On Developing Prescriptions for Freshwater Flows to Sustain Desirable Fishes in the Sacramento-San Joaquin Delta

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Abstract

Several methods for developing flow prescriptions to support desirable fish species in the Delta are compared. To be useful, flow prescriptions must respond to the changing characteristics of the Delta, including sea level rise, additional flooded islands, changes in water diversions, and new invasive species. Adaptive flow prescriptions for desirable fish species are likely to require a more causal, mechanistic, or process basis, so their effectiveness is not outstripped by underlying change and so they can be more easily modified with improvements in scientific understanding. A “bottom up” or process-based method for establishing Delta flow prescriptions shows promise for developing flows, where flows required for different functions are examined for independence and synergism to develop an overall flow regime. This “bottom-up” approach allows for the systematic organization, integration, and expansion of available scientific knowledge relating freshwater flows to native fish populations. No flow prescription approach will avoid controversy, but a “bottom-up” functional approach should be able to compartmentalize controversies so they are better addressed scientifically. The adoption of more causally-reasoned and quantified flow standards will require significant changes in the scientific and management institutions and infrastructure of the Delta, but ultimately should provide more effective and adaptable flow prescriptions.

> “I believe in getting into hot water; it keeps you clean.” - G. K. Chesterton

Introduction

This paper explores four approaches for establishing freshwater flow prescriptions for desirable fishes (*e.g.*, Moyle *et al*. 2009) in the new Sacramento-San Joaquin Delta in the coming decades. During this period, the Sacramento-San Joaquin Delta will undergo major changes, with some changes already underway. These changes include substantially more flooded islands, more rapid sea level rise, climate-driven shifts in seasonal flows (and perhaps changed annual flow volumes and flood frequencies), more invasive species, possible increased water use by upstream diverters, and possible shifting of remaining export diversions to a peripheral canal, pipeline, or tunnel (Lund *et al*. 2007, 2008, 2010). The new Delta also will have substantially more aquatic habitat not only from planned and unplanned island inundations but from purposeful investments in habitat creation (Moyle and Bennett 2008, Sandstrom *et al*. 2009, BDCP 2009).

We focus here on methods to establish environmental flow prescriptions in the context of habitat to support desirable estuarine fishes in a setting described by Moyle *et al.* (2009), and to suppress populations of undesirable species (such as *Microcystis*, *Egeria*, jellyfish and overbite clams). This long-term problem involves significant uncertainties which cannot be resolved here. Any serious scientifically-based effort to establish flows for desirable fishes, including our work, is therefore exploratory and cannot be a finished product. Moreover, it is not possible to resolve scientifically the major uncertainties over flow prescriptions within current planning timeframes. Managing uncertainty during the indefinite period of implementation for flow prescriptions will pose a far greater technical and institutional challenge than setting the initial prescriptions.

A major issue facing long-term management of the Sacramento-San Joaquin Delta is developing flow prescriptions that support habitat conditions for desirable fishes. The issue is important because 1) some native fishes are protected directly under the Endangered Species Act and must be accommodated; and 2) other species are valuable as indicators of desirable ecosystem function and by extension, important arbiters of human health, aesthetics, and recreation. For example, while all native fish are desirable, some introduced species also may be desirable, such as striped bass both as a good indicator of estuarine function and as a valuable recreational fishery. Freshwater flow prescriptions should be adaptable to the future landscape and habitat created by permanently flooded islands, or major habitat improvements in Suisun Marsh, Yolo Bypass, and Cache Slough areas, and other changes.

There have been relatively few systematic, published science-based attempts to establish flow prescriptions for the Delta (Jassby *et al*. 1995), and even less work exploring environmental flows responsive to major inevitable changes due to climate shifts, species invasions and levee failures. The larger professional literature contains much on environmental flows for rivers and other water bodies, with little consensus on method (Richter *et al.* 1997, King and Louw 1998, Montagna *et al*. 2002, Alber 2002, Powell *et al*. 2002, King *et al*. 2008). This stems, in part, from the complexity involved (Moyle *et al.* 2009). Estimating human demands for water, both in quantity and quality, is fairly straightforward with well-established methods. Estimating flows for improving habitat conditions, particularly to support fishes with different and often conflicting life history strategies, is much more complex and is hampered by numerous uncertainties. For the Delta, these difficulties are compounded by major geological, biological, and engineering challenges, particularly the return of diked, subsided lands to aquatic habitat (subtidal, intertidal and floodplains), changes in water management within and upstream of the Delta, including likely peripheral diversions of much of the water currently exported through the Delta, new invasive species, and water contamination from upstream and in-Delta uses. These massive ongoing and potential changes cast doubt on the future value of empirical relationships often used to establish required Delta flows. We are unlikely to ever resolve all these uncertainties and issues in the Delta before actions are required (Lund *et al*. 2010); courts, legislation and regulations are already requiring action. Initial flow prescriptions with a more mechanistic habitat and biological basis need to be developed to advance the planning and policy discussions, recognizing that any prescriptions will be based on incomplete data and understanding and will need to be modified in the future.

To support on-going policy and scientific discussions, we present four approaches for estimating fresh water flows needed to sustain viable populations of desirable fishes in the Delta. Using these approaches we show how illustrative quantities of water can be estimated. While these estimated flows might have some value in furthering discussions in light of the justifications and references provided, their greater value, for the time being, lies in comparing the approaches developed and applied here. Thus, although it may be tempting to grasp at these numbers, this should be avoided in favor of developing better scientific and regulatory processes for prescribing defensible quantities of water on a renewable basis. This comparison is developed largely to facilitate more transparent and scientific discussion of desirable freshwater flows and to suggest some methods for their estimation, including improvements on the methods presented here. We seek to organize this problem, which cannot yet be solved.

For this paper, we consider only flows entering and leaving the Delta. This most directly corresponds to conditions where remaining Delta water exports are via a peripheral conveyance only (canal, pipeline, or tunnel). Through-Delta conveyance (alone, or as part of a dual conveyance strategy) is particularly difficult because it greatly increases the number of internal flow requirements and restrictions needed to protect estuarine fish within the Delta, as demonstrated today by the profoundly unnatural southward flowing patterns created by large water diversions from the south Delta pumps (Fleenor *et al*. 2008). Flows into and from the Delta might have to be higher (or lower) to accommodate ecosystem flow purposes within the Delta given through-Delta exports, depending on details of export operations and Delta island and channel configurations. Higher Delta outflows and/or reduced exports are likely to be needed to overcome harm to native fish from through-Delta conveyance for exports, similar to the flow conditions suggested in the recent Biological Opinions for delta smelt and salmon. While preliminary, the methods and approach used here can, with considerable additional time and effort, be developed to set flow prescriptions for the current conditions using through-Delta conveyance.

Major Delta Environmental Flow Locations

Several categories of environmental flows are likely to be needed to improve conditions for native and other desirable fish in the Delta. Each category of flows has different functions, but often the same water could be used for more than one function and all would interact with each other and with habitat improvements and landscape changes (*e.g*., additional tidal marsh, seasonal flooding and permanently re-flooded islands). These efforts should be coordinated broadly. Major categories of environmental flows for the Delta should include:

- Inflows from the Sacramento Valley into the Delta (combining Sacramento River main stem flows and the Yolo Bypass).
- Inflows from the San Joaquin Valley into the Delta.
- Eastside stream flows into the Delta, primarily the Cosumnes and Mokelumne Rivers but also smaller streams such as the Calaveras River, Bear Creek, Dry Creek, Stockton Diversion Channel, French Camp Slough, Marsh Creek and Morrison Creek.
- Flows interior to the Delta, including any channel modifications, gates, or barriers and including Delta island abstractions and returns. (These are largely omitted for this paper.)
- Coordination of peripheral conveyance diversion rates and patterns.
- Overall net outflows from the Delta to Suisun Bay and San Francisco Bay, including the desirable variability of such net Delta outflows.

- Additional flows are needed upstream of the Delta to support fish migration, spawning, and rearing. However, at this time riverine environmental flows seem better handled by other efforts.

By considering a peripheral conveyance as the only major diversion in the system, we can limit this initial analysis to Sacramento River inflows, San Joaquin River inflows, inflows from eastside streams (Mokelumne and Cosumnes rivers), and overall Delta outflows to San Francisco Bay. If large quantities of water continue to be exported through the Delta, larger volumes of inflows and outflows will be needed to suppress the effects of the resulting unnatural flow patterns (Figure 9) and water quality gradients within the Delta (Appendix D).

Conditions in the Delta are currently hostile to native fishes (Lund *et al.* 2008, 2010; Moyle and Bennett 2008; Sommer *et al.* 2007). Greater amounts of well-implemented suitable habitat in Suisun Marsh, the northern Delta (*e.g.*, Yolo Bypass and Cache Slough areas), and from re-flooding subsided Delta islands, might help meet fish population objectives without significant increases in freshwater outflows. However, in general, it might be useful or necessary as a practical matter to move some estuarine habitat for native species eastward from its pre-development range, unless large reductions in upstream and export water use can provide increased flows required to retain salinity conditions at more western locations in the estuary. Analysis of these aspects awaits more detailed modeling capability, including the ability to better model the hydrodynamic, water quality and biological implications of sea level rise and permanently flooded islands.

Methods

Estimating desirable flow prescriptions for native fish in the Delta is difficult, complex, and unavoidably controversial. Others have tried to estimate and manage environmental flows for estuaries elsewhere in the United States, as summarized in Appendix A. Any scientific or technical basis for environmental flow prescriptions must be based on empirical or deductive understanding, requiring an accumulation of relevant data, experience, and theoretical knowledge.

Here we examine four approaches for prescribing environmental flows for the Sacramento-San Joaquin Delta: (1) unimpaired (quasi-natural) inflows, (2) historical impaired inflows that supported more desirable ecological conditions, (3) statistical relationships between flow and native species abundance, and (4) the appropriate accumulation of flows estimated to provide specific ecological functions for desirable species and ecosystem attributes based on available literature. This last "bottom-up" functional flows approach is in some ways similar to the more holistic Building Block Method (BBM), and like the BBM, "is a tool for organizing data and knowledge" (King and Louw 1998; King *et al.* 2008). Each approach explored provides a useful perspective on environmental flows for the Delta, and will require further examination and development before they provide insights for long-term Delta flow policies.

Any environmental flow prescription for native species in the Delta will be imperfect. The problem is too complex, uncertainties are too large, and the situation in the Delta is changing too rapidly in too many ways for any single flow prescription to be correct, or correct for long. A set of flow prescriptions for native species should be combined with habitat development activities and a scientific and technical program to improve flow prescriptions as opportunities and improved understanding becomes available. An effective regulatory framework will need to respond and adapt to these improvements in scientific information.

1) Environmental Flows Based on Unimpaired Flows

Native fishes in the Central Valley and the Delta evolved in, or adapted to, the natural flows and habitats of this region. Engineers have developed a surrogate for upstream natural inflow called "unimpaired" inflows that the Delta would likely have seen without interference from upstream dams or diversions, or in-Delta diversions. These flows have been estimated for the 1921– 2003 period by the California Department of Water Resources for use in various models of Central Valley water projects (DWR 2006). These are only estimates of stream flows for this period, and are unlikely to capture the effects of longer attenuation of spring flows by upstream marshlands and floodplains, evapotranspiration from vast floodplains and marshlands, riparian forests and unimpaired stream-aquifer interaction of the natural system. All were prominent features of the pre-development hydrology.

California's climate and hydrology are Mediterranean, with an annual dry season during the late spring through early fall and with high inter-annual variation in total runoff. The life history strategies of all native estuarine Delta fishes are adapted to this natural variability (Moyle and Bennett 2008). Flows and flow variability should reflect and support the complexity, connectivity and variability of habitat conditions needed for these native species. Moyle *et al.* (2010) introduce the nature and importance of complexity and variability for Delta habitat conditions. Pre-development flow, habitat, and water quality variability are likely to remain somewhat uncertain since precise pre-development measurements are imperfect and estimates are questionable because it is difficult to understand the full extent of changes in climate, base flow from groundwater, floodplain areas, and modified Delta channels. Early historical and paleological studies of hydrology and salinity provide some insights (CCWD 2010). However, as a practical matter, restoration of the Delta to pre-development habitat, flow, and biological conditions is precluded by irreversible historical and ongoing changes in the Delta's physical landscape and the addition of many invasive species (Lund *et al.* 2010).

Flows needed to support desirable Delta fishes are likely to have changed from pre-European settlement conditions because of extreme landscape changes, illustrated by the 1873 map of the Central Valley in Figure 1 with vast often-connected areas of seasonal and permanent wetlands. The changes include upstream watershed changes, tidal marsh reclamation and channelization of the upstream and in-Delta landscape, impacts of biological invasions, and on-going climate change and sea level rise. Greater or lesser flows might be needed to adjust for the conversion of most of the Delta from marshland to agriculture and the severing of river channels from floodplains. Greater flow and water quality variability than historically occurred might be also useful for suppressing invasive species which have disrupted much of the Delta's ecosystem and which tend to prefer less variable flow and water quality conditions (Lund *et al*. 2007, 2010; Moyle and Bennett 2008; Moyle *et al*. 2010). The variability in desirable environmental flows would significantly affect water supply operations, but might reduce exports less than current and potential future court decisions for environmental protection from through-Delta exports. Nevertheless, the region's unimpaired flows are likely to provide some insights into predevelopment conditions.

Figure 1. The Central Valley in 1873 (Report of the Board of Commissioners on Irrigation).

Seasonal and inter-annual variability of the major boundary flows of the Delta under unimpaired conditions appear in Figure 2. Table 1 presents annual unimpaired flow volumes and rates for major inflows and outflow.

