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Data to Decisions: How to Make Science More Relevant for Management of the San Francisco Estuary

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INTRODUCTION

In a region surrounded by some of the top universities in the nation—as well as headquarters for major federal, state, and local agencies—science in the San Francisco Estuary (the estuary) is arguably world-class. This conclusion is based not only on the sheer volume of literature on estuarine habitats, but also on the range of topics covered, which includes hydrology, chemistry, botany, invertebrate biology, restoration ecology, fisheries, estuarine ecology, political science, human uses, economics, and modeling.

While scientific publications are a good indicator of the intensity of research and monitoring in a given region, publications do not necessarily translate into effective resource management. If scientists only have a hazy idea of what resource management is, they may over-value the applications of their work. Another challenge is that resource managers frequently do not have the time to follow all the published scientific literature and may have insufficient contact with scientists working on many important resource issues. A common result is that resource managers provide working scientists with only general priorities for research and monitoring, rather than detailing specific needs that could more efficiently generate actionable science. Getting from science to implementation is hard.

To help address at least the first issue, in this essay we provide some suggestions for how scientists interested in having their work applied to resource management can enhance the relevance of their efforts. Here we use the term "management-relevant science" to include a very broad range of possible activities (e.g., monitoring, research, experiments, modeling, and analysis) that help us to understand how management actions generate different environmental responses. There are two general forms of management-relevant science: ***foundational research and hypothesis-driven monitoring and evaluation of management actions.***

FOUNDATIONAL RESEARCH

Management-relevant science that is ***foundational research*** enhances the knowledge base on a topic or aspect of the estuary that may influence decision-making but is not necessarily linked to a specific regulation or management action. An example of this foundational research may be a description of salinity patterns in wetlands and the associated species composition of fish or invertebrates across salinity regimes (e.g., Schacter et al. 2021; Young et al. 2018), which may then indirectly inform potential outcomes of specific management actions such as restoration. This type of management-relevant science may be broad, ranging from a characterization of contaminant concentrations across the estuary, to development of genetic tools to identify species presence more promptly or accurately, to synthesis work to examine trends in water temperature. In rarer examples of foundational research, science can directly lead to totally new management tools. For instance, research on life-history variation in Chinook Salmon using isotopic and genetic techniques (e.g., Banks et al. 2000; Carlson and Satterthwaite 2011; Johnson et al. 2017) has been the basis for informed strategies for supporting this species through management actions (CNRA 2017) as well as best practices for hatchery management in California (California HSRG 2012).

HYPOTHESIS-DRIVEN MONITORING AND EVALUATION OF MANAGEMENT ACTIONS

This research directly evaluates whether management actions have their hypothesized outcomes. An example of this type of management-relevant science is measurement of food-web responses to a human-induced flow pulse (e.g., Frantzich et al. 2021). The data used in these evaluations may be newly collected as part of the evaluation, or it may be gleaned from the estuary's rich data resource of routine monitoring programs. Notably, this form of management-relevant science commonly leverages existing models and data sets and may introduce analyses that compare predicted outcomes of proposed management actions. This kind of management-relevant science may be *proactive* by informing management decisions yet to made, or it can be *reactive,* evaluating management actions that have already occurred.

It is important to note that both kinds of management-relevant science can inform the **adaptive management** cycle, and that not all science is immediately policy relevant (Wiens et al. 2017). ***Foundational research*** has the power to profoundly alter our understanding of the system such that management decisions can be re-framed or re-structured based on new findings. ***Hypothesis-driven monitoring and evaluations of management actions*** directly inform expectations for specific management actions and their refinement in future iterations. Because the estuary is constantly changing, and many environmental causations we observe are subject to large noise-to-signal ratios, interpretation of project results is often difficult. We therefore suggest that a primary goal of management-relevant science is to improve the dialog between scientists and the agency managers who implement management actions. Understanding the nature of environmental variability, adaptability, and serendipity makes drawing clear lines between management actions and environmental causation difficult, and both management and scientific perspectives are important to decide when specific actions are suitable.

Our hope is that this essay will be particularly helpful for scientists in universities, non-governmental organizations (NGOs), and private industry who wish to improve the relevance of their work to resource management. These groups typically have less contact with resource managers than agency scientists, who, in contrast, often work side-by-side with decision-makers. However, we also expect that agency scientists will find some of our suggestions useful to improve their own research and monitoring, and to enhance communication with managers and the broader science community.

Our suggestions are based on decades of experience and lessons learned by the authors working in the Bay–Delta with resource managers and scientists within other agencies, NGOs, consulting firms, water districts, water treatment operators, and universities. Through our work in a complex, high-stakes environment, we have had substantial opportunity to observe how science is—or is not—used by decision-makers. We emphasize, however, that our recommendations are not meant to be comprehensive; instead, our suggestions are intended as useful ideas to help scientists develop actionable projects. Hence, this essay is not meant to replace the broader topic of science communication or the use of science in decision-making (e.g., structured decision-making; Gregory et al. 2013). Our essay also does not address how resource managers can improve their use of science, although we hope that if some of these suggestions are adopted, scientific investigations will be even more ostensibly relevant to managers. Finally, the examples we provide are focused largely on the upper estuary, where we have the most experience working with scientists and managers. Therefore, we do not provide a thorough accounting of some of the examples of successes of management-relevant science in San Francisco Bay (e.g., water quality, salt marsh restoration) and issues that traverse the entire watershed. Similarly, many of the citations are from some of our own programs and projects, simply because we can best explain linkages to management using these examples.

We wish to emphasize that our recommendations are not intended as a criticism of basic research, which is generally the foundation for scientific discovery. Nonetheless, improving awareness of some ways to connect research to management can help both the researchers and their potential audiences. For example, funding evaluations through the Delta Science Program and partners, or science funding via the California Department of Fish and Wildlife, specifically include Management Relevance as a ranking consideration for determining priorities for support, while also providing broad guidance for major areas of management interest (e.g., 2022–2026 Science Action Agenda; DSC 2022).

