# Preparing for a Fast-forward Future in the Sacramento-San Joaquin Delta

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This is the draft journal article on rapid environmental change that individual members of the Delta Independent Science Board have prepared for discussion at its August 2020 meeting.

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California's Sacramento-San Joaquin Delta has undergone a profound transformation since the Gold Rush of the nineteenth century (Whipple et al. 2012). Now, as the effects of climate change gain force, the environment is changing more rapidly and extreme events—droughts, heat waves, forest fires, and floods—are becoming more extreme. Ecosystems are being driven to or beyond thresholds of irreversible change. As these climate-driven changes compound with on-going changes in land use and other drivers, uncertainty increases. Ecological systems may not exhibit the same dynamics, follow the same trajectories, or respond to management in the same ways as they have in the past.

These new, more extreme conditions challenge how we perceive the Delta. They challenge how scientists frame environmental modelling, monitoring, and analyses. They challenge how stakeholders and the public understand their options and determine their preferences as earlier options become impossible and new possibilities emerge.

Delta science and management have the ability to respond to these challenges in a manner that can address human needs, assist other species, and respect the values of the Delta as an evolving place. Doing this, however, will require building on existing strengths with a recognition that environmental changes may be swift, create conditions we have not seen before, and produce surprises. New management approaches, new ways of doing science, and new ways of thinking about the environment are needed (Hobbs and Cramer 2008, Tonkin et al. 2019).

In this paper, we consider how scientists, managers, policy makers, and stakeholders can better cope with these new conditions. We assess some inherent difficulties of conducting science under more rapid change and more frequent surprises and encourage adapting some existing scientific frameworks and techniques to management in the Delta. To provide perspective, Box 1 retells the oft-told tale of the pelagic organism decline as an example of how conventional approaches to science have been slow to assess a rapid change.

## Box 1. The Pelagic Organism Decline

The pelagic organism decline (POD) in the Delta in 2002 was a rapid change between a prior and subsequent regime—a tipping point. The rapid decline of populations of four pelagic organisms during normal water years indicated that something quite different had happened. The POD was understood to be a regime change by 2005, yet in 2007, caution in interpreting the science was still advised:

> *Readers should be cautious when evaluating the relative importance of the hypotheses presented in this report. Hypotheses not based on peer-reviewed literature should be viewed with more skepticism but they represent the newest thinking on POD issues and may become new areas of research* (IEP 2007 Executive Summary).

Delta scientists were caught by surprise and were not in a position to inform a management response before a threshold was crossed. Multiple factors interacted to force the tipping to a new Delta regime, but the primary cause was the invasion of a non-native clam (*Potamocorbula amurensis*) that consumed phytoplankton that had previously fed other instream species. This in turn reduced the food supply to larger species, including Delta smelt and striped bass. Scientific understanding of the combination of causes that pushed the Delta ecosystem into a new regime only emerged well after the event (Sommer et al. 2007, Mac Nally et al. 2010).

This interpretation, however, is still not settled. Recent analyses show that environment-recruitment relationships for multiple species in San Francisco Bay and the Delta may change with the addition of newer data to previously published accounts, particularly if the sudden declines associated with the regime change are not considered in the analyses (Tamburello et al. 2018). Additionally, the pattern of a sudden decline in populations of several fish species apparent in the results of a single series of surveys is not so clear when multiple surveys are combined (Stompe et al. 2020). There may have been multiple tipping points, one in the early to mid-1980s before the introduction of *Potamocorbula* in 1986 and another around 2000 as species adjusted behaviorally to the consequences of the introduction. More data do not necessarily produce better predictions when the environment is changing rapidly, especially if thresholds are crossed.

## Doing Science in a Complex Dynamic Delta

For a long time, ecological scientists and resource managers worked under the assumption that ecological systems, if not in a steady-state equilibrium, at least stayed within a zone of relative stability and predictability—what came to be known as the Historical Range of Variation (Wiens et al. 2012). Scientists assumed that what they had learned would apply in the future, and management practices were based on what had worked in the past. Change was certainly acknowledged. In the Delta, scientists did not expect to be doing the same science on the same Delta year-after-year, nor did managers expect that the same actions would always produce the same results. Yearly variations in streamflow and salinity gradients, complicated by other changes such as invasions of new species, pollution events, or a levee collapse, made it difficult to establish baselines and detect trends (Nobriga and Smith 2020). But change and variation were expected to occur within defined limits. Now, however, rapid and accelerating changes, a greater frequency and magnitude of extreme events, and the crossing of multiple thresholds are compromising ecological science and its applications to management, in three ways.