Table 1. Annual unimpaired flow volumes and rates for major inflows to and outflow from the Sacramento- San Joaquin Delta for 1921 – 2003 (DWR 2006)

Location	Lowest	10%-ile	25%-ile	50%-ile	Highest	Average
	Unimpaired Annual Vol. (maf)					
Sac Valley	5.6	10.0	13.6	19.4	48.4	21.6
Eastside Streams	0.2	0.5	0.8	1.5	5.5	1.6
SJ Valley	1.1	2.5	3.4	5.9	19.0	6.2
Net Delta Outflow	5.6	12.1	16.2	25.3	71.9	28.2
	Unimpaired Annual flow (cfs)					
Sac Valley	7,700	13,800	18,800	26,800	66,800	29,800
Eastside Streams	300	700	1,100	2,100	7,600	2,200
SJ Valley	1,500	3,500	4,700	8,100	26,200	8,600
Net Delta Outflow	7,700	16,700	22,400	34,900	99,200	38,900

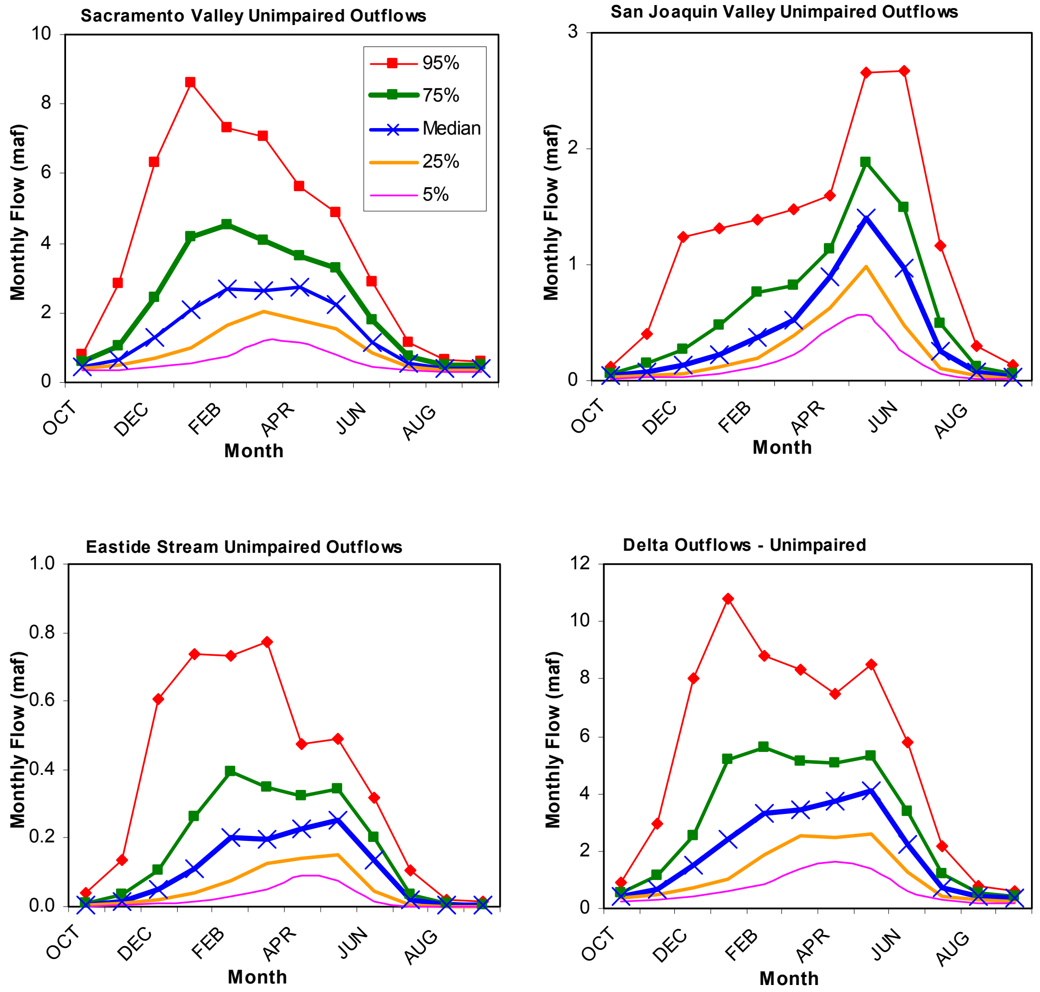

Figure 2. Seasonal and inter-annual flow variability for unimpaired Sacramento Valley, San Joaquin Valley, Eastside Stream, and Delta outflows. (These quartile plots have 95th %-ile monthly flows at the top (red, solid diamonds), followed by 75th %-ile flows (green, solid squares), median flows (blue-X), 25th %-ile flows (thick orange), and 5th %-ile flows from the unimpaired historical flow record (thin pink) Note that y-axis are not equal).

Sacramento River 95th and 75th percentile flows show early spring peaks while lower flows are more evenly distributed over later spring and early summer months. All San Joaquin River percentile flows show a late spring peak. The San Joaquin River has a delayed peak compared to the Sacramento River from a later snow melt in higher elevations of its upper watershed. On the San Joaquin River, a strong winter peak, common to the Sacramento River, occurs only in the wettest of years (data not shown). Eastside stream flow patterns are more comparable to the Sacramento River. Both river flows would have been smoothed somewhat by early season floodplain storage and drainage in the spring and summer. Flows extending back centuries would have a greater proportion of the annual runoff from snowmelt, but also show more inter-annual variability because of more extended droughts and more extreme floods than experienced in recent times (Graham and Hughes 2007, Yuan *et al*. 2004).

The unimpaired flow record clearly indicates substantial seasonal and inter-annual variability in Delta flows, with high winter flows, regular spring snowmelt flows, low summer flows, and substantial variability among years, especially for the wet and snowmelt seasons. Additional insights might be available from pairing these flows with stages in the life history strategies of various native fishes and the inundation of floodplain and riparian habitats before land and water development in the 19th and 20th centuries.

The historical unimpaired flows, or something very similar, supported habitat for native fish species under unimpaired land use conditions without invasive species. Native species evolved under these flow conditions. However, the unimpaired flow record does not indicate precise, or best, flow requirements for fish under current conditions, because their populations are biologically and physically disturbed in many ways, some of which act independently of flows. Nevertheless, the general seasonality, magnitudes, and directions of flows seen in the unimpaired flow record are likely to remain important for native species under contemporary and future conditions.

2) Environmental Flows Based on Historical Flows

During the post landscape-development period of the 1940s – 1970s, native populations were still reasonably robust, although some fishes had already gone extinct (*e.g*., Sacramento perch and thicktail chub). By this time most Delta marshland had been converted to agriculture, floodplains had been greatly reduced, dam development and upstream diversions reduced inflows and increased salinity intrusions, channelization of the Delta greatly reduced shallow water and intertidal habitat, and many invasive species had arrived. However, this period differed substantially from the contemporary era of rapidly declining populations, in part, because major water exports from the Delta had not yet begun. Contrasting flows from this period with unimpaired flows (when native fishes had more robust populations) and more recent flow conditions (when dam development was complete and native fishes fared worse) provides some indications for how much fresh water is needed to keep native fish populations healthy. Table 2 contains historical flow volumes for three periods: 1949 – 1968, 1969 – 1985 and 1986 – 2005. The early 20-year period represents a time when fish were known to be doing better and the last 20-year time frame when fish were doing worse (Moyle and Bennett 2008). The middle 17 years represents a transitional water export period and contains extreme wet and dry periods. Table 2 gives the lowest, average, and highest annual flows of each period. Figure 3 shows the distribution of water year types for these three periods and the 1921 – 2003 span of unimpaired flows presented in the preceding section.

The percentage distribution of water year types, Figure 3, shows that the full unimpaired period of record, 1921 – 2003, is not uniform. Including data back to the earliest records, 1906, increases the percentage of wet years only slightly (data not shown). The later period, 1986 – 2005, demonstrates a more bimodal distribution of wet and critically dry years, while the early period, 1949 – 1968, was slightly wetter since it contained no critically dry water years.

Table 2. Annual historical minimum, average, and maximum flow volumes for major inflows and outflow for the Sacramento-San Joaquin Delta

Flow Location	Minimum, **Average**, and Maximum Historical Annual Flows (maf/yr)											
	Unimpaired[a]			1949 – 1968[b]			1969 – 1985[b]			1986 – 2005[b]		
Sacramento River[c]	5.6	**21.6**	48.4	10.9	**19.1**	35.5	5.5	**23.0**	48.8	7.6	**18.8**	38.7
San Joaquin River	1.1	**6.2**	19.0	0.4	**2.7**	7.1	0.4	**4.1**	15.4	0.1	**0.9**	8.5
Eastside Streams	0.2	**1.6**	5.5	0.1	**1.4**	3.5	0.0	**1.4**	4.5	0.1	**0.9**	2.6
Delta outflows	5.6	**28.2**	71.9	9.6	**21.3**	42.8	2.5	**23.8**	64.5	3.9	**16.6**	43.6

[a] Includes the period from 1921--2003

[b] years since 1963 include supplemental flow from the Trinity system

[c] includes Yolo Bypass

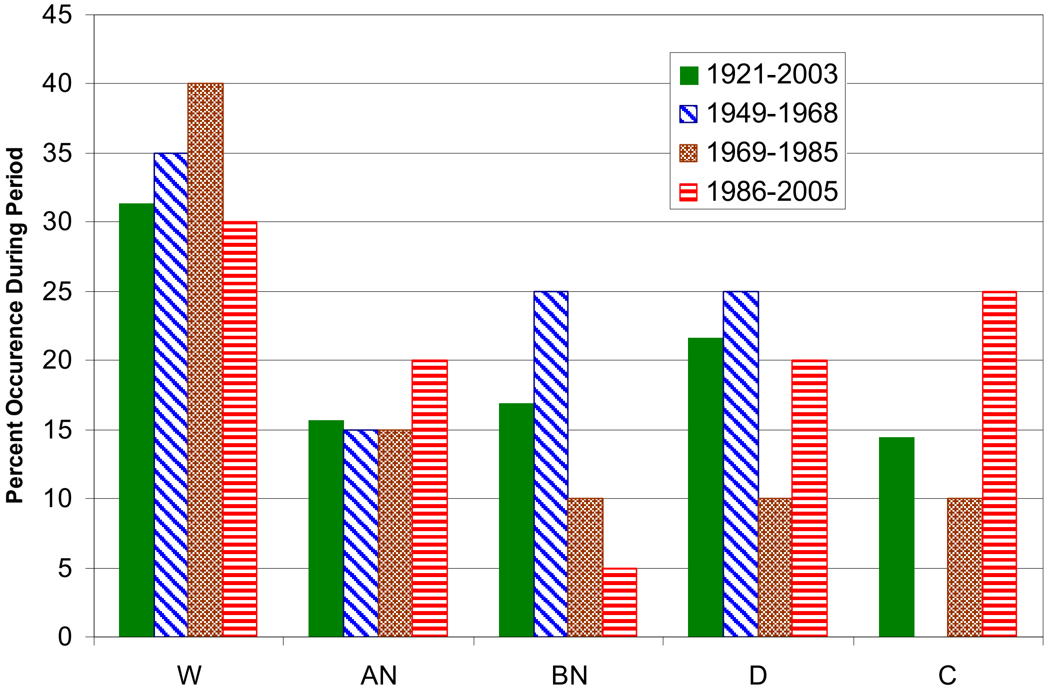

Figure 3. Inter-annual hydrologic variability of different historical periods, using DWR water year classifications. (W = wet, AN = above normal, BN = below normal, D = dry, C = critically dry).

Figures 4 and 5 compare unimpaired, 1949 – 1968, 1969 – 1985, and 1986 – 2005 Delta inflows from the Sacramento Valley and San Joaquin Valley, showing the considerable changes in inflows to the Delta that occurred during these periods (note differences in y-axis scales). In more recent years, both major tributaries have much-reduced flows overall and changes in seasonal pattern, with San Joaquin River flows being more severely reduced and altered. The unimpaired Sacramento River flows do not benefit from the later addition of Trinity River diversions included in the three historical data periods post-1963 when Trinity flows were partially diverted to the Sacramento system.

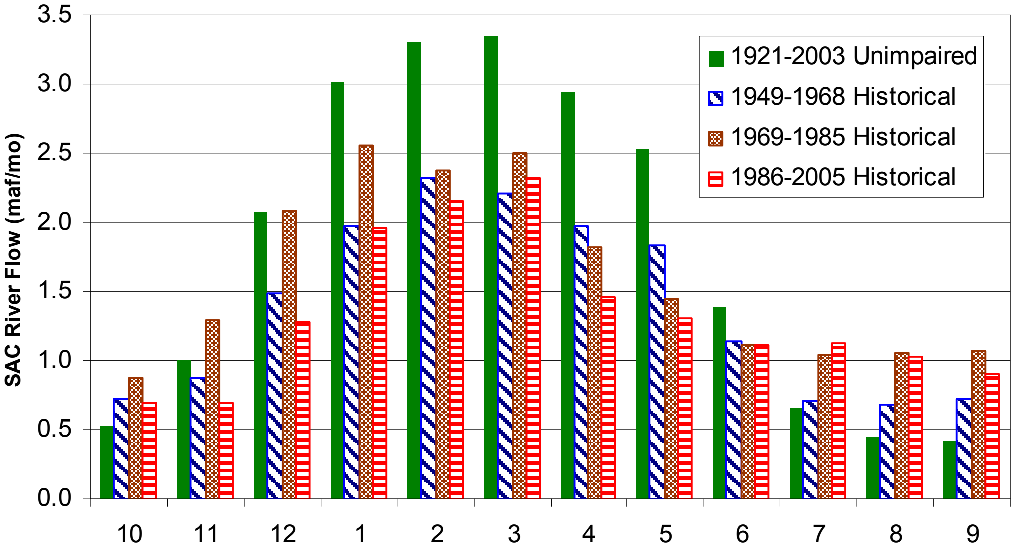

Figure 4. Changes over time to monthly average Sacramento Valley outflows (maf/mo) compared to the unimpaired record.

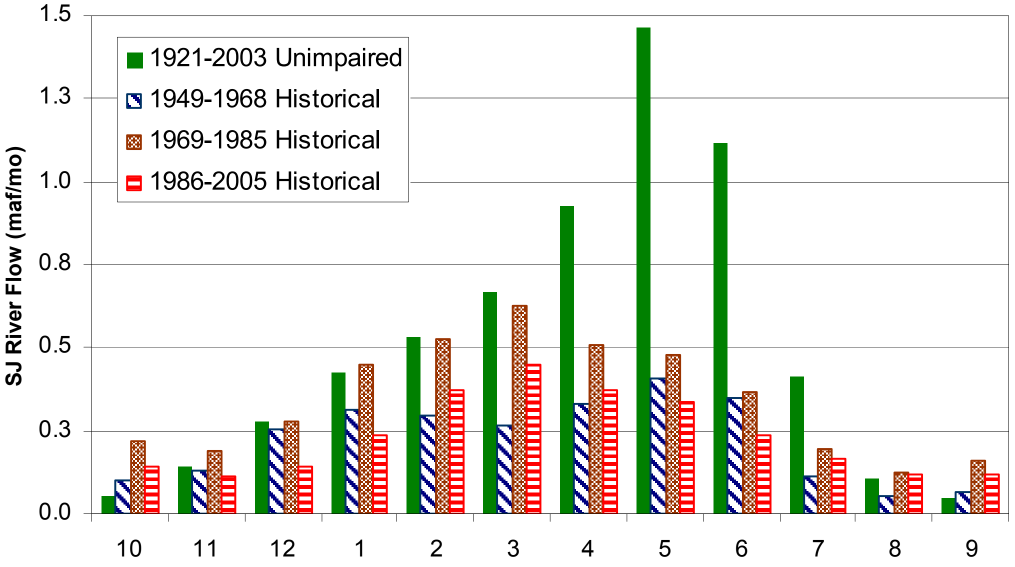

Figure 5. Changes over time to monthly average San Joaquin Valley outflows (maf/mo) compared to the unimpaired record.

These data illustrate the effects of large upstream diversions on the Sacramento and San Joaquin Rivers and how the use of reservoirs shifted Delta inflows from winter and spring to summer and early fall. Upstream withdrawals from the San Joaquin Valley are especially pronounced, reducing inflow, shifting the peak earlier in the year, and increasing summer and fall inflows. Even without considering the additional effects of through-Delta exports, inflows to the Delta have been tremendously modified from natural conditions (represented here by unimpaired flows). Changes in San Joaquin River inflow volume and timing to the Delta are especially stark.

Sacramento River annual flows into the Delta from 1949 – 1968 were reduced by 23% from unimpaired conditions, while 1986 – 2005 flows were reduced by 26% annually and by 30% and 39%, respectively, during early winter and spring flow periods. San Joaquin River annual flows into the Delta were reduced from unimpaired conditions by 57% for 1949-1968 and 55% for 1986 – 2005, with 68% and 67% reductions, respectively, during early winter and spring flow periods. The combined effects of water exports and upstream diversions reduced average annual net outflow from the Delta from unimpaired conditions by 33% for 1948 – 1968 and 48% during 1986 – 2005.