With the foregoing as context, we provide nine suggestions designed to enhance the relevance of projects, proposals, and conversations between scientists and managers. The list is in no particular and readers should not feel obligated to follow all suggestions. While the list is specifically tailored to the estuary, our hope is that some of these ideas may resonate for resource management issues in other regions.

Nine Suggestions for Enhancing Management Relevance of Scientific Investigations in the San Francisco Estuary

1. Seek to help solve problems, not create them.
2. Understand the management toolbox.
3. Understand the literature.
4. Understand the regulatory framework.
5. Be specific about management implications.
6. Follow the signal of environmental patterns.
7. Talk to the right people, early and at strategic points in the life of the project.
8. Use conceptual models.
9. Use multiple tools (e.g., monitoring, experiments, synthesis).

SUGGESTIONS

1. Seek to help solve problems, not create them.

Our first suggestion is more philosophical than technical. Specifically, projects designed to solve problems are more likely to generate management solutions than ones that create even more challenges for decision-makers.

In our experience, it is relatively common for researchers to assume that their project is helpful for management if the study identifies a major new issue or highlights a higher level of complexity than previously understood. We agree that it is always important to understand the range of challenges for decision-making but figuring out a brand-new problem (or higher level of uncertainty) is not usually seen as progress by decision-makers. Rather, it may simply be seen as a new issue to further complicate already challenging resource issues, not as actionable research. Put another way, results are not seen as actionable unless they provide a way forward. But this does not mean that scientists should avoid doing complex research, or sharing negative results with decision-makers, since not all issues have immediate solutions.

If researchers want to more immediately increase the chances that their results will be used by resource managers, we recommend a solution-oriented approach. First, consider designing studies that try to address a known issue. Second, for studies that identify a new issue, provide some specific guidance (see below) about next steps for research and management. Examples of studies that were solution-oriented and provided specific management recommendations include the Grimaldo et al. (2009) work on fish entrainment, the Kimmerer et al. (2019) evaluation of a drought barrier to reduce salinity intrusion, and many of the references we cite below.

2. Understand the management toolbox.

An underlying issue in Suggestion 1 is that scientists working outside of the policy arena may not be up to date on which management actions would be most improved by new science. New research results can be very helpful in improving our understanding of the estuary; however, the work may not be actionable if there is no feasible management tool to address the major findings. To help avoid this general disconnect between science and management, Sommer (2020) developed a short summary of the major management tools available in the estuary. The range of management activities is relatively broad, including regulatory, water infrastructure, habitat, and other biologically related activities. Similarly, the Delta Science Program's 2022–2026 Science Action Agenda contains a list of science actions that would be responsive to current major management needs, and specific management questions that were collaboratively identified by the estuary's community of scientists, managers, and the interested public. As Sommer (2020) recommends, researchers considering new studies should ask themselves the following question: *"If my research project is successful, is there a management tool available to incorporate (affect) the results?"* If there is no available tool to use this information, the study is unlikely to be directly management-relevant unless a totally new tool can be developed. Even within the range of available tools, some actions are much more feasible than others. Understanding the current toolbox may therefore provide scientists with insight into which options would be easiest to implement.

Still, other projects that may not be specifically relevant to management levers can still be useful and informative to managers if they are foundational research that address areas highly interesting to management and can broadly inform management decisions. An example involves water temperature, which is chiefly driven by air temperature in the estuary (Wagner et al. 2011). In one example, Brown et al. (2013) used down-scaled climate models to forecast how Delta Smelt (*Hypomesus transpacificus*) habitat will be progressively compressed in future years, given current knowledge of the species' physiology and temperature benchmarks for stress or death. This research did not evaluate the effect of a specific management tool but did point to specific Delta regions which temperature is likely to render—or is already rendering—uninhabitable for Delta Smelt, which in turn can inform decisions on where to invest in restoration. In these cases, where the focus of research is on a factor that cannot currently be controlled, it is important that scientists then relate their work to management tools that *do* exist, and take the time to be specific about the implications of their findings for management decisions.

3. Understand the literature.

An obvious starting point for any science investigation is to familiarize oneself with the literature. This task can be daunting for those focusing on the estuary since there are likely over a thousand publications about the system. To help early-career scientists and newcomers to the system, we developed a list of ten essential papers about the system, focusing on fisheries management and including follow-on suggestions for additional reading (Sommer et al. 2019). We specifically selected the papers based on their influence on management activities in the upper estuary. Although more intensive reading of the regional and national or global literature is needed to support good study ideas, we consider the Sommer et al. (2019) list to be a reasonable starting point for researchers to understand some of the basics of how science has informed local estuary management, at least in the upper estuary. Notably, this list focuses on how the biophysical sciences have informed management and does not address approaches to governance in the estuary or other aspects of decision-making (e.g., Lubell et al. 2020). As the social science literature for the region grows, updating the list to include key papers that

https://doi.org/10.15447/sfews.2023v21iss1art1

address political science, economic, and social ecological topics will be valuable. Additionally, the State of Bay–Delta Science is a periodic collection of papers that synthesize our scientific understanding of the estuary, and the most recent edition published in 2023 included topics that ranged from water quality to food webs to climate change (Larsen et al. 2022).

4. Understand the regulatory framework.

It is not possible to understand the interface between science and management in the estuary without at least a modest grounding in the regulatory framework. Simply put, regulatory activities influence or necessitate all the management activities described above. For example, designing a workable regulatory approach is often the first step in implementing major changes in water or ecosystem management (Sommer 2020). Some of the core regulatory activities include listing species with protection agencies, establishing fisheries harvest management plans, describing how project actions will affect water quality, and demonstrating how affected parties will maintain their associated water rights when an action is implemented. Multiple regulatory documents and laws for each of these areas often highlight the major concerns. Some, such as Biological Assessments, Biological Opinions, Incidental Take Permits, and Water Rights Permits normally provide a substantial technical background (e.g., literature, scientific summaries) that can help scientists understand critical issues and information gaps. While most of these documents are quite lengthy and challenging to read, we strongly encourage scientists with a specific expertise to review the regulatory context and the provided bibliographies associated with their proposed research. Not only will these reviews help scientists to understand some of the high priority technical challenges, but they also provide guidance on which regulatory groups to contact to suggest new research and monitoring.

