 2016). AM is an effective approach for reducing uncertainty, and predictions from models are essential tools (e.g., Kellens et al. 2013).

Traditional responses to rising seas involve costly revetments (walls, levees, culverts, bulkheads, etc.), one of which is still under construction in China—a sea wall along >11,000 km of the southeastern coast (as of 2010)—destroying 754,697 ha of coastal wetlands (Ma et al. 2014, Tian et al. 2016). Innovative alternatives are to replace concrete with softer engineering approaches (Palmer et al. 2015, Sutton-Grier et al. 2015). After 50 years of disappointing outcomes using hard structures, the UK is transitioning toward greener options, including retreating and moving inland, allowing natural vegetation to develop and dissipate tidal energy—a program called “set-back,” then “managed retreat” and now “managed realignment.” In support of greener

alternatives, it is clear now that salt marsh *vegetation helps stabilize shorelines*. A meta-analysis of 75 salt marsh studies (mostly in the USA and Europe) verified significant coastal protection by salt marsh vegetation (Shepard et al. 2011). In seven studies, marsh vegetation attenuated wave heights, and in 30 studies, salt marsh vegetation enhanced accretion, elevated the marsh surface, and reduced lateral erosion. For deeper water, the World Bank (2016) recommended coastal protection by sustaining mangroves and coral reefs, although it did not emphasize AM or AR.

Adaptive responses involve monitoring, data interpretation, and management actions that incorporate new knowledge. As a basic step, the USA conducts National Condition Assessments for 1104 sites along ~100,000 km² of coastal and Great Lakes waters. Such long-term assessments and responses need to be science-based, flexible, and holistic (Simenstad et al. 2006, Linkov et al., 2006, USFWS 2011, Giebels et al., 2013, Williams and Brown 2014, Brodie and Pearson In press 2016). The anticipated outcome is human well-being (MEA 2005; Costanza et al. 1997, 2014; Woodward and Wui, 2001, Luisetti et al. 2014). AM is potentially most useful in dynamic systems with uncertainties about environmental variation, where management actions can influence system behavior, and where management improves as uncertainty is reduced (Thom et al. 2005, Williams and Brown 2014). Coasts and estuaries certainly qualify. Although plans for AM are not always implemented (McFadden et al. 2011), Westgate et al. (2013) found 13 AM projects with clear goals, a quantitative model or experimental design, and actions based on monitoring data. Examples from estuaries and coasts are described below.

AM focuses on learning from science, adjusting actions accordingly, and disseminating knowledge to improve ecosystem management. The former Deputy Director of the US Dept. of Interior (Scarlett 2013) advised that, prior to setting up an AM framework, managers should identify knowledge gaps and opportunities to learn and adjust management, then clearly state how they expect AM to assist. Plans should specify when to revisit decisions about both the resources and the management process.

Innovations in AM

Like Traditional Resource Management, AM involves willingness to change in response to new information. AM can be very powerful when researchers and decision-makers work synergistically. Scientists can suggest modifications to projects; decision-makers can and should identify new questions, and together, they can develop priorities for reducing uncertainties—all of which can counter the constraints to AM that are noted in the literature (Allen and Gunderson, 2011, WIG 2013, LoSchiavo et al. 2013, Williams and Brown 2012,

2014, Day et al. 2015, DISB 2016). Of many recent innovations, I begin with guidance, then present new ways to confront uncertainty, engage stakeholders, improve governance, prioritize AM actions, give science and scientists a central role, and conduct field experiments (AR).

New Guidance for AM Projects

Many guidelines embrace flexibility and promote large-scale AM. Neither scientists nor managers can predict all events, but monitoring can capture unexpected outcomes and suggest further study to reduce uncertainty (USACE et al. 2015). In southern California, heavy rains in 1980 catalyzed exotic plant invasions from uplands into salt marshes. In an unplanned response, field experiments identified salt reduction thresholds for native vs. alien species, which led to guidance for discouraging invasions (Kuhn and Zedler 1997, Callaway and Zedler 1998, Noe and Zedler 2001, Zedler 2001). A local research team was able pursue opportunities as they arose. Elsewhere, a formal decision-making structure and AM Team would be helpful (Fig. 1).

I suggest first establishing the AM Team to establish such a structure. The user-friendly manual by Fischenich et al. (2012) illustrates essential steps and benefits of AM. The team would then consult relevant components of other manuals, including a new AM framework focused on *soil* (Birgé et al. 2016). A methods guide for estuary *freshwater inflows* (Olsen et al. 2006) has five steps: engage stakeholders, develop essential knowledge, respond to new information with necessary changes, formalize policy, and evaluate outcomes to learn from the process. Guidelines for protecting and restoring coastal Louisiana (WIG 2013) embrace a scientific approach that specifies goals and objectives, develops and implements management actions, assesses the system's response, and uses

new knowledge to make management decisions. Other regional guides include a book for monitoring, researching, and managing salt marshes in northeastern USA (Roman and Burdick 2012) and advice for adaptively managing the Everglades (LoSchiavo et al. 2013). The latter focuses on restoring natural *hydrological conditions* (water quality and flows)—establish a formal authority that integrates science into AM, characterize uncertainty and management options, and obtain robust peer review. The AM Team can adjust management actions and set up new tests or augment monitoring to continue reducing uncertainty through sequential feedback loops.

Williams and Brown (2012, 2014) followed their AM guide for the US Department of Interior with a call for even greater integration of science and management. Their one coastal AM example concerned Delaware Bay, where shorebirds threaten the horseshoe crab fishery by eating crab eggs, while the fishery threatens shorebirds by usurping their food. Shorebirds and crabs are monitored, and results lead to annual decisions, either to limit beach access to sustain shorebirds or to limit the fishery to sustain horseshoe crabs. An earlier Delaware Bay restoration of diked wetlands followed an AR approach in re-creating tidal marshes and fish (Teal and Weishar 2005 and nine more special-issue papers). Both projects base decisions on science.

Most recently, the Comprehensive Restoration Plan for the Gulf of Mexico mandates AM as part of the \$8.8 billion settlement with BP to restore ecosystems damaged by the Deep Horizon Oil Spill (PDARP/PEIS 2016). Each of the five Gulf states will have a restoration team reporting to an overarching Trustee Council (including three federal resource agencies). AM will include data management infrastructure, coordination with other research, and monitoring in the region plus frequent reports and program reviews (ibid., Section 7.5). Guidance on restoring ecosystems and species is extensive, and the goal for conserving and protecting marine, coastal, estuarine, and riparian habitats includes *land acquisition*, invasive species control, debris removal, and improved water quality (Chapter 5; Appendix D.1.7, p. 5.239f.). AM should allow managers to achieve restoration goals, given this long-term, large-scale, and well-funded project. The world will be watching to learn how AM is applied to improve restoration.

Is any guidance missing? Yes. Cause–effect relationships become clearer when restoration is undertaken with experiments to test the functional value of vegetation along shorelines. Despite the opportunity to set up restoration experiments and test approaches within and among five Gulf of Mexico states, the guidance documents focus on monitoring and “scientific support activities” rather than AR (large phased field experiments). While the Plan (PDARP/PEIS 2016) acknowledged that uncertainties might influence restoration outcomes, there was no call to address unknowns experimentally. In this multi-state effort, enormous opportunities exist to begin

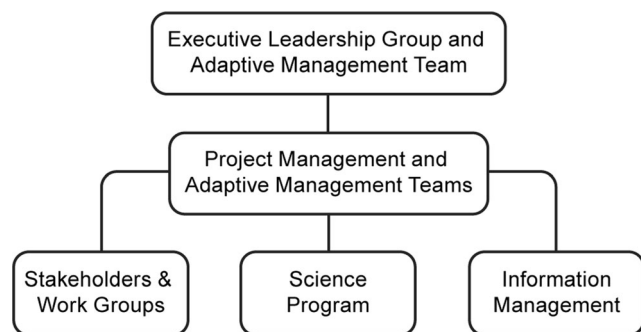


Fig. 1 The San Francisco Bay Salt Pond project AM components: *Top level* decides project direction, budget, major issues. *Middle* decides changes, monitoring, responses to triggers; calls for research; oversees contracts, outreach; reports progress. *Lower left* offers feedback to leaders' decisions. Scientists solicit funds, interpret findings, prioritize studies and changes, implement triggered actions, coordinate and report science. *Lower right* distributes and archives data; reports annual trends (modified from USACE et al. 2015)

large *manipulative* experiments to test alternative approaches to ecosystem restoration. Also, monitoring can support *observational* experiments by assessing the effect of the same action in multiple contexts. As evidence, the most common attribute of *effective restoration* that emerged from a recent compendium on large river restoration was an AM approach with learning by experimentation and monitoring (DeBruyne and Roseman 2015).

