California WaterFix Hearing
Exhibit No. SWRCB-56

Workshop on the Interior Delta Flows And Related Stressors Panel Summary Report

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Delta Stewardship Council
Delta Science Program

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Executive Summary

On April 16 and 17, 2014, the Delta Science Program convened an expert Panel (the Panel) and a workshop to identify the best available science to inform the State Water Resources Control Board's (the Board) decisions regarding interior Delta flow requirements to protect beneficial uses of water in the San Francisco Bay/Sacramento-San Joaquin Delta (Bay-Delta Plan). Here we summarize the conclusions of the Panel with regard to the specific questions it was charged to address.

> *Charge Question 1: What are the key studies and synthesis reports that the State Water Board should rely on in making their decisions on interior Delta flow requirements? Please comment on the strength, relevance and level of certainty of the science presented and reviewed*.

The Panel reviewed only a small fraction of the literature relating to Delta interior flows, making it difficult for us to say which are the key studies and synthesis reports. However, in all of the assigned reading and panel presentations, we saw few, solid, quantitative estimates of effects. The Panel was concerned that little experimentally validated quantitative guidance on flow management was available to the Board. We provide a set of criteria for identifying the most useful science on which to base updated flow standards. In particular, we suggest the Board look favorably on synthesis papers that have the following characteristics:

1. Hypotheses established *a priori*, not developed after the fact;
2. Parameter estimates (i.e., effect estimates) with uncertainty bounds are reported rather than simply significant P values; and
3. Models that are not overfit; the ratio of independent observations to the number of fitted parameters is at least 10.

The vast majority of inferences about the effects of flows in the Delta on listed species are based on correlation analyses. Although correlation analysis is a useful first step when searching for relationships among variables, it often tells little about cause and effect. Correlation analyses need to be followed up with carefully designed experiments to test any hypothesized causal relationships, and with numerical and simulation modeling to explore the likely effect of management manipulations.

> *Charge Question 2: Interior Delta flows have been altered in many ways, including timing, magnitude, variability, and in some cases, net direction. What are the relationships between these altered interior Delta flows and native fish survival, abundance, spatial distribution, migration, and life history diversity?*

The pre-1900 Delta with its dendritic network of marsh channels and large floodplain like storage at high tide must have been much more dissipative for tides, more depositional for river-borne sediments, and perhaps fresher than the present day network of trapezoidal channels with virtually no tidal wetting and drying, greatly increased tidal flows, and little sediment deposition. The impacts of the changes in Delta geometry on native fishes must have been profound as we can assume that native fishes were adapted to the habitats and flows that existed prior to this transformation.

Fish in the Delta are subject to a large number of stressors and untangling the independent effects of these stressors has proven very difficult. Population modeling and other analyses indicate that declines in native fish species are a consequence of a number of interacting factors so that there is no simple fix for ensuring population viability. Indeed, some factors are so poorly understood (e.g., toxic chemicals and their breakdown products) that it is not possible to determine if they are having an effect. Among the many stressors, the effects of interior Delta flows can only be approximated.

The decoupling of flow from variation in habitat type and area means that species that routinely accessed flooded marsh or floodplain habitats on tidal and seasonal cycles for feeding or breeding (e.g., salmon, smelt, Sacramento splittail) experienced a dramatic reduction in available habitat.

The seasonal migration of the Low Salinity Zone (LSZ) has been curtailed as the seasonal hydrograph has been flattened by river regulation and water operations have been designed to hold X2 in Suisun Bay as much as possible.

> *Charge Question 2a) What important environmental cues for native fish are affected by altered flows? Please comment on the timing and time scales of these effects, and the species and life stages affected.*

Fish perceive their environment through a variety of sensory systems including taste, olfaction, vision, hearing, magnetic sense and the lateral line system. These senses provide the fish with a fairly detailed picture of their immediate surroundings and some information on conditions further afield (through chemical signals carried on the current or vibrational signals propagated through the water). How fish respond to their surroundings depends on their motivation, their movement capabilities and their repertoir of behaviors.

Although the sensory abilities of fish are frequently different than those of humans (many fish, for example, can detect radiation into the ultra-violet or near infrared), a number of environmental variables that are routinely monitored in the Delta are variables that the fish cannot directly detect. For example, fish do not detect "flow" but the velocity and turbulence associated with flow. Many of the monitored variables are composite variables (made up of several component variables) and when such variables are correlated with measured responses of fish, one cannot know with confidence to which of the component variables the fish is reacting. Turbidity is a good example, being a composite of organic and inorganic particles of various types and sizes to which fish may respond differently.

Larval and juvenile fishes often migrate by drifting with the flow. Altered flow velocity and altered patterns of flow (e.g., southward direction of Sacramento River water toward the export pumps) can effect migration patterns. For example, when flow is high in the main channel of the Sacramento River relative to the Delta Cross Channel (DCC), few salmon smolts are entrained into the DCC but the number entrained increases as the ratio of flow in the main channel to that in the DCC declines. The position of fish in the channel is also important to their likelihood of entrainment. This suggests that fish survival could be improved by managing flow differentials and perhaps by using structural modifications to keep fish away from the entrance to secondary channels.

At night, Chinook salmon (*Oncorhynchus tshawytscha*) in the Delta tend to move away from shore where, lacking visual and tactile clues to their position, they probably drift with the current. In the historic Delta, with many blind ending tidal channels and reduced tidal velocities, fry might not be carried very far by tidal ebb and flow at night. However, in the modern Delta, with open trapezoidal channels and high velocity tidal flows, fry could be carried large distances at night and potentially to habitats that were not favorable nurseries.

Salmon smolts migrating seaward in the more riverine Delta appear to travel with the flow, primarily at night. In the tidal Delta, however, they move more during the day and likely depend on chemical clues to determine the direction of the sea. Reversal of flow in Old and Middle River (OMR) may be confusing in that the clues to the direction of the sea are disrupted and fish may simply go with the flow assuming it is carrying them toward the sea and thereby become entrained into Clifton Court Forebay.

San Joaquin River steelhead (*Oncorhynchus mykiss)* smolts, which are considerably larger than Chinook salmon smolts, migrate seaward mainly along the San Joaquin River corridor but some move into the southern Delta. Like Chinook salmon, steelhead in the southern Delta suffer higher mortality than those that stay in the San Joaquin River corridor, although overall survival of steelhead is much higher than survival of Chinook salmon. Although the migration routes of steelhead do not appear to be affected by OMR reverse flows, steelhead migrations are less well studied than those of Chinook salmon. Further work on steelhead smolts with acoustic tags would clarify migration routes and threats to survival under different flow scenarios. Movement of tagged individuals suggests that steelhead smolts use selective tidal transport during their seaward migration through the Delta but this needs to be confirmed.

Adult salmon can be cued to migrate upstream by pulse flows associated with storms. Capture of storm runoff in reservoirs can eliminate the pulse flow associated with all but the most severe storms, thus interfering with migratory cues. Straying of San Joaquin River salmon into the Sacramento River is negatively correlated with pulse flow but weakly positively correlated with exports suggesting that the joint effect of pulse flow and exports is important.

Odor clues help returning adult salmon find their appropriate home river. Redirection of river waters through the Delta and greatly reduced inflows from the San Joaquin River could confuse returning adult spawners.

Unnatural concentrations of substances such as copper and of toxic substances can affect salmons' ability to detect and respond to odors and may have other sublethal effects as well.

The development of acoustic tags small enough to implant in salmon smolts has provided invaluable detail on the migratory behavior of these fish. To date, however, the tags have only been used on the larger late fall run yearling Chinook salmon smolts and steelhead. The behavior of other runs and other sizes of Chinook salmon may well differ from that of late-fall run yearling smolts. Further experimentation is needed with all the runs of Chinook salmon to determine if similar strategies will work for all.

Combining acoustic tagging with detailed modeling of flow fields at channel junctions holds promise of clarifying the conditions that lead to entrainment into the central and southern Delta. The Panel recommends continued use of this technology and also more emphasis on studies that combine computational fluid dynamics models with realistic fish behavior to explore how changing inflows, tidal flows, exports and other drivers of internal Delta flows are likely to influence migration routes and timing of salmon and other species. Fine scale investigations of flow fields and fish behavior at specific junctions coupled with emerging technology for managing those flow fields may provide the means to maximize migration along routes that have higher survival for salmonids.

The primary habitat of Delta smelt is the LSZ, generally just upstream from the 2 PSU isohaline and in turbid water where Secchi depth is < 40 cm. Smelt are weak swimmers yet still undertake a winter dispersal upstream to low salinity habitats for spawning in spring and juveniles are able to congregate in the LSZ by early summer. Larvae and juveniles are very vulnerable to advection and many are entrained into the export facilities. Thus, interior Delta flows are particularly important for Delta smelt. Turbidity is also an important habitat variable for Delta smelt. Turbidity is declining in the Delta, placing Delta smelt at greater risk of predation.

Entrainment into the export facilities has the potential to affect population abundance of Delta smelt, but high natural variability in smelt abundance has made it difficult to detect any effect of entrainment on the population. Our understanding of the relationship between interior flows and Delta smelt populations would benefit from a combination of controlled experimentation and improved models capable of exploring the multiplicity of hypotheses that have emerged from analyses of historic data. Better understanding of the factors affecting Delta smelt movements in the Delta as larvae, juveniles and adults could indicate ways that flow fields could be managed to improve survival.

A clearer understanding of whether and how fish species use selective tidal transport in the Delta would also help with the design of any program to manage flow fields. Evidence for this behavior is not strong for any of the species.

> *Charge Question 2b) What are the effects of altered interior Delta flows on other parts of the ecosystem such as phytoplankton, zooplankton, and benthos? Please comment on the timing and time scales of these effects and the functional groups affected.*

<u>In principle</u>, modifications to interior Delta flows by export pumping or gate operations should affect net primary production. However, to the best of our knowledge this has not

been demonstrated by any extant modeling or field programs. Any effects of Delta flows on secondary production are similarly unexamined.

Microcystis appears to be increasing in the Delta, although it is still relatively rare. *Microcystis* may be more abundant in shallow, dead end, channels, but these are relatively rare in the Delta and have not been studied in detail. There may be a connection between water project operations and *Microcystis* since growth rates for *Microcystis* increase exponentially with temperature, which may be influenced by the strength and spatial structure of in-Delta flows. Over the long term, summer air temperatures probably play a greater role in determining Delta temperatures than interior flows.

The conclusion that emerges concerning the effects of interior Delta flows on primary and secondary production as well as on Harmful Algal Blooms is that, while in principle such effects should exist, there is no firm evidence that they do exist. The only connection between water project operations and food webs that can be made with any confidence is that diversions reduce the export of phytoplankton-derived Particulate Organic Material (POM) from the Delta to Suisun Bay.

> *Charge Question 3: How do non-flow stressors such as predation, physical habitat, fisheries management, and water quality interact with interior Delta flows to affect the issues discussed in Question 2? How have the landscape and ecosystem scale changes of the last 100+ years altered these interactions and the functions provided by flows?*

Several studies based on mass balance have shown that a significant fraction of the POM produced within the Delta can be lost to export rather than carried to Suisun Bay. Furthermore, since water project operations can route all of the organic matter produced in the San Joaquin River into the export pumps, exports can have a more significant effect on the supply of POM to Suisun Bay than would be expected from a simple mass balance calculation.

Patterns of flow in the Delta appear to have affected the success of exotic species. The successful invasions of exotic zooplankton and mysids all occurred during drought periods when a 3-year moving average of monthly X2 values was greater than 75. Therefore, management of interior Delta flows will be important during drought years to minimize the risk of further problematic invasions to the Delta.

> *Charge Question 4: What metrics of interior Delta flows (such as OMR and QWEST flows, and export-inflow ratios) are most useful to assess, predict and manage impacts to fish and the ecosystem?*
>
> > *Charge Question 4a) Do these remain important metrics, or are there better metrics that could be used?*

Metrics such as OMR and QWEST are tidally averaged flows and present a view of the Delta in which materials and organisms are moved as if in a river either out to Suisun Bay or to the pumps. However, interior Delta flow fields are primarily reflective of tidal flows, not net flows. Because of the interaction of tidal currents with the complex geometry of the Delta, dispersive transport by tides can significantly alter the picture presented by tidally averaged flows. For example, the Panel was shown model results of passive particles being transported to the pumps from places where mean flows would suggest transport to the Bay.

Numerical modeling of interior Delta flows suggests that when exports are high and San Joaquin River flows are low (conditions that give rise to large, negative values of OMR), passive particles from much of the Delta other than the Sacramento River itself are drawn into the export facilities. By contrast, when exports are small, the region of the Delta from which particles are entrained to the pumps is confined to a small area in the immediate vicinity of the export facilities. OMR flows may provide a useful index of entrainment.

> *Charge Question 4 b) For each metric, explain if the metric is useful to improve survival, abundance, spatial distribution and/or life history diversity.*

Numerical modeling combined with particle tracking can provide a reasonable estimate of entrainment of relatively passive organisms such as plankton or Delta smelt larvae. Accordingly, it appears that regulations based on OMR flow will have some value in limiting entrainment of Delta smelt larvae and perhaps juveniles. Juvenile salmon should be much less vulnerable to such passive entrainment although negative flows in OMR may provide confusing signals to migrating salmon (e.g., if they are attempting to use selective tidal transport to move toward the Bay) so that they also are drawn toward the pumps.

The Zone of Entrainment (i.e., region of the Delta where passive particles are most likely to be carried to the export facilities) can include most of the Delta south of the Sacramento River when San Joaquin River inflows are low and exports are high, but can be confined to a small area around the pumping stations when exports low. Thus, OMR may provide a useful index of entrainment risk.

> *Charge Question 5: What changes to interior Delta flows or other stressors would be most effective for improving survival, abundance, spatial distribution, and/or life history diversity of native fish and the ecosystem?*

Water management must consider the hydrograph over the entire year. Peak spring flows, access to floodplains and sufficient flows in the summer and fall are important for creating conditions that encourage the success of native fish species. Maintaining temperatures cool enough in the summer, trying to maintain higher turbidity, consideration of the availability of floodplain and other habitats and using extra caution during drought periods would also benefit native species. Actions that discourage the success of possible new invasive species and control the degree of success of existing invasive species would be prudent. How internal Delta flows affect the transport of energy (organic carbon, chlorophyll) to the LSZ needs further investigation.

As listed species have declined considerable effort has been expended to identify the causes and to “lay blame”. However, it is now generally agreed that population declines are a result of multiple stressors. Any attempt to rank stressors according to the severity of their effects assumes a great deal of separability among the stressors, which is usually not the case. Stressors may exert direct or indirect effects and may covary with other indirect or direct stressors, further complicating any attempt to identify the stressor that has the greatest effect on the individual or the population. Even if a ranking of stressor importance was possible, the ranking could change with changes in the ecosystem.

> *Charge Question 5a) Do the existing studies and analyses support threshold levels of specific interior Delta flows for protection of native fish species or other elements of the ecosystem?*

Considerable debate has focused on whether there is a threshold value for negative flows in OMR below which entrainment of Delta smelt is negligible. Statistical models have also suggested step changes (threshold change) in fish abundance during the 1980s and since 2000, suggesting a threshold response to some (unknown) environmental variable. Statistical models provide a set of tools for identifying possible threshold responses. However, the use of statistically-identified thresholds to establish flow criteria faces two major challenges. First, the location and very existence of an estimated threshold can depend critically on the statistical model used, as well as on the abundance of data near the purported threshold. Second, even if a threshold exists in a fish vs. flow relationship (or other ecologically relevant relationship), that threshold may not be useful for management.

> *Charge Question 5b) How could an adaptive management program be structured to improve understanding and management of the effects of interior Delta flows on native fish and the ecosystem? What are the key scientific uncertainties amenable to improved understanding through adaptive management experiments?*

Adaptive management is a powerful tool for assessing the consequences of management actions and at the same time learning about the system being managed. Properly designed adaptive management can help reduce uncertainty in the behavior of the managed system. For adaptive management to be successful, however, managers must have a great deal of control over the drivers of the system, and the value of the information that managers expect to obtain from the experiment should justify the cost. Thus, not all management problems are suitable for adaptive management. The manager needs to draw on a variety of tools in designing a program to address any complex management issue.

Adaptive management is one possible component of a larger programmatic science plan. Such a program typically consists of three parts: 1) a set of challenging science/management questions that are stated clearly enough to provide a template for designing specific investigations; 2) a process for taking data and information from individual investigations and transforming them into knowledge useful for management; and 3) procedures for minimizing knowledge leakage by encouraging data sharing and open communication. Programmatic science needs to conform to criteria of excellence that go beyond those used to judge the value of a single scientific study.

In the Bay-Delta, adaptive management has been implemented as a form of partnership between management (which includes monitoring to ensure that management goals are being met) and targeted research to address critical uncertainties. This approach has the advantage that targeted research may be the most efficient way to address uncertainties in highly complex ecological systems. It has the disadvantage, however, that the management action itself may not be designed to provide any useful information about the system. This is especially likely if the critical modeling phase of adaptive management is left out.

Large-scale management problems are "wicked" in that they defy specific and unique definition and therefore tend to become defined in relation to the management actions taken. Such problems also tend to evolve in response to management in that any significant management action initiates a cascading set of consequences that can change the nature of the problem, generate new uncertainties and necessitate new management interventions.

Wicked problems should be amenable to adaptive experimentation, however, much depends on whether inputs (e.g., interior Delta flows) can be manipulated to provide enough contrast to ensure a measurable result. Appropriate modeling should demonstrate whether a sufficient contrast can be created. If not, other approaches to addressing uncertainty may be more fruitful.

Introduction

On April 16 and 17, 2014, the Delta Science Program convened an expert Panel (the Panel) and a workshop to identify the best available science to inform the State Water Resources Control Board's (the Board) decisions regarding interior Delta flow requirements to protect beneficial uses of water in the San Francisco Bay/Sacramento-San Joaquin Estuary (Bay-Delta Plan). This workshop and others were convened to provide advice to the Board on issues important to updating the 2006 Bay Delta Plan. At the workshop, the Panel (consisting of the authors of this report) heard presentations from a variety of experts on Delta flows and on species and ecological responses to flow. The Panel was also provided with a selection of scientific reports relevant to the effects of interior Delta flows on fish and their environment in the Delta. This report is informed by both the written and oral information provided to the Panel as well as by other publications that the Panel felt were necessary to satisfy its charge. The Panel did not make a thorough independent search of the literature on the Sacramento-San Joaquin Delta to determine if there were additional publications that were relevant to its charge. In this report we summarize what is known about the direct and indirect relationships between interior Delta flows and listed fish species. We then use this knowledge to address a set of specific questions posed by the Delta Science Program and the Board.

The Panel was charged with addressing these five questions:

1) What are the key studies and synthesis reports that the State Water Board should rely on in making their decisions on interior Delta flow requirements? Please comment on the strength, relevance and level of certainty of the science presented and reviewed.

2) Interior Delta flows have been altered in many ways, including timing, magnitude, variability, and in some cases, net direction. What are the relationships between these altered interior Delta flows and native fish survival, abundance, spatial distribution, migration, and life history diversity?
   a) What important environmental cues for native fish are affected by altered flows? Please comment on the timing and time scales of these effects, and the species and life stages affected.
   b) What are the effects of altered interior Delta flows on other parts of the ecosystem such as phytoplankton, zooplankton, and benthos? Please comment on the timing and time scales of these effects and the functional groups affected.

3) How do non-flow stressors such as predation, physical habitat, fisheries management, and water quality interact with interior Delta flows to affect the issues discussed in Question 2? How have the landscape and ecosystem scale changes of the last 100+ years altered these interactions and the functions provided by flows?

4) What metrics of interior Delta flows (such as OMR and QWEST flows, and export-inflow ratios) are most useful to assess, predict and manage impacts to fish and the ecosystem?
   a) Do these remain important metrics, or are there better metrics that could be used?

b) For each metric, explain if the metric is useful to improve survival, abundance, spatial distribution and/or life history diversity

5) What changes to interior Delta flows or other stressors would be most effective for improving survival, abundance, spatial distribution, and/or life history diversity of native fish and the ecosystem?
   a) Do the existing studies and analyses support threshold levels of specific interior Delta flows for protection of native fish species or other elements of the ecosystem?
   b) How could an adaptive management program be structured to improve understanding and management of the effects of interior Delta flows on native fish and the ecosystem? What are the key scientific uncertainties amenable to improved understanding through adaptive management experiments?

Many elements of the charge questions were previously dealt with in the two National Research Council (NRC) reports examining the National Marine Fisheries Service's and U.S. Fish and Wildlife Service's Biological Opinions and water management in the Delta (Huggett et al. 2010, 2012). Partly to avoid covering old ground, and as a complement to the previous reports, the Panel chose to approach the charge questions through analysis of ten critical topics that emerged from our discussion of the materials we were provided. Ways to identify key studies and synthesis reports that will be most useful to the Board were identified in the course of these analyses. The topics and their relationship to the charge questions are summarized in Table 1. We will return to the specific charge questions in our concluding remarks.

We begin with a general overview of the most relevant information that we gleaned from the oral presentations and written documents and then proceed to a discussion of the topics in Table 1 in relation to interior Delta flows and conservation of Delta fishes and ecosystems.

Table 1: Discussion topics and relation to charge questions.

Topic	Relation to Charge Questions
Quality of science, statistics and the interpretation of flow data.	Relates to the identification of key papers, interpretation of correlations between flow and fish metrics, and setting of flow thresholds for management (charge questions 1, 2, 4, and 5)
Flow regimes and Delta geometry and hydrology	Relates to the interrelationship between flow fields and Delta geometry and its effects on fish distribution and entrainment (charge questions 2b, 3, 5b)
Flow regimes and turbidity	Relates to the relationship between flow regimes and an important habitat metric (charge questions 2a, 2b, 3, 4a, 4b)
Flow regimes and flow metrics	Relates to how best to characterize the flow regime for management purposes (charge questions 2a, 4a, 4b)
Flow regimes and primary and secondary production	Relates to the importance of flows to the base of the food web (charge question 2b)
Flow fields and fish behavior, cues and clues.	Relates to the interrelation of fish and flow that lead to distribution, abundance, and entrainment (charge questions 2a, 4, 5a)
Flow regimes, invasive species and food webs	Relates to the indirect effects of flow regimes coupled with another stressor on native species (charge questions 2b and 3)
Flow regimes, entrainment and salvage	Relates to the population level impact of flow regimes and exports. (charge questions 2b, 4a, 4b, 5a)
Flow regimes and population dynamics	Relates to population level effects of entrainment, export, and other stressors (charge questions 3, 5a)
Flow regimes, programatic science and adaptive management	Relates to the tools available for understanding and reducing uncertainty in the use of flow thresholds (charge questions 4a, 4b, 5a, 5b)

Emphasis in the oral presentations and documents the Panel was asked to review was understandably on listed fish species (Delta smelt, steelhead, and winter and spring run Chinook salmon). However, other fish species (e.g., striped bass, largemouth bass, threadfin shad, splittail, and others) also make extensive use of the Delta and are almost certainly affected by interior Delta flows (e.g., Grimaldo et al. 2009, MacNally et al. 2010). An additional listed species (green sturgeon) also resides in the Delta and passes through it when migrating to and from freshwater spawning and nursery areas and is likely affected by interior Delta flows. Unfortunately, there is limited information on the green sturgeon, making conservation actions extremely difficult. In its Biological Opinion, the National Marine Fisheries Service made the assumption that conservation measures to benefit salmon would also benefit green sturgeon, but this is by no means certain given the substantially different life histories of the species. Drawing from the material we were provided, this report is focused on salmonids and Delta smelt, but it should not be forgotten that alterations to interior Delta flows will likely affect other species both positively and negatively. Actions to assist salmonids or Delta smelt, therefore, may have unexpected and unexplored consequences for other species. Those responsible for managing interior Delta flows obviously recognize this, but it is not clear that there is a mechanism for addressing multispecies trade-offs or, for that matter, multiple water use conflicts and trade-offs. The NRC (Huggett et al. 2010, 2012) discussed this issue at some length and argued for a more integrated, model based, approach to water management planning. We concur with the NRC's recommendations and later in the report we also argue that programmatic science needs a proper organizing template.

Although many unknowns and uncertainties remain, research on the Delta and its fishes over the past decades indicates the following relationships between human activity in and outside the Delta, interior Delta flows, fish distribution, and survival:

1. Interior Delta flows have been dramatically altered over the past century and a half through a combination of impoundments and diversions in the two major river systems, water withdrawals from the Delta, changes in land use and landforms in and around the Delta, and changes in Delta geometry.

2. Outside of major flood events, hydrodynamics in the Delta are driven primarily by tides and only secondarily by freshwater inflows. Export pumping also drives circulation patterns in the southern Delta, in particular creating substantial flows toward the export facilities in Old and Middle Rivers when large volumes are being exported. The multiple drivers of internal flows result in very complex patterns of internal water movement that change on time scales from minutes, to hours, to weeks to months (Kimmerer 2004).

3. The dispersal of plankton and larval fish (such as larval Delta smelt) may sometimes be adequately approximated by assuming passive drift in the flow field (see e.g., Kimmerer and Nobriga 2008). But as fish grow and their swimming capability improves they can adopt a number of tactics for controlling their advection, although their degree of control is relative to velocities in the flow field (Bennett et al. 2002, Liao 2007, Goodwin et al. 2014). Predicting how fish of different species, sizes and life history stages will respond to changes in Delta internal flows is, therefore, complex.

4. Juvenile salmonids that are attracted or entrained into the central and southern Delta experience low survival (e.g., Perry et al. 2010, 2013; Newman and Brandes 2010; Delaney et al. 2014). Juvenile Chinook salmon migrating seaward in the San Joaquin River

have experienced particularly low survival in recent years, regardless of their route through the Delta (Brandes, oral presentation to the Panel). Predation is presumed to be the proximate cause of this mortality although other causes cannot be eliminated and predation itself can be a consequence of other ecosystem changes that increase a species' vulnerability, such as reduced turbidity.

5. Juvenile salmon are entrained into the export facilities as evidenced by the substantial numbers that are recovered at fish salvage facilities associated with the export pumps (more than 51,000 in an average year according to Rosenfeld, oral presentation). Kimmerer (2008) showed that the proportion of Chinook salmon smolts released in the upper Sacramento River that were captured at the fish salvage facilities increased with increasing export flows. Newman and Brandes (2010), however, found only a weak relationship between water exports and the numbers of marked juvenile Chinook salmon released in Georgiana Slough that were salvaged at the export pumps. The relationship between water exports and juvenile salmon entrainment remains uncertain. In the future, the relationship should be studied using the newest generation of 2- and 3-D computational fluid dynamics models that have recently become available for the Delta.

