Exhibit AR-1

STATE OF CALIFORNIA
STATE WATER RESOURCES CONTROL BOARD

INFORMATIONAL PROCEEDING TO DEVELOP FLOW CRITERIA FOR THE DELTA ECOSYSTEM NECESSARY TO PROTECT PUBLIC TRUST RESOURCES

TESTIMONY OF
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# SACRAMENTO AND SAN JOAQUIN FLOWS, FLOODPLAINS, OTHER STRESSORS, AND ADAPTIVE MANAGEMENT

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# TABLE OF CONTENTS

## Tables

## Figures

# I. INTRODUCTION AND SUMMARY

Inflows have a strong influence on the quality of Delta water, the productivity of the Delta ecosystem and the abundance, growth, and survival of many Delta species. Inflows mediate connectivity with the upstream watershed and contribute inputs of freshwater, nutrients, sediment, and energy to the Delta from upstream habitats and are necessary for the movement of migratory species. Anthropogenic flow regulation has substantially reduced spring flows and the frequency and magnitude of winter and spring pulse flows.

This testimony focus on the following limited number of essential functions provided by components of the winter and spring hydrograph.

- Water temperature, particularly on the San Joaquin outmigrating salmonids
- Channel habitat complexity and resulting water temperature dynamics
- Floodplain inundation
- Pulse flows and the transport of sediment, nutrients, and biota to the Delta

These essential functions provide different benefits for the Delta ecosystem but are highly interrelated. Suitable water temperatures across the Delta and throughout the anadromous migration period are essential for maintaining native fish abundance, distribution, life history diversity, and population stability. Inflows along with complex channel habitat and variable hydrology help mediate suitable water temperature conditions. Flood flows are essential for maintaining complex channel and floodplain features and, by inundating floodplains, provide essential spawning and rearing habitat for native fish. Pulse flows flush nutrients from inundated floodplains and create turbid habitat in the Delta improving growth and survival for native Delta species.

Flows to reestablish these functions would also mitigate the impact of other stressors. The existing Delta environment appears to provide a competitive advantage to many exotic species. Restoring cool waters, floodplain habitat, and turbid waters would provide more opportunities for native species to successfully compete with exotics. Increased inflows would also disperse and dilute contaminants that harm all species. Non-flow measures would also affect physical, chemical, and biological processes to help manage other stressors.

Developing and implementing an environmental flow regime will require an adaptive management approach specifically designed to "learn by doing." This testimony identifies a six step process for developing and testing and environmental hydrograph that utilizes both natural hydrology and mechanistic relationships as a guide for gradually transforming the existing regulated hydrograph into a flow regime that better protects the full range of public trust resources.

## II. HYDROLOGIC CHANGES

### A. Sacramento River

Most analyses of hydrologic alteration due to water management over time present average monthly changes. This description provides a higher resolution of hydrologic changes on a daily scale to illustrate how dams and diversions have altered ecologically significant flow events that often occur on the sub-monthly scale.

Figure 1 illustrates changes in the Sacramento River hydrograph at Verona.[1] The hydrograph at Verona is driven by flows from the Sacramento and Feather River, which are substantially controlled by Shasta and Oroville Reservoirs. Thus, Figure 1 illustrates changes in the Sacramento River due to the construction and operation of Shasta Dam.

The construction and operation of Shasta Reservoir has resulted in the following hydrologic changes:

- Summer base flows are significantly higher post-Shasta for all water year types. The average summer base flow pre-Shasta was 3,000-4,000 cfs, which is significantly less than the current average of 10,000-12,000 cfs. These artificially high summer flows are driven by summer water supply demands for agriculture and power.

- Spring peak flow events are significantly reduced in the post-Shasta era for below normal, above normal and wet year types and there is a truncated spring and early summer recession limb, particularly in wet years. The reduction in spring peak flows hampers cottonwood recruitment, seed establishment, and germination.

- Winter peak flows are significantly reduced in the post-Shasta era. The magnitude and duration of winter peak flows are responsible for channel forming flows. Channel forming flows affect cottonwood recruitment and off channel habitat formation critical for Chinook salmon rearing and survival.

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[1] We focused on Verona hydrology due to the correlation between Verona hydrology and inundation of the Yolo bypass. Due to time constraints, we were not able to address the role of the American River on Sacramento River inflows to the Delta.

- In addition to significantly altered hydrograph components, there is also a general decline in hydrologic variability in the post-Shasta era.

The construction and operation of Oroville dam and reservoir have significantly altered the hydrograph of the Feather River and Delta inflows at Verona. Oroville resulted in very significant changes to Feather River inflows to Verona.

- Very significant reductions in spring flows exist during all year types, particularly during April and May. Storage of spring runoff and snowmelt behind Oroville Dam has virtually eliminated any spring flows above a base flow of approximately 2,000 cfs.

- Increases in summer flows by 150-200% exist in all year types during July, August, and September.

- Reduction in the frequency and magnitude of peak flows, such as Q1.5[2] or channel forming flow follows an order of magnitude. There is substantially less reduction in the magnitude of the 5-year recurrence interval event.

- Reduction in the frequency of short duration fall and winter flow pulses is significant.

Flows at Verona are also influenced by several unregulated or less regulated watersheds including those in the interior coast range and Cascades including Cottonwood, Deer, Mill, Butte, and Battle Creeks as well as the Yuba River, which still exhibits large seasonal fluctuations during runoff events. This less regulated portion of the watershed has sustained relatively high flows on the Sacramento at Verona into the late winter. But regulation of snowmelt and spring flows behind Shasta, Oroville, and New Bullards Bar on the North Fork Yuba have significantly reduced spring inflows.

Figure 2 shows how spring flows at Verona have gradually declined over the period of record - first after Shasta, and then after construction of Oroville and New Bullards Bar. Spring flows declined further after the 1995 water quality control plan due to spring time pumping restrictions which discouraged releases from Oroville during spring months. Figure 3 shows how recent operations at Oroville have now resulted in a complete inversion of the natural hydrograph in the Feather River with the lowest flows of the year during March and April and the highest flows in July and August.

Comparisons of current and pre-project hydrographs in the Sacramento Basing show a consistent pattern into the last decade of decreased spring flows and increased summer

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[2] The instantaneous peak annual flow with a recurrence interval of 1.5 years.

flows.  Increasingly, water is more efficiently captured in the spring for delivery during peak summer months, eliminating peak spring flows and augmenting summer base flows well above pre-project levels. Large reservoirs also dampen winter floods in all but the wettest of years in the reaches below the dams, but this signal is somewhat obscured in Delta inflows due to runoff from the less regulated watershed throughout the Sacramento Basin.

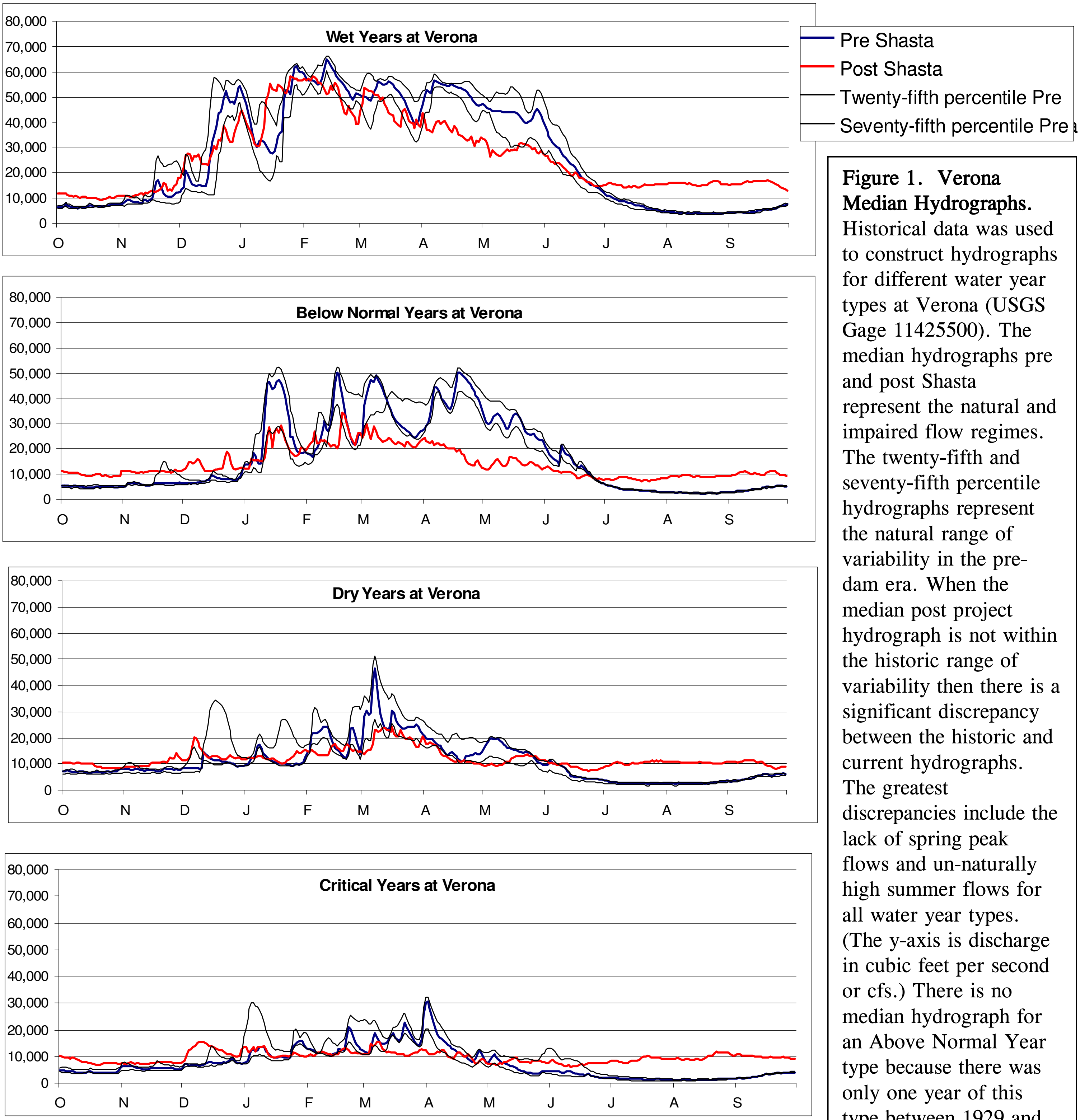

**Figure 1. Verona Median Hydrographs.** Historical data was used to construct hydrographs for different water year types at Verona (USGS Gage 11425500). The median hydrographs pre and post Shasta represent the natural and impaired flow regimes. The twenty-fifth and seventy-fifth percentile hydrographs represent the natural range of variability in the pre-dam era. When the median post project hydrograph is not within the historic range of variability then there is a significant discrepancy between the historic and current hydrographs. The greatest discrepancies include the lack of spring peak flows and un-naturally high summer flows for all water year types. (The y-axis is discharge in cubic feet per second or cfs.) There is no median hydrograph for an Above Normal Year type because there was only one year of this type between 1929 and 1944.

