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Key Points on Delta Environmental Flows for the State Water Resources Control Board

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Delta Environmental Flows Group*

1. Environmental flows are more than just volumes of inflows and outflows. The frequency, timing, duration, and rate of change of flows, as well as the occurrence of overbank flows also are biologically important. There is no one correct flow number. Seasonal, interannual, and spatial variability, to which our native species are adapted, are as important as quantity. Biological responses to flows rest on combinations of quantity, timing, duration, frequency and how these inputs vary spatially in the context of a delta that is geometrically complex, highly altered by humans, and fundamentally tidally driven. Overall, the freshwater flows under our control are small, yet important, when compared to the influence of the uncontrolled flows and the influence of the tides.

2. Recent flow regimes both harm native species and encourage non-native species. Flows to and within the estuary affect turbidity, salinity, aquatic plant communities, and nutrients that are important to both native and non-native species. Flows and habitat structure are often mismatched and favor non-native species. It will be imperative to better understand the appropriate interaction between flow and habitat which favors native species over now-dominant, non-native species.

3. Flow is a major determinant of habitat and transport. Effects of flow on transport and habitat are controlled by the geometry of the waterways. These will change through time, so flow regimes needed to maintain desired habitat conditions will also change through time. Delta inflows affect habitat and biological resources in three different ways: flood plain activation, in-Delta net flows and transport, and Delta outflows.

4. Recent Delta environmental flows are insufficient to support native Delta fishes for today's habitats. Flow can be modified to benefit native fishes and flow modification is one of the few immediate actions available. However, the links between flows and fish response are often indirect and not fully resolved. Habitat restoration, contaminant and nutrient reduction, changes in diversions, control of invasive species, and island flooding all interact with flow to affect aquatic habitats. Flow and physical habitat interact in many ways but they are not interchangeable. Future habitat improvements may change response of native fishes to flow and allow flow prescriptions to be revisited.

5. A strong science program and a flexible management regime are essential to improving flow criteria. Long-term research to develop the next generation of models linking hydrodynamics and population dynamics is crucial for refining flow criteria. Monitoring alone is inadequate; peer-reviewed scientific studies on ecological processes are essential to provide guidance on how functions change with climate change, changing geomorphology, island flooding, habitat restoration, new flow-control structures, emerging contaminants, and new invasive species. Scientific synthesis must integrate results and make scientific insights useful for policy purposes. Any set of flow criteria should include the capacity to readily adjust the flows to adapt to changing future conditions and improved understanding.

* William Bennett, Jon Burau, Cliff Dahm, Chris Enright, Fred Feyrer, William Fleenor, Bruce Herbold, Wim Kimmerer, Jay Lund, Peter Moyle, Matthew Nobriga

Point 1. Environmental flows are more than just volumes of inflows and outflows. The frequency, timing, duration, and rate of change of flows, as well as the occurrence of overbank flows also are biologically important. There is no one correct flow number. Seasonal, interannual, and spatial variability, to which our native species are adapted, are as important as quantity. Biological responses to flows rest on combinations of quantity, timing, duration, frequency and how these inputs vary spatially in the context of a delta that is geometrically complex, highly altered by humans, and fundamentally tidally driven. Overall, the freshwater flows under our control are small, yet important, when compared to the influence of the uncontrolled flows and the influence of the tides.

Justification

The science of setting instream flows has progressed substantively from the early days of simply setting a minimum flow below which discharge was never to drop. Thirty years of research has focused on the ecological effects of water withdrawals and advancing tools for determining flows required to sustain healthy aquatic ecosystems (Petts 2009) though most of this work has focused on riverine systems. Although these approaches provide an excellent starting point, it is not clear how well they will apply in the Delta - a system that is strongly tidally forced and consists of a complex interconnecting web of canals. The balance between the average of tidal timescale processes and the river inputs interacting within the Delta's complex geometry largely control regional-scale gradients in ecosystem processes. Thus, changes in system geometry (setback levees, marsh restoration, flooding of islands, etc.) and river inputs must be considered together.