5. Be specific about management implications.

Another common issue with scientific presentations, journal articles, and reports is that they do not clearly guide decision-makers about how results can be used. Obviously, scientists should not try to tell decision-makers how to do their jobs. But too many scientific presentations and reports simply say “managers should consider this information,” without any type of guidance. Therefore, decision-makers are often left to guess how to apply this new science. As noted above, understanding the nature of major management and regulatory activities already underway is crucial to providing clearer guidance. When the management implications of a study's findings are specific, they can be helpful to managers who may not have the same lens, expertise, or experience in applying new science as scientists do, but nonetheless, they have every interest in using the best available science as a basis for implementing management strategies.

6. Follow the signal of environmental patterns.

The science and management issues in the estuary are so complex and regional that it can be difficult to identify the highest-priority topics for research and monitoring. As a further challenge, the signal-to-noise ratio in the data is generally low, meaning it can be hard to link cause and effect—a key first step in making results relevant. Still, there are many examples of clear patterns in the long-term data or remarkable new observations (outliers) that can be especially informative (Cloern and Jassby 2012). Based on our experience in working with data from the estuary, we often find that trying to understand these new trends or outlier observations can be particularly fruitful topics for new work. Our recommendation, therefore, is that scientists who see a strong, remarkable environmental pattern should consider "following the signal." Put another way, when a remarkable new observation or signal is apparent in the data (despite all the variability in the system), this topic can be an excellent candidate for management-relevant science. To help illustrate this point, we provide two examples of how following a strong trend or outlier can lead to progress in resource management.

Estuarine Inflow. One of the most remarkable signals in the estuary is that estuarine inflow clearly affects the abundance of a suite of organisms (Jassby et al. 1995; Kimmerer 2002a). Despite the persistence of this signal, the mechanisms for changing abundance through time were not initially obvious for many species (Kimmerer 2002b). Hence, understanding potential drivers of flow–abundance relationships has been a vibrant area of research for decades. This has led to research on the effects of seasonal flow on many factors, including gravitational circulation (Schoellhamer and Burau 1998), water diversions (Kimmerer and Nobriga 2008), spawning habitat (Sommer et al. 1997), rearing habitat (Kimmerer et al. 2013), zooplankton behavior (Kimmerer et al. 2002), and access to marsh habitat (Sommer et al. 2020a; Beakes et al. 2021). Inundation of floodplain habitat has been a particularly fruitful area of research since seasonal flooding is a unique characteristic of wetter years (Sommer et al. 2001). Topics covered as part of floodplain research have included food web production (Sommer et al. 2004; Goertler et al. 2018; Frantzich et al. 2018), salmon rearing (Sommer et al. 2001), and adult fish migration (Sommer et al. 2014).

Research and monitoring for this flow–abundance signal has been especially influential on the management of the estuary as a whole. The previously described flow relationships have been an important basis for estuarine water-quality standards (State Water Resources Control Board), one of the most far-reaching regulations of management for the estuary. Not surprisingly, there has been debate about the utility of using flow relationships for management, including major litigation (e.g., Service 2007; Moyle et al. 2018). Similarly, research on the effects of flow on floodplain habitat has also been a rich source of management actions. For example, identifying issues with salmon rearing habitat and juvenile and adult migrations has led to important regulatory requirements (NMFS 2019), and the development of major fish passage and rearing projects (USBR and CDWR 2019). We expect there will be many other potential management applications based on future flow research.

Pelagic Organism Decline (POD). Another example of how following strong environmental signals has led to altered management is the POD. The excellent long-term data sets on multiple time-scales for the estuary help scientists to

https://doi.org/10.15447/sfews.2023v21iss1art1

identify when something unusual has happened (Cloern and Jassby 2012). One of the most stunning changes in the long-term data was the collapse in abundance of a suite of pelagic fishes around 2002 (Sommer et al. 2007; Mac Nally et al. 2010). This fish decline led to one of the most complex ecological investigations in the history of the estuary, including research on entrainment (Grimaldo et al. 2009), predation (Grossman 2016), food-web effects (Winder and Jassby 2011), nutrients, (Cloern 2021), contaminants (Fong et al. 2012; Connon et al. 2019), harmful algal blooms (Lehman et al. 2010), and physical habitat (Feyrer et al. 2007; Kimmerer et al. 2013). Following this POD-related line of investigation generated many management changes and actions, including revised regulations, improvements to minimize fish entrainment (USFWS 2019), a requirement to upgrade a major local water treatment plant (EchoWater, *https://www.regionalsan.com/echowater-project*), efforts to improve fall habitat conditions (USFWS 2008; Frantzich et al. 2018; Sommer et al. 2020a), and field-testing programs for native fish supplementation (Lessard et al. 2018).

These examples are but two for which we have of relevant research and synthesis—many other potential signals and observation are worthy of new or associated research, including species invasions, unusually productive habitats, temperature refugia, high levels of chemical constituents, and changes in fish behavior and distribution.

7. Talk to the right people, early and at strategic points in the life of the project.
Particularly for scientists outside resource or regulatory agencies, it is hard to gauge the relevancy of research projects—or to make sure important results are interpreted and used appropriately—without some contact with resource managers. Many groups already recognize this issue; for example, programs such as the Delta Science Program require a community mentor for their Science Fellows. Stakeholder engagement plans are also increasingly required as part of the deliverables for funded research in the Delta.

However, it is important to target agencies or groups that actually manage the topic or resource of interest. As described in Suggestion 4, reviewing some of the major regulatory documents and management tools can help scientists pick the right resource or regulatory agency to approach.

After selecting the relevant agency or group (water project operators, water treatment plants, habitat managers, regulators), another consideration is to whom specifically to provide input on the design of science projects. As noted in the Introduction, senior managers or agency directors are commonly overloaded with responsibilities, and cannot spend much time evaluating science. At the other end of the organizational spectrum, entry-level staff may be able to provide strong science input and technical know-how, but may not be well-situated to translate results into management actions, or access funding opportunities even within their own agencies. For this reason, it is often helpful to target mid-level staff who have a keener understanding of day-to-day management issues and have more reliable contact with decision-makers.