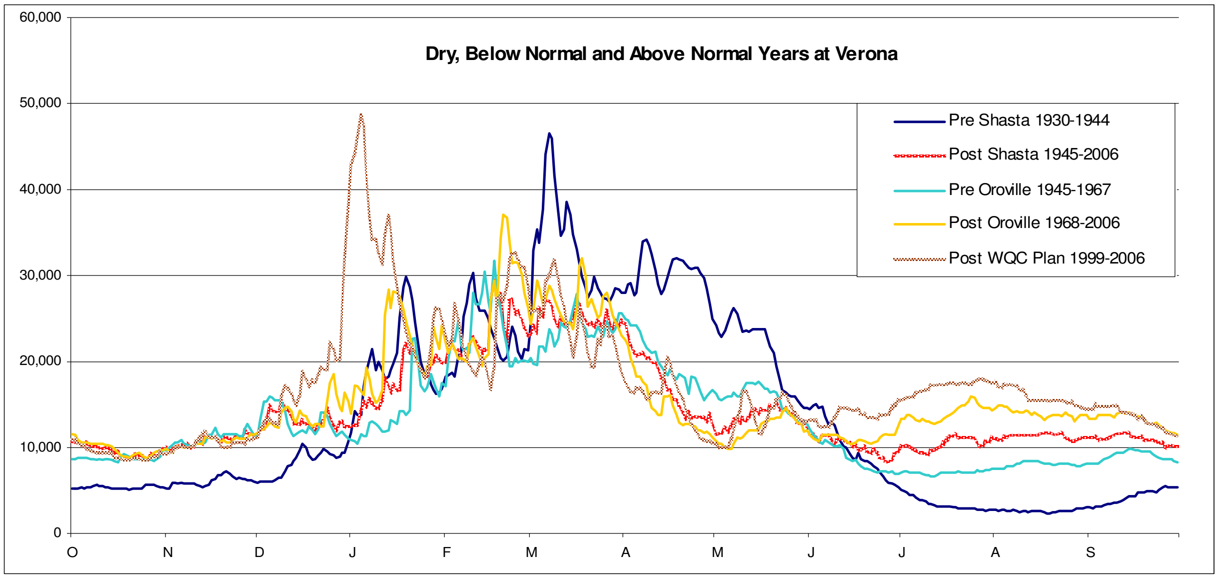

**Figure 2. Median Hydrographs, Sacramento River.** Median hydrographs for different time periods indicate a progression towards increased summer flows and decreased spring peaks. The increased regulation of the Sacramento and Feather Rivers with Shasta in 1945, Oroville in 1968 and the implementation of the Water Quality Control Plan in 1999 all had the effect of releasing increased flows during the summer when demands are high and as a consequence eliminated spring peak flows.

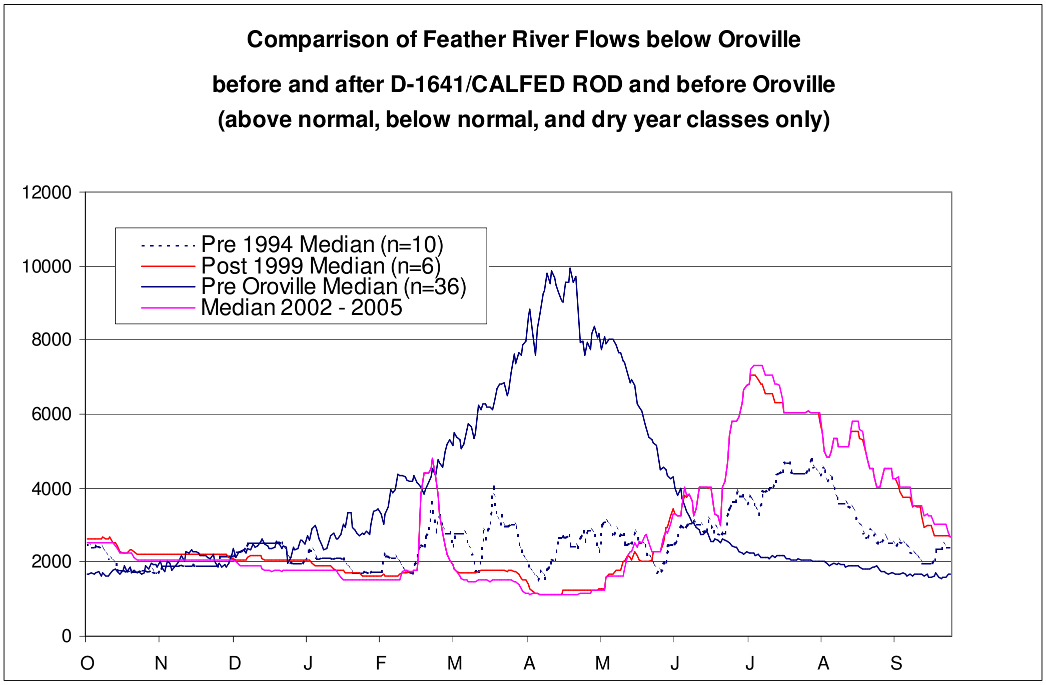

**Figure 3. Influence of Sacramento-San Joaquin Delta Regulations on Feather River Hydrograph**. The blue line of pre Oroville median flows represents the most natural hydrograph. In 1995 the Water Quality Control Plan tightened restrictions on the timing of Delta diversions. The pre 1994 hydrograph compared to the post 1999 illustrates how the hydrograph shifted spring flows to summer releases to meet Delta requirements.

## B. San Joaquin River

Dams and diversions have dramatically changed the magnitude and pattern of inflow to the San Joaquin Delta starting in the mid nineteenth century. Compared to the Sacramento River Basin, there is relatively little unregulated runoff from the San Joaquin Basin. In most years and months, dams heavily regulate at least 90 percent of inflow. Figure 4 presents changes in monthly average flows for different flow types based on percentiles developed from annual flows. Substantial changes to the hydrology of the lower river before the period of record for the Vernalis gauge, combined with a lack of *daily* unimpaired flow record for Vernalis, make it difficult to precisely describe anthropogenic changes to *daily* Delta inflow. The Natural Heritage Institute (Cain et al., 2003) conducted detailed analysis of daily scale hydrologic change, which is presented here to illustrate the magnitude of changes in Delta inflow from the San Joaquin Basin.

Figure 4 shows a dramatic decline in spring inflows for all year types. Unlike the Sacramento River, these spring flows are diverted out of the river into canals instead of being shifted to summer releases. The large capacity of the reservoirs and associated diversion infrastructure relative to runoff (Cain et al., 2003) allows operators to tightly control downstream releases in all but wet years or flood operations. Regulated flows during other seasons are generally similar to unimpaired conditions. Regulated flows in the fall and early winter of normal-wet years (60-80 percentile) and dry years (20-40 percentile) are higher than unimpaired flows due to compliance with flood reservation rules in years that follow wet years.[3]

Richter utilized the index of hydrologic alteration (Cain et al., 2003 – appendix A) to analyze hydrologic changes over the period of record at Newman and Vernalis USGS gauges. Although indicative of the trend, these changes understate the magnitude of anthropogenic change due to the significant level of hydrologic alteration from diversions at Mendota, Exchequer, Don Pedro, and Melones before the period of record. The largest changes between the early (1930-1940) and recent (1951-2000) periods as measured at the Newman and Vernalis gauges respectively show the following:

- Flow depletions of 74 to 76 percent in May and June
- Substantial increases in the 1 to 7-day minima (+51 to 63 percent)
- Substantial reductions in 1 to 90-day maxima (-45 to -52 percent)
- Shifts in the timing of annual maxima, from April-May to late December-early January
- Reductions of 46 to 48 percent in high and low pulse durations

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[3] This anomaly shows how the large volume of reservoir storage relative to runoff has not only altered spring flows, but has also shifted discharge from wet years to drier years. Dividing years into quantiles based on average inflows to upstream reservoirs rather then discharge at Vernalis would have resulted in a different percentile ranking and is probably the reason why median, average monthly spring flows are so similar between the three intermediate year types (dry, below normal, and above normal).

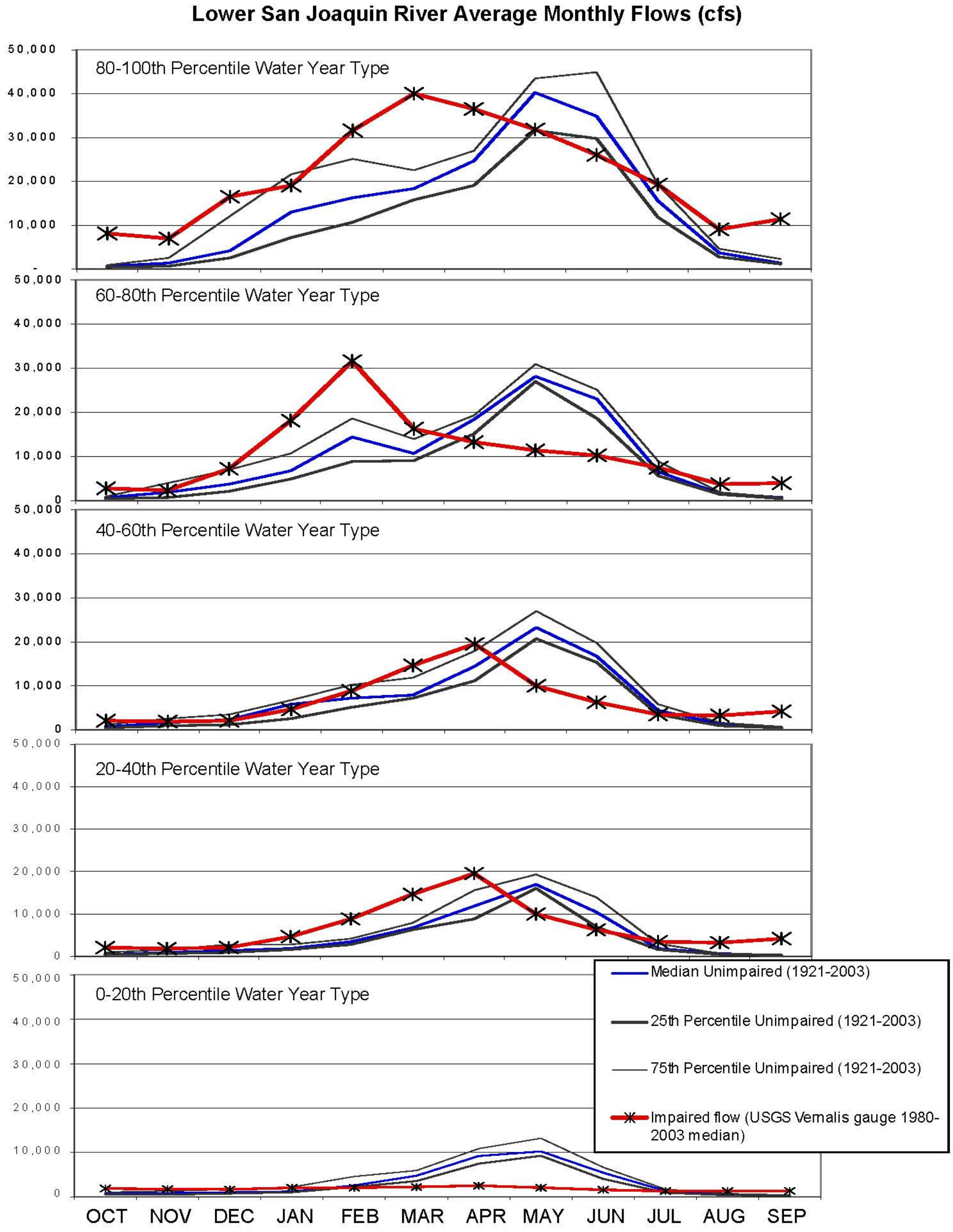
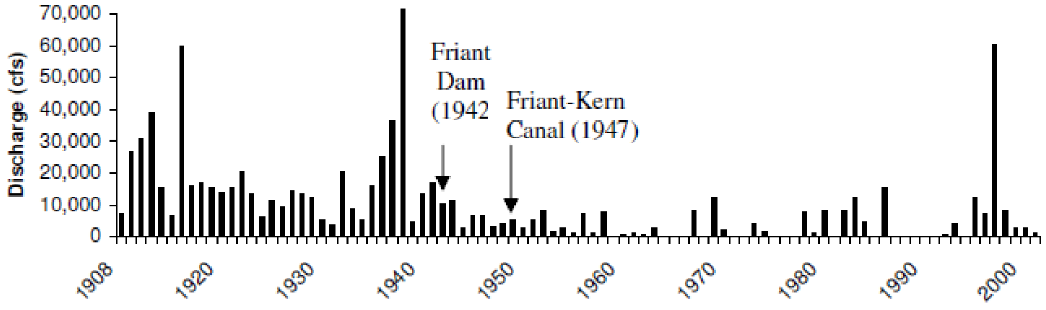
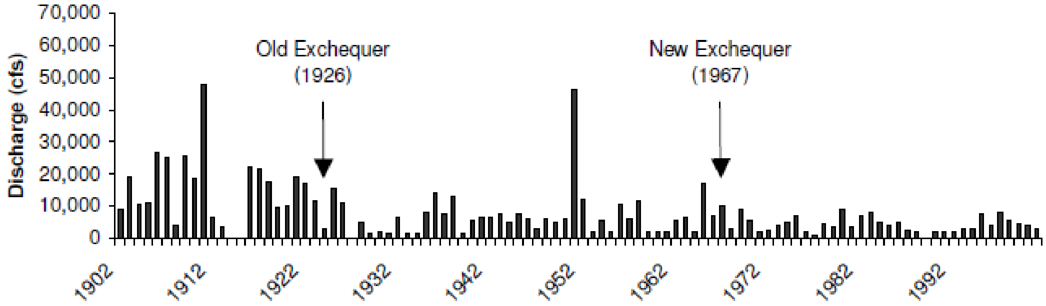