The flow regime (magnitude, frequency, duration, timing, and rate of change of flows) is widely viewed as of central importance in sustaining the ecological integrity of aquatic ecosystems (Poff et al. 1997, Richter et al. 1997). The flow regime affects water quality, food resources, physical habitat, and biotic interactions and therefore is a primary determinant of the structure and function of aquatic ecosystems (Poff et al. 1997, Poff et al. 2010).

The flow regime is important in determining physical habitat in aquatic ecosystems. This in turn is a major factor in determining biotic composition. Bunn and Arthington (2002) highlight four principles by which the natural flow regime influences aquatic biodiversity: 1) developing channel form, habitat complexity, and patch disturbance, 2) influencing life-history patterns such as fish spawning, recruitment, and migration, 3) maintaining floodplain and longitudinal connectivity, and 4) discouraging non-native species. Altering flow regimes affects aquatic biodiversity and the structure and function of aquatic ecosystems. The risk of ecological change increases with greater flow regime alteration (Poff and Zimmerman 2010).

Globally, many environmental flow methodologies are now widely used (Tharme 2003). Environmental flow assessments can be classified into four types of methods. These are 1) hydrologic methodologies focused on low flow indices and ecological relevance of specific flows, 2) hydraulic rating methodologies focused upon economically important fisheries, 3) habitat simulation methodologies that use hydrodynamic modeling relating flow to two-dimensional inundation patterns of the landscape, and 4) holistic methodologies that combine elements of the full suite of widely used techniques.

The ecological limits of hydrologic alteration (ELOHA) is an emerging framework for developing regional environmental flow standards that has support from leading scientists carrying out instream flow analyses. The goal of the framework is analyses and syntheses of available scientific information into ecologically based and socially acceptable goals and standards that acknowledge scientific uncertainty and proceed in an adaptive management context (Poff et al. 2010). Resulting flow standards consider the frequency, duration, timing, and rate of change of flows and not just volumes or magnitudes.

Point 2. Recent flow regimes both harm native species and encourage non-native species. Flows to and within the estuary affect turbidity, salinity, aquatic plant communities, and nutrients that are important to both native and non-native species. Flows and habitat structure are often mismatched and favor non-native species. It will be imperative to better understand the appropriate interaction between flow and habitat which favors native species over now-dominant, non-native species.

Justification

The major river systems of the arid western United States have highly variable natural flow regimes. The present-day flow regimes of western rivers, including the Sacramento and San Joaquin, are highly managed to increase water supply reliability for agriculture, urban use, and flood protection (Hughes et al. 2005, Lund et al. 2007). Recent Delta inflow and outflow regimes appear to both harm native species and encourage non-native species. Inflow patterns from the Sacramento River may help riverine native species in the north Delta, but inflow patterns from the San Joaquin River encourage non-native species. Ecological theory and observations overwhelmingly support the argument that enhancing variability and complexity across the estuarine landscape will support native species. However, the evidence that flow stabilization reduces native fish abundance *in the upper estuary* (incl. Delta) is circumstantial:

1) High winter-spring inflows to the Delta cue native fish spawning migrations (Harrell and Sommer 2003; Grimaldo et al. 2009), improve the reproductive success of resident native fishes (Meng et al. 1994; Sommer et al. 1997; Matern et al. 2002; Feyrer 2004), increase the survival of juvenile anadromous fishes migrating seaward (Sommer et al. 2001; Newman 2003), and disperse native fishes spawned in prior years (Feyrer and Healey 2003; Nobriga et al. 2006).