**First**, ecological systems may not hold still long enough for scientists to understand them, much less apply their findings to management. The speed and acceleration of changes may compromise the process of doing science.

To ensure reliability and accuracy, the scientific process involves many steps: identifying and refining a hypothesis, finding colleagues with complementary skills, designing a research project, convincing funders, obtaining approvals and permits, doing the research, analyzing data and interpreting findings, giving talks on the research, submitting a paper for peer review, responding to reviewers' comments, and submitting a final draft for publication so that others can use and build on the work. These steps entail time-consuming interactions with other scientists, editors, science administrators, and managers. The process may take several years even for research that can be conducted relatively quickly. Many ecological research projects involve multiple years of new data collection, extending the process over a decade or more. Within the Delta, doing science can be even more complicated because multiple agencies are involved in science and management. The slowness of doing and validating good research may reduce its usefulness during more rapid and uncertain changes.

Under some conditions, however, the scientific process may not take so long. With the onset of COVID-19, for example, research to develop a vaccine has been dramatically accelerated. Doing epidemiological research on a virus, however, is very different from doing ecological research on larger organisms such as Chinook salmon or Sandhill cranes, let alone on how ecosystems function. Microorganisms can reproduce quickly under laboratory conditions, with no regard to seasons. The organisms of greatest concern in the Delta live and reproduce over much longer time cycles and studying them and their ecological systems takes much more time. Neither ecological systems nor the science to understand them may be able to keep up with the rapid pace of environmental change.

The effects of the speed and acceleration of environmental changes on the scientific process are further exacerbated by extreme events and thresholds. As extreme events worsen and become more extreme, species and ecosystems are pushed to and may cross thresholds. The 2012 to 2016 drought had profound effects on water flows and availability and on salinity profiles in the Delta, affecting not only water management but also such things as populations of native fish or the abundance and distribution of invasive aquatic plants (Durand et al. 2020). Thresholds are even more disruptive. When ecological systems are pushed to their limits, a threshold may be breached, suddenly shifting the system into a new regime (e.g., the POD; Box 1). Extreme events and thresholds create outliers—conditions that do not fit the patterns scientists and managers expect under “normal” conditions. In addition, the effects of an extreme event on a threshold may not be immediately apparent, further complicating attempts to attribute effects to causes. For example, a major dieback of a non-native plant (*Lepidium latifolium*) in tidal salt marshes in San Francisco Bay in 2015 was apparently driven by a salinity increase associated with extreme drought in 2011 to 2012 — a 3-year time lag (Wigginton et al. 2020).

Anticipating thresholds or determining the causes of extreme outcomes is difficult. Predictive models, for example with parameters derived through regression analyses of past data, may not predict, limiting their effectiveness in guiding management. However, several early-warning signals may indicate the potential onset of thresholds or “critical transitions” in the parlance of complex system dynamics (Scheffer et al. 2009). Swain et al. (2020) have suggested some ways of reducing the uncertainty associated with attributing extreme events to climate change that might be applicable to other environmental changes.

**Second**, as changes in the Delta environment accelerate and become discordant in time and space, uncertainty increases.

Uncertainty usually can be reduced by gathering more data and by improving understanding and modeling of underlying natural processes. Fortunately, new tools and technologies have dramatically increased the speed, precision, and accuracy with which environmental changes can be measured and tracked. Advances in the use of drones, species detection through environmental DNA, and other technologies can generate massive amounts of data on the condition of species and ecosystems. Big Data and artificial intelligence make it possible to analyze observations in new ways, while the Internet speeds the communication and sharing of scientific findings. Better computer models are providing glimpses into the Delta’s complexities (Cloern et al. 2017). But more and more data alone will not suffice and data gathered at one time may become dated and less relevant at a later time as conditions change.

