How do flows affect fishes in the Sacramento-San Joaquin Delta? Recommended strategies for scientific research in support of adaptive management.

A report by the

Delta Independent Science Board

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(DRAFT)

NOTE: This is a draft report prepared for discussion by the full DISB and should not be cited.

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Summary

California's severe drought and the near disappearance of the Delta smelt highlight the challenge of managing freshwater flows for the benefit of fishes in the Sacramento-San Joaquin Delta. Understanding the dependencies of fishes on water flows is central to understanding how the Delta ecosystem functions and 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". The economic and ecological costs of scientific uncertainty in water management controversies are significant.

The state of science on fishes and flows in the Delta is reasonably robust and well-reviewed. Retrospective analyses show that at least some fish populations are affected by some flows, but fish and flow relationships have often not been causally explained or quantified adequately to make testable predictions on how specific management decisions on flows will affect the magnitude or sometimes even the direction of changes in fish populations. Improved understanding of the relationships between flows and fishes is critical for effective adaptive management, identifying uncertainty and risks and for creating specific outcome expectations.

The scientific challenges to providing a flow regime that benefits fishes (or minimizes the harm) while providing water reliability are well recognized;

- 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. Non-native fishes now predominate in the Delta. Pervasive changes to the ecosystem make it difficult to delineate habitat needs of specific native fishes now living in a transformed habitat.

- Flows in the Delta are spatially and temporally complex. Their effects on fishes may be direct or indirect through the influence of flows on other environmental factors, all of which vary among species and life stages within a species. Flow effects are confounded by other drivers of fish production in the ecosystem.

- Many agencies are involved in fish and flow decisions and scientific efforts to support management.

As part of its legal mandate to review Delta scientific programs in support of adaptive management, the Delta Independent Science Board (Science Board) has chosen to broadly examine the science focused on the effects of water flows on Delta fish populations. This report offers specific recommendations (below) on strategic science needs to improve understanding of underlying processes to benefit adaptive management, and to enhance collaboration and communication among institutions, scientists and managers on this important topic.

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Expand integrative science approaches and focus on mechanisms. Improved understanding of the causal relationships between flows and fishes is critical for effective adaptive management, identifying and reducing uncertainty and risks and for creating specific outcome expectations for management actions. Enhanced research focused on mechanisms is a well-recognized need for effective ecosystem-level adaptive management for the Delta (e.g. Mast 2015, Monismith 2014) and was highlighted by the 2012 NRC Report that concluded "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."

To develop specific science priorities requires the development of a comprehensive, strategic, integrative, and well-planned scientific approach driven by management questions and focused on processes, drivers, and predictions. The overarching question should be: What are the essential requirements of a fish species for population production and how does flow change those features? Adaptive science that is flexible and responsive to knowledge-gap identification can provide a more effective means to improve management capabilities. Research strategies that strengthen interagency and cross-disciplinary interactions can speed and solidify scientific developments and applicability. Effects of flows and other drivers on fishes need to be examined from the perspective of direct and indirect effects on essential fish production processes and vital rates (i.e., growth rates, reproduction success, mortality rates, and migrations/transport).
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Link quantitative fish and hydrodynamic models. The next step requires the development of a comprehensive, mechanistic modeling framework that can be used to help identify information gaps, key drivers and appropriate time and space scales and to guide scientific collaboration. A specific collaborative effort is needed to develop a 3-D open-sourced hydrodynamic water-quality model that can be more widely adopted and integrated with generic and species-specific models of fish growth, movement, mortality, and reproduction. This modeling effort should form the framework for integrating interagency and interdisciplinary science activities and priorities, help define major gaps in information and monitoring needs, and be targeted towards decision support.

Some steps forward should include developing a comprehensive modeling framework across major agencies and programs. Hydrodynamic modelers must meet directly with fish experts to define essential model parameters and needed time and space scales. The goal should be to design a detailed 3-D model that will include a generic fish model. 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. Significant progress can be accomplished in the short term.

Link time and space scales to causal mechanisms. A focus on mechanisms will likely require a closer consideration of time, space and parameter scales most relevant to biological processes. 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. Flow variability in time and

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space has important biological consequences that are often not captured in mean monthly flow values or annual population estimates.

Monitor vital rates. 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 the modeling efforts and time and space scales described above. Rate responses, such as growth rates, more rapidly reflect response to changing conditions and give more certain and causal insights than annual indices of population size.

Broaden species focus. The comprehensive research on salmon and smelt 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.

Promote timely synthesis of research. Agencies must recognize the importance of, and the need for, a routine practice of research synthesis and the importance of getting information out in a timely way. This requires higher management expectations for timely and insightful science and more staff time and resources.

