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SPECIAL ISSUE: THE STATE OF BAY–DELTA SCIENCE 2016, PART 3

Perspectives on Bay–Delta Science and Policy

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ABSTRACT

The State of Bay–Delta Science 2008 highlighted seven emerging perspectives on science and management of the Delta. These perspectives had important effects on policy and legislation concerning management of the Delta ecosystem and water exports. From the collection of papers that make up the State of Bay–Delta Science 2016, we derive another seven perspectives that augment those published in 2008. The new perspectives address nutrient and contaminant concentrations in Delta waters, the failure of the Delta food web to support native species, the role of multiple stressors in driving species toward extinction, and the emerging importance of extreme events in driving change in the ecosystem and the water supply.

The scientific advances that underpin these new perspectives were made possible by new measurement and analytic tools. We briefly discuss some of these, including miniaturized acoustic fish tags, sensors for monitoring of water quality, analytic techniques for disaggregating complex contaminant mixtures, remote sensing to assess levee vulnerability, and multidimensional hydrodynamic modeling.

Despite these new tools and scientific insights, species conservation objectives for the Delta are not being met. We believe that this lack of progress stems in part from the fact that science and policy do not incorporate sufficiently long-term perspectives. Looking forward half a century was central to the Delta Visioning process, but science and policy have not embraced this conceptual breadth. We are also concerned that protection and enhancement of the unique cultural, recreational, natural resource, and agricultural values of the Delta as an evolving place, as required by the Delta Reform Act, has received no critical study and analysis. Adopting wider and longer science and policy perspectives immediately encourages recognition of the need for evaluation, analysis, and public discourse on novel conservation approaches. These longer and wider perspectives also encourage more attention to the opportunities provided by heavily invaded ecosystems. It is past time to turn scientific and policy attention to these issues.

KEY WORDS

Sacramento–San Joaquin Delta, scientific advances, new scientific perspectives, new scientific tools, policy perspectives, novel conservation methods.

CONNECTING THE PAST WITH THE PRESENT

The State of Bay–Delta Science 2008 (Healey et al. 2008a, hereafter SBDS 2008) synthesized the scientific literature on the Sacramento–San Joaquin Delta that addressed the issues considered most important at that time. SBDS 2008 was written mainly for managers and policy makers and was successful in its objectives. The papers included in the special issues of *San Francisco Estuary and Watershed Science* that make up the State of Bay–Delta Science 2016 (SBDS 2016)[1], on the other hand, are written for a more technical audience, although we hope they will still be of value to policy-makers. As was the case in 2008, it was not possible to include in SBDS 2016 a paper on every scientific issue that affects water supply and the Delta ecosystem. To narrow the list, we canvassed senior managers, policy-makers and scientists familiar with the Delta and eventually selected 12 topics that led to the list of papers published in *San Francisco Estuary and Watershed Science* (Table 1). Some of the topics reprise issues examined in 2008 (e.g., water supply, levees, food webs) but take a different perspective and bring in new information. Others address issues that have come more to the fore since 2008 (e.g., nutrients, contaminants, predation). The chapters still address only a partial list of relevant topics, however, and we anticipate that additional papers will be commissioned as new concerns arise, keeping SBDS an up-to-date, growing source of synthesized information for Delta scientists and managers.

SBDS 2008 began with seven new perspectives on how the Delta functions that emerged from research conducted over the preceding decade (Table 2). In this paper, we draw from SBDS 2016 and other sources to examine how the perspectives put forward in 2008 have influenced policy and management; how well those perspectives have held up under a decade of intense research on the Delta; how they have evolved as a result of new information and changing conditions in the Delta; what new insights and perspectives have emerged since 2008; and how those new perspectives are contributing to the coequal goals of a reliable water supply and a healthy ecosystem in the context of protecting the Delta as a unique place.

It is a measure of how thinking about the Delta has evolved that the 2008 perspectives now appear self-evident whereas in 2008 they were quite novel. New Perspective 1 (Table 2) emphasized that the Bay–Delta is not a static environment and never has been. Human occupation of the Delta, particularly after 1850, brought accelerated change as well as entirely new directions of change. The ecosystems of the Delta are now structurally and biologically very different from those that existed before the Gold Rush (Whipple et al. 2012); they are novel ecosystems (Hobbs et al. 2006). As such, it is not possible to conserve desired native species by recreating the historic conditions in which they evolved. The new ecosystems, along with the changes impinging from beyond the Delta, will impede and likely undermine attempts to restore those past conditions. With climate change, sea level rise, and the possibility that water may be diverted around the Delta as part of California WaterFix[2], Delta ecosystems will continue to morph and adapt to new conditions. The Delta presents a moving target to which managers must adjust in their pursuit of the coequal goals of a reliable water supply and a healthy ecosystem. Perspectives 2 and 3 in 2008 were corollaries of Perspective 1, which emphasized the uncertainty and complexity that go with continual change (Luoma et al. 2015) but also the necessity of encouraging variability to support desired species and ecosystem services. Managing novel ecosystems calls for novel and flexible approaches (Seastedt et al. 2008). As described in Healey (2008) and further elaborated upon in Luoma et al. (2015), the Delta presents managers with a "wicked" problem (Rittel and Weber 1973) that cannot be solved but only managed.

Perspectives 4 and 6 were also interlinked, emphasizing that water and environmental management are not separate problems and that creative, integrated science is needed to help resolve the water supply/healthy environment nexus. The perspectives also acknowledged that, while providing insights into one set of problems, science may at the same time identify other, unsuspected problems. The nature of wicked problems is that even as you take action to resolve one issue, new issues arise.

1 The SBDS 2016 was published in a series of issues within *SFEWS*: *Volume 13, Issue 3*, *Volume 14, Issue 1*, *Volume 14, Issue 3*, and *Volume, Issue 4*.

2 *https://www.californiawaterfix.com* (accessed 2016 April 15).

Table 1 List of topics and papers published in *San Francisco Estuary and Watershed Science* as the SBDS 2016. Asterisked topics were also addressed in SBDS 2008 (Healey et al. 2008a).

Topic	Published Paper Title
Managing the Delta	Luoma SN, et al. ***Challenges Facing the Sacramento–San Joaquin Delta: Complex, Chaotic, or Simply Cantankerous?*** doi: *http://dx.doi.org/10.15447/sfews.2015v13iss3art7*
Water Supply*	Lund JR. ***California's Agricultural and Urban Water Supply Reliability and the Sacramento–San Joaquin Delta***. doi: *http://dx.doi.org/10.15447/sfews.2016v14iss3art6*.
Levees*	Deverel S, et al. ***Factors and Processes Affecting Levee System Vulnerability***. doi: *http://dx.doi.org/10.15447/sfews.2016v14iss4/art3*
Fluid Dynamics Models	MacWilliams M. et al. ***An Overview of Multi-dimensional Models of the Sacramento-San Joaquin Delta.*** doi: *http://dx.doi.org/10.15447/sfews.2016v14iss4/art2*
Water Constituents Transport	Schoellhamer D, et al. ***Recent Advances in Understanding Flow Dynamics and Transport of Water-quality Constituents in the Sacramento–San Joaquin River Delta***. doi: *http://dx.doi.org/10.15447/sfews.2016v14iss4/art1*
Climate Change	Dettinger M, et al. ***Climate Change and the Delta***. doi: *http://dx.doi.org/10.15447/sfews.2016v14iss3art5*
Contaminants*	Fong S, et al. ***Contaminant Effects on California Bay-Delta Species and Human Health.*** doi: *http://dx.doi.org/10.15447/sfews.2016v14iss4/art5*
Nutrients	Dahm C, et al. ***Nutrient Dynamics of the Delta: Effects on Primary Producers***. doi: *http://dx.doi.org/10.15447/sfews.2016v14iss4/art4*
Food Web*	Brown L, et al. ***Food Webs of the Delta, Suisun Bay, and Suisun Marsh: An Update on Current Understanding and Possibilities for Management***. doi: *http://dx.doi.org/10.15447/sfews.2016v14iss3art4*
Delta Smelt	Moyle P, et al. ***Delta Smelt: Life History and Decline of a Once Abundant Species in the San Francisco Estuary***. doi: *http://dx.doi.org/10.15447/sfews.2016v14iss2art6.*
Salmonids	Perry RW, et al. ***Anadromous Salmonids in the Delta: New Science 2006-2016***. doi: *http://dx.doi.org/10.15447/sfews.2016v14iss2art7*
Predation	Grossman G. ***Predation On Fishes in The Sacramento—San Joaquin Delta: Current Knowledge and Future Directions.*** doi: *http://dx.doi.org/10.15447/sfews.2016v14iss2art8*
Landscape Ecology	Wiens J, et al. ***The Delta as Changing Landscapes***. doi: *http://dx.doi.org/10.15447/sfews.2016v14iss2art9*