Once the right individuals have been identified, it will usually be beneficial to reach out early in the project—even during the design phase—to get input on how the project can be best designed to address management questions. A dialogue about the project *before it is carried out* can be a learning opportunity for the lead investigators and serves to raise awareness in the management community that relevant science-based actions are underway. Once the research has started, best practice is to maintain communications at strategic points in the project, perhaps at pivotal decision points and when the project findings are in hand. Thinking through these strategic communication points early in the project is often critical to making sure they happen, as capacity and expectation for the communications may need to be put in place ahead of time. Notably, best practices for communication specifically to advance learning opportunities for natural resource managers that enable adaptive management is the subject of extensive political science research, and recent work has identified the need for a common framework for strategic communications for natural resource management.

Although our previous discussion focuses on how scientists *outside* agencies can best contact resource managers, many of these concepts apply to agency scientists as well. Our experience suggests it is common for agency staff to wait for "top-down" science guidance from their senior managers or agency directors. This can be a mistake. We encourage agency staff to be more proactive in generating relevant science projects for consideration within and between their agencies. This is a particularly important point for mid-level resource managers, who sit at the interface between top decision-makers and staff-level technical experts, and who have established relationships with outside scientists and interest groups. The same applies to senior-level research scientists who have access to decision-makers and other interest groups. These supervisors, managers, and scientists have a special obligation to try to articulate clear, focused science priorities.

8. Use conceptual models.

Conceptual models are an increasingly valuable tool to help researchers identify critical research pathways and gaps (DiGennaro et al. 2012; Johnson et al. 2017). Conceptual models are an excellent way to visualize how different social ecological processes are connected and can be adapted to identify potential management linkages. These models range from relatively simple box models that identify the major categories of drivers (e.g., Sommer et al. 2007), to much more complex process models that note the strength of the driver and its evidence (e.g., DiGennaro et al. 2012). Conceptual models are often an excellent summary of the relevant literature, and usually represent a vital first step in the development of various life-cycle models for different species. We therefore suggest that scientists consider using existing or new conceptual models as an initial step in planning research. Fortunately, a wealth of existing conceptual models are already available for researchers to use as a starting point, and these have been collected in an online inventory by the Interagency Adaptive Management Integration Team led by the Delta Science Program: *https://deltacouncil.ca.gov/delta-science-program/interagency-adaptive-management-coordination*). Examples include models for species (Baxter et al. 2015; Johnson et al. 2017), food webs (Durand 2015), habitats

https://doi.org/10.15447/sfews.2023v21iss1art1

(Kimmerer 2004; Opperman 2012; Sherman et al. 2017), processes (Schoellhamer et al. 2012), and stressors (Connon et al. 2019).

9. Use multiple tools.

Resource-management issues in the estuary are formally recognized as "wicked" problems that do not offer simple solutions (Luoma et al. 2015). Such problems generally require multiple approaches, which may best be implemented using an adaptive management approach. An additional rationale is that having more than one line of evidence makes it easier for decision-makers to justify policy or management changes. It is therefore not surprising that a suite of science tools is needed to address management issues. To be most effective, we urge estuary researchers to consider designing integrated study programs that include at least *two or more* of the following tools: monitoring, experiments, synthesis, and modeling. There are numerous examples of these types of integrated projects, including Brown et al. (2014), Kimmerer et al. (2013), and Sommer et al. (2020a). Below, we provide examples of specific components to consider.

Monitoring

Monitoring is the core of science in the estuary, representing one of the best long-term sampling programs in the world (Cloern and Jassby 2012; Cloern 2019). The range of monitoring is impressive, with surveys across multiple regions for hydrology, hydrodynamics, water quality, phytoplankton, zooplankton, macroinvertebrates, and fishes (*https://iep.ca.gov/Data/IEP-Survey-Data*). More and more of this information is available online, providing an excellent resource for scientists planning new research or analyses, or designing new monitoring.

Experiments

Experimentation is typically the gold standard for science. However, laboratory work may not be easy to translate into management actions without using companion tools such as field monitoring or modeling. Field experiments can be particularly relevant for management, but such efforts are often exceptionally difficult or impossible. Some examples of large-scale experimental field manipulations are Frantzich et al. 2021; Kraus et al. 2017; Sommer et al. 2020a, and Sommer et al. 2020b, though such projects are rare because of multiple challenges, including cost, permitting, lack of infrastructure, and other logistical constraints. Enclosures, incubations, and mesocosms are therefore useful tools to generate multiple treatments and in moderately realistic conditions (e.g., Zeug et al. 2021; Strong et al. 2021).

Synthesis

Synthesis occurs when disconnected or disparate data, concepts, and/or theories are integrated in ways that yield new knowledge, insights, or explanations. Synthesis activities can thus include a wide range of activities, including analyzing monitoring data, linking models, reviewing scientific papers and reports, and distilling that information into something that is helpful for other scientists, managers, and stakeholders. Additionally, synthesis—as a conscious step in creating information from collected data— helps to point out where data are missing, how data-management plans can be improved or made more consistent, and where collecting data in different ways can improve their plans' quality and veracity. At a minimum, synthesis can help inventory what we *think* we know, attempt to describe *that* to ourselves and others, and discover where our data and scientific narratives hold new discoveries or hide logical shortcomings that need improvement.

A major asset for synthesis activities is the many long-term data sets available for the estuary, and there has already been substantial progress in developing publicly available analytical code to evaluate some of the major patterns (e.g., *https://github.com/InteragencyEcologicalProgram*, *https://github.com/Delta-Stewardship-Council*). Many examples of successful synthesis teams, including local collaborations as well as partnerships with groups such as the National Center for Ecological Analysis and Synthesis (NCEAS), have resulted in publications (e.g., Mac Nally et al. 2010, Thomson et al. 2010), and R packages that allow for import of large integrated data sets for the estuary (e.g., deltafish, *https://github.com/Delta-Stewardship-Council/deltafish*). Researchers are therefore encouraged to consider using some of the available data and code, example products, and existing synthesis teams as resources for future questions.