6. There is a positive relationship between flow in the San Joaquin River at Vernalis and the survival of Chinook smolts to Jersey Point and adult returns 2.5 years later (Brandes, oral presentation, Herbold, oral presentation). Similarly, survival of Sacramento River Chinook salmon through the Delta is higher when flows in the Sacramento River are higher (Brandes and McLain 2001). The causal mechanism underlying these relationships is unclear.

7. Delta smelt are most vulnerable to entrainment into the export facilities during winter, when adults enter freshwater to breed, and spring, before larvae and juveniles move seaward into the low salinity zone of the estuary.

8. Salvage of Delta smelt is high when flow in Old and Middle Rivers is toward the export pumps and low when flow in Old and Middle Rivers is seaward (Kimmerer 2008, Grimaldo et al. 2009). Salvage of Delta smelt increases as negative flows in OMR increase and is also higher when turbidity in the southern Delta is higher. Because Delta smelt are weak swimmers and are attracted to turbid waters these relationships probably reflect a combination of smelt distribution and vulnerability to entrainment. Greater salvage may also reflect lower predation mortality of smelt in turbid water.

9. As it was with salmon, it is difficult to assess the contribution of altered internal flows to population viability of Delta smelt. However, Kimmerer (2008) estimated that entrainment to the export facilities imposed a relatively high proportional mortality on both adult and larval Delta smelt in certain years. Thomson et al. (2010) estimated that an increase in exports by about 0.62 km^3 would result in a 22% decline in Delta smelt. As suggested for juvenile salmon, future studies of Delta smelt entrainment should incorporate the newest generation of 2- and 3-D computational fluid dynamics models that have become recently available for the Delta.

10. The data linking OMR reverse flows to Delta smelt salvage are variable and do not clearly demonstrate any threshold of flow at which salvage increases.

11. The Delta has experienced multiple invasions by exotic species that have dramatically altered the food chain supporting native species. Whether these changes have been influenced by Delta interior flows is unclear although there is evidence that invasion of some species has been facilitated by low outflow during prolonged droughts.

12. The transformation of the Delta from a seasonally and tidally inundated marsh to a patchwork of leveed islands separated by trapezoidal channels has effectively decoupled habitat area and type from flow so that variations in internal flows that would have given fish access to productive marsh habitat no longer serve that function.

Many uncertainties remain, but the evidence strongly suggests important relationships between interior Delta flows and the distribution and survival of juvenile salmon and Delta smelt. Clarifying and quantifying these relationships so that they provide a solid foundation for management decisions remains a challenge.

Quality of Science, Statistics and the Interpretation of Flow Data

The statements above are derived from science conducted in the Delta and interpreted with the help of statistical models (and sometimes numerical and simulation models) and reference to research results from analagous situations elsewhere. Management strategies and actions are based on this science and their effectiveness depends to a significant degree on the quality of the science. A key question, therefore, is 'How does one assess the quality of science'? Rarely, if ever, will a single study provide sufficient insight for development of a management or conservation strategy. Management of natural resources in the Delta, the Chesapeake Bay, the Hudson River and other systems that support multiple human use, typically relies on results from research programs that span large scales, both temporally and spatially and that are comprised of many individual scientific studies. In addition, particularly where hydrodynamics and other physical properties of the system are involved, numerical modeling plays an important role. Numerical and simulation modeling are also becoming standard tools for examining ecological processes (Schmolke et al. 2010). In combination with other types of models, numerical and simulation models are powerful tools for exploring the impact of proposed management programs (Laniak et al. 2013). Here, we begin by exploring criteria for evaluating the quality of single scientific studies and then move to a brief consideration of criteria for effective ecological models. Criteria for evaluation of research programs will be discussed later, as will adaptive management as a tool for reducing uncertainty.

What is the best scientific information?

Ideally, management policies and actions would be based on a firm scientific understanding of the dynamics of the ecosystem and its constituent species and on how the ecosystem will respond to management. In reality, management policies and actions must be decided with imperfect information. Decision-making that is based on limited scientific information is open to uncertainty (Sullivan et al. 2006). When scientific information is limited, it is imperative to seek out and consider the highest quality information available. Since science is always incomplete it is also important to apply decision analytic tools and to consider decisions in a risk management context. In this section we describe the characteristics of high-quality science and provide recommendations to the Board for assessing the quality of science pertaining to the Delta ecosystem and the Bay-Delta Plan. Much of this section derives from the material prepared by Sullivan et al. (2006). The use of decision analytic tools will not be addressed in this report, but they provide an important adjunct to management decision-making under uncertainty.

The elements of the scientific method

Careful, meticulous observation, continual confrontation, and self-reflection are hallmarks of science (Sullivan et al. 2006). The process used to produce high-quality science is the scientific method, which requires the following: 1) a clear statement of objectives; 2) a conceptual model or hypotheses about system function; 3) a rigorous experimental design; 4) standardized data collection methods; 5) appropriate and rigorous statistical and logical analysis and interpretation; and 6) clear documentation of the methods, results, and conclusions of the study (Sullivan et al. 2006). High-quality science is marked by full adherence to each of these elements and is best judged by independent peer reviewers. Table 2 elaborates on each of these elements and suggests criteria for evaluating the quality of single scientific studies. In addition, Appendix C from the Delta Plan provides a good description of 'Best Available Science' with special reference to the Bay-Delta ecosystem (Delta Stewardship Council 2013).

Carefully controlled and replicated experiments can provide reliable scientific knowledge. Large, complex systems such as the Bay-Delta, however, are not amenable to classical reductive experimentation in which a single factor is manipulated in replicate tests while all other factors are held constant. Replicate testing is impossible in the Delta because the system is unique and cannot be replicated. For such systems, scientists typically use observations from multiple years and multiple locations to examine the association between two factors, assuming that on average, all other conditions remain the same or similar or by developing models that can cope with variation in a number of factors. But the assumption of constant background conditions is likely untenable when ecosystems are changing due to climate effects, invasive species, and habitat alterations, as they are in the Delta. Because of the difficulty in conducting controlled experiments at the ecosystem level, it is generally accepted that knowledge of ecological effects in large systems can be amassed using an alternative weight-of-evidence approach that considers information from multiple investigative and interpretive studies. Such approaches are invariably subject to greater uncertainty than classical reductive experimentation.

The physical components of biophysical systems like the Delta can be modeled quite precisely with modern computational fluid dynamics. This is important because it allows for the possibility of modeling the complex and highly variable biological components of the system in the context of a dynamic but well described physical environment. For example, movements of juvenile salmon in tidal channels could be modeled as particles having particular behavioral responses to attributes of the velocity field that might vary according to tide stage or time of day. Such models could easily be tested using real fish carrying acoustic tags. A successful model developed for one part of the system could then, presumably be applied to other parts with some additional validating studies if necessary. Criteria for assessing such models are presented in Table 3.

Table 2. Criteria to judge the quality of individual scientific investigations at each stage in the scientific process (the process elements are from Sullivan et al. 2006). The evaluation criteria presented here are consistent with those in the Delta Plan (Delta Stewardship Council 2013), namely: relevance, inclusiveness, objectivity and transparency**.**

Scientific Process Element	Evaluation Criteria
Statement of objectives	Are the objectives relevant? Do the objectives give rise to the conceptual design in a logical manner?
Conceptual model	Does the model reflect current scientific understanding as revealed by a thorough review of the relevant information and analyses? What are the inputs, outputs and assumptions? If hypotheses are constructed, are they testable? If predictions are desired, how are predictions made? What are the sources of uncertainty?
Experimental design	Does the design allow testing of the hypotheses or characterization of the system? Are the assumptions of the design reasonable? Is the design properly implemented?
Standardized method of data collection	Are standard methods used? If new methods are developed, are they well described and calibrated? How is the quality of the data assessed?
Statistical rigor – analysis	Are sample sizes provided? Are 'treatments' replicated and properly randomized? Is the experimental design properly implemented (e.g., no pseudoreplication, models contain necessary rate functions)? How are outliers handled? How was correct estimation ensured? Are relevant, contemporary analytical methods used? Are statistical assumptions addressed (e.g., collinearity, autocorrelations, multiple comparisons, carry-over effects)? For modeling studies, are fixed rates or constants in the model reasonable? Are functional relationships plausible?
Statistical rigor – interpretation	Are interpretations plausible? (e.g., is there sufficient contrast in the data to reasonably detect an effect?) Are effect magnitudes presented? Are statistical significance and biological significance adequately addressed? Are interpretations made with reference to uncertainty? Are interpretations made in light of assumptions and limitations of the methods? Are the inferences valid given what is known ecologically? Are the results interpreted with the proper caveats? Are the results void of nonscientific influences and considerations?
Documentation of methods, results and conclusions	Are the methods adequately described so that the study is repeatable? Are the sources of uncertainty fully documented and discussed (e.g., uncertainty due to variability in parameter estimates vs. uncertainty due to incomplete knowledge of functional relationships)? Are the results unambiguous? Are the conclusions fully supported by the data? Do the findings represent a significant advance in scientific knowledge?
Peer review	Was the study reviewed by appropriate peers (fair, unbiased and knowledgeable) in a formal peer-review process? Are the peer reviewers independent such that there is no conflict of interest?

Statistical Inference and Modeling

The Charge to the Panel highlighted the Board's need to identify relationships between interior flow attributes (magnitude, timing, variability, pathways) and native fish endpoints (e.g., survival, entrainment in pumping facilities, abundance, migration). As described above, these relationships should be based on the best available science, as synthesized in key reports and studies. Question 4 of the Charge spells out the Board's need for flow metrics that can help "assess, predict and manage" the impacts of altered flows on fish and on the ecosystem. In addition, the Board would like to derive reliable flow-metric thresholds that could trigger management actions. For these reasons, our discussion of modeling and statistics is focused on estimating and predicting the quantitative effects of interior flows on fish and ecosystem endpoints such as the survival, abundance, spatial distribution, and migration of fish.

Oral presentations at the workshop offered numerous relationships between flow metrics and fish endpoints in the form of scatterplots, regressions, and correlations as well as conclusions from more complex models (e.g., MacNally et al. 2010, Thomson et al. 2010, Maunder and Deriso 2011). Some of the relationships presented had little or no statistical validity while others had rigorously quantified uncertainties. Two of the oral presentations (Hanson et al., and Rosenfield) expressed opposing conclusions about the general effects of flow on fish, based on relationships from many of the same studies. Modeled relationships were presented for various fish endpoints (abundance, entrainment, salvage, survival), for multiple life stages and species, for various flow metrics (OMR flow, exports, etc.), for various time periods and for various data sets, with and without covariates. We can only imagine the difficulty of trying to base management actions on such a large and disparate collection of relationships. In addition, the Panel was concerned that little experimentally validated quantitative guidance on flow management was available to the Board. The Panel feels that the Board badly needs a coherent, quantitative process for synthesizing the information from all of these relationships. In what follows we offer some criteria for assessing the value of modeled relationships as presented in the technical literature on the Delta. However, meeting the needs of the Board for quantitative guidance will necessitate a shift from correlation analysis of available time series to carefully designed experiments to explore and validate the results of the correlation analyses.

Modeled relationships are of greatest value to management if: 1) they are based on data obtained from sound sampling or experimental designs; 2) they are derived from clearly-stated, tolerably-realistic assumptions; 3) they have estimable, quantitative uncertainties; and 4) they predict the effects of flow variables that can be directly and quantitatively altered by management (see earlier discussion of quality of science). Unfortunately, the Panel did not have time systematically to assess these four features for the numerous relationships contained in workshop presentations and in our reading lists. The Panel recommends, therefore, that the Board commission an independent study to synthesize and evaluate the estimated effects of flow metrics on fish endpoints. By "effect," we mean the magnitude and direction of a model-predicted change in a fish endpoint that is due to a specified numeric change in a flow metric acting as a model predictor variable, either alone or in conjunction with other predictors. The word "predicted" is important; even though a regression-type model may not represent a direct, causal linkage between flow and fish, its predicted outcomes for management actions (i.e., flow alterations) may have less uncertainty than those obtained from complex models of realistic, causal processes (Beck 1987, Ludwig 1994). The most effective approach is to use a combination of regression-type analyses with more complex modeling that does attempt to address the causes underlying the specific model predictions. Our suggested study would focus on modeled "effects" because they directly predict a numeric outcome for fish from a flow-management action. As an example, Thomson et al.'s (2010) model predicted that an increase of 0.62 km^3 in winter exports would be associated with a 22% decline in abundance of Delta smelt. Manipulation of exports to test this prediciton may be difficult, even impossible, but careful evaluation of the linkages between exports and Delta smelt population dynamics might identify indirect or alternative ways to validate the prediction. Furthermore, application of improved computational fluid dynamics modeling coupled with particle tracking could help clarify the range of conditions under which exports would seriously affect Delta smelt abundance.

We recommend that the independent study review the published effects of Delta flow metrics on Delta fish, and assess their reliability by evaluating the data source(s), model assumptions, predictive uncertainty, and management utility. As an example of predictive uncertainty, Thomson et al. (2010) give a 95% posterior interval of -45% to +9% for their effect estimate of -22% change in Delta smelt abundance if exports were increased 0.62 km^3. Other estimates of flow effects and their uncertainties are given by Newman and Brandes (2010).

The study we recommend should be highly structured, perhaps as a formal meta-analysis, with a sharp focus on estimating the quantitative flow effects of direct utility to management. Such an analysis would need to be life-stage and temporally-explicit as the effects of flow variables on different life stages vary during the year (Delta smelt and longfin smelt; Grimaldo et al. 2009). Additionally, effects of flow in wet and dry years may yield different outcomes, because some species may exhibit different vulnerabilities to alterations in flow depending on drought conditions (Rosenfield 2010). In contrast, the Board's 2010 flow criteria document (SWRCB 2010) sketches many modeled relationships between flow and fish, but does not offer detailed quantitative syntheses. Ideally, the study we have in mind could estimate a single, composite effect by averaging multiple effect estimates such as Thomson et al.'s (2010), from a variety of studies. One approach might be to weight the individual estimates by their statistical soundness. Their individual uncertainties could also be combined into an uncertainty for the composite estimate. We expect that this idealized analysis would fully succeed for only a few flow metrics and fish variables, because of numerous incompatibilities among Delta studies and because relatively few of them have reported numeric effect estimates (e.g., regression coefficients). However, such an outcome would clearly show the Board how much (or how little) of the best available science on interior flows can be actually translated into management-usable flow effects. In addition, an approach that combined deterministic modeling of the physical aspects of the system with stochastic modeling of the biological aspects might yield valuable results.

Statistical strategies for the "best available science"

We offer some suggestions for assessing the statistical reliability and management utility of Delta research products. These suggestions were prompted by some of the statistical practices we observed in our review of oral presentations and journal articles from the Delta. We recommend that the Board assign greater weight to statistical analyses that use hypothesis testing (P-values) sparingly, and only for *a priori* hypotheses (Anderson et al. 2000). With regard to the statistical modeling of relationships, P-values have less meaning in the following cases:

1. If hypothesis tests are generated by "data snooping" (Ramsey and Schafer 1997), i.e., by looking at many bivariate scatterplots and then calculating correlations or regressions for only those cases that appear to show strong relationships. Detecting this kind of statistical bias may be difficult because authors will often only present significant results and do so in a context that implies *a priori* hypotheses;

2. If bivariate correlations are tabulated between numerous pairs of candidate response and predictor variables, with "statistically significant" correlations then highlighted (Van Sickle 2003; also see Burnham and Anderson 2002, re: "data dredging");

3. If a large number of candidate regression models are explored (for example, via stepwise selection) in order to select one or a few "best" models. P-values for those best models and any covariates that are included cannot be reliably interpreted because of the model selection process (Harrell 2001; Burnham and Anderson 2002);

4. If interpretation rests on the reporting of numerous P-values. A statistically-reliable analysis will report parameter estimates (i.e., effect estimates) for its models, with uncertainties characterized by parameter confidence intervals and/or expected prediction errors. Such an analysis may also compare the predictive performance (e.g., mean squared errors or explained variance) of alternative models (Hilborn and Mangel 1997). Zeug and Cavallo (2012), McNally et al. (2010), and Maunder and Deriso (2011) give examples of these strategies;

5. If many parameters are estimated on the basis of limited data. Such models are likely to be "overfit" (Harrell 2001; Burnham and Anderson 2002), which can lead to overly-optimistic R-squared values and poor predictive performance. We encourage authors to report the ratio between the number of independent observations in their calibration data set and the number of calibrated (fitted) model parameters. To avoid overfitting of multiple regression models, Harrell (2001) suggests a ratio of at least 10 to 1. We saw no reporting of this ratio in the Delta modeling papers that we reviewed. However, at least Maunder and Deriso (2011) clearly list their full set of estimated parameters.

In addition, the most reliable studies will evaluate model performance on an independent data set that was not used for model calibration. This is especially important for models at risk of overfitting. Truly independent evaluations are the gold standard for predictive performance. However, the hard-won data from some Delta studies is too precious to be set aside for the sole purpose of evaluating models. In such cases, cross-validation or bootstrapping calibration schemes will give a more honest expectation for predictive performance (Hastie et al. 2009). We did not see these strategies used in our review of Delta science products.

We also believe that the most useful models for management purposes will focus their model calibrations and performance evaluations on the (multidimensional) range within which model drivers, such as flows, can be feasibly altered by management now and in the future. Different stakeholders will, no doubt, have differing opinions about this multidimensional management space, but most would agree, we think, that it does not include Delta flow conditions that existed prior to State Water Project (SWP) exports. Thus, models calibrated solely from the subset of data collected since the start of SWP exports are likely to give more accurate predictions of flow-alteration effects on today's Delta. Applying such constraints to model calibrations would address Fleenor et al.'s (2010) concerns about outdated statistical models, as quoted in SWRCB (2010).

Flow criteria derived from statistically-estimated thresholds

Finally, we offer a few comments on thresholds and flow criteria (Charge question 5). SWRCB (2010) identifies four approaches for setting flow criteria in the Delta, and this section addresses only the use of statistically-estimated thresholds.

A slope break or step change perceived in a data plot of a fish endpoint versus a flow metric may imply a threshold response of fish to flow, and hence suggest a flow criterion. Thomson et al. (2010) give examples of statistical models that identify such "change points" or thresholds (in their case, for temporal trends of fish abundance). However, the use of statistically-identified thresholds as flow criteria faces two major challenges. First, the location, and very existence, of an estimated threshold can depend critically on the statistical method (see Table 3 of Dodds et al. 2010), as well as the abundance of data near the purported threshold (Toms and Lesperance 2003). Second, even if a threshold exists in a fish vs. flow relationship, that threshold may not be relevant for management. For example, SWRCB (2010, p.53) notes a potential threshold response of fall-run Chinook smolt survival to Sacramento River flows above 19,000 cfs. However, it does not automatically follow that flows less than 19,000 cfs would provide inadequate survival. For these reasons, we believe that statistically-identified thresholds can only be regarded as <u>potential</u> candidates for defining flow criteria. Before the candidate threshold could be considered as defining a flow criterion, it would be essential to identify the biological process(es) underpinning the candidate threshold (Dodds et al. 2010), as well the quantitative benefit to fish of managing to that threshold.

Ecological Models and Flow Criteria

Statistical analysis of existing long-term data sets have provided important insights into potential relationships between environmental variables and abundance and distribution of target species. Such relationships could be made more precise through the kind of analysis we propose. However, we also want to emphasize that there is a need to move beyond statistical modeling to make greater use of simulation and numerical modeling, particularly where physical variables like flow are proposed as drivers of biological variables like distribution and entrainment. The value and pitfalls of numerical modeling are discussed elsewhere in this report.

Ecological models of various sorts have been used to support some environmental decision making for a long time, and we think that such models will need to be used much more widely in the future. Ecological models are developed for different purposes and this has led to a great variety of model types and modeling styles. Models published in the scientific literature are typically assessed in terms of their scientific originality. However, models that will be used to support management decisions must satisfy two additional criteria: first, the model must mimic the real world well enough to provide realistic results; and second, managers must be confident that inferences about the real world based on model results are realistic. For managers to be able to make these judgments about model utility, transparent modeling approaches and comprehensive model tests and analyses are required. To ensure that ecological models can be used with confidence, a standard protocol for model formulation, documentation, testing, analysis and application is needed. Schmolke et al. (2010) propose thirteen elements of such a protocol (their Table 1). We summarize these elements here as a set of criteria for assessing the reliability of models that may be proposed for management of Delta flows (Table 3).

To date, with the exception of hydrodynamic models, most models used for making decisions about Delta flows have been based on statistical correlations. However, the trend is toward greater use of numerical and simulation models and we encourage the development of models that combine hydrodynamics and life cycle modeling. As such models become more sophisticated and useful, criteria for judging their quality, such as those in Table 3, will become more important.

Flow Regimes and the Geometry and Hydrology of the Delta

Much of the discussion about causes of declining populations of native fish has focused on changes in the Delta as fish habitat (Lund et al. 2008, 2010), and involves three distinct changes in the physical structure of the Delta that have occurred since the mid 19th century: 1) much of what had been a large tidal marsh has been converted to a network of rip-rapped channels carrying energetic tidal flows with little change in habitat type and quantity as water levels rise and fall (Lund et al. 2008; Whipple et al. 2012); 2) the seasonal variation of inflow (as well as timing and volume in dry years) into the Delta is different because of upstream storage, releases and diversions (e.g. Williams 1989); 3) subtidal (i.e., mean or average) flow patterns have been altered due to the operation of the export facilities in the southern Delta (Ball and Arthur 1979); and 4) upstream storage, channelization and landscape changes have changed the quantity and timing of transport of organic carbon and nutrients (e.g., Jassby and Cloern 2000).

The transformation of a brackish marsh into the current Delta may be the most profound change of all. Given what is known about tides in shallow estuaries (e.g. Fredrichs and Aubrey 1988; Nidzieko 2010) the change from a network of marsh channels with large floodplain-like storage at high tide to a network of prismatic channels with virtually no wetting or drying must have dramatically altered tidal propagation, tidal flows and tidal sediment dynamics. In particular, the pre-alteration Delta must have been much more dissipative for tides and had more frequent deposition and resuspension of river-borne sediments (Leonard and Luther 1995; Friedrichs and Perry 2001; Enright et al 2013). Presumably, the Delta might also have been fresher since a reduction in tidal mixing and the reduction in channel depths both imply a reduction of landward salt fluxes (see e.g., Fischer et al. 1979; MacCready and Geyer 2010).

Table 3. Elements of good modeling practice from Schmolke et al. 2010)

Modeling Element	Description
Were stakeholders included in model development?	Involvement of stakeholders (potential users, those likely to be affected by application of the model) through ongoing communication as the model is developed is a critical factor in developing the necessary confidence in the model and its application.
Were objectives clearly formulated?	Objectives of the model and its potential uses, including management issue(s), key variables and processes, available data, required outputs, how outputs will be used to inform decisions, need to be clearly specified at the outset.
Was a conceptual model developed?	As a foundation for the model and to ensure stakeholders concerns are fully addressed, a conceptual outline of the model is needed. This is the stage at which alternate views of how the system functions should be identified and reconciled if possible.
How was the modeling approach chosen?	The modeling approach chosen should be the one most appropriate for the context and goals of the project.
How was model complexity managed?	The model should be no more complex than is required to satisfy the goals of the project.
Were multiple models explored?	Where there are disagreements about the nature of the problem and the importance of different processes, the use of multiple models may help to clarify and reduce the uncertainty and level of disagreement.
How were variables parameterized and the model calibrated?	Model parameters can be determined from empirical data or drawn from analogous systems or set initially by expert judgment. If possible, the model should be calibrated against known values. Transparency is critical.
How were the model formulations verified?	A formal process must be established for ensuring that the model is correctly formulated.
Were sensitivity analyses performed?	The sensitivity of model outputs to variation in model inputs must be tested.
How were uncertainties quantified?	Confidence limits on model outputs must be determined. This is essential to any assessment of the value of the model as a decision support tool.
How was the model validated?	If possible, model performance should be compared against empirical data that were not used in model development.
Was the model peer reviewed?	Independent experts should assess the quality of the model and its outputs.
Is the model fully documented such that others can properly evaluate its structure and properties?	The structure of the model must be accurately communicated through thorough documentation of both the model and the process by which it was developed and evaluated.

The issue of seasonal variation in inflow volume and timing is more complex. On the one hand, the operation of water projects including both reservoirs and export pumps undeniably alters what would happen naturally. Storage of spring snowmelt must reduce spring runoff peaks and shift the peak runoff to later in the spring (Williams 1989), while reservoir releases, including those required to meet in-Delta water quality standards, might tend to keep the Delta fresher throughout the summer and fall than it would be naturally (Lund et al. 2008, 2010). On the other hand, it has been argued that the original Delta along with the large, seasonal freshwater marshes of the Central Valley, would have evapotranspired more water than does today's cropland (Fox 1987). Moreover, the levees that were built for flood protection purposes in the Sacramento and San Joaquin Valleys will ensure that a larger fraction of the inflow from the Central Valley watersheds makes it into the Delta rather than flowing over the river banks and out onto the fields and marshes of the Central Valley.

The role of overbank flows and evapotranspiration in Central Valley wetlands in reducing inflows to the Delta is important in that it bears on the definition of "Natural Flow" for the Delta. Unimpaired flow is the flow into the Delta given the existing levees on Central Valley rivers, but with no reservoirs and no other upstream diversions. Such flows are used by some as a benchmark of "healthy" flows, and can be calculated by a procedure originally developed by the Department of Water Resources (DWR) using hydrologic data collected in the Delta watersheds. However, it is clear that unimpaired flow is not the same as the flow that existed before the mid 19th century. Reflecting the importance of this distinction, the Panel understands from the State Water Contractors' presentation (Hansen et al., Delta Interior Flows and Related Stressors) and from later communications (5/2/14) with Dr. Paul Hutton of the Metropolitan Water District, that this is an active area of research supported by both DWR and by the State Water Contractors.