Table 2 New perspectives on the Delta as presented in SBDS 2008 (Healey et al. 2008b)

Number	Perspective
1	The Delta is a continually changing ecosystem. Uncontrolled drivers of change (e.g., population growth, changing climate, land subsidence, seismicity) mean that the Delta of the future will be very different from the Delta of today.
2	Because the Delta is continually changing, we cannot predict all the important consequences of management solutions. The best solutions will be robust but provisional, and will need to be responsive and adaptive to future changes.
3	It is neither possible nor desirable to freeze the structure of the Delta in its present, or any other form. Strengthening of levees is only one element of a sustainable solution and is not applicable everywhere.
4	The problems of water and environmental management are interlinked. Piecemeal solutions will not work. Science, knowledge and management methods all need to be strongly integrated.
5	The capacity of the Sacramento-San Joaquin water system to deliver human, economic and environmental services is likely at its limit. To fulfill more of one water-using service we must accept less of another.
6	Good science provides a reliable knowledge base for decision-making, but for complex environmental problems, even as we learn from science, new areas of uncertainty arise.
7	Accelerated climate change means that species conservation is becoming more than a local habitat problem. Conservation approaches need to include a broad range of choices other than habitat protection.

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Table 3 Some of the requirements for the Delta Plan as listed in paragraph 85302 of the Delta Reform Act of 2009

(c) The Delta Plan shall include measures that promote all of the following characteristics of a healthy Delta ecosystem:	
1	Viable populations of native resident and migratory species.
2	Functional corridors for migratory species.
3	Diverse and biologically appropriate habitats and ecosystem processes.
4	Reduced threats and stresses on the Delta ecosystem.
5	Conditions conducive to meeting or exceeding the goals in existing species recovery plans and state and federal goals with respect to doubling salmon populations.
(d) The Delta Plan shall include measures to promote a more reliable water supply that address all of the following:	
1	Meeting the needs for reasonable and beneficial uses of water.
2	Sustaining the economic vitality of the state.
3	Improving water quality to protect human health and the environment.
(e) The following sub-goals and strategies for restoring a healthy ecosystem shall be included in the Delta Plan:	
1	Restore large areas of interconnected habitats within the Delta and its watershed by 2100.
2	Establish migratory corridors for fish, birds, and other animals along selected Delta river channels.
3	Promote self-sustaining, diverse populations of native and valued species by reducing the risk of take and harm from invasive species.
4	Restore Delta flows and channels to support a healthy estuary and other ecosystems.
5	Improve water quality to meet drinking water, agriculture, and ecosystem long-term goals.
6	Restore habitat necessary to avoid a net loss of migratory bird habitat and, where feasible, increase migratory bird habitat to promote viable populations of migratory birds.

In the Delta Reform Act of 2009[3], the legislature implicitly acknowledged the multifaceted and complex nature of the Delta management problem in paragraph 85302, which includes a long list of characteristics of a healthy ecosystem and reliable water supply that were to be addressed by the Delta Plan (Table 3). They further acknowledged the importance of science to successful management by mandating creation of the Delta Science Program[4] with the mission: "... to provide the best possible unbiased scientific information to inform water and environmental decision-making in the Delta ... through funding research, synthesizing and communicating scientific information to policy makers and decision-makers, promoting independent scientific peer review, and coordinating with Delta agencies to promote science-based adaptive management." SBDS 2016 is, in fact, one of the Science Program's initiatives to synthesize and communicate scientific information to policy-makers and decision-makers. The Delta Reform Act also established the Delta Stewardship Council (the Council) as a new governance entity to help guide the overall management and development of the Delta. The Council is to coordinate the actions of state and, through leadership, federal, agencies responsible for water and environmental management, thereby helping to avoid the fragmented and sometimes conflicting actions that occur when agencies act independently. The Council also tracks progress using a suite of performance measures and facilitates avoidance of damaging actions. These charges to the Council reflect the ongoing incorporation of adaptive management into

3 *http://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=200920107SB1* (accessed 2016 April 15).

4 The already existing CALFED Science Program was simply transferred to the Delta Stewardship Council, maintaining a continuity of the science coordination begun under CALFED.

the operating procedures of state and federal agencies that began with CALFED (2000).

Perspective 5 pointed to the obvious but often-ignored fact that California has limited water resources, so hard decisions have to be made about water allocation. Indeed, much of the water supply/healthy environment conflict in the Delta has been about how water is allocated. Although the Delta Reform Act does not specifically mention limitations to water supply, it does establish that the policy of California is to reduce the state's reliance on the Delta for water. This is an implicit admission that the Delta, indeed California as a whole, is at the limit of its surface and groundwater supplies and that the future lies in making smarter use of the state's finite supply of water (DSC 2013; Luoma et al. 2015).

The Delta Reform Act of 2009, the Delta Plan (DSC 2013) and the Delta Science Plan (DSP 2013) are all consistent with the seven perspectives presented in 2008. Both the Delta Plan and the Delta Science Plan are in early stages of implementation; however, there are already some notable successes, such as the establishment of the Delta Regional Monitoring Program,[5] which reflects the improved monitoring proposed in SBDS 2008's Perspective 4. As required under the act, the Delta Plan lists a number of performance measures by which to gage progress. This is another new and positive feature of Delta management that was proposed in the 2008 perspectives. Unfortunately, many of the measures are satisfied by "improvement" as determined by status and trends monitoring. The problem is that conditions can be "improving" at the same time as species are going extinct (Moyle et al. 2016). The Delta Plan is to be updated on a regular basis. It is possible that within a few years advances in multidimensional fluid dynamics modeling coupled with physical, chemical, and ecological process modeling (MacWilliams et al. 2016; Perry et al. 2016; Schoellhamer et al. 2016) will allow specific endpoints to be identified that will constitute positive environmental and water supply outcomes. At the very least, development and testing of such models can become a priority in the Science Action Agenda (DSP 2013).

5 *http://www.waterboards.ca.gov/centralvalley/water_issues/delta_water_quality/delta_regional_monitoring/index.shtml* (accessed 2016 July 2).

We can, therefore, make a case that the perspectives identified in SBDS 2008 have influenced the evolution of policy and management for a reliable water supply and a healthy environment in the Delta. Furthermore, we argue that the new perspectives identified in SBDS 2008 remain relevant today, even as the evolving science of the Delta is bringing to light additional perspectives that will affect how the Delta is managed.

NEW PERSPECTIVES, 2016

In the years since SBDS 2008, Delta science has provided new insights into the functioning of the Delta ecosystem and into water supply and management. Here we offer seven new perspectives that emerge from the science.

1. Nutrients are important.

Whereas in the past we considered nutrients to be relatively unimportant in Delta productivity, increasing water clarity means that both the absolute and relative concentrations of different nutrients in the Delta can now be drivers of Delta productivity, including inhibition of phytoplankton growth by ammonium and promotion of the expansion of invasive* Microcystis*,* Egeria*, and* Eichhornia*.

Over several decades of research, a view of production at the base of the Delta food web (primary production) became established; nutrient concentrations were high, nutrient limitation was rare, and factors other than nutrients (e.g., grazing by *Potamocorbula amurensis*, water residence time, high turbidity) regulated rates of primary production (Jassby et al. 2002). That is to say, there seemed to be little need to worry about nutrient levels in the Delta. As turbidity is declining in the Delta, however, this view is giving way to a more complex narrative that considers the various forms of nitrogen as well as nutrient ratios, fluid dynamics, and the role of invasive species in productivity at the base of the food web (Dahm et al. 2016; Schoellhamer et al. 2016). Of particular interest now are the nutrient conditions that promote development of blooms of cyanobacteria, especially *Microcystis*, and expansion of the waterweeds *Egeria densa* and *Eichhornia crassipes*. High nutrient loads coupled with long

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water residence times may contribute to the growth of these invasive toxic and nuisance species.

In the past, high turbidity conferred a measure of resilience against high nutrient loading in the Delta, and high ammonium levels may also have inhibited phytoplankton growth in some parts of the Delta, preventing the development of blooms. Now, however, increasing water clarity (Schoellhamer et al. 2016) may allow phytoplankton to grow fast enough to escape the inhibitory effect of ammonium, and to develop blooms fueled by the abundant nitrate. But phytoplankton in the Delta will now be competing with *Microcystis*, *Egeria*, and *Eichhornia*, which can absorb ammonium preferentially and outcompete phytoplankton for the nutrient pool (Dahm et al. 2016). How these invading species will affect the food web is, as yet, uncertain.