A comparison of water use during the three study periods shows net Delta outflow, exports, Delta island consumptive use (DICU) and upstream effects of diversion and storage, Figure 6. Exports include the North Bay Aqueduct, the state and federal pumping projects, and in-Delta diversions of the Contra Costa Water District. In-Delta use accounts for agricultural consumptive use as well as local precipitation. Upstream effects include all consumptive diversions and water storage projects, including the Mokelumne and Hetch Hetchy aqueducts and major agricultural diversions in the Sacramento and San Joaquin basins. The total available water is based on the unimpaired flows for those periods. Since the earlier period, 1949 – 1968, covered a time of greater storage development, the upstream effects likely include some water involved in accumulated storage where the later periods would be less influenced by initial reservoir filling. Although the intervening period contained the most severe recent drought, the drought was short and higher precipitation periods made 1969 – 1985 an overall wetter period, increasing net Delta outflow while exports increased. The largest change from the earlier historical period when fish were doing better to the later period when fish were doing poorer is the increase in exports that reduce net Delta outflow. Exports increase from 0.9 maf during the 1949 – 1968 period (1.4 maf annual average over the 13 years of actual export) to 5.1 maf over the 1986 – 2005 period, an increase exceeding 450 percent.

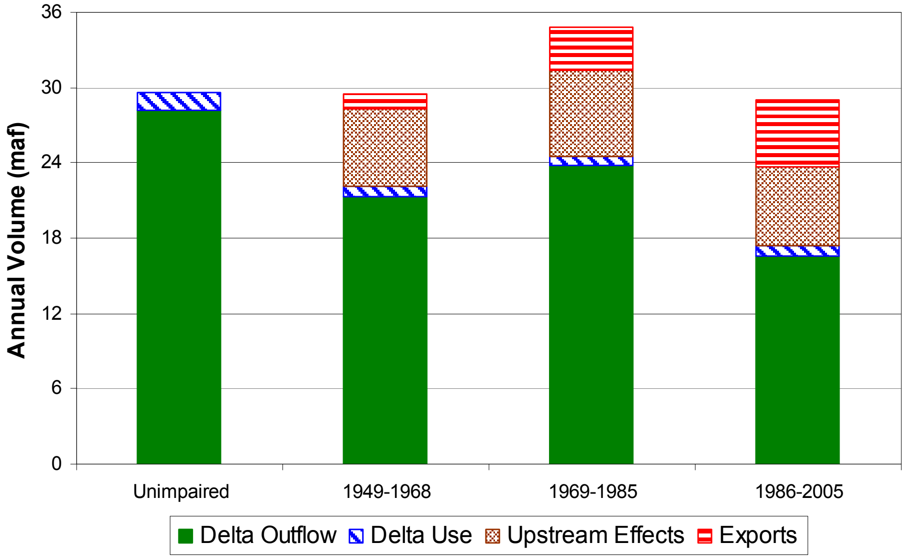

Figure 6. Comparison of annual water use during the three study periods (maf/year) compared to the Unimpaired flows from 1921-2003. Unimpaired data from DWR (2006) and other from Dayflow web site (Neglects upstream groundwater withdrawals).

Average monthly changes in net Delta outflow appear in Figure 7, showing dramatic reduction in Delta outflow in early winter and late spring/early summer. The April-June reductions largely result from the San Joaquin River diversions shown in Figure 5.

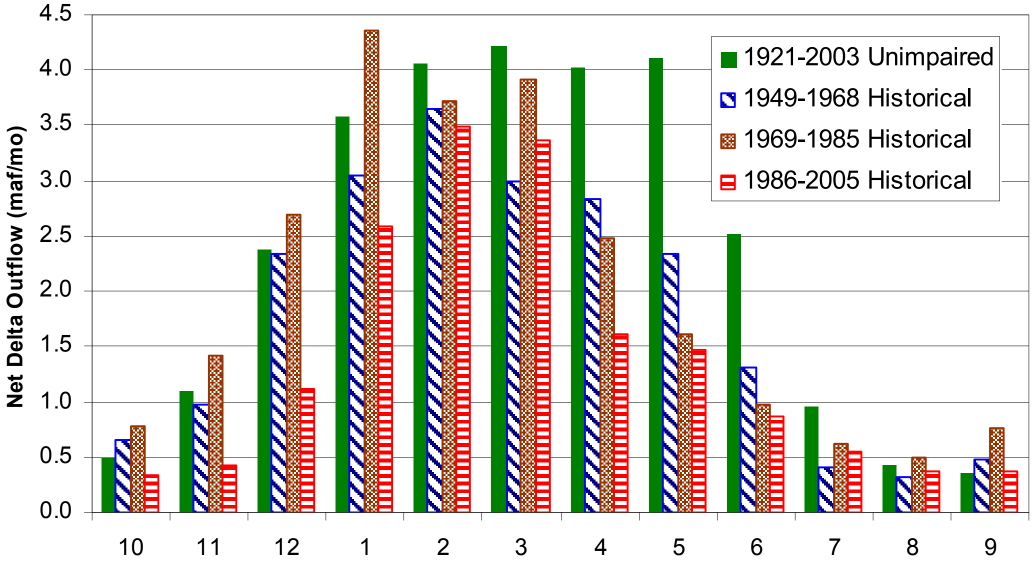

Figure 7. Monthly average Net Delta outflows (maf/mo) compared to the Unimpaired flows from 1921-2003. Unimpaired data from DWR (2006) and other from Dayflow web site.

Hydrodynamic simulations were made for the Delta using the RMA tidally averaged model, the Water Analysis Model (WAM), for unimpaired, 1949 – 1968, 1969 – 1985, and 1986 – 2005 boundary conditions (DRMS 2007; Fleenor *et al.* 2008). The unimpaired flow simulations omit all gates and barrier controls while the historical data included all gates and barriers as operated. All simulations use the current Delta bathymetry. Figure 8 shows the daily cumulative probability of these simulations for the 2 parts per thousand (ppt) salinity location (X2) in kilometers from the Golden Gate Bridge for these four sets of boundary conditions. These results indicate that for unimpaired inflows the location of X2 salinity would vary uniformly over a 54 km range between 43 and 97 km inland from the Golden Gate Bridge. Salinity location was somewhat less uniform with historical conditions between 1949 – 1968 and 1969 – 1985, and skewed further eastward from 1986 – 2005, significantly reducing the variability of salinity in the Western Delta and Suisun Bay.

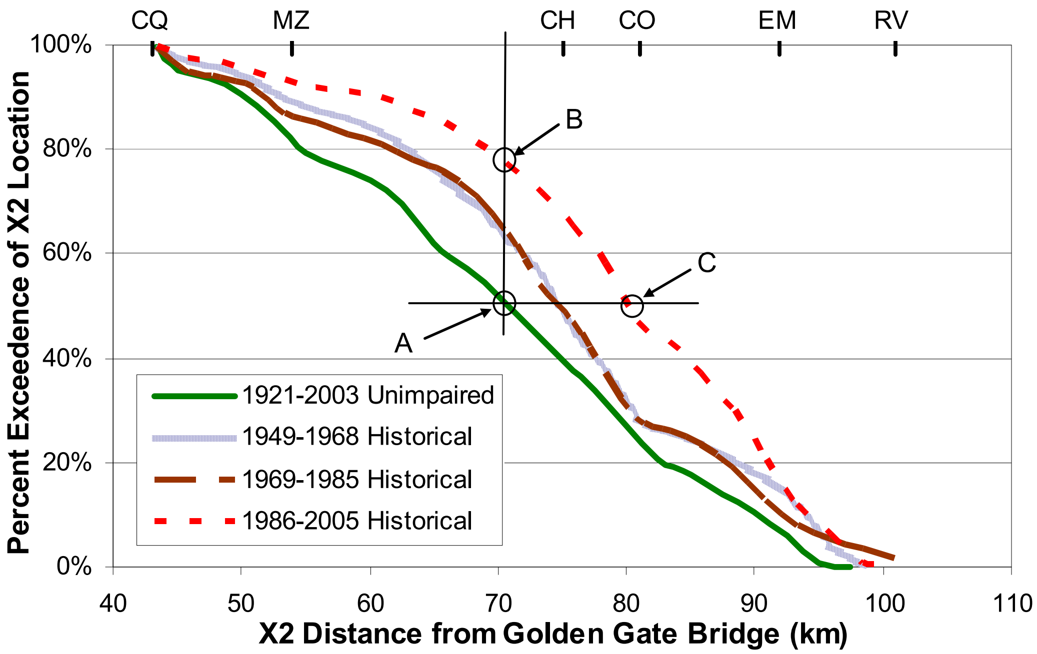

Figure 8. Cumulative probability distributions of daily X2 locations showing unimpaired flows (green solid line) and three historical periods, 1949-1968 (light solid blue line), 1969-1985 (long-dashed brown line) and 1986-2005 (short-dashed red line), illustrating progressive reduction in salinity variability from unimpaired conditions. X2 is the location of the 2 ppt salinity region of the estuary in kilometers from the Golden Gate Bridge. Paired letters indicate geographical landmarks. CQ, Carquinez Bridge; MZ, Martinez Bridge; CH, Chipps Island; CO, Collinsville; EM, Emmaton; and RV, Rio Vista.

The higher X2 values in Figure 8 indicate that the low salinity zone is farther upstream in the estuary. Point 'A' demonstrates that for Unimpaired Flows the X2 salinity was equally likely to be upstream or downstream of the 71 km location (50% probability) while recent operations hold the X2 location upstream of the 71 km location nearly 80% of the time, Point 'B', and upstream over 80 km 50% of the time, Point 'C'.

Model results also were compiled to show the frequency of summed flows in the Middle and Old rivers, showing the effects of through-Delta pumping for the three impaired periods compared to unimpaired results (Figure 9). The x-axis is the sum of Old and Middle river flows (with reverse flows shown by negative values) and the y-axis is the percent of time when flows exceed those on the x-axis. Continuing exports through the Delta (as opposed to a peripheral conveyance) results in reverse flow conditions in the Old and Middle rivers more than 91% of the time (for the 1986 – 2005 period). For fishes in the southern Delta and the lower San Joaquin River areas of the Delta, reverse flows from Delta pumping facilities seem especially harmful (Feyrer and Healey 2003, Grimaldo *et al*. 2009). Increases in through-Delta exports and flow modifications in more recent years have significantly boosted the likelihood of trapping fish in the pumps and in the southern Delta (Grimaldo *et al*. 2009). With the deeper, wider channels of post-development, and with unimpaired conditions and no through-Delta pumping, there was a net outflow in Old and Middle rivers at least 85% of the time. For unimpaired flows without the increased conveyance of additional channels, and particularly the dredged Stockton Deep Water Ship Channel, more frequent positive flows would likely have occurred, although tidal energy into these channels would increase. The increased conveyance of the Stockton Deep Water Ship Channel would encourage San Joaquin River flows to take the easier path. The historical periods represent gradually increasing levels of through-Delta pumping. Early in water development, 1969 – 1985, positive outflows were reduced to 50% of the time, and in recent years, 1986 – 2005 (pre-Wanger decision), positive flows occur less than 10% of the time. The model also estimates that during the intermediate period, 1969 – 1985, negative flows in Old and Middle rivers did not exceed -2,000 and -4,000 cfs for 81% and 92% of the time, respectively. Effects of San Joaquin River outflows on salinity gradients in the lower San Joaquin River and southern and central Delta are preliminarily examined in Appendix D. Through-Delta exports appear to reduce the salinity of water in the central and southern Delta, but consequently greatly expand the regions of the Delta where salinity increases upstream into the San Joaquin River, contrary to natural conditions and potentially confusing for fish migration. Much larger San Joaquin River flows would be needed to eliminate this adverse water quality gradient. Extending these types of analysis with new 3-dimensional models would be necessary for providing more detailed insights into how changes in through-Delta exports and inflows might improve conditions for fish within the Delta.

Historical flows under which native fish were more successful should have greater relevance for establishing fish flows for the current highly altered Delta. While the historical abundances of some fishes have been associated with outflows (Stevens *et al*. 1985, Jassby *et al*. 1995, Kimmerer 2002), these empirical relationships have worked as well since 2000 and, as empirical relationships, seem likely to be less relevant and useful as conditions change in the emerging new Delta. In the absence of more direct causal relationships, empirical evidence should be used until more specific processes can be quantified. The historical flows seem to reinforce lessons from the unimpaired record, showing the importance of flows in the fall and spring and of avoiding negative flows inside the Delta, but also indicating that native fishes can continue to prosper even under greatly altered flow (*e.g*., 1969 – 1985) and habitat conditions. The recent decline of native fishes, however, also seems to indicate that recent flow restrictions for fish and other human uses of the Delta have been inadequate to support native fishes in the Delta.

Flow prescriptions for the future will need to be able to respond to further changes in the Delta's biological composition from additional invasive species, continuing changes in sea level and climate, as well as the permanent inundation of many Delta islands and the intentional development of marshland and floodplain habitat.

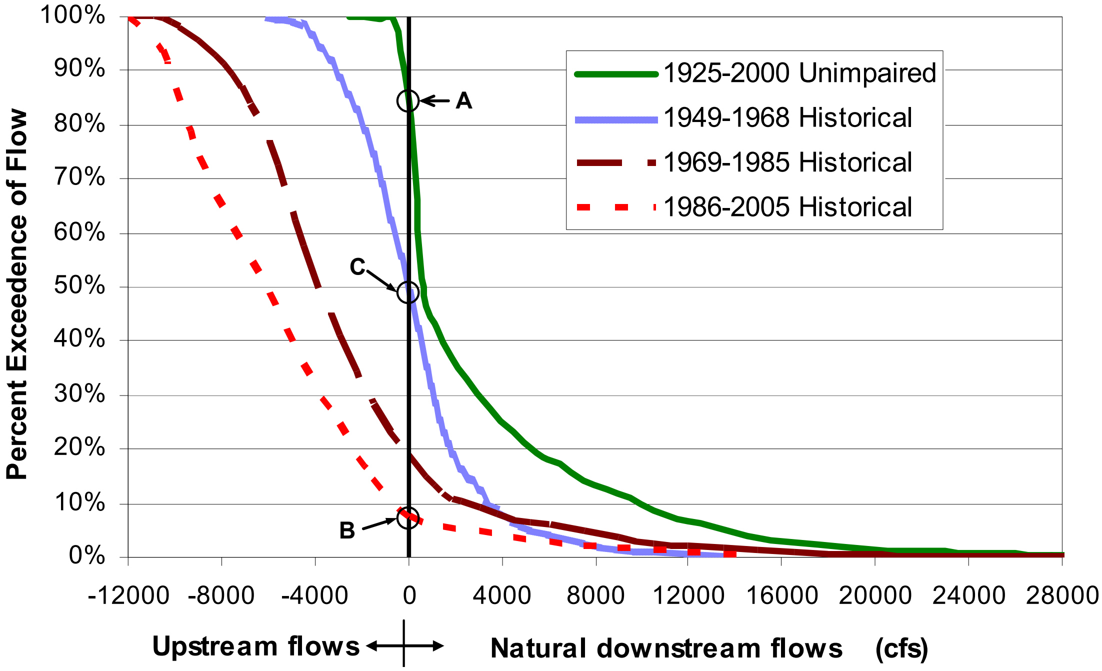

Figure 9. Cumulative probability distribution of sum of flows (cfs) in Old and Middle River resulting from pumping through the Delta showing unimpaired flows (green solid line) and three historical periods, 1949-1968 (light solid blue line), 1969-1985 (long-dashed brown line) and 1986-2005 (short-dashed red line).

