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RESEARCH

Management of Tidal Wetland Restoration and Fish in the Upper San Francisco Estuary:
Where Are We Now and How Do We Move Forward?

A Summary of the 2023 Wetland Science Symposium

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ABSTRACT

Tidal wetland restoration to benefit at-risk fish species in the Sacramento–San Joaquin Delta and Suisun Marsh has gained momentum over the past decade, much of it in response to mitigation requirements for the State Water Project and Central Valley Project. In fall 2023, the Department of Water Resources and the State Water Contractors convened a symposium, entitled *Delta–Suisun Tidal Wetland Restoration Symposium: State of the Science and Future Directions*, to discuss the latest wetland restoration research and future directions. The symposium was held 10 years after the 2013 symposium *Tidal Marshes and Native Fishes in the Delta: Will Restoration Make a Difference?*, and so served as an opportunity to follow up on the progress that has been made over the past decade. This paper synthesizes the key findings from the 2023 workshop.

The paper begins with the historical context of wetland restoration in the Delta and Suisun Marsh, and outlines the restoration process as it is currently implemented. It then describes the monitoring of tidal wetlands in terms of their capacity to support fish (*capacity*), the opportunity fish have to use the habitat (*opportunity*), and the *realized functions* provided when fish actually use the site.

Finally, the paper identifies priority science actions to advance our understanding and management of tidal wetland restoration sites. These actions include further research into fish habitat utilization, improved monitoring techniques, and enhanced adaptive-management strategies. This list of information needs is intended to inform future monitoring of restoration sites, scientific studies, funding, and prioritization of wetland research.

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KEY WORDS

Chinook Salmon, wetland, marsh, restoration, science priorities, estuary, Delta Smelt, Longfin Smelt

BACKGROUND

The 2023 Tidal Wetland Science Symposium

In fall of 2023, the California Department of Water Resources (CDWR) and the State Water Contractors (SWC) convened a symposium entitled *Delta–Suisun Tidal Wetland Restoration Symposium: State of the Science and Future Directions*. The symposium was held to review the state of the science in management, modeling, and monitoring of tidal wetland restoration projects in Suisun Marsh and the Sacramento–San Joaquin Delta (Delta). The restoration projects were built to benefit at-risk fishes (collectively defined as Delta Smelt *Hypomesus transpacificus*, Longfin Smelt *Spirinchus thaleichthys*, and Chinook Salmon *Oncorhynchus tshawytscha*). More than 80 scientists, restoration practitioners, and resource managers attended the day-long workshop in person, and another 150 participants attended virtually.

This symposium was a follow-up to the 2013 symposium *Tidal Marshes and Native Fishes in the Delta: Will Restoration Make a Difference?* held at the University of California–Davis, on June 10, 2013, and summarized in Herbold et al. (2014). In 2014, there was no consensus among experts on the benefits of tidal wetlands to native fishes, but it was concluded at the time that wetland restoration should proceed “boldly but carefully” and be accompanied by studies to fill information gaps.

Ten years after the 2013 symposium, the goals of the 2023 symposium were to:

- Provide a forum for wetland scientists and restoration practitioners to collaboratively discuss the research, modeling, and monitoring of tidal wetland benefits to at-risk fishes.
- Identify high-priority science activities (research, modeling, and monitoring) needed to support adaptive management of wetland restoration sites.
- Identify high-priority adaptive-management activities needed to maximize the effectiveness of wetland restoration.

The 2023 symposium provided a venue for assessing the current scientific understanding of restored tidal wetlands, specifically the capacity of restored wetlands’ to support fish, opportunity for fish to access resources, realized functional responses by fishes (the “effectiveness” of the restoration site; Simenstad and Cordell 2000), and tools to inform restoration design. Several restoration projects have been built since the 2013 symposium, with construction of others ongoing at the time of this paper’s publication (Figure 1). Effectiveness monitoring and research projects conducted on these restoration sites—combined with previous research on relic wetlands and unintentional restorations—are beginning to provide insights into wetland functions that benefit fishes. While directly assessing whether these sites are functioning as intended (providing habitat and food supply for at-risk fishes) is ideal, it is necessary to collect data throughout site evolution and over a range of hydrological conditions before it will be appropriate to fully assess their efficacy in providing these benefits to native fishes. It can take years, if not decades, for restoration sites to reach functional equivalency to natural wetlands (as reviewed in Moreno–Mateos et al. 2012). Therefore, the symposium assessed our current understanding, but did not draw conclusions about the “success” of these sites.

In this paper, we summarize the material presented in the symposium:

- We start with regulatory context and history of wetland restoration for at-risk fishes, with a description of avenues for scientific input into the restoration process.
- We then present the opportunity–capacity–realized function framework used to monitor the effectiveness of tidal wetland restoration in the estuary, and a brief review of monitoring to date.
- We end with a presentation of topics discussed during symposium break-out sessions and follow-up meetings after the symposium. These topics reflect high-priority science and

