Public Comment
Bay-Delta Phase II Working Draft Report
Deadline: 12/16/16 12:00 noon

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Will Increasing Outflow in the Summer Increase Delta Smelt Survival?

December 15, 2016

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ABSTRACT

Correlations between summer to fall survival of Delta smelt with flow and X2 are examined. It is found that because X2 and flow are both autocorrelated, one cannot draw conclusions that increasing flow in just summer months will significantly improve survival. Further, it is found that apparent correlations are driven by a few wet years, and there are no significant correlations in non-wet years. There is a similar result when one examines the 20 mm smelt index with prior fall X2: the correlations are driven by a few back-to-back wet years. It is found that it will be difficult to design an experiment involving increased summer or fall flows that provides a measurable result.

A recent paper from the California Department of Fish and Wildlife (CDFW) examines summer survival of Delta smelt, as measured by the ratio of the Fall Midwater Trawl Delta smelt index and the Summer Townet Survey Delta smelt index, as it relates to summer outflow in the Sacramento-San Joaquin Delta. This paper expands upon that analysis and shows the autocorrelation of outflow and X2, and the correlations of outflow and X2 with seasonal runoff indices (which are measures of the amount of runoff available to the system) are strong.

Some survival correlations found in the CDFW paper for the period 2002-2014 are in fact valid for the longer period 1992-2014. At the same time, summer survival is well correlated with runoff indices, and correlations between survival of Delta smelt and outflow or X2 are not limited to summer months. Similar correlations exist with runoff indices as well. These correlations are driven by a few years with high runoff (wetter years), while in drier years the correlations are weak or non-existent, suggesting a threshold effect. The same is true for the relationship between the 20 mm index and average fall X2. Because of the correlations between summer outflow and runoff indices (and summer outflow and spring outflow or spring X2), the apparent relationship between summer outflow and survival may simply be a manifestation of the spring X2 relationship to Delta smelt population, previously established.

A potential mechanism for the relationship of runoff to summer survival is discussed. The years in which survival is strongest (that is, those wet years that drive the correlations) are years in which the western Delta and Suisun Bay are fresh for extended periods in the spring. The data show that wet years (when runoff far exceeds the ability of reservoirs and diversion pumps to control flows) are good for smelt populations; in drier years, other factors control, and population and survival show no apparent relationship to outflow or runoff.

From the data examined, one cannot conclude that increasing summer outflow by itself will significantly improve summer Delta smelt survival, as the wet conditions that create the apparent correlation between survival and outflow are not isolated to summer; those high runoff years create an ensemble of wet conditions over winter, spring and summer. Similar conclusions can be drawn for fall X2 and subsequent 20 mm index for Delta smelt except that the drivers for the apparent correlation are a few back-to-back wet years. The data suggest a threshold effect: only

when flows are large enough to result in significant freshening of Suisun Bay for an extended period do smelt populations and survival significantly improve. Finally, from the data examined, it appears that it would be very difficult to design an experiment that could be practically accomplished and that would yield a measurable result to test the independent effects of increasing summer or fall outflow (or reducing X2) on Delta smelt summer survival or the 20 mm index.

Acknowledgements

The author thanks Richard Denton, Jay Lund, Jeff Mount, Steve Monismith and Deanna Sereno for reviewing earlier versions of the manuscript and providing very useful comments. Of course, any errors, mistakes, or problems with the analysis in this document are attributable solely to the author.

I. INTRODUCTION

A recent publication[1] (dated 7/8/2016, and referred to here as the CDFW Rationale paper) from the California Department of Fish and Wildlife (CDFW) posited that increasing Delta outflow in summer months would improve Delta smelt survival, as measured by the ratio of the Fall Midwater Trawl (FMWT) smelt index and the Summer Townet Survey (STN) smelt index, hereafter referred to as FMWT/STN (as used in the CDFW Rationale paper). In support of this hypothesis, the CDFW Rationale paper (Figure 4, page 9) provided the following graphs, which show an apparent relationship between mean summer Delta outflow in July, August, and September and FMWT/STN.