Enhance national and international connections. The problems faced in the Delta are not unique. Agency scientists need access to the wealth of knowledge and thinking from other ecosystems through regular access to the scientific literature and additional opportunities for travel to conferences and workshops.

Develop stable, long-term commitment and improved coordination. Improved cross-disciplinary understanding is needed between ecologists and hydrologists, and across agencies that have different missions and priorities to better appreciate the constraints under which all work. A comprehensive scientific framework and implementation plan is needed to guide these advances (see recommendation 1). Long-term commitment and continued coordination are needed for science that addresses such contentious and fundamental issues.

Overall, the specific recommendations in this report can be achieved with a targeted, purposeful effort. These recommendations are broader than just suggesting the development of 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, and specific scientific studies to fill major information gaps, and identify important time and space scales. Models can be improved through an adaptive, iterative, and evaluation process that tests management scenarios and explores the full range of possible outcomes.

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Introduction and Management Needs

California's ongoing four-year drought has brought renewed focus to the practical and scientific problems of managing flows for both fishes and water supply. When one-acre-ft. of water is worth $1000 or more, even significantly small amounts of water can affect millions of dollars in water supply. At the same time, the abundance of the endangered delta smelt in the Sacramento-San Joaquin Delta (hereafter, Delta) has reached an all-time low, triggering newspaper headlines that signal the near extinction of this critical indicator species. The economic and ecological costs of scientific uncertainty on the relationship of fishes and flows in water management controversies are significant.

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Understanding the dependencies of fishes on water flows is central to understanding the Delta ecosystem and 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" (Water Code 85054). 'Water flows' are key to management decisions on water supply, and 'fishes' are the key indicator of the Delta ecosystem's health and a major driver of ecosystem policies formulation. The relationships between both fishes and flows drive state and federal policy, related regulatory and management decisions, and have consequently been central to legal arguments and judicial decisions.

Since water flows are a defining process of the Delta, as in river ecosystems worldwide, 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 because of the precise way in which flows affect fishes, but because of the pervasive influence of flows on so many other variables in the Delta ecosystem. Water managers have considerable influence on flows into the Delta through reservoir releases and exports. People have come far in "mastering" water flows within the limits of climate-controlled water abundance and scarcity. Using this mastery to reach the coequal goals of water reliability and protecting the Delta's ecosystems requires improved knowledge of the relationship of water flows to fishes.

A robust body of scientific research has explored how water flows in the Delta and elsewhere affect fishes. The state of our scientific understanding 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., MAST 2015), groups of fish species (Baxter et al. 2010), specific issues such as entrainment (Grimaldo et al. 2009, Anderson et al. 2015) or assessments of new water transport systems (BDCP 2014). These reviews highlight the complexity of the problem and the challenges of defining the relative role of flows and

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other environmental drivers in a dynamic ecosystem such as the Delta. The state of science on fishes and flows in the Delta is reasonably robust and well-reviewed (see references cited above). Retrospective analyses show that at least some fish populations are affected by some flows, but fish and flow relationships have often not been causally explained or quantified adequately to make quantitative predictions on how management decisions on flows will 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.

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The Delta Independent Science Board (Science Board) is mandated in the Delta Reform Act, to "… provide oversight of the scientific research, monitoring, and assessment programs that support adaptive management of the Delta through periodic reviews of each of those programs…." In partial fulfillment of that responsibility, the Science Board has fully reviewed the state of the science on the effects of flows on fishes in the Delta in an effort to make specific recommendations on strategic science needs to reduce the scientific uncertainty associated with predicting outcomes of management decisions and to enhance scientific collaboration and communication pertinent to fishes and flows in the context of other drivers. The full review process is described in Appendix A.

Scientific Challenges

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

- 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. Pervasive changes to the ecosystem make it difficult to delineate habitat needs of specific native fishes now living in transformed habitats Non-native fishes and other invaders now predominate the Delta and food webs are likely disrupted.

- Flows in the Delta are spatially and temporally complex. Their effects on fishes may be direct or indirect through the influence of flows on other environmental factors, all of which differ among species and life stages within a species. Flow effects are confounded by other drivers of fish production in the ecosystem.

- Many agencies are involved in fish and flow decisions and scientific efforts to support management.

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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 bears 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). Pervasive changes to the ecosystem make it difficult to delineate critical habitat needs of specific native fishes now living in transformed habitats.

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, 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 access to extensive fish habitats.

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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% 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 within the Delta, groundwater pumping, evaporation, precipitation, and consumptive uses including those for local agriculture. Tidal flows dominate the western Delta, where instantaneous 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) 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

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facilitate water exports from the Delta and maintain water quality for in-Delta diverters, most of the Delta is maintained as a freshwater system, supported by many structures (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.