For well over a century, scientists have used statistics and sampling designs to define and reduce uncertainty in their results. By multiple samplings before and after a management action, for example, underlying variation can be assessed so the effectiveness of the action can be statistically evaluated (a before-after-control-impact (BACI) design (Underwood 1994). However, as changes in environmental conditions accelerate and increasingly differ from place to place, underlying before-and-after differences may obscure the impact of managerial actions (Smokorowski and Randall 2017). Statistically speaking, the assumption that samples are drawn from the same population becomes increasingly unrealistic. As the variation among samples caused by changes in environmental conditions increases, the confidence with which inferences from a statistical test can be accepted decreases.

**Third**, science-based management requires that the findings of scientific studies be readily available. This entails synthesizing the results of studies, translating them into understandable terms, and then communicating them to managers and decision makers. All of this takes additional time. In a rapidly changing environment, this increases the likelihood that the scientific findings will no longer be applicable when management decisions must be made.

Delta scientists have been striving to better coordinate their efforts and link them to management in accordance with the goals of *One Delta, One Science* elaborated in the Delta Science Plan (Delta Stewardship Council 2019). Considerable effort has been made to assure that science meets management needs, and synthesizing diverse Delta science findings with respect to their collective implications for management has been a critical issue for some time (CALFED 2010).

These efforts to accelerate and improve science for management in the Delta parallel broader efforts of environmental scientists and ecologists to make their sciences more relevant to management needs (Lubchenco 1998, Schlesinger 2010). Palmer (2012) and Bradford et al. (2018) have called for “actionable science” to produce the scientific guidance that policy makers and managers need. A group of ecologists has promoted “translational ecology” (Enquist et al. 2017), appealing to scientists to forge stronger links between research and its synthesis for application (Carpenter et al. 2009) in order to accelerate the incorporation of science into management and policy.

Translational ecology, actionable science, and more rapid and applied synthesis encourage more rapid and flexible application of science to decision making in the context of rapid change. They address the speed of environmental change. Yet, given the increasing uncertainty and the limitations on study design and statistical power, and the confounding effects of greater extremes and encountering thresholds more frequently, new approaches to foreseeing environmental changes, conducting ecological research, and applying the results to management are needed.

## Foreseeing Possible Futures

Several approaches have been developed to foresee possible futures and begin to understand their implications for management. Three stand out, namely horizon scanning, elicitation of expert judgment, and scenario analysis. We posit that these approaches can be enhanced, used together, and made more integral to Delta science. They are ways of conducting “anticipatory science” (Lindenmayer et al. 2010, Bradford et al. 2018).

### *Horizon Scanning*

Scientists routinely take stock of the state of their science and assess future challenges as they select topics for research. Such assessments within a discipline, however, tend to be narrow and can lead to increased specialization rather than broader understanding. In response to the growing complexity of problems humanity is facing, the increasing partitioning of scientific knowledge into discrete disciplines, and the limits to what any one person can know, scientists are organizing into interdisciplinary teams to take stock of knowledge and identify new phenomena that may emerge.

Horizon scanning formalizes the process of “taking stock” and looking forward; it collectivizes the process in light of new challenges to assess future trends. The scans are broader and deeper than scientists from any one discipline can conduct and are aimed at detecting new phenomena and responding to new challenges. The process draws on the scientific literature, science news, and experiential knowledge of scientists to detect unusual findings and new trends. Horizon scanning has been used in public health, medicine, and other fields for years. Amantidou et al. (2012) and Sutherland et al. (2019) have applied the technique in several assessments of emerging issues in conservation biology. However, horizon scanning has not been used extensively in ecology and resource management. Through formal, collective horizon scanning, scientists seek to foresee phenomena that they would have missed or were unlikely to discover by acting individually. Artificial Intelligence and other approaches to mining massive amounts of data for patterns can facilitate horizon scanning.

As a process of looking ahead, horizon scanning almost inevitably deals with the speed of environmental, technological, and social change. By formalizing the process, making it interdisciplinary, and explicitly addressing the speed of change, horizon scanning may alert scientists, managers, and policy makers to possible future conditions and identify new, critical issues for research.