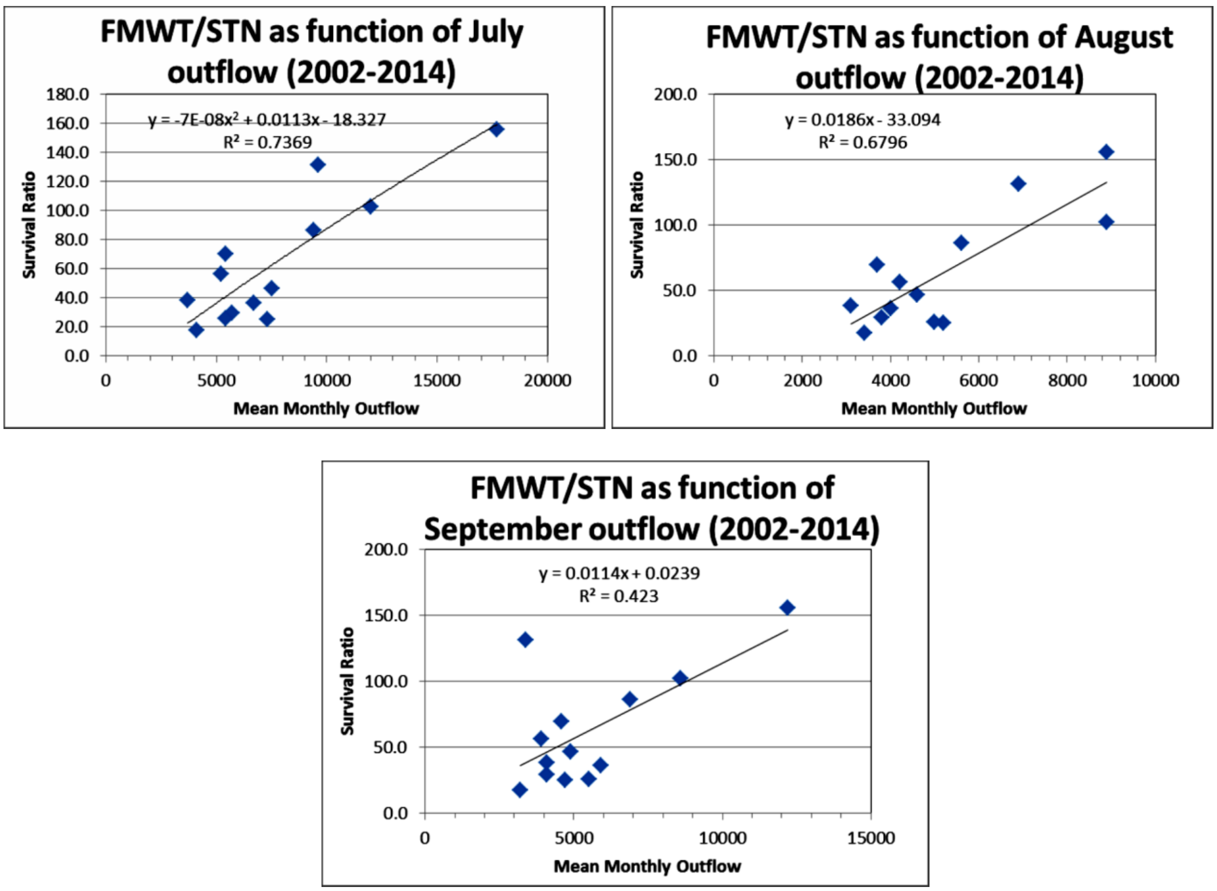

Figure 1. Graphs from the CDFW Rationale paper (Ref. 1), labeled Figure 4, Page 9 in that document, described as "Survival – fall abundance (FMWT) divided by summer abundance (STN) – plotted against a monthly mean outflow (cfs), for July (top left), August (top right) and September (bottom)." The CDFW Rationale paper does not explain why a quadratic fit was used for July, and, given that the coefficient is of the order 10^{-8}, it does not seem necessary.

The CDFW Rationale paper states that strong regressions such as this were only found for data starting in 2002, and that no significant relationship was found for years prior to 2002. However, as described in this paper, such relationships exist for earlier years, including years prior to the listing of Delta smelt in 1993.