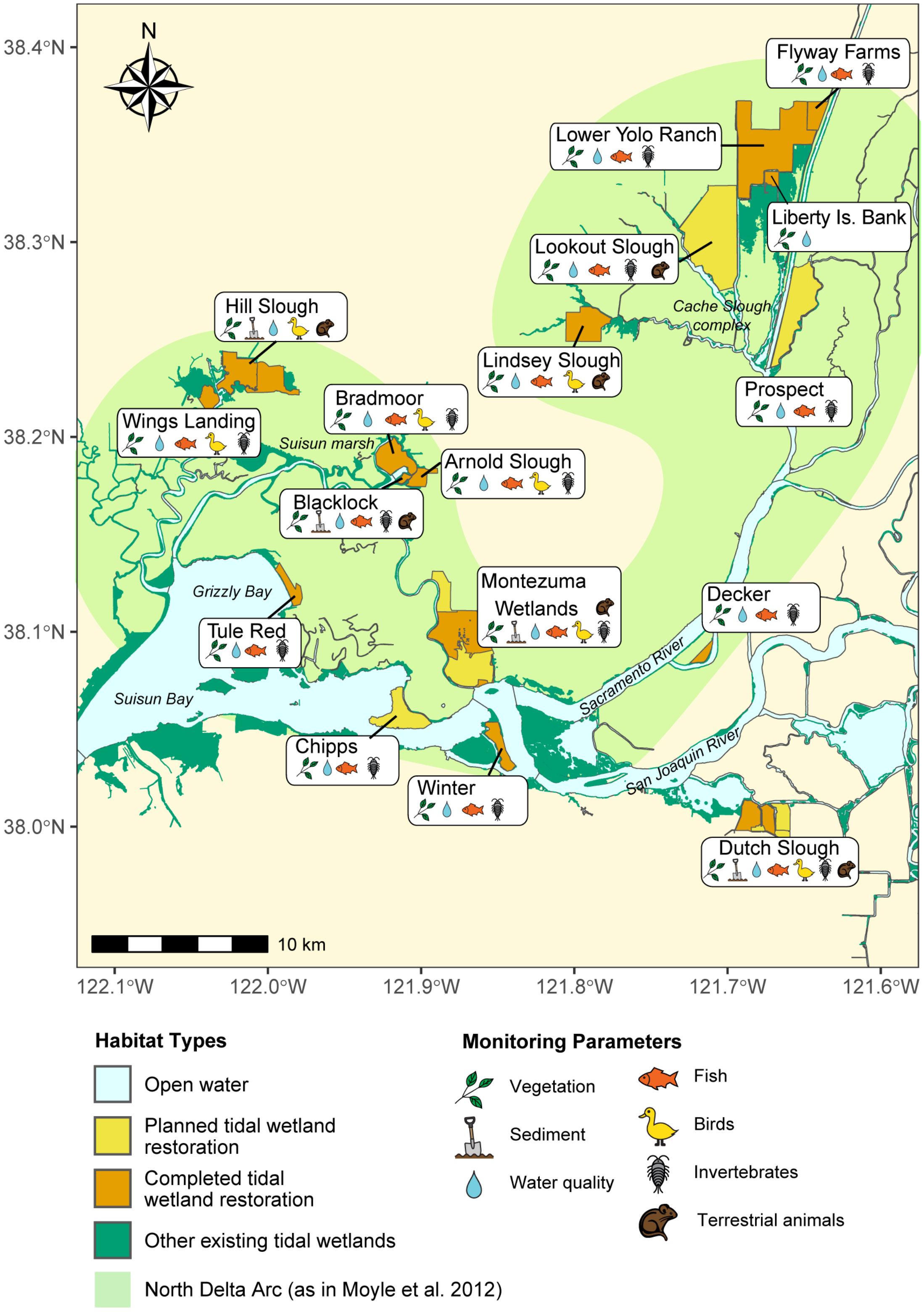

Figure 1 Map of intentional tidal wetland restoration areas in the Delta and Suisun Marsh, with existing tidal wetlands (either relic wetlands or unintentional restorations) in the upper estuary. This map includes all known tidal wetland restoration sites intentionally built in the region since 2000, and highlights the "North Delta Arc" (Moyle et al. 2012). The *icons* in each label indicate the broad categories of constituents monitored post-restoration. Time-frames of monitoring vary by site.

management actions that would improve our understanding of wetland restoration for at-risk fishes, as well as the importance of communication to move restoration forward.

Regulatory Context

Many fish species in the Delta have declined over the past several decades, likely related to low food availability and many other stressors (Sommer et al. 2007). Delta Smelt, Longfin Smelt, winter- and spring-run Chinook Salmon—among other species—are currently listed under the federal and/or California Endangered Species Acts. The fishery agencies responsible for permitting incidental take of these species require avoidance, minimization, and mitigation measures for activities likely to harm these fishes or their critical habitat.

Tidal wetland restoration is one such mitigation measure for the operation of the Central Valley Project (CVP) and State Water Project (SWP), with the intent of bolstering food web and habitat resources for listed fishes. The federal Endangered Species Act Biological Opinions for the CVP and SWP (BiOps), together with the Incidental Take Permit (ITP) for the SWP, require ~8,400 acres of tidal wetland restoration and an associated effectiveness monitoring program (NMFS 2019; USFWS 2019; CDFW 2020).

Along with the restoration that the BiOps and ITP mandate, restoration projects in the Delta must also be consistent with the Delta Plan, a comprehensive long-term regional management plan whose development was required by the 2009 Delta Reform Act (Simitian and Steinberg 2009), which calls for additional acreage of tidal wetland restoration for general ecosystem enhancement (a total of 32,500 acres). This includes acreage called for by the Suisun Marsh Habitat Management, Preservation, and Restoration Plan (USFWS et al. 2013), which is another regional management plan (5,000 to 7,000 acres).

Tidal wetland restoration built under the 2008–2009, 2019–2020 BiOps and ITP for listed fishes is based on a scientific adaptive-management framework layered on top of several sets of regulatory and permitting mandates. Adaptive management—a flexible decision-making process for ongoing knowledge acquisition, monitoring, and evaluation that leads to continuous improvements in project management, planning, and implementation—is considered best practice in restoration projects (Nagarkar and Raulund–Rasmussen 2016; Zedler 2017). Moreover, an adaptive-management plan is required for a restoration project to be consistent with the Delta Plan. Project adaptive-management plans are based on detailed conceptual models, and utilize a standard format for data collection, metrics definition, intervention thresholds, and potential management responses (WES 2016; IEP TWM PWT 2017).

The exact process of how a restoration site is conceptualized, designed, and built varies somewhat from site to site and region to region, but the basic steps—from design to permitting to construction—follow Figure 2 (expanded on in Appendix A). This restoration process includes multiple opportunities for scientific input throughout the adaptive-management life-cycle, including at project inception, and during the design, permitting, and monitoring phases. While manipulating existing restoration projects post-construction is technically possible, permitting, logistical, and budgetary constraints may render it infeasible (but see the Sonoma Creek Restoration Project for an example of lessons learned from the implementation of an initial restoration being incorporated into a second phase of site construction to improve tidal exchange—5 years *after* initial restoration actions; Audubon California 2024). Thus, incorporating lessons learned from previous projects into future projects is an essential aspect of the adaptive-management process in practice (Robinson et al. 2016).

While many types of habitat restoration have been proposed, here we specifically consider restoration of fully tidal wetlands where changes to water levels are caused primarily by the force of the tides, not altered by artificial water-control structures. We define "tidal wetlands" as areas between low-low tide and high-high tide that

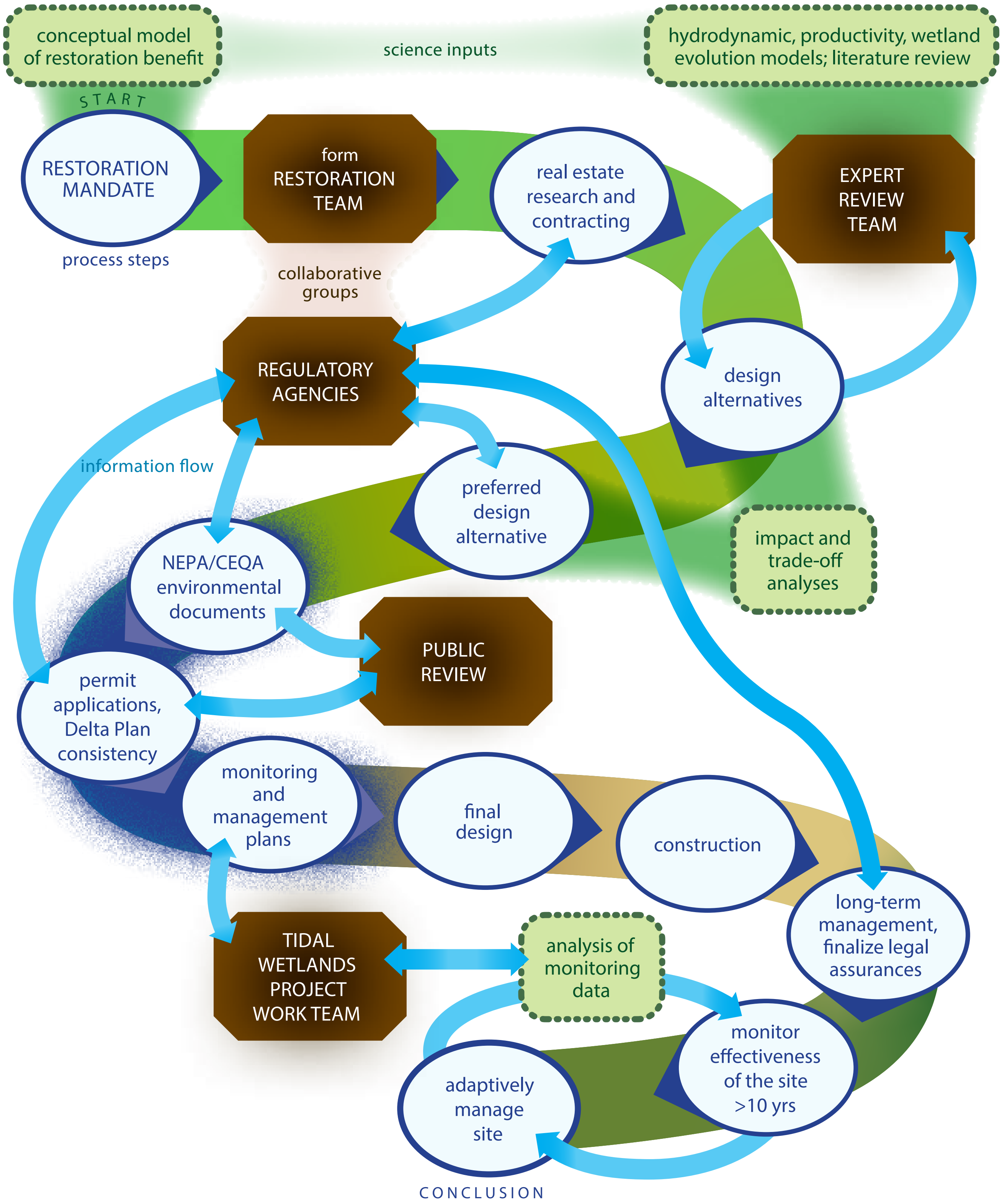

Figure 2 Steps in the process of constructing and evaluating tidal wetland restoration sites for fish. CEQA: California Environmental Quality Act; NEPA: National Environmental Protection Act.

