Flows and Fishes in the Sacramento-San Joaquin Delta

Research Needs in Support of Adaptive Management

A Review by the

Delta Independent Science Board

August 2015

The Delta Independent Science Board (Delta ISB) is a standing board of nationally and internationally prominent scientists with appropriate expertise to evaluate the broad range of scientific programs that support adaptive management of the Sacramento-San Joaquin Delta.

Created by the Delta Reform Act of 2009 and appointed by the Delta Stewardship Council, the Delta ISB provides oversight of the scientific research, monitoring, and assessment programs that support adaptive management of the Delta through periodic reviews.

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Acknowledgments

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Summary

Record-low counts of Delta smelt at a time of persistent drought underscore the importance and challenges of managing freshwater flows for the benefit of fishes in the Sacramento-San Joaquin Delta while also meeting human demands for water. Understanding the effects of water flows on fishes is central to understanding how the Delta ecosystem functions and is key to achieving the state's coequal goals of "providing a more reliable water supply for California and protecting, restoring and enhancing the Delta ecosystem … in a manner that protects and enhances … the values of Delta as an evolving place". The economic, ecological, and social costs of scientific uncertainty in water management controversies are significant - and to some degree unavoidable.

Scientific findings that relate fishes and flows increasingly guide decisions on how to manage flows for the well-being of threatened or endangered species in the Delta. Many studies – and management decisions – rely on correlations between water flows and fish populations. But the decisions warrant fuller understanding of precisely how the flows affect the fishes. Knowledge of these underlying mechanisms is likely to facilitate adaptive management by clarifying uncertainty and risk, by creating specific expectations for outcomes and by strengthening testable hypotheses. This report therefore recommends, first and foremost (there are other recommendations as well), redoubling effects to identify causes and effects concerning fishes and flows in the Delta.

The scientific challenges to providing a Delta flow regime that benefits desirable fishes (or at least minimizes harm) while providing water supply reliability are well recognized:

- The modern Delta estuary and its tributaries differ starkly from the conditions under which the Delta's native fish evolved. Non-native fishes now predominate, and the habitat and flow needs of the native species are difficult to define in the transformed place and in a novel ecosystem.

- Flows in the Delta, which vary greatly with location and season, affect fishes directly and indirectly. The indirect effects work through other environmental factors and differ among species and life stages within a species. Other drivers of fish production in the ecosystem confound the effects of flow.

- Many agencies are involved in Delta fish and flow decisions and in scientific efforts to support management of water supply and fishes.

The Delta Independent Science Board (Delta ISB), established under the Delta Reform Act of 2009, has a legislative mandate to review Delta science programs in support of adaptive management. The Board is structuring the review by themes. The theme in this review is research on how freshwater flows affect Delta fish populations. The report offers several recommendations on scientific strategies to benefit adaptive management, and to enhance collaboration and communication among institutions, scientists, and managers:

1) **Focus on cause and effect - the mechanisms that enable flows to affect fishes.** Deeper causal understanding is important for identifying and reducing risks to water supply and fish populations. It can yield specific hypotheses for use in adaptive management (e.g., MAST 2015, Monismith et al. 2014). Flows and other drivers need to be examined for their direct and indirect effects on fish

growth, reproduction, mortality, and migration or transport. The overarching questions include: What are the essential requirements of a fish species for individual and population growth and sustainability, and how do flows change those requirements?

2) **Expand integrative science approaches.** Examine these mechanisms through comprehensive, integrative studies that focus on drivers and responses, and which are relevant to management questions. In the words of a 2012 National Research Council report, "only a synthetic, analytical approach to understanding the effects of suites of environmental factors (stressors) on the ecosystem and its components is likely to provide important insights that can lead to enhancement of the Delta and its species." Strategies that strengthen interagency and interdisciplinary work can speed and solidify scientific discoveries and their application.

3) **Link quantitative fish models with three-dimensional models of water flows.** Such a linkage will provide a comprehensive, heuristic modeling framework for identifying information gaps, key drivers and appropriate time and space scales for integrating interagency and interdisciplinary science activities and priorities, and for improving and underpinning decision support. A specific collaborative effort will be needed to develop a 3-D, open-source, hydrodynamic model that can be more widely adopted and integrated with generic and species-specific models of fish growth, movement, mortality, and reproduction and with food-web models. The modeling framework should extend across agencies and programs. A well-led standing working group of both hydrodynamic and fish modelers as well as lower food-web modelers should carry this effort forward and provide linkages to other ongoing modeling efforts. Fish endpoints should drive model development. Significant progress can be accomplished in the short term.

4) **Examine causal mechanisms on appropriate time and space scales.** A focus on mechanisms will require a close consideration of time, space and parameter scales relevant to biological processes. Dealing with fish and flow scales that simply overlap is not sufficient, as there are other relevant drivers and intermediaries operating at different scales. Models for water management developed with time and space (depth, width, and time variation) scales appropriate for water management questions may not be useful to answer fish and ecosystem questions. For instance, flow variability in time and space has important biological consequences that are often not captured in mean monthly flow values or annual fish population estimates.

5) **Monitor vital rates (e.g., individual growth rates) of fishes.** Monitoring is done to estimate ecosystem conditions or to assess the consequences of specific management actions. A focused program is needed to monitor expected first-order responses by which flows affect fishes, linked to multiscale modeling efforts. Rate responses, such as individual fish growth rates, more aptly reflect response to changing conditions and give more certain and causal insights than annual indices of fish population size. A monitoring program that is organic with model expectations can improve the contribution of science to adaptive management.

6) **Broaden species focus.** The comprehensive research on threatened or endangered species needs to expand to other native species, as well as non-native species that now dominate fish populations in the Delta. Little is known about the impact of flows on many of these other

species, and they likely have important food-web relationships to threatened or endangered species.

7) **Enhance national and international connections.** Provide state-agency scientists with convenient access to scientific journals and with opportunities for travel to conferences, workshops, and relevant field sites. The problems faced in the Delta are not unique. To accelerate and improve scientific insights and reduce their costs, agency scientists need access to the wealth of knowledge and thinking from other representative ecosystems.

8) **Promote timely synthesis of research and monitoring.** Synthesis of results is needed for managing the Delta, managing the science, and stakeholder engagement. Agencies must recognize the importance and need for routine and timely scientific synthesis for both directing scientific efforts and summarizing scientific outcomes and uncertainties for managers. This requires additional dedicated staff time and resources.

9) **Improve coordination among disciplines and institutions.** Improve understanding among ecologists, hydrologists, hydrodynamicists and across the various institutions where they work. Interdisciplinary, interagency understanding can be facilitated through implementing the Delta Science Plan, which has been designed to encourage sustained commitment and increased coordination for addressing contentious issues and complex problems.

Overall, modeling capabilities and ecosystem understanding in the Delta have grown to a level that could support development of predictive and causally based approach recommended in this report, given sufficient targeted and purposeful effort. These recommendations are broader than just a suggestion to construct another model. The mechanistic modeling approach should serve as a framework to integrate interactions of scientists and agencies working on water flows with those working on fishes and lower food webs. The goals would be to develop decision-support tools and data, guide monitoring and data collection, conduct specific scientific studies to fill major information gaps, identify important time and space scales, and identify the uncertainties with which policymakers need to work. Adaptive management can be improved through an iterative evaluation process that tests management scenarios and uses modeling to explore the range of possible outcomes.

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Introduction and Management Needs

California's persistent drought has brought renewed focus to the practical and scientific problems of managing flows to benefit desirable fishes in the Sacramento-San Joaquin Delta (Delta) while also meeting human demands for water. When one-acre-foot of water is worth $1000 or more, even small amounts of water imply millions of dollars in water supply. At the same time, counts of the endangered Delta smelt in the Delta have reached an all-time low, triggering headlines and discussions that signal the near extinction of this critical indicator species. The economic, ecological, and social costs of scientific uncertainty on the relationships of fishes and flows in water management controversies are significant.