Modeling

Modeling has become an essential tool to help interpret monitoring and experiments at management- relevant scales. The range of models has expanded greatly over the past decades, including multiple hydrologic, hydrodynamic, chemical, and biological options. Hydrodynamic models have become particularly sophisticated, with one-, two-, and three-dimensional options (e.g., MacWilliams et al. 2016). Since many of these same models are used for management (e.g., USFWS 2019; CDFW 2020), projects that use these tools may be especially helpful for managers.

CONCLUDING REMARKS

Science is the foundation for a wide range of activities, including evaluation, innovation, and technology, which in turn support management. Without good science, resource management in regions such as the estuary is handicapped, and must proceed with outdated conceptual models, operating strategies, and technologies. At the same time, we recognize that poor communication can interfere with conversations between scientists and managers, even when high-quality data and publications are available. In this essay, we have tried to address an important part of this issue: helping scientists to understand how to produce *actionable* science. Our hope is that these suggestions will, at the least, help improve dialog between scientists and the managers responsible for the estuary's resources.

https://doi.org/10.15447/sfews.2023v21iss1art1

REFERENCES

Banks MA, Rashbrook VK, Calavetta M.J, Dean CA, Hedgecock D. 2000. Analysis of microsatellite DNA resolves genetic structure and diversity of Chinook salmon (*Oncorhynchus tshawytscha*) in California's Central Valley. Can J Fish Aquat Sci. 57:915–927. *https://doi.org/10.1139/f00-034*

Baxter R, Brown LR, Castillo G, Conrad L, Culberson S, Dekar M, Feyrer F, Hunt T, Jones K, Kirsch J, et al. 2015. IEP MAST: an updated conceptual model of Delta Smelt biology: our evolving understanding of an estuarine fish. [Accessed 2022 May 18]. Interagency Ecological Program for the San Francisco Bay/Delta Estuary. Technical report 90. Sacramento (CA): California Department of Water Resources. 206 p. Available from: *https://cadwr.app.box.com/v/InteragencyEcologicalProgram/file/763744160028*

Beakes MP, Graham C, Conrad JL, White JR, Koohafkan M, Durand J, Sommer T. 2021. Large-scale flow management action drives estuarine ecological response. North Am J Fish Manage. [accessed 2022 May 18]; 41(1):64–77. *https://doi.org/10.1002/nafm.10529*

Brown LR, Baxter R, Castillo G, Conrad L, Culberson S, Erickson G, Feyrer F, Fong S, Gehrts K, Grimaldo L, et al. 2014. Synthesis of studies in the fall low-salinity zone of the San Francisco Estuary, September–December 2011. [Accessed 2022 May 18]. US Geological Survey Scientific Investigations Report 2014–5041. 136 p. *https://doi.org/10.3133/sir20145041*

Brown, LR, Bennett WA, Wagner RW, Morgan–King T, Knowles N, Feyrer F, Schoellhamer DH, Stacey MT, Dettinger M. 2013. Implications for future survival of Delta Smelt from four climate change scenarios for the Sacramento–San Joaquin Delta, California. Estuaries Coast. [accessed 2022 Feb 16];36:754–774. *https://doi.org/10.1007/s12237-013-9585-4*

[California HSRG] California Hatchery Scientific Review Group. 2012. California Hatchery Review Report. [Accessed 2022 Nov 22]. Prepared for the US Fish and Wildlife Service and Pacific State Marine Fisheries Commission. 100 p. Available from: *https://swfsc-publications.fisheries.noaa.gov/publications/CR/2012/2012California.pdf*

Carlson SM, Satterthwaite WH. 2011. Weakened portfolio effect in a collapsed salmon population complex. Can J Fish Aquat Sci. [accessed 2022 Nov 22];68(9):1579–1589. *https://doi.org/10.1139/f2011-084*

[CDFW] California Department of Fish and Wildlife. 2020. California Endangered Species Act Incidental Take Permit No. 2081-2019-066-00. Long-term operation of the State Water Project in the Sacramento–San Joaquin Delta. [Accessed 2020 Sep 02]. 142 p. Available from: *https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/State-Water-Project/Files/ITP-for-Long-Term-SWP-Operations.pdf*

Cloern JE. 2019. Patterns, pace, and processes of water-quality variability in a long-studied estuary. Limnol Oceanogr. [accessed 2022 Nov 1];64: S192–S208. *https://doi.org/10.1002/lno.10958*

Cloern JE. 2021. Use care when interpreting correlations: the ammonium example in the San Francisco Estuary. San Franc Estuary Watershed Sci. [accessed 2022 May 18];19(4). *https://doi.org/10.15447/sfews.2021v19iss4art1*

Cloern JE, Jassby AD. 2012. Drivers of change in estuarine-coastal ecosystems: discoveries from four decades of study in San Francisco Bay. Rev Geophys. [accessed 2022 Feb 16];50:RG4001. *https://doi.org/10.1029/2012RG000397*

[CNRA] California Natural Resources Agency. 2017. Sacramento Valley salmon resiliency strategy. [Accessed 2022 Nov 22]. Available from: *http://resources.ca.gov/docs/Salmon-Resiliency-Strategy.pdf*

Connon RE, Hasenbein S, Brander SM, Poynton HC, Holland EB, Schlenk D, Orlando JL, Hladik ML, Collier TK, Scholz NL et al. 2019. Review of and recommendations for monitoring contaminants and their effects in the San Francisco Bay–Delta. San Franc Estuary Watershed Sci. [accessed 2022 May 18];17(4). *https://doi.org/10.15447/sfews.2019v17iss4art2*

DiGennaro B, Reed D, Swanson C, Hastings L, Hymanson Z, Healey M, Siegel S, Cantrell S, Herbold B. 2012. Using conceptual models in ecosystem restoration decision making: an example from the Sacramento–San Joaquin River Delta, California. San Francisco Estuary and Watershed Science [accessed 2022 May 18];10(3). *https://doi.org/10.15447/sfews.2012v10iss3art1*

Durand JR. 2015. A conceptual model of the aquatic food web of the upper San Francisco Estuary. San Fran Estuary and Watershed Sci. [accessed 2022 May 18];13(3). *https://doi.org/10.15447/sfews.2015v13iss3art5*