2) High freshwater outflows (indexed by X_2) during winter and spring provide similar benefits to species less tolerant of freshwater including starry flounder, bay shrimp, and longfin smelt (Kimmerer 2002; Kimmerer et al. 2009). Freshwater flows provide positive benefits to native fishes across a wide geographic area through various mechanisms including larval-juvenile dispersal, floodplain inundation, reduced entrainment, and increased up-estuary transport flows. Spring Delta inflows and outflow have declined since the early 20th century, but average winter-spring X_2 has not had a time trend during the past 4-5 decades (Kimmerer 2004).

3) The estuary's fish assemblages vary along the salinity gradient (Matern et al. 2002; Kimmerer 2004), and along the gradient between predominantly tidal and purely river flow. In tidal freshwater regions, fish assemblages also vary along a gradient in water clarity and submerged vegetation (Nobriga et al. 2005; Brown & Michniuk 2007), and smaller scale, gradients of flow, turbidity, temperature and other habitat features (Matern et al. 2002; Feyrer & Healey 2003). Generally, native fishes have their highest relative abundance in Suisun Marsh and the Sacramento River side of the Delta, which are more spatially and temporally variable in salinity, turbidity, temperature, and nutrient concentration and form than other regions.

4) In both Suisun Marsh and the Delta, native fishes have declined faster than non-native fishes over the past several decades (Matern et al. 2002; Brown and Michniuk 2007). These declines have been linked to persistent low fall outflows (Feyrer et al. 2007) and the proliferation of

submerged vegetation in the Delta (Brown and Michniuk 2007). However, many other factors also may be influencing native fish declines including differences in sensitivity to entrainment (sustained or episodic high “fishing pressure” as productivity declines), and greater sensitivity to combinations of food-limitation and contaminants, especially in summer-fall when many native fishes are near their thermal limits.

The weight of the circumstantial evidence summarized above strongly suggests flow stabilization harms native species and encourages non-native species, possibly in synergy with other stressors such as nutrient loading, contaminants, and food limitation.

Point 3. Flow is a major determinant of habitat and transport. Effects of flow on transport and habitat are controlled by the geometry of the waterways. These will change through time, so flow regimes needed to maintain desired habitat conditions will also change through time. Delta inflows affect habitat and biological resources in three different ways: flood plain activation, in-Delta net flows and transport, and Delta outflows.

Justification

Floodplain activation flows. Seasonal floodplain inundation activates a variety of biological processes. Activated floodplains produce and export biologically available carbon, stimulate food web activity from plankton to birds, and provide spawning and rearing habitat for floodplain adapted fish (Richter et al. 1997, Poff et al. 1997, Moyle et al. 2007, Williams et al. 2009). Today’s flood control system allows floodplain inundation by larger but less frequent floods (e.g. Yolo Bypass). Low-magnitude higher-frequency floods that historically influenced lower floodplain riparian vegetation and filled ephemeral ponds have been removed primarily by low water control levees (Sommer 2004). Elevation mapping and hydrodynamic modeling should be used to establish flow criteria for floodplain margin activation (e.g. Williams et al. 2009). Topography changes could reduce flow requirements for the same ecosystem function in future floodplain restoration.

In-Delta net channel flows. Habitat effects of Delta flows are poorly understood because linkages between ecosystem responses and net flow involve a cascade of interacting processes. Water motions are dominated by tides in the Delta. Tidal flows disperse constituent gradients on the tidal timescale (~1 day), while net flows exert influence over longer (>1-2 weeks) timescales. Seasonal high flows reduce tidal amplitude overall and simultaneously reduce flood and increase ebb tidal flows. This can mediate dispersive mixing and affect pelagic organism movement. Net flows also vary in space in concordance with the system geometry, river inflow, gates, diversions, and exports. Pre-settlement natural net channel flow moved water and some biota toward Suisun Bay and maintained downstream directed salinity gradients. Today, Delta gates and diversions can substantially redirect tidal flows creating net flow patterns and salinity and turbidity distributions that did not occur historically. These changes may influence migratory cues for some fishes. These cues are further scrambled by a reverse salinity gradient in the south Delta caused by higher salinity in agricultural runoff. Other examples include the San Joaquin River that carries high phytoplankton concentrations but which is largely exported or sequestered in the south Delta by export pump induced net flows. Eggs and larvae of striped bass and other fish are also vulnerable to net flow transports to export pumps or non-optimal habitats.