Confronting Uncertainty

Uncertainty can be reduced most effectively in long-term projects with phased research, yet continual changes in predictions for sea storms and sea levels can confuse the public. Even people who acknowledged severe risks from rising sea levels in New Brunswick denied their own vulnerability (Lieske et al. 2014). Uncertainty was addressed poorly by 44 climate adaptation plans across USA, most for coastal municipalities (Woodruff and Stultz 2016). Innovative planners can combat risk in two ways, developing plans to “adapt” to rising sea levels and plans to *recover from disasters* that coastal protection fails to avert. Both approaches are relatively new to most coastal jurisdictions surveyed along Atlantic and Gulf Coast states (Berke et al. 2014), and both require attention.

Century-long time frames are reasonable. Planning to protect London from Thames Estuary floodwaters began in 2002 by acknowledging “deep uncertainty” about climate change. Long-term monitoring clearly showed high interannual variability in sea levels and uncertain effects of sea storms. A 100-year project costing billions (called TE2100) was planned to upgrade the ~25-year-old, 520-m-long Barrier across the Thames River. The project’s cost and lifespan provided incentives to reduce uncertainty and allow adjustments over time. Ranger et al. (2013) considered the AM plan *innovative* in several respects, by acknowledging uncertainty at the start, considering policy before exploring sea level projections, and by addressing a range of scenarios and worst cases, not just climate models. Also innovative were the project’s timely responses to new data and its flexible risk management strategy, which allows actions to vary in response to indicators of flood risk. The long list of risks included rising sea level, peak surge and wave heights, peak river flows, failing flood infrastructure, erosion and deposition in intertidal habitats, proposed new developments, and citizen concerns.

In Sweden, a court verdict settled a dispute over the construction of a railway through a natural area by requiring a *100-year* monitoring program. Included were mandates to assess the long-term effects of the railway, track the progress of compensation measures, manage the site to sustain wildlife, and make data available to users (Länsstyrelsen Västerbotten 2015). Contrast these long-term commitments with guidance that monitoring must not *exceed* 10 years after project construction (Fischenich et al. 2012).

Project phasing can improve plans and reduce costs of coastal protection. For centuries, the Dutch have battled the sea for coastal land to cultivate. Their levees exclude tides, canals drain wetlands, and barriers impound river waters and sediment. Management of the Westerschelde estuary progressed from international conflict in 1985 to collaborative AM by 2007, after The Netherlands and Belgium acknowledged the need for rapid, flexible decisions (van Buuren et al. 2010). The catastrophic 1953 flood suggested damming the Oosterschelde estuary, but authorities chose a phased approach, since a 9-km dike was a huge challenge, even for Dutch engineers. Work began with smaller dams as pilot projects (van Staveren and van Tatenhove 2016), but even these had unexpected negative impacts. A eutrophic lake formed when the Rhine River’s polluted water was impounded. This outcome catalyzed protests against the Oosterschelde dam. Consequently, in an AM approach, planners devised a lesser storm surge barrier, completed in 1986, with 62 gates that could be opened to mix coastal and river waters.

Dams and barriers had many negative impacts, including erosion of mudflats, creeks and river levees, changes in services, and the need to import sand (van Wesenbeeck et al. 2014). As an alternative, setting levees back from the river edge allows floodwaters to spread across broad floodplains and reduce erosion, but at the expense of agricultural land. Soft and hard engineered structures are needed to adapt to rising sea levels and reverse subsidence of polders (fields behind levees; van Wesenbeeck et al. 2014, van Staveren and Tatenhove 2016). Decision-makers benefit from envisioning alternative futures.

Engaging Stakeholders

Stakeholders can generate *more alternatives*, resulting in *flexible actions* and *mutual benefits* (Nicholls et al. 2015). In Florida’s Tampa Bay watershed (~5700 km²), citizens were the key to de-eutrophying the bay; they called for restoration of clear water and developed voluntary limits on nutrient loading (Greening et al. 2014). Three cases that would have benefited from early stakeholder engagement follow: In the 1980s, a citizen group sued three federal agencies for not fulfilling mitigation requirements when a major highway was widened along the edge of San Diego Bay. The lawsuit led to costly delays in highway construction because the court ruled in favor of the plaintiffs. To mitigate damages to endangered species habitat, specific criteria had to be met in restoring salt marsh habitat for each of the three affected species. Individuals involved in monitoring and experimentation translated the science into advice for agency decision-makers and the public, and plaintiffs trusted the science. The evolving AM process produced workable outcomes for the biota and overall conservation (Zedler and Callaway 2003).

In New South Wales, a conflict over tidal influence took years to resolve. Agencies built extensive levees to keep industrial lands and farms from tidal flooding (ESM-2.1). A side effect was the loss of salt marshes over 41 % of the estuary, continuing a trend that began on Kooragang Island (Zedler et al. 1995). Problem analysis involved 17 stakeholder groups and 23 uses of the Hunter Estuary (Pierson et al. 2015). A 2007 compromise retained levees to protect land from flooding while adding gages to restore muted tidal flows. By mid-2012, 2.5 km² of salt marsh had recovered. The compromise also established climate-adaptation goals.

In Portugal, citizen resistance to *uncontrolled development* and *severe beach erosion* is being resolved slowly. Before stakeholders would trust and accept agency decisions for adapting to climate change, they wanted evidence of adequate science, clear policies and sufficient political will to enforce them (Schmidt et al. 2013, 2014). A subsequent merger of research and action planning (akin to AM) engaged a broad range of stakeholders, convened two workshops, achieved a common vision of the 2100 coast, and produced an action plan; keys to this outcome were the ability to participate and learn the latest technical-scientific information from scientists who translated knowledge for public understanding (Campos et al. 2016).

Including stakeholders early can smooth the way for AM. For European coastal lagoons, stakeholder involvement increased knowledge, understanding, and ideas for solving local issues (Newton et al. 2014, Lillebø et al. 2016). In an effort to conserve and restore San Francisco Bay shorelands, input from >100 scientists helped update habitat goals in relation to climate change predictions (BEHGU 2015). In many regions, stakeholders with similar goals can magnify their influence by forming coalitions. Twenty years ago, 11 community-based conservation organizations joined forces to form Restore America's Estuaries (RAE 2015), which now fosters AM in conferences for citizens, managers, and policy makers.

Improving AM Governance

Many programs will need *governance adjustments* for AM to improve negotiations, policies, plans, monitoring, decisions, enforcement, and education (Olsen et al. 2006, LoSchiavo et al. 2013, Gunderson et al. 2016). In the absence of AM, confusion and conflicts seem more likely. In the UK, the House of Commons recommended retreating from existing shorelines to adapt to rising sea level, but an earlier law had designated large areas of former marshes as Special Areas of Conservation, making it illegal to restore tidal influence. To align governance with uncertainties about climate change, the UK funded a research program to reveal risks to people and property, as well as benefits of restored ecosystem services. Researchers predicted how much setback would be needed (Pethick 2002), and a subsequent review of realignment

projects compared outcomes to predictions (Pendle 2013). When six sites did not meet expectations, researchers improved both the models and monitoring, with a broader range of comparisons and greater geographical variability to accelerate learning (Pendle 2013).