In light of the historic changes in habitat and flow, it is suggested that restoration of the Delta (i.e., restoration of its ability to support native fish) must involve: 1) some re-creation of marsh-like habitat connected to the Delta channels; 2) some restoration of natural inflow timing and possibly volumes; and 3) possible alteration of the intake point for the export facilities so as not to produce "reverse" flows in the Delta interior. The first and third issues form the basis of the 30,000 page BDCP. We focus on the second type of possible change, following up on comments made by J. Burau during his presentation on Habitat (Burau, Implications of (1) the historic delta, (2) existing habitat, and (3) restoration on hydrodynamics and transport in the Delta), the Panel recommends that the Board advise BDCP to consider the possible effects of increasing the amount of tidal, shallow water habitat on tides and the salinity field. Indeed, it seems conceivable that large-scale modification of Delta geometry through habitat creation may require reconsideration of any standards the Board may prepare in the near future.

With regard to Delta inflows, it is important to consider whether recreating a more natural hydrograph both in timing and volume is critical to producing an interior Delta flow regime that is beneficial to native species yet still allows reliable exports. One approach to reestablishing a more natural hydrograph, the one followed by the SWRCB in its flow criteria document (SWRBC 2010), is to set flow standards as various fractions of unimpaired flows. Because unimpaired flows may overestimate historic natural flows into the Delta, for the reasons discussed above, unimpaired flows as currently estimated may not be a good foundation for identifying flow standards. If historic losses to evapotranspiration were large, an argument can be made that current exports from the Delta essentially capture the excess flow that is present due to modification of the Delta and channelization of the rivers. Under this argument, reducing exports to increase the fraction of unimpaired flow that is allowed to flow through the Delta may actually increase Delta throughflow relative to what would have occured naturally.

On the other hand, an argument can also be made that unimpaired flows, as currently defined, reflect an hydrologic regime that in the past has supported much larger populations of native fish. Most of the channelization and leveeing etc. of the Delta and Sacramento Valley was completed by 1920 (Whipple et al. 2012). Although flow modifications were already substantial by the 1970s (the average date for the first year of operation of the major dams on the Sacramento and San Joaquin Rivers is 1961), through-Delta flows were higher than they are today and substantially larger populations of native fish like Delta smelt and Longfin smelt were observed. Thus, the Panel believes there is merit in considering the current calculations of unimpaired flows as a useful basis for deriving flow standards. The unresolved question is what proportion of unimpaired flows will best satisfy the coequal goals of environmental conservation and a reliable water supply. The factors that must be considered in determing reductions from unimpaired flows that will best satisfy these conflicting goals are discussed further below.

Flow Regimes and Turbidity

Restoration planning in the Sacramento River and Delta is partially based on the results of correlation analyses linking biological response variables (e.g., fall midwater trawl sampling for Delta smelt relative abundance) with an array of flow and water quality variables (e.g., temperature, salinity, flow, turbidity) from the Delta. These data are routinely collected and archived by State and federal agencies so they are readily available and have a relatively long period of record making them ideal for trend analysis. Several biotic variables consistently show weak correlations with flow and turbidity, suggesting that flow and turbidity could be manipulated as part of species conservation or ecosystem recovery plans. Unfortunately, weak correlations among variables do not lead to clear and unambiguous management actions because a lot of variance remains unexplained and the mechanisms behind the correlations are unclear.

The Delta science community relies heavily on correlations or other statistical relationships to link indices of abundance or distribution to uncertain measures of environmental condition. From a science quality perspective, we believe it is important to take animal sensory, cognition and behavior capabilities into account when trying to relate animal distributions or behaviors to environmental cues. That is, data describing environmental condition and trends should be collected using the sensory system of the target animal as a guide. For example, fish have no sensory mechanism to estimate channel discharge, so relating fish distribution and movement to flow is of dubious value. Instead, hydraulic variables within the sensory capability of fish, such as velocity and small-scale turbulence, should be considered as the basis for constructing indices on which management can be based. Similarly, we believe that improvements in how turbidity is measured and refinements in how flow is used should lead to stronger correlations with biotic response variables. Strategically, describing the physical and chemical conditions in the estuary in terms of attributes detected by the sensory system of the target animals should gradually lead from a reliance on weak correlations to more robust statistical models, and eventually to a causal framework as is typically used in water resources planning elsewhere.

Science is best conducted using a "first principles" approach. That is, a science challenge should be progressively disaggregated into its component parts until it cannot be reduced any further, at which point "first principles" are achieved. Unfortunately, flow and turbidity do not satisfy the "first principles" criterion because they are both composite variables that can be decomposed into several component variables to which aquatic biota may respond separately and differently. The relationship between the individual components may not be well captured by the composite variable making inferences from correlation analysis difficult. Flow (Q) in its simplest form is represented by: Q = velocity x width x depth; where the component variables are expressed as mean cross-sectional values.

The uncertainty introduced by use of Q instead of one of its component variables depends on the nature of the analysis. For example, calculation of a load to develop a nutrient budget correctly uses Q because: Load = Concentration x Q. Use of Q as a surrogate variable to relate flow in OMR to fish salvage could be misleading, however, because fish cannot estimate Q and because they are not entrained by Q. Fish are entrained by local water velocity, which is related to Q but with variation. Decades of fish swimming speed and entrainment studies use water velocity as the primary independent variable. At best, Q is a surrogate variable for water velocity and its performance is determined by how closely the relationship between Q and velocity adheres to a simple linear relationship. Of course, flow could be related linearly to velocity by assuming a simple uniform channel. Unfortunately, the Delta is spatially and hydraulically complex with two large pumping stations and many smaller withdrawals, upstream regulated inflows, internal boundaries (e.g., Clifton Court Forebay gate settings and temporary rock barriers) all interacting with pronounced diurnal tides. As a consequence, there are many different operations that may potentially yield the same Q in OMR, but with substantially different velocities. For example, high inflows from the San Joaquin River and reduced pumping will increase water elevation, increase cross-section area, and reduce water velocity in OMR. In contrast, low inflows from the San Joaquin River and similar reduced pumping will decrease water elevation, reduce cross section area, and increase water velocity in OMR. Further problems may arise when flow ratios are used because the ratio of two high flows may be the same as the ratio of two low flows, but the entraining velocities associated with the high flows are likely to be greater than the entraining velocities associated with low flows. Thus, use of Q-based metrics for management need to be considered with the proper level of uncertainty and effort is needed to decompose the composite variables, such as Q, into variables that relate directly to the sensory perception of the fish. We recommend that, where possible, the region move away from using correlations involving flow and flow ratios as a basis for conservation and restoration planning and instead use relationships involving average channel velocity (better), particle transport rate and destination (good), or Computational Fluid Dynamics (CFD) based fish behavioral rules (best). For example, we found the presentation by Gartrell to be more useful than flow ratios because his methods gave insight into net movement of passive particles relative to the pumps.

Turbidity is also a composite variable that measures the cloudiness of water. The problems associated with turbidity as a measure of environmental condition are best seen through a description of how turbidity is measured. Turbidity is typically measured as the behavior of light from a source of known strength and spectral qualities as it passes through (Jackson Turbidity Units, JTUs) or is reflected by (Nephelometric Turbidity Units, NTUs) a column containing sample water. We will only address turbidity as measured in NTUs because that appears to be the method used by the Delta science community. However, the comments made for the estimation of turbidity as NTUs also applies to the use of JTUs.

A nephelometer (a device to measure turbidity in NTUs) is comprised of a light source of known strength and spectral qualities that illuminates a sample water column. A light sensor located at right angles to the light rays from the source measures the reflectance of particles in the water. The higher the number of particles in the water (i.e., the greater the turbidity) the more light will be reflected and detected by the sensor. There are two major problems associated with this measure of turbidity as it relates to fish behavior. First, any particle in the water will reflect light including small biota (e.g., bacteria, algae, and micro-zooplankton), different sorting of the same suspended sediments and different kinds or sources of suspended sediments (e.g., upstream river sources versus internal sources such as resuspension of sediments by wave action). The composite nature of turbidity measurement makes it difficult to compare values across time or space since the components of turbidity may be completely different even though the composite turbidity values may be identical. People can visually differentiate between algal and sediment turbidity. It seems likely that Delta smelt, juvenile salmon, and other aquatic biota can do the same and may react differently to different sources of turbidity.

Second, the light source in a nephelometer emits primarily the light spectrum visible to humans because turbidity measurement is keyed to human uses of water. Many fishes, however, are known to see in the ultraviolet A-band (UV-A) spectrum (peak around 370 nm) in addition to the human visible spectrum (peaks at 445 nm (blue), 508 (green), and 565 nm (red)) and some can also see near infrared radiation (Flamarique 2000; Deutschlander et al. 2001; Scherbakov et al. 2013). Many fish can also detect polarized light (Hawryshyn 2010). In addition, the rate at which light attenuates underwater is related to wave length with red light being attenuated first and light in the UV-A spectrum having the greatest depth penetration. Ultraviolet radiaton is, therefore, most useful in clear water whereas infrared radiation is relatively more useful in turbid waters with a lot of light scattering.

Steelhead (*Oncorhynchus mykiss*, and rainbow trout) and sockeye salmon (*O. nerka*) are able to detect ultraviolet light (Flamarique 2000; Deutschlander et al. 2001), but it is not known if they can detect light in the near infrared. It is not known whether Chinook salmon can detect ultraviolet radiation but it seems highly likely that they do. Anadromous salmonids apparently lose some or all of their ability to detect ultraviolet light when they smolt but regain it some time after entering the ocean (Flamarique 2000; Deutschlander et al. 2001). It is not known if Delta smelt can detect ultraviolet radiation but, given the wide distribution of this ability in teleosts it seems very likely that they do. Neither salmon nor Delta smelt have been reported to detect light in the near infrared, however, given that Delta smelt prefer turbid waters it seems plausible that they may be able to detect the longer near infrared wavelengths.

There are many advantages to a fish having a visual pigment sensitive to the UV-A light spectrum. For example, calanoid copepods (a common prey of Delta smelt) are transparent and therefore difficult to detect in visible light, but appear as a solid color in UV-A radiation. Some of the components of chitin shells (possessed by crustaceans on which both Delta smelt and juvenile salmon feed) fluoresce in the UV-A making them much more discernible to predators. We are not aware of any studies that describe the use of the UV-A spectrum to differentiate among different sediment types or biota that cause reflectance in a nephelometer. However, there is ample evidence in terrestrial settings that the UV-A is used to great advantage by some animals (birds in particular) to acquire information about their surroundings not available in the human visible spectrum.

Turbidity can also affect predator-prey interactions. In general, turbidity has little effect on predation by small (larval) fish on microzooplankton because the fish larvae react only to nearby prey so their vision is not effected by the scattering of light by particles in the water. In fact, prey of larval fish may have enhanced contrast when seen against the brighter background of a turbid environment. At the same time, larval fish are protected against predation by turbidity because their predators typically detect prey visually at considerable distance. Larger fish may not receive the same anti-predator benefit from turbidity. However, Delta smelt, a rather pale, reflective fish that does not move fast, may be camoflaged against the bright background provided by turbid water. Much will depend, however, on the spectral composition of light scattered by particles in the water and the light reflected from a Delta smelt.

Identifying the environmental signals that cue reproduction, movement, or other behaviors of aquatic biota are critical to effective conservation and restoration planning. Flow and turbidity are two commonly measured variables that sometimes relate to distribution, abundance and survival of Delta fishes. However, these composite variables inject a substantial amount of uncertainty into any attempt to infer causal relationships and, thus, impede design of successful conservation measures. We recommend a program to understand the nature of turbidity in the Delta, how target species respond to different aspects of turbidity and how those responses reflect the visual abilities of target species (particularly at short and long wavelengths). Such a program may require development of an improved turbidity sensor that can distinguish different kinds of particles contributing to the overall turbidity measure (bacteria, algae, POM, inorganic particles) using light sources that illuminate the UV-A to near infrared wavelengths. The Applied Physics Labs of any of the major universities in the region should be equipped to engage this problem.

Advanced spectral analysis methods are used to describe environmental conditions at sea. Perhaps these methods could be explored to develop a similar capability in the Delta.

Flow Regimes and Flow Metrics

Flow patterns and thus transport of scalars (e.g., nutrients and contaminants) and non-swimming organisms in and through the Delta are affected by tides, water project operations, and high flows associated with storms (Monsen et al. 2007). By water project operations we mean reservoir releases that supply flows to the Sacramento, San Joaquin and eastside rivers (e.g., the Mokelumne) and thus represent controlled inflows to the Delta, exports from the State and federal pumping plants in the southern Delta, as well as smaller in-Delta diversions (e.g., the Contra Costa Water District intake in Rock Slough), and the placement and operation of gates and barriers (e.g., the Head of Old River Barrier (HORB)).

The longstanding view of Delta hydrodynamics (Ball and Arthur 1979; discussed by Kimmerer 2004) and thus regulations has focused on subtidal or average flows. For example, OMR flows (see Oltman 1998) can be determined observationally by applying a low-pass (tidal) filter to the combined flow through Old and Middle Rivers. Flows such as DAYFLOW and QWEST are also subtidal and can be determined by hydrologic balances of daily values of flows determined upstream of the Delta in non-tidal reaches or by observed export pumping rates. In this tidally averaged view of the Delta, materials and organisms are moved through the Delta as in a river either out to Suisun Bay or to the pumps. However, setting aside high flow events associated principally with winter storms, flows due to tides are generally stronger than tidally averaged flows (see e.g., Monsen 2001; Fong et al. 2009). Because of the interaction of tidal currents with the complex geometry of the Delta, dispersive transport by tides can significantly alter the picture of water movement in the Delta based on subtidal flows (Monsen et al. 2007; Monismith et al. 2008). For example, in his oral presentation Smith (Smith, OMR Flows, Turbidity, and Delta Smelt) showed model results of passive particles being transported to the pumps from places where mean flows suggest they should be transported to the Bay.

Given the hydrodynamic complexity of the Delta, much of what is understood about transport has been developed using numerical modeling including both tides and mean flows. These models include one-dimensional channel network models like DSM2 (used by Kimmerer and Nobriga 2008) as well as more sophisticated two-dimensional, depth averaged models like RMA-2 (see e.g., Resource Management Associates 2005) and fully three-dimensional models like SI-3D (Smith 2006), TRIM/UnTRIM (MacWilliams and Gross 2013), and SUNTANS (Wolfram 2013). The Panel heard several presentations that made use of the outputs from these various models (e.g., Cavallo, Is net flow (OMR) a meaningful metric for juvenile salmonids? Evidence from hydrodynamic analyses and tagging studies, and, Smith, OMR Flows, Turbidity, and Delta Smelt). One feature that seems robust in these models is that when exports are high and San Joaquin River flows are low, (conditions that give rise to large, negative values of OMR) passive particles from much of the Delta other than the Sacramento River itself are drawn into the export facilities. For example, in Smith's presentation (slide 14) the "Zone of Entrainment" (ZOE), or the region where particles inserted into the modeled flow were likely to enter the pumps, extended across much of the Delta in August 1999. During this time, exports were high and OMR flows, estimated using the formulae provided by Gartrell et al .(2014):

$$Q_{OMR} \approx -0.87\left(Q_{Exports} - 0.48Q_{SJR}\right) \qquad \textbf{without HORB}$$

$$Q_{OMR} \approx -0.84\left(Q_{Exports} - 0.56Q_{SJR}\right) - 406 \quad \textbf{with HORB}$$

and data from CDEC[1] were nearly -10,000 cfs (Figure 1). In contrast in late January, when OMR flows (again estimated) were small, the ZOE was confined to the southern Delta, north and east of the pumps. Note that for all three periods shown by Smith, the Export:Import (E:I) ratio was below 0.1, i.e. far lower than the D1641 standards of 0.35 (Feb-Jun) and 0.65 (Jul-Jan). The low E:I ratios reflect the fact that Sacramento River flows (not shown in Figure 1) were generally high throughout the three periods of study.

An important demonstration of the value of particle tracking modeling was given by Kimmerer (2008), who showed that particle entrainment as calculated by DSM2 provided a good estimate of the loss of larval and juvenile Delta smelt to the pumps. While this result may not be as strong as originally suggested by Figure 16 in Kimmerer (see critique by Miller 2011 and response by Kimmerer 2011), it does make clear that anything in the ZOE that moves with the water will be entrained into the pumps. Accordingly, it appears that regulations based on OMR flow will have value for limiting entrainment into the pumps of some organisms, notably Delta smelt larvae and juveniles, and Delta plankton.

We note that caution should be taken in making detailed interpretation of the results shown by Smith. Although the results are plausible, the circulation model was not fully calibrated and for the August run, the HORB was in place in the model whereas in reality it was not installed that summer (Smith pers. comm.). Nonetheless, the results are sufficiently informative that the Panel strongly supports continued modeling of this sort using state of the art 3D models like Si-3D to define the ZOE for different combinations of inflows, exports, barriers and tides. We believe that this kind of modeling also has the potential to suggest better independent variables for statistical analyses of ecological responses. Additionally, it may be possible to develop a more accurate and precise trigger to cease pumping than the present threshold of negative OMR flows.

There is one further point: since particle tracks integrate currents over time from the release point to the pumps, daily values of subtidal flow variables may not be appropriate flows metrics (Gartrell et al. 2014). In Figure 1, we shaded two-week periods (roughly one spring-neap cycle) following Smith's particle releases, showing that for these periods subtidal flows were reasonably constant. In contrast, examination of the most recent USGS flow data for Old and Middle River (Figure 2), shows significant variability in subtidal flows even at weekly timescales, reflecting opportunistic pumping carried out to capture storm flows for storage. In this case, inferences about particle entrainment due to strongly negative OMR flows may not be correct in that the time required for particles moving along the OMR corridor to reach the pumps may exceed the time for which OMR flows are strongly negative.

[1] http://www.water.ca.gov/dayflow/output/Output.cfm

On the other hand, it is well known that organisms with behavior can move in ways that are substantially different than would be predicted for passive particles. Numerous studies have shown how vertical migration in tidal flows ("selective tidal stream transport") enables organisms to maintain position in an estuary with strong outflows, or exit the estuary more quickly than would be possible with passive transport (North et al. 2008; Bennett et al. 2002; Simons et al. 2007; Kimmerer et al. 2014). Thus to the extent that behavior is important to the movement of a species of concern, e.g., Chinook salmon, simple flow metrics like OMR may have too much uncertainty to be an appropriate basis for setting standards. Ample evidence for this conclusion, at least for salmon and steelhead, was presented at the workshop [See also report section on fish behavior]. On the other hand, OMR may be quite useful for organisms, like Delta smelt larvae, that swim weakly if at all.

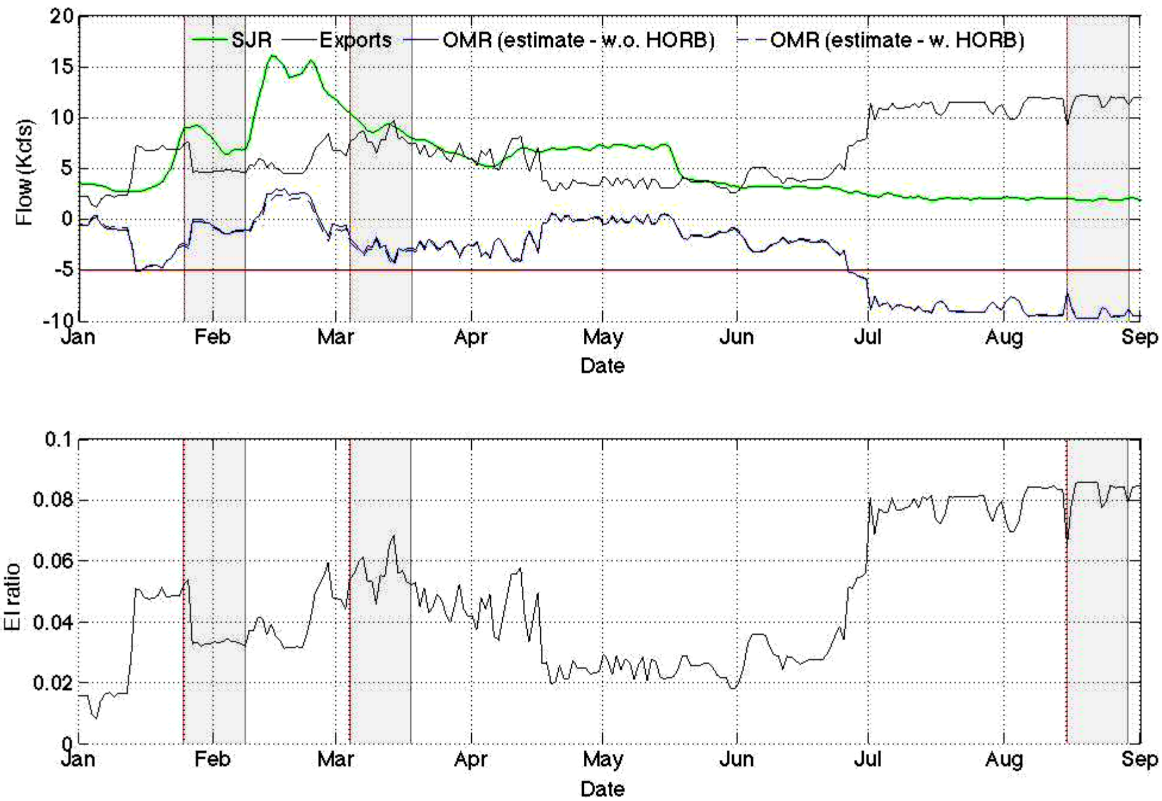

Figure 1: Flow data for WY 1999 – The three shaded areas represent the 3 two-week-long periods represented in Smith's calculations.

An aspect of flow that was raised by Gartrell in his oral presentation was the issue of flow reversal in the OMR channels. The strategy of a fish using tidally varying swimming behavior to move towards Suisun Bay will work only if the ebbs always flow towards the Bay (i.e., in the OMR corridor if the flow is positive for some part of the ebb). If the ebb doesn't reverse, swimming with the ebb will not result in outmigration and escape from the influence of the pumps. As shown by Gartrell in his oral presentation, when OMR flows are strongly negative, then flow can be southward to the pumps even during the ebb. While this is not seen in Figure 2, since the weakest ebbs in Old River (at the USGS OBI station) remain slightly positive, a similar plot for the Ultrasonic Velociy Meter (UVM) data at station OH4 (not shown) do show a lack of flow direction reversal on weak ebbs for several days. In any case, it appears that a more subtle effect of southward subtidal flows in the OMR corridor may be to increase the time required for fish to move through the Delta, potentially increasing their exposure to predation or other adverse environmental conditions. Such an effect is something that can be tested through modeling that incorporates current understanding of fish behaviors for species of interest.

OMR may be a useful metric for indexing entrainment, particularly for organisms that swim weakly. However, as discussed by Gartrell in his oral presentation and in Gartrell et al. (2014), it may be difficult to use operationally as it is only available after the fact (a consequence of the filtering to estimate OMR flow). The relevant variables for estimating OMR can also vary within the spring-neap cycle, so that from the standpoint of the mass balance for the Delta at timescales longer than a fortnight, exports must be balanced by inflows from the San Joaquin River, from the OMR corridor and from Indian Slough (which is south of the OMR flow gauges). As a consequence, a relatively simple relationship between exports, San Joaquin River flows and OMR, albeit depending on the presence or absence of the HORB, is reasonable. Thus, the Panel believes that it may be possible to use an estimate of OMR based on exports and San Joaquin River inflow as a flow metric for regulating entrainment risk of organisms moved passively by the current, such as Delta smelt larvae and juveniles.

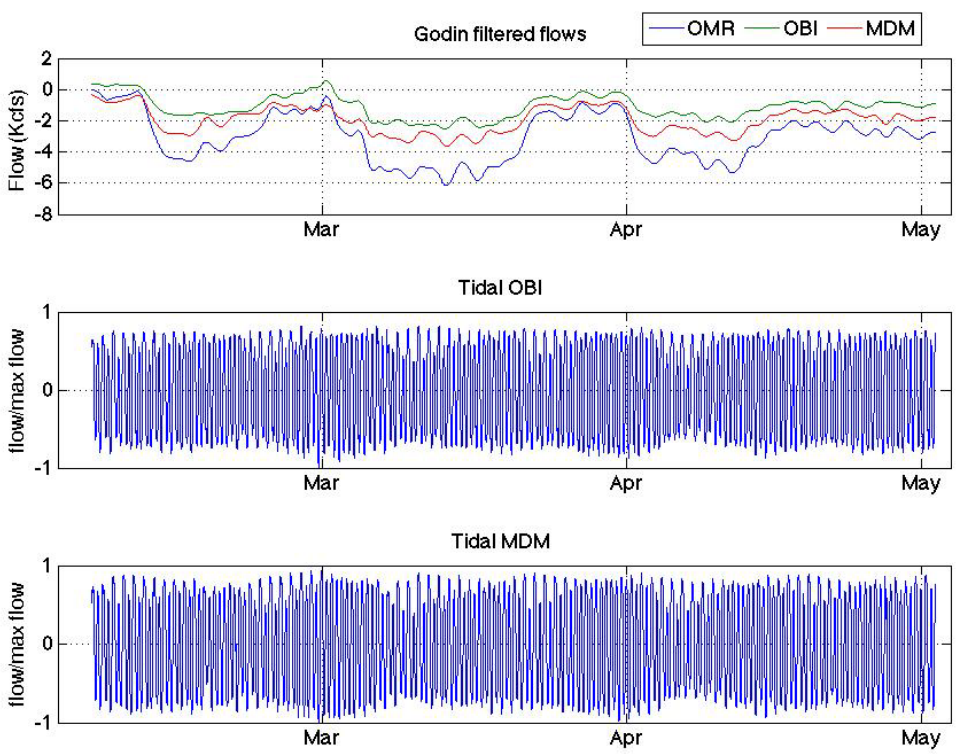

Figure 2: OMR flow data from Feb. to May 2014. What is plotted is USGS UVM data (downloaded from CDEC) for the stations OBI on Old River and MDM on Middle River.