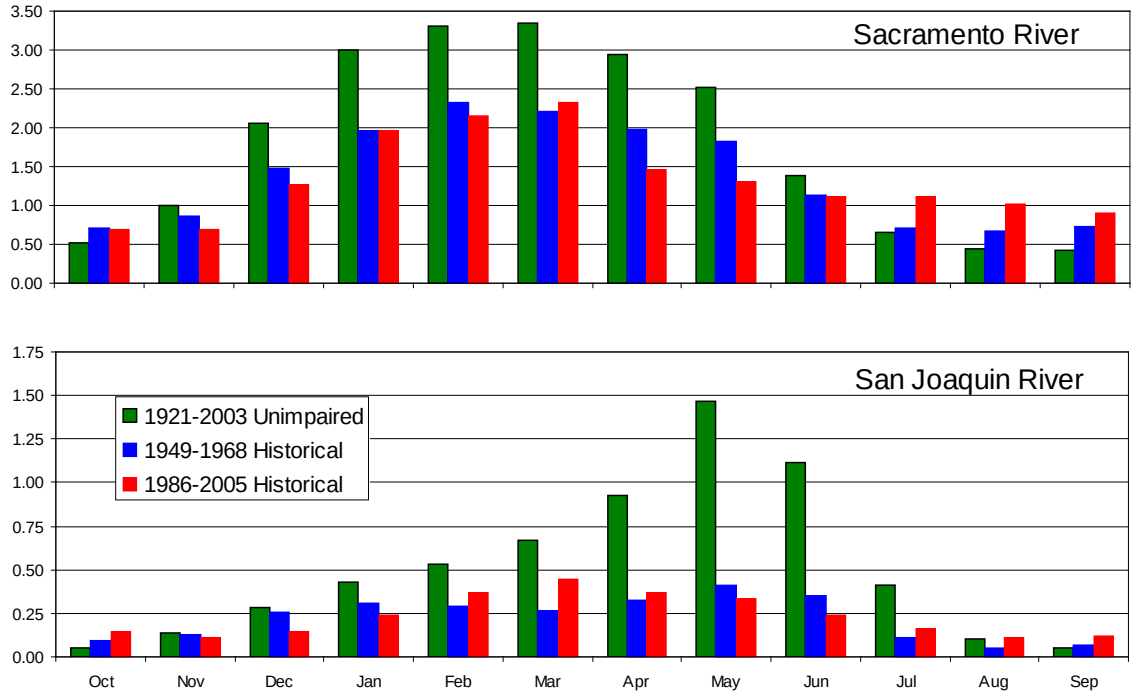

Figure 1. Changes in Delta flow patterns. The Y axis is the average flow in million acre feet per month (Fleenor et al. 2010). (Note: Unimpaired flow does not account for upstream natural evapotranspiration under pre-development conditions.)

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, 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 and changes in food webs are well documented. (Cohen and Carlton 1998, Moyle and Bennett 2008).

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 made up 8 out of 33 fish taxa and less than 0.5% of the total number of fishes sampled. Feyrer (2004) sampled fish larvae in the southern Delta from 1990-1995 and found that 98% of the fishes caught were nonnative species. Countless studies draw the same conclusions: native species in the Delta have declined substantially and nonnative species have become 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).

> The species in the Delta fish community has 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.

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 in habitat will affect fishes will become even more important.

Species-specific responses

Different species and different life stages within a species differ in their habitat requirements and their resilience/vulnerability to habitat changes and stressors. Therefore, the response of 'fishes' to 'flow' will be species- and life-stage 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 most (e.g. MAST 2015, add reference). The effects of flows on fishes are

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

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often discussed in relation to annual measures of (relative) population abundance. In an ecosystem, fish abundance (total population level 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 are often complex.

Multiple Drivers

Flow is but one potential factor affecting fishes. 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 a myriad of other factors in the Delta is confounded by: 1) the action of many drivers over long time periods, 2) system complexity, 3) complexities in functional relationships, and 4) a narrow focus of research on a few species and relatively little on other important species or processes (e.g., predation, food webs, behavior in migration corridors).

Specific reasons for the declines in abundances of native species remain unclear but are likely caused by multiple drivers (or stressors) and the interactions of these drivers (Bennett and Moyle 1996, Moyle 2002, 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, 2012), Hanak et al. (2013), Reed et al. (2014), and Monismith et al. (2014).

> 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.

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 interact in complex ways, so relating changes in one driver alone (i.e., managed flow) to changes in abundance of one or more species is challenging. Statistical correlations can support specific hypotheses. Several studies support the hypothesis that changes in historical flows (e.g., wet years and dry years,) affected fish population abundances.