Mandating AM is one innovation. In the USA, 28 research reserves are required to monitor and study representative estuaries on the Atlantic, Gulf, Pacific, and Great Lakes coasts (NERR 2015, Zedler 2015). Another 28 estuaries in the National Estuary Program are required to base long-term watershed-scale management plans on research and stakeholders. Progress is measured in area conserved, and >800,000 ha have been conserved or restored (NEP 2005). Several federal state projects also mandate AM, e.g., the Florida Everglades (LoSchiavo et al. 2013), California Delta (Luoma et al. 2015), and the Gulf of Mexico coast (PDARP/PEIS 2016). The USA's National Environmental Policy Act requires mitigation of impacts with indicators and standards to judge when a site has complied. If not in compliance, plaintiffs can take legal action. While law enforcement should promote compliance, Fischman and Ruhl (2015) concluded that AM criteria were often unspecified or standards were unmet in the lawsuits they reviewed. In contrast, some practitioners surveyed by Benson and Stone (2013) blamed laws for *hindering* AM by not allowing flexibility. Others argue that decisions based resource laws fall outside AM (ESM-1.4). I recommend that AM focus on clear criteria, standards, and *science-based decision-making*.

An ideal AM *governance structure facilitates the flow of scientific* information and ideas in all phases: planning, research, science, project management, engineering, and operations. Adaptive behavior can be challenging for managers, given multiple uncertainties—future environmental conditions, knowledge of how their ecosystems work, and predictions of ecosystem responses to alternative actions. However, institutions, administrative arrangements, stakeholder organizations, and community involvement can change to deal with uncertainties (Day et al. 2015). Folke et al. (2005) suggested that *key individuals* orchestrate informal networks as a first step toward adaptive governance for ecosystem management. Those players identify information needs, facilitate the flow of information, and create “nodes of expertise” to draw upon at critical times. When not constrained by rigidity, network members can think more creatively, envision different policies, and become more adaptive. In the San Diego Bay mitigation project, AM arose because we all wanted to understand and restore habitats to support endangered species (Zedler and Callaway 2003).

Evaluation is a critical step in AM, and results are more credible when studies pass peer review. In my experience, published results of research and monitoring convinced skeptics that two San Diego Bay mitigation sites met the criteria for endangered species but a third did not—the latter was a

contentious outcome—because project proponents were eager to “close the file.” Peer-reviewed research explained *why* an endangered bird could not nest in the habitat designed for it (Zedler 1993). As a result, the USFWS agreed that the site would never provide the necessary nesting habitat, and they were flexible in modifying the criteria.

Evaluation is useful throughout the three basic restoration phases (planning, implementation, and monitoring) as well as between phases, based on a review of ten long-term restoration projects and adjustments in response to assessments (Nilsson et al. 2016). Although not coastal projects, the recommendations are relevant: Evaluate continually, and disseminate new knowledge widely, using digital media.

Funding can jumpstart AM and monitoring. For example, establishing Santa Monica Bay as the USA’s 28th National Estuary in 1987 added federal support for the Bay’s Restoration Foundation and partners to assess the “before-restoration” condition of Ballona Wetland, a 62-ha remnant of a former 850-ha estuarine wetland. The 5-year report provides baseline data on 28 biological, chemical, and physical characteristics, with non-native plants dominating non-tidal, dry, hypersaline areas (Johnston et al. 2015). A \$6.5 million restoration project is in the final planning stages (CDFW et al. 2016), thanks to federal, state, and local stakeholder efforts. Monitoring will quantify actual trajectories and outcomes, potentially indicating corrective measures, per AM.

Prioritizing AM Actions

Estuaries and shorelines face increased flooding, eutrophication, and land use. With many ecosystems and real estate at risk, approaches are needed to set priorities. Several innovations are in recent papers.

To *prioritize flood protection*, Prandle and Lane (2015) derived four vulnerability indices from tidal data and depth at the estuary mouth, then compared climate change predictions for 96 UK estuaries. Indices agreed that, given a 1-m increase in sea level (time period unspecified), half of UK estuaries would undergo significant changes in currents and tides, vertical stratification and salinity intrusion, with little effect on the largest estuaries.

Chang and Huang (2015) employed H. T. Odum’s concept of “emergy” (comparable to the historical energy footprint) to calculate three components of flood vulnerability for Taiwan’s west coast, all in emergy units (emjoules). The three components were risk (sensitivity of flooded real estate), exposure (tendency to accumulate floodwater), and adaptive capacity (ability to mitigate flooding). Costly urban developments in lowlands (i.e., high risk, high exposure) were most vulnerable—except for cities with greater adaptive capacity. Using consistent emergy units made it possible to map overall flood vulnerability so decision-makers could prioritize locations for flood protection.

A similar exercise for a deltaic plain of the Mekong River considered risks for >17 million people (23 % of Vietnam’s population). Nguyen and Woodroffe (2016) weighted factors in an analytical hierarchy with multiple criteria to estimate risk, exposure, and adaptive capacity. Their combined results predict flood vulnerability, with scattered coastal hotspots (high priorities) for flood protection. In both the Taiwan and Vietnam cases, vulnerability calculations depended on the information available and how it was interpreted. For Taiwan, adaptive capacity was based on historical floods that people had experienced and addressed with hard engineering infrastructure. In Vietnam, weightings were based on stakeholder ratings of sea level rise impacts. Regardless, quantifications of risk should help decision-makers assign priorities to adaptive actions, including coastal realignment and restoring living shorelines.

Landscape processes need to be included where *biodiversity conservation* is the AM goal. Based on resilience (defined as the capacity of the biota to recover through immigration), Tambosi et al. (2014) asserted that the highest priority for restoration of Brazil’s Atlantic Forest landscapes should be given to areas with remnant habitats and connectivity. Their *landscape-classification procedure* helped *prioritize restoration* for 10 % of the 5000-ha units (15 million ha), and 5 % were considered resilient sources of biodiversity (top priority for protection; Tambosi et al., 2014).

Wetland restoration is needed, and some sites can achieve greater levels of ecosystem services per investment than others. The watershed approach of Miller et al. (2012) ranks subwatersheds on the basis of the wetland ecosystem services they have lost, as mapped (Fig. 2), so a planner can easily select a subwatershed that most needs the target service(s). Next, it prioritizes potentially restorable wetlands on the basis of their ability to provide each ecosystem service. This outstanding tool is free online, with data for three Lake Michigan watersheds. The approach is being expanded throughout Wisconsin and being considered by neighboring states. Scientists can also use the maps to find comparable subwatersheds to test effects of large-scale restoration on coastal water quality (as in Collins et al. 2013). Ambitious comparisons could test multiple effects of wetland restoration area, type, and locations.

Centralizing Science in AM

Scientists need to engage in decision-making. Information on risks (coastal flood and storm damage, threats to water supplies (including toxic algal blooms), impaired navigation, and disappearing beach sand, needs to flow from scientists to all players. An early conceptual diagram for managing and testing eFlows (Alber 2002) appropriately showed scientists occupying a central position among stakeholders, but did not show information flowing beyond managers (e.g., to scientists). Double-headed arrows (Fig. 3) link multiple players to scientists, who