The situation is complicated further because much of the ammonium that enters the Delta comes from wastewater treatment plants (Jassby 2008), which discharge a myriad of other substances (some toxic) that can also inhibit plankton growth (Dahm et al. 2016; Fong et al. 2016). Wastewater treatment plant upgrades to eliminate ammonium may not remove other pollutants, so that the upgraded discharges may still inhibit phytoplankton growth. The reality is that numerous environmental variables (abiotic and biotic) can affect the growth of phytoplankton and other aquatic plants, and different factors may play a role in different areas of the Delta. To develop effective nutrient and bloom management strategies, a holistic understanding is needed about the factors that affect phytoplankton growth in the estuary. The planned upgrades to the Sacramento Regional Wastewater Treatment Plant (SRWTP) offer an opportune experiment in nutrient reduction that could provide further insights into the relationship among nutrient loading, plant growth, and the functioning of the Delta ecosystem (Dahm et al. 2016).

2. Delta waters are contaminated.

The complex cocktail of contaminants that enters the Delta from agriculture, urban, and industrial discharges can cause serious damage to the ecosystem and human health.

The CALFED Ecosystem Restoration Program strategic plan (CALFED 2000) identified the effects of contaminants that enter the Delta as an area of critical uncertainty in need of focused research. SBDS 2008 echoed this need, noting that poor environmental water quality was a potential human health risk and a factor that contributed to ecological problems (Luoma et al. 2008). Despite the well-documented need for a comprehensive program of contaminant monitoring and assessment in the Delta, little has been accomplished. Recently, the Central Valley Regional Water Quality Control Board established the Delta Regional Monitoring Program. Once it is fully operational, this program will sample mercury, pesticides, nutrients, and pathogens at a number of Delta locations, both routinely and in response to events such as seasonal flush, storms, and dry periods.[6] The program ignores pharmaceuticals and personal care products among other contaminants, but, if implemented as described, it will be an important start toward developing an understanding of the status and trends of selected problem constituents in Delta water.

Targeted research in the Delta and adjacent waters has shown that Delta water is often acutely or sublethally toxic to a range of aquatic organisms, particularly near sources of urban or agricultural discharge (Brooks et al. 2012; Biales et al. 2015). Runoff from agricultural lands is a source of both nutrients and pesticides, and the pesticides in use change regularly, often in response to concerns about toxicity. For example, use of organophosphate and carbamate pesticides has declined because of insect tolerance, the toxicity of organophosphates to humans and the persistence of carbamates in the environment. These pesticides were largely replaced by pyrethroids and neonicotinoids, both of which are highly toxic to invertebrates, notably to the very bees on which agriculture relies (Sanchez–Bayo et al. 2014). Pyrethroids were believed to be less persistent in the environment than carbamates. However, pyrethroids adsorb to sediments and are persistent when adsorbed. In this form, pyrethroids can be carried with river borne sediments to deposition sites where they may accumulate to concentrations acutely toxic to test organisms (Fong et al. 2016).

6 *http://www.waterboards.ca.gov/centralvalley/water_issues/delta_water_quality/delta_regional_monitoring/wq_monitoring_plans/drmp_monitoring_design.pdf*. [Accessed 2016 June 5.]

Neonicotinoids are soluble and persist in the environment for a long time (Fong et al. 2016). Acute toxicity of these pesticides in the ecosystem is rare but sublethal concentrations can contribute to population declines by, for example, making organisms more vulnerable to predation or interfering with reproduction.

Contaminants likely played a role in the pelagic organism decline (POD) that began in the early 2000s (Sommer et al. 2007). For example, Fong et al (2016) used multi-factorial models to examine the relationship between species abundance indices in fall midwater trawls and a range of flow and water-quality variables. Pyrethroid use and flow explained the most variability in species abundance, except for Threadfin Shad (*Dorosoma petenense*), for which only pyrethroids were significant determinants. Among all species, pyrethroid use explained 21% to 73% of the variability of species abundance indices in fall midwater trawl samples. Although multiple factors likely contributed to the POD, this analysis provides strong evidence that contaminants were a contributing factor.

Once regular monitoring of contaminants is underway, analyses will be possible to improve our understanding of interacting and sublethal effects of contaminants in the Delta. As monitoring data accumulate, new multi-dimensional models of hydrodynamics and distribution of water constituents should become feasible (MacWilliams et al. 2016; Schoellhamer et al. 2016), allowing dispersal and concentrations of contaminants moving through the Delta to be predicted. Coupled with data on lethal and sublethal toxicities, species distributions, and food webs (Brown et al. 2016; Fong et al. 2016; Perry et al. 2016), these tools should facilitate assessments of the species-specific and ecosystem consequences of contaminant loadings in the Delta. Such analyses would have been nearly impossible a decade ago.

3. Aquatic food webs no longer sustain native species.

Food webs in the Delta now bear little resemblance to those that supported communities of native organisms before European colonization. Driven by physical and chemical changes in the Delta and invasions by alien species, the aquatic ecosystem has gone through an ecological regime shift that probably cannot be reversed. The present food web appears stable but is much less able to support native fishes than in the past.

The Delta food web today bears little resemblance to that which existed before 1850. Key among the causes of this change were the physical transformation of the Delta and its invasion by exotic species. When the Delta was transformed from a landscape of marshes and flood basins with a complex drainage system into a landscape of leveed islands separated by wide linear channels, the base of the food web shifted from high quality organic detritus from the marshes and flood basins to phytoplankton produced in the open waters of the channels. Much more recently, the invasive overbite clam, *Potamocorbula amurensis*, co-opted the majority of phytoplankton production, resulting in a Delta in which native fishes are severely food limited (Brown et al. 2016). The low-salinity zone, once the most productive region of the Delta, now produces little food, and its foragers are sustained by imports from upstream and downstream.

Although changes in Delta geometry and the invasion of the overbite clam can be identified as critical events, the transformation of the Delta food web unquestionably has multiple causes (e.g., water operations affecting Delta hydrology [MacWilliams et al. 2016], contaminant discharges [Fong et al. 2016], additional species invasions [Brown et al. 2016], sediment load [Schoellhamer et al. 2016]). The food web appears to have been relatively stable for the past 15 years or so (Brown et al. 2016) but new stressors (e.g., climate change [Dettinger et al. 2016], contaminant loads [Fong et al. 2016], further changes in hydrology [MacWilliams et al. 2016], and new invasions [Brown et al. 2016]) can push the ecosystem in undesirable directions. Any actions to improve conditions for native species will have to be undertaken in the light of this new food web structure. There is no returning to the pre-1970s structure. Delta Smelt (*Hypomesus transpacificus*), currently on the brink of extinction (Moyle et al. 2016), will likely be the first native fish species to succumb to the new regime. Others have only tenuous holds on survival (e.g., Katz et al. 2013). Improving conditions for listed species in the Delta remains a major challenge. And, as climate change begins to exert a stronger influence, it may become

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necessary to consider more radical approaches to species conservation.

4. Species declines are a result of multiple stressors acting together.

There are few instances in which a single stressor can be identified as the primary cause of any species' decline. Effective conservation of aquatic species requires a holistic approach to improve habitat quantity and quality.

Many species in the Delta are listed as threatened or endangered. The traditional approach to recovering viable populations of these species has been to search for the most important stressor and try to reduce its effect on the species. In the Delta, conservation actions have focused on improving hydrology and restoring habitat. It is now apparent, however, that no single stressor can be singled out as the "cause" of Delta species' declines. Rather, numerous stressors acting together are increasing the vulnerability of each species to the point that a viable population can no longer be sustained. The Delta Smelt illustrates this complexity very well. When this species first began to decline, attention focused on water exports and the changes in Delta hydrology that resulted in smelt being lost at the export pumps (Moyle et al. 1992). A precipitous decline in Delta Smelt and three other fish species beginning about 2002 (the POD) stimulated a focused analysis of available information, which showed that water export was only one cause of species declines in the Delta (Sommer et al. 2007). Research has continued so that Delta smelt, now virtually extinct, is one of the most thoroughly studied fish species in the world. However, the causes of its demise remain elusive. Food limitation (Brown et al. 2016), exposure to toxic chemicals (Fong et al. 2016; Moyle et al. 2016), interaction with exotic predators (Grossman 2016), and shrinking areas of suitable habitat (Moyle et al. 2016) are all implicated, in addition to water operations and water exports from the Delta. To this list of specific stressors must be added the artificial geometry of the Delta, which represents an alien habitat for most native species.