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are dominated by emergent vegetation with associated channels and subtidal areas. We do not include shallow tidal lakes dominated by submerged vegetation. We also do not include managed wetlands (where artificial structures influence site inundation). Managed wetlands provide many benefits for fish and wildlife (Aha et al. 2021; Schacter et al. 2021; Williamshen et al. 2021), particularly in Suisun Marsh where managed wetlands designed for waterfowl dominate the landscape (Moyle et al. 2014). While there is ongoing research into how managed wetlands may benefit fish and aquatic primary production, this paper focuses on fully tidal wetlands as mandated by the BiOps and ITP.

There is now a patchwork of tidal wetland restoration sites built under the BiOps and other initiatives across the Delta and Suisun Marsh (Figure 1), layered on top of a few relic wetlands and unintentional "restoration" caused by levee breaches (Figure 1). Out of the 32,500 acres of restoration included in the Delta Plan, more than 5,000 acres have been completed, and an additional 6,000 acres were in planning or construction at the beginning of 2024. Taking a landscape-scale approach, as suggested by Herbold et al. (2014), many of these sites are concentrated in the "North Delta arc" of native fish habitat. This region stretches from the Cache Slough complex in the North Delta through the confluence of the Sacramento and San Joaquin rivers and into Suisun Marsh. These regions have been highlighted by numerous scientists as important refugia for native fishes (Moyle et al. 2012; Brown et al. 2024), so restoration practitioners have targeted these areas for additional restoration that benefits at-risk fishes (Hobbs et al. 2017).

FRAMEWORK FOR MONITORING RESTORATION SITES: CAPACITY-OPPORTUNITY-REALIZED FUNCTION

Presentations at the symposium focused on results from modeling and monitoring tidal wetland restoration sites to identify what the community has learned. In intentional restoration sites, post-construction monitoring is an integral part of adaptive management and can occur at several levels. Most regulatory permits require some level of compliance monitoring—ensuring the site is built as specified. However, to evaluate whether the site is having the intended ecological benefits, more in-depth, long-term effectiveness monitoring is necessary (i.e., monitoring functional responses of wetland restoration; see IEP TWM PWT (2017) for a full discussion of monitoring). For example, restoration and monitoring in compliance with the BiOps is carried out jointly by the CDWR and CDFW via the Fish Restoration Program (FRP) (CDWR and CDFG 2010). Post-construction monitoring is ongoing but has provided enough monitoring data to identify gaps and opportunities for further research. Monitoring of restoration sites can also be combined with research on relic and unintentional restoration sites to better understand the benefits of wetlands for at-risk fishes.

In an estuary with ever-increasing non-native species diversity and abundance (Mahardja et al. 2020; Boyer et al. 2023) and undergoing climatic extremes (Dettinger and Cayan 2014; Herbold et al. 2022), many years of monitoring data will be required to evaluate the effectiveness of tidal wetland restoration projects. Globally, many wetland-restoration projects require years, if not decades, to reach the same levels of ecosystem structure and function as reference wetlands (Moreno–Mateos et al. 2012). Restoration practitioners aim to develop monitoring programs to show whether smelt, salmon, and other target species spend time in restoration sites where they experience improved foraging success, growth, and survival—metrics of *realized function* (*sensu* Simenstad and Cordell 2000). However, such benefits are difficult to detect in the wild because of the difficulty in detecting rare, at-risk fishes. It may be necessary to develop new monitoring methods or conduct field experiments with cultured fish to provide information on realized function. The *capacity* of restored tidal wetlands to support fish, through favorable abiotic conditions and abundance of appropriate prey, can more easily be measured, as can the *opportunity* for wild fish in the area to access the habitat and associated food resources (Simenstad and Cordell 2000).

This “capacity–opportunity–realized function” framework was first proposed by Simenstad and Cordell (2000), and used in evaluation of many restoration sites in estuaries of the Pacific Northwest. For example, synthesizing studies of the capacity, opportunity, and realized function at more than 150 locations throughout the lower Columbia River Estuary, Diefenderfer et al. (2016) found that hydrologic reconnection (opportunity) increased export of detritus, increased salmonid prey availability (capacity), and increased juvenile fish access and feeding (realized function). Taken together, this was evidence that the restoration program had increased the resiliency of the salmon population. Similarly, in the Nisqually River Delta, monitoring showed the restoration sites’ capacity to produce food for juvenile salmon (Ellings et al. 2016; Woo et al. 2017), providing similar bioenergetic growth potential (realized function) as reference sites (David et al. 2014). Notably, this framework is useful for assessing individual restoration sites, but can also be scaled to a larger region, to synthesize the cumulative effects of multiple restorations.

Given the utility of the capacity–opportunity–realized function framework in evaluating restoration effectiveness in other estuaries, the Interagency Ecological Program Tidal Wetlands Monitoring Project Work Team (IEP TWM PWT) adopted the idea for inclusion in their set of conceptual models, which inform restoration monitoring in the Delta and Suisun Marsh (Sherman et al. 2017). These conceptual models and accompanying monitoring framework are the foundation for the FRP’s monitoring and adaptive-management plans, and are recommended for other effectiveness monitoring programs as well (see also IEP TWM PWT 2017). Each FRP restoration site is monitored before restoration (if possible) and for 10 years post-restoration; not all restoration programs have the mandate or resources for this type of long-term monitoring. Additional data are collected in surrounding channels to evaluate the influence of restoration in neighboring areas and at nearby wetlands (called reference sites) to provide a point of comparison. These structured monitoring data are critical to effective adaptive management, and each FRP restoration project has prepared a site-specific adaptive-management plan to satisfy Delta Plan requirements (DSC 2013b).

The 2023 symposium brought together scientists across agencies and universities to jointly present and discuss findings and future directions within the context of capacity (abiotic and food web), opportunity (restoration design and invasive vegetation), and realized function (fish responses). The following is not a comprehensive assessment of the state of tidal wetland restoration for at-risk fishes, but rather a discussion of how capacity, opportunity, and realized function (Figure 3) can be used to inform management decisions.

CAPACITY – PHYSICAL HABITAT, WATER QUALITY, AND PRODUCTIVITY

Physical Habitat

Capacity, as defined by Simenstad and Cordell (2000), describes habitat attributes such as favorable abiotic conditions (see Water Quality section below) and abundance of appropriate prey (see Productivity section below) that promote fish foraging, growth, or decreased mortality. Wetland geomorphology plays an essential role in driving capacity because wetland depth, channel networks, and substrate influence water quality, primary productivity, and invertebrate productivity. Global research on natural tidal wetlands indicates that channel sizes and depth features play an important role in primary production (Christian and Allen 2014; Andrews 2020) along with predator (Whitfield 2020) and thermal refugia (Madon 2008) for wetland-rearing fishes (Desmond et al. 2000).