**Figure 4. Comparison of median average monthly unimpaired (1922-2003) and median average monthly post dam (1980 – 2003) for different year types.**

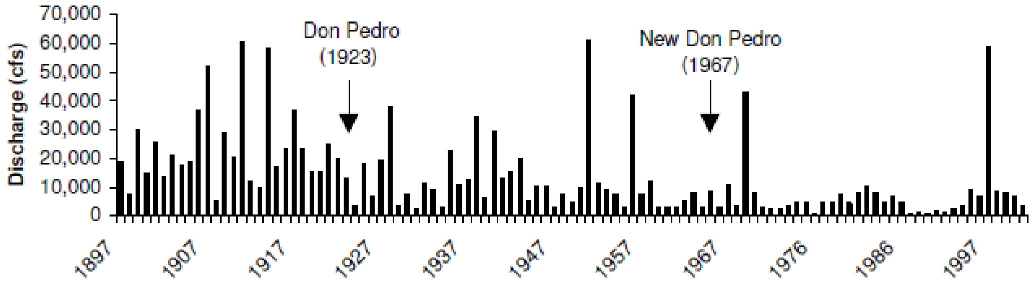
*Exhibit AR-1*
*SWRCB, Delta Flow Criteria*



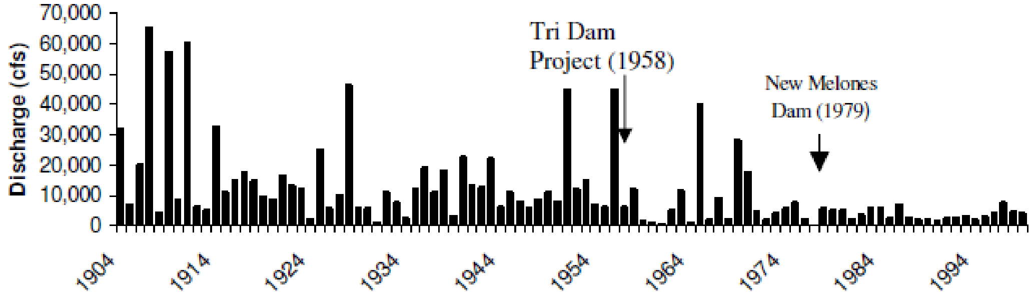
San Joaquin River, annual instantaneous maximum flow at Friant gauge below dam.



Merced River, annual instantaneous maximum flow at Exchequer (1902- 1964) and Merced Falls (1964-2001).



Tuolumne River peak annual flow at La Grange.



Peak Annual Flow, Stanislaus River at Knights Ferry

Figure 5. Changes in annual peak flows in the San Joaquin Basin.

Monthly averaged data do not reflect how flow regulation has dramatically reduced the magnitude and frequency of daily and weekly flow events in the San Joaquin. Figure 5 illustrates the significant decline in instantaneous peak flows and provides an example of the magnitude of change. McBain and Trush prepared a detailed hydrologic analysis of the San Joaquin Basin tributaries (Cain et al., 2003 – Appendix B) that graphically documents these changes. Figure 6 from that analysis illustrates how the San Joaquin hydrology has changed basin wide as a result of flow regulation. Clear graphic examples of these daily changes are not easily constructed for San Joaquin Delta inflows due to substantial hydrologic alteration in the nineteenth century before the period of record for the Vernalis gauge. The water board should attempt to reconstruct a daily unimpaired hydrology for the San Joaquin based on rim station inflow to better understand the nature of daily and weekly changes to inflow hydrology.

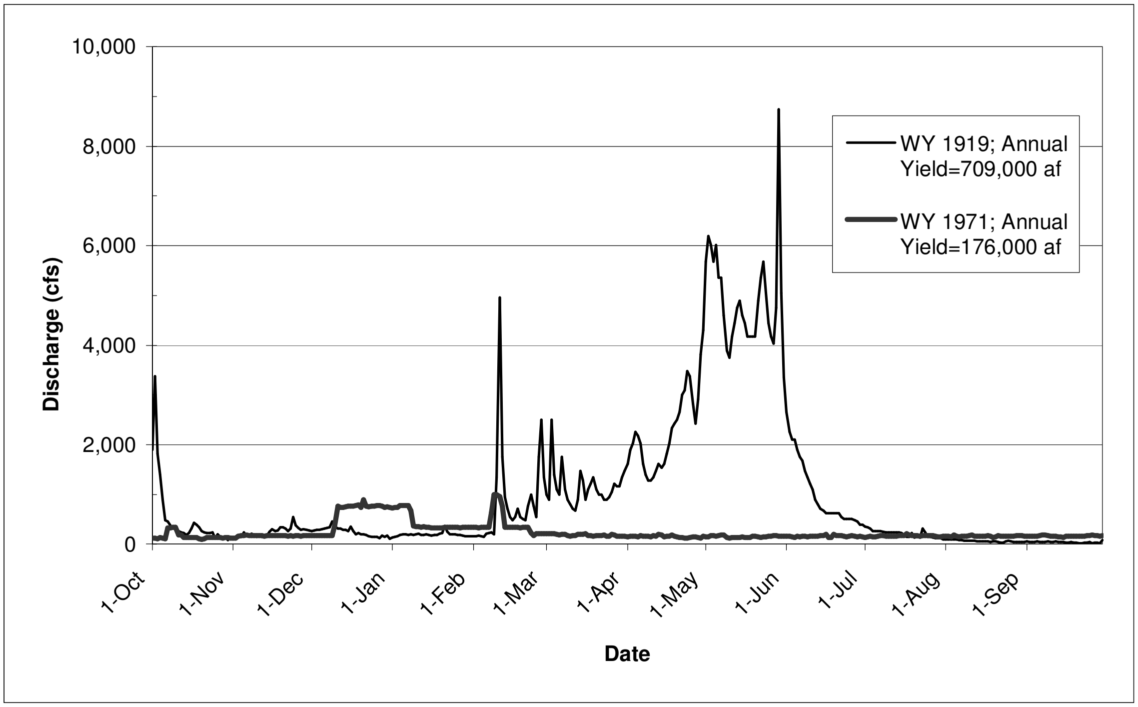


**Figure 6. Merced River Unimpaired (1919) and Regulated (1971) representative hydrograph for dry years.** This figure shows an example of how snowmelt floods were virtually eliminated under regulated conditions, primarily during dry and critically dry years. Unimpaired data from gauge below Merced Fall near Snelling; regulated data from gauge below Crocker-Huffman Dam near Snelling.

## III. INFLOW FUNCTIONS AND REQUIREMENTS

Inflows have a strong influence on the quality of Delta water, the productivity of the Delta ecosystem and the abundance, growth, and survival of many Delta species, particularly fish that spend some portion of their lifecycle in the rivers. These fish include splittail, sturgeon, salmon, steelhead, striped bass, and American shad. Inflows mediate connectivity with the upstream watershed and contribute inputs of freshwater, nutrients, sediment, and energy to the Delta from upstream habitats and are necessary for the movement of migratory species. Key components of the historical or unregulated flow regime appear to favor native fish over exotics. For example, pulse flow events transport turbid waters to the Delta and increase velocities in Delta channels, both of which may increase the competitive advantage of native species. High flows in the spring prolong the period of cooler water temperatures, which may also provide native species with a competitive advantage over exotic species.

Inflows function in the Delta ecosystem in many ways (Trush et al., 2000; Cain et al., 2003), but this document focuses on a limited number of functions associated with Delta inflow in late winter and spring, since as discussed above, these flows are the most highly altered component of the natural hydrograph in both basins. We focus on some of the key services provided by components of the winter and spring hydrograph and provide specific analysis regarding the timing, magnitude, frequency, and duration of inflows from the Sacramento and San Joaquin Rivers that may be necessary to support these essential functions.

1. Water temperature, particularly on the San Joaquin River
2. Maintenance of channel complexity and resulting water temperature dynamics
3. Floodplain inundation
4. Pulse flows and the transport of sediment, nutrients, and biota to the Delta

These essential inflow functions provide different benefits for the Delta ecosystem but are highly interrelated. Suitable water temperatures across the Delta and throughout the anadromous migration period are essential for maintaining native fish abundance, distribution, life history diversity, and population stability. Inflows along with complex channel habitat and variable hydrology help mediate suitable water temperature conditions. Flood flows are essential for maintaining complex channel and floodplain features and, by inundating floodplains, provide essential spawning and rearing habitat for native fish. Pulse flows flush nutrients from inundated floodplains and create turbidity plumes in the Delta improving survival and food resources for native Delta species.

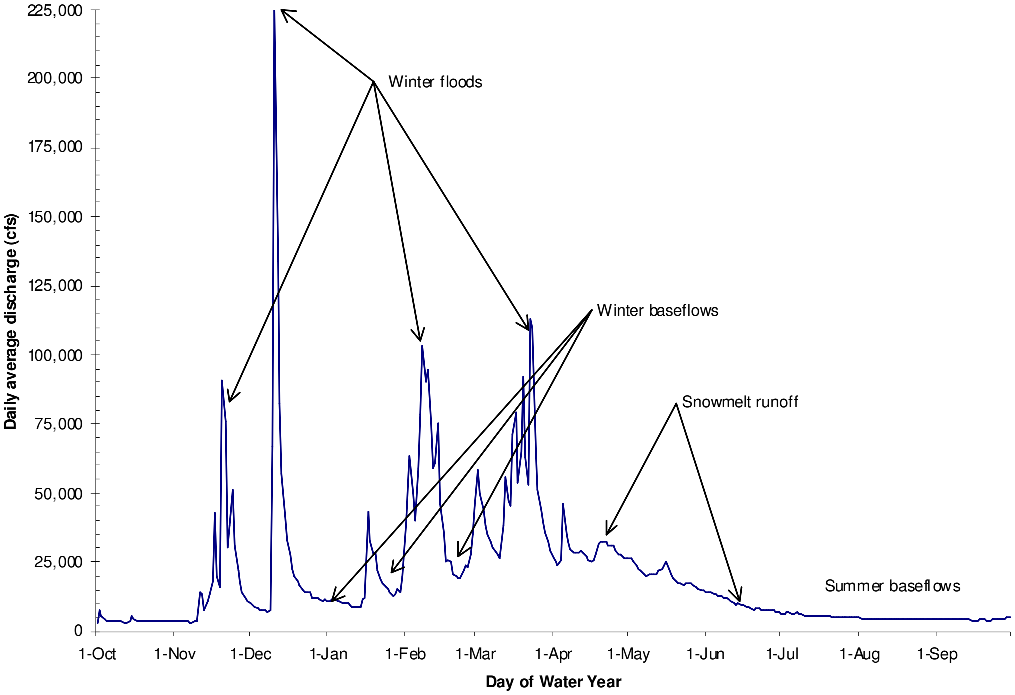


**Figure 7. Sacramento River Hydrograph Components (1938).** These are from the 1938 hydrograph for the Sacramento River above Bend Bridge, near Red Bluff gauging station. Modified from Kondolf et al. 2000.