Understanding the dependencies of fishes on water flows is central to understanding the Delta ecosystem and is key to achieving the state's coequal goals of "providing a more reliable water supply for California and protecting, restoring and enhancing the Delta ecosystem … in a manner that protects and enhances … the values of the Delta as an evolving place" (Water Code Section 85054). 'Water flows' are key to management decisions on water supply, and 'fishes' are the key indicator of the Delta ecosystem's health and services and a major driver of ecosystem policies. Relationships between fishes and flows drive state and federal policy and related regulatory and management decisions, and consequently have been central to legal arguments and decisions.

Since water flows are a defining process of the Delta, as in river ecosystems worldwide (e.g., Webb et al. 2015), scientific interest in this topic is keen. Water flow has been dubbed the 'master' ecological variable in the Delta (e.g., Mount et al. 2012), not

The economic, ecological, and social costs of scientific uncertainty on the relationships of fishes and flows in water management controversies are significant

because of the precise way in which flows affect fishes, but because of flows' pervasive influences on so many other variables in the Delta ecosystem. Water managers have considerable influence on flows in the Delta through reservoir releases, upstream and in-Delta diversions, levees, and flow barriers. People have come far in "mastering" water flows, within the limits of climate and society-determined water abundance, scarcity, and demand. Using this mastery to reach the coequal goals of water reliability and protecting the Delta's ecosystems requires improved knowledge of the relationships among water flows and fishes.
A large body of scientific research explores how water flows in the Delta and elsewhere affect fishes. The state of science of these processes in the Delta have been examined extensively in the scientific literature and through targeted reviews including two reports by the National Research Council linking water management and threatened and endangered fishes (NRC 2010; 2012) and the assessments of "Delta Outflows and Related Stressors" (Reed et al. 2014) and "Interior Delta Flows and Related Stressors" (Monismith et al. 2014). Other reports have focused on specific fish species (e.g., Sommer et al. 2007, Miller et al. 2012, Armstrong and Nislow 2012, Sommer et al. 2013, Cavallo et al. 2015, MAST 2015), groups of fish species (Baxter et al. 2010, SWRCB 2012), specific issues such as entrainment (Grimaldo et al. 2009, Anderson et al. 2015, Perry et al. 2015) or assessments of new water transport systems (BDCP 2013). These reviews highlight the complexity of the problem and the challenges of defining the

relative role of flows and other environmental drivers in a dynamic ecosystem such as the Delta.

Scientific findings that relate fishes and flows increasingly guide decisions on how to manage flows for the well-being of threatened or endangered species in the Delta. Many findings rely on correlations between flows and fish populations (e.g., MacNally et al. 2010, Thompson et al. 2010, SWRCB 2012, Latour 2015, Reed et al. 2014 and Monismith et al. 2014 and references cited therein). In a continuously changing system like the Delta, studies are needed that yield a deeper causal understanding of how flows affect fishes. It is important to look beyond correlations obtained using controlled studies or a limited number of variables to establish underlying mechanisms that can aid adaptive management, help identify uncertainty and risks, and create specific expectations for outcomes. This report recommends a scientific strategy intended to yield testable predictions and delineate mechanisms on how flow management decisions affect the magnitude or sometimes even the direction of changes in fish populations.

Improved understanding of the causal relationships between flows and fishes is critical for effective adaptive management, identifying uncertainty and risks and for creating specific outcome expectations

The Delta ISB established under the Delta Reform Act of 2009, is instructed to regularly review Delta scientific programs in support of adaptive management. The Board is carrying out this responsibility with reviews of overarching research themes. The theme in this review concerns how freshwater flows affect Delta fish populations. The report develops several recommendations on scientific strategies to benefit adaptive management, and to enhance collaboration and communication among institutions, scientists, and managers. The review process is described in Appendix A.

Scientific Challenges

The scientific challenges to determining a flow regime that benefits desirable fishes or minimizes the harm to them and, at the same time, provides water supply reliability are well recognized:

- The Delta ecosystem has experienced considerable changes and is still evolving. The modern estuary and its tributaries differ starkly from the conditions under which the Delta's native fish evolved. Non-native fishes now predominate, and the habitat and flow needs of the native species are difficult to define in the transformed place and in a novel ecosystem.
- Flows in the Delta, which vary greatly with location and season, affect fishes directly and indirectly. The indirect effects work through other environmental factors, and these differ among species and life stages within a species. Other drivers of fish production in the ecosystem confound the effects of flows.
- Many agencies are involved in Delta fish and flow decisions and in scientific efforts to support management of water supply and fishes.

These issues are briefly reviewed below.

Delta as an Evolving Place

The Delta ecosystem has experienced considerable changes and is still evolving. The current Delta and its tributaries bear little resemblance to the pre-development Delta in terms of its water flow regime, habitat structure, and fish communities (e.g., Nichols et al. 1986, Bennett and Moyle 1996, Moyle and Light 1996, Moyle 2002, Lund et al. 2010, Whipple et al. 2012) and differ starkly from the conditions under which the Delta's native fish evolved. Non-native fishes now predominate, and the habitat and flow needs of the native species are difficult to define in the transformed place and in a novel ecosystem.

> *The Delta ecosystem has experienced considerable changes and is still evolving. The current Delta bears little resemblance to the pre-development Delta in terms of its water flow regime, habitat structure, and fish communities*

Land development has greatly altered the Delta's geometry and its hydrologic system of water flow channels, flow volumes, and flow dynamics. Marshes were diked and drained for farming, dams were built upstream to store water, waterways were leveed for flood control, and large pumping diversions were constructed that moved water in unnatural ways. Collectively, these changes have transformed flow pathways and dynamics, altered sediment and organic matter supply (Canuel et al. 2009), and destroyed or limited the access to certain fish habitats.

Historical flow conditions in the Delta had more marsh area, more dynamic flow and salinity regimes, higher turbidity, and more seasonally and tidally inundated wetlands (Moyle 2002, Baxter et al. 2010, Whipple et al. 2012). Over 98 percent of marshes have been lost, and the inundation frequency has decreased (Whipple et al. 2012). Historically, the flow regime in the Delta was extremely variable and influenced by the seasons, rainfall, and snowmelt (Moyle 2002, Whipple et al. 2012). Channels of the historical Delta were dominated by the tides, and its large capacity for flood attenuation was due to the wide tidal channels, low banks, and broad wetland plain (Whipple et al. 2012).