Flow Regimes and Primary and Secondary Production

Much attention has been given to the possible role that changes in the planktonic food web may have played in declines in native fishes. To date, the discussion has emphasized the effects of benthic grazing (Kimmerer and Thomson 2014) and the effects of anthropogenic nitrogen, principally ammonium (Glibert et al. 2011). In contrast, to the best of our knowledge, there has been no evaluation of how in-Delta water project operations, i.e., exports (or OMR flows), gate operations (e.g., the DCC), or the presence or absence of barriers (e.g., HORB) might affect either primary or secondary production in the Delta. Several papers (Jassby and Powell 1994; Jassby and Cloern 2000) have estimated the effect of exports on the supply of particulate organic matter (POM) to Suisun Bay, finding that a significant fraction of the POM produced within the Delta can be lost to export. It is clear that simple mass balances may not tell the entire story of water export effects on POM as primary productionand POM are higher in the San Joaquin River than in the Sacramento River. Jassby and Cloern (2000) pointed out that current water project operations can route all of the organic matter produced in the San Joaquin River into the export pumps, thus having a greater effect on the supply of POM to Suisun Bay than would be expected from an overall mass balance for the Delta.

In a series of observational and modeling studies of primary production in the Delta (Lucas et al. 2002; Cloern 2007; Lucas and Thomson 2012), USGS scientists have shown that the different habitat types in the Delta, i.e., shallow lakes versus deep channels, can have very different net primary production depending on depth, water transparency, and the density of benthic grazers like *Corbicula fluminae*. Given that *in principle*, modifications to in-Delta flows by export pumping or gate operations should affect connectivity between the large open water areas and adjacent channels, in-Delta flows *should* affect net primary production and, therefore, secondary production. However, to the best of our knowledge this has not been demonstrated by any extant modeling or field programs.

Glibert et al. (2011) discuss the possible role of nutrient enrichment as a basis for the emergence of "blooms" of the harmful cyanobacterium, *Microcystis aeruginosa*. Lehman et al. (2005) suggested that "The impact of *M. aeruginosa* on the quantity and quality of phytoplankton biomass available to the food web may be a greater threat to the NSFE [Northern San Francisco Estuary] food web than toxicity." Noting that weak vertical mixing gives the positively buoyant *Microcystis* a competitive advantage (c.f., Huisman et al. 2004), Lehman et al. (2008) suggested that increasing mean (subtidal) flows could help reduce the occurrence of *Microcystis* by increasing vertical mixing. However, instantaneous flows that produce vertical mixing are tidal, and thus, even when mean subtidal flows are weak there is likely to be more than sufficient mixing to eliminate vertical temperature stratification. Moreover, as seen in measurements made in the San Joaquin River reported by Monismith et al. (2008), mixing by surface cooling (i.e., penetrative convection) also mixes out stratification on a diurnal basis (Hench et al. in prep.). Thus, physical conditions in the Delta differ from those where *Microcystis* typically appears.

There are several difficulties with assessing the effects of *Microcystis* on the food web and the extent to which its abundance is tied to in-Delta flows. First, it is a relatively small fraction of the overall phytoplankton biomass sampled by the Interagency Ecological Program (IEP). Indeed, only one sample taken since 2009 at sites sampled under the Environmental Monitoring Program (EMP)[2] has shown any *Microcystis* cells. Sampling targeted at finding *Microcystis* reported in Lehman et al. (2010) showed maximal Chlorophyll *a* concentrations of ca. 0.3 micrograms/l at their Old River station which was approximately 15% of the average Chlorophyll *a* concentration for August and September 2005 measured by the EMP at the nearby D28a station. This difference may reflect in part the difficulty of sampling *Microcystis* (Ahn et al. 2008). Given that routine sampling is largely confined to the larger channels and open water areas, it may be that *Microcystis* colonies sampled there were produced in more protected regions such as small dead end canals. Indeed, Lee and Jones-Lee (2006) anecdotally describe the Stockton Turning Basin as an incubator for cyanobacteria.

There may be a connection between water project operations and *Microcystis* since growth rates for *Microcystis* increase exponentially with temperature, which may be influenced by the strength and spatial structure of in-Delta flows. Temperatures in the Delta do vary with strength of inflow from the San Joaquin River (Monismith et al. 2009), but the extent to which in-Delta flows affect in-Delta temperatures is unknown. In the long term, summer air temperatures may play a bigger role in determining Delta temperatures (Wagner et al. 2011) than do flows and so may be more important to creating conditions favorable to *Microcystis* growth. Synoptic sampling of specific locations might help identify *Microcystis* hotspots, which might then be controlled with limited local intervention.

There is even less known about flow effects on secondary production or the availability of zooplankton for small fish. Orsi and Mecum (1986) suggested that: "..if zooplankton density in the Sacramento River water that is pulled into the San Joaquin is lower than that in the latter river, the result should be a reduction in zooplankton abundance in the affected area…" Although this makes sense intuitively, in part because the San Joaquin side of the Delta generally has higher phytoplankton biomass than does the Sacramento side, the first part of this premise has not been demonstrated by any analysis of the IEP zooplankton data of which we are aware. This may in part be due to the high intrinsic variability of zooplankton data (W. Kimmerer pers. comm. 2014)

A second effect of exports on zooplankton abundance could also be hypothesized. In effect, entrainment by export pumps is a form of grazing since entrained zooplankton are also lost to the Delta (and Suisun Bay). The strength of this sink can be estimated by computing the rate, *R* as:

[2] Available at http://www.water.ca.gov/bdma/meta/Phytoplankton/data.cfm

$$R = \frac{Q_{Exports}}{V_{Delta}}$$

where $V_{Delta} \approx 1 \times 10^9$ m^3 (Monsen 2001). This assumes that the Delta behaves as a well-mixed "reactor", clearly a weak assumption given the spatial variability of mixing within the Delta (c.f. Monsen 2001; Monsen et al. 2007). To estimate the importance of this loss to zooplankton abundance, R can be compared to estimates of zooplankton growth rates. Growth rates for the freshwater copepod, *Pseudodiaptomus forbesi*, averaged 0.014 d^{-1} between April and July 2006 but with high variability of 0.09 d^{-1} (Kimmerer et al. 2014). For this same period, using DAYFLOW data (http://www.water.ca.gov/dayflow/output/Output.cfm), R varied between 0.004 d^{-1} and 0.022 d^{-1}, suggesting that losses of *P. forbesi* to the pumps may have had population level effects. Of course, as with estimating entrainment effects on any Delta biota, the spatial distribution of zooplankton also matters, so that this calculation remains necessarily hypothetical. We note that Kimmerer is currently building an Individual Based Model (IBM) of *P. forbesi* (W. Kimmerer pers. comm. 2014) that may provide much needed information about the potential connection between zooplankton abundance and water project operations.

The conclusion that emerges concerning the effects of in-Delta flows on primary and secondary production as well as on Harmful Algal Blooms is that, while in principle such effects should exist, there is no firm evidence that they do exist. The only connection between water project operations and food webs that can be made with any confidence is that Delta outflows, the net effect of inflows and exports, have a direct effect on the food web downstream because diversions reduce the export of phytoplankton-derived POM from the Delta to Suisun Bay. Nonetheless, the existing evidence provides strong motivation for strengthening the food web component of monitoring and research in the Delta ecosystem.

Flow Fields and Fish Behavior, Cues and Clues

Fish respond to flow fields as individuals and at space and time scales commensurate with their sensory capabilities. Population level effects, when present, are the cumulative effect of individuals responding to local flow (velocity) fields in accordance with the information they have derived through their senses, their physical capabilities and their life stage "objectives." To understand the kinds of broad scale relationships between fish "end points" and Delta flows discussed above one needs to understand what attributes of the flow field the fish can sense, what kinds of responses it is capable of, and what it is motivated to do in the situation (Goodwin et al. 2014). Although native fishes use environmental clues to direct their movements and migrations in the Delta, these clues may be masked or overwhelmed by properties of the system that are outside the range of natural variability typically encountered by fishes. As a consequence, seaward migration routes of juvenile salmon, straying rates of adults returning to spawn, and seasonal movements of Delta smelt and other species may be affected.

Fish possess a broad array of sensory systems and behaviors that they can use to detect and respond to aspects of the flow field. Sensory systems include taste, olfaction, vision, temperature sense, magnetic field sense, and the lateral line system. By means of these senses a fish can develop a detailed image of their immediate surroundings and also derive limited information on conditions elsewhere (provided, for example, by taste and odor clues carried on the current or sound vibrations from a distant source). The way a fish uses its senses and its knowledge of its immediate surroundings, however, depends on its size, its life stage and what objectives it may be trying to achieve in relation to the flow field and other attributes of local habitat. Salmon, for example, can be characterized as transient species, always in the process of moving from one habitat to another or preparing for such a move. Healey (2000) characterized salmon in any habitat as motivated to satisfy three imperatives: 1) find food to gain mass as quickly as possible (so as to outgrow gape limited predators and/or to accumulate energy for migration, gonad maturation, and spawning); 2) avoid being eaten; and 3) get positioned for appropriately timed movement to the next habitat. Thorpe and Moore (1997) argued that salmon migration is a movement away from a habitat that no longer provides for their needs. This is true to a degree, but the relatively precise timing of movements from one habitat to another reflects the salmon's long history of successful habitat transitions. Seaward migration, for example, is not an escape from unproductive freshwater habitat but a genetically encoded behavior cued by photoperiod, temperature, age and size and clued (clues are sensory stimuli that allow the salmon to travel in the correct direction and with the correct timing to successfully complete its migrations) by a variety of local (velocity, salinity) and distant (sun, magnetic field) environmental factors. Salmon keep to the schedule and respond to environmental cues and clues in ways that were designed by natural selection to succeed in the Delta <u>as it was prior to human alteration</u>. That is not to say salmon cannot adjust their behavior to some degree in response to local conditions or slowly adapt genetically to changed conditions. However, there are likely cues and clues in the modern Delta that could lead salmon (and other species) badly astray.

Juvenile Chinook salmon in the Delta

For salmon, the estuary is a transitional habitat between freshwater and marine habitats that demand very different physiology. It is not uncommon for fall-run Chinook salmon to migrate to the river estuary shortly after emergence from the spawning nest. Chinook salmon fry entering the estuary do not yet have the physiological competence to make the transition to full sea water and so must reside and feed in the intermediate salinity of the estuary until they achieve this competence (usually at a size of around 70 mm total length). Sampling by the U.S. Fish and Wildlife Service showed that Chinook salmon fry were relatively abundant in the Delta and were also present in San Francisco Bay during January to March each year, residing for up to two months in the Delta feeding and growing (Kjelson et al. 1982; Brandes and McLain 2001). Chinook salmon fry, thus, have a comparatively long residence time in the Delta where they would be vulnerable to predation from a variety of native and non-native predators and, during their wandering in the Delta, could be vulnerable to entrainment into the export pumps. Kjelson et al. (1982), however, noted that most fry were found along the Sacramento River corridor, suggesting that few were entrained into the channels leading to the central Delta, although some tagged fry were recovered at the fish salvage facilities during dry years. Once they achieve osmoregulatory competence for sea water, Chinook salmon fry usually move into coastal waters where they continue to feed and grow for some time before moving offshore into deeper water. Chinook salmon fry virtually disappear from the Delta toward the end of March (presumably continuing their seaward migration) but their behavior is unknown after they leave the Delta.

In less modified deltas and estuaries, such as the Fraser River delta in British Columbia, the delta and its marshes are a favorable nursery habitat for juvenile Chinook salmon. Superficially, the channelized geometry of the modern Sacramento-San Joaquin Delta with its limited marsh habitat does not appear particularly suitable. However, Kjelson et al. (1982) reported growth rates of Chinook salmon fry in the Delta that were comparable to fry growth rates in less modified deltas suggesting that, at least in terms of foraging opportunity, the Sacramento-San Joaquin Delta was still favorable nursery habitat. Whether Chinook salmon fry have continued to grow well following the invasion of *Corbula amurensis* and the change in zooplankton community that has occurred in recent decades is not known (Winder and Jasby 2011).

Chinook salmon fry are not strong swimmers and typically hold in shallow embayments or use structures to keep from being carried along by the prevailing current. Kjelson et al. (1982) noted that beach seine catches of Chinook salmon fry in the Delta dropped significantly at night, suggesting fry were moving away from shallow nearshore areas at night. Larger fry were captured further offshore, near the surface during the day but broadly distributed in the water column at night. If the fry move away from shore at night they would lose visual and tactile clues to their position and would likely simply be carried by the currents. This is characteristic of salmon fry (and smolt) behavior during downstream migration, which occurs primarily at night due to passive drift, but may be less functional in the tidal Delta. In the historic Delta, with its extensive marshes and many blind ending dentritic channels, simply drifting at night might not take the fry very far. In the modern Delta, however, with open trapezoidal channels and high-velocity tidal currents, fry might be carried a considerable distance in the Delta and find themselves in unfavorable habitats when light returns.

Migration through the tidally energetic Delta and San Francisco Bay may be assisted by selective tidal transport (Moore et al. 1995). Cues for Chinook salmon fry emigration from the Delta may include photoperiod and temperature as fry are believed to time their seawater entry to take advantage of coastal plankton blooms. Clues to the direction of the sea would come from changing water chemistry as the tide ebbed and flowed, the same clues that would allow the fish to adjust their behavor to migrate on the ebbs and hold position on the floods. It is not known, however, that Chinook salmon fry make use of selective tidal transport but Jackson et al. (Oral presentation to the Panel) showed by means of an agent-based model that this behavior would improve survival of Chinook salmon migrating through the Delta.

Because of the multiple runs of Chinook salmon in the Sacramento and San Joaquin River systems, Chinook salmon smolts are present in the Delta for a protracted period. Highest numbers are present during April to June. Some Chinook salmon juveniles are found in the Delta most months of the year except that few are found during summer, possibly owing to high temperatures at that time. In recent years it has become possible to track individual Chinook salmon smolts in the Delta by acoustic telemetry, particularly those that migrate at large sizes, such as the late-fall run, which enters the Delta during the winter after over a year in fresh water. Michel et al. (2013) measured rates of travel of late-fall Chinook salmon down the Sacramento River, through the Delta and out to Golden Gate. Migration speed declined as the fish moved downstream and was slowest in the Delta and San Francisco Bay (under 20 km/day estimated from Figure 2 in Michel et al 2013). Hearn et al. (2013) estimated a similar rate of travel from the Delta to the Golden Gate (19.1 – 19.5 km/day). Perry et al (2010) estimated that late fall Chinook salmon smolts took 7 to 13.8 days to transit the Delta, those entrained into the central Delta having the longer transit time. Smolts released in January, when the Delta Cross Channel was closed and Sacramento River discharge was somewhat lower, took considerably longer to transit the Delta, 17.8 days for fish in the Sacramento River corridor and 33.9 days for a single fish that entered the central Delta. These residence times in the Delta seem long if the smolts perceive the Delta as a dangerous habitat. At easily sustained swimming speeds of 2 to 3 body lengths per second, smolts could transit the Delta in a few days. Even following the somewhat longer route through the interior Delta, smolts should be able to exit the Delta in less than a week. Reasons for the slow transit of the Delta and subsequently the relatively slow transit of San Francisco Bay may be that the smolts do not perceive the Delta as a particularly dangerous place or that their evolutionary programing tells them not to enter the ocean earlier than they do or that the cues necessary to initiate or sustain movement are ambiguous or not present. The timing of the transitions between these habitats has been set by evolution and can only be adjusted gradually by natural selection even if under present conditions the fish would be better off entering the Delta later, transiting faster and entering the ocean earlier.

While in the Delta, Chinook salmon smolts are subject to a variety of stressors including substances from agricultural and urban runoff, low oxygen concentration, high temperatures, exotic predators (and conditions that increase predator hunting efficiency such as reduced turbidity), reduced access to tidal marshes, changes in their zooplankton food supply, and entrainment into the export pumps. The population-level impact of these stressors is largely unknown. However, as we are here focusing on behavioral responses to flow fields and migratory cues and clues it should be mentioned that a variety of contaminants, both organic and inorganic can disrupt the sensory capabilities of fishes (Scott and Sloman 2004; Tierney et al. 2010) and that toxic metals are ubiquitous and persistent in the Bay-Delta ecosystem (Flegal et al. 1991; Buck et al. 2007). The sublethal impacts of toxic substances on listed species is a particularly complex subject and is also a moving target as the spectrum of toxic substances is continually changing. Kimmerer (2008) noted that increased export flows increase the proportion of winter-run juvenile Chinook salmon that are salvaged at water export facilities, suggesting obfuscation of cues associated with selection of successful migration routes through the interior Delta.

The clues that Chinook salmon smolts use to find direction when migrating through a delta are not known. Given their sensory capabilities, however, smolts should be able to determine direction of flow using visual and tactile clues and distinguish between ebbing and flooding tides on the basis of water chemistry. Drifting or swimming with the flow is a primary mode of downstream movement in rivers. Moving with the current is not an efficient tactic in the Delta because tides cause reversals of current direction approximately every six hours and also create complex and potentially confusing patterns of water flow around islands. Selective tidal transport would be expected behavior for smolts in the tidally dominated parts of the Delta. Data on movement behavior from acoustic tags is fairly extensive now and it should be possible to look for evidence of selective tidal transport in these data, much as Delaney et al. (2014) have done for steelhead smolts. Upstream of the Delta, tagged smolts move primarily at night, although the frequency of daytime movement increases as the fish move downstream. In the Delta, 69% of detected movements are at night and in the estuary smolts move as much during the day as at night (Chapman et al. 2013). Increasing seaward movement during the daytime suggests that the smolts are switching to active rather than passive migration, which implies some kind of positive response to directional clues. Fish use olfaction, taste, and possibly other clues to assess water quality and these sensory abilities are essential to any ability they may have to use selective tidal transport. The Delta receives a very broad spectrum of chemical contamination from agriculture, urban runoff, transportation, and a variety of other sources. Many of these contaminants are known to affect fishes' olfactory ability (Tierney et al. 2010), but these effects have not been studied in the Delta.

In the most upstream reaches of the Delta, where net seaward flows are still high, simply going with the flow is likely a reasonable tactic. Burau (oral presentation) reported that at night at Clarksburg bend in the Sacramento River, Chinook salmon smolts moved around the outer bend in the main river flow. During the day, however, smolts moved into slower moving water on the inside of the bend, making use of a small eddy and the shadow under the research vessel to hold position. These are expected behaviors of salmonids in moving fluids – taking advantage of the main flow when traveling but then making use of discontinuities in flow and boundary layers to hold position with little energy expenditure when not traveling. As Chapman et al. (2013) noted, migrating Chinook salmon smolts typically travel at night, which may be a predator avoidance tactic. While holding during the day, fish may be feeding or taking advantage of the relative safety of a group to minimize predation risk. This does not mean the smolts will not suffer high predation, particularly by the non-native predators in the Delta with which they as yet have little evolutionary experience. In the historic Delta, more complex geometry, the presence of woody debris and possibly higher turbidity likely provided a broader range of opportunities to avoid predators than does the present-day Delta.

Although Chinook salmon smolts do not go with the flow strictly in proportion to discharge they do make use of flow during migration. This raises the possibility that they could be confused by reverse flows in OMR. Because of the reverse flows in OMR when exports are large, the smolts are likely to receive mixed signals from tidal flux as water could be moving toward the pumps on both flood and ebb tides depending on the operation of the gates to Clifton Court Forebay (CCF). In this case, smolts may find themselves virtually trapped within OMR over several tidal cycles and potentially attracted into CCF because of inappropriate signals from water chemistry and flow. Since conveyance through the Delta is designed to ensure high quality of export waters (i.e., low salinity) it may be that near the pumps there is insufficient salinity signal on the tidal flow to direct the smolts and they simply go with the flow toward the pumps expecting that it is carrying them downstream. Salmon also make use of compass orientation during their migrations although the extent to which they might use this ability in the Delta is uncertain. It is possible that they might recognize that moving southward in OMR was inappropriate but whether they would be motivated to make some kind of corrective action is unknown.

Flow fields and flow responses are complex at tidally active junctions. Smolts migrating downstream in the Sacramento River may be entrained into the central Delta through the Delta Cross Channel (DCC) or Georgiana Slough. Those migrating seaward in the San Joaquin River will encounter many junctions that lead to OMR and potentially to the export pumps. Flow fields at all of these junctions change in complex ways on the tidal cycle. Figures 3 and 4 (from the oral presentation to the panel by Burau and Blake) show examples of idealized flow fields at junctions that potentially have very different entrainment consequences for migrating fish. The numbers of smolts that could be entrained depends on the distribution of the smolts relative to the critical streak line shown on the diagrams. In simple terms, the smolts north of the streakline in Figure 3 are more likely to be entrained into the side channel. No entrainment occurs during tidal stages that produce the flow fields in Figure 4. To the extent that salmon smolts are traveling with the flow, how they will distribute at junctions is critically dependent on their cross channel distribution and the attributes of the flow field they encounter. The velocity field at the junction will also be important as the ability of the smolts to avoid entrainment will depend in part on their ability to swim faster than the current velocity. Any tendency to use selective tidal transport will also impact entrainment probability.

Steel et al. (2012) investigated entrainment of acoustically tagged winter-run Chinook salmon smolts at the DCC. Twenty-eight tags provided useable data, of which 12 entered the DCC and 16 remained in the Sacramento River. Smolts that entered the DCC encountered the junction when velocities in the River were very similar to those in the cross channel whereas those that remained in the Sacramento River encountered the junction when velocities in the River were at least 3.8 times higher than in the cross channel. Smolts that entered the DCC traveled at a slower speed than those that remained in the Sacramento River (0.29 m/s compared with 0.41 m/s). Smolts that migrated through the DCC also had a greater median turn angle between detections than those that remained in the Sacramento River (26.1° compared with 14.0°). Although not significant in single factor analysis, including the position of smolts across the river in a multifactorial model significantly improved the fit (smolts further from the DCC were less likely to be entrained). These results appear consistent with Burau's and Blake's conceptual model of flow field effects on entrainment (Burau and Blake oral presentation to the Panel). The slower rate of travel and greater turn angle of smolts entrained into the DCC is suggestive of disorientation on the part of the fish and is worthy of further investigation.

Juvenile salmon using migration routes through the interior Delta suffer greater mortality than conspecifics that use the Sacramento River or other direct routes (Newman and Brandes 2010; Perry et al. 2013). Diversion of smolts from low-survival migration routes to high-survival routes seems like a reasonable management action, but because of the complexity of the connecting waterways in the Delta, outcomes of such diversions are likely to be highly variable. For example, diversion of smolts away from a low-survival route at a downstream river junction increased population survival by less than expected because a portion of the population used an alternative migration route at an upstream river junction (Perry et al. 2013). Thus, we agree with Perry et al. (2013) that actions that alter both migration routing and route-specific survival rates are likely to have more successful outcomes and achieve management goals.

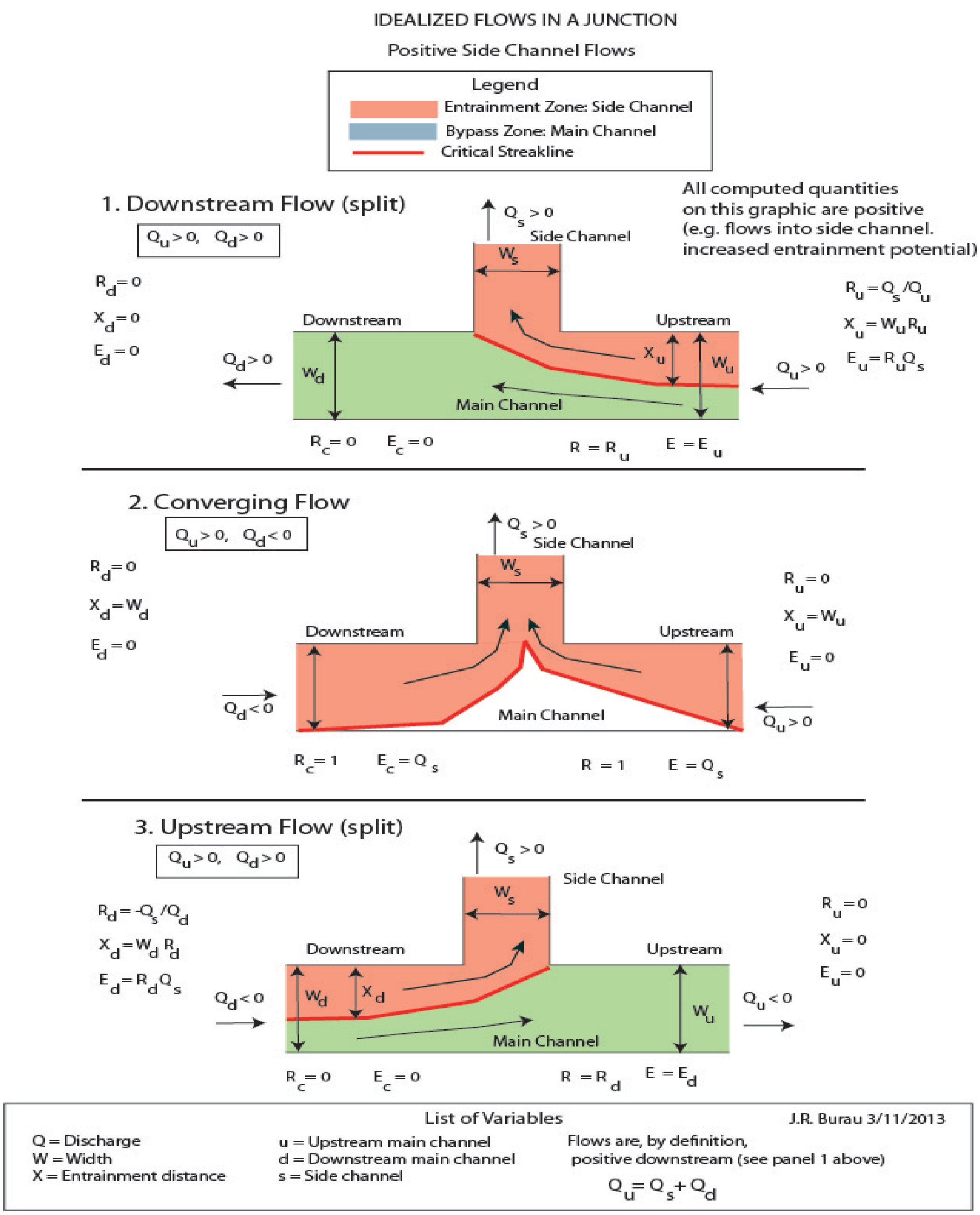

Figure 3. Examples of flow patterns at junctions that entrain into a side channel. Figure from the oral presentation to the panel by Burau and Blake.