3) Environmental Flows Based on Statistical Relationships

Statistical relationships between flows, salinity, and fisheries harvests are commonly used for establishing freshwater inflows worldwide (Drinkwater and Frank 1994, Montagna *et al*. 2002, Powell *et al*. 2002, Olsen *et al*. 2006). The previous major effort to establish a scientific basis for Delta flow prescriptions employed statistical relationships between populations of aquatic organism and characteristics of salinity gradient location in Suisun Bay and the Delta (the so-called X2 relationships, Jassby *et al*. 1995, Kimmerer 2002). These correlations formed the basis for many current Delta flow standards, and were successful for a time. However, these correlations seem to be losing some of their former predictive value in recent years for some desirable species (Kimmerer *et al*. 2009). This in part may be due to the scale at which X2 is averaged and the extremely low abundance of desirable fishes, which may not be tracked as effectively by the traditional monitoring programs.

The longer-lasting benefit of this earlier salinity analysis is establishing the location of the 2 grams of salt per liter of water isohaline (*i.e.*, X2) as a useful and potentially fundamental indicator of the salinity structure of the northern estuary and Delta (Jassby *et al*. 1995). This geography characteristic of salinity is then related to freshwater management in Suisun Bay and the Delta, and has launched a wealth of ideas for potential causal relationships between aquatic population abundance and the salinity and flow structure for Delta outflows (*e.g*., Kimmerer *et al*. 2009).

The present paper will not employ empirical correlations to estimate flow requirements except where more causal processed-based relationships do not exist. The general correlative approach, however, is common, sometimes effective, and often provides insights for more causal understanding. In a changing system correlation studies can be inherently misleading, particularly if the underlying equations are not carefully tied to more causal processes related to fish abundance. As the Delta changes, correlative studies at aggregated scales relying on historical fish data are likely to become less useful, unless they are tied to a more process-based or causal framework. Nevertheless, correlation studies within a causal framework are relatively straightforward and inexpensive, and so are likely to have enduring importance.

4) Environmental Flows from "Bottom-up" Accumulation of Functional Flows

Basing environmental flows solely on historical and estimated pre-development conditions, or on past aggregate correlations between flows and fish populations might not be the best approach alone. Since pre-development and historical times when native fish populations were large (before 1968), there have been many physical, hydrologic, water quality, and biological alterations to the Delta's habitats and ecosystems. Similarly great, or greater, alterations can be expected from sea level rise, permanent flooding of additional islands, additional invasive species, and climate change (Lund *et al*. 2010). Thus, fish relationships to flow that are established using past data might lead us astray, if not considered in light of how they may be influenced by changing conditions. A more fundamental, mechanistic, and process-based view of how changes in freshwater flow may interact with components of the habitat, ecosystem, and management actions to support desirable fish populations is more likely to provide more reliable insights. The fourth approach allows such bottom-up accumulation of process-based or causal flows, as well as more empirical flow estimates in their absence, into an integrated set of environmental flows.

A bottom-up strategy to estimating flows for sustaining desirable Delta fishes would itemize and estimate specific functional flows to support specific life stages and preferred habitat for fish. These estimates, based on the scientific literature or other technical information, would be collated based on their seasonality and inter-annual variability. A preliminary example with detailed monthly and yearly accounting was developed (Table 3). Table E-1 in Appendix E provides rough annual volume estimates for various objectives. Each functional flow prescription is based on recently published literature presenting flows for various life stages of fish based on data collected from a post-development Delta. This table of objectives may be far from complete; various functions are likely to have been overlooked or have yet to be identified and appreciated. For example, major episodic outflows may be required to stimulate the food web in the lower San Francisco estuary. In anticipation of such omissions, an overall safety factor was included in each functional flow estimate. Institutionally, such a safety factor might be reflected in a water reserve account to provide flexibility for long-term improvements, as well as for experiments in environmental water operations and to provide continuity of flows between periods where functional flows are specified with greater confidence.

An advantage of such a bottom-up approach is that it better allows updating of flows as more knowledge and information are obtained on the effectiveness of various flow, habitat, and other management activities. It provides a framework for incorporating additional scientific knowledge from a variety of methods, approaches, or lines of reasoning, including the other approaches discussed above. This functional flow framework also fosters a more technical and causal view of fish and flow interactions, providing a framework for further scientific studies. An important disadvantage of such a bottom-up approach is that it is likely to inadvertently omit flows that support particular unappreciated functions. Supplemental reasoning from historical or unimpaired flows or aggregated statistical relationships might augment, in the interim, flow prescriptions derived from a bottom-up approach. Certainly, this functional organization of flow prescriptions would focus, rather than eliminate, scientific controversies over how much flow would be needed by different fishes at different locations and times. However, it would provide a context and framework for such controversies and would presumably make these scientific controversies easier to resolve, as well as highlighting and distinguishing more versus less important controversies in terms of flow prescriptions. The following section illustrates a functional flow approach with exports occurring only via a peripheral canal, pipeline, or tunnel. Actual implementation of such an approach would require a greater effort to inventory and quantify each functional flow, systematically drawing on a wider range of scientific expertise, with capable scientific leadership to reconcile inevitable inconsistencies and uncertainties.

Individual Functional Flow Objectives

Each environmental flow component is tied to particular species or ecosystem functions, and is estimated separately and then combined logically. The organization of environmental flow functions should help refine and focus discussions and research regarding environmental water management in the Delta.

1a. and 1b. Annual flooding of the Yolo Bypass (YBP). Annual flooding would require a gate or notch in the Fremont Weir and creative operation of the gates at the Sacramento Weir. The YBP could be at least partially flooded in most years as it and similar floodplains would have done under pre-development conditions. In normal-to-dry years, a 150-200 m fringe along the Toe Drain would flood continuously every year, for 4-8 weeks, mid-February through mid-April. In wet years, more of the bypass would flood for longer periods. To attract juvenile salmon down into the bypass and to reduce the effects of a peripheral conveyance intake in the Hood area, much of the river might be diverted down the bypass. Minimum flow requirements are included as 2500 cfs during 3 months (February-April) for 8 of 10 years for Functional Flow #1a and supplemented to 4000 cfs during 2 months (Mar-Apr) for 6 of 10 years for Function #1b. It is estimated for the 2,500 cfs of Function #1a that 19,300 acres would be flooded and for the 4,000 cfs of Function #1b that 23,100 acres would be flooded (Bay-Delta Conservation Plan (BDCP) draft report 2008). Flows of about 10,000 cfs seem to provide the greatest area of shallow habitat in the Yolo Bypass (Moyle *et al.* 2004, Sommer *et al*. 2004, Harrell and Sommer 2003, Harrell *et al.* 2009) and would occur less frequently.

Preliminary work by the BDCP indicates that the Fremont weir could be modified to spill with flows of 23,100 cfs at Verona. The Verona location is upstream of the American and Feather river confluences. Because this document uses flows into the Delta, a simple regression was made between the Verona flows and those at Freeport, downstream of these confluences. The 23,100 cfs at Verona occurs when 23,500 – 28,500 cfs are flowing past Freeport. However, it currently requires an estimated average of 45,750 cfs at Freeport for Functional Flow #1a bypass flow and 50,150 cfs at Freeport for the Function #1b bypass flow (BDCP draft report 2008) with the Freemont weir lowered to the 17.5 foot level. Analysis of unimpaired flows shows that the Delta inflows for Function #1a would likely have occurred in 50% of years, and in 27% of years for Function #1b. Historically, the Yolo Bypass and other Delta and near-Delta riparian floodplains flooded more often - perhaps such Yolo Bypass flows can be supplied by siphons, pumps or other means (Booth *et al*. 2006).

2a. and 2b. Sacramento River flows for salmon. Sacramento flows for upstream migration of adult salmon and downstream movement of juvenile salmon require different flows over different months for the four runs of Chinook salmon. The flows differ from the reservoir flow and temperature requirements needed to sustain spawning and rearing habitat upstream. Functional Flow #2a is 10,000 cfs and specified for 9 months (January-June, October-December) for 6 of 10 years. Examination of unimpaired flows demonstrates that these conditions would have been expected to occur 87% of years, except for October and November which occur less than 25% of years. Function #2b requires 25,000 cfs for 4 months (March-June) for 6 of 10 years. Unimpaired flows suggest these conditions would have occurred in 79% of years from March through May, but only 28% of year for June. No additional flows are believed to be needed above the 10,000 cfs flow required by Functional Flow #2d, which is set at 10,000 cfs to prevent bidirectional flows at a peripheral conveyance intake (Newman and Rice 2002, Williams 2006, Harrell *et al.* 2009, USFWS Exhibit 31 1987, Kjelson and Brandes 1989).

2c. Sacramento River flows for adult sturgeon. At least once every 10 years, an extended high flow is prescribed for 5 months (January-May) both to bring adults up and to assist juveniles downstream. The 70,000 cfs flow rate might be accomplished through natural spills from reservoirs in wet years (Kohlhorst *et al.* 1991). Unimpaired flow data suggest these conditions would occur in 10% of years in January –March, but only 3% in April and less than 1% in May. There is some concern that sturgeon migration is limited by fish passage problems at Fremont Weir, which likely blocks sturgeon passage in all but extreme wet years (Harrell and Sommer 2003), so these flows can be reduced with appropriate changes to Fremont Weir.

2d. Sacramento River minimum flows past a peripheral conveyance diversion. To prevent bi-directional flows up the Sacramento River on flood tides, a minimum of 10,000 cfs was specified (Burau 2007) when exports are being diverted through a peripheral conveyance. This is included to prevent entrainment of biota from the northern Delta into the exports. However, the 10,000 cfs flow rate is preliminary and will require additional modeling work and monitoring, and will need to adapt with Delta changes including additional habitat rehabilitation in the Delta. Most of these flows seem likely to work well for salmon migrating through the Delta into the Sacramento River as well, per the requirements of Functional Flow #2a (Newman and Rice 2002).

3a. San Joaquin River flows for salmon. Minimum flows are needed to transport juvenile salmon through the Delta. Flows would come from the mainstem San Joaquin, Merced, Tuolumne, and Stanislaus rivers. Less water would likely be needed if there were significant improvements in the quality of agricultural return water and urban wastewater discharges on the San Joaquin, reducing the need for dilution flows. The Functional Flows naturally increase in magnitude and span a longer period of time as the available water supply increases for water year types (USFWS Exhibit 31 1987). Each of the five water year requirements was applied evenly over two years of the 10-percentile period and may need to be examined in a more rigorous statistical light since water years are not uniformly distributed over time (Figure 3). Unimpaired flow data show that all these monthly levels would be satisfied (Newman and Rice 2002, Williams 2006).

3b. San Joaquin River flows to improve dissolved oxygen conditions in the Stockton Ship Channel. These flows would reduce residence time in the Stockton Ship Channel to increase dissolved oxygen levels in summer and early fall (July-October), reducing fish kills and aiding fish migrations. A 2,000 cfs flow is included for this function (Lehman *et al.* 2004, Jassby and Van Nieuwenhuyse 2005). While analysis of unimpaired flows reveals no occurrence of flows as high as this throughout these four months, the dissolved oxygen problems resulting from the deepened, widened ship channel and agricultural and municipal loadings require the increased, non-historic flows or improvement of water quality.

Table 3. Functional Flow Locations, Purposes, Rates, Seasonality, and Annual Frequency [a]

Category	Item	Function	Flow (cfs)	Months Applied (10 = October)												# Years out of 10
				10	11	12	1	2	3	4	5	6	7	8	9	
1. Yolo Bypass	1a	juvenile salmon, adult splittail most	2,500[b]					1	1	1						8
	1b	juvenile salmon, adult splittail pulses	4,000[c]						1	1						6
2. Sac River	2a	SR adult salmon	10,000	1	1	1	1	1	1	1	1	1				6
	2b	Juvenile salmon migration – SR	25,000						1	1	1	1				6
	2c	Adult sturgeon	70,000				1	1	1	1	1					1
	2d	Min flow past PC intake	10,000	1	1	1	1	1	1	1	1	1	1	1	1	10
3. SJ Valley	3a	SJR juvenile salmon wet	20,000							1	1	1				2
		above normal	15,000							1	1	0.5				4
		below normal	10,000							1	1					6
		Dry	7,000							1	0.5					8
		Critical	5,000							1						10
	3b	Stockton Ship Channel DO	2,000	1									1	1	1	10
	3c	SJR adult salmon	2,000	1	1	1	1	1	1	1	1	1	1	1	1	10
4. Eastside Streams	4a	Mokelumne River flows	1,500						1	1						8
	4b	Eastside Stream minimum flows	1,060	1	1	1	1	1	1	1	1	1	1	1	1	9
5. Net Delta Outflows	5a	Delta smelt flows	48,000						1	1	1					5
	5b	Egeria suppression by reducing	8,000										1	1		3[d]
	5c	Overbite clam suppression by	120,000					1	1	1						3
Other	6a	Suisun Marsh Flows														
	6b	Close or Limit exports														
	7a	Safety Factor	20%													

[a] Table does not contend to contain all required functional flows or have precise prescriptions for each month for those listed.

[b,c] require flows at Freeport of approximately 45,750 and 50,150 cfs, respectively, based on regressions of historical data.

[d] applied during driest percentile years, all others applied during wetter years.

3c. San Joaquin River adult salmon. Adult salmon recruitment has been found to be successful when flows into the Delta exceed 2,000 cfs every year (USFWS Exhibit 31 1987). This flow will also provide the needed flow to maintain dissolved oxygen levels of Functional Flow #3b. As discussed in 3b, these flows were not experienced in unimpaired conditions, but likely result from the disturbed conditions.

4a. Mokelumne River salmon pulse flows. Such flows aid salmon migrations from and into the lower Mokelumne River. Pulse flows of an average of 1,500 cfs for 2 months (March-April) for 8 of 10 years (Henson *et al.* 2007). While the Mokelumne River is not separated from the rest of the eastside streams in the unimpaired flow numbers, flows of this level are seen to exist over 85% for unimpaired conditions.

4b. Eastside stream minimum flows. Such flows would create floodplain habitat, improving local water quality in the Delta and aiding fish migrations in these streams. This is estimated here preliminarily as the 25th percentile unimpaired flows for all 12 months for 9 of 10 years (Moyle *et al.* 2007). The flows would include adding water to the Cosumnes River from the Folsom South Canal to wet the section of the river that now goes dry due to groundwater pumping (Robertson-Bryan, Inc. 2006).

5a. Delta outflows for delta smelt. A 48,000 cfs Functional Flow for 3 months (March-May) for 5 of 10 years would maintain freshwater to low salinity habitat in the northeastern Delta to the Napa River, facilitating a broad spatial and temporal range in spawning and rearing habitat (Bennett 2005, Hobbs *et al.* 2005). In this particular case, delta smelt flows are needed every other year to maintain survival of a species with a 1-2 year life cycle. The unimpaired data reveal that these flows only occurred during 71% of the years, although they cannot answer the extent to which this occurred every 1 of 2 years. Large-scale permanent flooding of Delta islands may result in better upstream habitat for smelt, reducing the need for outflows (Moyle 2008).