Native species conservation in the Delta is, therefore, a multi-factorial problem. It is unclear which combinations of stress reductions would lift enough of the burden from native species to allow their persistence. Any viable solution must, however, address multiple stressors. To improve conditions for native species, Moyle et al. (2010) proposed restoring channel complexity and variable water residence time to mimic conditions before 1850, along with improving water quality and increasing marsh and brackish open-water habitat. Current emphasis is on reestablishing marsh and flood basin habitats that will be inundated tidally and seasonally in the northwestern part of the Delta, and reestablishing a more "normal" hydrograph. A somewhat broader but similar suite of management actions are proposed in the Delta Smelt Resiliency Strategy[7]. These are worthwhile experiments but could be sabotaged by the multitude of exotic species and contaminants that now populate the Delta as well as by our incomplete understanding of Delta Smelt.

5. Future water management will be driven more by extreme events (of all types) than by long-term averages, even as those averages change.

As California's climate changes because of global greenhouse gas emissions, more frequent and more extreme storms and droughts will occur. Management will have to restructure to respond to these changes.

The seventh "new" perspective in SBDS 2008 noted that climate change increasingly meant that species conservation is more than a local habitat problem (Healey et al. 2008b). However, Healey et al. (2008b) said little about the forms that climate change was likely to take. For many years, the focus of most assessments of climate-change vulnerabilities in California was on the likely impacts of the projected gradual change in average climatic and hydrologic conditions (Cayan et al. 2008; CDWR 2009; Cloern et al. 2011). Since publication of SBDS 2008, it has become increasingly clear in the Delta as well as globally that the most immediate and difficult problems that climate change will bring will be increased climatic and hydrologic extremes (e.g., Dettinger 2011; Dettinger et al. 2016; IPCC[8]). Average precipitation may not change much, but more will fall as rain rather than snow. Precipitation

7 *http://resources.ca.gov/docs/Delta-Smelt-Resiliency-Strategy-FINAL070816.pdf*. (Accessed 2016 September 13.)

8 *http://ipcc-wg2.gov/SREX/* (Accessed 2016 August 10.)

events will be more intense, and the intervening dry periods dryer. Wet episodes will be wetter and dry periods longer, so that the threat of both flood and drought will increase (Dettinger et al. 2016). Reservoir managers will be faced with conflicting challenges: maintain storage space in reservoirs as a hedge against higher flood risk; or store more winter streamflow for summer irrigation and stream-temperature management. Sea level will rise 60 centimeters or more by the end of the century, challenging managers' ability to control salt intrusion into the Delta from freshwater outflows, particularly during extended droughts. Rising temperatures and declining water supplies will make it difficult or impossible to maintain water temperatures tolerable to native species, particularly during heat waves and droughts. All of these changes will challenge the capacity of the water and environmental management systems to sustain ecologically desirable conditions in the Delta while providing a reliable water supply to millions of Californians. In addition, rising sea level and higher flood flows will increase the risk of levee failure (Deverel et al. 2016), with attendant dramatic effects on Delta agriculture and communities, on water exports from the Delta, and on the ecosystem.

Although climate change places extreme events into clear and urgent focus, the critical role of extremes in the Delta extends beyond climatic extremes supercharged by climate change. With various species on the precipice, with nutrients and foodwebs modified far beyond their natural ranges, with increasing risk of levee failure, with lethal and sublethal cocktails of contaminants in the Delta's waters, and with water resources pushed to their limits, the capacity of the Delta to absorb extremes of all kinds is declining. Thus, even before weather extremes supercharged by climate change force changes in management, other extremes in the Delta system will command the attention of management much more than they have in the past.

Fortunately, there is time for the water-management system to evolve so as to partially mitigate these effects, and managers now have a number of tools that give them greater flexibility to achieve multiple objectives. Replenishing the depleted groundwater basins in the Central Valley to provide an additional reservoir for use during extended dry periods will be particularly important (Lund 2016). However, both the water management system and water users will have to adjust to reduced and more variable inflows to the Delta and to overall less-predictable sources of water supply. Sustaining a Delta ecosystem hospitable to native species will be much more difficult—perhaps impossible. Under these conditions, it may become necessary to manage for novel plant and animal communities that provide desired ecosystem services (Hobbs et al. 2006) rather than focus almost entirely on attempts to restore native species.

6. Delta habitats work together as a landscape-scale mosaic.

The success of local restoration depends on what happens in adjacent habitats and vice versa. Any habitat restoration, therefore, has cascading effects that propagate far beyond the restored habitat. Landscape ecology provides a set of tools and concepts to identify and take into account these cascading effects.

SBDS 2008 recognized that the Delta's problems are not entirely local, but emphasized the external forces (such as climate change and invasive species) that restoration activities need to acknowledge and accommodate. In the past decade, the interconnectedness of the internal parts of the Delta has increasingly been recognized as imposing its own level of "non-locality" on Delta decision-making. The Delta is a mosaic of landscape patches that are interconnected geographically, hydrologically, and ecologically (SFEI–ASC 2016; Wiens et al. 2016). As a consequence, what is done at the restoration site itself only partially determines the success or failure of any habitat restoration. Where a particular patch of restored habitat is located in relation to other habitat patches in the landscape—and how it interacts with other patches, both nearby and distant—are also important to the success of a restoration project. Bond and Lake (2003) describe five reasons that habitat restoration may fail in a landscape context:

- If the restored habitat is within a matrix of unsuitable habitat, target species may not be able to find and colonize it.

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- The restored habitat may be mainly suitable for one life stage, which may not be the limiting stage for the target species.
- Alien species may be the first to colonize new habitat, and their presence may preclude successful colonization by target species (Brown et al. 2016; Dahm et al. 2016; Moyle et al. 2016).
- The legacy of past as well as ongoing large scale disturbances (e.g., regional land-use changes, hydrologic changes) and large scale temporal change (e.g., climate change) can compromise the success of local restoration (Dettinger et al. 2016; Fong et al. 2016; Luoma et al. 2015).
- The scale of a restoration may be inappropriate for the target species (Wiens et al. 2016).

All of these factors are important in decisions about habitat restoration in the Delta. The science of landscape ecology provides concepts and tools for designing habitat restorations that are robust to these and other factors. As yet, however, the tools of landscape design have not been fully integrated into Delta restoration planning (SFEI–ASC 2016).

7. The situation for native species is dire.

The ecological regime shift coupled with the emerging effects of climate change in the Delta are creating conditions that will likely accelerate the current downward spiral of native species. This situation makes it urgent that the scientific foundations for new management responses be developed.

Despite management actions that in some instances appear heroic, fish species continue to decline in abundance in the Delta (Moyle et al. 2011; MacNalley et al. 2010). Moyle et al. (2016) describe three scenarios for the imperiled Delta Smelt that may also apply to other declining species: (1) extinction; (2) establishment of intensively managed remnant populations in circumscribed habitats, such as flooded islands or upstream reservoirs; and (3) development of a semi-natural, although area-restricted, refuge for Delta Smelt by creating an arc of suitable habitat from Yolo Bypass, through the Cache–Lindsay Slough complex and the lower Sacramento River and into Suisun Bay and Marsh. Option 3 is generally consistent with habitat restoration or enhancement proposals in the Delta Plan and is likely to be undertaken. Option 2 constitutes assisted relocation—a hotly debated conservation option for species on the brink (Hewitt et al. 2011). In SBDS 2008, we argued that it was time to begin a serious debate about whether assisted relocation should be considered as a conservation measure (Healey et al. 2008b). We revisit this issue in the last section of this paper, and explore some policy issues about assisted relocation and other novel conservation ideas.

NEW TOOLS THAT ARE ADVANCING DELTA SCIENCE

Rapid advances in science often follow the introduction of new measurement tools or analytical techniques. The advance in scientific understanding of the Delta that has occurred over the past decade is in large measure a consequence of the development and deployment of such new tools. Here we discuss a few of the tools that we believe have contributed in major ways to the advancement of science in the Delta.