Currently, water flows in the Delta are driven primarily by the tides, with additional significant contributions of freshwater inflows (affected by major upstream releases and diversions), local Delta inflows downstream, pumped diversions and return flows within the Delta, groundwater pumping, evaporation, precipitation, drainage and consumptive uses including those for local agriculture. Tidal flows dominate the western Delta, where rapid channel flows of hundreds of thousands of cubic feet per second are overwhelmingly driven by tides. Farther upstream, tidal effects diminish, but have some importance as far upstream as Sacramento (on the Sacramento River) and upstream of Stockton (on the San Joaquin River). The California State Water Project (SWP) and federal Central Valley Project (CVP)

> *The species in the Delta fish community have changed markedly in the past century in response to ecosystem changes and deliberate introductions. Non-native species now predominate in most regions of the Delta*

pump water from the southern Delta, drawing on large amounts of fresher and higher quality Sacramento River water through the Delta Cross Channel and Georgiana Slough, down to the lowest parts of the Mokelumne River, and then up Old and Middle rivers (which reverses these river flows at times), and into the south Delta pumping plants (Jackson and Paterson 1977, Monsen et al. 2007, Lund et al. 2010). To facilitate water exports from the Delta and maintain water quality for in-Delta diverters, most of the Delta is maintained as a freshwater system, controlled by many structures

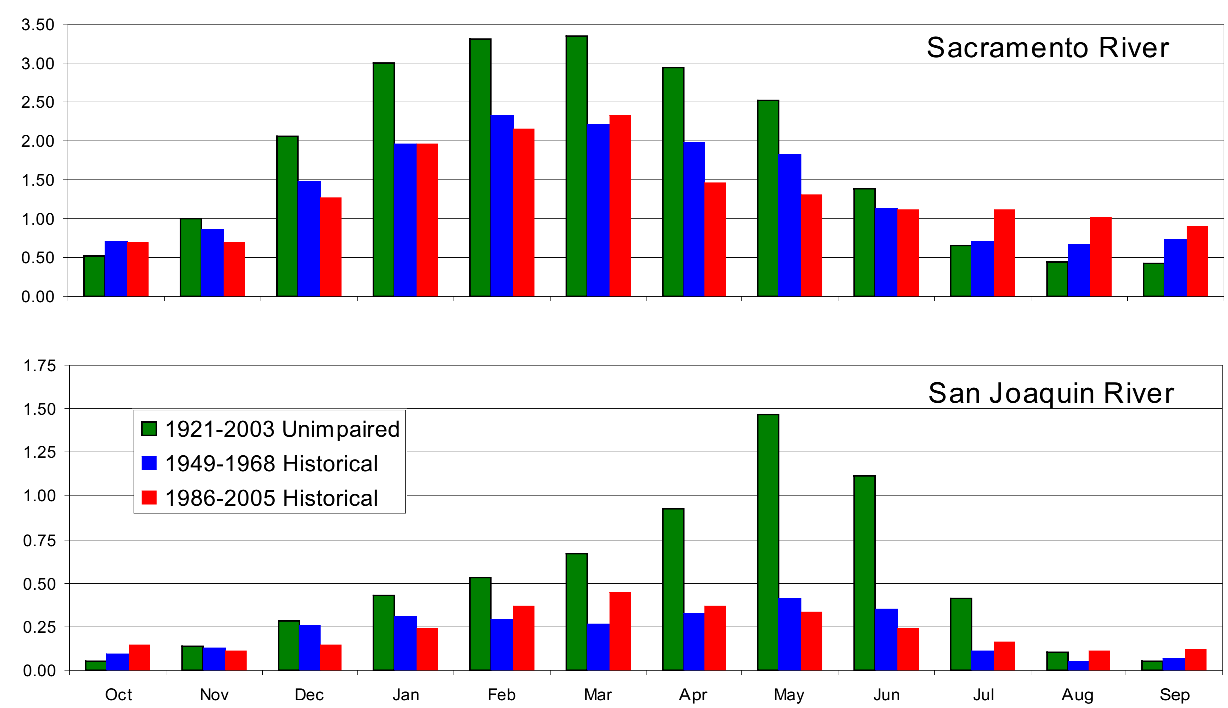

Figure 1. *Changes in Delta flow patterns. The y-axis is the average flow in million acre feet per month (Fleenor et al. 2010). (Note: Unimpaired flow does not account for upstream natural evapotranspiration under pre-development conditions.)*

(i.e., dams, gates, levees, etc.) and water operations (Jackson and Paterson 1977, Moyle 2002, Lund et al. 2010).

The Delta is now a simplified system of leveed islands, perennial freshwater-maintained channels with reduced outflow, less variability in salinity (in western areas), and altered channel morphology. Overall changes to annual total freshwater inflows and their seasonal patterns are illustrated in Figure 1. Upstream diversions for irrigation and cities have reduced inflows (somewhat counteracted by reductions in evapotranspiration from lost seasonal wetlands upstream). The regulation of streams by reservoirs and the highly seasonal patterns of upstream water diversions have made major changes to the seasonality of inflows, including increased inflows during the summer and reduced peak flows in winter and spring.

Other major changes have also affected the Delta ecosystem. These include large influxes of sediment from hydraulic and placer mining, changes in land-use patterns, increases in nutrient loading and pollutants (e.g., Dugdale et al. 2013, Glibert et al. 2014), commercial and recreational fisheries, and many introduced and invasive species of flora and fauna. The broader San Francisco Bay Estuary is one of the most modified and invaded ecosystems in the world (Cohen and Carlton 1998, Moyle and Bennett 2008, Greene et al. 2011). Changes in the lower food web of the Delta are well documented (e.g., Kimmerer 2006, Kimmerer et al. 1994, 2005, 2012).

Not surprisingly, the species composition of the fish community and abundances of individual species have changed markedly over the past century in response to changes in the ecosystem described above, as well as deliberate introductions (e.g., Striped bass, American shad). Currently over 30 fish species are common in the Delta (Moyle and Bennett 2008). This composition has shifted from dominant numbers of native fishes to today's dominance of non-native species with low numbers of natives (Moyle et al. 1986, Brown 2000, Marchetti and Moyle 2001, Moyle 2002, Feyrer and Healey 2003, Brown and Michniuk 2007). For example, Feyrer and Healey (2003) sampled fishes in the southern Delta from 1992-1999 and found that native species were 8 out of 33 fish taxa and less than 0.5 percent of the total number of fishes sampled. Feyrer (2004) sampled fish larvae in the southern Delta from 1990-1995 and found that 98 percent of the fishes caught were non-native species. Countless studies draw the same conclusions: native species in the Delta have declined substantially and nonnative species are now dominant in most of the Delta, particularly in the southern Delta. Several native species have been listed as endangered or threatened (Feyrer et al. 2007).

Interannual extremes of climate, such as the current drought, also affect flows and regulatory restrictions on flows. Substantial future changes in Delta flow volumes, pathways, and dynamics are expected. Engineering changes and enhanced adaptive management actions are being considered that include water flow management (e.g., operation of channel gates, pumping, reservoir releases, water diversions), wetland habitat restoration, and planned permanent and seasonal flooding. The Delta also will be subjected to interannual variations in water supply through changes in the patterns of precipitation and evaporation, sea level rise caused by climate change, continued growth of the human population and increased urbanization, changes in land-use, and extreme events such as droughts, floods, or levee failures. New species invasions are likely. The need to understand and predict how these evolving changes will affect fishes will become even more important.

Habitat requirements differ across species and life stages within a species. Flows favorable to one species may be unfavorable to another

Responses to Environmental Conditions Differ Among Species

Different species and different life stages within a species differ in their habitat requirements and their resilience/vulnerability to habitat changes and environmental drivers. Therefore, the response of 'fishes' to 'flows' will be species-, life-stage-, and location-specific. The status of selected, native Delta fish populations has been used to indicate the health of the Delta's ecosystem. The endangered Delta smelt and Chinook salmon have been studied extensively (e.g., Limm and Marchetti 2009, Sommer and Mejia 2013, Alexander et al. 2014, Zueg and Cavallo 2014, Cavallo et al. 2015, Perry et al. 2015, MAST 2015) and illustrate the wide breadth of responses to flows. The effects of flows on fishes are often discussed in relation to annual indices of (relative) population abundance. In an ecosystem, fish abundance (total population at a point in time) is determined by a combination of reproductive success, individual growth rates at different life stages, and mortality rates. The rates of these processes are driven by physical, chemical, and biological habitat conditions, and the mechanistic relationships thereof are complex.