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Direct and Indirect Effects of Flows

Many conceptual models illustrate the interdependencies of natural and managed flow processes for Delta fish resources, and a simplified diagram is shown in Figure 2. A more detailed perspective is presented in Appendix B. A conceptual approach that delineates the factors affecting fish production illustrates the scientific challenges and helps identify gaps in our understanding. Flows can affect fishes through multiple direct and indirect (i.e., proximate and ultimate) pathways. Direct effects largely include physical transport and alteration of migratory pathways. Indirect effects include the impact of flows on biotic and abiotic factors in the ecosystem that, in turn, affect fish growth, reproduction, and mortality and ultimately fish population size.

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

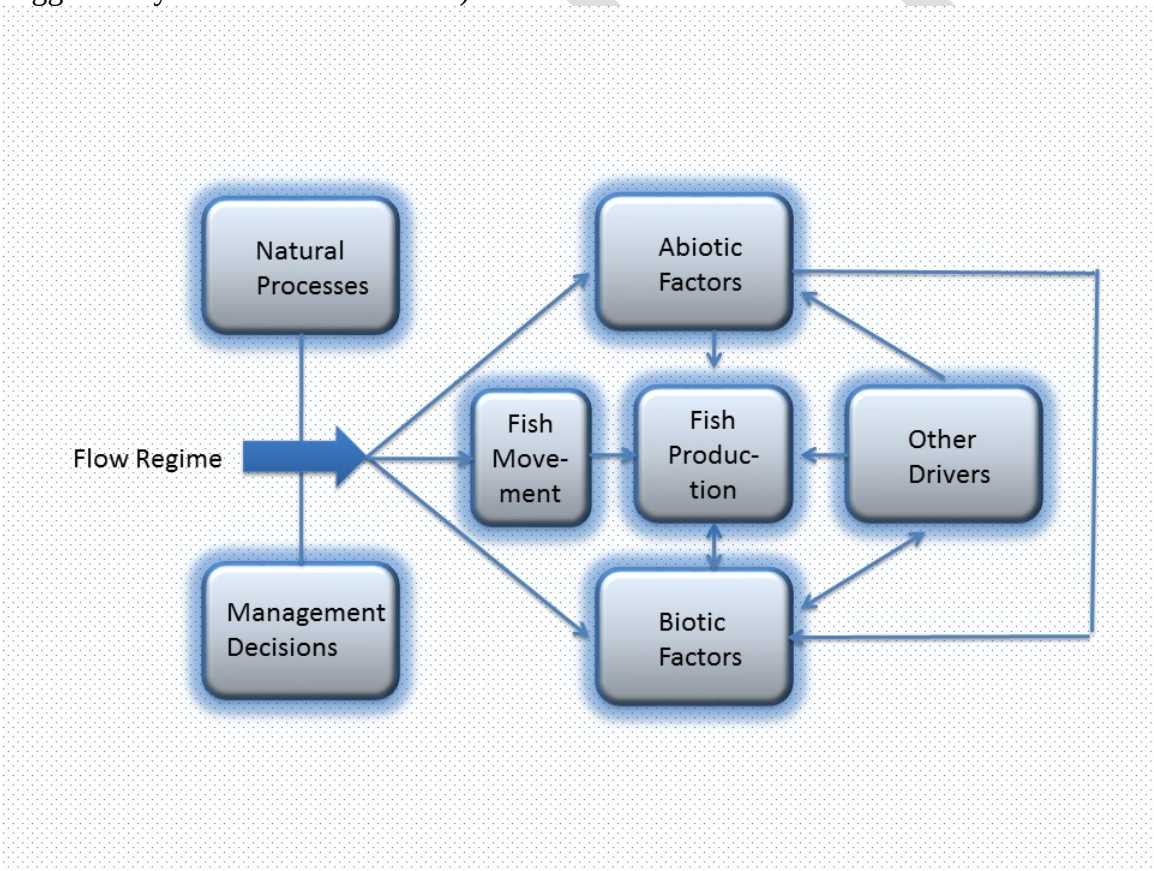

Figure 2. Simplified diagram of how flows affect fish populations directly and indirectly, interacting with other drivers.

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] / sec). Q is the product of water velocity (averaged over the flow's cross sectional area) 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, pathway, 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.

At any point in the Delta, the flow regime (volume, average velocity, depth/volume, unsteadiness, flow direction at different locations) 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 hydrologic framework. Precipitation, evaporation, basin runoff, snowmelt and tides are natural processes that affect the flow regime which can be modified through management decisions on storage and release of water from reservoirs, exports, consumptive uses, and diversions. The current California drought is an extreme example of how natural processes can drive flow dynamics and affect the management of water and ecosystems.