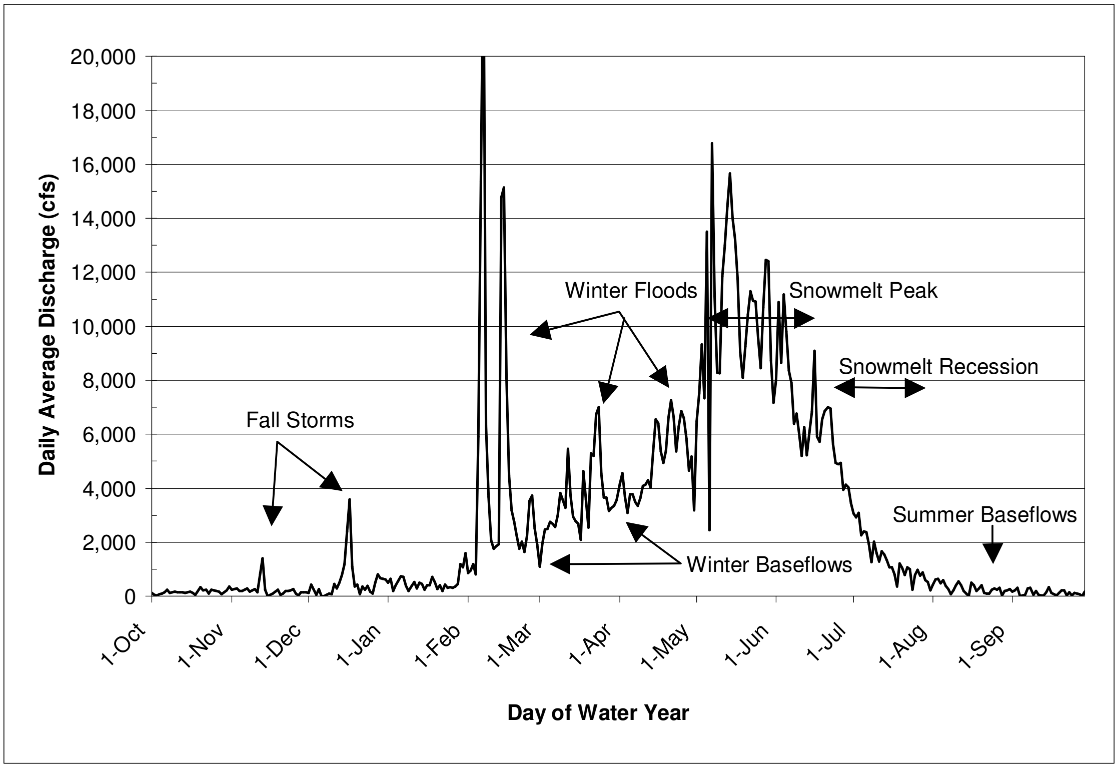


**Figure 8. Illustration of the important components of the annual hydrograph of daily average flows for a typical San Joaquin Basin Tributary.** Hydrograph from Tuolumne River as measured below La Grange Dam, Normal Unimpaired WY1937, prepared by McBain and Trush for Cain, 2003).

## A. Water Temperature

Water temperature plays a critical role in the life history of native fishes, particularly salmonids. Although easy to measure at specific locations, water temperature requirements vary substantially by life stage and actual water temperatures vary significantly both temporally and spatially. Furthermore, temperature requirements for individual life stages can vary depending on habitat quality, nutrition, and antecedent conditions. Thus, single temperature standards derived from laboratory studies are of limited use in actual ecosystems (Moyle, 2005). Moyle (2005) proposed a bio-energetic approach to temperature that considers temperature in the broader context of positive and environmental factors confronting an individual fish.

> "Generally, the ability of a juvenile or adult salmon to survive high temperatures is a function of the degree to which energy expended by dealing with stressful factors (e.g., avoiding predators, length of exposure to high temperatures) is balanced by energy gained from favorable factors (e.g., abundant food, daytime cool-water refuges)."

In short, healthy fish with a variety of habitat options are more likely to survive stressful temperatures than unhealthy fish. Table 1 identifies optimal and suboptimal temperature regimes.

Delta inflows, water temperatures in the lower reaches and floodplains of the Sacramento and San Joaquin Rivers and their tributaries, are particularly important, especially for juvenile salmonid life stages. Juvenile growth and survival can be enhanced by warmer temperatures in winter and early spring (Myrick and Cech, 2001). For example, research has shown that juvenile salmonids rearing on inundated floodplains in the Yolo Bypass, a lowland transition zone between the spawning reaches and the Delta, had significantly higher growth rates than juveniles reared in the mainstem of the Sacramento River (Sommer et al. 2001a).

Conversely, increased water temperatures, particularly in May and June, may negatively impact juvenile salmonids that remain in the tributaries and in the Delta later in the spring. Baker et al (1995) found 50 percent mortality for Chinook smolts that migrate through the Delta from the Sacramento River when temperatures reach 72-75°F (22-24°C). McCullough (1999) found that few fish can survive temperatures greater than 75.2°F (24°C), even for short periods of time.

**Table 1. Chinook salmon temperature tolerances (Fahrenheit).** Adapted from Moyle, 2005.

| | Sub Optimal | Optimal | Sub Optimal | Lethal | |
|---|---|---|---|---|---|
| Adult Migration | <50 | 50-68 | 68-70 | 70-75 | Migration usually stops when temperatures climb above 70 degrees F. Under most conditions fish observed moving at higher temperatures are moving to refugia |
| Juvenile Rearing | <55 | 55-68 | 68-75 | >75 | Past exposure (acclimation temperature) has a large effect on tolerance. Fish with high acclimation temps may survive at 84 degrees F for short periods of time. When food is abundant, fish that live under conditions between 61 F and 75 F may grow very rapidly. |
| Smoltification | <50 | 50-66 | 66-75 | >75 | Smolts may survive and grow at suboptimal temps but are primarily avoiding predators. |

## 1. Water temperature dynamics and channel complexity

Complex alluvial ecosystems can moderate harmful temperature fluctuations and provide cool water refugia for aquatic species. Average surface water temperatures are important, but interactions between surface and ground water, combined with shading from riparian vegetation, can create pockets of cool water even when average temperatures are relatively warm. Groundwater, particularly shallow subsurface flow through the hyporheic zone in alluvial channels, can also moderate potentially harmful fluctuations in daily and seasonal water temperature. The hyporheic zone is the saturated interstitial area below the channel bed or in the banks with some water derived from surface water from the channel (White 1993; Triska et al. 1990; Kasahaara and Wondzel (2003), Malard et al. 2002).

Hyporheic exchange, the interaction between surface water and shallow groundwater, occurs when surface water enters river gravels or sands and flows downstream along hydraulic gradients, eventually re-emerging in the river channel. Hyporheic exchange flow paths can vary in length, spanning long floodplain areas in some rivers (Stanford and Ward 1993) and relatively short alluvial bedforms in others (Wondzell and Swanson 1996). Kasahara and Wondzel (2003) observed that the majority of hyporheic exchange associated with rivers in alluvial valleys occurs along the channel and is related to geomorphic complexity of the channel bed. The influence of hyporheic exchange on river water temperature dynamics is often small scale and localized, with limited impact on temperatures of primary surface flows. Therefore, even detailed surface water temperature monitoring or modeling could fail to detect the presence of locally reduced water temperatures at hyporheic upwellings.

### 2. Linkages Between Floodplain Connectivity, Channel Complexity, and Hyporheic Exchange

Floodplain connectivity (i.e. the magnitude, frequency, duration, and timing of a natural or artificial hydraulic connection between a river channel and its floodplain) is a critical element of a healthy river ecosystem (Bayley 1995). The ability of a river channel to overflow its banks and inundate its adjacent floodplain is essential to maintaining channel and complexity and habitat. Reduced floodplain connectivity results in increased velocities and scour which ultimately lead to reduced hydraulic and habitat diversity. (Schiemer et al. 1999). For example, channel confinement by levees increases bed shear stresses and velocities of high flows, thereby increasing the frequency of channel bed mobilization and bank erosion and potentially reducing complexity of the river channel.

Floodplain and channel complexity can influence water temperature dynamics in several ways. Riparian vegetation shading reduces rates of water temperature warming while inundation of complex channel and floodplain features increases hyporheic exchange (Tompkins 2006; Arrigoni et al. 2008). High inflows drive hyporheic exchange directly by forcing water into alluvial features such as side channels and sand bars, and indirectly facilitate hyporheic exchange by creating and maintaining complex channel and floodplain morphology.

During low flow conditions that occur along with high ambient air temperature, hyporheic exchange can have significant cooling effects. Figure 9 is a plot of one day of water temperature data from downwelling and upwelling hyporheic exchange sites in lower Deer Creek, a tributary to the Sacramento River near Vina, CA. The figure illustrates the potential influence of hyporheic exchange on river water temperature. Peak temperature reduction is the difference between the daily peaks of the downwelling and upwelling water temperatures. Amplitude reduction is the difference between the downwelling amplitude of water temperature fluctuation (i.e. daily peak minus daily minimum) and the upwelling amplitude of water temperature fluctuation. Lag time is the difference between the time of the upwelling daily peak temperature and the downwelling peak temperature.

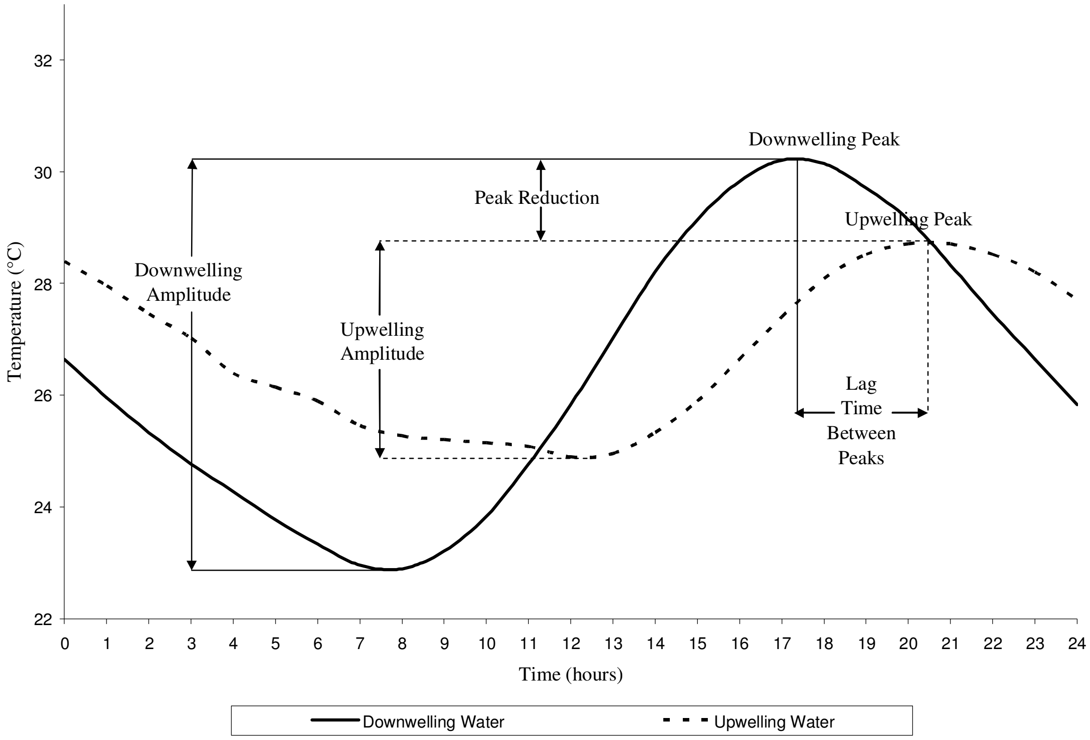


**Figure 9. Temperature impacts of hyporheic exchange.**

Arrigoni et al. (2008) observed that upwelling hyporheic water cooled relative to downwelling surface water by up to 1.1 °C, and the magnitude of fluctuations of upwelling hyporheic water were reduced relative to downwelling surface water by up to 2.7°C. In Deer Creek, significant peak temperature reduction (1.55 – 3.47 °C) and amplitude reduction (3.5 – 7.2 °C) was documented at hyporheic exchange sites in the lower 11 miles of the river. These studies were conducted between July and October, a period when average surface water temperatures in the lower river are typically unsuitable for salmonids.