5b. Egeria suppression by reducing outflows in some years. An experimental minimum Delta outflow would allow the western and parts of the central Delta to become much more saline to suppress the invasive Brazilian waterweed, *Egeria densa*. The net Delta outflow would be reduced to 8,000 cfs for 2 months (July-August) in 3 of 10 years. The unimpaired data indicate that these low flows would have occurred in 28% of the years. The reductions would occur in the driest of years when Sacramento inflows would already be too low, below 10,000 cfs, to allow exports through a peripheral conveyance as seen in the unimpaired values for that period and return interval (Hauenstein and Ramirez 1986). This experimental flow is included to illustrate that there might be cases where it is beneficial to increase variability in salinity to suppress invasive species by restricting freshwater flows. This flow also illustrates the important experimental nature of many flows for the Delta.

5c. Overbite clam suppression by increasing outflows in some years. An experimental high Delta net outflow of 120,000 cfs for 3 months (January-March) for 3 of 10 years that would freshen the western Delta and Suisun Marsh and Bay for several months to suppress the Asian overbite clam (*Corbula amurensis)*. The increased outflows would be performed during the wettest of years (Thompson 2005). This is an experimental flow and the unimpaired data indicate that these low flows would only have occurred in 11% of the years. As with Functional Flow #5b, this flow may need to be accompanied by episodic reduced flows to suppress the more freshwater invasive Asian clam (*Corbicula fluminea*), and monitored by a scientific program with a field data component. The need for clam suppression flows could be reduced if other means were found to control clam abundance (*e.g*., dredging).

6a. Suisun Marsh flows. Typical year flows might be managed well using internal and existing gates in Suisun Marsh. Such flows for Suisun Marsh would allow much of the tidal and subtidal marsh to become fresh or nearly so for varying periods of time to maintain conditions (salinity and temperature) favorable to native fish species and to discourage alien species.

6b. Close or limit water exports. At some times and places, it is likely to be desirable to limit or prevent major water exports due to the presence or migration of native fishes.

7. Safety Factor. We are unlikely to have identified all flow requirements or to have made the definitive estimate of flows needed for many of these functions. A safety factor of 20% is applied to each flow in Table 3 to help compensate for such uncertainties. The full 20% is applied for all percentile flow examples shown in Figure 10.

Estimation of Individual Function Flows

There will often be different ways to estimate the magnitudes, variability, and frequency of specific functional flows. This can be a messy business, provoking reasonable controversies among scientists. We have based our estimates here preferentially on available published peer-reviewed studies. This discourages speculative and interest-driven estimates, without eliminating these possibilities. We strongly prefer functional flow estimates from process-based studies; these should usually provide a more scientifically-reasoned and adaptable basis for establishing flow prescriptions. Statistical relationships backed by plausible, so-called conceptual models are likely to have lesser utility, but, as explained earlier, considerable initial value. Flows from historical periods of greater native fish abundance also have some utility in this process, as do the patterns of pre-development and unimpaired flows. Ultimately, establishing specific flow patterns for each function must be based on the technical judgment of those delegated the task. Bayesian modeling has been suggested to provide a more mathematical means of expressing such judgments in establishing and evaluating functional flow quantities (Hart and Pollino 2009). An important by-product of this process should be the systematic identification and prioritization of research efforts to narrow important uncertainties. If the resulting functional flows are to be environmentally effective, there is an obvious need to institutionally protect this process.

Flows and Habitat

Tidal and freshwater flows in the Delta have two fundamental ecosystem functions, to mobilize and transport solutes, particles, fish, and other organisms, as well as to support desirable habitat. Flows move fish both as a stimulus for upstream spawning (salmon, splittail, delta smelt) and as a physical transport mechanism, especially for larvae and juvenile life stages. Flows also distribute nutrients, particles and prey organisms for fish, and interact to produce areas of high productivity. Flows also provide physical habitat for fish, as well as appropriate chemical, nutrient, and biological conditions, and disrupt habitat for competing undesirable fish or ecosystem engineers (*e.g*., such as non-native mollusks or water-weeds). Flows without suitable accompanying habitat conditions provide little benefit or can even harm some fishes. Different flow and habitat combinations should be designed in a portfolio approach to suit the different life stages of desired species in an ecosystem context. Sandstrom *et al.* (2009) summarize major Delta habitat development options within the context of expanding habitat characteristics in the

Delta suitable for native estuarine species described in Moyle *et al.* (2010). Flow management can then expand the major seasonal habitats of tidal marshes, flooded wetlands and floodplains, important for the spawning and rearing of fish and, probably, important for producing nutrients that are used downstream.

Comparison of Methods

Methodologically, the four approaches discussed above are compared in Table 4. Generally, approaches that rely on data from the past will become more risky as the underlying changes in the Delta accumulate. However, since the objective is to provide flows for species which evolved under past conditions, information on past flows and life history strategies of fish provide considerable insight and context. Aggregate statistical approaches, which essentially establish correlations between past conditions and past species abundance, are likely to be less directly useful as the Delta changes. However, statistical approaches will continue to be useful, especially if developed for causal insights. More focused statistical relationships can be of more enduring value in the context of more causal models, even given underlying changes. In the absence of more process-based science, empirical relationships might be required for some locations and functions on an interim basis. Insights and information can be gained from each approach. Given the importance of the problem and the uncertainties involved, the strengths of each approach should be employed to provide greater certainty or improve definition of uncertainties.

Table 4. Methodological Comparison of Approaches to Establishing Delta Environmental Flows

Approach	Advantages	Disadvantages	Contributions
Unimpaired flows	Known pre-development effectiveness	Increasingly remote from contemporary and future conditions	General pattern of flows and magnitudes for original conditions
Historical Flows	Known effectiveness for past conditions	Increasingly remote from contemporary and future conditions	General pattern of flows and magnitudes for historical conditions
Statistical	Relies on more contemporary data. Often provides insights into causation. Inexpensive.	Can become increasingly remote from contemporary and future conditions, assumes stationarity	Insights into important causal mechanisms, empirical characterization of causal mechanisms
Functional flows	Flexibility and greater scientific understanding	Reliance on more detailed science	Framework for assembling knowledge from a variety of approaches into adaptable prescriptive flows

Initial values of environmental flows are compared in Table 5 for three of the approaches discussed above. The first column shows the low, average and high unimpaired inflows estimated by DWR for the period 1921 – 2003 (DWR 2006). Similarly, estimates based on the 1949 – 1968 historical inflows and on the accumulated functional flow rationale are also shown. These numbers are only average and extreme annual flows. Estimation and representation of intra-annual variability would also be important for a more rigorous flow recommendation.

Table 5. Illustrative Comparison of Possible "Desirable" Low, Average, and High Annual Environmental Flow Volumes Estimated by Three Approaches for Various Locations

Flow Location	Average and Extreme Annual Flows (maf/yr)								
	1921-2003 Unimpaired flow			1949-1968 Better Historical			Total Functional Flows[a]		
	Low	**Ave**	High	Low	**Ave**	High	Low[b]	**Ave**	High[b]
Sacramento River (including Yolo Bypass)	5.6	**21.6**	48.4	10.9	**19.1**	35.5	8.6	**13.1**	31.1
San Joaquin River	1.1	**6.2**	19.0	0.4	**2.7**	7.1	1.9	**2.8**	4.3
Eastside Streams	0.2	**1.6**	5.5	0.1	**1.4**	3.5	0.1	**1.0**	1.0
Delta Outflows	5.6	**28.2**	71.9	9.6	**21.3**	42.8	5.6	**27.3**	47.3[c]

[a] Ten-year average of accumulated estimates, includes a 20% safety factor.

[b] The low is the 10th %-ile and the high the 100th %-ile flows.

[c] Delta Outflows include Functional Flow #5b and #5c experiments.

As an example of adding up the prescribed Functional Flows of Table 3, Figure 10 presents monthly flows for four percentile years. For simplification the calculations are based on percentile flow years. Each prescribed flow objective has been applied against the percentile flow that the prescribed flow would be required to meet over the months that were specified. For example, a flow prescribed over 3 months March-May for 2 years out of 10 (Functional Flow #3a) is applied against the 90th- and 100th-percentile years for those 3 months. The red line represents the unimpaired inflows available with no attempt to account for possible storage management. The three blue shades represent the accumulated prescribed inflows from the Eastside stream, the Sacramento River, and the San Joaquin River. Yolo Basin flow prescriptions require substantial Sacramento River flows to spill over the weir (yellow shade). The net required flow (light green) is the maximum of the inflow sums or net outflow. The difference between Yolo Basin and net required flows for percentiles under 80% demonstrates a major management challenge to producing prescriptive flows while providing needed exports. The dark green dashed line represents the prescribed outflows and will control the net required flow when they exceed the inflow prescriptions. No effort has been made to manage the imposed Sacramento 10,000 cfs minimum (Functional Flow #2d) when flows cannot be exported through peripheral conveyance to save water for periods when exports are possible. See Appendix C for detailed explanation.

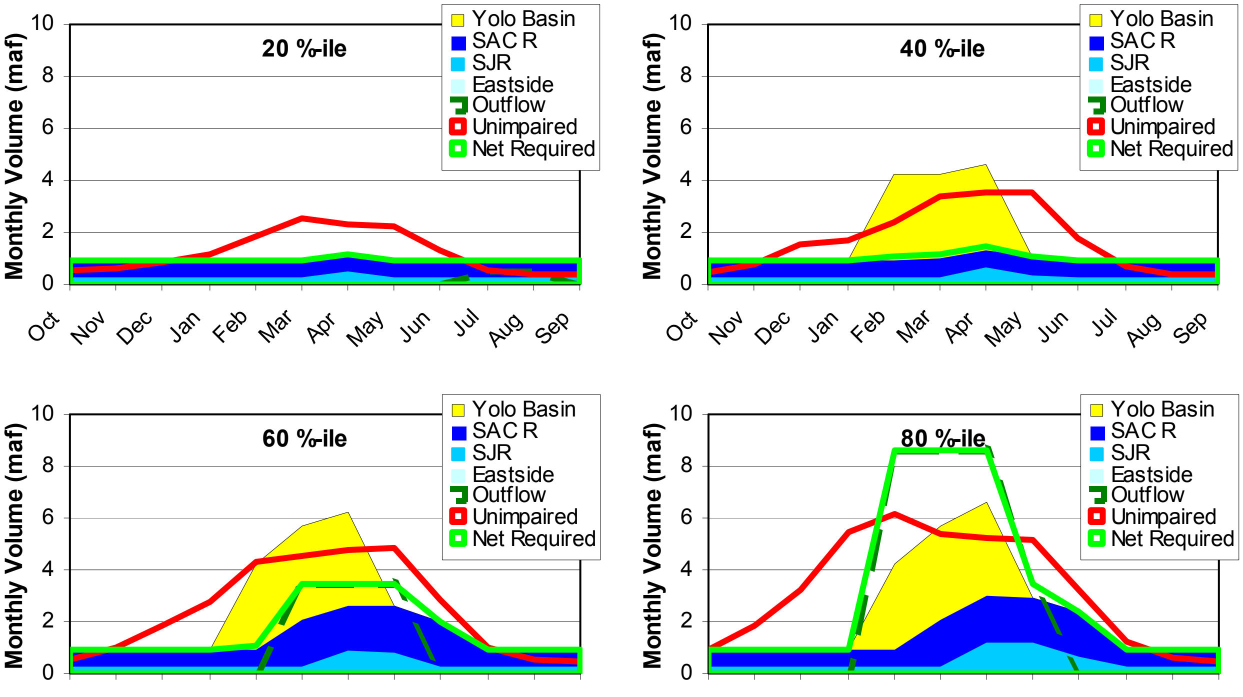

Figure 10. Preliminary monthly flow recommendations and unimpaired flows for different percentile years (top – 20th & 40th %-ile) and (bottom – 60th & 80th %-ile). Dark, medium and light blue represent Sacramento, San Joaquin and Eastside inflows. The dashed dark green line represents the prescribed outflow levels while the light green solid line is the net required flows by the maximum of the inflow or outflow. The red line is unimpaired flow.

Limitations and Contingencies

Several specific limitations and contingencies should be noted:

- The unimpaired flows incorporated here are used only to represent the potential water available to flow into the Delta. The ability of the system to be managed for flood control and Delta water supplies has not been examined. There is currently not enough water to meet minimum flow limits past the peripheral conveyance intakes (functional flow 2d); exports would have to be suspended or reduced to increase environmental flows. The coordination of water diversion operations with these flows would require further examination.

- Sacramento River flows past a peripheral conveyance intake could drop below 10,000 cfs under some circumstances, including changes in downstream island flooding and times when export pumping was suspended or reduced. Further work is needed to establish a relationship for the low functional net Delta outflows (functional flow 5b) and no-exports period to determine how to manage the system for conveyance exports.

- Yolo Bypass flows are not too demanding by themselves. However, flow rates in the Sacramento River greater than 41,750 -50,100 cfs are currently needed to provide water elevations to spill over the current weirs. More effort is needed to determine what minimum upstream Sacramento River flows would be required to produce the smaller Yolo Bypass flows desired with modification of the weirs. The graphs also assume that all excess flow in the Sacramento River necessary to create the required Yolo Bypass flows can be recovered at the peripheral conveyance intake. However, these flows may exceed the capabilities of the intake.

- The management of eastside flows would be incomplete, since the Cosumnes River is largely unregulated, although base flows are certainly less than naturally occurred due to reduced groundwater levels.
- Many of the net Delta outflow requirements are highly experimental, particularly for suppression of invasive species. Greater examination of these flows is needed. Their presence here illustrates how experimental flows can be included in the functional flows framework.
- Additional environmental flow functions might be important and should be explored for inclusion in the bottom-up accounting. Estimation for some of these flows will pose challenges, particularly at first. Fall outflows to support smelt habitat might be one such example (Feyrer, per. comm.)
- The monthly time steps developed from published articles and presented here will need to be adjusted to many ecological responses that occur at smaller time steps (weeks or days). This will be particularly important as new scientific information becomes available.
- There are likely to be occasions where flow functions for different fish species or life stages conflict, there functional flows for the Delta conflict with desired upstream environmental flows, or total functional flows under present habitat and biological conditions exceed the amount of water physically available to the system. Functional flows might also exceed the levels of environmental flows desired by other economic or social interests in the Delta. Such conflicts are unavoidable, but can be specified and quantified in this framework, which should make them easier to resolve with in an appropriate institutional framework.
- The institutional setting of flow and habitat management is likely to be of paramount importance. Since it is unlikely that certainty will be achieved before actions or responses are required by geologic, biological, and legal processes, it might be valuable to provide substantial financial and water reserve resources, along with responsible institutional wherewithal to respond to changes and undertake necessary experiments for more successfully transitioning into the largely unexplored new Delta.

The implementation of the functional flows approach involves three tasks. First, the flow functions for each location must be identified to support desired ecosystem and biological characteristics for the Delta (Moyle *et al*. 2010). Given uncertainties, some experimental flow functions probably should be included (Holling 1978). Many flow functions will essentially be working hypotheses, in a scientific sense. Second, for each function and location, estimates must be made of how much freshwater flow is needed at which times of year with what frequency. A variety of approaches will usually be available to make such estimates. This is a scientific and technical matter involving some uncertainty, a multiplicity of estimation methods, and sometimes considerable economic, risk management, and therefore political implications. Third, some adjustments of functional flow prescriptions for implementation are likely to be needed. There will be times and locations where compromises must be made where flow prescriptions for different species or desirable functions conflict, where water availability or compatibility with upstream environmental flows might be a concern, where environmental flow prescriptions conflict with other important economic and social objectives, and where there is concern that important flow functions have been omitted.