### *Expert Elicitation*

While horizon scanning is one formalized way of drawing on expert opinion to anticipate future conditions, expert judgments can also be mobilized through expert elicitation. The Delphi method was developed during the Cold War to elicit and narrow the range of judgments of experts with respect to the consequences of introducing different technologies into defense systems. The method has since been modified, enriched, and applied in numerous other areas to assess and predict the future (Rescher 1998). The reports of the Intergovernmental Panel on Climate Change (IPCC) are products of deliberations among hundreds of experts from different disciplines who collectively assess the scientific literature. “Experts” may also include policymakers and managers, who may ask different questions, differ in their assessments of the quality of scientific information, and express confidence in the assessments in different ways than would scientists (Mach et al. 2017). In the Delta, Mac Nally et al. (2010) built and ran a model of the pelagic organism decline that partly depended on parameters determined by eliciting expert judgment.

### *Scenario Assessment*

Scenario assessment is a disciplined way of breaking out of the expectation that the future will follow a trajectory extrapolated from the present. Scenario assessment is a way to consider what might develop under specified “what if” alternative assumptions about the future (Wollenberg et al. 2000, Peterson et al. 2003). Scenarios provide a way to structure thinking about the consequences of possible future trajectories and possible ways to respond to them, including identifying new research priorities. Coupled with simulation models, scenarios are an effective way of exploring the consequences of different assumptions or information in complex systems with multiple pathways of interactions (e.g., ecosystems).

Scenarios have been at the core of scientific assessments of possible futures. At a global scale, the Millennium Ecosystem Assessment used scenarios to considered alternative governance scenarios (Alcamo et al. 2003). Scenario analyses have figured importantly in projections of future climate processes and consequences (Moss et al. 2010, Mach and Field 2017). Cloern et al. (2011) used scenarios to project the effects of changing climate on multiple features of San Francisco Bay-Delta ecosystems under two models of climate change. Although the scenarios differed in their projections (because the underlying climate models made quite different assumptions), the analysis suggested that extreme events might become more frequent, with an increasing probability that ecosystems might be pushed over thresholds to new regimes. These are important messages for managers.

### ***Framing Futures***

Horizon scanning, expert judgment, and scenario analysis are formalized, structured ways of looking into the future. They are typically founded on our current knowledge of environments and ecosystems and how they function. Delta environmental science and ecology have been shaped by the types of questions they have been asked to answer, and over time these questions have become institutionalized in legislation, court rulings, and agency structures. Several existing approaches may offer fresh ways of doing Delta science in an era of rapid change and greater extremes.

### ***Distributional Ecology***

As environments change, the distribution and abundance of species change in response, albeit with sometimes substantial time lags. These shifts produce a continuing turnover in the species present in an area, presenting a moving target for management and restoration. Understanding these changes is the aim of distribution ecology. The focus is not just on where species are, but also on how they may respond spatially to changing conditions, now and in the future.

Biogeographers and ecologists have been interested in distributional dynamics since von Humboldt recognized ecological zones in the early 19$^{th}$ century (Wulf 2015).

More recently, sophisticated models and statistics have been developed to relate species distributions to habitat suitability (Franklin 2010, Guisan et al. 2017), and these tools have been coupled with climate models to forecast the distribution of species under scenarios of future climate change. In California, for example, projections of the future distributions of landbirds indicate that, as climate changes and habitats shift, species will respond differently, creating assemblages that have no contemporary analog (i.e., “novel ecosystems”) (Stralberg et al. 2009, Wiens et al. 2009). Rapid change is incorporated in the distributional models through its incorporation in the underlying climate models and the resulting effects on habitat (vegetation types, in the case of the California birds analyses). The effects of extreme events or tipping points, however, are not considered; these could lead to even more uncertain distributional dynamics. These aspects of environmental change are challenging models of distribution (Woodin et al. 2013) and new ways of thinking are being tested.

***Disturbance Ecology***

Disturbances alter the state of an ecosystem or divert it from whatever trajectory of change it is following. The effects of disturbances have been a focus of ecological thinking and research for a century. Initially, disturbances were viewed as moving an ecological system from a stable state (e.g., a “climax community”), to which it would then return in the absence of further disturbance. Draining of a wetland to create conditions for farming permanently changes it into something else and restoring the farmland back to a wetland does the same. More recently, ecologists have recognized that disturbance may be frequent enough to keep a system in a state of flux or even cause it to change into something different (Pickett and White 1985, Turner 2010).