Multiple Drivers Affect Fishes

Flow is but one factor affecting fishes and its effects are confounded by other drivers of fish production in the ecosystem. Five major drivers are considered as agents of change in any given ecosystem. These are habitat alteration and loss, resource use and exploitation, invasive species, pollution, and climate. All of these drivers have played a role in the Delta and affected fishes. Separating the influence of flow from myriad other factors in the Delta is confounded by the action of many drivers over long time periods, ecosystem complexity and nonlinear responses to drivers, a narrow focus of research on a few species and relatively little on other ecologically important species or processes (e.g., predation, food webs, behavior in migration corridors), and lack of comprehensive, integrated data sets.

Specific reasons for the declines in abundances of native species in the Delta remain unclear but are likely caused by multiple drivers (or stressors) and the interactions thereof (Bennett and Moyle 1996, Moyle 2002, Kimmerer 2002a, 2002b, Feyrer and Healey 2003, Brown and Michniuk 2007, Feyrer et al. 2007, Moyle and Bennett 2008, Hanak et al. 2013). The NRC 2010 report concluded that "Nobody disagrees that engineering changes, the introduction of many exotic species, the addition of contaminants to the system and the general effects of an increasing human population have contributed to the fishes decline", but the relative contributions of these drivers and the significance of their interactions are inadequately known. The role of multiple stressors in the Delta has been discussed in previous reviews by Mount et al. 2012, NRC 2010 and 2012, Hanak et al. 2013, Reed et al. 2014, and Monismith et al. 2014.

It is almost impossible to assess how flows affected fishes historically in the Delta because the ecosystem has undergone and is still experiencing dramatic alterations in habitat, species composition and interactions, channel morphology, and water quality. These factors also interact in complex ways.

Fish abundance is driven by many factors that may or may not be influenced by water flows. The relative contributions of these drivers and the significance of their interactions are inadequately known

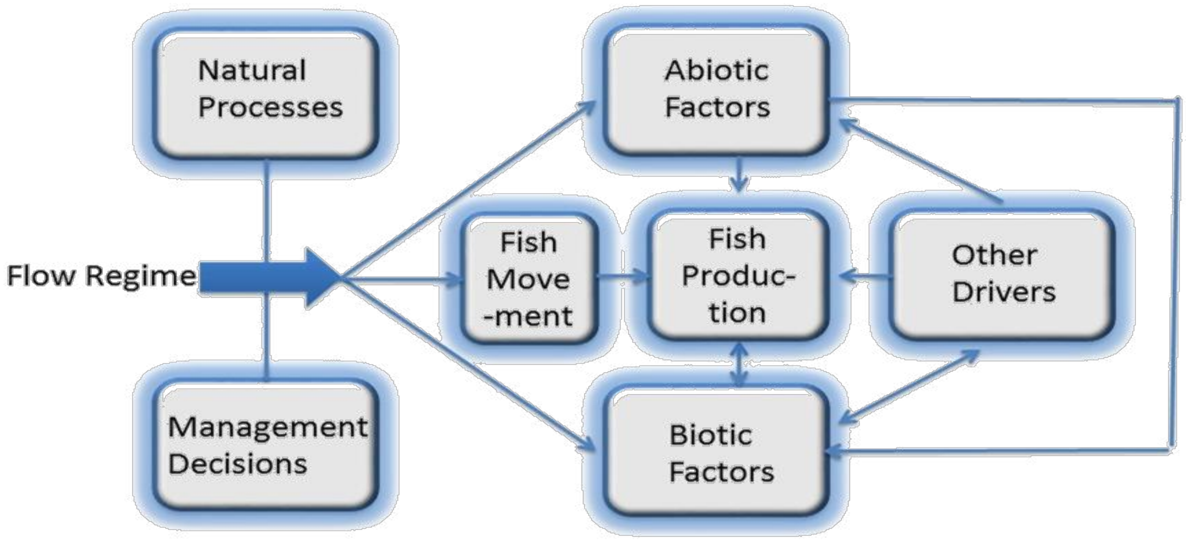

Figure 2. *Simplified diagram of how flows affect fish populations directly and indirectly, interacting with other drivers.*

Statistical correlations support specific hypotheses. For example, studies support the hypothesis that changes in historical flows (e.g., wet years and dry years,) affected certain fish population abundances and that the location of the salinity gradient (X2) is correlated with abundances of certain species (e.g., Kimmerer 2002b, Feyrer and Healey 2003, MacNally et al. 2010, Reed et al. 2014, Monismith et al. 2014 and references cited therein).

Direct and Indirect Effects of Flows

Flows may affect fishes through multiple direct and indirect (i.e., proximate and ultimate) processes. Direct effects largely include physical transport and alteration of migratory pathways. The indirect effects work through other biotic and abiotic factors in the ecosystem that, in turn, affect fish growth, reproduction, mortality, and ultimately fish population size. A conceptual diagram of the potential factors affecting fish production illustrates the scientific challenges and helps identify gaps in our understanding (e.g., Figure 2and Appendix B).

Water flows generally define and shape a delta and the term 'flow' is used in different ways, often without explicit definition. "Flow" commonly is used by water managers to be an amount or volume of freshwater. To assess how freshwater 'flow' affects fishes, explicit definitions of the components of flow is required that better reflect the potential processes affecting fishes (as also suggested by Monismith et al. 2014).

In simple terms, flow (Q) is a rate that defines the total volume of water moving through a given cross-section of the river per unit time (ft^3 or m^3 / s). Q is the product of cross-sectional averaged water velocity and the channel's cross sectional area. Fishes cannot detect flow per se because they do not know the width and depth of the channel. Thus the relevant parameters of a 'flow' for fishes are the local water velocity, duration, direction, timing, rate of change, and intensity of turbulence. Flows can have high or low velocity in different locations depending on channel morphology, be irregular in time (e.g., seasonality of precipitation), intermittent (e.g., floods), change regularly (e.g., tides), and have a particular direction. Water flows in the Delta are complex, and are the combined result of tidal movements, freshwater inflows, return flows, diversions, precipitation, evaporation, drainage, and water exports.

Fishes experience the combined flows of freshwater in the context of a tidal environment (Figure 2). At any point in the Delta, the bulk flow regime (volume, average velocity, unsteadiness, flow direction) is determined by a combination of natural processes and management decisions (historic or operational). Current conditions of land-use and cover, channel morphology, dams, and levees set the morphologic framework. Precipitation, evaporation, basin runoff, snowmelt, and tides are natural processes that affect the flow (hydrologic) regime which can be modified through management decisions on storage and release of water from reservoirs, exports, consumptive uses, barriers, channel cuts, levees, and diversions. The current California drought is an extreme example of how natural processes can drive flow dynamics and fundamentally alter water management scenarios.

Understanding the coupling of water motion to fish movements is a key aspect of fishes and flows research

Coupling water motion and fish movements is a key aspect of fishes and flows research. Overall flow dynamics directly affect fish movement by defining viable routes (e.g., channeling) and pathways, restricting movements (e.g., dams), providing upstream homing (e.g., olfactory) cues to direct fish migrations to spawning grounds, providing currents through which fishes must swim, and through passive transport downstream. Fishes that evolved in an ecosystem with characteristic flow dynamics may use those flow dynamics as part of their life history strategy, and thus, changes in flows may trigger migrations, or seasonal flooding may cue spawning activity. Water velocity, which is directly perceived by fishes, affects migration rates because fishes can drift with currents or must swim against/across currents to reach reproductive or nursery areas (Mesick 2001, Nislow et al. 2004, Nobriga et al. 2006, del Rosario et al. 2013). High river flows can increase energy expenditures to maintain position or to swim upstream (Rand et al. 2006, Martins et al. 2012). Artificial changes in these flows could disrupt normal migratory cues and behavior or cause larval or juvenile fishes to drift to unsuitable habitats or to entrainment locations (e.g., Bennett and Moyle 1996). For example, pumping for water exports alters Delta-wide hydrodynamics and may draw fishes towards export facilities and away from more productive or safe habitat areas (Jackson and Paterson 1977, Herbold and Moyle 1989, Monsen et al. 2007, Kimmerer 2008, Kimmerer and Nobriga 2008). Pump entrainment has been implicated in the decline of certain fishes in the Bay-Delta system, especially the Delta smelt (Kimmerer 2008, Baxter et al. 2010, Anderson et al. 2015).