The likelihood of flow function identification and functional flow estimates being environmentally effective is likely to be reduced unless this process has considerable insulation from political influences. However, there are appropriate political roles for balancing species, ecosystem, economic, and social objectives, particularly in the third task, and also to a lesser degree in identifying experimental functional flows. Establishing environmental flows is a scientifically imperfectible process and will always be complex and controversial for the Delta. Establishing a functional organization of flow purposes should provide a more technical and scientific basis and focus for this enterprise. This will not eliminate controversy, but might better organize and focus controversies so they can be better dealt with scientifically, where possible, and politically, where necessary.

Need for Science and Adaptability in Flow Prescriptions

Flow prescriptions change slowly and often reluctantly in the Delta. Arguably, the Delta has been changing faster, and native species have been declining faster, than scientific and regulatory institutions have been able to improve their understanding, regulation, and management of the system. It is desirable to have a flow prescription system more tightly coupled with scientific findings and to have institution of flow prescriptions more closely tied to a scientific program – not just a monitoring program.

The coming changes in the Delta are fundamental, widespread and wide-ranging. It is unlikely that any initial set of flow prescriptions will be effective alone in restoring native fish populations. Any set of initial flow prescriptions is likely to become less relevant for native fishes as the Delta continues to change. Therefore, a scientific program is needed to accompany a set of Delta flow prescriptions, along with regulatory and management institutions which can and will support and respond to scientific advances and changing conditions. Without these, even the best set of flow prescriptions today is destined to become an ineffective impediment to the recovery and maintenance of healthy native fish populations and pose greater risk from legal actions.

Such a scientific program requires independence, reliable funding, and credible leadership. Independence allows the scientific program to investigate inconvenient subjects and actions – not just conduct “monitoring.” Some accountability is needed to have relevance in regulatory and management decision-making, but not so much that important and insightful problems and opportunities are ignored when politically inconvenient. Reliable funding is needed so the infrastructure of models, data, and expertise are well-developed and applications of these and special studies are continuous, well maintained, and organized. Credible leadership, with clear communication of results, is required to maintain a useful and effective scientific program in the midst of a difficult scientific and political environment.

More research is always needed, but for the development of environmental flows it is important that the precision and complexity of recommended flow prescriptions not exceed our level of understanding. At this point, having dozens of flows catering to dozens of hypothetical or conceptual functions is unlikely to provide an environmentally effective, much less a scientifically testable, flow prescription framework. An overly complex framework is also likely to dilute and Balkanize scientific and management efforts and diminish flexibility, rather than promote synthesis. Having an institutional capability which can conduct and integrate effective scientific research as well as modify policies to reflect such results will require profound changes in science and management activities for the Delta.

Conclusions

Preliminary *illustrative* methods for estimating fresh water flows needed to sustain viable populations of native fishes in the Delta have been compiled along with justifications and available references. Several approaches to this problem are explored and illustrative annual quantities of water are estimated. These estimated flows might have some value in furthering discussions in light of the justifications and references provided, but greater value, for the time being, lies in the comparison of quantitative methods used to develop them. Greater and more systematic effort is needed to combine scientific information and options for habitat and flow policies to support native and desirable fishes. This paper is a preliminary exploration in this direction.

Estimated freshwater flows presented here are likely to be sensitive to assumptions, particularly those regarding the future landscape and habitat created by permanently flooded islands or major habitat improvements in Suisun Marsh, Yolo Bypass, and Cache Slough areas. Additionally, these estimates are made assuming water exports only through some form of peripheral conveyance. Including through-Delta conveyance (alone or as part of a dual conveyance strategy) is most likely to increase the number of internal flow requirements and restrictions needed to protect fish within the Delta, given the profoundly unnatural flow patterns created by large water diversions from the south Delta pumps. Higher Delta outflows, or reduced exports, are likely to be needed to overcome harm to native fish from through-Delta conveyance for exports. However, the methods used here can, with additional time and effort, be applied to setting near-term flow prescriptions including the use of through-Delta conveyance.

Recommendations

Several recommendations arise from this work:

1) Flow prescriptions should be supported preferably by causally or process-based science, rather than correlative empirical relationships or other statistical relationships without supporting ecological basis. Having a greater causal basis for flow prescriptions should make them more effective and readily adapted to improvements in knowledge and changing conditions in the Delta. A more explicit causal basis for flow prescriptions will also create incentives for improved scientific understanding of this system and its management as well as better integration of physical, chemical, and biological aspects of the problem.

2) Ongoing managed and unmanaged changes in the Delta will make any static set of flow standards increasingly irrelevant and obsolete for improving conditions for native fishes. Figure 11 illustrates how the variability of the position of X2 has changed from unimpaired flow to current conditions, and how it would change with unimpaired flows and sea level rise. Flows should be tied to habitat, fish, hydrologic, and other management conditions, as well as our knowledge of the system. Flows needed for fish native to the Delta will change.

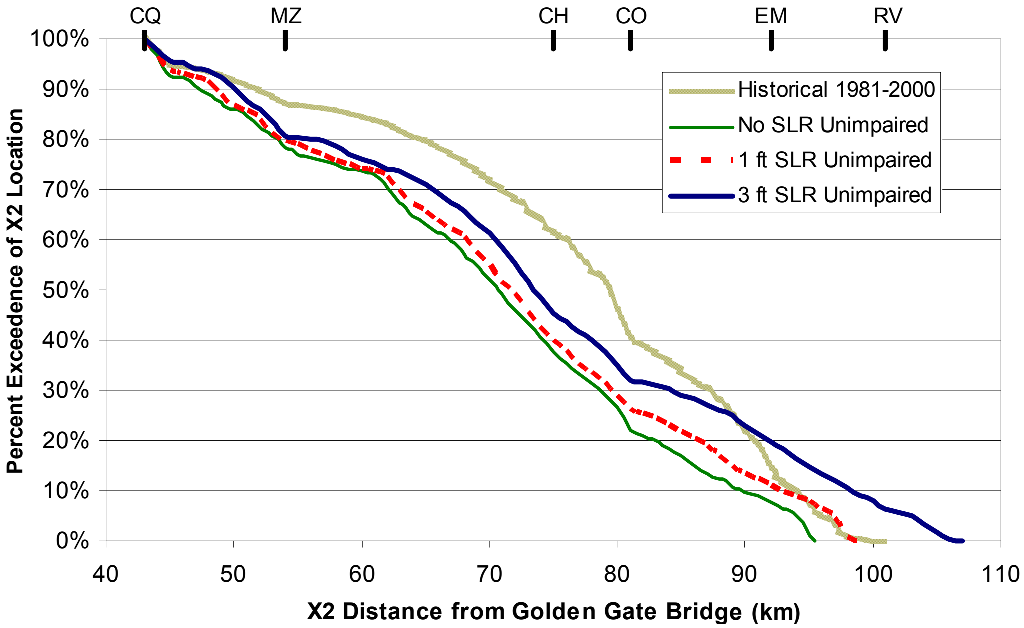

Figure 11. Cumulative probability distributions of daily X2 locations for unimpaired flows (thin green solid line) with 1-ft of sea level rise (red dashed line), 3-ft of sea level rise (thick solid blue line), and 1981-2000 historical condition (opaque brown line), illustrating progressive salinity variability for unimpaired conditions with sea level rise. X2 is the location of the 2 ppt salinity region of the estuary in km from the Golden Gate. Thus a lower X2 value indicates that the low salinity zone is farther downstream in the estuary. Results from Water Analysis Module using unimpaired flow and historical boundary conditions (Fleenor *et al.* 2008). Paired letters indicate geographical landmarks. CQ, Carquinez Bridge; MZ, Martinez Bridge; CH, Chipps Island; CO, Collinsville; EM, Emmaton; and RV, Rio Vista.

3) A more in-depth and formal development of the functional flows “bottom-up” method should be pursued. The method, documentation, and flow estimates provided here are preliminary. This effort should involve a greater range of scientists in an organized technical process under a coherent scientific leadership.

4) To better adapt environmental flows for the Delta, an ongoing science and technical development program is needed to continually improve scientific understanding and synthesis of the Delta’s ecosystem and how to best manage this system with habitat and flow management. This program will need to be quite different from any existing scientific efforts and will require sustainable funding, institutional commitment, and a greater degree of independence.

5) It might be useful for regulators to offer several sets of flow prescriptions, each coupled with different sets of habitat development and other actions. This would provide more regulatory certainty to help water managers act collectively to improve flow and habitat conditions in the Delta for desirable fishes.

A Further Note of Caution

“How much water do fish need?” has been a common refrain in Delta water management for many years. The estimates developed here are not the answer to this question, but are intended to illustrate various approaches that may be explored to address this problem in the future. Moreover, it is highly unlikely that any fixed or predetermined prescription will be a "silver bullet". The performance of native and desirable fish populations in the Delta requires much more than fresh water flows. Fish need enough water of appropriate quality over the temporal and spatial extent of habitats to which they adapted their life history strategies. Typically, this requires habitat having a particular range of physical characteristics, appropriate variability, adequate food supply and a diminished set of invasive species. While folks ask "How much water do fish need?" they might well also ask, "How much habitat of different types and locations, suitable water quality, improved food supply and fewer invasive species that is maintained by better governance institutions, competent implementation and directed research do fish need?" The answers to these questions are interdependent. We cannot know all of this now, perhaps ever, but we do know things that should help us move in a better direction, especially the urgency for being proactive. We do know that current policies have been disastrous for desirable fish. It took over a century to change the Delta's ecosystem to a less desirable state; it will take many decades to put it back together again with a different physical, biological, economic, and institutional environment.

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Appendix A – Estuary Flow Prescriptions Elsewhere in the United States

Since the introduction of the Instream Flow Incremental Methodology (IFIM) over 30 years ago, advances have been made in establishing flow requirements to sustain healthy riverine ecosystems (Richter 2009). The main instrument of the IFIM, widely used in the USA, has been the application of the Physical HABitat SIMulation (PHABSIM) model. However, the complex nature of biological responses to hydrological changes prevents the direct application of such models from system to system without considerable expert knowledge. The added complexity of tides and salinity compounds the effort for estuaries.

Florida and Texas recently have established procedures for regulating impairments on estuarine systems. In Florida, methods similar to the IFIM methodology for stream flows have been applied. As the result of these studies, most rules are implemented as a percent of natural stream flow with larger percentages required in lower flow periods than in higher discharge regimes. Florida Statutes (Chapter 373.042) set the goals of flow rules as ‘‘the limit at which further withdrawals would be significantly harmful to the water resources or ecology of the area.’’ Early rulings were established as a low fixed percentage of median flow (Flannery *et al.*, 2002, 2008). On the Alafia River Estuary, a maximum extraction limit of 19% was placed during the low flow period with lesser percentages allowed for higher flow periods. For the estuary of the small Hillsborough River, the 2006 rules doubled the previous minimum outflow to the estuary established in 1999 (Montagna *et al.* 2007).

The rivers flowing into most Texas estuaries are significantly regulated and, although the estuaries have very different temperature regimes and species than the Sacramento-San Joaquin Delta, are likely more similar to our local situation. Beginning with legislation as early as 1975, the Texas legislature established "beneficial inflows" associated with "a salinity, nutrient, and sediment loading regime adequate to maintain an ecologically sound environment in the receiving bay and estuary system”. In 2001 Senate Bill 2 sought to "establish … an instream flow data collection and evaluation program and … determine appropriate methodologies for determining flow conditions … necessary to support a sound ecological environment". The monitoring program was delegated to the Texas Commission of Environmental Quality (TCEQ), the Texas Water Development Board (TWDB) and the Texas Parks and Wildlife Department (TPWD). The method developed from these efforts and later adopted as the State Method involved the use of two models. The first model, TxEMP, was an optimization model designed to establish optimum monthly flows to provide the maximum harvest or abundance potential (mostly for commercial fishing), maxH, as well as a lower, minQ, and upper flow bound, maxQ, around which flows could be managed. The calculations were performed on all species determined to be vital for the particular estuary and based on constraints to ensure values remained within physical reality. A hydrodynamic model, TxBLEND, was then applied to verify the flow regime and produce a minimum flow, minQsal, that would limit the maximum salinity intrusion (Powell *et al.* 2002).

This work follows other applications of optimization to establish freshwater flows for Texas estuaries, typically to maintain a given level of reliability for fish harvests (Martin 1987; Bao and Mays 1994a, b). These methods rely on salinity hydrodynamic model results and empirical regressions with confidence intervals of fish harvests and seasonal freshwater flows. The large computational burden of solving this problem allowed only very coarse optimization.

The Programmatic Work Plan and the Technical Overview developed by the three Texas agencies were reviewed by the National Academy of Sciences (National Research Council Committee, 2005; TPWD *et al.* 2002, 2003). The Texas legislature also appointed a Study Commission on Water for Environmental Flows and a Science Advisory Committee to provide further advice and assessment (Science Advisory Committee 2004). The consequences of these reviews were to involve more stakeholder participation and provide more latitude in examining environmental flows beyond the State Method. The Bay and Basins Area Stakeholder Committee (BBSAC) was established for each basin in Texas. The BBASC responsibilities included the selection of a Bay and Basin Expert Science Team (BBEST) that provides the scientific basis for environmental flow regulations. Texas Senate Bill 3 provides that the BBESTs are to "develop environmental flow analyses and a recommended environmental flow regime for the river basin and bay system for which the team is established through a collaborative process designed to achieve a consensus. In developing the analyses and recommendations, *the science team must consider all reasonably available science, without regard to the need for the water for other uses*, and the science team's recommendations must be based solely on the best science available." The Science Advisory Committee (2006) to the Governor's Environmental Flows Advisory Committee provided the following *guidance*, stating that a sound ecological environment is one that:

- sustains the full complement of native species in perpetuity;
- sustains key habitat features required by these species;
- retains key features of the natural flow regime required by these species to complete their life cycles; and
- sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations.

The stakeholder committee (BBASC) then uses the findings of the expert team (BBEST) to provide the regulating agency (TCEQ) with their recommendation on environmental flows for the basin. Each BBEST is encouraged to use a variety of methods to make environmental flow recommendations. TCEQ recognizes that perfect knowledge of estuarine systems is not feasible before flow decisions are made and therefore encourages flexibility and adaptation to future understanding. Decisions are required to be re-evaluated periodically within ten-year intervals. The methods include but are not limited to (Science Advisory Committee 2009):

- Texas State Methodology: as summarized above.
- Salinity Zone Approach: assesses the suitability of the distribution of salinity within an estuary for a specific organism. The link to freshwater inflow is through its control on salinity distribution.
- Hydrology-Based Environmental Flow Regime (HEFR) Method: a flexible computational approach based solely on hydrologic data for developing a flow regime matrix that identifies multiple flow regime components and hydrologic conditions across different months, seasons, or years.
- NWF Inflow Pattern Approach: a National Wildlife Federation-developed method called an "inflow pattern" approach for establishing some portions of an estuarine inflow

regime. It focuses on specific naturally-occurring inflow patterns that appear to be important for the estuary.