1. ***Miniaturized acoustic tags have allowed the migratory pathways of salmon and steelhead through the Delta to be measured in detail, including rates of travel and rates of mortality in different Delta channels.***

It has been long known that migrating salmon smolts passing through the central Delta survive more poorly than those that remain in the main channel of the Sacramento River. However, traditional tagging could not determine the conditions that brought them into the central Delta, or where the additional mortality occurred. One of the most important new tools for fisheries research in recent years, therefore, has been the miniaturized acoustic tag (McMichael et al. 2010; Pincock et al. 2010). These tags and associated software to analyze data from receiver arrays are now widely used to understand fish migration and survival in the Delta and elsewhere (Welch et al. 2009; McMichael et al. 2010; Perry et al. 2016). The tags are small enough to be implanted in larger salmon smolts, and provide detailed information about individual fish as they migrate through the Delta. By situating telemetry monitoring stations at important junctions and locations, researchers can

estimate migration speed, choice of migration route and survival between monitoring stations. When coupled with real-time hydrodynamic measurements and modeling, the behavior of individual fish can be correlated with tidal mixing and fine-scale features of water movement at junctions. Use of acoustic telemetry techniques has provided detailed information on when and where juvenile salmon travel in the Delta and location-specific survival rates. Managers now have a more thorough understanding of how Delta hydrology affects migrating smolts and the options available to protect them.

2. *Deployment of sensors that provide almost continuous measurements of nutrients, carbon and other water-quality variables allows new insights into water quality.*

Historically, water-quality monitoring has involved collecting water samples weekly or monthly. The resulting infrequent observations impeded timely responses to unusual discharges of contaminants or nutrients, and limited managers' ability to identify specific causes (Pellerin and Bergamaschi 2014). Data sets with poor spatial and temporal resolution limited the ability of scientists to model and interpret water-quality processes. The interpretation of these data was also largely based on assumptions of linear system behavior, even though it is well established that hydro-ecological systems are strongly non-linear (Krause et al. 2015). Sampling at fixed intervals also allowed pulsed events, such as discharge of nutrients or contaminants during a storm, to be missed, resulting in serious underestimation of the mean and range of environmental conditions.

Automated, near-continuous recording of water-quality parameters using a variety of fixed and mobile sampling platforms, as well as remote sensing, is increasingly possible. This technology can provide much better information on sources, concentrations, and distributions of water-quality variables. However, the technology can generate huge amounts of data, and the sensors and associated equipment are very expensive. Designing monitoring programs to use this technology cost effectively remains a challenge (Pellerin and Bergamaschi 2014; Pellerin et al. 2016). As a result, automated, high-frequency sampling of water quality has only recently begun in the Delta (Dahm et al. 2016). Eight nutrient-monitoring stations currently operate in the Delta. Nitrate is the only nutrient continuously recorded, but phosphate and ammonium are recorded on an event basis. The data are being used to identify nutrient sources and nutrient dynamics in relation to phytoplankton uptake, and to provide insight into how the SRWTP affects downstream nutrient concentrations and food web dynamics. A commitment to adaptive high-frequency monitoring in the Delta (Krause et al. 2015) would provide insight into how ecosystem processes are affected by short-term (storms) and long-term (droughts) events, and might permit impending regime shifts to be forecasted (Scheffer et al. 2012).

3. *Advances in 2- and 3-dimensional hydrodynamic modeling have allowed much more detailed understanding of water and suspended particle movements in the Delta.*

One dimensional (1-D) hydrodynamic models (i.e., models that resolve only average flow in the channel), such as DSM2[9], have been the mainstay of hydrodynamic modeling in the Delta for many years, and have been coupled with particle tracking modules to simulate the movement of plankton or fish (Culberson et al. 2004; Kimmerer and Nobriga 2008). Although it was well known that 1-D models had important limitations, the computational requirements for models of higher dimension often precluded their development and application. Advances in modeling technology have made it much more practical to develop and apply two-dimensional (2-D, able to resolve flow along the channel and variations in flow either across channel or with depth) and three-dimensional (3-D, able to resolve flow variation along the channel, across the channel and with depth) models. It is now possible to apply multidimensional modeling that spans geography from the Gulf of the Farallones through San Francisco Bay, the Delta, and upstream in the Sacramento and San Joaquin rivers (MacWilliams et al. 2016). More narrowly focused models allow detailed resolution of complex flow and transport patterns at channel junctions over tidal cycles. These models make it possible to address coupled physical/ecological questions that could not be

9 *http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/models/dsm2/dsm2.cfm* (accessed 2016 April 10).

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addressed in the past, such as how flow patterns affect the choice of migration route by salmon smolts and how changes in Delta geometry (e.g., habitat restoration, island flooding) and sea level rise may affect salt intrusion and sediment transport in the Delta. In addition, coupling high-resolution models with lower-resolution measurements in the field can greatly increase the temporal and spatial resolution of data and thereby help to reveal causal factors that underlie the measurements. This coupling, by allowing detailed representation in space of the distribution of variables such as salinity, turbidity, nutrients, and temperature, also allows for the mapping of species-preferred habitats at landscape scale and dynamic analysis of production processes (Dahm et al. 2016; MacWilliams et al. 2016).

This does not mean that 1-D models can be consigned to the scrap heap. For many questions, a 1-D model is the right tool. Furthermore, comparison of high-resolution 3-D models with lower resolution models shows that in some instances (e.g., mixing at the Georgiana Slough/Mokelumne junction) lower-resolution models can give very similar results. Where a 1-D model is inadequate, the improved representation of a 2-D model may be sufficient, and the extra computational effort of 3-D models may not provide much improvement (MacWilliams et al. 2016). However, physical processes that are themselves inherently 3-D, such as stratified flows associated with salinity gradients in Suisun Bay and the western Delta, generally require 3-D modeling.

We anticipate that modeling of physical processes at various levels of resolution in space and time, coupled with improved population and ecosystem modeling, will become a critical tool for habitat restoration and species recovery in the Delta. We also anticipate that these complex coupled hydro-ecological models will provide insight into the circumstances under which species recovery can actually be accomplished.

4. ***Remote sensing tools used in conjunction with* in situ *measurements of levee internal structure from boreholes are providing more reliable mapping of levee structure and vulnerability.***

The hundreds of kilometers of levees in the Delta not only protect human life, farmland, and a network of roads, railways, and water, gas and power lines, but also establish critical ecological corridors and habitats, all while ensuring movement of high-quality water from northern to southern California for drinking water and irrigation. Levees are, thus, critical to the human service function of the Delta, and any major disruption of the levee system would have serious consequences for human use of the Delta and its waters as well as dramatic but uncertain effects on the Delta ecosystem. Threats to levee stability include earthquakes, seepage, sea level rise, floods, and land subsidence inside the levees. Because the levees were constructed over a long period of time using a variety of materials, their internal structure and, therefore, their vulnerability are poorly known.

In SBDS 2008, Moore and Schlemon (2008) summarized the history of levee construction in the Delta, the history of levee failure, and what was known at the time about the vulnerability of levees to the various threats listed above. They recommended greater use of geophysical and remote sensing techniques to evaluate the condition and vulnerability of the levee system. In 2007, to determine interior structure of levees, CDWR began conducting topographic surveys of levee condition using combinations of airborne and in situ LiDAR (Light Detection and Ranging) surveys, as well as geomorphic analysis using cone penetrometers, boreholes and electromagnetic surveys.[10] These surveys indicated that 84% of the length of levees surveyed conformed to the minimal Hazard Mitigation Plan standard, whereas only 61% of the surveyed length conformed to the stricter PL84-99 standard. Most non-compliant levees were located in the central Delta (Deverel et al. 2016). However, because of the variable material composition of the levees, borehole surveys are insufficient to fully characterize internal levee structure. Over the past decade, remote sensing techniques have been more widely used to assess levee structure. Two techniques that have provided important information about levee deformation are synthetic aperture radar (SAR) and LiDAR (Deverel et al. 2016).

Synthetic aperture radar interferometry (InSAR), which can be used from high altitude aircraft or spacecraft, now offers options for enhanced

10 *http://www.water.ca.gov/levees/evaluation/docs/factsheet-levee-eval-prog.pdf* (accessed 2016 June 22).

measurements of surface deformations of the levees. InSAR measurements are taken in image swaths that can be up to hundreds of kilometers wide, while detecting surface deformations as small as 5 to 10 mm. Significantly higher accuracy of 1 to 2 mm deformation per year can be achieved from repeated measurements (Deverel et al. 2016). InSAR also has the advantage that it can see through clouds, smoke, and haze, and can image surfaces without solar illumination. These techniques have provided useful information on changes in levee shape and subsidence that can signal weakness and potential for failure, and offer a basis for much more confident monitoring of levee deformations and breaches.