Inspection of the CDFW figures replicated in Figure 1 shows the apparent relationship between mean monthly outflow and FMWT/STN survival is driven by 4 points, which are all wet or above normal years, in which outflow from the Delta was high for many months in the spring and summer. As shown later, non-wet (below normal, dry and critical) years exhibit no significant correlation between FMWT/STN and summer outflow (the weak correlations sometimes suggest that less outflow improves survival in those years). This suggests a threshold effect with respect to outflow conditions between wet and non-wet years.

The CDFW Rationale paper does not consider the autocorrelation of Delta outflow. That streamflows are autocorrelated is not a new concept,[2] and when flow is autocorrelated, a correlation between a variable and flow in one period is also likely to be correlated with the flow in a previous or subsequent period. This and its consequences are more fully explored later.

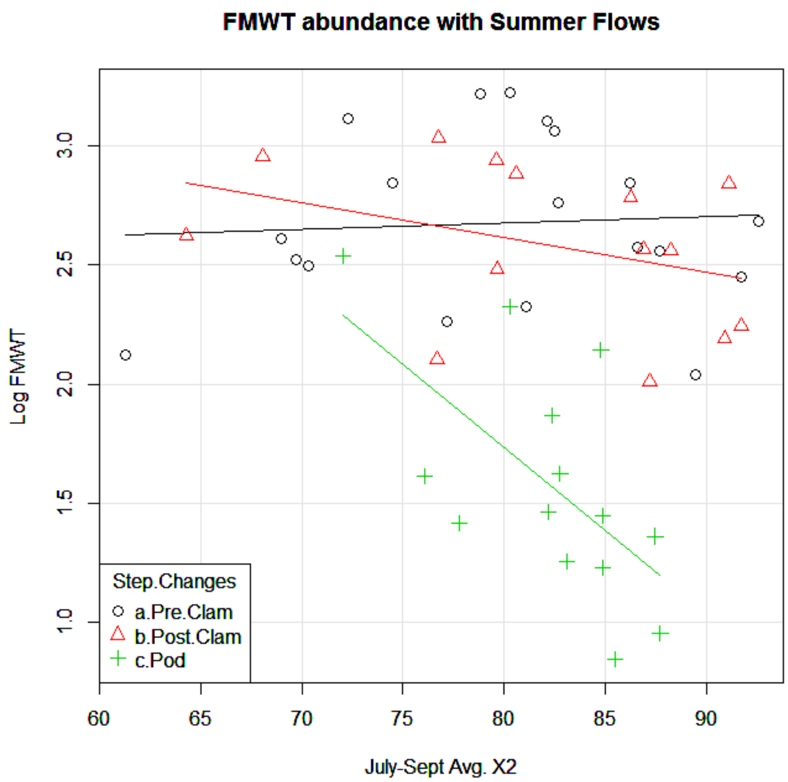

Figure 2. Graph from the CDFW Rationale paper (Ref. 1), labeled Figure 3, Page 8 in that document, described as "Fall Delta Smelt abundance (log_{10} transformed) plotted against a July – September monthly mean X2 for three time periods: pre-clam (1967-1986), post-clam (1987-2015) and POD (2002-2015). Historically, summer flows did not appear to influence fall abundance (step changes a. & b.). However, since 2002 there is a significant ($r_2 = 0.3905$, $p = 0.016$) negative relationship between FMWT and X2 (i.e., more water, more Delta Smelt). Water year 2002 is associated with the start of the Pelagic Organism Decline and represents the approximate start of current ecological regime of the Delta ecosystem (see Baxter et al. 2010)."[3]

In further support of its hypothesis, the CDFW Rationale paper provided Figure 3, on page 8 of that document, reproduced here as Figure 2. Figure 2 shows the log-transformed absolute value of the FMWT index versus average July-September X2 (X2 being a function of prior Delta outflows, and a measure of the location of the 2 ppt salinity line). No rationale is given in the CDFW Rationale paper for using the log-transformed FMWT (that is, why FMWT should be exponentially related to summer averaged X2). Appendix A shows that X2 is related to the log of prior outflows, so this graph would imply that FMWT is a power function of prior Delta outflows for the period after 2002. Often a logarithmic graph is used to give the appearance of less scatter in the data than would be found in a non-transformed graph. It is shown later that 1) using a logarithmic transformation is unnecessary, and that 2) the relationship between X2 and FMWT normalized by the prior year FMWT extends much further back than 2002 (prior to the listing of Delta smelt in 1993). It is also shown that the autocorrelation of outflow and the much stronger autocorrelation of X2, which depends on prior outflows (see Appendix A), precludes attributing the effect of outflow in a single particular time period to FMWT or FMWT/STN with the data at hand: the same correlations will be found with many time periods.