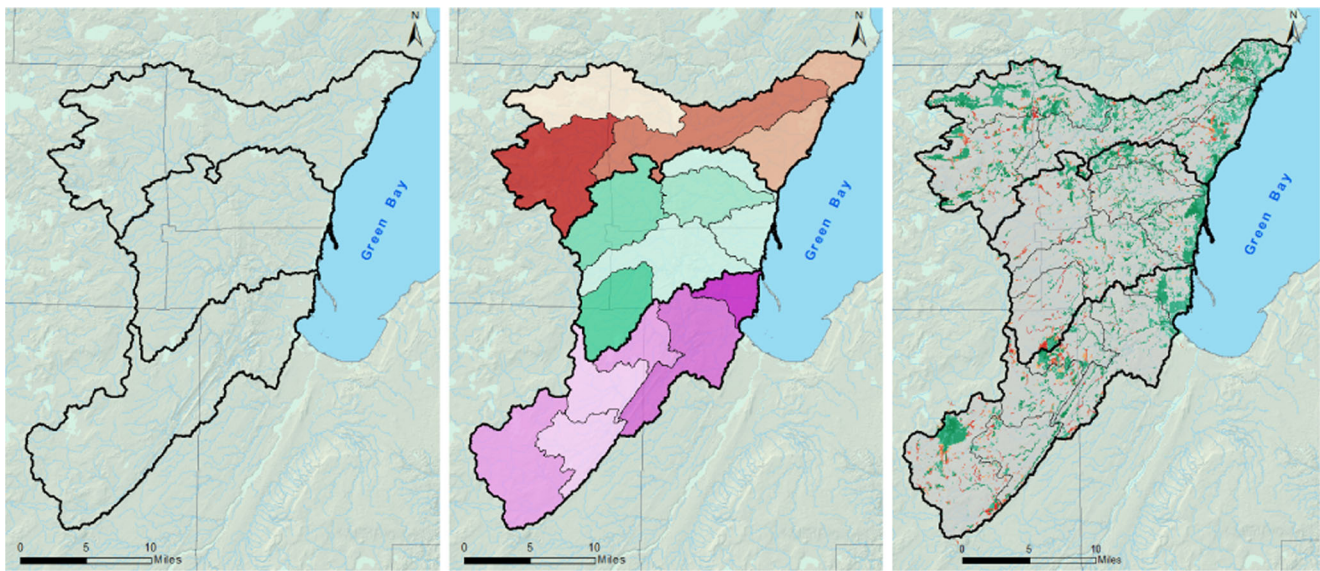


Fig. 2 Three watersheds (on left) in northeastern Wisconsin flow into Lake Michigan. For each wetland ecosystem service, subwatersheds are shaded darker to show greater historical loss of that service (middle map).

Also for each service, the potentially restorable wetlands that could best deliver that service are mapped (on right) (adapted by The Nature Conservancy of WI). Color maps for all services are in Miller et al. (2012)

should interpret and report their findings in multiple formats for all participants.

Adequate, appropriate *evaluation criteria* and a *robust monitoring program* should lead to accurate assessments of restoration progress. A review of 44 river restoration projects in France found that poorly evaluated projects generally had the most positive ratings (Morandi et al. 2014). Superficial observations do not withstand scientific scrutiny, and the temptation (and perhaps political/social pressure) will be to judge partial restoration as compliant. Evaluation criteria and *a priori standards* need to be linked to restoration objectives, reference sites, and pre-project conditions (Morandi et al. 2014). Indeed, Australia has just released *national restoration standards* (McDonald et al. 2016).

Evaluation strategies for monitoring, metrics, and reference sites should pass peer review before assessments begin. Later, both management and monitoring efforts can be improved. An example is San Francisco Estuary's Regional Monitoring Program for Trace Substances, which multiple partners conduct to identify hotspots and inflows of copper and nickel (Hoeneke et al. 2003). Monitoring locations changed based on where heavy metals were found in sediments, and research was added to encompass pollution from agricultural and urban lands. Anticipating new metrics, stable isotopes are being tested as tracers of nitrogen sources (Kendall et al., 2015). Both *management and monitoring are adaptive*.

Innovations in *remote sensing* help managers assess and monitor coastal habitats with increasing precision. Murray et al. (2012) presented a simple method (although computationally demanding) for mapping tidal flats along China and Korean coasts. Mapping was possible (cloud-free imagery) for about 87 % of the 13,800-km coastline. To identify tidal

flats, the authors first matched satellite images to predicted tide heights, then selected 78 images to represent higher and lower tides. Using the Normalized Differenced Water Index (NDWI), they quantified land area between those tides and subtracted it from the total area to delineate the tidal flat. This tool allows regional mapping of tidal flats and could promote large-scale AM.

Further distinctions in tidal flat subhabitats of the Wadden Sea separated water from flats using NDWI, then separated shellfish beds, vegetation (salt marsh, sea grass/algae), and types of bare sediment using a modified soil-adjusted vegetation index (Jung et al. 2015). Specificity of habitat types is warranted, given that sediments and internal recycling release more nutrients to the Wadden Sea than freshwater and seawater inflows (Leote et al. 2016). For shallow water seagrass beds, fine-scale accuracy of seagrass maps by applying a linear spectral unmixing classifier to seagrass polygons (i.e., digital aerial images based on manual delineation) (Uhrin and

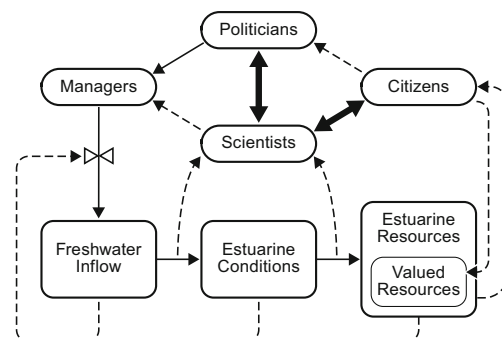


Fig. 3 Scientists have a central role in the AM of eFlows to estuaries. Double arrows emphasize interactions added, with permission, to the diagram in Alber (2002)

Townsend 2016). The actual area of seagrass vegetation in this North Carolina test case was substantially lower than in the polygon approach. With more precise monitoring, changes should become easier to detect.

Long-term coastal change in western Florida was documented recently by combining contemporary remote sensing tools with *historical maps* (T-sheets). A net expansion of coastal marsh over 100 years' time was measured along Florida's Big Bend coast, despite rising sea level (Raabe and Stumpf 2016). Sea level rose 15 cm along a 1:2500 slope, but only 120 m of former marsh became flooded by seawater, while 230 m of former coastal forest shifted to intertidal marsh. The new use of old maps showed that shoreline change alone might not assess the full impact of rising sea level, i.e., tidal marsh expanded inland into former lowland forest, causing an *increase in wetland area without the formation new land*. Tidal wetlands can also rise in elevation along with sea level via a feedback, with plants growing more biomass and trapping more sediment (Kirwan and Megonigal 2013).

Small, *unmanned aircrafts* (drones) offer great promise for monitoring wildlife and habitat (Christie et al. 2016). The future looks bright for mapping ecosystems where access is difficult (dissected with tidal creeks and channels or impenetrable vegetation), treacherous (deep mud, steep cliffs, sharks), sensitive (used by endangered species), or dangerous (hazards from mosquitoes to alligators). NOAA calls them the "storm chasers of tomorrow" (see uas.noaa.gov), suggesting future use in documenting extreme events.

Databanks must be adequate and accessible for science to fulfill its central role in AM, and accurate predictions require the integration of large amounts of data. To meet core needs, the USA's 28 NERRs and 28 NEPs observe and monitor estuarine resources. In tracking coastal and Great Lakes conditions, benthic indicators used by USEPA (2016a, b) suggest that waters are in good condition and improved from previous surveys, but nutrients are excessive in many areas. Sediment quality is typically good, but not improving. Fish tissue is often contaminated. Nitrogen was not assessed in the Great Lakes, but perhaps the 2020 survey will address this problem nutrient and suggest thresholds for protecting wetlands from weeds. It is not sufficient to track just lake waters and phosphorus; wetlands and nitrogen need attention (Paerl et al. 2014), including the newly recognized legacy of nitrogen fertilizers in soil (Van Meter et al. 2016).

Infrastructures are needed to facilitate data storage and retrieval, protect records from loss, make data accessible to scientists, and permit hindcasting, forecasting, and hypothesis testing. Where quantitative data are locatable, the next hurdle is integrating data from multiple sources and formats (Thessen et al. 2016). Gardner et al. (2014a) called attention to the paucity of monitoring data on aquatic ecosystem restoration, including USACE projects that cost of over \$400 million/year. They advocated principles and procedures for centralizing

such data to assess restoration programs. "Better data and information are needed...to ensure that restoration investments maximize environmental benefits to the nation" (Gardner et al. 2014a). In a supplement, Gardner et al. (2014b) provided guidance on data entry and documentation—for a *national database on ecosystem restoration*.