In the estuary, dendritic channels have been identified as a key feature of natural tidal wetlands, with variation in habitat morphology significantly affecting the hydrodynamic properties of each wetland (Malamud–Roam 2000) and influencing fish distribution and prey availability (Desmond et al. 2000; Visintainer et al. 2006). However, wetlands in the upper estuary

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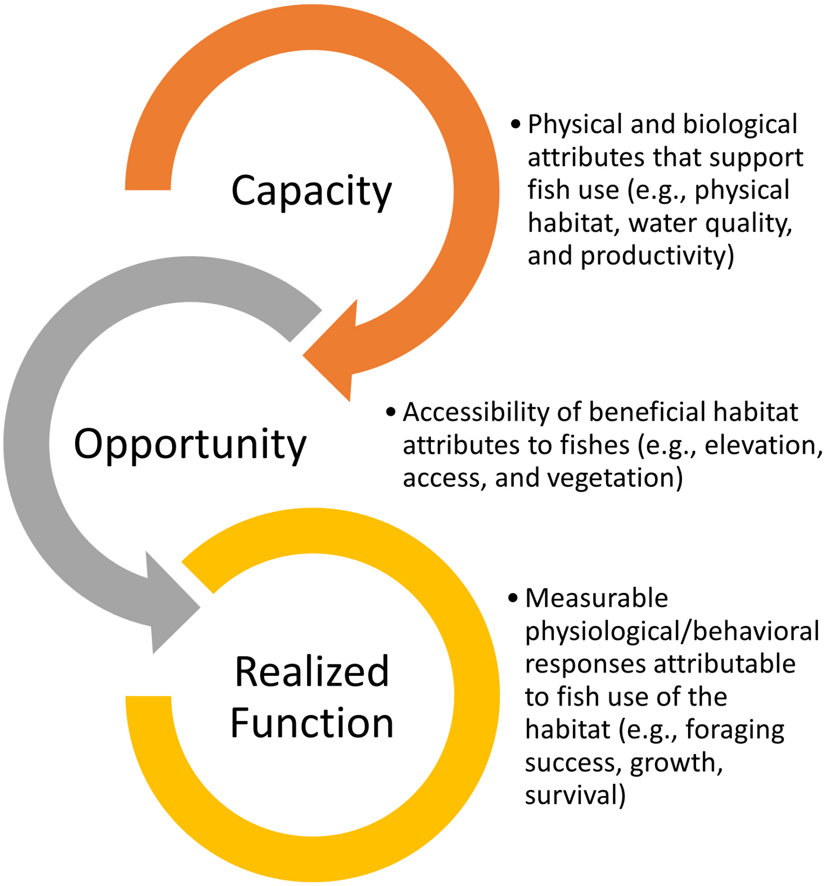

Figure 3 Diagram showing how capacity, opportunity, and realized function can be used to design monitoring programs

have a range of geomorphologies, reflecting their history. Some wetlands have a dendritic structure of branching tidal channels of varying size, incorporating elements such as pannes or ponds (such as Rush Ranch Open Space or Brown's Island). Others reflect the agricultural history of the Delta and are flooded polders, lacking both defined channel structure and traditional tidal floodplains (such as Liberty Island, see Lehman et al. 2010; Clause et al. 2024). Still others reflect even more anthropocentric origins and uses, such as wetlands that are intentionally disconnected from surrounding water bodies and actively managed for seasonal waterfowl (Casazza et al. 2021; Williamshen et al. 2021)—historically at the expense of habitat connectivity and local water quality.

Although contemporary wetland restoration design focuses primarily on multiple channel order networks, symposium participants highlighted the fact that the broad portfolio of wetland types in the estuary offers important learning opportunities. For example, dendritic channel networks, flooded polders, and managed wetlands all have different hydrodynamic attributes (e.g., water velocity, water exchange, and residence time), and by comparing habitat attributes with habitat capacity, we may be better able to inform restoration design for specific ecological outcomes. Various numerical models have been developed in recent years that can help link hydrodynamic attributes and ecological outcomes (Andrews 2020; Stumpner, Burau, et al. 2021). For example, Delta-wide hydrodynamic models have indicated variability in the historical frequency of tidal wetland inundation (Andrews et al. 2017), with current research focused on quantifying the effect of tidal wetland configuration and elevation on water velocity, residence time, and pelagic primary productivity (Stumpner, Andrews, et al. 2021). Moving forward, this approach could be applied to tidal wetlands that range from flooded polders to dendritic channel networks. Doing so would provide insight into optimizing the productive capacity of tidal wetlands through both prototypical landforms and new restoration designs—and is foundational to predicting ecological outcomes of landscape-modification projects.

Water Quality

Water quality—meaning physical and chemical properties of the water, including temperature, turbidity, salinity, and dissolved oxygen—serves as a primary determinant of fish habitat capacity in tidal wetlands (Simenstad and Cordell 2000). Availability of suitable fish habitat—such as appropriate temperatures and dissolved oxygen, and sufficient turbidity for predator avoidance—is linked to the site's capacity. Therefore, discrete and continuous measurements of water-quality parameters are taken as part of FRP tidal wetlands monitoring (Sherman et al. 2023) and almost all other wetland studies (see Lehman et al. 2010; Howe et al. 2014; Feyrer et al. 2021, among many others), with recent insights into spatial and temporal patterns of water quality. In particular, high-frequency collection of water-quality parameters using multi-parameter sondes can identify ephemeral events or short-duration variability that discrete sampling events can miss. In addition, high-resolution spatial-mapping techniques, either by boat or by air, complement *in situ* monitoring efforts by providing insights into the spatial variability of water quality within tidal wetlands (Gustine et al. 2023; Brown et al. 2024). Hydrodynamic and water-quality modeling can be used when designing restoration sites to anticipate changes to salinity, turbidity, and flow (RMA 2015).

Wetland geomorphology influences local hydrodynamics, and thus can substantially affect local water quality (Enright et al. 2013). For example, research in the estuary's tidal wetlands has shown that tidal wetland water temperatures may be cooler than surrounding habitats (Gustine et al. 2023). High hydrodynamic residence time in wetlands, particularly in terminal wetland channels, may lead to high chlorophyll concentrations (Brown et al. 2024), which provide an increase in overall primary productivity in the wetland. Wetland turbidity generally reflects turbidity trends in the surrounding water bodies, although expansive shallow open water may provide opportunity for re-suspension of sediments and increased turbidity (Lehman et al. 2015; Brown et al. 2024). In contrast, extensive vegetated areas in the wetland will decrease water velocity and turbidity (Work et al. 2020).

Symposium participants suggested that expanding the temporal and spatial resolution of water-quality monitoring may improve the ability to accurately describe capacity. Increased resolution would identify times and areas where habitat capacity may be compromised by localized degradation or pollution, or areas that have particularly high productivity (Bergamaschi et al. 2020). These monitoring efforts provide valuable insight into the habitat suitability of restored wetland habitats relative to reference or exterior habitats, as well as the suitability of micro-habitats within spatially complex wetlands (e.g., the back marsh in the Tule Red restoration area). Further research that identifies how variability in water quality (especially temperature, turbidity, and dissolved oxygen) across different wetland geomorphologies and locations could contribute to habitat quality for fishes of interest and would directly link abiotic capacity to fish functional responses and tidal wetland restoration design.

Productivity

Net aquatic primary productivity of wetlands—including vegetation, phytoplankton, and attached microalgae—is expected to outweigh all other habitat types if tidal wetland restoration acreage goals are met (Cloern et al. 2021); thus, productivity is the mechanism explicitly hypothesized by restoration practitioners to increase capacity (Herbold et al. 2014; Sherman et al. 2017). This elevated primary productivity of tidal wetlands supports a diverse invertebrate community, including zooplankton, and epiphytic, epibenthic, and drift invertebrates (Howe et al. 2014; Kimmerer et al. 2018; Hartman et al. 2019; Young et al. 2021)—measurement of which is key to assessing the benefits of these habitats.