[DSC] Delta Stewardship Council, Delta Science Program. 2022. 2022–2026 science action agenda: a vision for integrating Delta science. [Accessed 2022 Nov 22]. Available from: *https://scienceactionagenda.deltacouncil.ca.gov/pdf/2022-2026-science-action-agenda.pdf*

Feyrer F, Nobriga ML, Sommer TR. 2007. Multi-decadal trends for three declining fish species: habitat patterns and mechanisms in the San Francisco Estuary, California, USA. Can J Fish Aquat Sci. [accessed 2022 May 18];64:723–734. *https://doi.org/10.1139/f07-048*

Fong S, Louie S, Werner I, Davis J, Connon RE. 2016. Contaminant effects on California Bay–Delta species and human health. San Franc Estuary Watershed Sci. [accessed 2022 Feb 16];14(4). *https://doi.org/10.15447/sfews.2016v14iss4art5*

Frantzich J, Davis BE, MacWilliams M, Bever A, Sommer T. 2021. Use of a managed flow pulse as food web support for estuarine habitat. San Franc Estuary Watershed Sci. [accessed 2022 May 16];19(3). *https://doi.org/10.15447/sfews.2021v19iss3art3*

Frantzich J, Sommer T, Schreier B. 2018. Physical and biological responses to flow in a tidal freshwater slough complex. San Franc Estuary Watershed Sci. [accessed 2020 Jul 16];16(1). *https://doi.org/10.15447/sfews.2018v16iss1/art3*

Gerlak AK, Heikkila T, Smolinski SL, Huitema D, Armitage D. 2018. Learning our way out of environmental policy problems: a review of the scholarship. Policy Sci. [accessed 2022 May 18];51(3):335–371. *https://doi.org/10.1007/s11077-017-9278-0*

Goertler P, Jones K, Cordell J, Schreier B, Sommer T. 2018. Effects of extreme hydrologic regimes on juvenile Chinook Salmon prey resources and diet composition in a large-river floodplain. Trans Am Fish Soc. [accessed 2020 Jul 16];147:287–299. *https://doi.org/10.1002/tafs.10028*

Gregory R, Failing L, Harstone M, Long G, McDaniels T, Ohlson D. 2013. Structured decision making: a practical guide to environmental management choices. London (UK): Wiley–Blackwell. 312 p.

Grimaldo LF, Sommer T, Van Ark N, Jones G, Holland E, Moyle PB, Herbold B, Smith P. 2009. Factors affecting fish entrainment into massive water diversions in a tidal freshwater estuary: can fish losses be managed? N Am J Fish Manag. [accessed 2020 Jul 15];29:1253–1270. *https://doi.org/10.1577/M08-062.1*

Grossman GD. 2016. Predation on fishes in the Sacramento–San Joaquin Delta: current knowledge and future directions. San Franc Estuary Watershed Sci. [accessed 2020 Jul 15];14(2). *https://doi.org/10.15447/sfews.2016v14iss2art8*

Harwell MC, Molleda JL, Jackson CA, Sharpe L. 2020. Establishing a common framework for strategic communications in ecosystem-based management and the natural sciences. In: O'Higgins T, Lago M, DeWitt T, editors. Ecosystem-based management, ecosystem services and aquatic biodiversity. Springer, Cham. p. 165–188. *https://doi.org/10.1007/978-3-030-45843-0_9*

Healey, M, Goodwin, P, Dettinger M, Norgaard R. 2016. The state of Bay–Delta science 2016: an introduction. San Franc Estuary Watershed Sci. [accessed 2022 May 18];14(2). *https://doi.org/110.15447/sfews.2016v14iss2art5*

Jassby AD, Kimmerer WJ, Monismith SG, Armor C, Cloern JE, Powell TM, Schubel JR, Vendlinski TJ. 1995. Isohaline position as a habitat indicator for estuarine populations. Ecol Appl. [accessed 2020 Jul 15];5:272–289. Available from: *https://www.sciencebase.gov/catalog/item/50537c09e4b097cd4fcdeee1*

Johnson RC, Windell S, Brandes PL, Conrad JL, Ferguson J, Goertler PAL, Harvey BN, Heublein J, Israel JA, Kratville DW, et al. 2017. Science advancements key to increasing management value of life stage monitoring networks for endangered Sacramento River winter-run Chinook Salmon in California. San Franc Estuary Watershed Sci. [accessed 2022 May 18];15(3). *https://doi.org/10.15447/sfews.2017v15iss3art1*

Kimmerer WJ. 2002a. Physical, biological, and management responses to variable freshwater flow into the San Francisco Estuary. Estuaries. [accessed 2022 May 18]; 25:1275–1290. *https://doi.org/10.1007/BF0269222*

Kimmerer WJ. 2002b. Effects of freshwater flow on abundance of estuarine organisms: physical effects or trophic linkages. Mar Ecol Progr Series. [accessed 2022 May 18];243:39–55. *https://doi.org/10.3354/meps243039*

Kimmerer W. 2004. Open water processes of the San Francisco Estuary: from physical forcing to biological responses. San Franc Estuary Watershed Sci. [accessed 2022 May 18];2(1). *https://doi.org/10.15447/sfews.2004v2iss1art1*

Kimmerer WJ, Bennett WA, Burau JR. 2002. Persistence of tidally-oriented vertical migration by zooplankton in a temperate estuary. Estuaries. [accessed 2022 May 18];25:359–371. Available from: *https://www.jstor.org/stable/1352960*

Kimmerer WJ, Nobriga ML. 2008. Investigating particle transport and fate in the Sacramento–San Joaquin Delta using a particle-tracking model. San Franc Estuary Watershed Sci. [accessed 2022 May 18];6(1). *https://doi.org/10.15447/sfews.2008v6iss1art4*

Kimmerer WJ, MacWilliams ML, Gross ES. 2013. Variation of fish habitat and extent of the low-salinity zone with freshwater flow in the San Francisco Estuary. San Franc Estuary Watershed Sci. [accessed 2022 May 18];11(4). *https://doi.org/10.15447/sfews.2013v11iss4art1*