Exemplary AM Projects

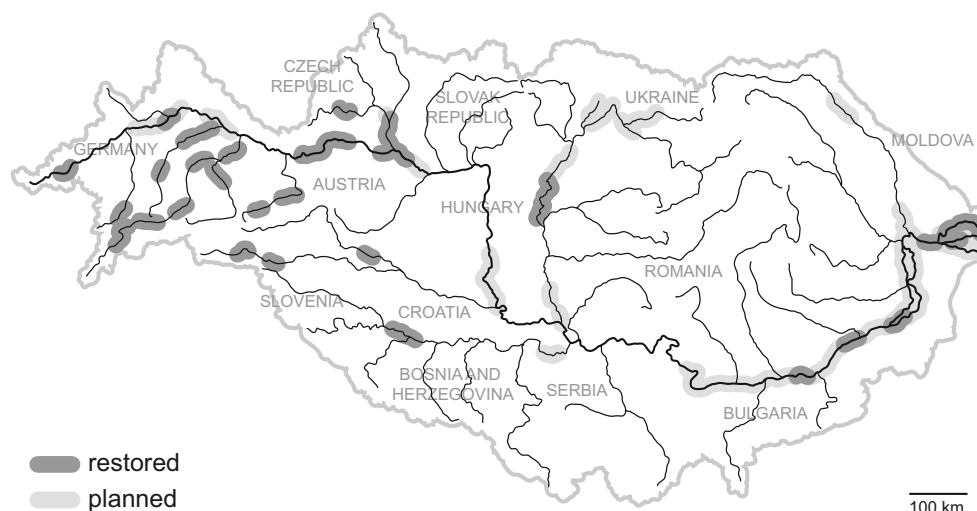
AM can help fulfill the 2015 Ramsar Briefing Note, "to avoid further wetland loss and degradation and to strengthen wetland assessment, monitoring and restoration efforts in support of the wise use of all wetlands" (Gardner et al. 2015). I suggest the following projects as global models of AM of estuaries and coasts.

Tasmania's 200-km² Derwent Estuary (ESM-2.2) is exemplary in science-based planning, implementation, and monitoring to sustain its wetlands, seagrass beds, tidal flats, and rocky reefs. Its 8900-km² watershed includes multiple hydroelectric dams, the capital of Tasmania, and >200,000 people. Although the estuary supports industry and a major port, problems with sedimentation, eutrophication, overfishing, heavy metal contamination, invasive marine species, and reduced native biodiversity are being addressed, and pollution is being reduced. Stakeholders (>16 voluntary organizations, plus local businesses, communities and agencies) contributed to an Environmental Management Plan. Water quality, habitat, and recreational opportunities are improving (Coughanowr and Whitehead 2013).

The Danube Delta on the Black Sea is Europe's largest delta, with diverse biota (~1800 plants, ~3500 animals) that are vulnerable to altered freshwater inflows and rising sea levels, as well as pollution from upstream. Low water quality relates to urban runoff, pollution, and bank erosion (Habersack et al. 2016). Levee dams and culverts have been lowered to re-connect floodplains with the river. Substantial riverine restoration is finished and underway high in the 801,463-km² watershed (Fig. 4). Thousands more km² of upstream floodplains could be restored to improve Delta water quality and habitat (Stammel et al. 2012; Hein et al. 2016). To prioritize restoration efforts, Hein et al. (2006) proposed a multi-criteria decision-support approach.

UK's Norfolk coast is eroding. A new book explains how sponsors funded a research effort (the Tyndall Centre) and promoted AM to combat climate change. The Tyndall Centre simulated future scenarios for coastal management and recommended regular reviews given new information. The simulation model is probably the first to predict both erosion and flooding on coastal ecosystems. Innovative visualization tools display the range of erosion and flooding scenarios, which helps coastal administrators and citizens understand uncertainty (Nicholls et al. 2015).

Fig. 4 The 2857-km Danube River flows from 19 countries into the Delta estuary (far right). River restoration has been completed (dark segments) or is underway (light segments) in a program of phased reconnection to the main channel (Habersack et al. 2016, Hein et al. 2016)



California's 3000-km² Delta of the Sacramento and San Joaquin rivers (ESM-2.3) is a mosaic of streams and channels that receive water from 194,250 km², including the Central Valley. Channels support rare native fish and exotic biota. Only 3 % of the Delta's former wetlands are unfarmed. Agriculture dominates the drained wetland islands, which are surrounded by 1770 km of levees, which are vulnerable to earthquakes (Bates and Lund 2013). Water is withdrawn for irrigation and for redistribution state-wide, but with a federal-state mandate to consider nature and human needs equally (Delta Plan 2013). Uncertainties for achieving co-equal goals include rising sea level, subsiding islands, inadequate rainfall and snowpack, sequential droughts, salt intrusion, over-allocated water rights, endangered native fish, invasive fauna and plants, and greatly diminished wetlands. Meanwhile, twin tunnels have been proposed to transport more of the Sacramento River's water under the Delta to continue supplying thirsty customers in southern California, with uncertain impacts (Luoma et al. 2015). Phased restoration is planned for 12,140 ha, emphasizing habitat for rare fish and waterfowl. A review of eight early restoration projects (Nagarkar and Raulund-Rasmussen 2016) and a proposal to tailor restoration goals to Delta subregions (Lund and Moyle 2013) support the need for AM and *strategies to prioritize restoration* (DiGennaro et al. 2012, Woodruff and Stultz 2016). The lack of such strategies led Vleig and Zandvoort (2013) to characterize AM in the California Delta as *reactive* to specific indicators, compared to the Dutch *anticipatory* AM (envisioning future scenarios). A hybrid approach is recommended, with scientific manipulations and forward-looking, long-term projections (ibid.).

Opportunities for Holistic Approaches

Future innovators have many opportunities to *integrate* separate models to improve the management of estuaries and

coasts. We need integrated models to predict *holistic* changes in geomorphology, flooding, water quality, soils, ecosystem services, and human health (Robins et al. 2016). Estuarine ecosystems need to be resilient to future stressors, such as ocean acidification, storms, heat waves, floods, and droughts. The AM of estuaries and coasts must extend upstream to include watersheds.

Integrate Habitat and Hydrodynamic Models

Conceptual models for Suffolk's Blyth Estuary were the first stage in planning *salt marsh restoration* by removing dikes and allowing tides to flood agricultural land. The goal was to restore an 80-ha salt marsh as an adaptation to rising sea levels (French 2008). However, hydrodynamic modeling predicted catastrophic erosion in the outer estuary if such a large area were restored to tides, whereas small patches would avoid erosive flows. Thus, planners reduced the scale of salt marsh restoration (WIG 2013). In Finland, combining hydraulic modeling with long-term biological monitoring is advised to predict salmon responses to upstream restoration (Koljonen et al. 2013). In California (SCC 2016), extensive hydrodynamic modeling helps designers plan *estuary reconstruction* projects along the 1350-km coast. For example, models help designers plan the removal of historical fill in former oil-producing fields and the recontouring of topography to retain high ground for adaptation to rising sea levels. An ambitious example is Bolsa Chica near Los Angeles, where an ~\$150 million ocean connection and tidal basin were excavated and a highway bridge built in 2006; restoration of the 500-ha site is mostly complete (SCWRP 2016).

There should be ample opportunity to integrate habitat and hydrodynamic models and for experimentation to test model predictions in a 50-year project to *build deltas*, by redirecting flows of the Mississippi River (CPRA 2012). This river's delta has lost a quarter of its former 25,000-km² area due to flood

control levees and other modifications upstream. A \$50 billion plan would expand and restore the delta's ecosystem services within an AM framework. To build land rapidly and efficiently, Day et al. (2016) recommend large but rare water releases, rather than many small flows to reduce unintended negative impacts. See CPRA (2012) for the attention this project warrants.