While peak daily temperature and amplitude reductions in Deer Creek (and other rivers with hyporheic exchange) may only affect water temperature in the immediate vicinity of upwelling hyporheic sites and may not significantly cool receiving surface water, in some locations hyporheic exchange could provide local "micro-refugia" for aquatic organisms, especially benthic macroinvertebrates that can live in the interstitial spaces of the hyporheic zone. More extensive channel complexity driving more widespread hyporheic exchange in alluvial rivers like the San Joaquin could extend the period during which suitable temperatures are accessible to salmonids and other aquatic species. Observations of salmonid smolts in the upwelling zone of a hyporheic exchange site in lower Deer Creek in July (Figure 10) when surrounding surface water temperatures were as high as 86°F (30°C) indicates that this occurs, and if properly analyzed and incorporated into management of Delta inflows, could help maximize the value of flows delivered to the Delta for ecological purposes.

It is clear that channel complexity and floodplain inundation can influence river water temperature dynamics in small ways that may not be captured in standard analyses. In heavily impacted rivers like the San Joaquin and other sources of Delta inflows, small localized temperature reductions linked to floodplain inundation processes could be important to fish populations and should therefore be considered in assessments of Delta inflows.

**Figure 10. Juvenile salmonid in lower Deer Creek at a hyporheic exchange upwelling location in July**. Daily peak water temperature in surrounding surface water peaked at 30°F.

## B. Floodplain Inundation

The characteristics of inflow to the Delta—such as magnitude and duration—are positively correlated with flow characteristics in the upstream watershed. A wide range of flow characteristics in the upstream watershed are environmentally significant and are correlated with a variety of processes that promote the ecological health of the Delta and the viability of many species of management concern.

Here we will focus on the characteristics of inflow necessary to provide floodplain inundation and associated processes that benefit public trust resources in the Delta. Although floodplain inundation supports a broad variety of public trust resources, we focus on the inflow attributes associated with floodplain inundation that benefits the following resources:

1. Food web productivity from floodplains, which provides energy for Delta fish species
2. Chinook salmon
3. Sacramento splittail

In the discussion below we will emphasize four characteristics of flow—timing, magnitude, duration, and frequency—that collectivity influence the production of benefits from inundated floodplains (Table 2).

Table 2. Important characteristics of flow events such as floods.

| **Flow characteristic** | **Definition** | **Importance** |
|---|---|---|
| Magnitude | The flow rate, or the amount of water moving past a point during an interval of time (e.g., cubic feet per second). Also referred to as discharge. | The magnitude of flow is directly related to the *stage* or surface water elevation of water in a river channel. For river water to enter a floodplain a given stage, and thus a given magnitude, must be exceeded. For example, flows begin to crest over Fremont Weir and enter the Yolo Bypass floodplain when the magnitude of Sacramento River flow exceeds 56,000 cfs. |
| Duration | The length of time that a flow event occurs, or that a specific flow magnitude is exceeded, defined in hours, days, weeks, etc. | The biological benefits of floodplain inundation generally require a certain minimum duration of flooding. For example, splittail spawn on floodplains, so the duration of inundation must be sufficient for adults to enter and spawn and for eggs to hatch. Juvenile Chinook benefit from the high productivity of floodplains and thus would benefit more from two weeks of floodplain access than two days. |
| Timing | The season or period of the year that a flow event occurs. For example, winter floods, or floods that occur between March 15 and May 15. | River species, such as fish, often use specific habitats at specific times of the year and so the timing, or seasonality, of hydrological conditions can be very important. For example, spilttail require floodplains for spawning and only spawn in the Spring, so a flood that inundates floodplain in April directly benefits splittail spawning while the same flood (in terms of magnitude or duration) in December has no direct value. |
| Frequency | The rate of occurrence of a flow event. Generally discussed in terms of the "expected rate of occurrence" or the probability that an event will occur. Can be expressed as recurrence interval (e.g., a ten-year flood is a flood magnitude expected to happen about once in a ten-year period, on average) or exceedance probability, which is the annual probability that a certain flow magnitude will be exceeded (e.g., a "ten-year flood" has an exceedance probability of 10%). | The frequency of floodplain inundation will determine the frequency that a biological resource, such as a fish population, benefits from floodplain inundation. For example, floodplain benefits produced only rarely (e.g., once every ten years) will provide little population-scale benefits to short-lived fish species. |

### 1. Magnitude and connectivity

The prerequisite for an ecologically functional floodplain (i.e., that which can produce the benefits considered here) is hydrological connectivity between the river and floodplain (Amoros, 1991; Tockner and Stanford, 2002). Connectivity drives all hydrologic and geomorphic processes on the floodplain and can be achieved through multiple pathways including lateral overflow as river stage rises, through breaks in natural or constructed levees, and through sloughs or side channels into a flanking flood basin. Water on the floodplain can then perform geomorphic work (erosion and deposition), facilitate the exchange of organisms, nutrients, sediment, and organic material between the river and floodplain, and provide a medium in which biogeochemical processes and biotic activity (e.g., phytoplankton blooms, zooplankton and invertebrate growth and reproduction) can occur.

The threshold for inundation is the river stage at which connectivity begins between river surface water and the floodplain. A primary control on this threshold is the floodplain elevation above the river channel; the greater the elevation the greater the threshold for inundation (i.e., a higher discharge and stage is required to exceed the threshold). Channel incision—due to channelization, levees that confine high-energy flows to narrow channels causing bed degradation, or "hungry water" below sediment-trapping dams (Kondolf, 1997)—increases the elevation difference and thus increases the threshold for inundation. Other factors that influence the threshold of inundation include channel geometry, roughness and gradient, and factors that either inhibit connectivity (e.g., levees and rip-rap) or promote it (e.g., weirs, sloughs, or levee breaches). Large woody material or other factors can locally increase roughness and thereby decrease the inundation threshold. Thus, the flow magnitude at which the inundation threshold is exceeded varies throughout the upstream river system.

Williams et al. (2009) recently explored the effect of altered flow regimes on the functionality of floodplains along the Sacramento River. They found that due to channel incision and regulation from upstream reservoirs, long duration spring floods have been greatly reduced compared to pre-dam conditions. Currently, the production of benefits associated with these floods—food-web productivity and native-fish habitat—are mostly restricted to the Yolo Bypass, a large (24,000 ha) engineered flood bypass that conveys overflow from the Sacramento River (Sommer et al., 2001a). Thus, due to the alteration of the flow regime, even areas that are hydrologically connected to the Sacramento River during larger magnitude floods have a much lower frequency of inundation by long duration spring floods than occurred historically, limiting their ability to provide this important component of a functional floodplain.

### 2. Food web benefits of floodplain inundation

Floodplains can potentially export biologically available carbon to downstream food webs (Junk et al., 1989; Benke, 2001). Central Valley floodplains can produce high levels of phytoplankton and other algae, particularly during long-duration flooding that occurs in the Spring (Schemel et al., 2004; Sommer et al., 2004; Ahearn et al., 2006). Downstream of Central Valley floodplains, the Delta contains several fish species with declining populations, such as the Delta smelt (*Hypomesus transpacificus*), and food limitation is likely one of the factors contributing to these declines (Jassby and Cloern, 2000). Algae provide the most important food source for zooplankton in the Delta (Muller-Solger et al., 2002) and these zooplankton are a primary food source for numerous Delta fish species. Consequently, a potential benefit of floodplain restoration is an increase in the productivity of food webs that support Delta fish species (Ahearn et al. 2006).

In addition to exporting biologically available carbon from floodplain habitats, inundated floodplains provide benefits to the Delta system by increasing the total area of Delta habitats. For example, Jassby and Cloern (2000) reported that a flooded Yolo Bypass essentially doubles the area of the Delta. Increased connectivity between shallow water habitats and open water can substantially increase aquatic productivity in estuaries (Cloern, 2007). Organisms within the Delta can then access the resources available in the bypass during the periods of inundation.

Specific flow conditions promote these food-web productivity benefits for the Delta. As described above, flow magnitudes must be sufficient to inundate enough floodplain area for these benefits to be produced at biologically relevant levels. Below we describe other important flow characteristics, including the timing, duration, and frequency of floodplain inundation flows.

#### *Timing*

For the balancing of benefits between native and non-native fish within the typical flood season, spring is most valuable for food-web productivity because of increasing light and temperature. Photosynthesis increases with increasing light so greater light availability in the water column leads to increased production of phytoplankton (Cushing and Allan, 2001). Within the boundaries of typical spring temperatures, phytoplankton productivity also increases with temperature (Cushing and Allan, 2001; Sommer et al., 2004). Thus, springtime flooding, with more sunlight and warmer temperatures, will lead to greater productivity of phytoplankton than winter flooding. The productivity benefits of flooding can be limited if floods do not occur within a temperature range conducive to algal growth (Schramm Jr. and Eggelton, 2006).

### *Duration*

Both phytoplankton and periphyton require a minimum duration of inundation for growth and reproduction. Algal growth is also strongly influence by residence time—the length of time that a given unit of water remains in a given place and thus reflects the exchange rate of water at that place. Residence time is influenced by the duration of flooding and by the hydraulics of the floodplain (e.g., the rate of draining). The greatest productivity tends to occur during high residence time flooding during the falling limb of the hydrograph (Ahearn et al. *2006*).

### *Frequency*

Because phytoplankton concentrations tend to be greatest during the draining period of an inundation event (Schemel et al., 2004; Ahearn et al., 2006), researchers have recommended that total phytoplankton production from a given floodplain could be maximized by increasing the intra-annual frequency of floods. For example, several shorter pulses, each having a high residence time draining stage, could result in more total productivity than a single longer pulse (with the same total duration or volume of flooding as the several pulses). A high frequency (e.g., every year or nearly every year) will provide the most benefit to food-limited species in the Delta, particularly for short-lived species.

## 3. Chinook salmon benefits of floodplain inundation

Juvenile Chinook salmon (*Oncorhynchus tshawytscha*) have faster growth rates on floodplains than in main-stem river channels (Sommer et al., 2001b; Jeffres et al., 2008). Juvenile Chinook can enter and rear on floodplains during their downstream migrations in the winter and early to mid spring. The juveniles have access to a diverse and dense prey base on floodplains—zooplankton density can be 10-100 times greater in a floodplain compared to the river (Grosholz and Gallo, 2006)—along with generally more favorable habitat conditions (warmer, slower water, fewer predators). These conditions translate to faster growth compared to juveniles rearing in rivers. Faster growth has been documented in the upper Sacramento (Limm and Marchetti, 2003), the Yolo Bypass (Sommer et al., 2001b), and the Cosumnes River (Jeffres et al. 2008). Faster growth rates allow juveniles to attain larger sizes when they enter the estuary and ocean, and body size has been found to be positively associated with survival to adulthood for salmonids (Unwin, 1997).

Specific flow conditions promote salmon use of floodplains. As described above, flow magnitudes must be sufficient to inundate enough floodplain area for these benefits to be produced at biologically relevant levels. Below we describe other important flow characteristics, including the timing, duration, and frequency of floodplain inundation flows.

### *Timing*

The migration of juvenile salmon generally coincides with peak flows and so also generally coincides with access to floodplains. However, the specific timing of emigration varies from run to run, from river to river, and from year to year. Most fall-run fish emigrate between December and March (Williams, 2006). Non-native fish begin to access the floodplain later in the spring (Crain et al., 2004) so, in general, flooding to benefit native fish over non-natives would occur in the winter and early spring, ending in mid-spring.

### *Duration*

In general, floodplain benefits for juvenile Chinook should increase with increasing duration of flooding, as longer time on the floodplain provides more opportunities for feeding within a more productive environment than river channels. However, even relatively short periods of access may provide benefits as fish reared in enclosures on floodplain habitats showed rapid growth in a two-week interval on the Cosumnes River floodplain (Jeffres et al., 2008).

### *Frequency*

Salmon population benefits will increase with increasing interannual frequency of flooding. As described above, several pulses (and associated high residence time draining periods) within a year may be associated with greater productivity and so several pulses may also benefit salmon growth rates. Several pulses may also give salmon the opportunity to exit the floodplain, although stranding does not appear to be a major problem for native fish (Sommer et al., 2005; Moyle et al., 2007).