Perhaps the greatest impact of flows on fishes is through water flows' influences on other environmental factors. In river ecosystems and the Delta, flows have pervasive effects on physical, biological, and chemical aspects of the environment that drive biological processes and fish vital rates (e.g., physiology and behavior) (Bunn and Arthington 2002, Baxter et al. 2010). Flow rates can directly affect water temperature, salinity, depth, oxygen concentration, food supply, chemical concentrations, turbidity, and sediment load, among other factors (e.g., Jassby et al. 2002, Wagner et al. 2011, Arismendi et al. 2012, Walters and Post 2011, Anderson et al. 2015). These directly affect the fish vital rates and other biological factors that affect fish production. For example, temperature affects fish growth rates and mortality directly, but also indirectly, because temperature affects predation rates and thus predation-induced mortality. As another example, flows can affect residence time (e.g., Kimmerer et al. 2014, Glibert et al. 2014), which can affect phytoplankton production, zooplankton movement, or even phytoplankton clearance by sedentary invasive bivalves. In addition, these flow-related factors "co-vary" with one another, and their effects on fish growth, mortality, and reproduction are not static. Rather, they change under different circumstances and ecosystem conditions. Understanding the quantitative relationships of these drivers to fish growth rates, reproductive success, and survival, and understanding how a flow regime affects these drivers is important to making informed management decisions and predicting the consequences of these decisions.

Water flows have pervasive effects on the physical, biological, and chemical aspects of the environment that drive biological processes and fish vital rates

Mathematical models of hydrodynamics have been developed to simulate Delta flow regimes so the flow implications of management decisions are reasonably well understood on a broad scale. Yet, understanding flow regimes is insufficient, as local nuances of flow may determine the local response of fishes and collectively, the overall behavior of fishes. Science should be able to assess how particular changes in flows affect a change in environmental conditions and how those changes might affect fish vital rates. Since flows can affect multiple habitat features, the final result will depend on cumulative impacts.

Drivers other than flow also can affect fishes directly or through changes in the biological, chemical, or physical habitat. Fundamental drivers in all ecosystems are habitat alterations, pollution, climate, resource use (e.g., fishing) and invasive species. For example, temperature also is driven by overlying weather conditions, food levels can be affected by invasive species such as filtering by bivalves, predation risk is a function of predator densities and availability of alternative prey, and fishing causes additional fish mortality. Anadromous species spend only part of their life in the Delta, so their abundance also is influenced by ocean conditions. The strength of these effects on fish production differs among species and with prevailing conditions, and they should not be ignored in population assessments.

Challenges in the Organization of Management and Science

Many agencies are involved in Delta fish and flow decisions and in scientific efforts to support management of water supply and fishes. A key scientific challenge is that decision-making on water flows and fisheries management are made by different agencies, and agency science and monitoring align with agency priorities and mandates. Most science and models developed for water management may not be appropriate in time (e.g., water releases, timing of diversions), space (e.g., local entrainment, diversions), or parameter (e.g., temperature) level for models needed to understand fish production driven by growth, reproduction, survival, and transport/ movement.

The central management challenge is encompassed in the state's coequal goals for the Delta. How do decisions on water reliability affect fishes? Legal requirements also focus on threatened or endangered species where much of the science has been done. Key management challenges include: 1) fish abundances are affected by various interrelated factors that are insufficiently quantified, and 2) many separate agencies and programs have responsibilities for different aspects of the issue (Table 1).

Agencies that manage fish populations in the Delta include the California Department of Fish and Wildlife (CDFW), the federal National Marine Fisheries Service (NMFS), the U.S. Fish and Wildlife Service (USFWS), and the U.S. Environmental Protection Agency (USEPA). Their strongest authorities lie in federal and state Endangered Species acts. The State Water Resources Control Board (SWRCB) has discretionary authority under state and federally delegated clean water legislation, as well as state constitutional and water rights authorities, to balance reasonable use of water resources. Flow management and model development are largely designed to improve water reliability for cities and agriculture. However, flow management in the Delta serves several, sometimes competing, purposes that are often overseen by different agencies. For example, high flows, which provide the greatest access to floodplain habitat, are limited for flood control by the Division of Flood Management of California Department of Water Resources (CDWR), the U.S. Army Corps of Engineers (USACE), and numerous local levee districts. Fish habitat in Suisun Marsh, Yolo Bypass, the northeastern Delta, and the lower San Joaquin River is restricted by flood management in these regions.

Flows in the interior Delta are affected by reservoir releases into the Delta, from both the Sacramento and San Joaquin rivers, the operation of gates and pumps by the federal CVP (operated by the U.S. Bureau of Reclamation [Reclamation]) and California's SWP (operated within CDWR), and decisions of the SWRCB, which has water rights and water quality regulation authority. Local water diversions also have some effect on flows and water quality within the Delta. The myriad agencies with differing mandates and missions make the challenges for maintaining flows that support a variety of native fish populations difficult.

Table 1. Governmental agencies involvement in Delta fish and flows

Level of government	Primary fish management responsibility	Primary flow management responsibility
Federal	NMFS, USFWS, USEPA	Reclamation, USACE
State	CDFW, SWRCB, Council	CDWR, SWRCB, Council
Local		Local water diverters, individuals, counties

Over several decades, the Delta scientific community has made substantial strides in understanding this complex ecosystem. As with most large ecosystems, the scientific effort is scattered among mission-oriented state and federal agencies, academic institutions, private consultants, and NGOs. Science communication is fostered through scientific conferences (e.g., the Bay-Delta Science Conference), meetings, workshops, newsletters, websites and peer-reviewed publications (e.g., *San Francisco Estuary and Watershed Science*). The Delta Science Program has helped increase the rigor by contributing a number of scientific reviews, providing a forum for reasoned scientific debate, providing educational and training opportunities and leading the development of a unified science plan for the Delta. Examples of successful interdisciplinary collaboration and synthesis of research in the Delta have been the result of excellent leadership and willing participants.

All relevant state and federal agencies have some scientific activities and responsibilities in the Delta, although not all are relevant to fishes and flow. Some of the largest local water agencies and university scientists also have their own science programs or participate in the joint science program of the State and Federal Contractors Water Agency. There have been several successful models of interagency science collaboration in the Delta. For instance, the Interagency Ecological Program (IEP) is a longstanding effort of federal and state agencies to have a combined biological monitoring and research program for the Delta. The Collaborative Adaptive Management Team and the Collaborative Science and Adaptive Management Program is a collaboration among state and federal agencies, public water agencies, water contractors and NGOs to develop science and adaptive management programs to implement biological opinions on smelt and salmon (Anderson et al. 2014). The California Water and Environmental Modeling Forum (CWEMF) promotes exchange of information and discussion on California water modeling issues. The Management Analysis and Synthesis Team completed a comprehensive conceptual model of the Delta smelt (MAST 2015), and there have been some successful attempts to connect hydrologic and fish models (e.g., Rose et al. 2013a, 2013b). However, implementation of a comprehensive, focused, and strategic framework for scientific research linking water flow to the complex processes influencing fishes is required for managing both the Delta ecosystem and Delta science.