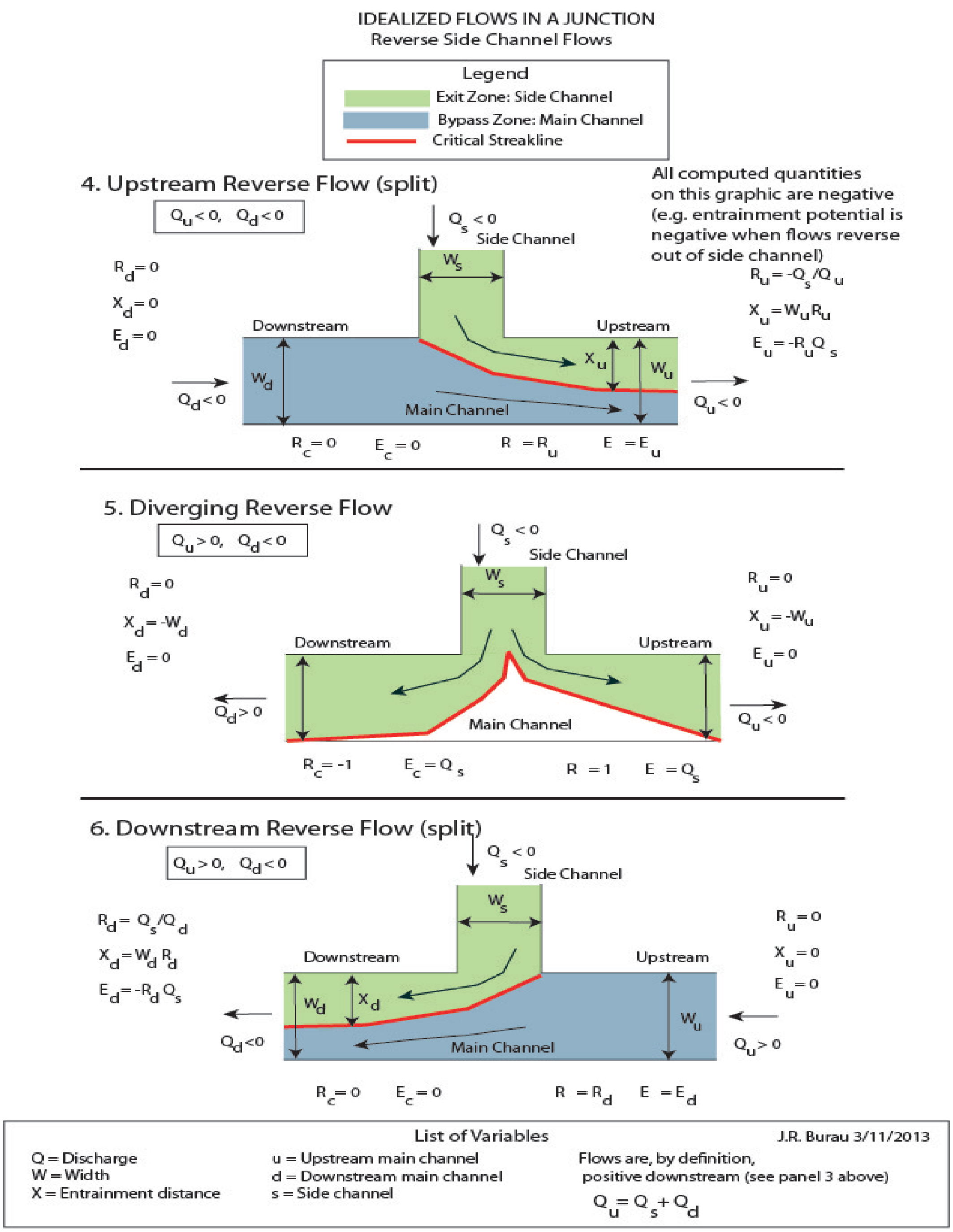

Figure 4. Examples of flow patterns at junctions with no entrainment. Figure from the oral presentation to the panel by Burau and Blake.

Both physical and non-physical (behavioral) barriers can be used to divert smolts from sub-optimal migration routes. The probability that a smolt will select a given route depends on the instantaneous hydraulic pattern at a junction, the precise location of the smolts in the flow field and the characteristics of individual smolt. The ratio of mean water velocities at a junction can be used to help understand smolt migration route selection, but size and behavior also matter (Steel et al. 2013). As demonstrated by Burau at the Panel meeting in April 2014, velocity at a river junction varies spatially. Route selection potential can be predicted by adding ‘smart’ particles that emulate the behavior of smolts to CFD models that represent flow fields during the period of interest (e.g., Goodwin et al. 2006, Goodwin et al. 2014). Such predictions can be verified with field experiments using high-frequency location data from 2-dimensional acoustic telemetry of smolts coupled with CFD models. This approach can provide valuable insight into the feasibility of managing migration route selection.

The development of acoustic tags small enough to implant in salmon smolts has provided invaluable detail on the migratory behavior of these fish. To date, however, the tags have only been used on the larger late-fall run yearling smolts. The behavior of other runs and other sizes of Chinook salmon may well differ from that of late-fall run yearling smolts. For example, Williams (2006) reports anecdotal information that in late fall, smolts hold near shore during the day but move into the main channel at night, making them vulnerable to entrainment into the DCC during rising tides. In spring, however, smolts appeared to be migrating during the day so that their vulnerability to entrainment would be different. Strong generalizations about vulnerability to entrainment will have to await detailed information on other runs and the identification of any differences in migration behavior with season. Since behavior at specific junctions and its effect on entrainment under different flow fields and times of day is critical to survival in the Delta more detailed investigation of this behavior could pay dividends in terms of options for managing smolt migration routes and maximizing survival through the Delta. For smaller salmon, smaller acoustic tags could be employed as only short tag life would be needed to monitor movements of fish released near a junction. In some cases, PIT tags might provide a workable alternative for small fish in some locations.

Migration routes through the interior Delta pose a higher mortality risk to juvenile salmonids because of prolonged migration times, increased predation probabilities, and the greater likelihood of entrainment associated with these routes. Management actions that minimize migration time through the Delta, decrease predation pressure on smolts, and reduce the likelihood of entrainment should result in higher survival of smolts that use the interior Delta route to reach the sea. Conditions in selected portions of the Delta could be targeted for improvement (see e.g., Cavallo et al. 2012) and such changes may yield desired population-level effects (e.g., increased survival). Cavallo et al. (2012) suggested that conditions in tidal transition areas are critical to the survival of smolts; these areas are characterized by the change from uni-directional to bi-directional flow. Reducing the time Chinook salmon outmigrants spend in tidally-influenced habitats in the interior Delta could be beneficial.

Juvenile steelhead in the Delta

The migration of steelhead smolts is less studied and much less well known than that of Chinook salmon fry and smolts. The biology of steelhead is complex because *O. mykiss* exists as both a resident (rainbow trout) and an anadromous (steelhead) form and the offspring of one form can adopt the life history of the other (McEwan 2001; Williams 2006). Most steelhead are produced in hatcheries and released as yearling smolts in January, apparently migrating quickly downstream and through the Delta. Wild steelhead smolts migrate seaward mainly in April and May and also pass rapidly through the Delta (Williams 2006). Despite their relatively large size, steelhead smolts appear to survive poorly in the Delta and Williams (2006) suggested that this might be pushing populations to become predominantly resident rather than anadromous. Improved understanding of steelhead migration and survival in the Delta is, therefore, sorely needed.

A recent study of acoustically tagged steelhead smolts released into the San Joaquin River at Buckley Cove (Delaney et al. 2014) has provided useful data on smolt movements and likelihood of entrainment under different OMR flows. Three groups of tagged steelhead were released in the lower San Joaquin River at Buckley Cove during April and May and their migration routes and survival probabilities monitored until they reached Chipps Island. Not unexpectedly, tagged steelhead dispersed much more quickly than passive particles. Most smolts (77.6%) moved seaward along the San Joaquin River while 22.4% were entrained into the southern Delta via Turner Cut. Survival of steelhead that remained in the San Joaquin River was 56.7% whereas survival of those that were entrained through Turner Cut was 27%. Survival of steelhead smolts was, therefore, much greater than the survival of Chinook salmon smolts regardless of the route travelled to Chipps Island. In this study there was no clear relationship between negative flows in OMR and the route taken by tagged steelhead. The data provided some evidence that the steelhead smolts were using selective tidal transport to assist their seaward migration. There was no consistent pattern of primarily daytime or nighttime movement although the data suggested that nighttime movement was more prevalent in the San Joaquin River whereas daytime movement was more prevalent in the southern Delta.

It appears that steelhead, which are larger than Chinook salmon smolts, are less affected by interior Delta flow fields, move through the Delta more quickly than Chinook salmon and experience greater survival. Nevertheless, steelhead are entrained into CCF and into the export pumps suggesting that some of the cues and clues they receive during their migration through the Delta lead them in the wrong direction. It may be that, like Chinook, when they get within a zone of entrainment near the export facilities, the clues from the flow field and tidal ebb and flow are either confusing or direct the fish toward the pumps. Further understanding of the behavior of steelhead at channel junctions and in OMR under different conditions of tide and OMR flows is needed in order to work out a strategy for preventing entrainment to the southern Delta and into the export facilities.

Adult Salmon in the Delta

Adult salmon returning to spawn must also find their way through the Delta and into the main rivers and tributaries at an appropriate time to spawn successfully. Because of the number of different Chinook salmon runs in the Sacramento/San Joaquin systems, adult salmon are entering the Delta most months of the year. Factors that cue upstream migration are not well understood and individuals may hold in the estuary for a considerable time before migrating upstream. Once in freshwater, Chinook salmon may move back to the estuary and subsequently move upstream again (Williams 2006). Adult sockeye salmon are known to use selective tidal transport moving through the tidal reaches of the Fraser River (Levy and Cadenhead 1995) and adult Chinook salmon may do the same. However, their primary orientation mechanism in fresh water is olfaction (Dittman and Quinn 1996). Numerous factors could affect the movement of adult salmon through the Delta, including exposure to the broad cocktail of anthropogenic chemicals that discharge into the Delta, many of which are known to affect olfaction in fish at very low concentrations (Tierney et al. 2010). However, the pattern of river flows and exports can also have an effect. Marston et al. (2012) found that increased pulse flow (measured as the 10-d average of the highest flow in October and November) was negatively correlated with the straying rate of fall-run San Joaquin Chinook salmon into the Sacramento River. Straying rate was also weakly positively correlated with water export rate. As export rate increases, progressively more of any pulse of flow in the San Joaquin is entrained into the export pumps and less moves through the Delta. This led Marston et al. (2012) to suggest that a combination of pulse flow and exports may determine stray rates. Annual straying rate of San Joaquin Chinook salmon was as high as 70% (in 2007) and the average, straying rate of San Joaquin River fish (18%) was orders of magnitude greater than the straying rate of fish from the Sacramento River (0.1%). This suggests that some aspect of flow is important, and that pulse flow, exports and operation of barriers directly or indirectly affect straying.

Delta Smelt Movements

Unlike the salmonids, Delta smelt is a resident species and must satisfy all of its life cycle needs within the Delta and estuary. Smelt abundance has declined dramatically since the 1970s and statistical analyses of sampling data suggest a step decline in abundance during the early 1980s and a second, steeper decline in the early 2000s (Thomson et al. 2010). The causes of these declines remain uncertain although a variety of biotic and abiotic factors have been linked to the declines (Bennett 2005, Thomson et al. 2010, MacNally et al. 2010). Because of its listing as endangered, the need to protect Delta smelt continues to drive much of the regulation of water extraction from the Delta.

The primary habitat of Delta smelt is the low salinity zone (LSZ) of the estuary at salinities between about 0.2 to 2.0 PSU, although their range extends over salinities of 0 to 19 PSU. The majority of Delta smelt habitat is, therefore, outside the Delta proper. Smelt are most abundant in water of low clarity (Secchi depth < 40 cm) and at temperatures below 24 C (Bennett 2005, Nobriga et al. 2008). Using data from the long term Delta and estuary sampling programs, Murphy and Hamilton (2013) described the center of smelt distribution as extending from Suisun Bay east to the confluence of the Sacramento and San Joaquin Rivers and north into the Cache Slough complex (Figure 5).

In the fall and winter, adults move from the channels and bays of this region into nearby freshwater marsh and channel habitats to spawn. According to Murphy and Hamilton (2013) this redistribution is more a dispersal to adjacent habitats than a distinct migration from a summer feeding region to a spring spawning region (Figure 5). Spawning occurs from March to May at temperatures between 15 and 20 °C. Individual females may spawn more than once during the spawning period but virtually all smelt die once spawning is complete (Bennett 2005). Eggs are demersal and adhere to the substrate or vegetation. The precise location of spawning is unknown but spawning areas are inferred from the capture of spent females and recently hatched larvae. Larvae are poor swimmers and are dispersed through much of the Delta by advection. Many are entrained into the export facilities. By early summer, smelt have grown larger and are better swimmers. At this time, they begin to accumulate in the LSZ, mainly just upstream of the 2 PSU isohaline, where they use tidal and diel vertical and lateral migration to maintain position (Bennett et al. 2002).

Smelt feed most successfully in turbid waters and most are found where Secchi depth is less than 40 cm (Nobriga et al. 2008). Their preferred food was the copepod, *Eurytemora affinis*, but this species is now only present for a short period in spring, having been displaced by another exotic copepod, *Pseudodiaptomus forbesi*, which is a less valuable food source for the smelt. *P. forbesi* itself is being displaced by yet another exotic species, *Limnoithona tetraspina*, which is an even less suitable food for smelt. Concurrent with changes in the zooplankton community has been the arrival of the overbite clam, *Corbula amurensis*, in the mid 1980s, which now consumes a high percentage of phytoplankton and zooplankton in the LSZ. The Atlantic silverside was introduced to the estuary in the 1970s and has become progressively more abundant. The Atlantic silverside competes with smelt for food and preys upon its eggs and larvae (Bennett 2005).

A

B

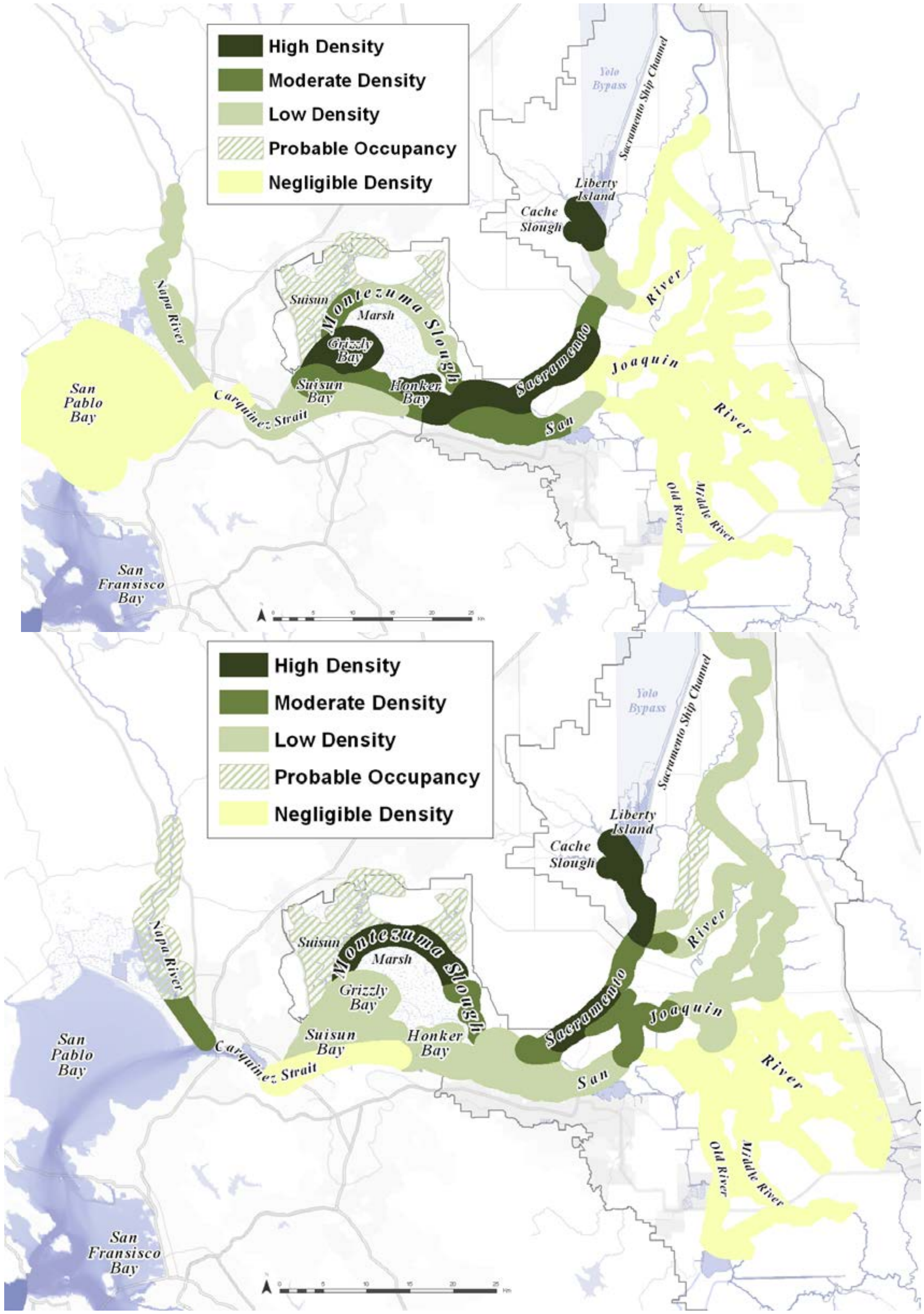

Figure 5. Distribution of Delta smelt: (A) in summer and fall before spawning redistribution, and; (B) in spring after spawning redistribution. From Murphy and Hamilton (2013).

Delta smelt are not strong swimmers and even adult smelt can be reluctant to swim vigorously (Bennett 2005). Yet, they appear to be able to maintain a fairly specific distribution in the Delta despite strong tidal flows and high velocities. Although they are not well studied, we must presume that smelt have rather finely tuned ability to detect and work with the flow and velocity fields in the Delta to find their preferred habitats and stay within them. In the historic Delta it is conceivable that the fish would not have to do much as net flows would, in time, bring them to the low salinity zone. Under present-day Delta geometry and flow fields, however, depending on net flow is not likely a good strategy in much of the Delta. Even in the historic Delta, simply depending on net flows may not have allowed the smelt to achieve the optimal timing of its seasonal distributions. One way that the smelt might have influenced the timing and geography of larval redistribution is by choosing appropriate locations to deposit their demersal eggs. The resulting larvae would experience Delta flow fields that were most likely to deliver them to nursery habitats at an appropriate time. Bennett's (2005) observation that smelt tend to spawn on the spring tides so that their larvae would emerge on the neap tides may be linked to this kind of strategy as tidally driven flows would be weaker on the neap tides. Bennett et al. (2002) found that smelt at some locations moved laterally in the channel on the tidal cycle but in other locations migrated vertically on a diel cycle. Bennett et al. (2002) interpreted these behaviors as tactics for maintaining position in the low salinity zone. They also indicate, however, that the smelt are capable of different complex behaviors that are presumably a response to local circumstances. As we suggested for salmon, behaviors that may have worked well historically may be maladaptive in the present-day Delta. A better understanding of how smelt respond to internal Delta flow fields at different life stages might provide ideas about how to adapt flow fields for the benefit of smelt. It seems clear that our understanding of the relationship between interior flows and smelt would benefit from a combination of controlled experimentation to reduce some of the uncertainty inherent in existing models and analyses and improved models capable of exploring the multiplicity of hypotheses that have emerged from analyses of historic data.

Fish Behavior Conclusions

Broad, generalized relationships between Delta flow fields and fish response (e.g., OMR reverse flows and entrainment; X2 and population response) have been very useful in establishing a regulatory framework that is beneficial, or at least not detrimental, to listed species. However, these relationships do not take account of the particular capabilities of the listed species to detect and respond to Delta velocity fields. Further refinement of the statistical models that underlie the regulations may not allow precise definition of thresholds or offer any new options for further protecting listed species. New approaches that take account of the sensory and swimming capabilities of the fish are needed.

Fine-scale investigations of flow fields and salmon behavior at specific junctions coupled with emerging technology for managing those flow fields may provide the means to maximize migration along routes that have higher survival for salmonids. In a similar vein, better understanding of how Delta smelt manage their movements in the Delta as larvae, juveniles and adults could indicate ways that flow fields could be managed to match their behavior and survival strategies. Appropriate research would measure and develop models of junction flow fields at different river discharges, tide stage, gate operations, and export levels. In conjunction, salmon and steelhead smolt behavior at these junctions should be monitored and analyzed in relation to entrainment and migration tactics. The research on salmon should address both run and seasonal effects. Possibly fish too small to carry an acoustic tag could be monitored with PIT tags in some circumstances.

Developing a better understanding of how Delta smelt respond to flow fields and salinity clues would probably have to be undertaken in a laboratory setting but we feel improved understanding of Delta smelt behavior could pay regulatory dividends.

A clearer understanding of the ability of the species to use selective tidal transport would also help with the design of any program to manage flow fields. Evidence for this behavior is not strong for any of the species. The research should be designed to determine the circumstances when the fish will use selective tidal transport as opposed to passive drift or active migration.

Flow Regimes, Invasive Species, and Food Webs

Many non-native species have become established in the Bay-Delta and a number of these have had profound effects on native species by altering their food webs, by competing with them for food and other resources, and by preying upon them. The great success of some non-native species, which has magnified their effects on native species, has been facilitated by a general failure to control the continual seeding of the Delta with a multiplicity of exotic species, by the physical changes to the Delta and by the ways in which flows in the Delta have been managed. The physical transformation of the Delta from a landscape dominated by tidally and seasonally inundated marsh to a patchwork of leveed islands separated by trapezoidal drainage channels was completed early in the 20th century. Subsequently, the Delta and estuary were literally flooded with exotic species through deliberate introductions and through incidental introductions by international shipping, by the aquarium and horticultural industries, and by the baitfish trade. By the 1990s Cohen and Carleton (1998) speculated that the San Francisco estuary and the Delta might be the most invaded estuary in the world. Today, non-native species dominate many communities, accounting for 40 to 100% of the common species, up to 97% of the number of organisms, and up to 99% of the biomass (Cohen and Carleton 1998). The zooplankton community, which is the primary food source for many native fishes, was sufficiently altered by successive invasions of organisms from Asia that Orsi and Ohtsuka (1999) described it as an "East Asian community." Many non-native fish species that prey upon and/or compete with native species for food have also become abundant in the Delta and estuary. Feyrer (2004) captured 15 species or taxonomic groups of fish larvae in the southern Delta during 1990-1995, of which three comprised 98% of the total catch by number; the non-native shimofuri goby (71%), the non-native threadfin shad (15%), and the native prickly sculpin (12%). Non-native striped bass was the only other species that represented as much as 1% of the total catch. Ignoring the prickly sculpin, native species represented about 1% of the sampled fish assemblage. He also noted that native species peaked in abundance earlier in the spring than non-native species. Grimaldo et al. (2004) found that non-native species dominated the catch in marsh habitats in the central Delta, with threadfin shad, centrarchidae, and inland silversides accounting for about 60% by number. Brown and Michniuk (2007) found that the overall catch of non-salmonid fishes in the Delta and River systems was 59% non-native species but varied regionally with 93% non-native in the San Joaquin River, 89% in the interior Delta, 50% in the northern Delta, 45% in the lower Sacramento River, and 23% in the upper Sacramento River. Both species composition and species life history strategies differed among sampling regions, which complicates any attempt to develop a water management strategy that would discourage invasive fish.

Water flows in the Sacramento and San Joaquin Rivers are heavily managed primarily to satisfy human demands for water. This has resulted in flattening of the seasonal hydrograph in both rivers and significant reduction in flows entering the Delta from the San Joaquin River. Within the Delta a considerable volume of Sacramento River water is routed south through the Delta to be exported by the federal and State water projects. Although a considerable volume of fresh water flows into the Delta, flows in the Delta tend to be dominated by tides, which transport a volume of water much larger than the freshwater inflows most of the time. The changes in physical structure of the Delta, flattening of the seasonal hydrograph and reduced inflow from the San Joaquin River, together with routing of Sacramento River water south to the export pumps and the water exports themselves result in patterns of water flow through the Delta that must be dramatically different than those prior to 1900. An important consequence of all the physical changes in the Delta is that, whereas historically flow and habitat type were intimately connected throughout the Delta, now they are largely decoupled. Historically increases and decreases in flow, on both tidal and seasonal time scales, resulted in major changes in the types and amounts of habitats available to fishes and other organisms in the Delta. In the leveed and riprapped channels of the present Delta organisms are presented with a set of relatively simple habitats regardless of flow.

Patterns of flow in the Delta appear to have had consequences for the success of non-native species (Winder et al. 2011). The successful invasions of non-native zooplankton and mysids all occurred during drought periods when a 3-year moving average of monthly X2 values was greater than 75 (Figure 6). The pattern leading to invasion was several years of drought conditions followed by high flow peaks in winter and spring. Drought resulted in a more saline Delta and contracted the habitat available for native zooplankton adapted to low-salinity or freshwater conditions.

Droughts are also associated with a shift in the benthic community to suspension feeding clams (*Mya arenaria* during 1976-77; *Corbula amurensis* after 1986). Increases in suspension feeding clams were followed by declines in phytoplankton and a shift from a diatom-dominated community to one with high proportions of phytoflagellates and cyanobacteria (Winder and Jasby 2011). Thus, water management has to be especially sensitive to invasive species during drought conditions. Although the volume of water needed to reduce the risk of further invasions or to prevent the expansion of clam populations may not be large, water demand during drought is very high and any water reserved for environmental purposes is likely to be a source of conflict. However, allowing X2 to move upstream to permit a modest increase in water exports can, according to

Winder et al. (2011), facilitate the establishment or expansion of non-native species with important consequences for the food web supporting native species.

The decoupling of habitat from flows has disadvantaged some native species and may have favored some non-native species. Some native species, like Sacramento splittail move to inundated floodplains to spawn during the spring runoff, and the resulting juveniles then move back into the main channel (Kratville 2008). Juvenile salmon also make use of tidal marsh habitats in estuaries, moving into and out of the marsh along tidal channels as the tide floods and ebbs (Levy and Northcote 1982). Sommer et al. (2001) found that the Yolo Bypass, the most significant floodplain of the lower Sacramento River, provided better rearing and migration habitat for juvenile Chinook salmon when flooded than adjacent river channels. Seasonally and tidally inundated floodplain and marsh habitats have been virtually eliminated throughout most of the Delta. By contrast, the non-native largemouth bass prefer warm, fresh, shallow and stable flow conditions (Moyle et al. 2012), and their abundance has increased in shallow waters following the increase in the invasive weed, *Egeria*, and increasing water clarity (Brown and Michiniuk 2007, Ferrari et al. 2013).