To predict levee failures, however, the internal condition of the levees also needs to be determined and tracked. Boreholes continue to be the primary source of information on internal condition; however, two promising methods for remote subsurface assessment are Electromagnetic Induction (EM) and Capacitively Coupled Resistivity (CCR), both of which measure variations in conductivity with depth. When correlated with borehole data, conductivity maps can be used to identify subsurface materials between boreholes. A combination of EM and CCR proved useful to assess foundation conditions and potential under-seepage areas, and compared favorably with borehole data along a section of levee on the Feather River.[11] As experience grows with these remote sensing techniques it should become possible to produce reliable maps of levee composition and failure risk.

5. *Improvements in—and greater availability of—regional downscaling of global climate predictions are allowing better-informed prediction of local climate changes and their effects.*

Each new generation of climate change assessments has included more climate projections from a greater diversity of climate models, thus providing more detailed and varied sets of climate variables. This greater "depth" of the projections has enabled climate projections and their uncertainties—and thereby the climate we will soon be facing—to be better understood (Dettinger et al. 2016). One factor that limits the exploration of these projections has been the fact that global climate models (GCMs) still yield climate projections on coarse spatial grids of 100 to 200 km. To translate these coarse spatial projections of climate change into the finer scales of local climate variability that drive the watersheds and rivers of California, a process called "down-scaling" is performed. Two common approaches to down-scaling are dynamical down-scaling and statistical down-scaling (CCTAG 2015). Dynamical down-scaling involves simulating local-to-regional weather responses to coarse GCM outputs. These models represent the physics of weather and climate as well as we understand them at high resolution and, thus, provide a full suite of climate variables. However, they suffer from significant uncertainties that arise from our incomplete understanding of the factors and forces that determine local weather. These models are also burdensome in terms of computation and data storage. Statistical down-scaling, by comparison, involves using statistical methods to interpolate coarse scale GCM outputs onto much finer scale historical weather observations. Statistical down-scaling's advantage is that it is less computationally burdensome than dynamic down-scaling and, therefore, can be applied to the many climate-change projections that are now available for analysis. A disadvantage is that statistical down-scaling assumes that historical large- to fine-scale relationships will apply in the future.

At present, statistical down-scaling is the most widely used method and has been a basis for much greater insight into the detailed character of climate-change influences that are most likely to challenge the Delta. One major advance in the past decade has been the development of new classes of down-scaling methods that represent climatic extremes more completely than was possible in the past (Dettinger et al 2016). The resulting high resolution and higher-fidelity climate scenarios have made important contributions to our understanding of the importance of changing climate extremes on the Delta's future. In years to come, new statistical tools—hybrids of statistical and dynamical modeling, and, eventually, fully dynamical down-scaling—will be needed to address the climate change issues most likely to threaten California water and the Delta.

11 *http://www.erdc.usace.army.mil/DesktopModules/ArticleCS/Print.aspx?PortalId=55&ModuleId=23844&Article=476685* (accessed 2016 June 22).

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6. New analytic tools, such as liquid chromatography and high-resolution mass spectrometry, allow water samples to be screened for a very broad spectrum of potential contaminants.

In the past, contaminant studies have typically targeted a few chemicals from a particular contaminant group (e.g., pesticides or metals or pharmaceuticals) because analysis for more than a few possible contaminants was time consuming and costly. In some cases, analytic techniques did not exist for certain contaminants. New products (e.g., pesticides, pharmaceuticals, personal care products, and flame retardants) continually come onto the market, and scientists have struggled to expand their analyses to the latest chemicals of interest. Furthermore, most toxicity values refer to the concentration of a single chemical that causes mortality of one or a few test organisms in a specified period of time. Because of this, relatively little information exists on toxicity of mixtures, on toxicity to different life stages or species not routinely used in laboratory tests, on toxicity of chemical breakdown products, or on a wide range of sublethal effects. Because of these constraints, it was virtually impossible to fully assess the toxicity of Delta water at any particular time and place, or to monitor effectively for chemical contamination. However, toxicity tests are now available that integrate the effects of multiple contaminants, even when they are below the levels detectable by chemical analyses (Fong et al. 2016). To get meaningful results, however, it is crucial that appropriate test species and endpoints are chosen. Toxicity tests with multiple species—preferably across multiple trophic levels, and including *in vitro* tests for specific sublethal effects—broaden the range of risks that can be assessed but significantly increase the time and resources needed to complete an assessment.

Water samples taken from the Delta contain an unknown cocktail of contaminants at different concentrations. These samples can be tested for toxicity, but if an effect is found it has been very difficult to determine the chemical species responsible. New analytical techniques, such as liquid chromatography-high-resolution mass spectrometry, allow simultaneous analysis for more than 200 compounds and more than 100 transformation products (Moschet et al. 2014). Non-targeted analyses using the new techniques do not require scientists to hypothesize what chemicals they expect to find; instead, chemical spectra can be compared to whole libraries of chemicals for identification of the particular ones present in a sample. Using this new technique, Moschet et al. (2014) determined that, by relying on traditional analytic methods, Swiss authorities were underestimating mixture toxicity by a factor of 2, and up to 10 in extreme cases. Recent evaluations using non-targeted chemical analyses on water samples from the Cache Slough complex detected over 100 chemicals after storm runoff events (Fong et al. 2016). In addition, the toxicity risk associated with chemical mixtures, as well as chemical and species co-occurrence, can be assessed with interactive mathematical models such as the Co-Occurrence Pesticide Species Tool (Fong et al. 2016). These new analytical assessments and models could greatly advance our understanding of contaminant effects because current studies typically analyze fewer than half of the pesticides applied in the Bay–Delta (Kuivila and Hladik 2008) and rarely analyze for pharmaceuticals or other contaminants.

An important adjunct to a better understanding of the complex mix of contaminants in the Delta and their toxicity risk would be the development of bio-markers. Bio-markers are measurable biological responses that serve as indicators of organismal health, allowing sublethal stressor effects to be evaluated. They can be used to predict responses at higher levels of biological organization. Bio-markers are particularly useful as part of a weight-of-evidence approach, and are informative for understanding mechanisms behind sublethal organismal responses, such as behavioral alterations. Bio-markers have been used by generations of epidemiologists, physicians, and scientists to study human disease and have been employed in the Delta to detect physiological response to endocrine disruptors (e.g., Brander et al. 2013; Biales et al. 2015). However, a suite of bio-markers has not yet been identified to address ecosystem health questions in the Delta.

POLICY PERSPECTIVES

The current state of Bay–Delta science is technically advanced and progressing rapidly, but it is also

too narrowly focused in several regards. As a consequence, the papers included in the special issues that comprise the State of Bay–Delta Science 2016 tend to underplay or ignore some major issues. As editors of the State of Bay–Delta Science reports, we identified some missing perspectives and policy implications in composing this summary and felt it was appropriate that we discuss them. We emphasize that, although we may link our discussion to individual papers, the policy perspectives we present are our own and not those of the authors referenced. Some of our discussion elaborates on policy perspectives we previously identified in SBDS 2008 (Healey et al. 2008a). Others highlight the need to evaluate new ways of approaching long-standing problems in the Delta.

Policy Perspective 1

The "state" of Delta science is held back by, and needs to push beyond, its tendency to focus on near-term issues and crises. Taking a longer, 50-year viewpoint was part of the Delta Vision exercise. That kind of long-range thinking needs to be incorporated into the whole Delta science and management endeavor. Progress towards that goal is lagging.

In SBDS 2008, we emphasized that the Delta is a continually changing ecosystem. In both SDBS 2008 and SDBS 2016, as well as more generally, much has been made of the changes to landforms and hydrology imposed by human occupation of the Delta and its catchment area, and the multiplicity of alien species introduced either deliberately or inadvertently. However, from its beginnings, the Delta has been changing physically and ecologically. Our concept of the Delta is anchored by what science has revealed about its structure and functioning over the past half century, and by what we can piece together from historic documents and paleoecology (Whipple et al. 2012) about what it was like 200 years or more ago. In the distant past, changes in the Delta were driven by natural processes: sea level rise as the Wisconsinian ice age retreated; tectonic rebound as the ice disappeared; post glacial climate warming with changing weather patterns; and species invasion as land, ocean, and freshwaters warmed in the post-glacial climate regime and as present-day ocean circulation patterns developed (Culberson et al. 2008). These were all dramatic events, but occurred over a long time and before we were present to witness them. Some continue into the present day, but, today, the most important drivers of change are human caused, and occur on a much compressed time-scale.