## 4. Splittail benefits of floodplain inundation

Sacramento splittail may be the only obligate floodplain spawner among California's native fish fauna, although some extirpated species, such as Sacramento perch (Moyle et al. 2007) may have been highly dependant on floodplains. Recruitment of splittail is strongly correlated with the duration of inundation in the Yolo Bypass; inundation of at least a month appears to be necessary for a strong year class of splittail (Sommer et al., 1997). Splittail benefit from inundated floodplain in numerous ways. Flooded annual vegetation is the preferred spawning substrate and floodplains may provide abundant food resources for adults prior to spawning and for larva after hatching. Flooded areas may also reduce predation on both eggs and larval fish. Extensive spawning of splittail has also been observed in the Cosumnes River Preserve and splittail rearing in these floodplain habitats generally had higher condition factors than fish rearing in the river or ditch habitats (Ribeiro et al., 2004).

Specific flow conditions promote splittail use of floodplains. As described above, flow magnitudes must be sufficient to inundate enough floodplain area for these benefits to be produced at biologically relevant levels. Below we describe other important flow characteristics, including the timing, duration, and frequency of floodplain inundation flows.

### *Seasonal Timing*

Adult splittail move into inundated areas in late February or early March and spawning occurs in March and April; however, spawning can occur later in April and into May as well. The spawning time range is perhaps as broad as late February to early July, but later than May is "highly unusual" (Moyle et al., 2004). Recent research from the Yolo Bypass suggests that spawning is most likely to occur near the vernal equinox (late March) (Feyrer et al., 2006). Splittail young of the year (YOY) have been observed leaving floodplains (Yolo Bypass and Cosumnes) in May (Moyle et al., 2004). Thus, inundation in March through May is conducive to successful splittail spawning.

### *Duration*

Continuous inundation is necessary for successful spawning, incubation and initial rearing of larval splittail. Splittail eggs require 3-5 days to hatch (Moyle et al., 2004). Larval and juvenile splittail will remain on the floodplain while conditions are appropriate. Emigration from the floodplain appeared to be related to fish size as most YOY leaving the Yolo Bypass were between 30-40 mm in length. This size range suggests that a duration sufficient for fish to reach this size will be optimal (Feyrer et al., 2006). Spawning success may also be improved by longer duration flooding that allows adults time to feed on earthworms on floodplains prior to spawning. The energy gained by feeding on worms may improve adult condition factor and egg production (Moyle et al., 2004). Thus the optimal duration will allow for adults to enter floodplains, feed and spawn, for eggs to incubate and hatch, and then provide sufficient duration for the YOY to reach 30-40 mm in length. The strongest year classes of splittail occur in years with continuous inundation of floodplains (e.g., Yolo Bypass, Cosumnes) during March and April (Moyle et al., 2004).

### *Interannual frequency*

Splittail populations can be maintained without annual occurrence of the appropriate spawning conditions on floodplains, both because occasional strong year classes can maintain populations and because there is some spawning even in very dry years (e.g., along channel margins) (Moyle et al. 2004). However, splittail populations will generally increase with increasing frequency of appropriate spawning and rearing conditions on floodplains.

## C. Pulse Flows and Transport of Sediment, Nutrients, and Biota to the Delta

Pulse flows and turbidity events generated by pulse flows may be important to the migration, feeding, and survival of many Delta species. Dams and their operation have reduced pulse flows and turbidity events on the rivers flowing into the Delta. It may be possible to increase the frequency of turbidity events by increasing the frequency of pulse flow releases from reservoirs and timing those releases to coincide with turbid inflow from unregulated drainage areas.

Large, short duration pulse flows, particularly in the late fall and winter were once a common feature prior to flow regulation by dams. The magnitude, frequency and potential function of these pulse flow events are often overlooked, because hydrologic data is often averaged and presented by month or year type. Pulse flows of various magnitudes perform a variety of functions including maintenance of channel habitat and transport of nutrients from inundated floodplains and side channels (Junk et al., 1989). We have limited our testimony to a discussion of the role of pulse flows in the inter-related functions of turbidity in the Delta and successful migration of salmon through the Delta.

Pulse flows convey suspended sediment to the Delta resulting in turbid water conditions in parts of the Delta. Turbid water may provide important benefits to a number of native Delta species including Delta smelt and migrating salmonids. Delta smelt larvae require turbidity to initiate feeding (Baskerville-Bridges et al. 2004). Distribution of juvenile delta smelt is strongly influenced by turbidity and decreasing turbidity in the Delta may be the cause of decreasing may constrain the distribution of juvenile Delta smelt (Feyrer et al. 2007; Nobriga et al 2008). Turbidity increases the ability of juvenile salmon to avoid predation (Gregory 1992; Gregory and Levings 1996, 1998) and predation is an important source of mortality in the Delta and upstream rivers. Lastly, turbidity limits light penetration, which in turn, limits the growth and extent of submerged aquatic vegetation such as *Egeria densa.*

Dams and associated hydrologic alteration can substantially reduce turbidity. Dams trap sediment from the upper watershed, while reduced downstream flows reduce erosion of the channel and disrupt the transport of sediments delivered to the channel from drainages downstream of the dam. Under natural conditions, mainstem flows would rise and fall in synchrony with smaller drainages increasing the likelihood that sediments inputs to the main channel would be transported downstream during the same event that transported them to the channel. Under highly regulated hydrology, as exemplified by the San Joaquin Basin, fine sediment input to the stream may be out of sync with mainstem flows causing sediment to deposit on the channel bottom rather than be conveyed downstream by high flows in the channel. This may not only harm benthic organisms, but also may limit the amount of turbid pulses entering the Delta.

It may be possible to reestablish turbid pulse flows through carefully timed and monitored pulse flows releases from upstream reservoirs. Pulse flows carefully timed with rainfall-runoff from the unregulated portions of the watershed could both enhance transport of sediment inputs from small drainage to the Delta as well as recruit new sediment from bed and bank erosion.

Lastly, pulse flows to push nutrients from floodplains and side channels into the main channel and the Delta may be important to overall productivity of the Delta (Cloern, 2007). As discussed above, inundation and slow velocities water in floodplains and side channels can be important sources of both primary productivity and macro invertebrates. Multiple, carefully timed pulse flows could optimize the production and transport of these food resources to the Delta.

## D. Sacramento River Functional Inflow Requirements

### 1. Floodplain Inundation Recommendation

As discussed above, floodplain inundation provides important ecological benefits for the Delta, but floodplain inundation flows are now relatively rare events along the Sacramento River due to levees and hydrologic alteration by dams (Williams et al., 2009). Inundation events do occur in wetter years both in the reach of the river between Red Bluff and Colusa as well as in the flood bypass system. Inundation of secondary channels, gravel bars, and low lying floodplains between Red Bluff and Colusa encompasses relatively few acres compared to inundation of the bypasses, but may be particularly important for subsequent growth and survival of salmonids. Inundation of the Yolo and Sutter bypasses has a very large effect on the overall acreage of aquatic habitat in the Delta watershed. Inundation of the Yolo Bypass, for example, doubles the wetted surface area of the Delta (Sommer et al., 2001a). Although not as wide as the Yolo Bypass, inundation of the Sutter Bypass increases shallow water riverine habitat by one to two orders of magnitude.

Inundated off-channel habitat such as high flow channels can also provide rearing habitat for salmon (Peterson and Reid, 1984), but regulated spring flows are generally insufficient to inundate these habitats for prolonged periods (30-60) days. A recent study of these habitats in the Sacramento River determined that a large proportion of secondary channels between Red Bluff and Colusa become fully connected to the river at flows above 12,000 cfs (Kondolf, 2007). Regulated flows seldom exceed 10,000 cfs in the drier year types (dry and below normal) during late winter and spring when salmon are most likely to require spawning habitat. Even in normal wet years, median April flows are generally below 10,000 cfs.

The occurrence of inundated floodplain habitat has been substantially altered by both levees and dams. Dams have reduced the frequency of high flows sufficient to inundate floodplains, while levees have prevented high flows, even very high flows, from inundating floodplains particularly in the lower reaches of the river below Colusa. It is not reasonable to reestablish inundated floodplains by overtopping levees, because it would require extremely, even unnaturally, high flows and would cause widespread flood damage.

Adequate duration of flooding in the designated flood bypasses generally occurs in the wet years and sometimes in normal wet years creating excellent conditions for salmon and splittail. However, overtopping the weirs and flooding the bypasses in normal dry and dry years would require prohibitive amounts of water to achieve in drier year types. Practically, it is probably only realistic to achieve prolonged (30-60 days) floodplain inundation in normal dry and dry years by notching (or removing) the upstream weirs to allow a small amount of water to pass (3,000-5,000 cfs) and installing inflatable weirs in the low flow channels of the bypasses to back-up water.

Strategically breaching levees and using flood control weirs to inundate flood bypasses and other undeveloped land is a more achievable approach for creating inundated habitat. Although there may be many places to create inundated floodplain habitat with strategic levee breaches, we have focused on identifying flows that would create inundated habitat in the Yolo and Sutter Bypasses if modifications are made to the weirs that control flow onto the bypasses. The area of inundation under a given flow is determined by topography and drainage. We assume changes in the topography and drainage of the bypasses (i.e. berms or inflatable weirs) to maximize the area of inundation at lower flows and minimize the potential for fish stranding. While it might be possible to create large areas of habitat at low flows, higher flows may be necessary to optimize temperatures on the flood plain and conveyance of nutrients from the floodplain to the Delta.

### *Magnitude*

Table 3 lists inundation thresholds for multiple locations along the river. Flow thresholds were developed from a review of reports, hydrologic data, and topographic maps to estimate the floodplain inundation thresholds. The inundation threshold, however, is not enough to push a substantial amount of water down the bypasses. For example, achieving 5,000 cfs on the Yolo bypass requires an additional 12,000 cfs above the 23,100 cfs inundation threshold.

**Table 3. Inundation thresholds for floodplains and side channels at various locations along the Sacramento River**. Inundation threshold refers to the discharge when floodwaters begin to inundate the floodplain. Target discharge is the amount of water necessary to produce substantial inundation and flow across the floodplain.

| Location | Stage | Inundation Threshold (cfs) | Target Discharge (avg. cfs) | Gauge Location | Source |
|---|---|---|---|---|---|
| Freemont Weir | | | | | |
| existing crest | 33.5 | 56,000 | 63,000 | Verona | USGS |
| proposed notch | 17.5 | 23,100 | **35,000** | Verona | USGS |
| Sutter Bypass | | | | | |
| Tisdale weir | 45.5 | 21,000 | | Colusa | NOAA; Feyrer |
| Tisdale with notch | | | | | |
| Lower Sutter Bypass | 25 | 30,000 | **30,000** | Verona | USGS |
| Upper Sacramento | | | | | |
| meander belt side channels | various | 10,000 | **12,000** | Red Bluff | USGS |

Relatively small discharges can inundate large areas (Sommer et al. 2004). According to DWR modeling analysis, large areas of the bypass become inundated with as little as 5,000 cfs flowing through the bypass (Figure 11) (Harrell, B., 2008). Flows in excess of 35,000 cfs in the Sacramento River, however, may be necessary before it is possible to get 5,000 cfs down the bypass.