Net Delta outflow. Net Delta outflow (NDO) is the sum of Delta inflows, diversions, and exports and does not account for the spring-neap filling and draining of the Delta (Oltmann, 1998). During dry periods, NDO is a few percent of the instantaneous tidal flow in the western Delta. Nevertheless, over periods longer than 2 weeks, NDO transports a carbon subsidy to Suisun Bay and controls the location of the salinity gradient. NDO also directly or indirectly influences the abundance of several key estuarine species. Although these species inhabit the Delta for part of their lives, the effect of NDO on abundance may be far outside of the Delta (e.g., longfin smelt, bay shrimp, possibly striped bass; Kimmerer 2002, Kimmerer et al. 2009). The correlation of net Delta outflow with abundance is related to a wide variety of estuarine conditions that prevail from the floodplains to the Gulf of the Farallones. The X2/outflow standards were based on months-long averages of X2 in relation to annual patterns of fish abundance. However, natural outflow variability combined with physical habitat complexity is recognized as a key factor promoting diverse native communities (Moyle and Mount 2007; Moyle et al. 2010), and these concepts are being used increasingly in management of rivers (Poff et al. 2007). Therefore, the time scales of flow variability that may be relevant for maintaining native species are likely to increase going from the rivers through the Delta into Suisun Bay.

Point 4. Recent Delta environmental flows are insufficient to support native delta fishes for today's habitats. Flow can be modified to benefit native fishes and flow modification is one of the few immediate actions available. However, the links between flows and fish response are often indirect and not fully resolved. Habitat restoration, contaminant and nutrient reduction, changes in diversions, control of invasive species, and island flooding all interact with flow to affect aquatic habitats. Flow and physical habitat interact in many ways but they are not interchangeable. Future habitat improvements may change response of native fishes to flow and allow flow prescriptions to be revisited.

Justification

The Delta and Suisun Bay currently provide little high-quality habitat for native estuarine fishes. Most of the Delta channels are now narrow, deep, steep-sided and armored canals with little resemblance to natural deltaic channels. Circumstantial evidence suggests that the conversion of the Delta's natural river channels into canals degraded the native ecosystem, such as by interfering with the migration of juvenile salmon and other native species. More recent degradation has included the introduction of waterweeds that choke Delta channels, introduced fish and other animals, and various pollutants.

In the context of the degraded Delta, manipulation of freshwater flow and limiting export flows have become the principal management tools to benefit native fishes, and are almost the only such tools available in the short term.

The links between freshwater flow and fish responses are many, and the responses are often indirect and are not fully known. For example, spring flows that bring lower salinities and higher turbidities to the western Delta and Suisun Bay and Marsh provide important cues to the spawning migrations of native fish which may improve their reproductive success. Floodplain inundation improves provisioning of salmon and steelhead smolts and provides rearing habitat for many native estuarine fish species. Compression of the salinity gradient by high freshwater flow causes subtle but important changes that improve retention and increase populations of several species (Jassby et al. 1995, Kimmerer et al. 2009). Export flows cause direct mortality and alter net flows in the south Delta to the likely detriment of some native fish species.

All of these responses depend on the interplay of freshwater and tidal flows with other attributes of the system such as channel configuration and water quality. Habitat restoration, contaminant and nutrient reduction, alternative points of diversion, control of invasive species, and island flooding have been discussed for their potential benefits to native fishes. A central premise underlying these actions is that improved physical habitat and water quality can be coupled to a more predictable water supply exported from the Delta. This premise needs rigorous investigation because flow and physical-chemical habitat interact in many ways but are not interchangeable. Implementation of large-scale habitat improvements must include a well-designed program of evaluation to assess whether responses of native fishes to these measures allow flow prescriptions to be revisited.