In light of this continual change, two policy-relevant facts are evident. First, many aspects of the Delta ecosystem probably came into existence in the not-too-distant past, and may have been destined to fade away even if there had been no human-caused transformation of the Delta. Second, the Delta has always been a changing place and, looking to the future, further dramatic change is inevitable. The pace of change is accelerating so that Delta science needs to begin answering the questions, "What kind of a Delta ecosystem is it feasible for us to have 50 or 100 years from now?" and "What actions would allow the Delta to evolve in desirable directions?" To respond to the current and approaching challenges will require more of a scientific (and policy) focus on long range thinking, and acknowledging and determining in a realistic way what we can accomplish in the future, with less focus on trying to re-create what we "had" in the past.

Taking a forward-looking, 50-year viewpoint was part of the Delta Vision exercise, but it is not clear that most scientists and policy-makers are actively continuing that perspective. An appreciation of the changes that are coming, particularly those associated with global climate change (Dettinger et al. 2016), needs to more strongly inform our planning. Even if current efforts to reduce global greenhouse-gas emissions are successful, climate will still change dramatically over the coming century or two. California will become hotter and dryer, and precipitation and water supply will become more variable and less predictable. At the same time, changing land use, agriculture, economic changes both local and global, and other factors will impose their own stresses on the Delta. In the short to medium term, skillful water and environmental management may mitigate some of these effects and allow the Delta to remain more or less as it is (Luoma et al. 2015; Dettinger et al. 2016; Lund 2016). Ultimately, however, rising sea levels and temperature, enhanced floods and long droughts, and changing land use and economic conditions will

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transform the Delta as we know it, likely before the end of this century. Even before that time, most of the listed native species will likely be gone from the Delta. Scientific, policy and management frameworks need to be developed now to minimize the negative and maximize the positive consequences of these inevitabilities (Luoma et al. 2015). Delaying action until the crisis is upon us will greatly increase the risk and cost of failure.

A key to developing forward-looking policy is well organized and active science. The Delta has an exceptional science community that has vigorously engaged with the complex problems of water and environmental management. New tools—particularly remote sensing, new analytic approaches and modeling opportunities, and new sensors for real-time measurement of water quality—offer Delta science more powerful machinery for looking forward. Linked climatological-hydrological-ecological models are now possible and would allow scientists to explore a wide range of potential futures and to provide policy makers with plausible scenarios within which to assess policy outcomes. Indeed, advances in modeling technology and computing power now offer the opportunity to develop fully integrated models of the wider Delta ecosystem that extends from the Sierras to the sea (MacWilliams et al. 2016). The USGS-led CASCaDE[12] project (Computational Assessments of Scenarios of Change for the Delta Ecosystem) was an initial attempt to develop such a set of models. Work on the components of CASCaDE continues, and this strategy could be elaborated further through inclusion of even more detailed hydrodynamic and water-quality monitoring, and by building in the essential food web dynamics in a landscape ecology context (Brown et al. 2016; Dahm et al. 2016; Fong et al. 2016; Grossman 2016; MacWilliams et al. 2016; Schoellhamer et al. 2016; Weins et al. 2016). Like global climate models, the kind of integrated ecosystem models we have in mind should be designed to look ahead to develop plausible future scenarios that can inform policy. Like the early global climate models, such models would, at first, include many uncertainties. However, simply constructing such models would reveal a great deal about how the Delta system functions as a whole, about the limits of our current knowledge, and about new directions for both science and policy. Redirecting even 15% of current science budgets to this kind of long-range forecasting would have an important effect.

12 *http://cascade.wr.usgs.gov* (accessed 2016 June 15). *http://cascade.wr.usgs.gov/reports/C2_final_report/CASCaDE_2_Final_Report.pdf* (accessed 2016 June 15).

Policy Perspective 2

Major obstacles to integrating forward-looking science and policy are the common constraints on science within government agencies that tend to focus narrowly on immediate policy and management issues with little freedom to investigate more broadly and to look far into the future. Conflicting agency mandates can also sometimes put agency-supported science at cross purposes.

Science within government agencies, particularly state agencies, tends to be narrowly focused on immediate issues and to be constrained by each agency's mandate. If, as we believe, science is the key to developing forward-looking policy, then we need more forward-looking science. As the speed and uncertainty of change in the Delta increases—driven by climate change, socio-economic globalization and local developments—closer integration of basic and applied research and greater investment in forward looking research are needed. Compared with the billions of dollars spent on Delta infrastructure, levees, roads, pipelines, and water conveyance, investment in science is tiny. Governments at all levels will need to invest more in exploratory science not linked to any current policy if science is to stand ready to support policy-makers when the inevitable surprises emerge in the Delta (Doak et al. 2008). The Delta Science Plan provides a collaborative framework to bring research and policy to the table, but the science community also needs to be willing to shift some of its emphasis from the immediate to the longer-term future. Short-term science cannot be expected to lay the groundwork to address long-term change. We realize this is not an easy transition for agencies struggling to keep on top of multiple immediate problems, but in times of rapid uncertain change, it is essential.

Policy Perspective 3

We need to begin laying the scientific (and societal) foundations for alternatives to conservation in place, including such approaches as assisted relocation, the

creation of refuge populations, assisted evolution, and genomic banking. At present, scientific understanding is not sufficient for these tools to be engaged with confidence as conservation options. Targeted science within an adaptive management framework is needed to demonstrate the potential of these techniques.

The most vulnerable orphans in this era of rapid change are likely to be the Delta's endangered native species. Given the scope of the changes the Delta faces, it is increasingly insufficient to focus entirely on a policy of *in situ* conservation through habitat protection and restoration. Many, if not all, native species are likely doomed in the Delta. This is not a signal that they should simply be abandoned. They are not going to disappear from the Delta tomorrow and endangered species laws require that all reasonable effort be made to provide for them. The increasing likelihood of extinctions is, instead, a strong signal that we should begin exploring alternatives to conservation in place, including approaches such as assisted relocation, the creation of refuge populations, assisted evolution, and genomic banking.

Assisted relocation, which goes by various names in the conservation literature, is hotly debated and divisive (Minteer and Collins 2010; Seddon 2010; Hewitt et al. 2011). Issues run the gamut from ethical to technical. Assisted relocation is presented as either an abandonment of ecological integrity or the last hope for threatened species—as the logical and necessary application of ecological understanding to achieve a desirable goal—or as a flawed and unproven over-reach. Assisted relocation has been attempted many times but often has proved unsuccessful (Dodd and Seigel 1991; Fischer and Lindenmayer 2000). Nonetheless, some deliberate and many accidental relocations have been successful. The Delta, in particular, is a highly invaded ecosystem because of deliberate and accidental introductions of exotic species (Cohen and Carlton 1998; Healey et al. 2008a). This checkered history points to the need for targeted science to determine the viability of this strategy. A good place to start would be Moyle et al.'s (2016) suggestion that a refuge population of Delta Smelt might be established to help ensure the species' survival. Delta Smelt are already successfully cultured in a hatchery at Byron in the south Delta, providing a source of potential colonists as well as a captive refuge population. However, the technique of successful assisted relocation is likely to differ from species to species, so it will be necessary to begin exploring approaches for other species as well. It is telling that policy options like assisted relocation do not receive even a comment in strategic documents such as the Delta Smelt Resiliency Strategy recently published by the California Resources Agency.[7]

The proper choices of recipient ecosystems for species relocation will require scientific research and public debate. If climate change is the primary driver of extinction, then recipient ecosystems need to be chosen that will remain within species tolerances for decades or longer, even if humanity achieves its goal of preventing average global temperatures from increasing more than 2.0 °C (Kinley 2016). In tandem with scientific uncertainties, legal and ethical issues will also arise. Although not prohibited by the Endangered Species Act or by California's fish and wildlife laws, such relocations for conservation purposes are problematic under U.S. Fish and Wildlife Service policy (Shirey and Lamberti 2010). Among the ethical issues is the question of which species are worthy of conservation through relocation. As distasteful as it is, rules for species triage need to be developed (Bottrill et al. 2008; Hagerman et al. 2010). Decisions to pursue these options will presumably benefit from a strong scientific foundation that does not yet exist, and will also presumably require wide-ranging discussions by scientists, policy-makers and the general public. Even though extinctions of Delta species from climate change are mostly some time in the future, it is not too early to begin such discussions and, especially, to begin preparing for them. If we wait for the crisis to be upon us, it will be too late.