- Percent of Flow Approach: developed in Florida, the method defines the need for inflows broadly as “the limit at which further withdrawals would be significantly harmful to the water resources or ecology of the area.” It is similar to the hydrological approach.
- The Science Advisory Committee also identified other methods that have been used in outside of Texas that could also be valuable:
- Nature Conservancy (IHA/EFC) Method: The Index of Hydrologic Alterations was developed by the Nature Conservancy to quantify alterations within the stream ecosystem and is primarily used to evaluate past impact.
- LCRA-SAWS Inflow Criteria Method: an independent development of thorough modeling and data analysis used in the Matagorda Bay Health Evaluation. It involved examinations of salinity, habitat condition, species abundance, nutrient supply, and benthic condition (MBHE 2007).

The approaches employed and considered for Florida and Texas provide a broader perspective for establishing environmental flows for the Sacramento-San Joaquin Delta. In particular, they illustrate different ways that flow volumes, flow patterns and variability, habitat availability, and organism needs can be considered in establishing environmental flows. The importance of considering several methods and the development of an institutional structure to balance the results of different methods and other water management interests is an especially interesting aspect of estuary management in Texas. Giving stakeholders an ability to select the method which suits them best is a potentially dubious feature in Texas’ system.

Appendix B - Delta outflows and salinity

The salinity at any given spot in the western Delta and Suisun Bay is the result of a complex process, with significant interaction between tides, outflows from the Sacramento and San Joaquin rivers, and through-Delta exports. Detailed analysis of this process requires extensive modeling analysis and specification of many assumptions. For this quick study we employed a simpler method, using the RMA WAM model assuming zero through-Delta exports.

The figure below shows results from this model, which was run in a series of 3-month steady flow steps to give an estimate of the rough magnitude of net Delta outflows needed to move the average salt concentration of 2,000 ppm (about 6% of seawater) closer or farther from the Golden Gate, the so-called X2 location. A regression of the model output is also shown (blue lines). The earlier Monismith-Kimmerer relationship for the X2 location is also included (which includes exports and was calibrated based on field data available at that time).

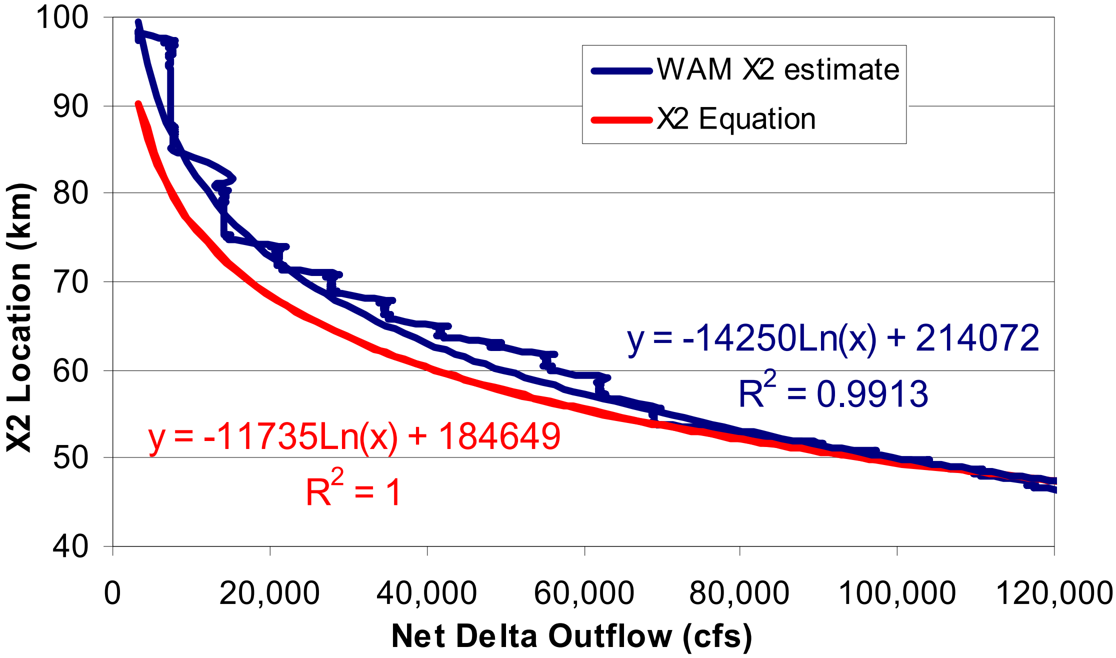

Figure B-1. Relationship of X2 location versus net Delta outflow.

Appendix C: Details of Flow Accumulation Across Years

Eastside Streams

For simplification the flow prescriptions have been aggregated into ten ranges on the basis of percentile flow years for 10th, 20th, …100th percentiles. For example, the Eastside Streams (primarily the Cosumnes and Mokelumne Rivers) have two flow prescriptions to consider, Table C-1. The minimum flow, 4b, is specified at 1,060 cfs during every month. In addition, pulse flows have been found beneficial and are specified at 1,500 cfs during 2 months (March and April) for 8 out of 10 years. These two months will supplement the minimum flows for the 8 wettest years.

Table C-1. Monthly flow prescriptions for Eastside Streams

Prescription	Flow (cfs)	Requirement for each month of water year (10=October)												# Yrs
		10	11	12	1	2	3	4	5	6	7	8	9	
4a Mokelumne River flows	1,500						1	1						8
4b Eastside Stream minimum flows	1,060	1	1	1	1	1	1	1	1	1	1	1	1	9

In all the graphs the red line represents the unimpaired inflows available with no attempt to account for possible storage management. For the 60th percentile flows the available unimpaired flows are presented in Figure C-1. For 60th percentile flows the higher Mokelumne flow of 1,500 cfs for March and April in 8 years of 10 will prevail in March and April over the lower 12-month minimum of 1,060 cfs minimum required of the Eastside streams. This particular instance will have greater uncertainty in the total flow from the Eastside streams since the Cosumnes is unregulated and the flows are not managed. One could calculate a 60th percentile estimate of the Cosumnes flow for these months if desirable, but the flows would not be very significant. The inflows from the Eastside (light blue shade) are so much less than the rest that an additional graph with an exaggerated scale is shown to demonstrate the flows, Figure C-1.

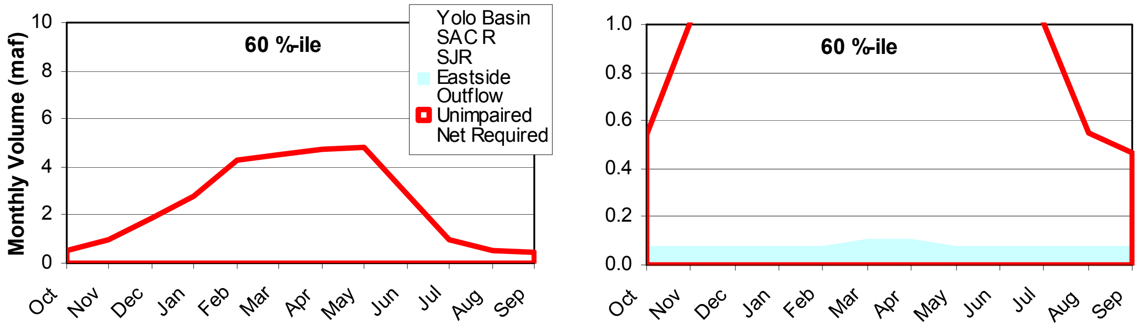

Figure C-1. Sixty percentile flows for the Eastside streams (light blue) with 1/10 scale on right side

San Joaquin River

Next, consider the San Joaquin River (SJR) prescriptions detailed below in Table C-2 and apply them to the 60th percentile flow. The SJR has only 3 prescribed flows and 3b is actually automatically covered by the application of 3c which matches the flow rate and covers all 12 months for all 10 percentile flow periods. Prescription 3a for the SJR is specified as increasing flow rates for increasing numbers of days as the water year becomes wetter. A year classified as critical requires 5,000 cfs for only 1 month, April. As water years become wetter the flow eventually increases to 20,000 cfs over 3 months, April-June, for a year classified as wet. Flows for prescription 3a would supplement for the specified months the minimum flows prescribed by 3c. For the purpose of this work, the water years have been assumed to be uniformly distributed and each applied evenly over 20% percentile increments (*e.g.*, critical for 10 and 20th percentile,… wet for 90 and 100th percentile). For the 60th percentile case the 3a flow prescription for below normal water years is applied, which specifies 10,000 cfs in April and May for six years out of ten, while the 2,000 cfs minimum will apply for the remainder of the months.

Table C-2. Monthly flow prescriptions for the San Joaquin River

Prescription	Flow (cfs)	Requirement for each month of water year (10=October)												# Yrs
		10	11	12	1	2	3	4	5	6	7	8	9	
3a SJR juv salmon wet	20,000							1	1	1				2
above normal	15,000							1	1	½				4
below normal	10,000							1	1					6
dry	7,000							1	½					8
critical	5,000							1						10
3b Stockton Ship Channel DO	2,000	1									1	1	1	10
3c San Joaquin Valley Outflows	2,000	1	1	1	1	1	1	1	1	1	1	1	1	10

The 60th percentile flows for the San Joaquin River have been added to Figure C-1 and are shown in Figure C-2 (medium blue area). For the 60th percentile case the flow prescription for above normal water years is applied which specifies 10,000 cfs during April and May in 6 out of 10 years. This peak shows up clearly in Figure C-2 while the minimum 2,000 cfs is maintained in the balance of the months.

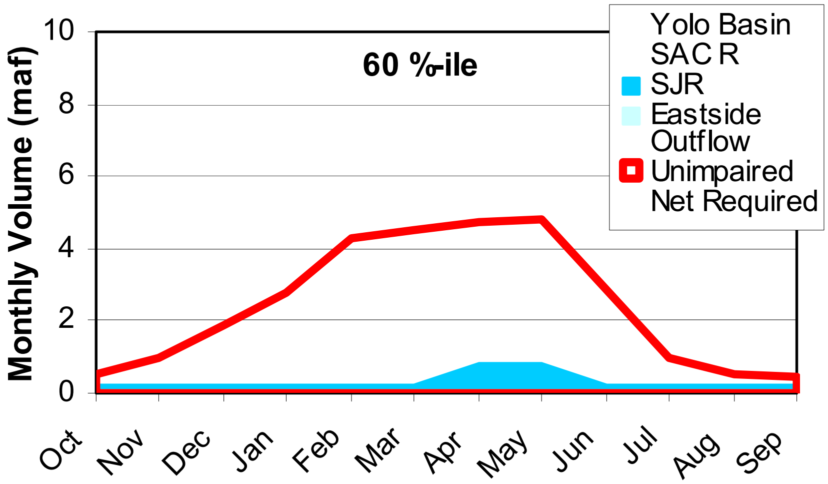

Figure C-2. Sixty percentile flows for the San Joaquin River (medium blue)

Sacramento River

The four prescribed flows for the Sacramento River, shown in Table C-3, are values specified near Freeport flowing into the Delta. In this case the minimum flows, 2d, represent an environmental constraint based on a 10,000 cfs minimum flow to prevent bi-directional tidal flows near a peripheral conveyance intake facility, Figure C-3 in dark blue shade. The flow rate will need to have careful modeling, monitoring and planning to be more accurately determined; and it will no doubt change over time as both natural and anthropogenic changes occur in the Delta and Bay.

Table C-3. Monthly flow prescriptions for the Sacramento River

Prescription	Flow (cfs)	Requirement for each month of water year (10=October)												# Yrs
		10	11	12	1	2	3	4	5	6	7	8	9	
2a SR adult salmon	10000	1	1	1	1	1	1	1	1	1				6
2b Juvenile salmon migration - SR	25000						1	1	1	1				6
2c Adult sturgeon	70,000				1	1	1	1	1					1
2d Min flow past PC intake	10,000	1	1	1	1	1	1	1	1	1	1	1	1	10

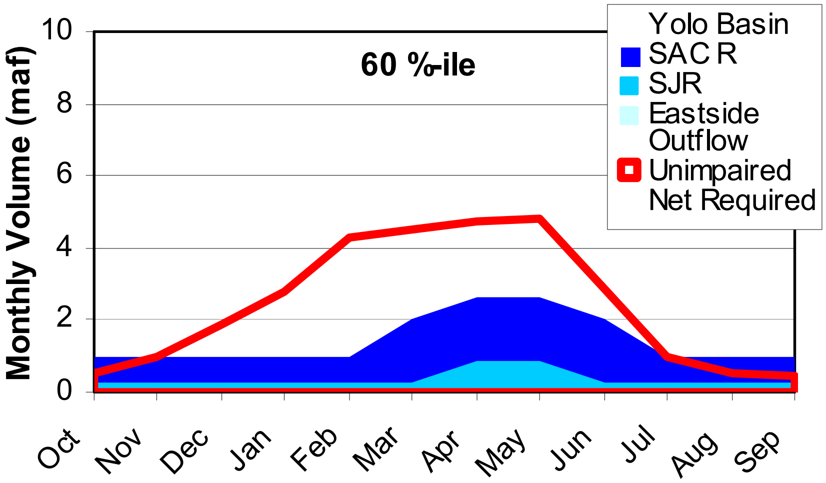

Figure C-3. Sixty percentile flows for the Sacramento River (dark blue)

For the Sacramento River, the 10,000 cfs flow for 9-months of 12 for 6-years of 10 for adult salmon (2a) does not influence the flows because of the environmental constraint. However, the 25,000 cfs flows during 4-months for 6-years of 10 for juvenile salmon (2b) increases the minimum in March through June. It is clearer in Figure C-3 that the Eastside, San Joaquin and Sacramento flows are cumulative.

Yolo Basin

Yolo Basin flow prescriptions (Table C-4) are unique in that they require substantial Sacramento River flows to produce the stages necessary to spill over the weir (yellow area in Figure C-4). The actual flow prescriptions for the Yolo Bypass during February are 2,500 cfs for 8-years of 10 and during March and April 4,000 cfs in 6-years of 10 but approximately 45,750 and 50,100 cfs, respectively, are required at Freeport to produce these spills. The current flows required for the appropriate stage needed to spill the needed flow into the bypass were estimated from regressions. That flow at the weir was then related to the flow at Freeport. It is the estimated Freeport flows are shown for the Yolo Basin flows in Figure C-4 (yellow shade).

Table C-4. Monthly flow prescriptions for the Yolo Basin

Prescription	Flow (cfs)	Requirement for each month of water year (10=October)												# Yrs
		10	11	12	1	2	3	4	5	6	7	8	9	
1a juvenile salmon, adult splittail	2,500[a]					1	1	1						8
1b juvenile salmon, adult splittail	4,000 [b]						1	1						6

[a] [b] requires Sacramento River flows at Freeport of approximately 41,750 and 50,100 cfs, respectively

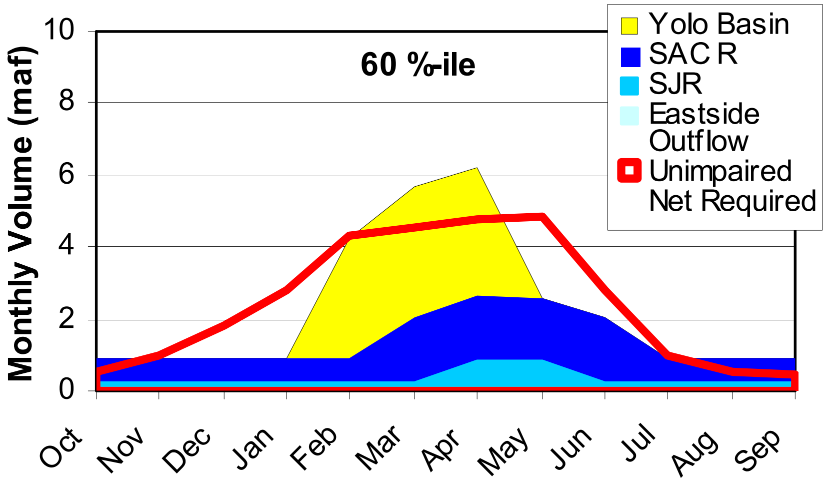

Figure C-4. Sixty percentile flows for the Yolo Basin (yellow)

Outflow Requirements

The outflow prescriptions are presented in Table C-5 and graphed in Figure C-5 by a dark dashed-green line. The flow prescription for Delta smelt is to provide a net Delta outflow of 48,000 cfs for 3 months in 5 years of 10. Other outflow objectives currently available are less causal but likely need to be considered in this type of flow prescription, particularly if exports are still pumped across the Delta. However, in this work, where we only consider peripheral conveyance, the 10,000 cfs minimum flow on the Sacramento River, 2,000 cfs on the San Joaquin River and 1,060 cfs flow on the Eastside Streams will likely provide a sufficient minimum outflow in the absence of through-Delta exports.