Disturbances such as hurricanes or earthquakes occur naturally, of course, but human-caused disturbances are increasingly part of the changing world of the Anthropocene (Newman 2019). Much of California is subject to both lightning-caused and human-caused fires that re-set vegetation succession and have cascading effects on other species and ecosystem processes. People are affecting the frequency and intensity of fires, both directly and as a consequence of climate change (Keeley and

Sanford 2016). In the Delta, species and ecosystems are affected by severe droughts and extraordinarily wet years. Such disturbances are examples of extreme events, which are expected to become more frequent and of greater magnitude. Thinking of extreme events in the context of disturbance ecology may provide an appropriate perspective to understand and anticipate the effects of rapid change (Newman 2019).

### *Resilience Thinking*

As ecological systems have become increasingly stressed by climate change, altered disturbance regimes, and the other manifestations of rapid change, "resilience" has become a much-desired attribute of systems. People in many areas of activity — wealth managers, city planners, child psychologists, hospital administrators, electricity systems analysts, as well as environmental scientists and resource managers — talk of enhancing the resilience of the systems they manage. The intent is to maintain desired features of a system despite the changing environmental conditions.

"Resilience" has multiple meanings (Angeler et al. 2018, Falk et al. 2019). The term frequently refers simply to the ability of a system to quickly spring back to its previous state after a disturbance, but it may also refer to the potential of a system to remain in a particular configuration and maintain its functions despite disturbance, the ability of the system to reorganize following a disturbance-driven change, or the time it takes to return following disturbance (Gunderson 2000, Walker et al. 2002). Broadly, "resilience" now refers to the ability of a system to buffer or cope with perturbations under changing conditions while avoiding regime changes and retaining most of its character. The greater the resilience of a system, the more likely it will be able to persist or retain its basic structure and function when environmental conditions change rapidly, extreme events occur, or thresholds loom.

Explicitly directing management toward fostering system resilience can be an important way to adapt to rapid environmental change. For example, Beller et al. (2019) applied the concept of resilience to the Delta, focusing on how landscape attributes could be managed to ensure that water temperatures were suitable for native fish while maintaining landscape connectivity and recognizing the needs of agriculture. Managing for resilience entails keeping a system within acceptable boundaries rather than aiming for a specific (stable) state of the system.

### *Coupled Human-Natural Systems*

Resilience thinking is increasingly cast in the broader context of coupled socio-ecological systems (Walker and Salt 2008, 2012; Gunderson et al. 2010). It's not just that the environment is changing rapidly. Human societies, economies, and the technologies that support them are also undergoing rapid and accelerating change (Friedman 2016). The coupling of complex ecological systems with even more complex social systems leads to nonlinear dynamics with thresholds, feedback loops, time lags, and surprises (Liu et al. 2007).

Dealing scientifically with all this complexity is a formidable challenge, but it is a reality that cannot be ignored. Attempts to manage Delta ecosystems or enhance their resilience in the face of rapid change are by themselves unlikely to be adequate unless the rapidly changing socio-ecological context is also considered. Putting people into the system highlights that the resilience of the system, for example, depends on how quickly scientists are able to detect system change and how quickly managers are able to respond to change. In a coupled-systems framing, the human response to change is as critical as the natural system response in determining resilience.

Formally modeling coupled human-natural systems requires highly interactive teams of researchers from multiple disciplines. Team members start with different assumptions, use different conceptual frameworks, and have expert knowledge in different aspects of the larger picture. What makes interaction and shared learning possible is the broader coupled systems frame of mind. Yet actually doing empirical research more broadly and interactively has numerous complications that make it considerably more time consuming, and thus not well matched to the speed of social, technological, and environmental change. Complexity suggests that research should be framed more fully and incorporate data for multiple variables, while the speed of change may not allow sufficient time to systemically model and empirically evaluate the multiple and diverse complexities that create growing uncertainty.

The changes in the Delta have been human-driven for more than a century. A broad coupled human-natural systems approach to thinking about the Delta is long overdue. The State of California has long tried to resolve “Delta problems” through natural-science analysis and natural-science-based technical remedies, while giving less emphasis to systematically addressing the human drivers of Delta problems. Recent efforts to expand the role of social scientists in the Delta science community will make human-natural system thinking more likely (Social Science Task Force 2020).