Kimmerer W, Wilkerson F, Downing B, Dugdale R, Gross E, Kayfetz K. et al. 2019. Effects of drought and the Emergency Drought Barrier on the ecosystem of the California Delta. San Franc Estuary Watershed Sci. [accessed 2022 May 18];17(3). *http://doi.org/10.15447/sfews.2019v17iss3art2*

Kraus TEC, Carpenter KD, Bergamaschi BA, Parker AE, Stumpner EB, Downing BD, Travis NM, Wilkerson FP, Kendall C, Mussen TD. 2017. A river-scale Lagrangian experiment examining controls on phytoplankton dynamics in the presence and absence of treated wastewater effluent high in ammonium. Limnol Oceanogr. [accessed 2021 Oct 10];62(3):1234–1253. *https://doi.org/10.1002/lno.10497*

Larsen LG, Bashevkin SM, Christman MA, Conrad JL, Dahm CN, Thompson J. 2022. Ecosystem services and disservices of Bay–Delta primary producers: how plants and algae affect ecosystems and respond to management of the estuary and its watershed. San Franc Estuary Watershed Sci. 20(4). *https://doi.org/10.15447/sfews.2023v20iss4art1*

Lehman PW, Teh S, Boyer GL, Nobriga M, Bass E, Hogle C. 2010. Initial impacts of Microcystis aeruginosa blooms on the aquatic food web in the San Francisco Estuary. Hydrobiologia. [accessed 2022 May 18];637:229–5175. 248. *https://doi.org/10.1007/s10750-009-9999-y*

Lessard J, Cavallo B, Anders P, Sommer T, Schreier B, Gille D, Schreier A, Finger A, Hung T–C, Hobbs J, et al. 2018. Considerations for the use of captive reared Delta Smelt for species recovery and research. San Franc Estuary Watershed Sci. [accessed 2020 Jul 15];16(3). *https://doi.org/10.15447/sfews.2018v16iss3art3*

Lubell M, Mewhirter J. Berard, R. 2020. The origins of conflict in polycentric governance systems. Public Admin Rev. [accessed 2022 May 18]; 80(2):222–233. *https://doi.org/10.1111/puar.13159*

Luoma SN, Dahm CN, Healey M., Moore JN. 2015. Challenges facing the Sacramento–San Joaquin Delta: complex, chaotic, or simply cantankerous? San Franc Estuary Watershed Sci. [accessed 2022 May 18];13(3). *https://doi.org/10.15447/sfews.2015v13iss3art7*

Mac Nally R, Thompson JR, Kimmerer WJ, Feyrer F, Newman KB, Sih A, Bennett WA, Brown L, Fleishman E, Culberson SD, Castillo G. 2010. An analysis of pelagic species decline in the upper San Francisco Estuary using multivariate autoregressive modeling (MAR). Ecol App. [accessed 2022 May 18];20:1417–1430. *https://doi.org/10.1890/09-1724.1*

MacWilliams ML, Ateljevich ES, Monismith SG, Enright C. 2016. An overview of multi-dimensional models of the Sacramento–San Joaquin Delta. San Franc Estuary Watershed Sci. [accessed 2022 May 18];14(4). *https://doi.org/10.15447/sfews.2016v14iss4art2*

Moyle PB, Hobbs JA, Durand JR 2018. Delta Smelt and water politics in California. Fisheries. [accessed 2020 Jul 15];43:42–50. *https://doi.org/10.1002/fsh.10014*

[NMFS] National Marine Fisheries Service, Southwest Region. 2019. Biological opinion for the reinitiation of consultation on the long-term operations of the Central Valley Project and State Water Project. [accessed 2020 Sep 02]. Long Beach (CA): NOAA Fisheries Endangered Species Act Section 7 Consultation Biological Opinion. October 21, 2019. Available from: *https://www.fisheries.noaa.gov/resource/document/biological-opinion-reinitiation-consultation-long-term-operation-central-valley*

Opperman JJ. 2012. A conceptual model for floodplains in the Sacramento–San Joaquin Delta. San Franc Estuary Watershed Sci [accessed 2022 May 18];10(3). *https://doi.org/10.15447/sfews.2012v10iss3art4*

Schacter CR, Peterson SH, Herzog MP, Hartman CA, Casazza ML, Ackerman JT, 2021. Wetland availability and salinity concentrations for breeding waterfowl in Suisun Marsh, California. San Franc Estuary Watershed Sci. [accessed 2022 May 18];19(3). *https://doi.org/10.15447/sfews.2021v19iss3art5*

Schoellhamer DH, Burau JR. 1998. Summary of findings about circulation and the estuarine turbidity maximum in Suisun Bay, CA. [Accessed 2022 May 18]. USGS Fact Sheet FS-047-98. *https://pubs.er.usgs.gov/publication/fs04798*

Schoellhamer DH, Wright SA, Drexler J. 2012. A conceptual model of sedimentation in the Sacramento–San Joaquin Delta. San Franc Estuary Watershed Sci. [accessed 2022 May 18];10(3). *https://doi.org/10.15447/sfews.2012v10iss3art3*

Service R. 2007. Delta blues, California style. Science. [accessed 2022 May 18];317:442–445. *https://www.science.org/doi/10.1126/science.317.5837.442*

Sherman S, Hartman R, Contreras D, editors. 2017. Effects of tidal wetland restoration on fish: a suite of conceptual models. IEP Technical Report 91. Sacramento (CA): California Department of Water Resources. 358 p. Available from: *https://cadwr.app.box.com/v/InteragencyEcologicalProgram/file/571038692179*

Sommer T. 2020. How to respond? An introduction to current Bay Delta natural resources management options. San Franc Estuary Watershed Sci. [accessed 2022 May 18];18(3):1. *https://doi.org/10.15447//sfews.2020v18iss3art1*

Sommer T, Armor C, Baxter R, Breuer R, Brown L, Chotkowski M, Culberson S, Feyrer F, Gingras M, Herbold B, et al. 2007. The collapse of pelagic fishes in the upper San Francisco Estuary. Fisheries. [accessed 2020 Jul 15];32:270–277. *https://doi.org/10.1577/1548-8446(2007)32[270:TCOPFI]2.0.CO;2*