Flows can directly impact fishes by affecting fish movements. Understanding the coupling of water motion to fish movements is a key aspect of fishes and flows research. Overall flow dynamics directly affect fish movement by defining pathways and 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, so, changes in flows may trigger migrations, or seasonal flooding may cue spawning activity. Water velocity, which is directly perceived by fishes, affects migration rates for some fishes because fishes can drift with currents or must swim against currents to reach reproductive 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 fishes in the Bay-Delta system, especially the Delta smelt (Kimmerer 2008, Baxter et al. 2010, Anderson et al. 2015).

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

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Perhaps the key impact of flows on fishes is through the influence of flows on other environmental factors. In river ecosystems and the Delta, water flows have pervasive effects on physical, biological, and chemical aspects of habitat that drive biological processes and fish vital rates (e.g., physiology and behavior) (Bunn and Arthington 2002 in Australia; Baxter et al. 2010) Flow rates can directly affect water temperature, salinity, depth, oxygen concentration, food supply, chemical concentrations, turbidity, and sediment load e.g. Wagner et al. 2011, Arismendi et al. 2012, Anderson et al. 2013, Walters and Post 2011). These directly affect 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 which can affect phytoplankton production or even phytoplankton clearance by sedentary invasive mussels. 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 the 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 habitat that drive biological processes and fish vital rates.

Hydrodynamic computer models have been developed to simulate Delta flow regimes so the flow implications of management decisions are reasonably well understood. Yet, understanding flow regimes is insufficient, as local nuances of flow sensitively 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 a habitat feature and how that change in habitat affects fish vital rates. Since flow can affect several 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 prevailing weather conditions, food levels can be affected by invasive species such as filtering by clams, predation risk is a function of predator densities and availability of alternative prey, and fishing will cause fish mortality. Anadromous species spend only part of their life in the Delta, so their abundance will also be influenced by ocean conditions. The strength of these effects on fish production will differ among species and with prevailing conditions but cannot be ignored in population assessments.

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Challenges in the Organization of Management and 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 is lacking.

Many state and federal agencies are involved in decisions related to water flows and to fishes. Most of these agencies also conduct or fund science to support their management actions or required authorizations. A key scientific challenge is that decision-making on water flows and fisheries management are made by different agencies, and agency science aligns 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 exports), space (e.g., local entrainment, diversions) or parameter level for models needed to understand fish production driven by growth, reproduction, survival, and transport.

The central management challenge is encompassed in the state's co-equal 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 poorly 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), and the federal National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service, the U.S. Fish and Wildlife Service (FWS), and the federal Environmental Protection Agency. 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 (DWR), the US Army Corps of Engineers (COE), and numerous local levee districts. Fish habitat in Suisun Marsh, Yolo Bypass, the northeastern Delta, and the lower San Joaquin River is severely restricted by the need for effective flood management in these regions. Flows in the interior Delta are affected by reservoir releases into the Delta, on both the Sacramento and San Joaquin rivers, the operation of gates and pumps by the federal CVP (operated by the US Bureau of Reclamation [USBR]) and California's SWP (operated within DWR), 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 makes the challenges for maintaining flows that support a variety of native fish populations difficult.

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Table 1. Governmental agencies involvement in Delta fish and flows

Level of government	Primary fish management responsibility	Primary flow management responsibility
Federal	NOAA, FWS, USEPA	USBR, COE
State	CDFW, SWRCB, DSC	DWR, SWRCB, DSC
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 and number of scientific reviews, provided a forum for reasoned scientific debate, and led in developing 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 federal and state water contractors. 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 on the Delta. The California Water and Environmental Modeling Forum promotes exchange of information and discussion on California water modeling issues. The Management Analysis and Synthesis Team (MAST, 2015) have completed a comprehensive conceptual model of the Delta Smelt, and there have been some successful attempts to connect hydrologic and fish models (e.g., Rose et al. 2013a, 2013b). However, a comprehensive, focused, and strategic framework for scientific research linking water flow to the complex processes influencing fishes is lacking.

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 and value.

The Workshop reports by Reed et al. (2014) and Monismith et al (2014) clearly lay out a

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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 Science Board concurs that management decisions could be improved with more robust 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 Science Board recommends the following actions to address the near- and long-term scientific challenges related to management of flows relative to fishes.

1. Expand integrative science approaches and focus on mechanisms

Improved understanding of the causal relationships between flows and fishes is critical for effective adaptive management, identifying and reducing uncertainty and risks and for creating specific outcome expectations for management actions. Enhanced research focused on mechanisms is a well-recognized need for effective ecosystem-level adaptive management for the Delta (e.g. Mast 2015, Monismith 2014) and was highlighted by the 2012 NRC Report that concluded "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."

> Get organized scientifically. A comprehensive, strategic, 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.