Research to date on invertebrates in tidal wetlands often focuses on one of these taxonomic or functional groups at a time. For example, several studies have shown that benthic and drift macroinvertebrates are more abundant in tidal wetlands than open-water areas in the estuary (Howe et al. 2014; Hartman et al. 2019) and that wetland zooplankton communities differ across areas of the estuary (Bollens et al. 2014; Hartman et al. 2022). Several studies of net export of zooplankton have been conducted and found that results are highly variable for the copepod *Pseudodiaptomus forbesi* (Kimmerer et al. 2018; Yelton et al. 2022), or the mysid shrimp *Neomysis kadiakensis*, but only examined these two species.

Symposium participants recognized that monitoring each invertebrate functional group helps to understand the productivity of a wetland, but a more holistic assessment is required to better understand the effectiveness of the project in providing benefits for at-risk fishes. The FRP is currently evaluating recent and upcoming restoration sites using a "before–after, control–impact" analysis across all the aforementioned invertebrate communities (e.g., zooplankton, macroinvertebrates) that represent the forage base for at-risk and other native fishes. These data can be combined with habitat-specific fish diets to help assess how productivity affects fish capacity by identifying the invertebrate functional groups (and underlying habitat features) that restoration designers should prioritize. For example, existing Delta Smelt diet studies have mostly occurred in open water, but when Delta Smelt are captured in areas with tidal wetlands they are more likely to have eaten wetland-associated invertebrates (Slater and Baxter 2014; Whitley and Bollens 2014).

Additional research is needed because habitat-specific diets likely vary across several factors, including ontogeny, prey availability, and prey quality. In particular, zooplankton are the most commonly monitored invertebrate in the estuary, but epibenthic, epiphytic, and drift invertebrates may make up a larger percentage of available fish food in tidal wetlands (O'Rear 2012; Hartman et al. 2019; Colombano Handley, et al. 2021). Ultimately, a better understanding of links between wetland geomorphology, primary production, secondary production, and prey consumption would allow for capacity-driven monitoring to inform adaptive management of tidal wetlands.

OPPORTUNITY—ELEVATION, ACCESS, AND INVASIVE AQUATIC VEGETATION

Elevation and Access

Opportunity, as described by Simenstad and Cordell (2000), refers to the ability of fish to access and benefit from a given habitat's capacity. Many elements affect opportunity, including location along the salinity gradient (Feyrer et al. 2021), tidal elevation (Ziegler et al. 2019), geomorphology (Simenstad et al. 2000), proximity to artificial structures (Lehman et al. 2019), and predation risk (Boswell et al. 2019; Jones et al. 2021). However, land elevation has perhaps the most ubiquitous effect on the habitat opportunity of tidal wetlands within the estuary and beyond. Numerous studies from other systems have shown that land elevation interacts with the local tidal regime to generate constant temporal variability in the depth and spatial extent of wetland habitat (Kneib et al. 2008; Ziegler et al. 2021). In addition, work from the estuary shows that variation in landform elevation (e.g., a dendritic channel network) generates spatial variability in water depth and topography (Visintainer et al. 2006; Gewant and Bollens 2012). Together, these features can result in an aquatic environment that possesses variation in aquatic habitat conditions across both space and time, which may facilitate niche partitioning and coexistence of diverse fish assemblages.

The spatio-temporal variability inherent in natural tidal wetlands (described above) likely influences habitat opportunity for many fish species, though data from the estuary is currently lacking and we must draw inferences from other tidal wetland systems. For example, research in the southeast United States shows that small and juvenile fishes use shallow intertidal areas where their larger-bodied predators may face stranding risks (Kneib and Wagner 1994; Rozas 1995; Brose et al. 2019) and less effective foraging (Munsch et al. 2016). Edge habitat and connectivity is also seen as important in the estuary (Gewant and Bollens 2012), though predation risk was not specifically analyzed. However, intertidal habitat often dewaters on ebb tide, obliging these juvenile fishes to emigrate (Bretsch and Allen 2006; Hering 2010). Predator fishes may respond to this tidally driven pattern by intercepting prey in deeper water at low tide (Tupper and Able 2000; Colombano, Handley, et al. 2021). Research in other systems shows that juvenile fishes often return to intertidal areas as soon as their minimum depth threshold is reached again during the flood tide (Bretsch and Allen 2006; Hering 2010; Boswell et al. 2019). These water-depth-to-body-size relationships may play an important role in defining both foraging and refuge habitat, but still need to be studied locally, as much of this knowledge comes from other regions.

The ability of sites to act as nurseries—areas where juvenile fish can grow to maturity—is at least partly driven by the interaction of tides and wetland elevation (Colombano, Manfree, et al. 2020, the latter of which restoration practitioners control (Metzger and Brancalion 2016). Early restoration sites in the estuary frequently had simplified geomorphology that did not emulate the historical Delta (Nobriga and Feyrer 2007; Callaway et al. 2011), which often consisted of four channel orders or more (Whipple et al. 2012). These simple restoration designs were driven by the high costs of channel excavation and expectations that more extensive channel networks would evolve over time (Callaway et al. 2011). More recently, wetland scientists have documented the benefits of heterogeneous channel networks, such as those found at Rush Ranch Open Space and the Liberty Island Conservation Bank (Colombano, Donovan, et al. 2020; Colombano, Handley, et al. 2021; Clause et al. 2024), and restoration practitioners have begun using this approach (CDWR and CSCC 2014; ICF and WES 2016). In addition to field research, *a priori* modeling can now be used to estimate the functional connectivity of tidal networks based on the preferred depth ranges of target fish species (Alp and Le Pichon 2021). This approach—using species-specific depth ranges from the literature validated through fish movement (Hering et al. 2010) and predation studies (as reviewed in Whitfield 2020)—appears to be a promising path toward estimating spatio-temporal refuge from predation, an important driver of habitat opportunity for fishes.

Invasive Aquatic Vegetation

The aquatic vegetation community in the Delta is dominated by non-native species (Christman et al. 2023), and some species have growth and proliferation habits that become invasive in the system, overtaking native species and dominating shallow-water habitats and the marsh plain (Brazilian waterweed (*Egeria densa),* Santos et al. 2011; water primrose (*Ludwigia peploides),* Khanna et al. 2018; common reed (*Phragmites australis),* Hagani et al. 2023). Tidal wetland restoration sites are particularly vulnerable to invasion by floating, submerged, and emergent aquatic plants because they present new habitat suitable for many of the species present in the Delta (Christman et al. 2023).

Proliferation of non-native vegetation in restored tidal wetlands will limit opportunities for access in multiple ways. Dense submerged and floating vegetation may form migration barriers either directly by blocking movement (Johnston et al. 2018) or indirectly by causing low dissolved oxygen or low turbidity (*sensu* Le Pichon et al. 2020). Extensive aquatic vegetation also provides underwater structure that supports non-native piscivorous fish, thus influencing predation risk (Ferrari et al. 2014; Conrad et al. 2016). Dense vegetation may also affect hydrological and geochemical cycling, plausibly altering phytoplankton and zooplankton dynamics, as well (Yarrow et al. 2009; Drexler et al. 2021). However, direct sampling of submerged and floating aquatic vegetation has shown increased epiphytic invertebrate densities compared to channel and emergent-vegetation habitats (Hartman et al. 2019). Invertebrate taxa in submerged vegetation beds support non-native fishes such as Largemouth Bass (*Micropterus salmoides*) (Young, Conrad, et al. 2018; Weinersmith et al. 2019) and contribute to the biomass of littoral fishes, including native species (Young et al. 2021).

Symposium participants discussed the complexities of relationships between aquatic vegetation, water quality, invertebrate production, and the fish community, suggesting the need to understand thresholds at which aquatic vegetation in tidal wetlands becomes detrimental to intended outcomes. Currently, vegetation control actions are one of the few post-project management tools that are regularly implemented, but there are substantial uncertainties regarding the efficacy of currently available control methods (see Conrad et al. 2023 for a review). Differential susceptibility of aquatic plants to herbicides, unintentional consequences of herbicide applications, and the ability of tidal flows to dilute herbicides before they can act all hamper the efficacy of vegetation control (Santos et al. 2009; Rasmussen et al. 2022; Khanna et al. 2023).