## Conclusions

The recognition that the environment is changing rapidly is not new. Rapid, massive change has been highlighted in numerous scientific publications (e.g., Hobbs and Cramer 2008, Lindenmayer et al. 2010, Barnosky et al. 2012, Beach and Clark 2015, Bradford et al. 2018) as well as popular literature (e.g., Friedman 2016). Considerable attention has been given to how management can adapt to change. For example, plant species threatened with extinction as habitats are lost to climate change are being propagated in nurseries and translocated to places where conditions are becoming more favorable. Not widely appreciated, however, are the consequences of the accelerating speed of change, of more frequent and larger extreme events, and of increasing encounters with tipping points. These will affect how ecological and environmental science are conducted and applied. So, what is needed to help society cope with accelerating environmental change?

First, science and management must be more nimble and flexible to keep pace with rapidly changing conditions and deal with surprises (Bradford et al. 2018). The approaches we have briefly described all rest upon broad collaboration—among scientists in different disciplines, among managers stationed in different agencies at different levels of government, among legislators and judges who make and enforce environmental laws and regulations, among stakeholder groups and the public whose lives and livelihoods will be affected by decisions now and in the future, and among all these groups with one another. Too often, however, the cultures, methodologies, languages, and infrastructure of different disciplines, agencies, or other groups create barriers; they act centripetally, drawing inward rather than reaching out. There are few incentives for crossing disciplinary or institutional boundaries. Environmental laws and regulations may further restrict broad, integrative actions and polarize positions among people who should be seeking common ground. All of this limits the insights and restricts the flexibility needed to respond to rapid and unanticipated changes.

It doesn't have to be this way. New legislative action and laws, for example, may not be needed to adjust to changing conditions; there may be enough inherent flexibility in the interpretations and regulations associated with many existing laws to allow changes in their implementation that will foster resilience or enable multi-agency collaboration (Garmestani et al. 2019). Rapid data collection and processing are enabling interconnected teams of scientists from multiple disciplines to be in constant communication, discussing new findings and hypothesizing how the diverse processes of the geosphere are changing and the biosphere is responding. Many scientists already work across disciplines and interact with managers, policy makers, and the public. This is what is fueling the emergence of actionable science and translational ecology. Even so, environmental scientists and managers will need to put greater effort into working with the public generally, and with legislators, judges and regulators, and stakeholders in particular. As the environment changes, previous expectations of what is possible must fade, while new knowledge and conditions may create new opportunities.

Second, we have noted how the process of doing good science may impede its ability to quickly adjust to rapid environmental changes, extremes, and thresholds. Scientists like to strive for high levels of certainty and are trained to do so. Yet, given the challenge of designing scientific studies that will produce statistically reliable results, scientists and managers may have to be content with conducting studies and making decisions with less complete knowledge. Scientists should not hold things up while they seek more definitive answers. Great precision may be unnecessary in many situations undergoing rapid change. Rather than pursuing a high level of certainty to gauge the effectiveness of a management action, we may need to settle for science that is "good enough." "Good enough" is a matter of defining an acceptable level of probability that an action will produce the desired result. The risk is that science that is only good enough may be wrong and lead one to do “something stupid” (Wiens 2008). In a rapidly changing environment, it is even more important to conduct management in an adaptive-management framework.

There is also a risk that, with so much changing so rapidly, there will be no shortage of questions to answer, and that important questions will not be addressed. Scientists may be unable to recognize and focus on the important changes and might flit from one interesting question or apparent crisis to another. Recognizing what is “important,” however, requires an understanding of the primary drivers of change and the complex pathways of interactions that determine how they affect a system. Thus, the conundrum: gaining this knowledge takes time, which is precious in a rapidly changing Delta.

The 2019 Delta Science Plan encourages looking ahead and watching what is on the horizon. This Plan indicates that the 2021 updated Science Action Agenda will elaborate on horizon scanning and how it might be incorporated in Delta science. In our judgment, because the times are so different, we suggest that a new interdisciplinary science unit be created specifically tasked to undertake horizon scanning, scenario analysis, and the formal practice of eliciting expert judgment while also promoting the use of new frames of analysis appropriate to more rapid and uncertain change among Delta scientists generally.

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