Some endangered Delta species—such as the Delta Smelt, Lange's metalmark butterfly (*Apodemia mormo langei*), and salt marsh harvest mouse (*Reithrodontomys raviventris*)—are endemic and are restricted to small areas of habitat in the Delta. When these species go extinct in the Delta, they will be gone forever. Such species might be prime candidates for assisted relocation, although endemism should not be the only consideration in such choices. Some listed Delta species are widely distributed (e.g., Chinook Salmon, Steelhead Trout, Green Sturgeon) and their

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disappearance from California would not constitute extinction. These species are threatened by climate change from British Columbia to California, and could be extirpated from most of the southern part of their range within a few decades (Healey 2011). At the same time, as Arctic ice recedes, new habitat suitable for salmonids (and sturgeon) is opening up on some Canadian Arctic islands and in mainland Arctic rivers. It might be prudent for California to begin discussions with Canada and Alaska to ensure that suitable habitats for colonization in the Arctic are not compromised by other forms of development. Assisted relocation to speed the colonization of these habitats would help ensure their protection.

Relocation strategies will also raise scientific and policy issues regarding management of the receiving ecosystems. Relocated species can disrupt the receiving ecosystem. It may also be desirable or necessary to modify receiving ecosystems to make them more hospitable to the relocated species. The complexities and the conflict that will attend any proposed relocation will be huge and only partially ameliorated by reliable science, so that adaptive-management experiments will generally be required. Perhaps even more unsettling for agencies and communities in the Delta is the possibility that the Delta might become a receiving ecosystem for threatened species from the south, intentionally or otherwise. Though we may prefer to ignore such difficult questions, they will almost certainly be presented to us. Sound policies to undertake or respond to these options will likely depend on stronger scientific understanding of their prospects and consequences—before they arise.

Closely related to assisted relocation is the development of refuge populations to ensure preservation of critical genomes. Refuge populations can be captive or free living in constructed or appropriated habitats. California and the National Marine Fisheries Service (NMFS) have already done this with a captive winter-run Chinook Salmon broodstock program at Bodega Bay (discontinued in 2004) and for Delta Smelt in a hatchery at Byron in the south Delta. In addition, Moyle et al. (2016) suggested that a refuge population of Delta Smelt could be established in a pond near the Delta. Similar approaches could be taken with other species. Local refuge populations might not be viable for long, as climate and water temperatures continue warming. However, lessons learned in the process might allow the species to be relocated again later, or might buy time for other options to be developed

A further alternative to conserving species *in situ* is assisted evolution—helping the species to evolve tolerance to changing local conditions, usually thermal tolerance in the case of climate change (Jones and Monaco 2009). This approach is being attempted with corals near Hawaii ,where researchers are selecting for individuals with high temperature tolerance as a way to protect the reefs from bleaching as a result of rising ocean temperature (van Oppena et al. 2015). Artificial selection for desirable traits has been a common practice in agriculture for centuries but has only recently been proposed as a conservation measure. Presumably, modern techniques of genetic modification could be used to hasten the process of establishing higher thermal tolerances in selected species. However, assisted evolution raises important questions about biodiversity conservation. The United Nations Convention on Biodiversity highlights conservation not just of species and ecosystems but also of genetic diversity. The extent to which modification of genomes to adapt species to the effects of climate change can be reconciled with this principle of biodiversity conservation is not clear. A critical question in this context is whether a genetically modified species is the equivalent of the unmodified species.

Another approach with a genetic focus is genome conservation through cryopreservation (Kaviani 2011; Comizzoli and Holt 2014). Like genetic modification, this technology has been relatively little used in conservation, although more so than assisted evolution. The technology is fairly well developed for plant species (Engelmann 2011) and has been promoted to ensure the preservation of charismatic wildlife species such as lions and tigers (Kumar 2012). The appropriate tissue and method depends on the physiology and genetics of reproduction, which is unknown for many species (Fickel et al. 2007), posing important research questions in the Delta context.

Policy Perspective 4

Ecosystems worldwide are lightly to heavily invaded by alien species. To date, the conservation focus, enshrined in the UN Convention on Biodiversity, has been to prevent, eradicate, or contain species invasion. The Delta ecosystem is now dominated by alien species. A growing contingent of conservation ecologists worldwide is calling for active management of invasive species for human benefit.

One of the important stressors on threatened native species in the Delta is the large number of alien species found there. Whatever decisions are made about *in situ* conservation of native species, large parts of the Delta are likely to remain dominated by alien species. This poses the question, "How should these parts of the Delta be managed?" Too little attention has been given to how best to use the habitats that are no longer suitable (and that cannot be made suitable) for native species. Without downplaying the substantial economic and ecological effect of invasive species, these species are here to stay (Pejchar and Mooney 2009). Important questions for both science and policy are what ecological, recreational, and economic value these species could provide, and how management could realize those values. Fishbio[13] ranked the south Delta Largemouth Bass fishery—a species that invaded in the early 20th century—9th out of the 100 best bass fishing waters in the US. Other Centrarchids are also present, contributing to a diverse, warm-water sports fishery. Under global warming, these species will likely fare better in the Delta than native fish. We are not suggesting that native species should be written off (see Policy Perspective 3), but we *are* suggesting that ecosystems dominated by invasive species can also have value that we should strive to understand and nurture.

Policy Perspective 5

Current Delta science has focused almost entirely on the co-equal goals of water supply reliability and ecosystem conservation, but a legislated constraint on management to attain the coequal goals is largely being neglected. Achievement of the co-equal goals must happen in a manner that protects and enhances the "Delta as Place." The current state of science in the Delta is lacking in terms of the definition and strictures of this mandate.

Delta scientists have actively pursued research projects to address questions related to the "co-equal goals" of water supply reliability and ecosystem conservation. The Delta science community, however, has missed an opportunity to examine another important legislative condition. The Delta Reform Act of 2009 requires that the coequal goals of water supply reliability and ecosystem conservation "be achieved in a manner that protects and enhances the unique cultural, recreational, natural resource, and agricultural values of the Delta as an evolving place" (CA Water Code §85054). The Delta Plan prepared by the Delta Stewardship Council elaborates on the Council's understanding of "Delta as place."[14]

Existing Delta science uncovers information related to "Delta as place," and acting on existing science to achieve the co-equal goals can affect "Delta as place," but these effects are incidental to the research design, are rarely mentioned in the interpretation of results, and are not being effectively communicated through policy channels. There are likely multiple interacting reasons for this deficiency including:

- "Delta as place" is not the mandate of any agency or academic research unit with a significant science budget;
- A key word in the definition of "Delta as place" is "values," which scientists consider not to be in their domain. However, the goals of water reliability and ecosystem conservation are only pursued because they have values, so applying this argument to "Delta as place" is no more binding than it is for the co-equal goals;
- "Delta as place" is not well specified, making it difficult for scientists to deal with the multiple issues and questions included in the term.

The Delta Protection Commission has sponsored the "Delta Narratives Project" that brought together historians, Delta librarians, and Delta museum archivists to prepare new portrayals of the history of the Delta and to organize a Delta cultural

13 *http://fishbio.com/field-notes/wildlife-ecology/the-delta-californias-big-bass-lake* (accessed 2016 July 2).

14 *http://deltacouncil.ca.gov/sites/default/files/documents/files/CH_05_2013.pdf* (accessed 2016 August 30.)

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bibliography, among other products. The project provides a start on the cultural values of "Delta as place" but it does not provide clear pointers for natural science aspects of "Delta as place."

In the process of reviewing Delta science in the context of the Delta Plan, the Delta Independent Science Board has been grappling with the questions around "Delta as place." It intends soon to identify the issues more thoroughly and provide some guidance. However, it is our view that Delta science, across the agencies, should begin to include the "Delta as place" in its planning and analyses.

CONCLUSION

Science has informed policy-making in the Delta for decades, and we expect it will continue to do so into the foreseeable future. The papers included in the State of Bay Delta Science 2016 illustrate major advances that science has provided over the past decade. Now, as we continue through a period of great change and great uncertainty, science is all the more important as a source of reliable, verifiable information on which to base policy. We believe this is a time to invest more heavily in science, particularly forward looking, integrative and exploratory science. As was pointed out in SBDS 2008 (Healey 2008) and in Luoma et al. (2015), the Delta presents managers with a "wicked" problem, a problem that cannot be solved in the traditional sense but only managed. Broadly based, reliable, forward looking, and integrated information is the key to managing such problems. The problems of the Delta are destined to become ever more wicked as climate change unfolds. An investment now in forward-looking science—particularly in integrative models that represent the labyrinth of interacting processes at work in the Delta and that allow the most likely outcomes from a diversity of future scenarios under various management policies to be forecasted—will pay dividends in identifying and testing novel management options, particularly when the inevitable surprises arise (Doak et al. 2008).

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