Natural and regulatory environments currently constrain the success of aquatic vegetation control (Conrad et al. 2023). Improved efficacy will require an expansion of control tools (e.g., an expanded list of permitted herbicides and application strategies), providing explicit mitigation efforts for non-native submersed, floating, creeping emergent, and submerged aquatic vegetation types. In addition, a better understanding of vegetative habitat requirements is required. This would allow project design to explicitly aim for conditions inhospitable to aquatic vegetation, where possible. Finally, a more thorough understanding of how aquatic plants and their associated control methods influence both habitat capacity (e.g., invertebrate abundance, predation risk) and opportunity (e.g., access) would help to prioritize aquatic vegetation control efforts.

REALIZED FUNCTION—FISH USE OF TIDAL WETLANDS

Function and Occupancy

Realized function, as defined by Simenstad and Cordell (2000), refers to “any direct measures of physiological or behavioral responses that can be attributable to fish occupation of the habitat and that promote fitness and survival.” The ultimate metric of realized function is survival, but we define realized function as including a range of benefits to fish, including foraging success, growth, reproduction, and refuge, all of which are associated with increased capacity and opportunity.

Research in the estuary has indicated that tidal wetland capacity results in realized functional responses for fish, because tidal wetlands provide valuable foraging habitat to a range of native (Davis et al. 2019; Hammock et al. 2019; Colombano, Handley, et al. 2021) and non-native (Whitley and Bollens 2014; Young et al. 2022) fishes. This can, in turn, improve the potential for nursery functions, including recruitment success, although foraging responses can vary with geomorphic features of the habitat (Visintainer et al. 2006; Colombano, Handley, et al. 2021). Sometimes tidal wetlands can provide high-value foraging habitat for fishes of interest as well as pernicious non-native species (e.g., Striped Bass *Morone saxatilis*; Young et al. 2022), which may prey directly upon native fishes (Grossman 2016). However, local research indicates that wetland design can mediate overall capacity (Stevens 2020) for fishes of interest, and mediate predation by non-native piscivores (Colombano, Donovan, et al. 2020).

Occupancy, or the presence of target fish in restored habitats, is a prerequisite to measuring realized function, and can be used to confirm opportunity. Our understanding of occupancy is a function of location, site design, and sampling methodology. Location along the estuarine salinity gradient dictates the available species pool (*sensu* Peterson 2003), ultimately affecting habitat suitability for certain species (Young, Feyrer, et al. 2018; Feyrer et al. 2021; Colombano et al. 2022). Site design affects environmental conditions (i.e., bathymetry or vegetation type) and thus local habitat suitability (Visintainer et al. 2006; Howe et al. 2014; Whitley and Bollens 2014), while also affecting how tide moves across the landscape. Interactions between the physical landform and tides mediate water depth across space and time, which influences food resources, predation risk (Colombano, Handley, et al. 2021) and fish habitat availability—which research indicates is an ephemeral resource (Ayers 2020; Colombano, Handley, et al. 2021; Clause et al. 2024). Furthermore, sampling gear and timing can substantially affect observations (Sherman et al. 2023) and require consideration when evaluating occupancy.

Evaluating Realized Function

Symposium participants concluded that integrating information about realized function into the adaptive-management process will improve when restoration practitioners: (1) expand assessment of realized function beyond occupancy, (2) develop a better understanding of how different habitat features (channels, tidal floodplain, pannes, and associated subtidal areas) influence realized function, and (3) use information from across the diverse array of existing habitat features to isolate the effect of habitat on realized function. These basic ideas are expanded upon below.

1. First, an occupancy-based monitoring framework is an effective way to establish that fishes of interest are potentially colonizing restored habitats. However, continued field experiments are needed to tie occupancy to a realized function—that is, to provide direct evidence of *how* fish are benefitting from using the site. Simenstad and Cordell (2000) note that unambiguous measurement of realized function usually requires both experimental manipulation and assessment across various stages of restored habitat maturation. Experimental manipulation of existing habitats may be complicated because of regulatory requirements, but may also demonstrate restoration effectiveness more efficiently than other methods. For example, removal of aquatic vegetation or manipulation of local hydrodynamics may have immediate ecological consequences that could be experimentally evaluated. Where experimental manipulation of restoration sites is not possible, comparisons across restoration and reference sites can provide useful information for assessing realized function.

2. Second, a holistic understanding of how different habitat elements influence realized function will help inform restoration design and adaptive management. For example, the influence of elevation and tides on opportunity could have substantial implications for the type of benefits fishes realize. By manipulating land surface elevation as part of site design, restoration practitioners have some element of control over habitat function. By understanding the relationships between wetland geomorphology and both capacity (e.g., primary and secondary productivity) and opportunity (e.g., water depth and inundation), restoration practitioners can identify mechanisms that influence realized function (e.g., foraging success, growth, and survival). These direct or modeled measurements of realized function can then be used to inform future restoration designs. Explicitly accounting for future manipulation (either experimentation or management) and incorporating experimental features into restoration design could inform adaptive-management options and provide opportunities to quantify habitat effects on realized function. This mechanistic understanding of the value of specific habitat features to fishes will greatly improve our ability to prioritize tidal wetland management.

3. Third, existing restored habitats represent a range of conditions, providing opportunities to isolate the relative effect of wetland geomorphologies and design on capacity, opportunity, and realized function. Because different habitat wetland geomorphologies result in different capacity and opportunity, one restoration design is unlikely to serve all functions equally. It is therefore important

to define the primary intended benefits to fishes when evaluating the success of habitat restoration: if the site is designed to provide foraging opportunities, then monitoring should include feeding success; if the site is designed to provide spawning habitat, then egg or larval sampling should be included. A mosaic of habitat features will likely provide a range of opportunities for fishes to display a variety of realized functions. Diversity of available habitats may also allow for adaptation to the inevitability of climate change, sea level rise, and other anthropogenic effects by providing at least *some* habitats that can be used in *all* future scenarios (*sensu* Schindler et al. 2015). Scaling site-specific results to landscape-level restoration targets can enhance the benefits of wetland restoration overall, and activate the adaptive-management cycle, providing a flywheel to continually improve restoration outcomes in the estuary.

NEXT STEPS IN RESTORATION OF TIDAL WETLANDS IN THE SAN FRANCISCO ESTUARY

Using the *capacity–opportunity–realized function* framework described above, we have learned a great deal about how our restoration sites are currently serving to support at-risk fishes. However, many aspects of restoration science and wetland management remain uncertain. During the symposium, presenters highlighted many of the unknowns, data gaps, and future needs to improve our understanding. During break-out sessions, several follow-up meetings, and a follow-up survey, we discussed these gaps in more detail to guide a path forward for restoration practitioners. We created a final list of priorities for future research and action using symposium results and follow-up meetings.

Management and Science Priorities

We have distilled the discussions into a list of priorities for the future of tidal wetland restoration in the Delta and Suisun Marsh (Table 1). These priorities are divided into "management priorities" (problems to be addressed by restoration practitioners, managers of restoration sites, funders of restoration implementation, or regulatory agencies), and "science priorities" (problems to be addressed by restoration monitoring teams, restoration and wetland scientists within agencies, as well as academic scientists). However, these categories have considerable overlap, and there is considerable feedback between categories. For each management priority, there are recommendations for one or more scientific research topics that will help inform the management priority, as well as an example of a specific research project and management feedback mechanism. Example studies do not imply endorsement or prioritization, but instead are intended to help articulate examples that fit within the listed management and science priorities. As mentioned above, we developed this list based on topics that came out of the symposium and was further vetted by members of the IEP TWM PWT and the Interagency Adaptive Management Implementation Team (see "Communication"). It is not an exhaustive list of all data gaps or management problems for wetland restoration in this region; instead, it prioritizes topics considered most important by a wide range of restoration practitioners and scientists.