To develop specific science priorities requires the development of a comprehensive, strategic, integrative, and well-planned scientific approach driven by management questions and focused on processes, drivers, and predictions. The overarching question should be: What are the essential requirements of a fish species for population production and how does flow change those features? Adaptive science that is flexible and responsive to knowledge-gap identification can provide a more effective means to improve management capabilities. Research strategies that strengthen interagency and cross-disciplinary interactions can speed and solidify scientific developments and applicability.

Effects of flows and other drivers on fishes need to be examined from the perspective of 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.

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

- Understanding how the time and space dynamics of water flow affect fish movement through passive transport, active swimming (with or against flow direction), and as triggers that cue migrations or spawning. Fish movement cues, swimming ability, and behavior are critical to understanding how flow aids or disrupts 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, thereby reducing mortality.

- Understanding how flow velocities, depths, and dynamics affect key physical and biological habitats important to fishes.

- 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.

2. Link quantitative fish and hydrodynamic models

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

The next step requires the development of a comprehensive, mechanistic modeling framework that can be used to help identify information gaps, key drivers and appropriate time and space scales and to guide scientific collaboration. A major collaborative effort is needed to develop a 3-D open-sourced hydrodynamic water-quality model that can be more widely adopted and integrated with generic and species-specific models of fish growth, movement, mortality, and reproduction. This model should be developed from the perspective of fish habitat requirements and management decision needs and should be developed jointly by hydrodynamic and fish 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 home that can provide continuous maintenance, upgrades and support for the users.

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Modeling water management for the purposes of understanding its effects on fishes will require, a more fish-centric approach for modeling flows. 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. For example, fish growth 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 are also affected by temperature, salinity, oxygen level and prey availability (prey density, detectability, catchability). Prey density can be affected by the presence of competitors, prey production dynamics and the prey's habitat requirements. Factors that directly affect fish growth can be affected by changes in flows (e.g. Arnekleiv et al. 2006, Davidson et al, 2010, Nislow et al. 2004, Rose et al. 2014, Fiechter et al. 2015))

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),"

Modeling capabilities and ecosystem understanding in the Delta is well established, making development of such a predictive approach possible, and 3-D models are being increasingly used for the Delta. Three-dimensional hydrodynamic water quality models have been used successfully in other systems to examine fish production processes (e.g., the Chesapeake Bay, Dalyander and Cerco 2010). The hydrodynamic model should capture both natural processes and water management drivers of the flow regime. A key difference being proposed here is that the water quality hydrodynamic models be developed for the purpose of a mechanistic evaluation of biological processes. Parameter scale, time scale, and space scale should be relevant for fishes.

The development of a generalized fish model that can be parameterized for different fish species (e.g., Wisconsin Bioenergetics model) 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 (Rose et al. 2011, Hendrix et al. 2014) provide a solid foundation for this process.

A modeling effect focused specifically on a mechanistic evaluation of how changes in fish affect fish production dynamics will provide an operational tool for adaptive management and decision forecasts. 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. Regional hydrologic models predict variability of precipitation, snow and melt conditions, temperatures, sea level rise, and changes in land use; and they can be integrated with climate modeling outputs to predict the future. Hydrodynamic water quality models need to deal with such fish-critical habitat variables as water temperature, velocity, and turbidity General fish vital

A modeling effect focused specifically on a mechanistic evaluation of how changes in fish affect fish production dynamics will provide an operational tool for adaptive management and decision forecasts. .

rate models can be developed (or borrowed) based on fish physiology and behavior and parameterized separately for each species and life stage. Physiological models deal with constraints imposed by 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 adequate coupling of critical variables. Model applications should also examine species or ecosystem tipping points and thresholds as well as cumulative impacts.

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

Although 3D and 2D hydrodynamic models produce detailed profiles of hydrodynamic parameters, for computational convenience some of the important parameters are removed from the governing equations. A clear example is omission of the temperature equations while retaining salinity, reflecting the assumption that the dynamical (buoyancy) effects are dominated by salinity. Yet, temperature is a key variable for determining fish habitat quality (Cloern et al. 2011), spawning (Bennett 2005), and mortality and growth (Feyrer e al. 2007). Water temperature is also affected by air temperature and wind mixing, which are usually omitted in water flow models although it is be possible to include them in 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. 2013, Stillman et al. 2015). The most direct effect of flows on fishes is through its influence on fish movement (Figure 2) and the can be modeled. Individual-based models can follow movement and resultant growth, and survival of a large number of individuals and have been effective when coupled with a hydrodynamic model (e.g., Hook et al. 2007, 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

> Hydrodynamic modelers must work directly with fish experts so that essential model parameters and necessary time and space scales are synergized.

include model improvements and obtaining 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 sustenance of viable models should be ensured.