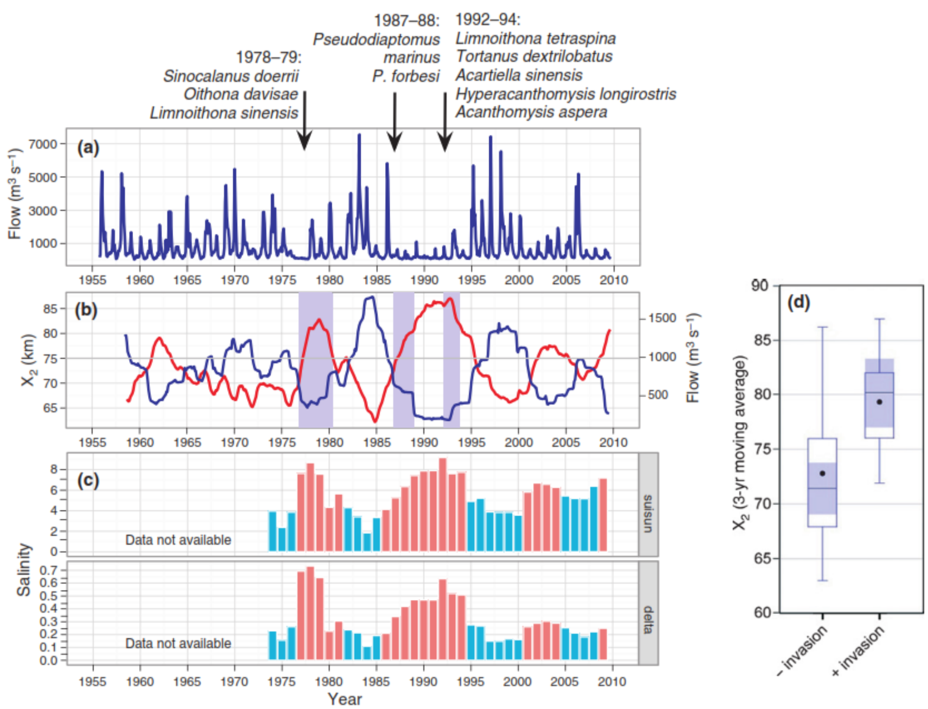

Figure 2 Chronology of zooplankton species invasion in the upper San Francisco estuary related to long-term flow and salinity patterns. (a) Freshwater inflow and timing of first appearance of invasive zooplankton (arrows). (b) Extension of the salinity field indexed by the positioning of 2 ‰ salinity distance from the Golden Gate (X_2, red) and freshwater flow (blue). A 3-year backward moving average of monthly values was applied to emphasise persistent long-term conditions. Shaded areas highlight invasion periods. (c) Three-year backward moving average of annual salinity during the growing season (May–November) in the downstream 'suisun' and upstream 'delta' subregions (for subregions see Fig. 1 in Winder & Jassby 2010). Years when long-term X_2 averages extend above 75 km are highlighted, corresponding to < 300 $m^3 s^{-1}$ outflow from the Delta into Suisun Bay. (d) Boxplots of the 2 ‰ isohaline distance, X_2, in years when an invasion occurred (+invasion) compared with years without zooplankton invasions (−invasion). The shaded areas are approximate 95% confidence limits for the median of the 3-year moving X_2 average. The shadings of the two plots do not overlap, which is 'strong evidence' that the two medians differ (Chambers *et al.* 1983).

Figure 6: From Winder et al. (2011) showing relationship between drought conditions and the establishment of important non-native species.

Turbidity is emerging as an important environmental variable in the Delta, particularly for Delta smelt that prefer turbid water (Secchi depth < 40 cm; Bennett 2005, Sommer and Mejia 2013). Suspended sediment is brought to the Delta primarily by the inflowing rivers. When the Delta was a giant marsh considerable deposition probably occurred in the Delta itself with numerous episodes of resuspension and redeposition on tidal, seasonal and annual timescales. This kind of sediment dynamics is largely absent from the present day Delta. Turbidity of Delta waters prior to European settlement is unknown.

Schoellhamer et al. (2013) describe the pattern of changing sediment loads associated with human development in a catchment as involving an initial increase as land is cleared for forestry, agriculture and other uses, followed by decreasing supply leading to a new stationary condition. The Sacramento-San Joaquin system is experiencing this sequence beginning with an initial large pulse of sediment associated with hydraulic mining starting in the mid 1800s, followed by decreasing sediment supply associated with restrictions on hydraulic mining in the late 1800s, the construction of dams that trapped sediment from upstream, and finally the construction of levees, which reduced bank erosion and eliminated channel avulsion and river metamorphosis. The Sacramento River is the primary source of sediments for the Delta. The distribution of this sediment is determined by the pattern of internal water flows and local hydraulic conditions. Delta smelt are more prevalent in turbid waters, which affords them some protection from predation (Sommer and Mejia 2013, Ferrari et al. 2013). There has been a dramatic increase in water clarity in the Delta in recent years as sediment inputs have decreased (Schoellhamer 2011). The trapezoidal channels of the present-day Delta act as conveyance channels moving sediment through the Delta rather than allowing episodes of deposition and resuspension. Increases in water clarity due to decreased sediment input increase the vulnerability of Delta smelt to predation. Increasing water clarity has also been facilitated by the expansion of *Egeria* beds, which slows water flow and promotes deposition as well as providing hiding places for potential predators. Ferrari et al. (2013) found that Delta smelt were more vulnerable to predation by largemouth bass in clear water and that they would not enter adjacent beds of *Egeria* even when faced with significant predator threat.

Changes in the Delta zooplankton community as a result of successive invasions of alien species have dramatically altered the food supply of listed fish species. Winder and Jassby (2011) documented abrupt changes in the zooplankton community in the Delta and Suisun subregions between 1972 and 2008. In the Suisun region, the historically abundant calanoid copepods (*Eurytemora, Acartia*) and rotifers have declined significantly, whereas the introduced cyclopoid, *Limnothoina tetraspina*, has increased dramatically since 1990, partially compensating for the loss of biomass of other species. *L. tetraspina*, however, is a small bodied species, less suitable as food for Delta smelt and other native species. The Delta has also experienced long-term declining biomass of cladocerans and rotifers, although the introduced calanoid copepods, *Pseudodiaptomus* spp, have increased since the early 1990s. *Mysid* biomass declined significantly throughout the estuary at the end of the 1980s. Mean size of zooplankton has also decreased.

The changes in abundance, biomass and size composition of the zooplankton community imply major alterations in pelagic food webs, including a drop in prey quantity and quality for some planktivorous fish and an increase in the importance of the microbial food web for higher trophic levels. Beyond the inferred link between drought conditions and success of species invasions (Winder et al. 2011), it is not clear whether internal Delta flows have much direct impact on food web processes. However, as climate changes, more and longer droughts are projected which will push the location of X2 upstream, potentially increasing the likelihood of further invasions of exotic species. The Panel could not determine from the available information whether internal Delta flows could be manipulated to influence the transport of carbon (e.g., chlorophyll) from the Delta to the LSZ and possibly influence the zooplankton food base available to fish in the LSZ.

Statistical analyses directed at identifying the causes of the Pelagic Organism Decline (POD) included some covariates related to flows and to invasive species. MacNally et al. (2010) and Thomson et al. (2010) both examined the drop in abundance of delta smelt, longfin smelt, striped bass, and threadfin shad in relation to X2, water clarity, biomass of *Limnoithona* copepodites and adults during the summer, mean catch rates of inland silverside and largemouth bass during July-September, and a presence/absence variable for *C. amurensis*, among other covariates. Interpreting their results as to the effects of flow and invasive species is not straightforward as some of their other explanatory variables, such as zooplankton biomasses, included invasive species effects. Both analyses were inconclusive as to the causes of the POD, and they generally identified X2, water clarity, and volume of exported water as being correlated to the declines, not the dedicated invasion species explanatory variables. However, neither analysis was designed to address directly the relationship between flow and invasive species.

Flow Regimes, Invasive Species and Food Webs, Conclusions

Water management must consider the hydrograph over the entire year. Peak spring flows, access to floodplains, and sufficient flows in the summer and fall are important for creating conditions that encourage the success of native fish species. Maintaining temperatures cool enough in the summer, trying to maintain certain turbidity levels, consideration of the availability of floodplain and other habitats, and using extra caution during drought periods would also benefit native species. Actions that discourage the success of possible new invasives and contain the degree of success of existing invasives would be prudent. How internal Delta flows affect the transport of energy (organic carbon, chlorophyll) to the LSZ needs further investigation.

Flow Regimes, Entrainment and Salvage

Metrics useful for managing water diversions (e.g., water exports, Old and Middle River flow) must be used with caution because they represent highly aggregated measures of the velocities fish detect and respond to in the near field. Outflow is related to water velocity, but the latter varies on small spatial scales depending on bathymetry. In many cases, these and other environmental factors can have direct and indirect effects on processes of interest such as survival, growth, and migration of fishes (see Figure 2 in Miller et al. 2012; MAST 2012). Simulation models that explicitly link external factors to population and individual-level responses have shown that multiple factors can operate simultaneously to result in the decline of populations (Maunder and Deriso 2011: Rose et al. 2013a). The effects of a single factor, such as flow or the relative importance of any given factor, depends on species, life stage, hydrologic year-type, and time of year.

Water exports indirectly affect survival, abundance, and growth of Delta smelt and other fishes. A number of correlation-based studies bear this out, but provide little insight as to the mechanisms of action. For example, water diversions may alter hydrodynamics within the Delta and result in the transport of larval and juveniles fishes to habitats that are sub-optimal for growth and presumably, survival (Rosenfield 2010).

Losses of individual fish due to entrainment have been estimated from salvage rates, which in turn have been related to water exports. Salvage is the subset of fish that are entrained and pass through the export facility that are recovered and recorded, and can be represented as the product of two probabilities: probability of entrainment × probability of recovery at the export facility conditional on the entry of the fish into the facility (the latter depends on the efficiency of the louvers, among other factors). The use of salvage at the water export facilities to estimate entrainment has a long history in the Delta scientific community, and has been revisited and debated multiple times (Kimmerer, 2008; Miller 2011; Kimmerer 2011). Salvage is the result of multiple processes and does not include the indirect entrainment losses due to elevated predation, which are sometimes estimated in a separate step. The uncertainties and issues concerning the use of salvage to estimate entrainment persist because there is a relationship, however uncertain and incomplete (e.g., Delta smelt larvae are salvaged), and because the accumulated historical database on salvage allows for long-term analyses and comparisons. Advances in understanding the relationship between entrainment losses and interior Delta flows is problematic without a more reliable estimate of entrainment, which includes losses at the facilities, indirect losses in CCF, and consideration of all susceptible life stages. All of these are important to quantify with higher accuracy and precision than is possible with existing monitoring and analyses.

Improved measurement of salvage rates is possible (Grimaldo et al. 2009; Castillo et al. 2012), but a major issue leading to uncertainty in these measurements is the low experimental replication. Adequate replication of batches of marked fish released into the intake waters at the export facilities could provide more precise (and less biased) estimates of salvage rates. Salvage of small-bodied fishes such as Delta smelt, threadfin shad, and longfin smelt (Grimaldo et al. 2009) must be considered losses from the population because it is highly unlikely that these fishes survive handling and transport. However, salvage is not a useful proxy for mortality unless salvage rates are carefully calibrated with estimates of relative abundance in order to express the numbers of individuals salvaged relative to the number of individuals present in some defined area (Kimmerer 2011). Determining the population at risk of entrainment is problematic given that the Zone of Entrainment can vary dramatically depending on inflows, exports, temporary barriers, etc.

Losses resulting from the entrainment of fish, particularly Delta smelt and outmigrating juvenile Chinook salmon, in CCF remain uncertain, but the magnitude of this loss is likely to be significant in certain years for Delta smelt populations (Kimmerer 2008; Kimmerer

2011), and possibly, Chinook salmon as salmonid populations in the Central Valley are severely depressed. For Delta smelt, population-level effects of entrainment losses can be 'obscured' by the high variability (50-fold) in survival rates of fish prior to fall (Kimmerer 2008), and may explain why simple correlation analyses or regression approaches are unable to reveal the magnitude of entrainment losses. For example, Kimmerer (2011) showed that a loss of 60% or more of the Delta smelt population in spring would need to occur in order to detect the effect of OMR flow on entrainment losses using regression analysis. Field experiments involving the release of tagged fish into CCF may help to elucidate the magnitude of entrainment losses for Delta smelt and similar species. The residence time of water in CCF and variations in export volume are likely to affect entrainment and estimates of efficiency of the louvers at the export facilities; such effects may be identified using a weight-of-evidence approach.

Entrainment is an important source of mortality for the Delta smelt population in some years. There is growing consensus that entrainment effects are important at the population level on an episodic basis (Kimmerer 2008; Kimmerer 2011; Rose et al. 2013b), with the caveat of likely overestimation biases in entrainment fractions (Miller 2011). Entrainment was identified as a major within-Delta stressor for Delta smelt that could be influenced by management actions (Huggett et al. 2010). Kimmerer (2008) noted that larval and juvenile Delta smelt are rarely salvaged or entrained when Old and Middle River flow is northward. One of the Reasonable and Prudent Actions for Delta smelt is avoiding OMR flows that are more negative than a threshold value (Huggett et al. 2010) but what this value should be is a subject of considerable debate. The evidence is strong for a relationship between negative OMR flows and increased salvage of adult Delta smelt during the winter and suggestive of a relationship between entrainment of juveniles and OMR flow later in the year as they migrate to the LSZ (e.g., see Grimaldo et al. 2009). However, the data are sufficiently scattered that the exact nature of the relationship between OMR reverse flows and salvage is not obvious. There may be a breakpoint in the relationship. However, a continuous relationship may fit the data about as well as one that includes a breakpoint. Furthermore, the scatter in the data becomes larger as negative OMR flows increase, making it more difficult to specify a precise relationship. The Panel is not prepared to say, given the available data and analyses, whether or not there is a breakpoint in the data (threshold) or exactly where it might be. The links between salvage and entrainment and between entrainment and population-level effects on Delta smelt also involve considerable uncertainty, which magnifies the overall uncertainty associated with setting any flow standard (Huggett et al. 2010). Choosing a value of OMR flows to use as a tool for Delta smelt conservation involves a tradeoff between risk to Delta smelt and impacts on export water delivery. The tradeoff decision is not a scientific decision, but could be assisted by application of formal decision analytic methods.

The relationship between flow and survival of juvenile Chinook salmon during their migration through the Delta and San Francisco Estuary system has been examined using releases of tagged hatchery fish. Indeed, hatchery fish have been used in many field experiments in the Delta (e.g., Castillo et al. 2012; Zeug and Cavallo 2012; Cavallo et al. 2012), which is likely necessary given the large numbers of fish required for experimentation. However, if understanding the movements and survival of wild fish is the objective, then using hatchery fish as surrogates poses a number of problems. Hatchery raised fish differ in many ways from wild fish (e.g., Swain and Riddell 1990, Berejikian 1995, and Chittenden et al. 2008) and the assumptions associated with the use of hatchery fish as surrogates for wild fish do not appear to have been fully investigated in the Delta. Consideration of the differences between wild and hatchery raised fish might provide a different perspective on the results of these studies. As noted elsewere, the different runs of Chinook salmon also behave differently so that working out the complex patterns of salmon movement and survival in the Delta will involve a rather complex suite of experiments.

Survival of outmigrating Chinook salmon released in the interior Delta was consistently lower than that of fish released in the Sacramento River, and fish released in the interior Delta were 16 times more likely to be recovered at the pumping facilities (Newman and Brandes 2010). Increasing exports resulted in an increase in the proportion of tagged fish recovered at the pumping facilities between 1993 and 2005 (Newman and Brandes 2010), but the importance of water exports relative to environmental conditions was not clear. The inability to resolve the role of these factors may be due to the low number (15) of paired groups of hatchery fish released in this experiment. The authors suggested, and we agree, that many more paired releases would be required to detect the effect of exports on survival rates of juvenile Chinook salmon (Newman and Brandes 2010). Statistical power analysis should be part of the planning for any experiments of this sort to ensure that sufficient tags are released to provide a reliable result. Part of the problem may also be that a 3-day average of combined exports at the two export facilities was used in the model. Daily variations in exports were not well captured by this average.

Michel et al. (2013) used acoustically-tagged Chinook salmon to examine downstream movement in the Sacramento River during three dry years, 2007-2009. Movement rates increased with increasing flow and turbidity, but decreased with the ratio of river width to depth (slower movement in shallow, wide reaches). Flow was relatively similar among reaches but varied during the migration season; thus, variations in flow likely represented temporal differences and not spatial differences (Michel et al. 2013). Movement rates of outmigrating smolts were higher in upstream reaches and slowest in the Delta, suggesting that prolonged occupancy of the interior Delta may be associated with inadequate migration-route clues. Movement through San Francisco Bay was as slow or slower than movement through the Delta.

In addition to the relationship between water exports and fish mortality as measured by salvage rates and entrainment of Delta smelt (e.g., Grimaldo et al. 2009), researchers have attempted to relate exports to abundance indices derived from long-term monitoring data. The weak statistical influence of exports on abundance indices (Delta smelt and threadfin shad; MacNally et al. 2010) is not surprising given the uncertainties in the explanatory and response variables and the coarseness and potential collinearity among the explanatory variables related to exports. When exports are included in regression models along with other potentially influential factors, the importance of exports in contributing to variations in the abundance indices must be interpreted with caution, as these models provide partial regression coefficients that depend entirely on the presence of other predictors in the model. Thus, the unique effect of water exports is conditional on the other predictors in the model (see discussion of statistical inference earlier in the report).

Although predators have been invoked as a source of mortality for fish in the interior Delta, few studies exist on the magnitude of predation effects. Grossman et al. (2013) reviewed the available evidence and concluded that it was not possible to determine the proportion of juvenile salmon mortality that can be attributed to predation. In particular, information from the bioenergetics of predation within the estuary and interior Delta is surprisingly lacking (Feyrer et al. 2007). The Panel believes that such an approach could provide insight into predator-prey interactions in CCF, where predation mortality affects fishes entrained into CCF by water exports.

Improving Conditions for Native Fishes

Although interior Delta flows may be manipulated to achieve management objectives (e.g., OMR flows and entrainment; DCC operations), the efficacy of a given strategy is unknown and likely to depend on site-specific conditions. For example, opening the DCC gates significantly reduced the travel time and increased the survival rate of juvenile Chinook salmon migrating in the North Fork of the Mokelumne River (3.2 days vs 0.2 days; Cavallo et al. 2012), but the effect of flow on survival varied by reach. Flow was correlated with survival in a reach subject to predator removals, but not in a control reach (Cavallo et al. 2012). In both reaches, average daily flow increased by an order of magnitude in response to opening of the DCC gates. Reach-specific survival rates may be related to predator removals, but the results of this field experiment were inconclusive as it appeared that predators from adjacent habitats moved into the area previously depleted of predators. Such actions might benefit the native fishes as they traverse the Delta in the long-term, but will show highly variable responses year-by-year and could be largely tempered by other stressors negatively affecting the population of interest in other spatial areas or at other life stages.

Flow Regimes and Population Dynamics

Population Dynamics and Communication

There is need for more clarity in communications about flow and stressor effects on fish and fish populations. Phrases like “flow effects on fish” and “effects of reduced habitat” are vague and their use adds to the confusion about water management options and effects. Presentations during the workshop were also characterized by inconsistent use of terms and phrases. Flow itself can refer either to discharge or velocity. Altered flow and other stressors may affect individual fish, specific life-stage abundances, or total population abundances. Thus, a high degree of specificity must be used when describing effects of flow or other stressors. Abundance implies the total number of individuals in a defined geographic area. However, laboratory experiments and most field studies make measurements on individuals and may not reveal the effects of stressors on population abundance. In the case of fish species of concern (e.g., Delta smelt), long-term monitoring has sufficient spatial and temporal coverage to allow generation of indices of abundances (Fall Midwater trawl); however, these are indices of abundance and not true abundances. The distinction between an index and true abundance is important when flow and stressor effects are discussed because all indices and abundance estimates have biases and measurement error, but the biases and error are not necessarily the same between indices and abundance estimates. With repetitive and uncritical use, such indices can be increasingly mistaken for actual abundances. Likewise, when flow is used as a proxy for velocity, important changes in velocity fields along a reach (and through time) that may be very important to the fish will be masked.

To provide useful information, the effects of flow and stressors should be linked to processes of growth, mortality, reproduction, or movement of the species of interest. Mortality and reproduction affect numbers of individuals and, if properly scaled (i.e., samples are extrapolated to abundance), can be interpreted as affecting stage or population abundances. Growth affects the size of individuals, and because mortality rates and reproduction rates are almost always size-related, slow or fast growth can have significant effects on the numbers of individuals and with proper scaling, on population abundances. Movement determines the location of individuals through time. If environmental conditions were the same everywhere, movement would be inconsequential to growth, mortality, and reproduction, however, since environmental (e.g., temperature) and biological (e.g., predators) conditions vary in time and space, movement can directly affect growth, mortality, and reproduction rates. Movement can also indirectly affect mortality and reproduction through effects on growth.

Thus, discussion of flow or stressor effects on fish should be in terms of the relevant biological scale (individuals, life stage, or population) and metrics of abundance (true abundance estimate or an index) as well as the relevant metric for flow or the stressor. It will then be realistic to discuss how a change in flow or stressor affects growth, mortality, reproduction, and movement for a particular life-stage in a specific region and at a specific time. We recognize that consistent use of terminology and specificity will not solve any problems, but consistent usage will lead to increased clarity about points of agreement and disagreement during discussions. The conceptual models developed as part of the Delta Regional Ecosystem Restoration Implementation Plan (DRERIP, DiGennaro et al. 2012), the logic chains initiated with BDCP (Reed et al. 2010), and the recent update of the conceptual model for Delta smelt (MAST 2013) are useful ways to reach agreement on exactly which effects are being discussed and how they relate to population and food web dynamics and the link between effects and potential water management actions.

Population, Food Web, and Ecosystem

Although a population focus is useful, practical, and required in some circumstances (Endangered Species Act), it is important to keep the community, foodweb, and ecosystem perspectives in mind because sometimes these are more important in relation to particular stressors. Taking a population approach does not eliminate or ignore the community, food web, and ecosystem aspects; rather, these aspects are subsumed in the process rates (growth, mortality, reproduction, movement) represented in the population approach. This is important to remember because flow and stressors often affect the species of interest through their effects on other aspects of the ecosystem. There are direct effects between population processes and (flow and non-flow) stressors, such as contaminant exposure that causes an increase in mortality rate, but many effects (e.g., transport to habitats with less food or more predators) are manifested through the food web or through ecosystem dynamics. A population-centric approach still requires a certain amount of knowledge about the food web and ecosystem interactions and dynamics.

Food Limitation and Density-Dependence

Most fish experience food limitation in nature. We know this because when individuals are placed in a laboratory setting with unlimited access to food they consume more food than wild conspecifics. Food limitation is not necessarily a stressor. Food becomes a stressor when the degree of food limitation increases (i.e., organisms eat less and grow more slowly or produce fewer eggs than they ordinarily would) or when organisms increase their mortality risk in order to feed. However, food limitation does not necessarily mean that density-dependence is operating. Density-dependent growth occurs when individuals reduce the amount of prey available to conspecifics (i.e., crowding reduces prey abundance, which leads to decreased growth rates). Fish can be severely food limited but if their densities are low, then density-dependent processes are not likely to be operating despite the severe food limitation. It is also important to distinguish between density-dependence that is continuous versus density-dependence that results in a bottleneck at a particular life stage. An example of continuous density-dependence would be declining growth rates with increasing life-stage abundance, while an example of a bottleneck would be juvenile production proportional to larval production until a critical habitat becomes saturated, and once saturated, mortality increases such that no additional individuals survive to the juvenile stage. The specification of management actions and expectations for responses depend on a clear understanding of the degree of food limitation and the likelihood of density-dependent controls.

Stressors and Separability

There is general agreement that the dynamics of listed populations in the Delta (resulting from growth, mortality, reproduction, and movement) are affected by multiple stressors. Perhaps less apparent is the complicated manner in which flow-related and other stressors interact or combine to affect population abundances. Attempts to attribute declines (or increases) in fish indices of abundance to a subset of the broad list of stressors (i.e., to "assign blame") are widespread. Some investigators have attempted to rank stressors according to the severity of their effects (e.g., Huggett et al. 2012), but this strategy assumes a great deal of separability among the multiple stressors, which is usually not possible. Stressors may exert indirect effects and may covary with other indirect or direct stressors, further complicating attempts to identify the stressor that is most or least important in affecting change to the individual or the population. Indeed, this approach assumes the existence of a static ranking. Even if a ranking of stressor importance was possible, the ranking could change with changes in the ecosystem. Specificity is needed to describe the logic trail from management actions to multiple, potentially interacting, stressors to the processes of growth, mortality, reproduction, and movement of the species or life stage of interest.

Adaptive Management and Multiple Stressors

Adaptive management (AM), if properly implemented, could provide an approach to unravel the inter-relationships among multiple stressors. Active AM involves direct and purposeful manipulation of the system, which then ensures appropriate covariation among the stressors, and allows for responses to be measured in nature. In the Delta, potential AM actions are constrained because several species are protected under the Endangered Species Act, and because of the multitude of demands for water from the system. Nevertheless, projects such as the VAMP (Vernalis Adaptive Management Program) and FLaSH (Fall Low Salinity Habitat) have involved deliberate manipulation of flows to test hypotheses about the relationship between flow parameters and Chinook salmon survival (VAMP) and Delta smelt abundance (FLaSH). Furthermore, there is now a "forced" or coerced AM program dictated by court proceedings (Hastings presentation at the SWRCB Delta Outflows and Related Stressors Workshop, February 11, 2014). Issues and opportunities around the use of adaptive management are discussed further in the section on adaptive management.