Sommer T, Baxter R, Herbold B. 1997. The resilience of splittail in the Sacramento–San Joaquin Estuary. Trans Am Fish Soc. [accessed 2020 Jul 16];126:961–976. *https://doi.org/10.1577/1548-8659(1997)126<0961:ROSITS>2.3.CO;2*

Sommer T, Conrad JL, Culberson S. 2019. Ten essential Bay–Delta articles. San Franc Estuary Watershed Sci. [accessed 2020 Jul 15];17(2). *https://doi.org/10.15447/sfews.2019v17iss2art1*

Sommer T, Harrell WC, Feyrer F. 2014. Large-bodied fish migration and residency in a flood basin of the Sacramento River, California, USA. Ecol Freshw Fish. [accessed 2020 Jul 16];2014:23:414–423. *https://doi.org/10.1111/eff.12095*

Sommer TR, Harrell WC, Mueller–Solger B, Tom B, Kimmerer W. 2004. Effects of flow variation on channel and floodplain biota and habitats of the Sacramento River, California, USA. Aquat Cons: Mar Freshw Ecosys. [accessed 2020 Jul 16];14:247–261. *https://doi.org/10.1002/aqc.620*

Sommer T, Hartman R, Koller M, Koohafkan M, Conrad JL, MacWilliams M, Bever A, Burdi C, Beakes M. 2020a. Evaluation of a large-scale flow manipulation to the upper San Francisco Estuary: response of habitat conditions for an endangered native fish. PLoS ONE. [accessed 2022 May 18];15(10). *https://doi.org/10.1371/journal.pone.e0234673*

Sommer TR, Nobriga ML, Harrell WC, Batham W, Kimmerer WJ. 2001. Floodplain rearing of juvenile Chinook Salmon: evidence of enhanced growth and survival. Can J Fish Aquat Sci. [accessed 2020 Jul 15];58(2):325–333. *https://doi.org/10.1139/f00-245*

Sommer T. Schreier B, Conrad JL, Takata L, Serup B, Titus R, Carson J, Holmes E, Katz J. 2020b. Farm to fish: lessons from a multi-year study on agricultural floodplain habitat. San Franc Estuary Watershed Sci. [accessed 2022 May 18];18(3). *https://doi.org/10.15447/sfews.2020v18iss3art4*

Strong AL, Mills MM, Huang IB, van Dijken GL, Driscoll SE, Berg GM, Kudela RM, Monismith SG, Francis CA, Arrigo KR. 2021. Response of lower Sacramento River phytoplankton to high-ammonium wastewater effluent. Elementa: Science of the Anthropocene. [accessed 2021 Oct 10];9(1):040. Available from: *https://online.ucpress.edu/elementa/article/9/1/040/116040/Response-of-Lower-Sacramento-River-phytoplankton(1)*

Thomson JR, Kimmerer WJ, Brown LR, Newman KB, Mac Nally R, Bennett WA, Feyrer F, Fleishman E. 2010. Bayesian change-point analysis of abundance trends for pelagic fishes in the upper San Francisco Estuary. Ecol Appl. [accessed 2022 May 18];20:181–198. Available from: *https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/california_waterfix/exhibits/docs/petitioners_exhibit/dwr/part2_rebuttal/dwr_1253.pdf*

[USBR and CDWR] US Bureau of Reclamation and California Department of Water Resources. 2019. Yolo Bypass Salmonid Habitat Restoration and Fish Passage Project environmental impact report. Sacramento (CA): US Dept. of the Interior, Bureau of Reclamation. [accessed 2022 May 18]; Available from: *https://www.usbr.gov/mp/nepa/nepa_project_details.php?Project_ID=30484*

[USFWS] US Fish and Wildlife Service. 2008. Formal Endangered Species Act consultation on the proposed coordinated operations of the Central Valley Project and State Water Project. Sacramento (CA): USFWS. 410 p. [accessed 2020 Jul 15]. Available from: *https://www.usbr.gov/mp/cvo/OCAP/docs/OCAP_BA_2008.pdf*

[USFWS] US Fish and Wildlife Service. 2019. Biological opinion of consultation on the coordinated operations of the Central Valley Project and State Water Project. Sacramento (CA): USFWS.

Wagner RW, Stacey M, Brown LR, Dettinger M. 2011. Statistical models of temperature in the Sacramento–San Joaquin Delta under climate-change scenarios and ecological implications. Estuaries Coasts. [accessed 2022 June 11]; 34:544–556. *https://doi.org/10.1007/s12237-010-9369-z*

Wiens, JA, Zedler JB, Resh VH, Collier TK, Brandt S, Norgaard RB, Lund JR, Atwater B, Canuel E, Fernando HJ. 2017. Facilitating adaptive Management in California's Sacramento–San Joaquin Delta. San Franc Estuary Watershed Sci. [accessed 2022 May 18];15(2). *https://doi.org/10.15447/sfews.2017v15iss2art3*

Winder M, Jassby AD. 2011. Shifts in zooplankton community structure: implications for food web processes in the upper San Francisco Estuary. Estuaries Coasts. [accessed 2022 May 18];34:675–690. *https://doi.org/10.1007/s12237-101-9342-x*

Young MJ, Feyrer F, Colombano DD, Conrad JL, Sih A. 2018. Fish-habitat relationships along the estuarine gradient of the Sacramento-San Joaquin Delta, California: implications for habitat restoration. Estuaries Coasts. [accessed 2022 May 18];41:2389–2409. *https://doi.org/10.1007/s12237-018-0417-4*

Zeug SC, Beakes M, Wiesenfeld J, Greenwood M, Grimaldo L, Hassrick J, Collins A, Acuña S, Johnston M. 2021. Experimental quantification of piscivore density and habitat effects on survival of juvenile Chinook Salmon in a tidal freshwater estuary. Estuaries Coasts. [accessed 2022 May 18];44:1157–1172. *https://doi.org/10.1007/s12237-020-00836-8*