Some specific steps forward are needed to develop a comprehensive modeling framework across major 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. 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 firmly-led standing working group including both hydrodynamic and fish and food modelers from agencies, academia and consulting should carry this effort forward and provide linkages to other ongoing modeling efforts (e.g. California Water and Environmental Modeling Forum, Interagency Ecological Program), other intra-agency modeling efforts and academic developments.

3. Link time and space scales to causal mechanisms

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

A focus on mechanisms will likely require a closer consideration of time, space and parameter scales most relevant to biological processes. Models for water management that were developed for water management questions may not be appropriate to answer fish and ecosystem management 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, pointing 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 population estimates because of the many drivers operating in this system.

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 (maintain metabolism) and growth, for which the energy exerted against the flow is important (Rombough 1994). The relevant time scales to deal with fish processes are often shorter (sometimes on the order of hours) than particular life stages. Modeling of fish-flow relationships should be conducted at space-time scales compatible with resolving the characteristics of flow and fish. For fish, the possible spatial scales are tens of meters horizontally to resolve habitat variability, with

time scales of an hour or so, representing migration and exposure to environment. For example, fish growth rates can change daily based on daily changes in temperature, and a 1 ºC change in temperature can be significant, particularly near thresholds. For flow, similar horizontal scales are expected to be suitable, with vertical delineation and boundaries with resolution on the order of meters. Because of higher frequency variation of salinity and associated factors, flow models ought to be able to resolve variations on the order of hours. 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 salinity 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). This requires time integration of models with environmental conditions and drivers can be incorporated through hydrodynamic models.

4. Monitor vital rates

Monitoring is done to measure the conditions or health of an ecosystem and to examine the consequences of specific management actions. A specifically designed program is needed to monitor expected first-order responses by which flows affect fishes, linked to the modeling efforts and time and space scales described above. Monitoring should focus more on factors having immediate effects on fishes and be used to calibrate and test models. Monitoring should be coordinated with water quality monitoring and water flow monitoring and perhaps use an integrated data framework.

> 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.

Rate responses, such as growth rate, more rapidly reflect response to changing conditions and give more certain and causal insights than annual indices of population size which integrate across multiple drivers. Monitoring that only estimates fish population abundances is insufficient, error-prone, and expensive. Additional monitoring for more mechanistically related characteristics, such as growth rates, might provide improved and more relevant information for ecosystem management. Techniques such as measuring bioelectrical impedance have shown promise for measuring short-term responses of fish to food availability (Calderone et al. 2012). Monitoring should be undertaken with the aim of understanding major mechanisms (e.g., growth rates, movement and migrations). 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 lack of a modeling and question-driven framework that links fish modeling to water quality and flow monitoring hinders synthesis.

5. Broaden species focus.

> The research focus on salmon and smelt needs to expand to other native species as well as non-native species that dominate Delta fish populations.

Much research in the Delta has been understandably focused on salmon and smelt although significant work has also been done on other native species such as the green sturgeon and steelhead and non-natives such as the striped bass. Nonnative species dominate fish biomass in much of the Delta and have disrupted historic food webs. Ecologically important species of fish are often those that dominate the ecosystem and or play key roles in the food web. Little is known about the impact of flows on these species and their relationships to threatened or endangered species. For instance, flow rates and volumes may affect nutrient concentration as well as retention time and thus the relative efficiently of phytoplankton filtering by invasive clams. 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. A 3-D model can be parameterized for different fish species to advance this understanding.

6. Promote timely synthesis of research

Considerable research has addressed aspects of the impacts of flows on fishes, but synthesis of this research has been limited, particularly in the context of integration of physical and biological processes and for developing adaptive management scenarios and adaptive science as well. Agencies must recognize the importance of, and the need for, a routine interdisciplinary synthesis and the importance of getting information out in a timely way. This requires more staff time and resources. Agency policies are needed that (1) attract and retain the next generation of agency scientists capable of doing synthesis; (2) enable some productive scientists to remain as scientists when promoted rather than becoming managers, because these are the likely leaders of synthesis efforts; (3) 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 (4) ensure the maintenance and upgrading, as necessary, of sophisticated models and essential databases focusing specifically on the Delta. An overall scientific and modeling

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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.

7. Enhance national and international connections

> The problems faced in the Delta are not unique. Agency scientists need better opportunities to assess results and thinking from other estuaries.

The problems faced in the Delta are not unique, and there is a wealth of knowledge from other ecosystems to which agency scientists need access through enhanced access to the recent scientific literature and opportunities for travel to conferences and workshops. 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 Delta scientists and managers face. Although nominally similar habitat 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).

It is especially important that state and federal scientists have 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. Develop stable long-term commitment and improved coordination

Improved cross-disciplinary understanding is needed between ecologists, hydrologists, and hydrodynamic modelers and across agencies 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. A management focus on a single controllable feature (e.g., flows) may miss many 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. This has been effective elsewhere (e.g., the Alaska Pollock industry is a well-regulated fishery based on a good scientific understanding of the species, which was achieved because scientific research on the species was well funded). A decadal modeling effort is needed, with tiered sophistication, parsimonious models for expeditious decision making and comprehensive models for detailed studies.