Integrate Urban Stormwater Management and Estuarine Management

Estuarine water quality, annual flow volumes, and hydroperiods depend in part on the urban land use upstream (Simenstad et al. 2006). Thus, it becomes necessary to *couple estuary AM with watersheds*. If water management is extended to the region, then practices such as “harvesting stormwater” can reduce excess runoff from urban hardscaping (Fletcher et al. 2014). Harvested water can recharge groundwater or be stored in tanks for later use in irrigation. *Stormwater harvesting* might even abate urban warming (heat island effects). Trial watershed retrofits are urgently needed (Fletcher et al. 2014). Retaining water upstream not only helps reduce flooding and streambank erosion, it reduces contaminant and sediment loads to coasts. In Guam, a small-scale tree planting experiment in an eroding watershed allowed researchers to estimate that 11,000 trees (plus sediment filter socks) would stabilize sediments and protect coral reefs (Shelton and Richmond 2016).

Habitat restoration upstream to improve water quality downstream might require long time periods. In Portland, Oregon, four urban watersheds that flow into the Willamette River Estuary underwent restoration to improve water quality and biodiversity (Rios-Touma et al. 2015). Efforts included managing stormwater, planting native species, stabilizing banks, enhancing stream habitat, connecting floodplains, and improving access for salmonids from the Willamette River. The city of Portland used a *before:after/control:impact design* to identify effectiveness, based on conductivity, oxygen, macroinvertebrate indicators, substrate, coarse particulate organic matter, large wood pieces, and canopy cover. However, indicators did not improve substantially in 4 years. Rios-Touma et al. (2015) called for more time for the forest canopy to recover, so it can provide higher quality habitat for macroinvertebrate recovery. *Holistic assessment* requires long-term monitoring, large spatial scales, and multiple response variables.

Integrate Wetland Restoration and Nutrient Management

The global loss of wetlands might be as great as 87 % of the area that existed in 1700 (Davidson 2014). Some of those wetlands offer opportunities for restoration, which can be planned to support biodiversity or nutrient removal or other

ecosystem services within coastal watersheds. To date, most plans focus on one primary goal, e.g., habitat or flood abatement or nutrient management (mapped individually by Miller et al. 2012). Future innovators, however, need to predict and restore synergisms and tradeoffs among services—interactions that are not yet well known (Doherty et al. 2014). Next, planners will need to find optimal sites for restoring multiple services.

Aiming to manage both nitrogen and phosphorus is a step in the right direction (Paerl et al. 2014, Randall et al., 2015). In Germany, N and P sources and hotspots have been identified and used to *set limits for loadings to rivers* (Trepel 2016). Overall, predictions are that downstream waters cannot be protected simply by reducing agricultural sources of N and P. Upstream rivers and wetlands also need to be restored and buffered to fulfill nutrient management mandates, with preference to green approaches upstream, not concrete structures downstream. Where sufficient wetlands are not available for restoration, Trepel (2016) suggests using retention ponds, denitrification walls, and reactive ditches.

In Argentina, Kopprio et al. (2015) promote *wetland restoration within watersheds*, adding a call for large buffers between wetlands and human settlements to forestall effects of future conditions with more people, a warmer climate, and altered hydrological conditions. They provide a potential chain of causes and effects on estuaries, including prolonged water residence times, stratification, shifts in salinity and dissolved oxygen, more pollutants and nutrients, algal blooms, warmer and more anoxic sediments, greater water turbidity, and negative impacts on plants and animals. Pathogens and toxic cyanobacteria are also threats. Preserving, restoring, and creating wetlands could reverse eutrophication in Argentina, where there is still time to assess threats and set aside space to manage estuaries adaptively.

A meta-analysis of smaller unrestored, restored, and reference watersheds (Smucker and Detenbeck 2014) found that stream biodiversity and habitat conditions improved where contaminants were trapped upstream in stormwater ponds, created wetlands, and riparian vegetation. This begs the question: How does de-eutrophication relate to watershed size?

At the mouth of the Mississippi River, eutrophication and bottom-water anoxia remain extensive, despite AM efforts since 2001. The Action Plan has a watershed perspective, a goal to keep the mid-summer dead zone below 5000 km², monitoring since 1985, outstanding science, and advice to reduce nutrient loading (Rabalais et al. 2007). Nutrient-rich Mississippi River water is clearly the cause of algal blooms that lead to bottom hypoxia, and while nitrate is the main stressor, an exhaustive test (158 laboratory bioassays) demonstrated that *nitrogen can also act synergistically with phosphorus* to increase phytoplankton biomass more than either nutrient added alone (Turner and Rabalais 2013). Although extensive research supports nutrient control, the

watershed is immense ($>3,220,000 \text{ km}^2$), with stakeholders in 31 states and two provinces in Canada. De-eutrophication is progressing more slowly than in Denmark (land area = $43,000 \text{ km}^2$; ESM-1.1).

Watersheds need to be included in AM frameworks for estuaries and coasts (ELI and TNC 2014, Harding et al. 2016, Moreno-Mateos and Palmer 2016). Watershed approaches are needed to regulate nutrients in surface water discharges. Setting total daily maximum loads (TMDLs; USEPA 2016a, b) can help manage nutrients if standards are established appropriately (for both phosphorus and nitrogen), if suitable measures are taken (green infrastructure), if water quality is monitored (especially during stormflows), and if regulations are enforced. Desired outcomes are not met where municipalities only reduce the *predicted* total suspended solids (modeled instead of measured), and when the target is an average for several discharges, rather a requirement for all. In rural areas, goals are unmet when manure is spread onto frozen fields, where it can flow to the nearest stream with the first spring thaw (personal observation).

In the USA's largest estuary, Chesapeake Bay (ESM-2.4, with an 11,000-km long shoreline and $\sim 166,000 \text{ km}^2$ watershed), researchers are teasing apart the impacts of human actions and climate change on water quality and valued fish and shellfish. Chesapeake Bay showed early (1976–1992) reductions in nutrient loading as AM governance increased to involve multiple agencies and as goals evolved toward multiple bay-wide indicators of ecosystem health (Hennessey 1994). More recently, however, improvements in water clarity have slowed, which Harding et al. (2016) attribute to negative effects of wet and dry years, i.e., variable conditions counter the positive effects of reduced nitrogen loadings. TMDLs are now in place for both nitrogen and phosphorus. The ecology and AM of this complex system and its watershed warrant book-length treatment.

High-quality fishable/swimmable water is a compelling vision (USEPA 2016a, b), and watershed approaches are required to achieve it. Equally important is optimal water *quantity* for estuaries. Again, managers need to take a holistic, watershed approach.

Test Environmental Flows (eFlows)

Freshwater inflows are a major human influence on estuaries, which are sensitive to changes in salinity (Pierson et al. 2015). Upstream dams are often responsible for diverting river flows, while neglecting estuaries downstream (Montagna et al. 2009, Adams 2014). Without eFlows, the estuarine salinity gradient moves upstream, the freshwater pulse might not flush out contaminants, and productivity and fisheries will change in uncertain ways (Alber 2002). Differing salinity requirements of estuarine species preclude a simple target of mean annual runoff; hence, Estevez (2002) called for more study of the

quantity, timing, and quality of eFlows. AM has proven useful in determining optimum eFlows via sequential reservoir-discharge tests that are carefully monitored, using downstream data to improve models and adjust eFlows. Konrad et al. (2011) listed 41 rivers around the globe that have undergone experimental eFlows. However, in 2014, few tests were part of an AM framework, and those were mainly in the USA and Australia (Adams 2014).

Around the globe, eFlow targets for estuaries take different forms (Adams 2014). In Texas, eFlows are set to provide salinities that sustain commercial fisheries. In Florida, multiple methods are used to manage eFlows (Adams 2012). In a southwest district, development competes with eFlows and a percentage of daily flows is set to sustain ecosystems, while a southern district sets eFlows to sustain riverine cypress swamps and The Everglades target considers the needs of charismatic wildlife (large birds, alligators, otters, for which Congress mandated eFlows in 1970). Perhaps the most innovative target is for San Francisco Bay, where freshwater inflow from the inland Delta (ESM-2.3) is based on the distance in km of X2 (the 2-ppt isohaline, measured 1 m off the bottom; Jassby et al. 1995) from the Golden Gate Bridge. When X2 migrates as far as 75 to 81 km upstream (depending on season), eFlow is increased to sustain habitat for diverse salt-sensitive fish.