Modeling and Multiple Stressors

Two major approaches have been used in the Delta for quantifying the effects of stressors (either singly or in combination) on fish. One is a correlation analysis of abundance indices in relation to flow, temperature, food, and predators (MacNally et al. 2010; Thomson et al. 2010; Miller et al. 2012; many PowerPoint presentations at the workshop). These analyses have a long history in the Delta and have provided some insights into important covariates (but see section on statistical inference). People sometimes refer to this approach as (statistical) modeling of abundances. The second approach is to simulate population abundances over time and space by explicitly representing growth, mortality, reproduction and movement rates. Such life-cycle population modeling has progressed during the last five years, but the progress has been uncoordinated and, at times, even confrontational. The two approaches are fundamentally different. Correlation analyses use measured values of state variables (e.g., indices, densities) and relate those values to covariates over time (i.e., correlation analyses explain variability). Understanding or specifying how the covariate affects the state variable (e.g., abundance index) is not required. Life-cycle modeling, on the other hand, represents the rates of change of the state variables (e.g., abundance of larvae) and then solves the differential or difference equations to obtain the values of the state variables such as abundance over time. In life-cycle modeling, the relationship between the stressors and rate of change of a state variable must be explicitly specified (e.g., mortality rate as a function of water velocity). One of the strengths of life-cycle modeling is that all effects of stressors must be defined quantitatively as a relationship between the stressor and growth, mortality, reproduction, or movement. Otherwise, the equations of the model that include the stressor effects cannot be solved.

Almost everyone accepts the utility of modeling in general terms but issues frequently arise with specific models. These issues arise in part from the challenge of documenting (communicating) the details of a model, and in part from the need for the model builders to make judgment calls about the specific relationships or data that are used in the model. The kinds of judgments or assumptions that must be made depend on the kind of model. For example, statistical modeling uses data to determine which model is best, and disagreements center on data evaluation techniques such as which transformation is best and which observations are considered to be outliers. Hydrodynamics models all solve the same basic set of fundamental physics equations (i.e., conservation of mass and continuity of momentum), so that the major judgment decisions in hydrodynamic modeling concern development of the model grid and how to address subgrid-scale processes (e.g., turbulence). Life-cycle modeling relies heavily on expert judgment to formulate the specific numerical relationships among variables and there are many possible approaches to designing the model. This does not mean life-cycle modeling provides weak inference but it does present challenges in documentation, communication, and comparison among alternative models. Conflict in life-cycle modeling typically centres on these expert judgments. Initial guidance for life-cycle modeling was provided in the life-cycle model of Central Valley salmon (Rose et al. 2011), and there is now a growing trend toward using life-cycle models in large-scale ecosystem restoration.

Managing Expectations

Stakeholders may have an unrealistic expectation that fish populations targeted by a management action will respond quickly (immediately) and decisively. Population responses are either measured with monitoring data as indices of abundance or may be predicted using models. When the measured indices do not match expectation, there is often a premature conclusion that the action was ineffective or the model was incorrect. Fish population dynamics is often highly variable, which presents challenges to both monitoring and modeling (Rose 2000). Fish have complex life cycles, with different life stages having different habitat requirements, and population processes are affected by multiple environmental and biological factors that often exhibit interactive effects. Fish populations, even short-lived species like Delta smelt, can exhibit lagged responses. The expectation of an immediate and unequivocal response to a management action is often unrealistic and can create inefficiencies in water management. Inefficiencies arise because an action can be prematurely deemed ineffective when it is in fact, effective, and then a more stringent action (e.g., one that requires more water) or a different action (which is actually less effective) could be selected.

Stakeholders may also harbor unrealistic expectations about the level of certainty of the knowledge gained from statistical and life-cycle modeling. Even the best statistical models will leave substantial variance unexplained, and parameter estimates based on past observations from an ecosystem that is constantly changing may not provide useful statistically-based predictions of the future under different management actions. Life-cycle models are also unlikely to fit the data as well as some would expect or hope, but that is part of the price for having a tool to predict responses to previously unobserved conditions. The best approach is a weight-of-evidence approach, whereby all of the analyses are undertaken in a planned and coordinated manner, or at least in an exchangeable manner and then synthesized (see discussion of statistical inference).

Delta Smelt and Stressors

Perceptions of the major stressors (flow and non-flow) that affect Delta smelt population dynamics have evolved, largely driven by new data and modeling results. Conceptual models, statistical analyses of long-term monitoring data, and the development of life-cycle population models have all contributed to this evolution. For example, a series of conceptual life-cycle models for key species, including Delta smelt (Nobriga and Herbold 2009) was developed for the DRERIP. This was followed by a conceptual model based on the analyses of the POD team (Baxter et al. 2010), and this model is being refined again as part of the Management Analysis and Synthesis Team (MAST 2013). Statistical analyses of the monitoring data concerning the POD were reported in MacNally et al. (2010) and Thomson et al. (2010) whereas Miller et al. (2012) reported on a correlation analysis of the monitoring data. Finally, life-cycle models designed to examine stressor effects have been published (Maunder and Deriso 2011; Rose et al. 2013a,b), and there is an ongoing program to construct additional life-cycle models at the U.S. Fish and Wildlife Service (Newman, USFWS, personal communication). It is hoped that these models will provide new insights into ways to manage water in the Delta for the benefit of Delta smelt.

Several flow and non-flow related stressors have been implicated in Delta smelt population dynamics. These include: 1) sporadically high entrainment of adults (winter) and larvae and juveniles (spring); 2) spring water temperatures that reduce the duration of the spawning season; 3) warm summer-fall water temperatures that decrease growth of juveniles and adults; 4) decreased summer-fall habitat in the LZS for juveniles and adults due to changes in salinity and water clarity; 5) reduced quantity and changes in species composition (reduced quality) of zooplankton prey leading to decreased growth of juveniles and adults, and thereby, to decreased egg production; 6) increased predation mortality; 7) reduced growth of juveniles and early adults (winter and early spring) prior to spawning; 8) a flattened annual hydrograph with elimination of peak spring flows; and 9) eastward (up estuary) positioning of X2 that limits access to habitats where growth is rapid and mortality is low. Although it is generally accepted that these stressors affect Delta smelt dynamics there is no agreement on their relative importance. The data and reasons why these stressors are important to Delta smelt has been discussed in detail elsewhere (most recently in MAST 2013). Of these stressors, entrainment is truly a "within Delta" management issue. Water management and operations affect many of the other stressors which depend on the amount of water diverted and thus, those stressors are primarily related to outflow considerations (see report on Outflow and Related Stressors).

A possibility that may not be feasible or practical is to use water management within the Delta to augment production in the LSZ. We note that this idea was not considered in the materials provided to the Panel. The LSZ plays an important role as critical habitat for Delta smelt and other species (Sommer et al. 2011; Rose et al. 2013a,b). A recent intensive study documented how primary production within the LSZ is influenced by imported production from up-estuary sources (Kimmerer and Thomson 2014). Clearly, outflow can influence the location of the LSZ. But can chlorophyll be transported to the LSZ by management actions that control the mix of waters from the Sacramento and San Joaquin Rivers and the pathways along which water is routed within the Delta? We don't know, but believe it is worth exploring the possibility of such management action.

Salmon and Stressors

Tagging studies with juvenile Chinook salmon and to a lesser extent, juvenile steelhead, consistently point to large variability in survival rates associated with migration routes (Perry presentation at Workshop); and for a given migration route, annual variability in survival rates is high (Brandes presentation at the Workshop). Survival of outmigrating salmon was highest among fish using the Sacramento River route; fish that used the interior Delta always exhibited lower survival rates. Although flow was an important determinant of the proportion of fish surviving and arriving at Chipps Island, behavior of fish also contributed to variation in survival rates (Jackson presentation at the Workshop). Using a mechanistic model of the movement of coded-wire tagged juveniles, Jackson and others demonstrated that fish that swim with downstream flow and hold otherwise or that swim with the ebbing tide and hold otherwise have significantly higher survival rates than fish exhibiting other behaviors (such as passive drifting or swimming at night only). Survival rates of fish using the more 'successful' behavior did not vary with flow (measured in cfs), suggesting that behavior of fish can modulate flow effects. Fish exhibiting less successful behaviors, however, may be subject to the negative effects of flow. *In situ* studies of individual fish behavior are likely to provide greater understanding of the manner in which individuals interact with velocity fields at river junctions to select migration routes (as demonstrated by Burau at the workshop). Observations of tagged fish in Clarksburg Bend indicate that route selection depends on the position of fish in the river relative to the streakline, the timing of their arrival at the junction, and local hydrodynamic conditions. Predators may alter the behavior of outmigrating fish, thereby affecting the position of juvenile salmonids in the river or their arrival time at critical junctions; such modified behavior may increase the likelihood of selecting a route with lower survival rates.

Accurate estimates of survival rates of outmigrating juveniles require a high degree of experimental replication, which may not have been achieved in previous studies. However, large-scale, manipulative field experiments are logistically challenging and costly. Coordinated and collaborative studies are more likely to provide significant gains in understanding and reveal important mechanisms. We encourage their pursuit. Coded wire tags have provided important coarse grained estimates of survival but as the questions become more refined acoustic tags provide finer grained estimates of both behavior and survival. It is clear that behavior of individuals is paramount to understanding mechanisms, and as such, acoustic telemetry studies can provide the necessary information. Acoustic tags allow survival to be measured with greater precision and along relatively small reaches; in this manner, reach-specific survival rates may be estimated and rates for multiple reaches combined to yield route-specific survival rates (Brandes presentation at workshop). In conjunction with these studies, physical and non-physical barriers may be tested for their efficacy to alter migration routes. Other approaches such as alteration of habitats to provide effective refuges from predation or suitable areas for fish holding should be investigated as well. The role of predators in migration-route selection and migration-route survival also warrants consideration.

Flow Regimes, Programmatic Science, and Adaptive Management

The Importance of Well Structured Programatic Science

Programmatic science, composed of multiple, individual studies performed by a team of investigators, is now the most common form of science performed to address large complex resource management problems. It must conform to standards in addition to those used to gauge the scientific quality of single studies. Science performed at the programmatic scale, particularly as implemented by State and federal agencies, has a strong applied component. That is, the outputs and conclusions of individual scientific studies must be integrated to generate comprehensive, multi-disciplinary and broad-scale findings that can be used to support robust decision-making either directly or indirectly by feeding into decision-analysis and support tools. These tools allow decision makers to use scenario analysis (as is traditional in water resources planning and as is becoming more acceptable in natural resources planning (Rowland et al. 2014)) and other methods to make good decisions in the face of uncertainty and conflicting objectives.

Science Program Foundation

Science program quality can be best understood by examining the structure of a typical science program organized to support resource management decisions (Figure 7). The program can be separated into three major parts. The first part is comprised of a set of scientifically challenging questions and issues about management of critical natural resources. These questions and issues must be stated clearly and unequivocally so that the scientific community can use them to structure scientific investigations.

A well-designed science program will include a portfolio of conceptual models that describes how the system components are organized and how they may each respond to internal system dynamics and various natural and anthropogenic drivers. Importantly, these conceptual models should connect potential management actions (derived from questions and issues) to possible resource or system responses. The conceptual models may need to be updated as the program is executed.

Science Program Information Transformation

The second part of the program is a science information “machine” (information processing strata) that progressively transforms raw data into knowledge that can be used to support resource management decisions (Figure 7, pyramid levels 3-8). The base of the pyramid (3) is comprised of the system components and critical resource categories. At the next higher level is an integrated set of scientific studies (4) that collect, synthesize, and collate data identified by the conceptual models. As the program is executed, data obtained by individual studies (4) are summarized and integrated into progressively more comprehensive syntheses (5) – shown as a single stratum in Figure 7, but could be multiple strata or a network. Study results are coordinated with partners and stakeholders (level 6 in the pyramid) prior to a rigorous tradeoff analysis using a variety of decision-analysis tools (level 7). The product of the information machine is a set of robust decisions (level 8) that meet program objectives and make maximum use of scientific inputs.

Minimizing Knowledge Leakage

The third part of the program is comprised of three steps to help reduce knowledge leakage during data summarization and synthesis. This part of the structure is important because knowledge leakage (labeled 9 in Figure 7) is an inevitable corollary of data synthesis as individual data points are systematically replaced by trend lines, regression analyses, simple models or other types of approximations and data that appear inconsistent with the emerging synthesis are marginalized or ignored. The first step to reduce data leakage is the development and use of information technology (labeled 10 in Figure 7 - symbolically represented as a fabric matrix underpinning program structure) to ensure that all relevant data can be readily used to meet program objectives. The information management system ensures that all program-level information is properly collected, validated, archived, and retrievable. The use of information technology helps the program recognize science quality criteria that are in addition to the single study criteria identified earlier. Program data must be collected or synthesized at scales appropriate to the process or resource category of interest, but must also be:

1) consistent with the needs and expectations of all team members that may use the data (including modelers and decision analysts);
2) representative of the state-of-the-art in its component disciplines (or nearly so), of a form and scaling that will support future decision-making;
3) readily available in useful formats to all study partners; and
4) accompanied by metadata describing methods, shortcomings, error and uncertainties, and other descriptors that are needed to understand the information content of data sets.

A useful guide to development of an information management system can be found for the description of the multi-disciplinary National Science Foundation funded NEON project at http://www.neoninc.org/about/FAQ.

The second approach to reducing knowledge leakage is the requirement for horizontal communication among program participants. Goals, objectives, funding, and authority are typically distributed outward from a centralized source to widely distributed program participants who in turn report data and findings upwards back to the program office. In such a setting, there is a natural tendency for communications to occur vertically (represented by the vertical arrows in Figure 7) across program strata. Necessary horizontal communication (represented by the horizontal blue arrows in Figure 7) typically does not occur unless program participants are so inclined by friendship or collaboration experience. Establishing and maintaining horizontal communication among program researchers must be an important component of the program's science structure and can be achieved through workshops, collaborative studies, and joint publications.

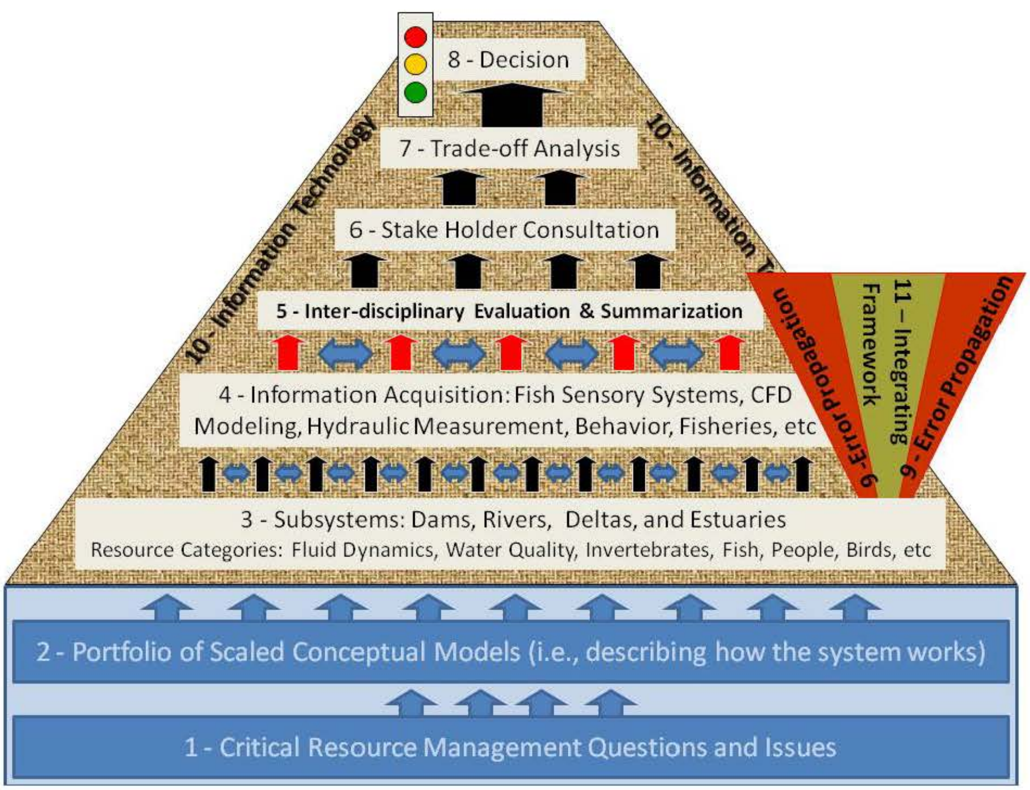

Figure 7. Symbolic representation of components of programmatic science:
Foundation level (transparent blue) comprised of a set of consensus management questions and issues (1) and portfolio of conceptual models (2). The questions and issues focus the

portfolio of conceptual models describing, in general terms, how researchers and resource managers think the ecosystem works (or did work prior to degradation).
Science information "machine" (pyramid of information processing strata) that progressively transforms raw data into information that can be used to support wise resource management decisions (pyramid levels 3-8). The base of the pyramid (3) is comprised of the system components and critical resource categories. An integrated set of scientific studies (4) derived from the conceptual models (2) collects, synthesizes, and collates data identified by the conceptual models (2). As the program executes, data obtained by individual studies (4) are summarized and integrated into progressively more comprehensive syntheses (5) – shown as a single stratum, but could be multiple strata or a network). Study results are coordinated with partners and stakeholders (6) prior to a rigorous tradeoff analysis using a variety of decision-analysis tools (7). The product of the information machine is a set of robust decisions (8) that equitably meets program objectives making maximum use of scientific inputs.

The third approach to minimizing knowledge leakage is the use of an integrating framework (labeled 11 in Figure 7). A variety of such frameworks have been used successfully in different contexts. Nestler et al. (2007) used the Integrated Reference Framework Concept to optimally structure computational fluid dynamics modeling, juvenile salmon movement data and projections, and fish behavior into a single, relatively seamless framework (Goodwin et al. 2006) useful for decision-making (Goodwin et al. 2014). The Chesapeake Bay program uses a large-scale estuarine water quality model as an organizing template (Cerco and Cole 1993, Cerco 1995a, b, Cerco et al. 2010) and the Comprehensive Everglades Restoration Program uses hydrologic and landscape models as an organizing framework (Swain et al. 2009, Sklar et al. 2001, see also South Florida Water Management Model and River of Grass Evaluation Methodology (ROGEM) at http://www.evergladesplan.org/about/rest_plan_pt_07.aspx and the Model Tab at http://cerpmap1.cerpzone.org/arcgisapps/cerpmms/mmsviewer/). Without an organizing scientific framework, program management may deteriorate into "cat-herding" as each investigator employs organizing principles unique to their individual disciplines that may not be compatible with other investigators. Without an appropriate organizing framework it may prove difficult or impossible to synthesize data across disciplines in a form that supports robust natural resource decision-making.

Methods for managing error propagation (fabric-textured triangle and red/green triangles in Figure 7) are required to minimize knowledge leakage during data summarization and synthesis. A sophisticated information management system (9) must be constructed to facilitate horizontal and vertical communication and information exchange. Error propagation (10) is an inevitable byproduct of summarization and synthesis, but can be minimized with use of an integrating framework (11).

We note that many of the studies documented in presentations we were shown or in papers that were provided for review do not meet the quality criteria for program science. For example, the use of legacy analyses correlating fish entrainment to negative discharge in the

OMR may be scientifically adequate in isolation from the availability of detailed computational fluid dynamic model outputs. However, in a program context, these analyses should take advantage of the more recent models. To maintain consistency with historic data, the models should be rerun to simulate the time periods covered by the fish salvage data from the State and federal water projects but moving forward, modern CFD models should become the foundation of management decision-making. The scientific problems associated with the use of legacy scientific analyses is described in more detail in another section of this report (see the section on flow and turbidity).

Adaptive Management

Adaptive management was introduced to the management of Delta flows and habitats with the CALFED Bay-Delta program. The CALFED Strategic Plan for Ecosystem Restoration (CALFED 2000) provides a description of the adaptive management process as developed for the ecosystem restoration program. The Delta Plan articulates a similar description of adaptive management (Delta Stewardship Council 2013) as a process involving three stages: plan; do; evaluate and respond. These descriptions both emphasize that adaptive management is about acknowledging uncertainty and treating complex management problems as opportunities to learn about the system from management interventions. Both documents define adaptive management as a structured process that requires careful definition of the management problem, use of conceptual and simulation models to explore how the system is likely to respond to various management interventions, rigorous design of the management intervention to ensure that it generates statistically reliable information about the system and timely analysis of monitoring data to feed into ongoing management decision-making.

As adaptive management has been implemented in the Bay-Delta and elsewhere in the U.S. and other countries (notably, Australia) it has tended to morph into something of a hybrid between historic approaches to management, which largely ignored uncertainty, and fullblown adaptive management, which views every management intervention as an opportunity to reduce uncertainty through experimentation. What we are calling a hybrid approach represents a significant advancement in that it accepts the necessity of monitoring and assessing quantitatively the outcome of management interventions (something that was frequently absent from past management) and thereby captures, at least superficially, the three stages of adaptive management (plan, do, evaluate and respond). Under the hybrid approach, management interventions are seldom designed specifically as experiments to address uncertainty. Instead, major uncertainties are addressed through a separate program of targeted research.

The hybrid approach has both strengths and weaknesses. Since management problems are complex, involving many uncertain variables and processes, it is not practical to design a management experiment to address the spectrum of uncertainties. Targeted research projects may, in fact, be the most practical way of improving understanding of the system and ultimately reducing uncertainty. The targeted research program is also likely to be more attractive to the scientific community, which typically adopts a reductionist approach to complex problems. Inefficiencies can arise, however, if the various targeted research projects are not designed within a well structured agency research program so that the results from individual projects can be efficiently and effectively synthesized into a better understanding of the system as a whole (see Section on Programmatic science). Furthermore, the management action itself, if relieved of the requirement to be designed as a rigorous experiment, may produce little practical information, either about the system being managed or about the effectiveness of the management intervention (Walters 1997).

The difficulties of implementing a rigorous adaptive management program are well described in the literature (Walters 1997, Gregory et al. 2006, Allan 2008, Allen and Gunderson 2011). The difficulties of implementation notwithstanding, most commentators continue to argue that adaptive management represents a powerful tool to assist managers and policy makers to address problems characterized by high uncertainty in the dynamics of the system being managed. However, adaptive management is not and should not be the only management approach available to managers. Not all problems are best addressed by adaptive management, regardless of the degree of uncertainty in system dynamics. Even when adaptive management is the appropriate prescription other constraints may limit its effectiveness. It is in the context of these considerations – the form of adaptive management implemented in the Delta and the fact that adaptive management is not universally applicable to all management problems – that we address the question of how and when adaptive management could be used in managing interior Delta flows.

Large-scale water management is generally considered to be a "wicked problem". Rittel and Webber (1973) coined this term to refer to large-scale, complex problems in public policy that defy clear scientific definition. Characteristics of wicked problems relevant to adaptive management include:

1) The problem involves an evolving set of interlocking issues and constraints. Hence, there is no definitive formulation of "the problem" and perceptions of the problem and its causes are likely to differ dramatically among interests. That is to say, uncertainty and conflict are high.

2) Since there is no definitive formulation of the problem, there is also no definitive solution. In fact, the problem is often defined in terms of solutions that are considered workable by various interests. Multiple and conflicting solutions are often in play.

3) Solutions are not right or wrong, only better or worse.

4) Experience with analogous problems in other contexts may not be relevant. This is because wicked problems have high social and political content, which tend to be location specific.

5) Potential solutions are costly and usually irreversible. Any choice of solution commits society to sets of consequences many of which are unknown at the time the choice is made.

6) There is no ultimate test of a solution. Rather, all solutions have successive waves of consequences and it is impossible to know how all will play out. As the system evolves in response to management interventions, managers must continually develop new approaches.

Many features of wicked problems suggest that they can best be tackled by adaptive management and numerous experts have championed this application of adaptive management (Habron 2003, Gunderson and Light 2006, Allen et al. 2011). Characteristic one above implies that the process of solving the problem is identical with understanding its nature so that learning about the problem through management seems imperative. The existence of multiple and conflicting solutions implies that some form of experimentation might allow managers to determine which solution(s) produce the best consequences. Other features, however, appear as obstacles to adaptive management. At the whole-system scale, the irreversibility of solutions (e.g., building the isolated facility forecloses on other solutions) effectively eliminates the possibility of testing alternate solutions. None of this undermines the potential value of a carefully designed adaptive management program as a means to understand the managed system better. It does, however, point to the need for managers and policy makers to consider a range of management options whereas at present adaptive management is offered as the overwhelming if not the only approved choice.

Allen and Gunderson (2011) offer a taxonomy of management and policy design approaches for complex problems in relation to uncertainty and controllability (Figure 8). In this taxonomy, adaptive management is most applicable to situations with high uncertainty and high controllability. As far as interior Delta flows are concerned, there is some controllability through variations in export pumping, opening and closing of gates, and reservoir operations. However, there are important constraints on all of these controlling variables. The Vernalis Adaptive Management Program (VAMP) provides a good illustration of the difficulties of conducting an active adaptive experiment in the Delta. VAMP was designed to assess the relationships between flows at Vernalis, export volumes, and survival of migrating Chinook salmon smolts. The planned experimental conditions included flows at Vernalis that ranged from 3200 to 7000 cfs and exports that ranged from 1500 to 3200 cfs. Despite best efforts, even these relatively low contrast conditions could not be met. Over the eight years of the experiment, Vernalis flows were 3200 cfs and export flows were 1500 cfs during five years, Vernalis flows were 4450 cfs and exports 1500 cfs during two years, and Vernalis flows were 5700 cfs and export flows were 2250 in one year (Herbold oral presentation). There were no years of high Vernalis flow with low exports and no years of low Vernalis flow with high exports, the conditions that would have provided maximum contrast in the experiment. Results of the experiment did not reveal any unqualified relationships between survival and Vernalis flow or exports although when data from other years were included there was a statistically significant relationship between survival and flow at Vernalis when the Head of Old River barrier was in place (Hankin et al. 2010).