Modeling and model validation. The first topic on the list involves improving our use of numerical models in restoration design and evaluation. Most restoration sites use hydrodynamic models in their design and planning process, but they are not always re-assessed post-restoration. Validating models used for design by comparing hydrodynamics at appropriate time-frames post-construction will help create better models for future restoration sites and inform potential adaptive-management changes on current sites. Few restoration projects currently use ecological models of productivity or fish habitat use in their planning phases because of the high uncertainty in these models. Improving our understanding of primary and secondary productivity, fish behavior, and the relationship between physical features and fish behavior may facilitate use of more integrated models in future wetland designs. These integrated models will also allow

Table 1 Management and science priorities necessary to inform management priorities for tidal wetland restoration sites being built for fishes in the Delta

	Management Priority	Science Priority	Example course of action
1	Ensure that models used in the design are validated, expanded, and updated for future use (including hydrodynamic models, sediment models, fish habitat models, productivity models, etc.).	Advance use of integrated models for design of restoration sites, including linking physical (e.g., hydrodynamic, sediment) models with ecological (e.g., productivity, fish habitat) models.	During the restoration design process, model potential primary production rates and hydrodynamic transport in wetland channels. After construction, monitor primary production to validate model and update model as needed.
2	Incorporate experimental design and opportunities for adaptive management in restoration planning.	Identify associations between desired tidal wetland functions and restoration site features that can be adaptively managed.	Divide a restoration site into parcels with different vegetation planting strategies. Monitor which planting strategy provides the greatest native species coverage.
3	Clearly define the adaptive management time-frames for various performance metrics of tidal wetlands. "When can we make a decision about adaptive management actions in tidal wetlands?"	Determine appropriate monitoring time-frames for each performance metric based on physical and biological processes—such as rates of tidal wetland evolution and generation times—to inform how much data are needed to make future management decisions.	Review existing literature and data to establish monitoring time-frames. After this time-frame, evaluate data to judge whether enough time has elapsed.
4	Identify pathways to take corrective action on existing sites (e.g., re-sizing breaches, treating weeds, dredging) if a site is not meeting ecological goals and objectives.	Identify metrics and thresholds which denote impaired ecological functions of a restored tidal wetland.	Link size and depth of channels to preferred depth for juvenile salmonid rearing. If the breach of the site fills in past preferred depth, re-excavate breach.
5	Improve the monitoring of realized function to inform adaptive management.	Increase understanding of fish use of wetlands beyond occupancy, including rearing, reproduction, foraging, and refuge.	Conduct field experiments of predation rates in different wetland sites.
		Understand associations between primary producers and invertebrates (especially non-zooplankton) with physical habitat features, and the role of different invertebrates as fish food.	Pair studies of fish diet with monitoring of epiphytic, epibenthic, and planktonic invertebrate communities across different tidal wetland habitat features.
		Understand how constituents—including primary and secondary production—are transported into or out of wetlands, and how the spatio-temporal footprint of wetland production is affected by wetland size or geomorphology.	Conduct field experiments to measure primary and secondary production rates, rates of flux into and out of the site, and how these rates vary through space and time.
		Develop and validate new monitoring tools, including remote sensing, on-water platform-based mapping, *in situ* primary productivity measurement, phytoplankton species identification, and genetic tools (e.g., environmental DNA species identification).	Pair use of meta-barcoding and imagery with traditional microscopy for identification of phytoplankton and zooplankton to determine if new tools can be more cost-effective.
6	Connect outcome of scientific studies to the long-term management of the restoration site to increase resiliency to future change.	Develop science to predict future changes on restoration and reference sites, including climate change, drought, and sea level rise.	Model expected rates of sediment accretion to see whether they are anticipated to keep pace with climate change. Measure rates of sediment accretion to validate the model.

restoration practitioners to better quantify the benefits of restoration sites, as suggested by Rose et al. (2015).

Experimental design. Parameterization and use of integrated models requires adequate information on the relationship between restoration site features and the biotic community. This is frequently difficult to achieve without manipulative experiments. Therefore, we encourage use of appropriate experimental designs within restoration sites, as was suggested by Herbold et al. (2014). For example, different parcels within the site could be built with different channel geomorphologies to test whether channel order, depth, or sinuosity result in different fish habitat benefits. Monitoring of these experimental treatments can then feed back into future adaptive management of the site, design of future sites, and parameterization of models used in planning and assessment. For instance, experimental design was used effectively in the South Bay Salt Ponds restoration area where bird nesting islands of different size and densities were tested in different parcels to see which designs the birds preferred (Ackerman et al. 2014). Experimental design was also used in planning the Dutch Slough restoration site, which was divided into three parcels with different geomorphologies. The parcels were then built sequentially, with the opportunity to learn from the first parcel before the next parcel was built.

Monitoring duration. Effectiveness monitoring of restoration is important in assessing the site's benefits to the fish of interest, but the question "How long do we need to monitor?" is one that still stumps many scientists and restoration practitioners. Many monitoring programs use a 5- or 10-year monitoring horizon because it is a "nice, round number," but may not be relevant for parameters of interest. Fish may occupy a site within weeks of the site being breached (Grimaldo et al. 2012 and references therein), but vegetation, invertebrates, sediment, and microbes may take years or decades to converge with reference sites (Brand et al. 2012; Lowe et al. 2014; Sloey et al. 2015; David et al. 2016). Therefore, additional scientific research is needed to determine the appropriate monitoring scale for water quality, sedimentation, vegetation, primary productivity, zooplankton, and fish that takes into account the generation time of the taxa in question—similar to the approach proposed by Baumsteiger and Moyle (2017)—and the climatic variability inherent in the system. Information on appropriate monitoring time-frames can come through review of published literature, data collected on existing restoration sites, and data from reference sites. Data from multiple sources should be integrated before appropriate time-frames are determined. Only when a sufficient time-period of scientific information is collected can restoration practitioners determine whether the site is performing as expected—and make decisions about future changes in the system.

Thresholds and corrective actions. Another key question in restoration science is "How do we use our monitoring information to make changes on the site?" This speaks to the need to evaluate the progress of restoration and thresholds for intervention, and to take corrective actions if needed. After the appropriate monitoring period, if the site is determined to be under-performing with respect to some aspect of realized function, restoration practitioners may want to take corrective actions. This requires a scientific determination of when the site has crossed an ecological threshold, such as too many invasive weeds, not enough production, or restricted access for fish. Once the threshold has been defined and assessed, restoration practitioners must determine what remediation actions can be implemented.

Advances in science. All the priorities listed above will be aided by improving our understanding of wetland modeling, research, and monitoring. Many questions about thresholds, interventions, and model parameterization may not be resolved by existing monitoring, and may require special studies, field experiments, or new technology to answer. In particular, improving our understanding of fish use of tidal wetlands beyond occupancy—studying diets, behavior, or reproduction—will help us understand the benefits to fish of restoration at the population scale. For example, export of organic matter, phytoplankton, and zooplankton was one of the major hypotheses behind restoring wetlands for Delta Smelt, but updated conceptual models and research studies describe net flux to be variable (Lehman et al. 2010; Herbold et al. 2014; Yelton et al. 2022), with increased production available locally (Sherman et al. 2017; Colombano, Litvin, et al. 2021) or transported via trophic relay (Kneib 2000). Monitoring the movement of constituents into and out of the site will help parameterize future models of wetland productivity. Development of remote sensing, environmental DNA sampling, and automated photographic identification methods for organisms at all trophic levels will allow us to collect more data, faster, on many of the under-studied aspects of wetland science.