In what follows, autocorrelations and their impacts on the CDFW Rationale paper hypotheses are considered. Other parameters besides mean summer outflow are strongly related to FMWT/STN, including outflow and X2 in other months, and seasonal runoff indices. In addition, an analysis of an expanded data set (beyond 2002-2014) is presented, showing that strong relationships with flow parameters exist back before the time Delta smelt was listed. These relationships are driven by the very high flows that occur in wet and above normal years. A mechanism that fits the data is proposed along with data supporting that mechanism. Finally, the relationship of the 20mm smelt index with prior year fall X2 is considered and discussed in relationship to the proposed mechanism.

II. AUTOCORRELATION OF OUTFLOW AND X2

Streamflows are often strongly autocorrelated. If this is true for Delta outflow, then a parameter correlated with July mean Delta ouflow is likely to be correlated with the outflow in other months, such as June and August. As a consequence of strong autocorrelations, conclusions regarding causality of outflow in a particular month or season become muddled: one cannot tell if it is the monthly outflow, the ensemble of outflows over several months or seasons, or general flow conditions related to the parameter.

Autocorrelations for Delta outflow are examined below. Because the CDFW Rationale paper focused on summer (July, August, and September) Delta outflow, this examination is also focused primarily on those months. The period 1987-2014 was chosen for the regression analyses. This corresponds to the “post-clam” period, subsequent to the invasion of the overbite clam, *Corbula amurensis*, into the Bay-Delta system, and it is the period of focus for other relationships considered in this paper.

Outflow data from 1987 to 2015 were checked for autocorrelation and for 1, 2, 3, and 4 month lags. The respective autocorrelation coefficients are 0.4, 0.15, 0.04, and 0, with the autocorrelation rising again at 11 and 12 months to 0.10 and 0.13, indicating autocorrelation that arises from the annual cycle of outflows. This is fairly typical for streamflows and suggests that outflow correlations should be explored further. Given the strongly seasonal nature of California hydrology with a definite wet period and a long dry period, as well as the fact that flows (and outflow) can be controlled for extended periods with reservoirs and irrigation diversions, it seemed worthwhile to explore the correlation of outflow between particular months (for example, July outflow compared to August outflow).

Table 1 shows coefficients of determination r^2 for mean monthly Delta outflows as correlated to July mean Delta outflow, illustrating the strong correlation of outflow between months.

Table 1
Coefficients of determination r^2 between monthly mean outflow in one month and monthly mean outflow in July
1987-2014

Months	r^2
April	0.42
May	0.66
June	0.86
Aug	0.82
Sept	0.90

Table 1. Coefficients of determination for correlations of mean monthly Delta outflow for various months correlated with July mean outflow. These results show that outflow is highly correlated in the summer months and with months prior to July as well as post-July.

Further evidence of the correlation of outflow is found when other months are considered. For example, monthly mean Delta outflow in June is correlated with mean Delta outflow in April (r^2 of 0.59), May (0.72), August (0.78), and September (0.84).

Because some analyses use X2 as a parameter, X2 was also examined to determine its level of autocorrelation. As discussed in Appendix A, X2 is expected to be autocorrelated, even if outflow were found to be poorly autocorrelated, because the standard formulae for calculating X2 include a linear term with X2 from the prior time period. For the period 1987-2015, X2 was found to be highly autocorrelated. The autocorrelation coefficients for 1, 2, 3, and 4 month lags are 0.75, 0.41, 0.16, and 0.03 respectively. The autocorrelation also rose to 0.05, 0.17, 0.30, and 0.36 at the 9, 10, 11, and 12-month lag periods, also indicating the annual cycle of X2 (which is of course related to outflow). Again, this suggests a look at the correlations of X2 between months in summer with other months.