Conclusions

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The Delta science program is mature and robust. Thus, the specific recommendations in this report can be achieved with a targeted, purposeful effort. The mechanistic modeling framework should be used as a catalyst to bridge interactions of scientists and agencies working on water flows to those working on fishes and lower food webs. The goals would be to develop decision-support tools and associated data frameworks, guide monitoring programs to fill major information gaps, and identify important time and space scales. Models can be improved through an adaptive, iterative, and evaluation process that tests management scenarios and explores the full range of possible outcomes.

Additional recommendations that apply to all of the science being done in the Delta have been identified in other DISB 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 the need to buffer science from politics and activism. The Delta Science Plan has incorporated 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 lessen uncertainties for management.

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Appendix A: Review process

The Science Board 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 er al. 2010), specific issues such as entrainment (Grimaldo et al. 2009, Anderson et al. 2015) or assessment of new water transport systems (BDCP 2014). The Science Board 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 Science Board also received presentations on this topic at Science Board meetings. The Science Board 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 Science Board 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 Science Board 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 Science Board members and the public, and the final report was approved by the full Science Board for release on **DATE**.

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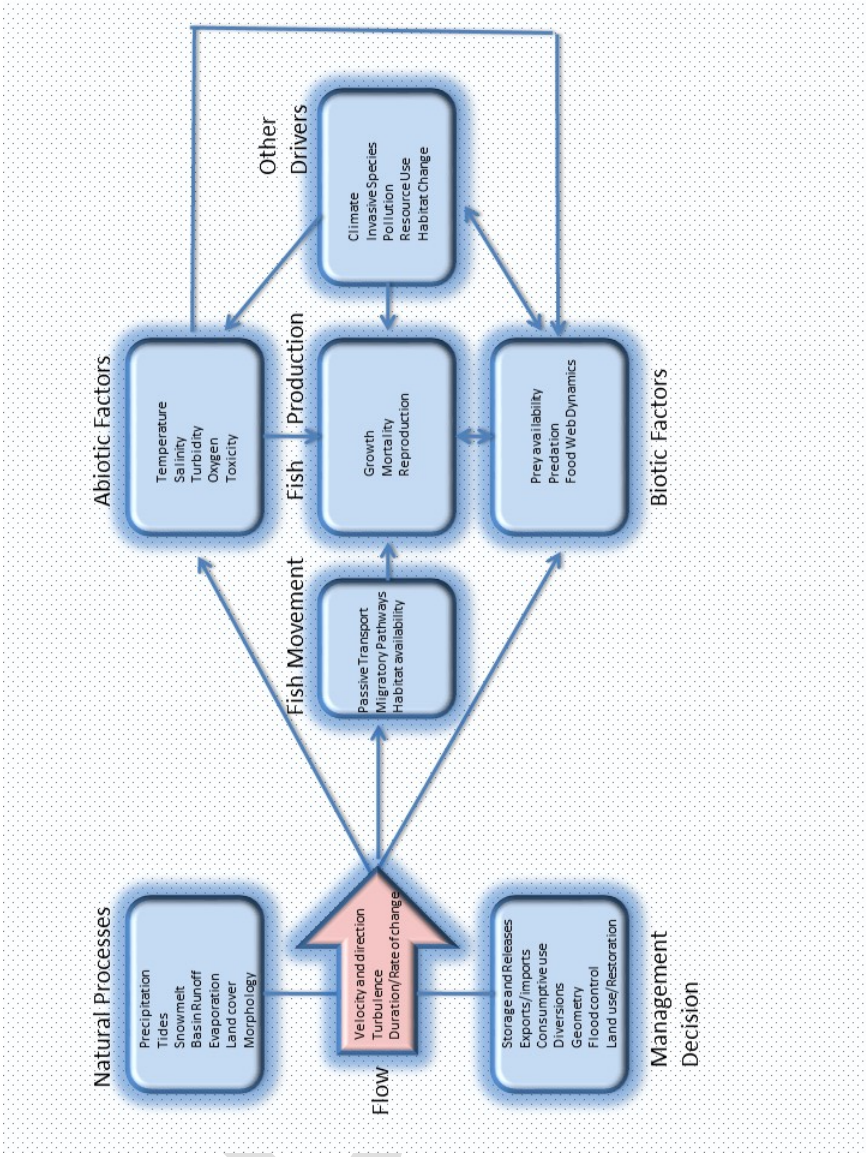
Appendix B: A conceptual diagram of the linkages between flows and fishes in the Delta