Many state and federal agencies are involved in decisions related to water flows and to fishes. However, a comprehensive, focused, and strategic framework for research linking water issues to a complex of fishes has not been implemented

Recommendations on Strategic Science Needs

Improving scientific understanding of fishes and flows, and bringing this knowledge into useful decision-support for adaptive management has clear urgency. Workshop reports by Reed et al. (2014) and Monismith et al. (2014) clearly lay out a series of management-critical questions related to water management and effects on fishes. The reports also identify scientific gaps in our information on these topics. Among these, the Delta ISB concurs that management decisions could be improved with better forecasts of outcomes, greater understanding of the conditional impacts of other drivers on fishes, and quantitative assessments of the combined effects of flows on other parts of the physical and biological ecosystems as they relate to fishes. The Delta ISB recommends the following scientific strategy to address the near- and long-term scientific challenges related to management of flows relative to fishes and for its ability to yield testable predictions on how flow management decisions will affect the magnitude of changes in fish populations.

1. *Focus on cause & effect – mechanisms that enable flows to affect fishes*

Deeper understanding of the causal mechanisms by which water flows affect fishes is critical for effective adaptive management, identifying and reducing uncertainty and risks, and for creating specific outcome expectations for management actions. It can also yield specific hypotheses for use in adaptive management (e.g., MAST 2015, Monismith et al. 2014).

> *Improving scientific understanding of fishes and flows, and bringing this knowledge into useful decision-support for adaptive management has clear urgency*

> *For effective adaptive management, improved quantitative understanding of causal mechanisms is required*

Flows and other drivers on fishes need to be examined for their direct and indirect effects on essential fish production processes and vital rates (i.e., growth rates, reproduction success, mortality rates, and migrations/transport). Increased focus on measurable rate processes (e.g., individual fish growth rates) can complement annual population levels that integrate all factors affecting fishes. The overarching questions include: What are the essential requirements of a desirable fish species for individual and population growth and sustainability and how do flows change those requirements?

A mechanistic understanding of the responses to environmental drivers/conditions will improve quantitative predictions. Strategic scientific efforts should focus on:

- *Understanding how the time and space dynamics of water flows affect fish movement through passive transport, active swimming (with or against flow direction), and as triggers that cue migrations or spawning activities.* Fish movement cues, swimming ability, and behavior are critical to understanding how flows assist or disrupt life history strategies. For example, better understanding of hydrodynamics (flow fields) and fish behavior at channel junctions could help keep migrating salmon from the interior Delta, and perhaps reduce mortality.

- *Understanding how flow velocities, depths, and dynamics affect key physical, chemical, and biological factors important to fishes as well for developing fish-flow models.*
- *Quantifying how fish vital rates (growth rate, reproductive success, and mortality rate) are affected by the interaction of biotic and abiotic conditions in the environment and how these interactions translate into population abundances.*

Effects of flows and other drivers on fishes need to be examined for their direct and indirect effects on essential fish production processes and vital rates (i.e., growth rates, reproductive success, mortality rates, and migrations/ transport)

2. Expand integrative science approaches

Addressing specific science priorities requires the development of an integrative, and well-planned scientific approach grounded on management questions and focused on processes, drivers, and predictions. In the words of a 2012 National Research Council report, "only a synthetic, analytical approach to understanding the effects of suites of environmental factors (stressors) on the ecosystem and its components is likely to provide important insights that can lead to enhancement of the Delta and its species." Adaptive science that is flexible and responsive to knowledge-gap identification can provide an effective means to improve management. Research strategies that strengthen interagency and cross-disciplinary work can speed and solidify scientific discoveries and their application. An integrative approach is essential for developing flow management tools that also ensure the health of fish populations.

3. Link quantitative fish models with 3-D models of water flows

The direct linkage of quantitative fish models with 3-D models of water flows is needed to provide a comprehensive, heuristic modeling framework for identifying information gaps, key drivers, and appropriate time and space scales for integrating interagency and interdisciplinary science activities and priorities and underpinning decision support. A targeted collaborative effort will be needed to develop a 3-D open-source hydrodynamic model that can be widely adopted and integrated with generic and species-specific models of fish growth, movement, mortality, and reproduction and with food-web models. The modeling approach should be fish-centric with fish endpoints driving model development. To be relevant for modeling effects on fishes, hydrodynamic models will need to be more related to the habitat (biological, chemical, physical) requirements for fish species and the proximal causes that affect fish reproduction, mortality, and individual growth rates. This framework can be refined as the model development proceeds. The inputs/outputs should be developed jointly by hydrodynamic and fish modelers as well as lower trophic level modelers. Such a modeling framework should catalyze interagency and interdisciplinary science collaboration and directions, help define major gaps in information and monitoring needs, and be targeted towards decision support. Such a model needs a dedicated home that can provide continuous maintenance, upgrades, access, transparency, and support for the users.

A comprehensive, integrative, and well-planned scientific approach focused on processes, drivers, and predictions is needed to aid near-term and long-term adaptive management and to predict how future changes might affect fishes

This recommendation is consistent with the conclusions drawn in the 2010 National Research Council (NRC) Report that stated: "the agencies have not developed a comprehensive modeling strategy that includes the development of new models (e.g., life-cycle and movement models that link behavior and hydrology)" and forms a core conclusion of the Delta ISB.

A major collaborative effort is needed to develop a 3-D open-sourced hydrodynamic model that can be more widely adopted and integrated with generic and species-specific models of fish growth, movement, mortality, and reproduction and with food-web models. This model should be developed from the perspective of fish habitat requirements

Modeling capabilities and ecosystem understanding in the Delta have grown to where development of such a predictive mechanistic approach is possible. Three-dimensional hydrodynamic and water quality models have been successful in other systems to examine fish production processes (e.g., the Chesapeake Bay, Kemp et al. 2005, Boesch 2006, Dalyander and Cerco 2010, Townsend 2013) and are being increasingly applied in the Delta. The hydrodynamic model should capture both natural processes and water management drivers. A key difference being proposed here is that the hydrodynamic models be developed for the purpose of a mechanistic evaluation of biological processes and designed to make testable predictions. Parameter scale, time scale, and space scale should be relevant for both fishes and flows.

The growth rates of individuals within a fish population are important to overall fish production and can be used to illustrate this type of modeling approach. The growth rate of an individual fish is determined directly through a balance of the difference between energy intake (consumption) and energy expenditure (metabolic costs) plus waste products (egestion and excretion). Key factors affecting energy expenditure are activity levels of the fishes, temperature, oxygen, and salinity. Fish consumption rates also are affected by temperature, salinity, oxygen level, and prey availability (prey density, detectability, catchability). Prey density can be affected by the presence of competitors, and production dynamics and habitat requirements of lower trophic levels (e.g., Kimmerer et al. 2005, Kimmerer 2006). Many of the above factors are sensitively affected by changes in flows (e.g., Myrick and Cech 2004, Nislow et al. 2004, Arnekleiv et al. 2006, Davidson et al. 2010, Arismendi et al. 2012, Rose et al. 2014, Fiechter et al. 2015) and these need to be considered in model development and execution.

The development of a generalized fish model portable for different fish species and for different water management decisions is needed to forecast expected consequences and timelines for adaptive management strategies. The life cycle models developed for species such as the Delta smelt (Rose et al. 2014, MAST 2015) and salmonids (Hendrix et al. 2014) provide a solid foundation for this process. General fish vital rate models can be developed (or borrowed) based on fish physiology and behavior, and parameterized separately for each species and life stage (e.g., Wisconsin Bioenergetics model, Chipps and Wahl 2008). Physiological models deal with constraints imposed by the water temperature, water quality (e.g., hypoxia), swimming abilities, and cover types (e.g., root wads, large boulders, shallow water, and vegetation). Currently, available models used in the Delta appear to use only a subset of these without temperature (Myrick and Cech 2004, Arismendi et al. 2012). Model applications should also examine adequate coupling of some critical variables such as species or ecosystem tipping points and thresholds as well as cumulative impacts. The task of such coupling is simplified, given that water flows may affect fishes but not vice versa, and hence only one-way coupling of models is required.