Table C-5. Monthly flow prescriptions for net Delta outflow

Prescription	Flow (cfs)	Requirement for each month of water year (10=October)												# Yrs
		10	11	12	1	2	3	4	5	6	7	8	9	
5a Delta smelt	48,000						1	1	1					5
5b Egeria supression	8,000										1	1		3
5c Overbite clam supression	120,000					1	1	1						3

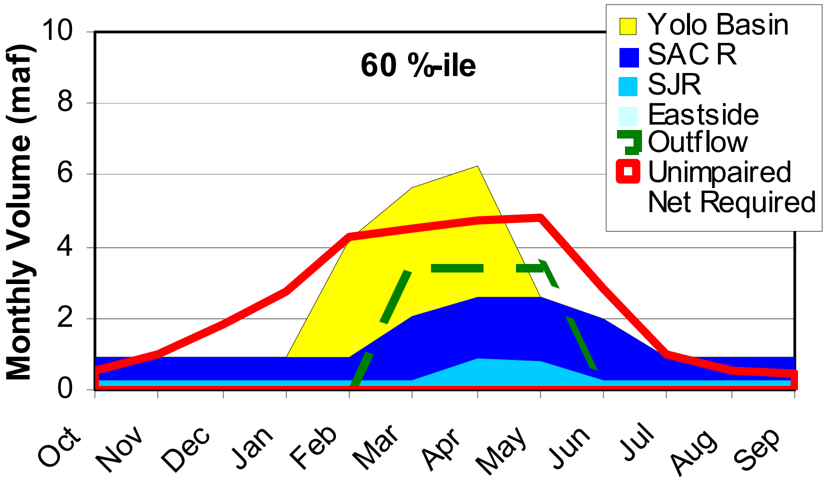

Figure C-5. Sixty percentile flows for the Net Delta Outflow (dark dashed-green)

Required Flow

The net required flow in Figure C-6 (light solid-green) is determined by the maximum of the prescribed inflow and the prescribed outflow. It can be seen that March through May is determined by outflows while the remainder of the year by the inflows. The maximum inflow is the sum of total prescribed inflows and only the smaller Yolo Basin spill flow. The Yolo Basin flow on the graph is the higher total flow needed in the Sacramento River at Freeport to produce the small Yolo Basin flows. The Yolo Basin flow (yellow shaded area) exceeding the net required flows should be available for export. It demonstrates a major management challenge to producing prescriptive flows while providing needed exports. Certainly engineers will find more effective ways to produce the Yolo Basin flows without the high stages that require the high Sacramento River flows.

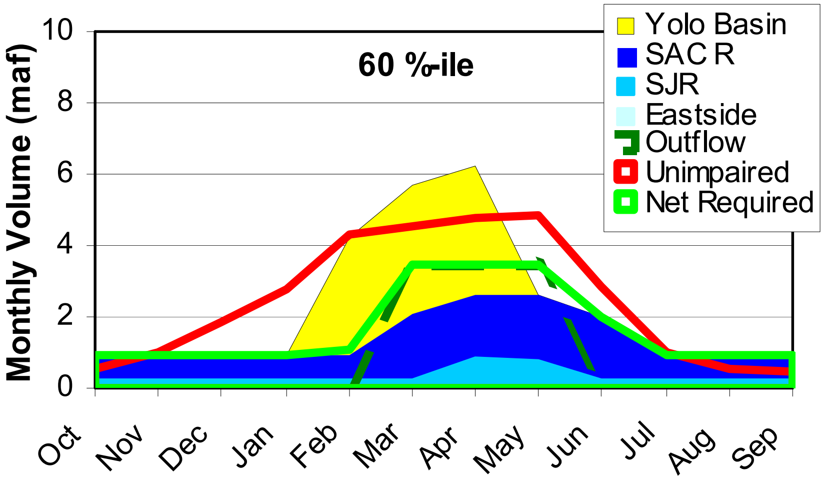

Figure C-6. Sixty percentile flows for the Net Delta flow (light solid-green)

Appendix D – San Joaquin River salinity gradient

In an estuary with the ocean mixing with fresh water from inland, there exists a monotonically increasing salinity gradient from upstream to the sea. A widely held assumption is that, among other gradient cues, salmon smolt follow this increasing gradients to the ocean. For a river system as impaired as the San Joaquin River, where flow velocities have been reduced by impaired flows and greatly increased cross-sectional channel areas, this gradient could be even more important. In the Delta, the southern pumps pulling water down through the Delta also affect the salinity gradient in the San Joaquin River. Although high spatial and temporal resolution salinity data are not available for analysis, model simulations can be used to examine salinity gradients over the model's domain. Salinity along the Sacramento and San Joaquin rivers are shown in Figure D-1 for May 20, 2000. While salinity in the Sacramento River increases steadily toward the ocean, the San Joaquin River displays over 60 kilometers of adverse gradient (highlighted with red background).

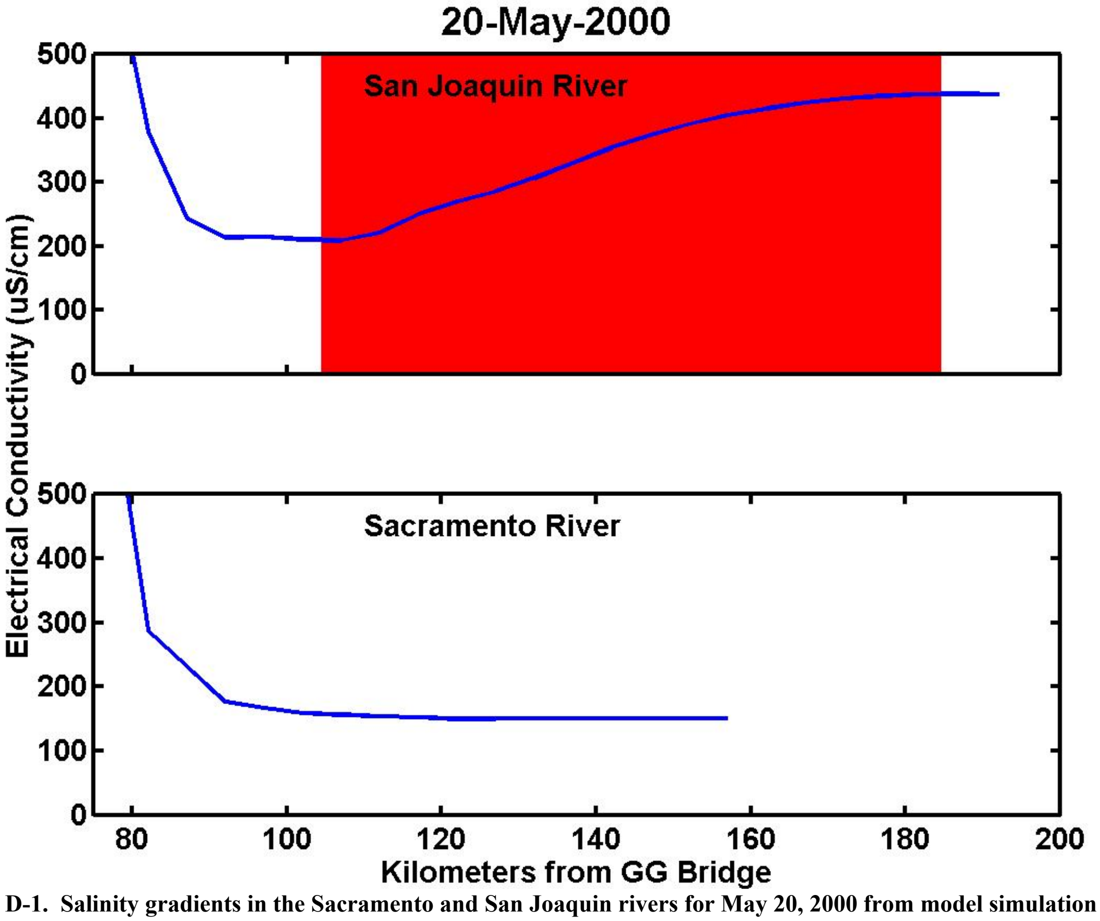

Figure D-1. Salinity gradients in the Sacramento and San Joaquin rivers for May 20, 2000 from model simulation of historical boundary conditions.

Additional analysis was made of modeling work that simulated water years 1981-2000 for historical conditions and compared with simulations of unimpaired flows. Figure D-2 compares these two operational differences over the same period. Unimpaired flow results produce a gradual increase in the salinity form upstream to the confluence of both rivers. Only the Sacramento River produces the increase in salinity for historical conditions. Unimpaired flows also demonstrate that the salinity is pushed farther toward the sea producing a fresher western Delta.

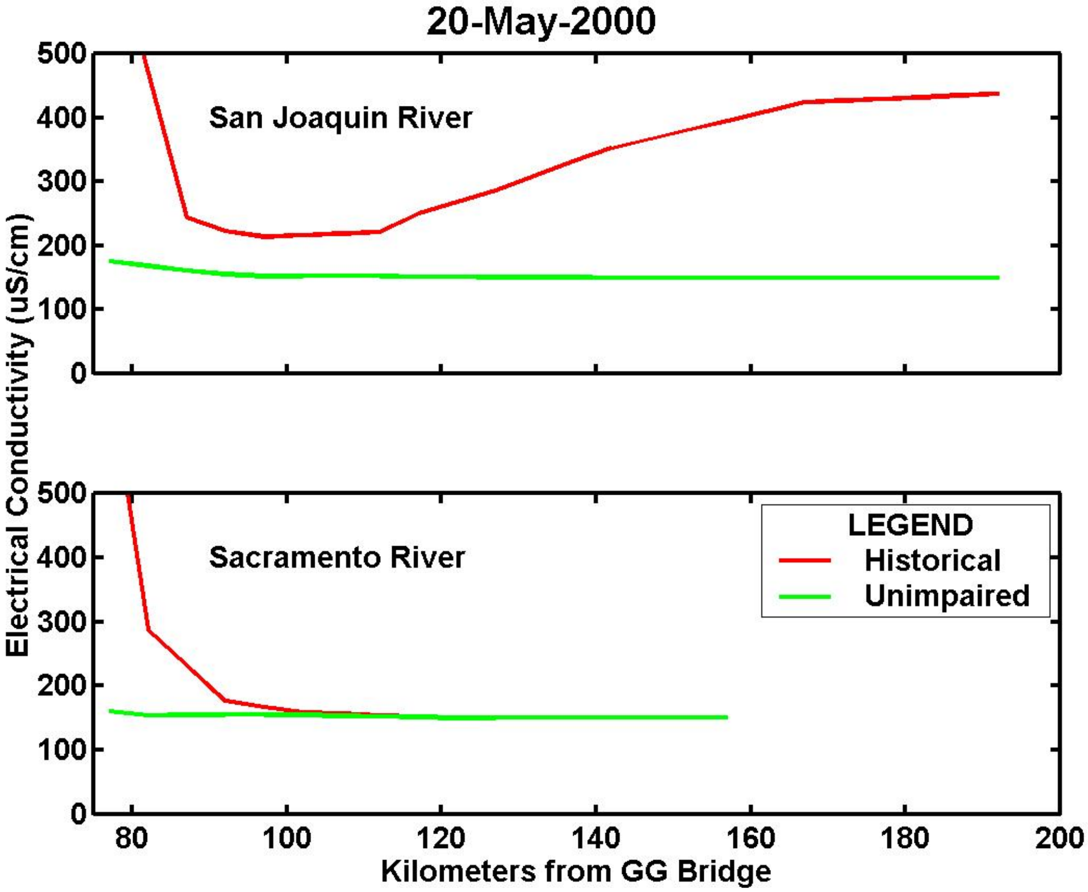

Figure D-1. Salinity gradients in the Sacramento and San Joaquin rivers for May 20, 2000 from model simulation of historical boundary conditions compared to unimpaired flows.

Appendix E – Preliminary Annual Flow Volumes for Functions and Locations

Table E-1. Preliminary Annual Flow Volumes for Functions and Locations

Category	Item	Junction		Average flow (taf/yr)
1. Yolo Bypass Flooding	a	juvenile salmon, adult splittail most years		362
	b	juvenile salmon, adult splittail pulses		288
		Sacramento Weir flows hydraulically needed to provide Yolo Bypass flows a & b		Est[1]
2. Sacramento River	a	Adult salmon migration		3,260 Est[1]
	b	Juvenile salmon migration		3,623
	c	Adult sturgeon		2,113
	d	Minimum flow past a peripheral conveyance intake		7,245
3. San Joaquin River	a	Juvenile salmon	wet	1,140 Est[1]
			above normal	960
			below normal	660
			dry	444
			critical	300
	b	Stockton Ship Channel DO		483[2]
	c	San Joaquin Valley Outflows		1,449
4. Eastside Streams	a	Mokelumne River flows		145 Est[1]
	b	Eastside Stream minimum flows		691
5. Net Delta Outflows	a	Delta smelt flows		4,347
	b	Egeria suppression by reducing outflows		290
	c	Overbite clam suppression by increasing flows		6,521
6. Other	a	Suisun Marsh flows		Est[1]
	b	Close or Limit exports		Est[1]
7. Safety Factor	a	Greater certainty of adequate flows		20%[3]

[1] More reliable estimates are sought for these flow requirements. Documented estimates have not yet been found for these flow functions. For accumulation purposes at this level of development, it is believed that other flows for this inflow (for instance, minimum flows past a peripheral conveyance intake for the Sacramento River) were adequate to meet the minimum requirements.

[2] Flow is covered by the outflow requirement of 3c

[3] We are unlikely to have identified all functions with this initial effort, nor estimated flow requirements for all functions without uncertainty. A safety factor is later applied to these values to address some of these uncertainties.

Table E-1 includes 10-year averages (taf/yr) of the prescribed flow calculated as follows:

$$\left(\frac{2500\,ft^3}{\sec}\right)\left(\frac{86400\sec}{day}\right)\left(\frac{af}{43560\,ft^3}\right)\left(\frac{30.44\,days}{mo}\right)\left(\frac{3mo}{yr}\right)\left(\frac{8\,yr}{10\,yr}\right)\left(\frac{taf}{1000af}\right)=362taf\,/\,yr$$