Table 2 presents monthly X2 coefficients of determination from their correlation with mean July X2, and it is seen that X2 is indeed highly correlated over the period of spring and summer.

Table 2 Coefficients of determination r^2 between monthly mean X2 in one month and monthly mean X2 in July 1987-2014	
Months	r^2
April	0.85
May	0.89
June	0.94
Aug	0.91
Sept	0.90

Table 2. Coefficients of determination r^2 for correlations of mean monthly X2 for various months correlated with July mean X2. The coefficients of determination show that X2 is highly correlated in the summer months and with months prior to July and post-July.

April mean outflow is much less correlated with July mean outflow (r^2 of 0.42) than is April X2 to July X2 (r^2 of 0.85). Inspection of the data indicates this is driven by a few months in the record of exceptionally high April outflow, the logarithmic relationship between X2 and outflow, and the autocorrelation inherent in calculating X2 (see Appendix A). April outflows can be exceptionally high in wet years or just very high, depending upon when the flows arrive in the Delta; consequently, a few exceptionally high April flows can degrade the outflow correlation. X2, however, in its logarithmic relationship, shows less change with outflow (log of 100,000 is 5, and of 50,000 is 4.7), so X2 data is likely to show less scatter and a better correlation between April X2 and subsequent months.

However, Delta outflow is autocorrelated with a lag that extends over a few months, and X2 is even more highly autocorrelated, and both outflow and X2 are highly correlated among the various months in spring and summer. This suggests that outflow in periods outside of the summer are likely to correlate well with FMWT/STN if July outflow correlates well with it. Indeed, this is the case, as mean outflow in May, June, and May-June combined correlate well with FMWT/STN, with coefficients of determination, r^2, of 0.56, 0.59, and 0.61 respectively, for the same 2002-2014 period shown in Figure 1, where the July r^2 is about 0.74 when a quadratic fit is used (although a quadratic fit seems unnecessary). As shown later, correlations extend back to 1992, when smelt populations had their first large decline, just prior to the Delta smelt listing under the Endangered Species Act in 1993.

III. CORRELATION OF OUTFLOW AND X2 WITH RUNOFF INDICES

Because there is a strong correlation among outflows in spring and summer months and average X2 among spring and summer months, it seemed worthwhile to examine correlations of monthly mean outflow and X2 with seasonal runoff indices. The Sacramento Valley River Runoff for April through July (referred to as the April-July runoff index or A-JI, although it is not an index *per se*) is quantified annually as the runoff (in millions of acre-feet, or MAF) above the major dams in the Sacramento, Feather, American, and Yuba Rivers from April through July. The A-JI and Delta outflow are not entirely independent, but neither are they directly proportional in the months of April through July. Delta outflow volume in these months is the A-JI less the change in reservoir storage (which can be positive or negative), less the consumptive use along the rivers (substantial in these months), less in-Delta consumptive use (*ca*. 0.25 MAF in July), less Delta exports (*ca*. 0.5 MAF in July), plus other accretions and depletions between the dams and Chipps Island in the Delta (groundwater, smaller tributaries, urban and agricultural waste discharges, etc.). Consequently, it is interesting to see the correlation of A-JI and monthly outflow and X2. Table 3 presents the results.

Table 3
Coefficients of determination r^2 between monthly mean outflow or mean X2 and the April-July runoff index
1987-2014

Months	Outflow r^2	X2 r^2
April	0.74	0.82
May	0.88	0.86
June	0.80	0.91
July	0.68	0.86
Aug	0.60	0.75
Sept	0.63	0.72

Table 3. Coefficients of determination r^2 for correlations of mean monthly Delta outflow and mean monthly X2 for various months correlated with the April-July runoff index (A-JI). These results show that outflow and X2 are highly correlated with the A-JI.

Similarly, the 40-30-30 Sacramento Valley Water Index (referred to as 403030 runoff index), a measure of the water availability in any year, is calculated from 40% of the current A-JI plus 30% of the current water year October-March runoff index (O-MI) and 30% of the prior year 403030 index (a rough measure of potential water availability in storage from the prior year). The 403030 runoff index, which includes runoff many months prior to the spring and summer, is also found to be well correlated with spring and summer Delta outflow as shown in Table 4.