An important lesson from VAMP in terms of adaptive management is the difficulty of achieving sufficient contrast in flows in a highly constrained and managed system like the Delta. Another important lesson in terms of adaptive manipulation of large-scale systems is the unexpected problems that can arise when many years are required to gather sufficient information. The VAMP was designed to run for 12 years, which included only eight combinations of Vernalis flow and exports, a rather small number of replicates for any statistical comparison. Yet, over this time period there appeared to be a long-term decline in Chinook salmon smolt survival, which added additional variability into the results. Uncontrolled and unanticipated changes of this sort are likely to bedevil any experiment that extends over many years. Large-scale experiments that extend over many years may not be an efficient way to address uncertainty. A more practical approach may be to employ the hybrid approach but ensure that the monitoring design is rigorous and informed by a well formulated system model so that the data have at least the potential to clarify system behavior. The monitoring program should also be predesigned to take advantage of any unusually high or low flows that will provide maximum contrast for the model. At the same time, specific features of the model (e.g., the effect of attributes of the flow field) could be addressed through localized targeted research.

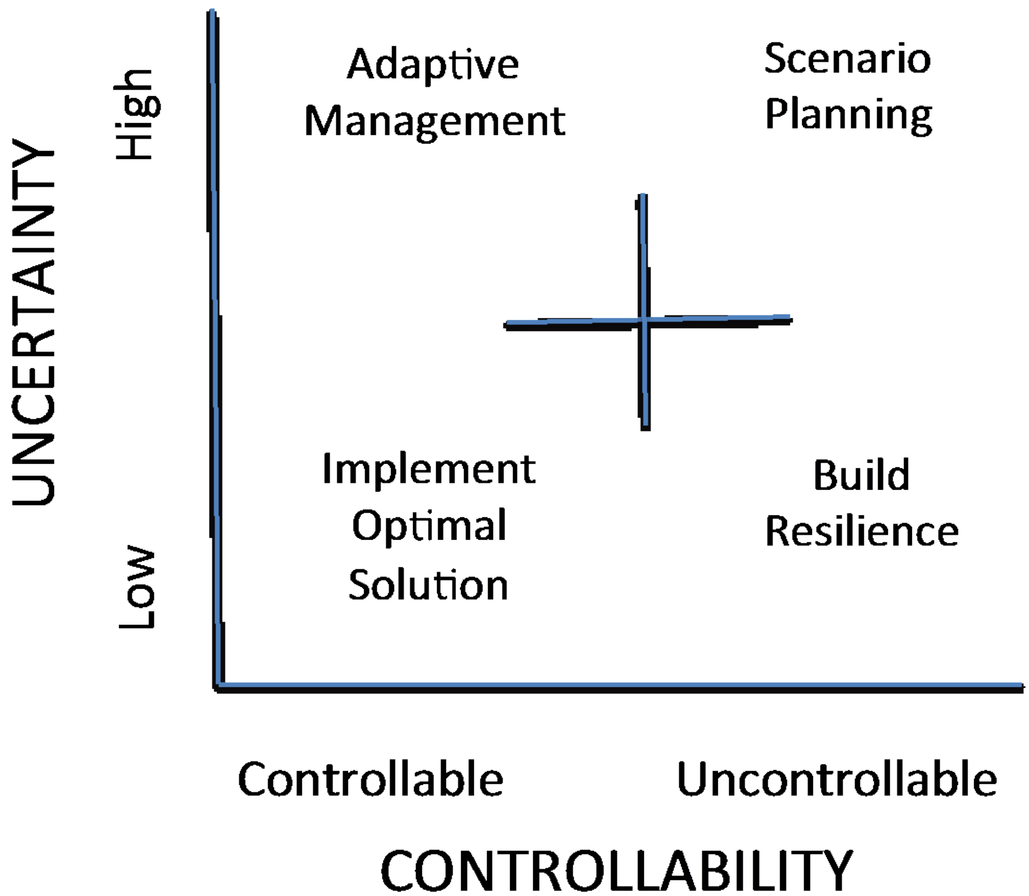

Figure 8. Taxonomy of management and policy design approaches in relation to uncertainty and controllability (Adapted from Allen and Gunderson 2011).

More traditional adaptive management involving flow manipulation may be effective where the uncertainty is well defined, involves only a single flow variable or situation and, in particular, where several data points can be collected over a short time period. An example might be the effect of reverse flows of various magnitudes in OMR on the entrainment of Delta smelt. The development of miniature acoustic tags has greatly expanded the potential for experimentation examining the effect of flow and velocity fields on entrainment of juvenile Chinook salmon. Similar experimentation with Delta smelt is much more difficult but it might be possible to fit hatchery raised smelt with PIT tags and to monitor their entrainment in particular locations with appropriate antenna arrays. In any event, the effects of OMR flows on Chinook salmon smolts is amenable to such local and short term experimentation.

Figure 8 offers three management tools in addition to adaptive management that are appropriate for different combinations of controllability and uncertainty. Where uncertainty is low and controllability is high, optimization methods can be used to identify the best management intervention. Even theoretically optimal management interventions need to be carefully monitored, however, to ensure the outcomes are as expected. Where uncertainty is high and controllability is low, Peterson et al. (2003) suggest that scenario planning is an efficient approach. Scenario planning involves negotiation among interests over possible futures under different operating and management programs. It is particularly useful for examining the mid- to long-term impact of factors like climate change, species invasion, or a significant seismic event in the Delta on both the ecosystem and water supply. Alternative possible scenarios can provide a foundation for developing contingency management approaches. Exploring "what if" futures through scenario planning can identify potentially serious pathologies in present and planned management systems. Scenario planning also allows a broader examination of the intricate and convoluted nature of wicked problems than adaptive management, which demands a more narrow definition of the problem. Scenario planning has not been much used in natural resource management as yet but Rowland et al. (2014) offer some useful examples of its application.

Where both uncertainty and controllability are low, Allen and Gunderson (2011) suggest that building resilience is the best management approach. Resilience is defined as the capacity of a system to resist pulse and press stressors without fundamental change in ecological character. Building resilience implies that managers are able to identify thresholds for dynamic change in the ecosystem and are able to steer the system away from these thresholds.

So far as we are aware, neither scenario planning nor resilience building have received any serious attention in developing management plans for the Delta. Adaptive management remains the management model of choice, but as we have shown, adaptive management is not the best approach in some circumstances. We suggest that Delta management would benefit from a more diverse toolbox of management models, particularly as the problems to be addressed range from the tame to the wicked (Rittel and Webber 1973). A long-term strategy that the region should consider is to use advances in science and computer science to shift the management problem from the peripheral quadrants of Figure 8 closer to the origin. There is a long tradition in the physics-based disciplines of studying complex systems by first developing a family of equations that appear to describe the salient dynamics of the system. Conclusions about the system are derived from the mathematical behavior of the equations. Many of the questions and issues in the Delta meet this tradition. For example, if one dissects the phrase "fish behavior in response to flow", then flow simulation is certainly in a deterministic paradigm. The mechano-sensory system of fish allows it to couple its behavior to the small-scale physics of flow fields and this coupling can be modeled. Sensory response to salinity, geomorphology, and aspects of water quality could similarly be modeled. Increased use of physics based models coupled to biological response (e.g., Goodwin et al. 2014) would help shift issues into the "controllable" area. This shift will decrease the dependence on the more subjective approaches in Figure 8.

Conclusions

In this section we show more explicitly how our discussion above is related to the charge questions.

> *Charge Question 1: What are the key studies and synthesis reports that the State Water Board should rely on in making their decisions on interior Delta flow requirements? Please comment on the strength, relevance and level of certainty of the science presented and reviewed*.

The Panel reviewed the literature provided by the Delta Science Program, but these studies represented only a small fraction of the literature relating to Delta interior flows. Some of the individual papers were quite good but it is difficult for us to say what are the key studies and synthesis reports without having surveyed much more of the relevant literature. However, in all of the assigned reading and panel presentations, we saw very few, solid, quantitative estimates of effects. The Panel was concerned that little experimentally validated quantitative guidance on flow management was available to the Board. We think that Delta science can provide the Board with much more directly applicable, quantitative guidance on flow management.

In the section on quality of science we provide a set of criteria that we hope the Board will find helpful for identifying the most useful science on which to base updated flow standards. A more comprehensive list of criteria for assessing quality of science is provided in Table 2. In addition, we suggest the Board look favorably on synthesis papers that have the following characteristics:

1. Any hypotheses the authors purport to test must be established *a priori*, not developed after the fact to validate relationships found by searching through a large data set and screening the data with a number of statistical models.
2. Statistically reliable analyses will report parameter estimates (i.e., effect estimates) rather than simply reporting significant P values. In addition, uncertainties will be characterized by confidence intervals and/or expected prediction errors. Such an analysis may also compare the predictive performance (e.g., mean squared errors or explained variance) of alternative models.
3. Models must not be overfit. The ratio of independent observations (the data) to the number of model parameters that is fit should be at least 10. Ideally, the model will be fit with a subset of the total data (the training set) and then the fitted model will be tested by using it to "predict" the balance of the data.

The vast majority of inferences about the effects of flows in the Delta on listed species are based on correlation analyses. Although correlation analysis is a useful first step when searching for relationships among variables, it often tells little or nothing about cause and effect. Correlation analyses need to be followed up with carefully designed experiments to test any hypothesized causal relationships, and with numerical and simulation modeling to explore the likely effect of management manipulations. To date, hydrodynamics is the only aspect of the Delta environment that has a solid base of theory and numerical modeling.

Delta ecology and processes linking hydrology with ecology have some theoretical underpinning, but there has been very little exploration of theory with numerical or simulation modeling.

> *Charge Question 2: Interior Delta flows have been altered in many ways, including timing, magnitude, variability, and in some cases, net direction.What are the relationships between these altered interior Delta flows and native fish survival, abundance, spatial distribution, migration, and life history diversity?*

The transformation of the Delta from a network of marsh channels with large floodplain-like storage at high tide to a network of prismatic channels with virtually no wetting or drying must have dramatically altered tidal propagation, tidal flows, and tidal sediment dynamics. In particular, the pre-alteration Delta must have been much more dissipative for tides and more depositional for river-borne sediments. Presumably, the Delta might also have been fresher since a reduction in tidal mixing and the reduction in channel depths both imply a reduction of landward salt fluxes. The impacts of restructuring the Delta on native fishes must have been profound as we can assume that native fishes were adapted to the habitats and flows that existed prior to this transformation.

Fish in the Delta are subject to a large number of stressors and untangling the independent effects of these stressors has proven very difficult. Population modeling and other analyses indicate that declines in native fish species are a consequence of a number of interacting factors so that there is no simple fix for ensuring population viability. Indeed, some factors are so poorly understood (e.g., toxic chemicals and their breakdown products) that it is not possible to determine if they are having an effect. Among the many stressors, the effects of interior Delta flows can only be approximated. In principle, interior flows can affect native species directly (through entrainment to the export pumps) and indirectly (by influencing food availability, predation risk, and exposure to contaminants).

The decoupling of flow and habitat means that species that routinely accessed flooded marsh or floodplain habitats on tidal and seasonal cycles (salmon, smelt, Sacramento splittail) for feeding or breeding experienced a dramatic reduction in available habitat.

The seasonal migration of the LSZ upstream as inflows declined in summer and downstream with increasing flows in autumn and winter and still further seaward during the spring freshet has been curtailed as the seasonal hydrograph has been flattened and water operations were designed to hold X2 in Suisun Bay as much as possible

The seasonal and tidal marshes were, presumably, net exporters of particulate and dissolved organic carbon. That source of organic carbon for the open water food chain has been largely eliminated.

> *Charge Question 2a) What important environmental cues for native fish are affected by altered flows? Please comment on the timing and time scales of these effects, and the species and life stages affected.*

Fish perceive their environment through a variety of sensory systems including taste, olfaction, vision, hearing, magnetic field sense, and the lateral line system. These senses provide the fish with a fairly detailed picture of their immediate surroundings and some information on conditions further afield (through chemical signals carried on the current or vibrational signals propagated through the water). How fish respond to their surroundings depends on their motivation and their physical capabilities.

Although the sensory abilities of fish are frequently more sophisticated than those of humans (many fish, for example, can detect radiation into the ultra-violet, can detect the polarization of light, and some can detect radiation in the near infrared) a number of environmental variables that are routinely monitored in the Delta and correlated with indices of fish abundance and distribution are variables that the fish cannot directly detect. For example, fish do not detect "flow" but they can detect the velocity associated with flow. Many of the environmental variables that are routinely monitored are also composite variables (made up of several component variables) and one cannot be confident to which of the component variables the fish is reacting. Turbidity is a good example, it is a composite of organic and inorganic particles of various types and sizes to which fish may respond differently.

Chinook salmon fry in the Delta show shore seeking behavior during the day but move away from shore at night where, lacking visual and tactile clues as to their position, they probably drift with the current. In the historic Delta, with many blind ending tidal channels and reduced tidal velocities, fry might not be carried very far by tidal ebb and flow at night. However, in the modern Delta, with open trapezoidal channels and high velocity tidal flows, fry could be carried long distances at night and potentially to habitats that are not favorable nurseries.

San Joaquin steelhead smolts, which are considerably larger than Chinook salmon smolts, migrate seaward mainly along the San Joaquin River corridor but some move into the central Delta. Like Chinook salmon, steelhead in the central Delta suffer higher mortality than those that stay in the San Joaquin corridor although overall survival of steelhead is much higher than survival of Chinook salmon. Migration routes of steelhead do not appear to be affected by OMR reverse flows.

The migrations of steelhead are less well studied than those of Chinook salmon and further work on this species with acoustic tags is recommended to clarify migration route, and threats to survival under different flow scenarios. Movement of tagged individuals suggests that steelhead smolts use selective tidal transport during their seaward migration through the Delta. It is not known whether Chinook salmon smolts also use selective tidal transport, but results of an agent based model showed that this kind of behavior would increase survival of Chinook salmon migrating through the Delta (Jackson et al. Presentation to the Panel).

Salmon smolts migrating seaward in the eastern Delta appear to travel with the flow, primarily at night, but in the tidal Delta they likely depend on chemical clues to determine the direction of the sea. Reversal of flow in OMR may be confusing in that the clues to the direction of the sea are disrupted and fish may simply go with the flow into CCF assuming the flow is carrying them toward the sea.

Larval and juvenile fishes often migrate by drifting with the flow. Altered flow velocity and altered patterns of flow (e.g., southward direction of Sacramento River water toward the export pumps) can effect migration patterns. Relative velocity in the main and secondary channel at important junctions like the DCC and Georgiana Slough appears to be important to determining whether fish will be entrained into the central Delta. When velocities in the main channel are high relative to the secondary channel, few fish are entrained but when there is little difference many fish are entrained. Also, salmon moving in the half of the main channel adjacent to the secondary channel are more likely to be entrained. Managing flow differentials and perhaps structural modifications to keep fish away from the entrances to secondary channels may help survival.

Adult salmon can be cued to migrate upstream by pulse flows associated with storms. Capture of storm runoff in reservoirs can eliminate the pulse flow associated with all but the most severe storms, thus interfering with migratory cues. Straying of San Joaquin salmon was negatively correlated with pulse flow but weakly positively correlated with exports suggesting that the joint effect of pulse flow and exports was important.

Odor clues help returning adult salmon find their appropriate home river. Redirection of river waters through the Delta and greatly reduced inflows from the San Joaquin River could confuse returning adult spawners.

Unnatural concentrations of substances, such as copper and toxic chemicals can affect salmons' ability to detect and respond to odors and may have other sublethal effects as well.

The development of acoustic tags small enough to implant in salmon smolts has provided invaluable detail on the migratory behavior of these fish. To date, however, the tags have only been used on the larger late-fall run yearling smolts. The behavior of other runs and other sizes of Chinook salmon may well differ from that of late-fall run yearling smolts. Further experimentation is needed with all the runs of Chinook salmon to determine if similar strategies will work for all.

Combining acoustic tagging with detailed modeling of flow fields at channel junctions holds promise of clarifying the conditions that lead to entrainment into interior Delta channels and designing ways to maximize use of migration routes that have high survival for salmonids. The Panel recommends continued use of this technology and also more emphasis on combining computational fluid dynamics models with realistic fish behavior to explore how changing inflows, tidal flows, exports, and other drivers of internal Delta flows are likely to influence migration routes and timing of salmon and other species.

The primary habitat of Delta smelt is the LSZ, generally just upstream from the 2 PSU isohaline and in turbid water where Secchi depth is < 40 cm. Smelt are weak swimmers yet still undertake a winter dispersal upstream to low salinity habitats for spawning in spring and juveniles are able to congregate in the LSZ by early summer. Larvae and juveniles are vulnerable to advection and many are entrained into the export facilities. Thus, interior Delta flows are particularly important for Delta smelt. Turbidity is also an important habitat variable for Delta smelt. Turbidity is declining in the Delta, placing Delta smelt at greater risk of predation.

Entrainment into the export facilities has the potential to affect population abundance of Delta smelt and exports are controlled to try to minimize this loss. Whether or not entrainment into the export facilities actually affects the abundance of Delta smelt is uncertain. High natural variability in smelt abundance and uncertain estimates of entrainment have made it difficult to detect entrainment effects on the population although recent analyses suggest that the population is affected at times. The data relating salvage and entrainment to flow (specifically negative flow in OMR) are sufficiently scattered that it may not be possible to specify a precise relationship. It seems clear that our understanding of the relationship between interior flows and smelt would benefit from a combination of controlled experimentation to reduce some of the uncertainty inherent in existing models and analyses and improved models capable of exploring the multiplicity of hypotheses that have emerged from analyses of historic data. Better understanding of how Delta smelt manage their movements in the Delta as larvae, juveniles, and adults could indicate ways that flow fields could be managed to better match their behavior and survival strategies.

Developing a better understanding of how Delta smelt respond to flow fields and salinity clues would probably have to be undertaken in a laboratory setting, but we feel improved understanding of Delta smelt behavior could pay regulatory dividends.

A clearer understanding of the ability of the species to use selective tidal transport would also help with the design of any program to manage flow fields. Evidence for this behavior is not strong for any of the species. The research should be designed to determine the circumstances when the fish will use selective tidal transport as opposed to passive drift or active migration.

> *Charge Question 2b) What are the effects of altered interior Delta flows on other parts of the ecosystem such as phytoplankton, zooplankton, and benthos? Please comment on the timing and time scales of these effects and the functional groups affected.*

<u>In principle</u>, modifications to in-Delta flows by export pumping or gate operations should affect connectivity between the large open water areas and adjacent channels and thereby affect net primary production. However, to the best of our knowledge this has not been demonstrated by any extant modeling or field programs.

Microcystis appears to be increasing in the Delta, although it is still relatively rare. Plankton samples from the main channels seldom contain *Microcystis*, and the vertically mixed main channels are not typical habitat for *Microcystis*. *Microcystis* may be more abundant in shallow, dead end, channels, but these are relatively rare in the Delta. There may be a connection between water project operations and *Microcystis* since growth rates for *Microcystis* increase exponentially with temperature, which may be influenced by the strength and spatial structure of in-Delta flows. However, summer air temperatures probably play a greater role in determining Delta temperatures.

Flow effects on secondary production within the Delta are virtually unexamined.

The conclusion that emerges concerning the effects of in-Delta flows on primary and secondary production as well as on HABs is that, while in principle such effects should exist, there is no firm evidence that any effects do exist. The only connection between water project operations and food webs that can be made with any confidence is that Delta outflows, the net effect of inflows and exports, has a direct effect on the food web downstream in that diversions reduce the export of phytoplankton-derived POM from the Delta to Suisun Bay. Nonetheless, the existing evidence provides strong motivation for strengthening the food web component and research on the Delta ecosystem.

> *Charge Question 3: How do non-flow stressors such as predation, physical habitat, fisheries management, and water quality interact with interior Delta flows to affect the issues discussed in Question 2? How have the landscape and ecosystem scale changes of the last 100+ years altered these interactions and the functions provided by flows?*

Several studies based on mass balance have shown that a significant fraction of the particulate organic material (POM) produced within the Delta can be lost to export rather than carried to Suisun Bay. However, simple mass balances may not tell the entire story of this loss. For example, current water project operations can route all of the organic matter produced in the San Joaquin River into the export pumps, thus having a greater effect on the supply of POM to Suisun Bay than would be expected from an overall mass balance for the Delta.

Patterns of flow in the Delta appear to have had consequences for the success of invasive species. The successful invasions of exotic zooplankton and mysids all occurred during drought periods when a 3-year moving average of monthly X2 values was greater than 75. Drought resulted in a more saline Delta and contracted the habitat available for native zooplankton adapted to low-salinity or freshwater conditions. Management of interior Delta flows will be important during drought years to minimize the risk of further problematic invasions to the Delta.

> *Charge Question 4: What metrics of interior Delta flows (such as OMR and QWEST flows, and export-inflow ratios) are most useful to assess, predict and manage impacts to fish and the ecosystem?*
>
> > *Question 4a) Do these remain important metrics, or are there better metrics that could be used?*

Metrics such as OMR and QWEST are tidally averaged flows and present a view of the Delta in which materials and organisms are moved as in a river either out to Suisun Bay or to the pumps. However, setting aside high flow events associated principally with winter storms, tides are the major driver of interior Delta flows. Because of the interaction of tidal currents with the complex geometry of the Delta, dispersive transport by tides can significantly alter the picture presented by tidally averaged flows. For example, Smith showed model results indicating that passive particles were being transported to the pumps from places where mean flows would have suggested transport to the Bay.

A robust result from numerical modeling of interior Delta flows is that when exports are high and San Joaquin River flows are low (conditions that give rise to large, negative values of OMR), passive particles from much of the Delta other than the Sacramento River itself are drawn into the export facilities. By contrast, when exports are small, the region of the Delta from which particles are entrained to the pumps is confined to a small area in the immediate vicinity of the export facilities. OMR flows may, therefore, provide a useful index of entrainment.

> *Charge Question 4 b) For each metric, explain if the metric is useful to improve survival, abundance, spatial distribution and/or life history diversity.*

Numerical modeling combined with particle tracking can provide a reasonable estimate of entrainment of relatively passive organisms such as plankton or Delta smelt larvae. Accordingly, it appears that regulations based on OMR flow will have some value in limiting entrainment of Delta smelt larvae and perhaps juveniles. Juvenile salmon should be much less vulnerable to such passive entrainment although negative flows in OMR may provide confusing signals to migrating salmon (e.g., if they are attempting to use selective tidal transport to move toward the Bay) so that juvenile salmon are also drawn toward the pumps.

> *Charge Question 5: What changes to interior Delta flows or other stressors would be most effective for improving survival, abundance, spatial distribution, and/or life history diversity of native fish and the ecosystem?*

Water management must consider the hydrograph over the entire year. Peak spring flows, access to floodplains, and sufficient flows in the summer and fall are important for creating conditions that encourage the success of native fish species. Maintaining temperatures cool enough in the summer, trying to maintain certain turbidity levels, consideration of the availability of floodplain and other habitats, and using extra caution during drought periods could also benefit native species. Actions that discourage the success of possible new invasives and limit the degree of success of existing invasives would be prudent. How internal Delta flows affect the transport of energy (organic carbon, chlorophyll) to the LSZ needs further investigation.

As listed species have declined considerable effort has been expended to identify the causes and to "lay blame." However, it is now generally agreed that population declines result from multiple stressors. Some investigators have attempted to rank stressors according to the severity of their effects, but this strategy assumes a great deal of separability among the multiple stressors, which is usually not possible. Stressors may exert indirect effects and may covary with other indirect or direct stressors, further complicating any attempt to identify the stressor that is most or least important in affecting change to the individual or the population. Even if a ranking of stressor importance was possible, the ranking could change with changes in the ecosystem. Specificity is needed to describe the logic trail from management actions to multiple, potentially interacting, stressors to the processes of growth, mortality, reproduction, and movement of the species or life stage of interest.

> *Charge Question 5a)Do the existing studies and analyses support threshold levels of specific interior Delta flows for protection of native fish species or other elements of the ecosystem?*

A slope break or step change perceived in a data plot of a fish endpoint versus a flow metric may imply a threshold response of fish to flow, and hence suggest a flow criterion. Thomson et al. (2010) give examples of statistical models that identify such “change points” or thresholds (in their case, for temporal trends of fish abundance). However, the use of statistically-identified thresholds to establish flow criteria faces two major challenges. First, the location, and very existence, of an estimated threshold can depend critically on the statistical method, as well as the abundance of data near the purported threshold. Second, even if a threshold exists in a fish vs. flow relationship, not all conditions above or below that threshold may be relevant for management.

> *Charge Question 5b) How could an adaptive management program be structured to improve understanding and management of the effects of interior Delta flows on native fish and the ecosystem? What are the key scientific uncertainties amenable to improved understanding through adaptive management experiments? Is there sufficient flexibility in interior flow regimes*

Adaptive management is a powerful tool for assessing the consequences of management actions and at the same time learning about the system being managed. Properly designed adaptive management can help reduce uncertainty in the behavior of the system being managed. For adaptive management to be successful, however, the system being managed must be amenable to a high degree of control and the value of the information that managers expect to obtain from the experiment should justify the cost. Thus, not all management problems are suitable for adaptive management. The manager needs to draw on a variety of tools in designing a program to address any complex management issue. Effective adaptive management also requires a level of trust among all of the parties and stakeholders, which may not presently exist in the Delta.

Adaptive management is one possible component of a larger programmatic science plan. Such a program, typically including a diversity of investigators and investigations, needs to conform to criteria of excellence that go beyond those used to judge the value of a single scientific study. A well-designed science program typically consists of three parts: 1) A set of challenging science/management questions that are stated clearly enough to provide a template for designing specific investigations; 2) a process for taking data and information from individual investigations and transforming it into knowledge useful for management; and 3) procedures for minimizing knowledge leakage by encouraging data sharing and open communication.

In the Bay-Delta, adaptive management has been implemented as a partnership of management (which includes monitoring to ensure that management goals are being met) and targeted research to address critical uncertainties. This approach the advantage that targeted research may be the most efficient way to address uncertainties in highly complex ecological systems. It has the disadvantage that the management action itself may not be sufficiently rigorous to provide any useful information about the system, especially absent the critical modeling phase of adaptive management.

Large-scale management problems are also "wicked" in that they defy specific and unique definition so that they tend to become defined in relation to the management actions taken. The problems are also continually evolving in that any significant management action initiates a cascading set of consequences that can significantly change the nature of the problem generating new uncertainties and necessitating new management interventions.

Wicked problems should be amenable to adaptive experimentation, however, much depends on whether inputs (e.g., interior Delta flows) can be manipulated to provide enough contrast to ensure a measurable result. Appropriate modeling should demonstrate whether a sufficient contrast can be created. If not, other approaches to addressing uncertainty may be more fruitful.

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