A modeling effort focused specifically on a mechanistic evaluation of how changes in flows affect fish production dynamics will provide an operational tool for adaptive management and forecasting biological outcomes of water decisions. Such modeling will require components of regional climate (hydrology), hydrodynamics, water quality, food availability, and physiological and habitat requirements at various fish life stages across different fish species.

The Delta ISB recognizes the value of one and two-dimensional models that are also used for riverine ecosystem studies and management (e.g. Anderson et al. 2013), but some important physical processes are eliminated in simplification. For example, 2-D models eliminate the effects of vertical and horizontal density driven (baroclinic) motions, and therefore gravitational circulation (Lucas et al. 2002, Chua and Fringer 2011). Baroclinic circulation is critical in fish recruitment and X2-fish relationships (Monismith et al. 2002). Even inclusion of nonhydrostatic dynamics may not capture the baroclinic circulation accurately because of the dependence of salt mixing on the turbulence (vertical mixing) models used in the 3-D modeling system. Therefore, appropriate turbulence models for Delta hydrodynamics for both shallow and deeper regions is a topic that needs further research.

Modeling focused on a mechanistic evaluation of how changes in flows affect fish production dynamics will provide an operational tool for adaptive management and forecasting outcomes

Although 3-D and 2-D hydrodynamic models that are currently used produce detailed profiles of hydrodynamic parameters, for computational convenience some parameters important for fish are removed from the governing equations. A clear example is omission of the temperature equations while retaining salinity, reflecting the assumption that buoyancy effects are dominated by salinity. Yet, temperature is a key variable for determining fish physiological rates (Cloern et al. 2011), spawning (Bennett 2005), and mortality (Feyrer et al. 2007). Water temperature also is affected by air temperature and water-surface wind mixing, which are usually omitted in water flow models although it is possible to include them through parameterizations. Temperature should be included in models developed for fish-flow studies.

Greater use of individual-based models of fishes in a spatially explicit context can yield spatially, temporally, and life-stage specific information on fish vital rates, especially when linked to 3-D hydrodynamic models (e.g., Dalyander and Cerco 2010, Rose 2000, Grimm and Railsback 2005, Rose et al. 2013a, 2013b, Stillman et al. 2015). The most direct effect of flows on fishes is through its influence on fish movement (Figure 2) and this can be modeled. Time-varying 3-D models also allow incorporation of fish movement and behavior (e.g., Kimmerer et al. 2014). Individual-based models can follow movement and resultant growth, and survival of a large number of individuals have been effective when coupled with a hydrodynamic model (e.g., Höök et al. 2008, Beletsky et al. 2008, DeAngelis and Grimm 2014, Rose et al. 2014). The basic modeling framework can be scaled to different species by changing movement rules and fish bioenergetic parameters.

Overall, such a modeling framework can help assess the potential responses of different species of fish to management actions, habitat restoration efforts, and different climate conditions. After initial development, continuing development must include model improvements and acquisition of high-resolution benchmark data sets for characteristic flow regimes. Improved indices of ecosystem status and management action set-points will have traceable drivers. Subsequently, reduced (parsimonious) models may be valuable for management support. All such modeling development must be done in the context of assessing uncertainty, hypothesis-based parameter testing, evaluation of parameter sensitivity and continued communication between model developers, model users, managers, and monitoring programs. Long-term support for viable models should be ensured.

Some specific steps forward are needed to ensure that the proposed modeling framework spans across major stakeholder agencies and programs. Hydrodynamic modelers must work directly with fish and lower food web experts as well as decision-makers so essential model parameters and necessary time and space scales are employed and the best biophysical understanding is incorporated. An initial workshop should describe the detailed framework and implementation plan for development of the 3-D model that will include a generic fish model. A suitable taxonomy may identify the model version and application information. Synthesis will help solidify conclusions and interactions. Formation of a well-led standing working group including both hydrodynamic and fish and food web modelers from agencies, academia, NGOs, and consulting should carry this effort forward and provide linkages to other ongoing modeling efforts (e.g., CWEMF, IEP) and with formal adaptive management processes.

> *Hydrodynamic modelers must work directly with fish experts to ensure that essential model parameters and necessary time and space scales are included*

4. *Examine causal mechanisms on appropriate time and space scales*

A mechanism-based focus will require a close consideration of time, space, and parameter scales relevant to biological processes as well as driving physical (flow) mechanisms. Models with time and space (depth, width, reach and time variation) scales appropriate for water management questions may not be useful to answer fish and ecosystem questions that may require higher temporal and spatial resolution, although progress has been made to link water and fish models (e.g., Rose et al. 2013a, 2013b). Water-management models can provide useful inputs to more detailed hydrodynamics models via model nesting. This points to the need for a comprehensive modeling framework that can serve diverse modeling needs of Delta environmental management, including fish. Space-time flow variability has important biological consequences that are not necessarily captured in mean monthly flow values or in annual fish population estimates because of the many drivers operating in this ecosystem.

Flows that affect a particular life stage of a fish species may have consequences in later life stages. Of particular importance is the metabolic cost of growth, which deals with energy partition between life support (maintenance of metabolic rate) and growth, for which the energy exerted against the flow is important (Rombough 1994). The relevant time scales of fish processes are often shorter (sometimes on the order of hours) than particular life stages. For example, fish growth rates can change daily based on daily changes in temperature, and a 1°C change in temperature can be significant, particularly near thresholds (e.g. Chipps and Wahl 2008). The sensitivity of fish behavior to salinity and temperature depends on the species and life stage, among other factors, and the models should be able to resolve gradients for optimal nursery habitats for fish species (Hobbs et al. 2006). Timing of flow management and monitoring should reflect major mechanisms that affect fish health across an entire year. Fish responses should be measured at the time and space scales of expected responses (e.g., fish movements and fish growth rates might respond rapidly to changes in flow).

> *Space, time, and parameter scales must be relevant to fish processes*

5. Monitor vital rates of fishes

Monitoring is done to estimate ecosystem conditions or to assess the consequences of specific management actions. To this end, a monitoring program that is organic with model expectations can improve the contribution of science to adaptive management. A specifically designed program is needed to monitor expected first-order responses by which flows affect fishes, linked to multiscale modeling efforts. Monitoring should focus more on factors having immediate effects on fishes and be used to calibrate and test models and specific hypotheses. Fish monitoring should be coordinated with water quality monitoring and water flow monitoring, and perhaps use an integrated data framework. State-of-the-art sensor technologies and data transfer methods can enable routine monitoring data to be useful for comprehensive research purposes and model evaluations.

Rate responses, such as fish growth rate, more aptly reflect response to changing conditions and provide more certain and causal insights than annual indices of population size which integrate across multiple drivers. Additional monitoring for more mechanistically related characteristics, such as growth rates or movement, might provide improved and more relevant information for adaptive management. Techniques such as measuring bioelectrical impedance have shown promise for measuring short-term responses of fish to food availability (Calderone et al. 2012). Field studies on fish growth rates have given major insights into the mechanisms behind successful fish habitats on seasonal floodplains for the Delta (Sommer et al. 2001; Jeffries et al. 2008). Acoustic tagging studies have been valuable to assess fish movements and would be strengthened if linked with hypotheses driven by hydrodynamic models with particle tracking capabilities. Integrating mobile multibeam acoustics with pelagic trawl surveys could strengthen assessments since they can provide detailed measures of fish distributions across environmental gradients. Similarly, monitoring of fish populations should be targeted to factors likely to respond to changes in flow (e.g., growth rates, movement). The lack of integrative, coherent, centralized, and quality controlled/assured monitoring data and the unavailability of a modeling and question-driven framework that links fish modeling to water quality and flow parameters hinders synthesis.