In Mozambique, the rare wattled crane (*Bugeranus [Grus] carunculatus*) depends on Zambezi Delta wetlands. Hydrodynamic modeling identified seven eFlow regimes from Cahora Bassa Dam that could benefit the water quality, waterbirds, vegetation, invasive species control in the estuary $\sim 650 \text{ km}$ downstream, while also supporting electrical power, agriculture, fisheries, and navigation (Beilfuss and Brown 2010). Beilfuss, who directs the International Crane Foundation, calls the effort to provide dependable eFlows “a perennial work in progress.” In 2003, the southern part of the Zambezi Delta became a Wetland of International Importance under the Ramsar Treaty, which promotes waterbird protection. In South Africa, a science-based approach gives priority to the requirements of an estuary before allocating water for other uses (Adams et al. 2002, Adams 2014). Individual eFlows are based on a reference site for each estuary, and a Health Index tracks progress from “extremely degraded” to “unmodified, natural” based on water quantity and quality, habitat, and biotic condition.

Estuaries with large inflows tend to be less sensitive to the variable effects of freshwater inflow than more saline estuaries with less freshwater inflow (Adams 2014, Prandle and Lane 2015). Coastal embayments with restricted seawater access are considered vulnerable sentinels for climate change, requiring long-term monitoring and AM to sustain highly valued ecosystem services (Newton et al. 2014). Even very large lagoons with small watersheds become eutrophic when nitrogen fixation occurs in situ and fuels algal blooms, as in Texas'

Laguna Madre (Gardner et al. 2006). In Mediterranean-type estuaries and lagoons, inflows tend to be restricted to cool season rainfalls. Without eFlows, they can become both hypersaline and stagnant. Southern California's small coastal lagoons can lose their ocean connection during neap tides or whenever longshore currents transport sand that blocks the mouth until the next erosion event. Without tidal mixing, this region's warm lagoon waters develop algal blooms that can cause anoxia and fish kills. Preventative bulldozing of the mouth of Los Peñasquitos Lagoon is triggered by high salinity and low dissolved oxygen. Similar AM is needed in saline estuaries of the Canning River in Western Australia, and Rietvlei near Capetown (Zedler et al. 2015), but not necessarily in temperate-climate regions.

Prolonged droughts and water diversions are major challenges for reservoir managers who are required to supply customers with water before releasing eFlows for estuarine biota. In a vicious attempt to obliterate Iraq's downstream Mesopotamian Marshlands and Marsh Arab residents, Saddam Hussain ordered the construction of dikes to divert upstream waters and immense channels to drain and desiccate a 20,000-ha wetland landscape by the 1990s. After Hussain was overthrown, dikes were breached and ~40 % of former wetland was rewetted from 2003 to 2007. However, new dams on the Tigris and Euphrates Rivers and diversions in Turkey and Syria usurped water supplies, and large areas of recovering wetlands were re-desiccated. Ecosystems leading to the Black Sea Delta experienced catastrophic losses of natural and human resources (Alwash, 2013, Stevens and Salman 2015). Political instability makes future water supplies uncertain, yet some Marsh Arabs continue their wetland-based culture in greatly diminished and altered wetlands, exploring opportunities for governmental action and international agreements (Fawzi et al. 2016).

Watershed-scale restoration is needed globally to provide more natural flows of improved quality water to coasts. An enticing vision is to restore and sustain the ecosystems that provide the world's most valuable ecosystem services, namely, estuaries (Costanza et al. 1997, 2014). Toward that vision, experimentation would help managers identify optimal approaches.

Restore Habitats as Experiments (Adaptive Restoration)

For some, the concept of experimentation implies too much risk to justify the effort. However, even a test that does not improve restoration leads to new knowledge. Interpretations can be blamed, but not experimentation. The ideal AR experiment is a field test of alternative approaches to identify significantly different outcomes, while indicating *how to improve* restoration. At Tijuana Estuary (ESM-1.2), we found greater growth of seedlings planted in tight clusters, near creeks and with soil amendments (O'Brien and Zedler 2006). Field

experimentation is quite feasible in salt marshes, seagrass beds, dunes, coastal prairies, and even tidal creek networks (Larkin et al. 2016, ESM-1.2). Other treatments of entire estuaries are not easily replicated, as for eFlows. As an alternative to repeating tests over time, some compare before:after/control:impact outcomes. Regardless of the experimental design, field tests need to be monitored before and after treatment.

AR has great potential for improving restoration of coastal and estuarine habitats by testing alternative soil amendments (or soil removal to de-eutrophy), introductions of plants and animals (numbers and combinations of species), herbivory (via exclosures or enclosures), pollinator limitation, and use of fire and pesticides to sustain vegetation, while only 15 papers reported large-scale experimentation in an early review (Wagner et al. 2008). The research record has since improved to support three meta-analyses of global scope. First, 89 studies found that restoration increased biodiversity and ecosystem services above degraded conditions, but not enough to match reference ecosystems (Rey Benayas et al. 2009). Second, 621 restored wetlands averaged 26 % lower in structural attributes than reference sites and 23 % lower in functions, especially carbon storage (Moreno-Mateos et al. 2012). Third, 70 restored wetlands (including 13 salt marsh or mangrove sites) were 16 % lower in supporting services and 22 % lower in regulating services than reference wetlands, although they matched desired levels of provisioning and cultural services (Meli et al. 2014). AR is an efficient means to reduce uncertainty among alternative restoration methods. I call the approach AR when field experiments simultaneously compare multiple actions, preferably in phased tests, so early results can inform later restoration (ESM-1.2, Zedler 2001; Larkin et al. 2008; Shelton and Richmond 2016).

AR of salt marsh in The Netherlands Ecologists tested three factors that influenced vegetation in a 120-ha former salt marsh: near/far breach, near/far creek, and $\pm$ grazing (Fig. 5) (Chang et al. 2016). Plots were sampled for a year before 3 creek mouths were cut to allow tidal influence. Surface soil salinity increased rapidly (Veeneklaas et al. 2015) and most of the target salt marsh species were present within 10 years, although community diversity was low. Based on ANOVA, the *interaction* between distance to the nearest creek and livestock grazing explained the most variation, i.e., the target high marsh developed *near a creek without grazing*, but not in other treatments. Accordingly, Chang et al. (2016) recommended variable grazing regimes for the higher areas to promote vegetation mosaics and prevent dominance by tall grasses; also, lower areas should retain soil drainage networks before de-embankment. The combined cause would not have been revealed by single-factor experiments.

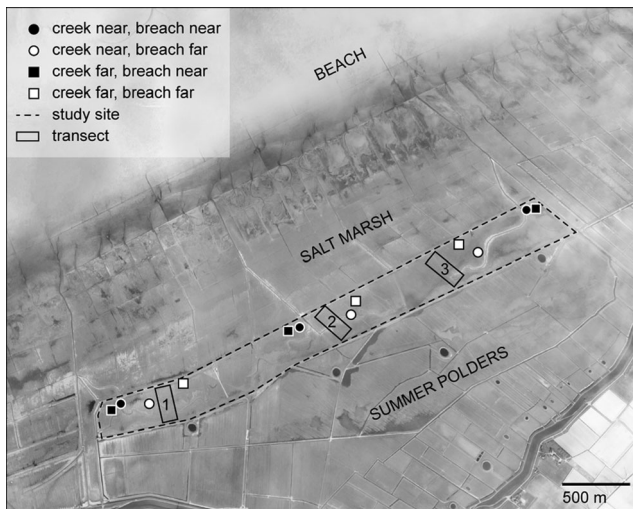


Fig. 5 Salt marsh restoration at Noard-Fryslân Bûtendyks, The Netherlands, is underway as AR in a 3-factor field experiment with 72 4×4 m plots comparing: near/far creek, near/far breach, and $\pm$ livestock grazing (via 12 exclosures). The 1.5-km² site has 3 catchments with artificial creeks (treatments from Chang et al. 2016; base image from Google Earth)