Future change. Finally, the environment of the estuary is rapidly changing, and tidal wetlands—on the border between the aquatic and terrestrial ecosystem—may be changing faster than other habitat features (Colombano, Litvin, et al. 2021; Herbold et al. 2022). Sea level rise, increasing salinity, increasing temperature, and new invasive species may limit our ability to use previous monitoring data to make inferences about future management (Williams 2022). Therefore, a major science priority is to develop tools for predicting future change on wetland sites that can inform long-term management plans.

While some of these priorities have already begun to be addressed, we hope this paper can be used as a communication tool to inspire others to continue addressing these challenges. Papers like this are one of many tools we use in communication of wetland science, because the success of tidal wetland restoration relies not only on modeling, effectiveness monitoring, research projects, and adaptive management—but also on communicating results.

Communication

The need to communicate cut across all symposium sessions, highlighting the importance of cooperation and collaboration between all parties involved in tidal wetland restoration in the estuary. Sharing of data and information between scientists has increased generally over the last 10 years with the rise of the Open Data Movement (Baerwald et al. 2020), and the mandate to publish water-related data codified in California Assembly Bill 1755 (Dodd 2016). Specific to tidal wetland science, the number of venues for sharing information has also grown, with formation of the IEP TWM PWT in 2014, the California Monitoring Council's Estuary Monitoring Work Group formed in 2010, and many other informal venues (see Table 2). Wetland science is regularly shared with restoration practitioners and scientists at the IEP Annual workshop, the Bay–Delta Science Conference, and the State of the Estuary Conference.

Despite the number of communication outlets for tidal wetland science, symposium participants noted several persistent shortcomings in the available opportunities. These gaps included minimal opportunities to share emerging science with those able to shape policy, a lack of understanding of the site locations among those not directly involved with the restoration or study of tidal wetlands, and issues related to the dispersion of scientific information across many different venues.

Available venues are largely populated with scientists, with little engagement from those developing mandates for restoration or shaping planned restoration efforts. Improved communication would help ensure a good fit between wetland science and site management needs, and advance adaptive management in general. Some symposium participants expressed frustration about their perception that the best available science was not always incorporated into designs as a result of lack of understanding, lack of resources, or logistical constraints—a concern shared by many scientists across the region (Rittelmeyer et al. 2024). Scientists focused on a particular species or aspect of ecosystem function may also not recognize that trade-offs are necessary to prevent or mitigate harm to other species or existing ecosystem function. At the symposium, FRP representatives discussed the importance of lessons learned across a

Table 2 Communication venues for restoration science in the Delta and Suisun Marsh

Venue	Scope	Participants	Products	Meeting frequency
IEP Tidal Wetlands Monitoring PWT	Effectiveness monitoring of tidal wetland restoration sites for at-risk fishes	Wetland scientists and restoration practitioners; open to the public	Recommendations and standard operating procedures for monitoring	Twice per year
Interagency Adaptive Management Integration Team	Strategies for implementing adaptive management for conservation efforts in the Delta	Wetland scientists and restoration practitioners from agencies and stake-holder groups	Adaptive- management resources and examples; Adaptive Management Forum every 2 years	Quarterly
Delta Science Program's Adaptive Management Forums	Promoting dialogue and information exchange related to adaptive management in the Delta	Wetland scientists and restoration practitioners; open to the public	Recordings; information sheets	Every 2 years
CA Monitoring Council's Estuary Monitoring Work Group	California-wide monitoring of estuaries for a variety of purposes	Wetland scientists and restoration practitioners	Planning documents; future products in discussion phases	Quarterly
Suisun Adaptive Management Advisory Team	Adaptive management of wetlands in Suisun for multiple benefits	Representatives from Suisun Marsh Preservation agreement agencies, restoration practitioners	Presentations on planned or recently completed restoration; recommendations for changes to restoration plans	Quarterly
Bay-Delta Science Conference	All aspects of science in the estuary, including wetlands and restoration	Scientists working on all aspects of the San Francisco Bay, Suisun Marsh, and the Delta	Presentations and posters covering research from the past 2 years	Every 2 years
State of the Estuary Conference	Management, science, and policy, focusing mostly on the San Francisco Bay with some information on the Delta, too	Resource managers and scientists working on all aspects of the San Francisco Bay, Suisun Marsh, and the Delta	Presentations and posters covering research from the past 2 years	Every 2 years
Interagency Ecological Program annual workshop	Work conducted by IEP and associated groups, including wetland studies	Scientists working within the auspices of the IEP	Presentations and posters covering research from the past year	Every year
San Francisco Estuary and Watershed Science	All aspects of science in the estuary, including wetlands and restoration	Scientists working on all aspects of the San Francisco Bay, Suisun Marsh, and the Delta	Peer-reviewed research articles and essays	Issues published quarterly

sequence of projects that inform on-the-ground implementation of construction delivery and land-management methods that have evolved parallel to the science and play a major role in the implementation of adaptive management. For scientists, greater awareness of the realities of what is and is not possible in restoration design and implementation, given those constraints, will help them provide more useful suggestions for design alternatives. For restoration practitioners, a better understanding of the scientific basis for designs will help them weigh the costs and benefits of those alternatives. Gaining input from multiple scientific, regulatory, and other interested parties (as shown in Figure 2) will ensure that the best science is incorporated into designs as well as possible, thus realizing adaptive management for restoration design.

A lack of familiarity with site locations was also seen to hamper the advancement of adaptive management. Symposium participants highlighted the ability of field visits to break down barriers and let people observe how science, restoration management, and regulations work together to create wetlands. On-the-ground experience can heighten viewers' awareness of a problem and increase their ability to participate in activities related to a given site more meaningfully and productively, whether that participation is related to permitting, reporting, or science activities.

Finally, the third communication theme was related to different scientists communicating different messages. Communication has long been recognized as improving the outcomes of restoration programs, and symposium participants felt the growth in communication outlets to be a positive signal of the level of interest in tidal wetland science. However, there may not be consistent messages across scientists, and this lack of consistency may lead to confusion among restoration practitioners and policy-makers. Effective transmission of information calls for periodic efforts to distill the current state of knowledge and provide it transparently and accessibly to the desired audience—whether a permitting entity or members of the public. Diversifying the form, frequency, and audiences for communications will allow science to be appropriately integrated into guidance for design, additional research, and requirements for tidal wetland restoration.

Symposium presenters shared an example of integrated communication for adaptive management implementation at the CDWR Delta Levees Program-led Dutch Slough Tidal Marsh Restoration Project[1], whose Phase I was breached in 2021 (CDWR and CSCC 2014) and whose monitoring is supported by the CDWR Land Stewardship Program. Dutch Slough was planned as a "living laboratory," as suggested by Herbold et al. (2014), with parcels functioning as experimental replicates, and a broad suite of monitoring coordinated by a working group of agency, university, and private-sector scientists. Communication among scientists at Dutch Slough continues through bi-monthly collaborative working group meetings focused on implementation, monitoring, and data sharing. Based on the adaptive-management plan, working group conversations, and data collected to date, the CDWR is using 3 years of monitoring data from Phase I to refine the design of Phase II, thus integrating scientific findings into project planning.

CONCLUSION

Tidal wetland restoration projects in the Delta are being constructed at an unprecedented rate. With all the monitoring and research projects that target the effectiveness of tidal wetlands, we've learned much about their structure and function, yet many questions remain. Moving forward, adaptive management of restoration sites will be most effective with continued application of integrated models of hydrologic and ecological function, monitoring realized function to clarify how fish use the sites, and identifying specific thresholds and corrective actions. Implementing lessons learned from restoration sites into new management actions can increase the sites' resilience to future environmental change. While conceptually straightforward, this enterprise requires continued efforts to foster clear communication between restoration practitioners, scientists, and policy-makers.

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[1] *https://water.ca.gov/Programs/Integrated-Regional-Water-Management/Delta-Ecosystem-Enhancement-Program/Dutch-Slough-Tidal-Restoration-Project*

land managers, and technicians working hard to restore tidal wetlands in the estuary.

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