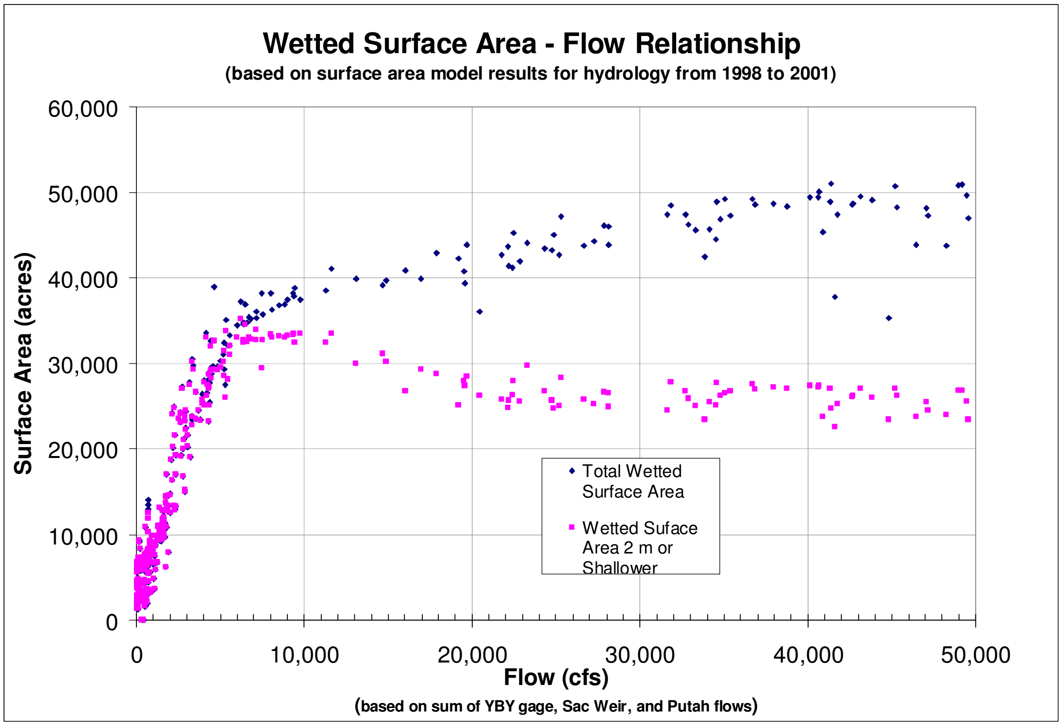


Figure 11. Wetted surface area-flow relationship for flows in the Yolo Bypass

### *Duration and Timing*

Table 4 identifies flow recommendations for various year types at key sites based on flows necessary to maintain inundated habitat in the Yolo Bypass for varying durations depending on years type. These flows would probably result in inundation of the Sutter bypass as well, particularly if the Tisdale or Moulton weirs were also notched. Table 4 illustrates duration and timing targets to provide floodplain inundation flows for 15 to 120 days between December and May 30 into the Sutter and Yolo Bypasses to provide rearing habitat for salmon and splittail, spawning habitat for splittail, improved migration corridor opportunities for downstream migrants, and food web productivity benefits. Reservoir releases should be timed to coincide with and extend duration of high flows on less regulated rivers and creeks such as the Yuba River, which still exhibits a more natural hydrograph. The duration target is fixed for each year type, but actual hydrograph timing should vary across the optimal window depending on hydrology and life history diversity requirements.

Table 4. Flow recommendations for floodplain inundation flows.

**Floodplain Inundation Flow Targets**

| | Dec | Jan | Feb | March | April | May | Average c.f.s. | Days | MAF |
|---|---|---|---|---|---|---|---|---|---|
| *Inundation Target Window* | ░░ | ░░ | ░▒ | ▒▓ | ▓▓ | ▒░ | | | |
| Wet (80 - 100 percentile) | | 🟨 (second half) | 🟨🟨 | 🟨🟨 | 🟨🟨 | 🟨 (first half) | 35,000 | 120 | 8.3 |
| Normal wet (60 - 80 percentile) | | | 🟨🟨 | 🟨🟨 | 🟨🟨 | | 32,500 | 90 | 5.8 |
| Normal dry (40 - 60 percentile) | | | 🟨 (second half) | 🟨🟨 | 🟨 (first half) | | 30,000 | 60 | 3.6 |
| Dry (20 - 40 percentile) | | | | 🟨🟨 | | | 27,500 | 30 | 1.6 |
| Critica (0 - 20 percentile) | | | | 🟨 (first half) | | | 27,500 | 15 | 0.8 |

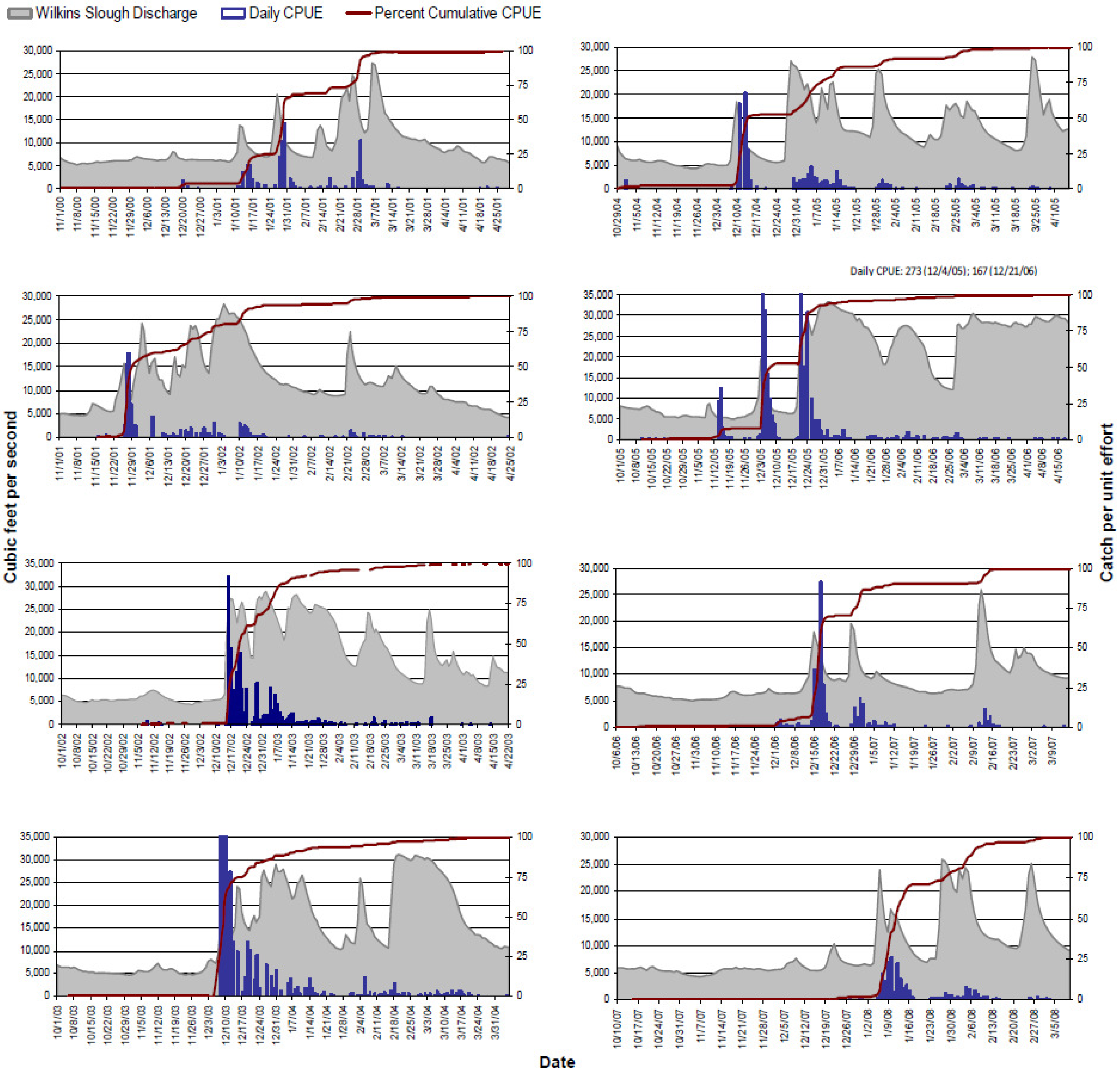
*Frequency*
Ideally, it would be possible to inundate the bypass every year to enhance food web productivity and improve rearing habitat for every year class of salmon. It may be possible to do this while economizing on water by inundating relatively small areas in dry years and very large areas in wet years, with no inundation in critical dry years.

### 2. Pulse Flows Recommendation

Multiple pulse flows of 15,000 cfs in the Sacramento at Wilkins Slough and up to 20,000 at Freeport at different times of the winter and spring may be necessary to aid migration of a broad diversity of salmon runs. Recent analyses shown in Figure 12 indicate that the onset of emigration of winter-run fish to the Delta at Knights Landing is triggered by flow pulses of 15,000 cfs at Wilkins Slough, and emigration from the Sacramento River to Chipps Island follows pulse flows of 20,000 cfs at Freeport (del Rosario, 2009). Previous studies found that smolt survival increased with increasing Sacramento River flow at Rio Vista, with maximum survival observed at or above about 20,000 and 30,000 cfs (USFWS, 1987).

Pulse flows may also be necessary to erode sediment in the upper Sacramento and create turbid inflow pulses to the Delta. Despite uncertainty about the exact magnitude of flow necessary to initiate substantial bank erosion, there is growing evidence that flows between 20,000 and 25,000 cfs will erode some banks while flows above 50,000 to 60,000 cfs are likely to cause widespread bank erosion (Stillwater, 2007). Meander migration modeling analysis for the Sacramento River assumed that 15,000 cfs was the lower threshold for meander migration (Larsen, 2007).

Lastly, pulse flows are needed to transport foodweb resources from inundated floodplains and side channels. Kondolf (2007) found that multiple side channels along the San Joaquin became inundated at 8,000 – 10,000 cfs from the downstream end and became connected on the upstream end at approximately 12,000 cfs. Periodic inundation of these side channels during the winter and spring followed by short pulses of flow (i.e. 14,000 cfs) sufficient to flush food resources could increase foodweb inputs to the Delta. Similarly, pulses of flow through an inundated bypass could result in foodweb pulses. For example, the flow prescription might call for periods of low inflow to the bypass (1,000 cfs) followed by short pulses 5,000 – 10,000 cfs through the bypass.



Daily CPUE: 273 (12/4/05); 167 (12/21/06)

Figure 12. **Pulse flows and winter run juvenile salmon migration past into the Delta.** From del Rosario, 2009.

## E. San Joaquin River Functional Inflow Requirements

### 1. Water temperature

Inflow on the San Joaquin at Vernalis in the legal Delta is essential to maintain suitable water temperature conditions in the lower San Joaquin for salmonids, particularly during the spring out-migration period. As discussed above, temperature is determined by a number of factors including reservoir release, channel geometry, and ambient air temperatures. The variability of air temperature, particularly during the spring and fall when temperatures are rising and falling, makes it difficult to determine the exact flow release necessary to maintain water temperatures in the lower San Joaquin. A given flow may be sufficient during average meteorological conditions to achieve suitable water temperatures, but it may be inadequate during heat waves, which periodically occur during the spring.

Maintaining suitable temperature and habitat conditions for salmonids in the lower San Joaquin River is necessary to maintain and restore broad spatial distribution of anadromous fish in the Central Valley. The San Joaquin Basin and its tributary rivers are the southern extent of the geographic range for fall-run Chinook salmon, Central Valley steelhead (a federally listed distinct population segment), white sturgeon, and Sacramento splittail, among other species. Flow conditions that block passage or cause substantial mortality of upmigrating adults or outmigrating juveniles reduce the geographic range and spatial structure of these species. Furthermore, spring run Chinook salmon will be reintroduced to the San Joaquin watershed pursuant to the San Joaquin restoration settlement. The high elevation, snowmelt dominated nature of the San Joaquin watershed could make it an important refuge for salmonids in the Central Valley under a warming climate.

Water temperature data from the Vernalis gauge, although from a limited period of record, shows that flows over 5,000 cfs in the late spring are necessary to provide water temperatures suitable for juvenile salmon and smolts. Cain et al. (2003) evaluated water temperature data from Vernalis to determine what flow thresholds achieved suitable water temperature conditions in the past under a range of hydrologic and meteorological conditions during the six-week period between April 15 and May 31. Figure 13 shows the results of these analyses and indicate that temperatures during this six-week period generally drop below 65 degrees and always remain below 70 degrees at flows above 5,000 cfs. Temperatures rise above 65 degrees even at very high flows in some cases either due to unseasonably warm weather or water from inundated floodways as far upstream as the Chowchilla and James Bypasses. The overall pattern shows that water temperatures generally drop with increases in flow, but some high water temperatures can occur at very high flows due to the warming effects on artificial floodways that divert floodwater from the Tulare and San Luis basins into the Delta.