A specifically designed program is needed to monitor major mechanisms by which flows affect fishes, linked to the modeling efforts and relevant time and space scales

6. Broaden species focus

Much research in the Delta has been understandably focused on endangered or threatened species and some non-natives such as the Striped bass. Non-native species dominate fish biomass in much of the Delta and have disrupted historic food webs. Ecologically important species of fish are those that dominate the ecosystem and/or play key roles in the food web. Little is known about the impact of flows on many of these species and they likely have important food-web relationships to threatened or endangered species. More generally, little is known about predator and competitor distribution and abundance, the influence of flow on predators and predation rates, and predator impact. A multispecies framework that incorporates food web connections has been adopted elsewhere and should be considered here, particularly given the threat of new invaders. For example, the Chesapeake Bay formally adopted multispecies management goals as part of the Chesapeake Bay 2000 Agreement (Boesch 2006, Townsend 2013 and references cited therein). A 3-D model can be parameterized for multiple fish species to advance this understanding.

The research focus on threatened or endangered species needs to expand to other native species as well as non-native, ecological important fish species that populate the Delta

7. Enhance national and international connections

The problems faced in the Delta are not unique. A wealth of knowledge exists from other ecosystems. To accelerate and improve scientific insights and reduce their costs, agency scientists need access to these other studies and scientists through expanded access to the recent scientific literature and opportunities for travel to conferences, workshops and relevant other field sites. Large U.S. ecosystems heavily impacted by population growth, changes in land use, and multiple stressors include the Great Lakes, Chesapeake Bay, Mississippi Delta, the Everglades, Columbia River, and Puget Sound. The scientists and managers in these ecosystems are addressing many of the same issues that Delta scientists and managers face (e.g., Boesch 2006). Although nominally similar habitats can differ greatly in stressors and dominant mechanisms (e.g., low productivity ecosystems and those impaired by nutrient enrichment), comparisons can yield important insights and shared tools (Malone et al. 1999).

The problems faced in the Delta are not unique. State-agency scientists need better opportunities to assess results and thinking from the perspective of other estuaries

It is especially important that state and federal scientists have convenient access to national and international scientific journals. This might be accomplished with a high-level agreement between the state and/or federal governments and the large library system of the University of California.

8. Promote timely synthesis of research and monitoring

Considerable research has addressed the impacts of flows on fishes, but synthesis of this research has been limited, particularly on integration of physical and biological processes and for developing adaptive management scenarios and adaptive science as well. Agencies must recognize the importance and need for routine and timely scientific synthesis for both directing scientific efforts and summarizing scientific results and uncertainties for managers. This requires additional dedicated staff time and resources.

Agency policies are needed that provide synthesis teams with adequate resources to complete their work in a time frame useful for decision-makers and to reward cross-disciplinary, multi-authored scientific efforts, and ensure the maintenance and upgrading, availability, and documentation of sophisticated models and essential databases focusing specifically on the Delta. An overall scientific and modeling approach specifically targeted on the mechanistic understanding of how flows affect fishes could provide an organizing framework and forum for regular interagency and interdisciplinary synthesis.

Synthesis is not the end point – the use of knowledge is. Considerable effort to translate the science to a full range of users including stakeholders, managers, and adaptive management team(s) is needed. Sophisticated but user-friendly management tools that build upon scientific knowledge and modeling are most helpful in this regard.

9. Improve coordination among disciplines and institutions

Improved understanding is needed among ecologists, hydrologists, and hydrodynamic modelers and across their various institutions having different missions and priorities to better understand the constraints under which all work. A comprehensive scientific framework and implementation plan will help guide these advances (see recommendation 1). Long-term commitment is needed for science that addresses contentious and fundamental issues that span traditional agency and disciplinary lines. Interdisciplinary, interagency understanding can be facilitated through implementation of the Delta Science Plan, which has been designed to encourage sustained commitment and increased coordination for addressing contentious issues and wicked problems. A management focus on a single controllable feature (e.g., flows) may miss a myriad of underlying ecological processes and management opportunities, so funding and coordination are needed for more integrative programs. Monitoring, research, and adaptive management focused on management-relevant mechanistic understanding should be incorporated into studies.

Conclusions

Overall, modeling capabilities and ecosystem understanding in the Delta have grown to a level that could support development of predictive and causally based approach recommended in this report, given sufficient targeted and purposeful effort. These recommendations are broader than just a suggestion to construct another model. The mechanistic modeling approach should serve as a framework to integrate interactions of scientists and agencies working on water flows with those working on fishes and lower food webs. The goals would be to develop decision-support tools and data, guide monitoring and data collection, conduct specific scientific studies to fill major information gaps, identify important time and space scales, and identify the uncertainties with which policymakers need to work. Adaptive management can be improved through an iterative evaluation process that tests management scenarios and uses modeling to explore the range of possible outcomes.

Additional recommendations that apply to all of the science being done in the Delta have been identified in other Delta ISB reports, workshop panels, and the National Research Council. They include: consideration of environmental uncertainty; coordination of scientific research with planned management decisions, including adaptive management; use of risk analyses; recognition of the importance of long-term sustained research and monitoring; and the need to buffer science from politics and activism. The Delta Science Plan includes many of these recommendations and, if wisely and firmly implemented, should provide a framework for science that establishes research priorities and recognizes the essential role of long-term, sustained research that is not driven to ineffectiveness by short-term crises. A targeted mechanistic focus on the effects of flows on fishes may provide a way forward to increase insights and lessen uncertainties for management and the development of a Delta with healthy fish populations.

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Appendix A: Review Process

The Delta ISB reviewed many specific articles on fishes and flows in the Delta and other ecosystems published in the scientific literature or in extensive reviews including the two reports by the National Research Council linking water management and threatened and endangered species (NRC 20110, 2012) and other reports on specific fish species (e.g., MAST, 2015), groups of fishes (Baxter et al. 2010), specific issues such as entrainment (Grimaldo et al. 2009, Anderson et al. 2015) or assessment of new water transport systems (BDCP 2013). The Delta ISB also attended the "Delta Outflows and Related Stressors" workshop (February 2014) and the "Interior Delta Flows and Related Stressors" workshop (April 2014) conducted by the Delta Science Program for the State Water Resources Control Board, and read related panel reports (Reed et al. 2014, Monismith et al. 2014). The Delta ISB also received presentations on this topic at Delta ISB meetings. The Delta ISB has not tried to duplicate these extensive literature reviews, and cited references are intended to be illustrative.

During the initial stages of the review, the Delta ISB also conducted two sets of interviews (on June 17, 2013 and June 11, 2014) with a wide range of interested and involved parties (16 individuals) holding a variety of perspectives, and included scientists in state and federal agencies, consulting firms, special-interest groups, and academia. The purpose of these one-hour interviews was to gain an initial, broad perspective on current scientific research on the effects of flow on fish populations in the Delta, how that research was organized, collaboration mechanisms and key publications on the topic.

A subset of Delta ISB members undertook the interviews, workshop attendance, and literature review and wrote the first drafts of the report. Initial drafts were revised in response to comments received from individual Delta ISB members and the public, and the final report was approved by the full Delta ISB for release on July 17, 2015.

Appendix B: Detailed Conceptual Diagram of the Linkages Between Flows and Fishes in the Delta