AR of Ponds in Guadalquivir Estuary Spain's Doñana Wetland is a Ramsar Wetland of International Importance with a former 2700-ha seasonal marsh that had been diked, drained, and cultivated since the 1960s. Instead of excavating one large lake for waterbirds, researchers designed a powerful experiment (96 ponds of the same age and history but different sizes, depths and isolation); they are now tracking bird and invertebrate prey use (Fig. 6). This AR approach followed the 1998 mine-waste spill into the Guadalquivir River, for which G. K. Meffe, T. Dunne, and I advised experimentation (2002, unpublished report). Indeed, diverse birds revealed habitat

Fig. 6 AR in Guadalquivir Estuary showed how pond size, depth, and isolation affect aquatic biota. Labels mark sampled ponds. Dark ellipses are two ponds that merged upon flooding (from Frisch et al. 2012; Feb. 2006 photo: Hector Garrido)



preferences among pond sizes, depths and locations (Sebastián-González and Green 2014). AR was feasible and fruitful.

AR of Salt Marsh in southern California Our 1997 salt marsh plantings restored a salt marsh while showing that 5 marsh plain species need to be planted, three can self-recruit and two can dominate (ESM-1.2) (Bonin and Zedler, 2008), and diverse plantings can increase production and nitrogen accumulation (Callaway et al. 2003). A companion greenhouse test of each of the 16 assemblages (Sullivan et al. 2007) and long-term field assessment showed that diversity effects faded over time. Our random, species-rich assemblages were overtaken by the regional dominant within 10 years (Doherty et al. 2011). In 2000, we planted only the poor recruiters to an 8-ha site, where we added a large-scale test of tidal creek networks. As predicted, tidal creeks favored fish use of the marsh plain (ESM-1.2). Soon, the third phase will scale restoration up to 100 ha (see tnerr.org).

In the future, “designer assemblages” could use plant traits to restore selected ecosystem functions, e.g., restoration practitioners could plant species that best resist weed invasions or provide other target services. Indeed, new trait-based mathematical models (Laughlin 2014) are predicting assemblage functions from *response* traits (which determine interspecific interactions and species’ tolerance to site conditions) and from *effect* traits (how a species affects an ecosystem service).

AR of Salt Marsh in Oregon Cornu and Sadro (2002) and Cornu et al. (2011) created three intertidal elevations within a diked, subsided estuarine wetland, and found that marsh elevation changed in relation to depth of fill material, correlated

with vertical accretion, influenced the size of tidal channels, affected abundance and species richness of salt marsh vegetation, and affected marsh fish density and species richness (Fig. 7). Their findings led directly to recommendations for future restoration: construct mid-marsh elevations to favor colonization by emergent marsh vegetation and allow vertical accretion to counter sea level rise; construct low marsh elevations to facilitate fish use of the marsh. At the same time, the researchers' monitoring approaches were refined to provide longer-term protocols.

Phased AR of salt marsh from ~1200 ha of salt ponds The San Francisco Bay's Shoreline Study outlines phased AM, which is considered a model approach (ESM-2.5) (USACE et al. 2015). Former commercial salt ponds are being restored to tidal influence to achieve a 50:50 ratio of salt marsh/pond area to maintain waterfowl and shorebirds. The target is flexible, with up to a 90:10 ratio of marsh/pond area, based on monitoring data. Uncertainties are being addressed in experiments, e.g., to learn how tidal flows erode channels (excavating starter channels rather than entire creek networks as in ESM-1.2). Large landscape units are being manipulated and monitored for sedimentation and wildlife use. Repetition over time will test cause and effect (USACE et al. 2015). Similar work is underway in San Diego Bay, where returning tides to former barren salt flats allows salt marsh vegetation to self-restore (pers. Obs. June 2016).

AR of Coastal Prairie in Oregon, USA Sandy coastal uplands are vulnerable to human and natural disturbances, and

eroded bare areas can be revegetated (ESM-2.6). To restore prairies, managers need to mimic historical disturbance regimes that favor native grasses over shrubs. That means optimizing the timing and intervals of historical disturbances, such as fires and shifting sands. A large field experiment in Oregon is field-testing herbicide application, topsoil inversion, and topsoil removal. Once results are clear, larger plots will receive the more promising treatments in an AR program (Welch et al. 2015).

Establish and Fund a National Restoration Act

Federal, state, and local agencies need to work with nongovernmental organizations to restore the nation's coasts and estuaries using AR. Asking governments to fund research and long-term monitoring is hardly innovative. In 1989, Milt Weller and I called for a National Wetland Restoration Act to move the practice from trial-and-error to science-based approaches to restore wetlands, especially their functioning (Zedler and Weller 1989). The Estuary Restoration Act of 2000 looked promising, and it catalyzed cooperation among five federal agencies and nongovernmental organizations, but the anticipated restoration is yet to occur. A National Restoration Act should fund comparisons of natural and constructed landscapes, regional sites that demonstrate the effectiveness of field experimentation, and a national database on ecosystem restoration. Our 25-year-old request draws support from nine recent calls to increase the scale and pace of restoration (ESM-1.3).

Conclusions

The uncertainties of future sea level rise and sea storms, land use intensification, and human actions all challenge our ability to manage waters and lands to serve the needs of ecosystems and people. A solution is to learn while managing and restoring, using adaptive approaches. Adaptive Management (AM) is now an essential means to learn while doing. Recent innovations help managers guide AM, confront uncertainty, engage stakeholders, improve governance, prioritize actions, and centralize the role of science, while global examples offer AM models. The future holds many opportunities to integrate models for habitat and hydrodynamics, link management of stormwater upstream to estuaries downstream, and manage nutrients while restoring wetlands. Any reluctance to manage adaptively should yield to science-based decision-making, from project inception forward. At its best, AM can sustain biodiversity and ecosystem services and deal with an uncertain future.

Adaptive restoration (AR) simultaneously recovers ecosystems and accumulates knowledge from experiments that test alternative actions, such as plantings, soil amendments, weed abatement, and contoured topography. Experimentation is



Fig. 7 At South Slough National Estuarine Research Reserve in Oregon, USA, a 10.4-ha AR experiment showed how marsh plain elevation affected tidal channel development and salt marsh restoration (treatments from Cornu et al., 2011; base image from Google Earth)

needed to reduce the uncertain outcomes of unique species combinations, site-specific environmental conditions, and varied stakeholder advice. Where restoration actions can be replicated, well-designed research will lead to cause–effect understanding. For tests of eFlows, temporal repetitions and before:after/control:impact comparisons substitute for spatial comparisons. AR is an efficient and powerful way to learn what works well—and why—in actual restoration sites.

Ecosystem management and restoration both improve when projects are adaptive, long-term, large-scale, and holistic. Watershed approaches are emerging, e.g., the Wisconsin model allows a planner to select suitable subwatersheds and restorable wetlands to help recover downstream coastal ecosystems (water quality and habitat). Integrative approaches are also emerging to achieve multiple goals simultaneously. The iterative use of new knowledge in AM and AR can improve outcomes while restoring millions of hectares of degraded estuaries and coasts around the globe. For the USA, a National Restoration Act would expand and support AR, while aiming for resilient coasts and estuaries.

Acknowledgments When I was 5 years old, my dad introduced me to restoration by disassembling our farmhouse, keeping all the parts, and teaching me to straighten bent nails for re-use. He learned carpentry while building, and I absorbed his adaptive approaches. Thanks to all my adaptive collaborators and to CERF for finding our work worthy of an Odum Lifetime Achievement Award. My supportive family (Drs. Paul, Sarah and Emily Zedler), illustrator (Sarah Friedrich), and reviewers (John Callaway, Iris Anderson, Si Simenstad, and Wayne Gardner) were very helpful.

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