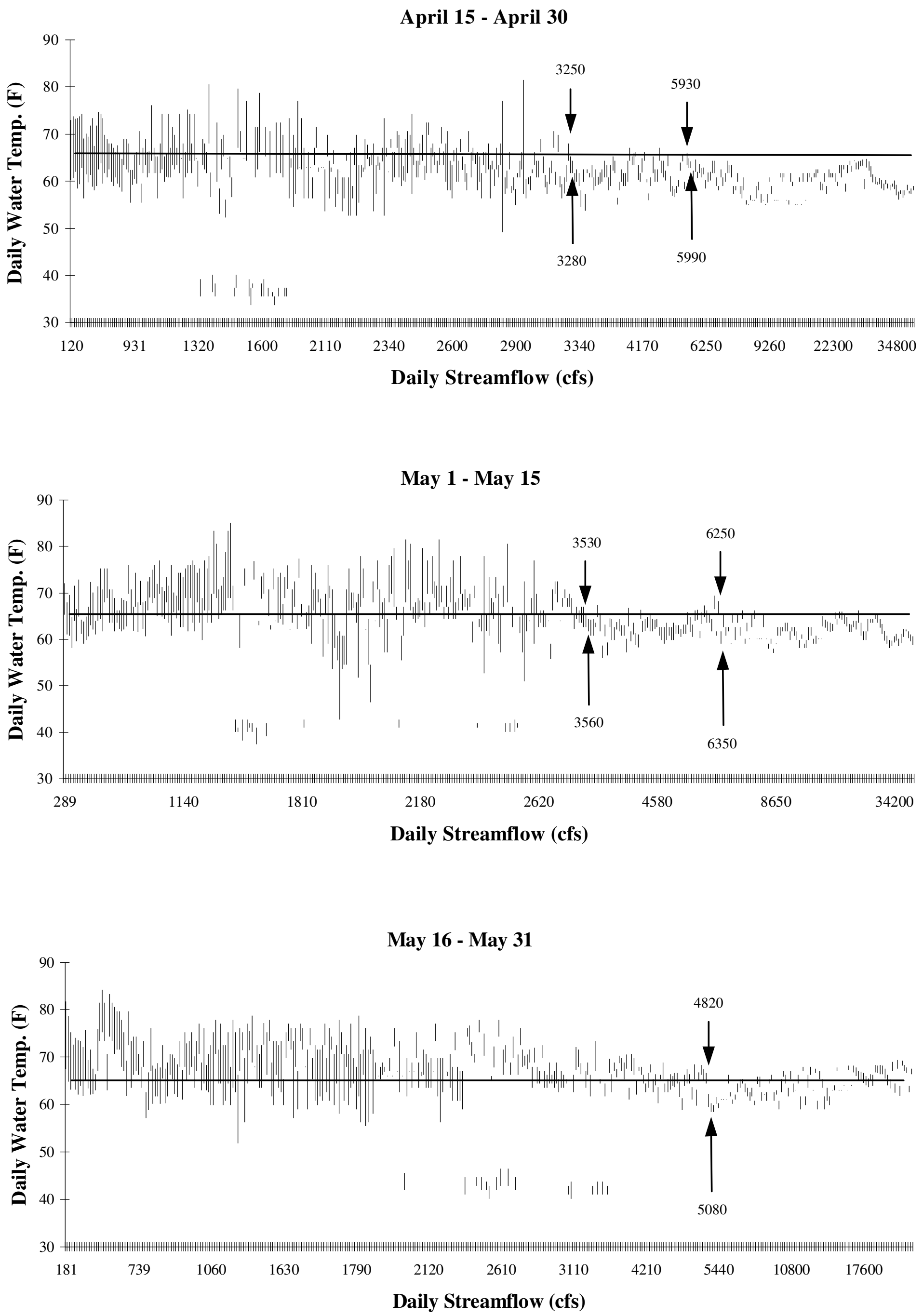


**Figure 13. Water Temperature vs. Flow at Vernalis, April 15–May 31.** The few data points for very high flows between May 16 and May 31 appear to be associated with very wet years when large scale inundation of floodplains and warm water contributions from the James Bypass occur, thus explaining the apparent rise in water temperatures at very high flows.

### 2. Floodplain Inundation Recommendation

Floodplain inundation on the lower San Joaquin, particularly between Vernalis and Mossdale, is limited by levees as well as hydrologic alteration from upstream reservoirs. Degradation of levees upstream of Vernalis in the San Joaquin National Wildlife Refuge over the last decade has increased the area of land available for floodplain inundation by 3,100 acres. Below we describe the flow magnitudes necessary to trigger inundation under existing conditions and estimate the magnitude of flows that would be necessary for inundation if the levees were modified to increase the area and frequency of inundation.

Table 5 lists inundation thresholds for the lower San Joaquin River. Thresholds for Vernalis are estimates based on hydrologic and topographic data. Thresholds at the San Joaquin National Wildlife Refuge are based on detailed modeling analysis.

**Table 5. Inundation thresholds for the lower San Joaquin River.**

| Location | Stage | Inundation Threshold (cfs) | Notes |
|---|---|---|---|
| Lower San Joaquin River | | | |
| Vernalis - Mossdale | | | |
| parital inundaion | 21 | 15,800 | |
| widespread inundation | 23 | 19,300 | initial levee seepage |
| deep inundation | 26 | 26,000 | severe seepage |
| San Joaquin Wildlife Refuge | | | |
| Maze Road full inundation | | 16,000 | |
| Maze Road partial inundation | | 9,000 | |

Under existing conditions, flows of approximately 20,000 cfs at or more at Vernalis is necessary to trigger substantial floodplain inundation. A flow of 16,000 cfs at Maze Road upstream of Vernalis and the Stanislaus River confluence inundates large areas of the San Joaquin National Wildlife Refuge (PWA, 2001). An evaluation of floodplain inundation threshold on the tributaries (Cain, 2003) documents that flows of 3,000 – 6,000 cfs (4,500 on average) are necessary to inundate various low-lying floodplains below the terminal reservoirs on the upper Stanislaus, Merced, Tuolumne, and San Joaquin rivers. A hydraulic study of the upper San Joaquin (JSA, 1998) estimated bankfull discharge of 4,500 for a substantial reach between Firebaugh and Bear Creek. In short, flows of 4,500 cfs from the mainstem and each of the three tributaries plus 2,000 or more from the coast range and other smaller streams result in inundation of riparian floodplains from the upper watersheds to the lower river between Vernalis and Mossdale.

Modification or elimination of the levee system downstream of Vernalis could increase the area and perhaps the frequency of inundation at any given magnitude. Levees currently limit inundation to approximately 1,000 acres between Vernalis and Mossdale, which is relatively small compared the amount of area inundated in the Yolo Bypass Removing levees and reestablishing connectivity with low-lying backwater areas could reconnect up to 10,000 acres of inundated floodplain and restore the temperature and habitat benefits of a complex alluvial channel system.

### 3. Pulse Flows for Transport of Sediment, Nutrients, and Biota through the Delta

As described above, the frequency and magnitude of pulse flows have been substantially reduced in the San Joaquin Basin. Total suspended sediment data at Vernalis show that volume of suspended sediment has dropped substantially since completion of New Melones Dam. Pulse flows in synchrony with unregulated runoff from the interior coast range and valley floor or peak flows sufficient to mobilize channel bed and banks could substantially increase turbidity pulses to the Delta.

Increased frequency of pulse flows, particularly during the juvenile salmon out-migration period (March – June) could substantially reduce mortality from predation and entrainment. Increased turbidity during the juvenile salmon migration period would reduce predator efficiency and increased net flows would presumably reduce entrainment to the pumps.

## IV. ENVIRONMENTAL FLOW REGIMES AND ADAPTIVE MANAGEMENT

Due to the level of scientific uncertainty inherent in an ecosystem as complex as the Delta, developing an environmental flow regime requires utilizing an adaptive management approach to gradually reduce uncertainty over time. The whole point of adaptive management is to learn by doing, which is very different than years of study without action. Implementation of a hypothesis based plan will yield more information and benefits the studies or action alone. It is very difficult, however, to build a series of hypotheses into a hydrograph that can be implemented 365 days per year.

Tharme (2002) and Cain et al. (2003) provide a review of various environmental flow methods that include hydraulic, hydrologic, and simulation based methods. Holistic approaches rely largely on multidisciplinary expert panels to recommend instream flows (Tharme 2000). They represent a significant departure from earlier environmental flow methods, in that their recommendations are almost wholly subjective. However, more advanced holistic methods, such as the Building Block Methodology (BBM), may utilize several of the analytical tools described for other environmental flow methodologies (EFMs) to assist in the decision-making process (Tharme 2000). An early step in the BBM and some other holistic methods is identification of the magnitude, timing, duration, and frequency of important flow events for various ecosystem components and functions. The decision-making process for integrating these flow events may include a number of activities, including workshops, site visits, and limited data collection and analysis. The final output of the consensus process is a recommended flow regime to meet various specific management objectives.

Most holistic methods are relatively quick and inexpensive to apply. They have limited requirements for technical expertise and hydrologic data. And with appropriate interdisciplinary representation, these methods can comprehensively address all major components of the riverine ecosystem, including geomorphological, riparian, biological, water quality, social, and other elements. Holistic methods can recommend flows at a variety of temporal scales. They are site-specific and allow for assessment of whole stretches of river rather than extrapolation from sample cross sections. The major weakness of holistic methods is the subjectivity of their approach, which may open their findings to controversy and criticism.

Holistic methods are still very much in the infancy of their development. Most of these methods have their roots in South Africa and Australia. Few have been applied outside of these countries of origin. Application of holistic methods for environmental flow management is expected to grow rapidly over the next decade, as EFMs become better established as river management tools in developing countries. Holistic methods are well suited for use in these countries, where data, finances, and technical expertise are frequently limited.

Cain et al. (2003) used a modified holistic approach (King et al. 2000) that included a 6-step process to identify an environmental flow regime:

1. Identify specific environmental objectives (i.e., target species, aquatic and riparian communities, and desired ecological conditions that are flow dependent).
2. Approximate the timing, magnitude, frequency, and duration (TMDF) of flows necessary to support target species, communities and desired ecological processes. This step may require identifying specific functional mechanism triggered by flow or correlative relationships between specific flow attributes and species abundance.
3. Compare existing vs. historical hydrology to understand natural hydrologic patterns and how they have been altered.
4. Identify obvious gaps between objective flow requirements and existing flows.
5. Develop an environmental flow hydrograph to achieve ecological objectives based upon a clear understanding of historical and existing hydrologic patterns,

and identify key hypotheses and uncertainties regarding the relationship between flow patterns and environmental objectives.

6. Design an adaptive management program to test and refine environmental flows in the field.

## V. OTHER STRESSORS

Numerous stressors other than changes in hydrology and hydraulics have reduced the abundance and diversity of native species in the Delta. A partial list of other stressors that may have a significant impact on native species includes:

- Loss of habitat
- Exotic fish that prey on native fish
- Submerged aquatic vegetation that changes the character of shallow water habitats
- Toxic run-off from agricultural and urban areas.
- Ammonia from waste water discharges

Flows to trigger the functional mechanisms described above will address, at least partially, many of these other stressors by boosting the competitive advantage of native species. For example, cool water temperatures in the spring provided by increased flows will improve health and associated predator avoidance for native species and may also reduce the ability of exotic species to optimally prey, feed, and reproduce.

Floodplain flows and inundation create high quality rearing habitat for species like salmon and splittail that is largely predator free due to its intermittent nature. While native species have evolved to move onto floodplains inundated habitat coinciding with winter and spring flows, many exotic fish are less likely to rapidly colonize intermittently flooded habitat. Furthermore, the complexity, diversity, and shear area of floodplain habitats gives natives a better chance at avoiding predation where predators are present.

Substantially increased spring flows would dilute contaminant discharges. It is not clear what dilution factor may be necessary to fully address individual contaminants, but it is possible that increases of pulse flows for floodplain or temperature may also be sufficient to lower contaminant concentrations below significant thresholds. For example, if ammonia concentrations over a certain threshold disrupt primary productivity in the spring, increased spring flows may reduce ammonia levels below that threshold. Or if pulses of urban run-off create a "toxic shock" of a sudden increase in contaminants, perhaps pulse flows timed to coincide with rain-fed run-off events could help disperse and dilute these contaminants to less than significant levels.

Pulse flows designed to create turbid waters could also benefit native species. As discussed above, turbid water helps some native species like larval Delta smelt capture prey while it helps other natives fish such as juvenile salmonids avoid prey. Turbid water could also help control submerged aquatic vegetation which is dependent on sunlight for growth.

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