Determining the timing, volume, and water quality required at different times of the year for the Delta ecosystem is controversial. Higher freshwater inflows and outflows in the winter-spring from the Sacramento River have been linked to various benefits to native estuarine and anadromous fish (see justification for key point 2). The overall evidence for important benefits from adequate winter-spring inflows and outflows to native fish populations is strong. The future Delta (e.g. Lund et al. 2010; Moyle et al. 2010) may be able to supplant some flow requirements with enhanced physical habitat and improved water quality, but this potential opportunity requires rigorous scientific examination as implementation proceeds.

Point 5: A strong science program and a flexible management regime are critical to improving flow criteria. Long-term research to develop the next generation of models linking hydrodynamics and population dynamics is crucial for refining flow criteria. Monitoring alone is inadequate; peer-reviewed scientific studies on ecological processes are essential to provide guidance on how functions change with climate change, changing geomorphology, island flooding, habitat restoration, new flow-control structures, emerging contaminants, and new invasive species. Scientific synthesis must integrate results and make scientific insights useful for policy purposes. Any set of flow criteria should include the capacity to readily adjust the flows to adapt to changing future conditions and improved understanding.

Justification

Current efforts Scientific efforts to understand the Delta's estuarine ecosystem in the last decade have been impressive, and ongoing research continues this trend (Healey et al. 2008). Arguably, more scientific effort has been conducted on the effects of freshwater flow on fish and the ecosystem in the San Francisco Estuary than in any other estuary on Earth. We are in an excellent position to parlay that knowledge into a comprehensive system of science-based management, in which ongoing learning provides the basis to improve the effectiveness of policy and management.

Most of this research has been published in peer-reviewed scientific journals. Although peer review is the gold standard for scientific work, the demands of management are not met only by the content of scientific journals. First, even the most thorough peer review may not address management needs, since the reviewers are usually unaware of management needs and concerned primarily with the paper's scientific contributions. Second, management needs are often more urgent than the publication review process. Pre-publication use of scientific results is therefore necessary, but published scientific findings should be given more weight than other forms of communication. In addition to research, monitoring programs, mostly maintained by the Interagency Ecological Program, continue to provide valuable, high-quality data for management, scientific studies and comparisons, and tracking trends.

The role of uncertainty Despite this extensive scientific understanding, substantial knowledge gaps remain about the ecosystem's likely response to flows. First, ecosystem processes in a turbid estuary are mostly invisible, and can be inferred only through sampling. Second, monitoring programs only scratch the surface of ecosystem function by estimating numbers of fish and other organisms, whereas the system's dynamics depend on birth, growth, movement, and death rates which can rarely be monitored. Third, this system is highly variable in space (vertical, cross-channel, along-channel, and larger-scale), time (tidal, seasonal, and interannual), flow, salinity, temperature, physical habitat type, and species composition. Each of the hundreds of species has a different role in the system, and these differences can be subtle but important. As a result, we have little ability to predict how the ecosystem will respond to the numerous anticipated deliberate and uncontrolled changes.

How can we manage with this uncertainty? We continue to advocate an adaptive management approach (*sensu* Holling 1978, Walters 1986; CALFED 2000). Although this concept has gained little traction (e.g., BDCP seems not to have adopted this approach) adaptive management is the most suitable approach for managing with uncertainty. Although experimental manipulation may be feasible only in limited situations, the other elements of adaptive management apply to most management problems. These elements include setting up all actions as if they were experiments, with explicit conceptual and simulation models, predicting outcomes, and feedback loops so that the course of management and investigation can change as the system develops and knowledge is gained. A talented group of people tasked to integrate, synthesize, and recommend actions based on the data being gathered are essential for making such a system work. Failure to implement an effective adaptive management program will likely lead to a continued failure to learn from the actions, and a lack of responsiveness to changing conditions and increased understanding.

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