Table 4 Coefficients of determination r^2 between monthly mean outflow or mean X2 and the 403030 runoff index 1987-2014		
Months	Outflow r^2	X2 r^2
April	0.67	0.87
May	0.75	0.86
June	0.65	0.80
July	0.69	0.85
Aug	0.71	0.87
Sept	0.54	0.75

Table 4. Coefficients of determination for correlations of mean monthly Delta outflow and mean monthly X2 for various months correlated with the 403030 runoff index. These results show that outflow and X2 are well correlated with the 403030 runoff index.

The fact that the 403030 runoff index is used to determine minimum Delta outflow from July through the fall under Water Right Decision 1641 might explain some of the high correlations with monthly outflows in this period. From April through June, the minimum outflow is driven by the X2 standard, and that in turn is calculated from the previous month's hydrology—a factor in determining the 403030 and A-JI indices—which might explain some of the high correlations as well. However, the minimum outflow requirements from July through the following January are step functions, with the same value for many year types (for example, September is 3000 cfs for all year types; August is 4000 cfs for wet, above normal, and below normal years; for October the minimum is 4000 and for November through December the minimum is 4500 cfs for all year types except critically dry, when it is 3000 cfs). If the system is operated to the minimum, this would make a correlation with the 403030 rather poor for many of these months, since the minimum is the same for a wide range of the 403030 index. On the other hand, in above normal and wet years, outflow is often well above the minimum requirements, and varies more in step with the hydrology, which helps create the strong correlation.

The strong correlation of A-JI and 403030 indices with mean monthly outflow and X2 should not be surprising. There is a distinct connection between the A-JI and Delta outflow for April through July, and an important component of the 403030 index is the A-JI. However, the correlation extends beyond the April through July months, and that correlation suggests strongly that if outflow or X2 in any month (summer or otherwise) is found to be correlated with a parameter such as FMWT/STN, other months (not just summer) and the seasonal runoff indices themselves might be strongly correlated with the same parameter. If this is the case (and it is, as illustrated in the next section), then sorting out if a particular time frame is more important than others for survival becomes very difficult.

IV. CORRELATION OF OUTFLOW, X2 AND RUNOFF INDICES WITH FMWT/STN AND FMWT

The CDFW paper focused on the 2002-2014 time-frame. That paper argued that this time frame corresponds to the Pelagic Organism Decline (POD) and that other periods were not found to have a significant correlation between survival and summer outflow. The following analysis starts with the 2002-2014 time-frame, and builds on the previous sections regarding correlations of outflow and X2 among spring and summer months and their respective correlations with runoff indices. Then, the 1987-2014 period is examined, and finally the time frame 1992-present is analyzed: this period starts with the sudden decline in the 1992 FMWT for Delta smelt, immediately followed by the ESA listing in 1993, and the Delta Accord in 1994.

IV.A 2002-2014, FMWT/STN as It Relates to Outflow, X2, and Runoff Indices

The data in Figure 1 (reproduced from Figure 4 in the CDFW Rationale paper) show that there is a strong correlation between the survival of Delta smelt from summer to fall (as measured by FMWT/STN) and the monthly averaged outflows in the summer. The September correlation is weaker than the July and August correlations, largely driven by the shift in one point (an above normal year) where FMWT/STN was high but the outflow dropped to near the minimum level (the minimum outflow in September is 3000 cfs in all years). It is instructive to examine correlations of FMWT/STN for this time period further.

Because outflow and X2 are both autocorrelated, a relationship between FMWT/STN and June mean outflow (or X2) is also found and shown in Figure 3, where the trend line has an r^2 of 0.59 for June outflow and 0.63 for June X2 (July X2 is also shown and has an r^2 of 0.67). The relationships seen are quite similar to those found in Figure 1.

Figure 4 shows FMWT/STN plotted against A-JI and the 403030 Index, along with trend lines (the respective r^2 values are 0.59 and 0.53). The same trends are seen in Figures 1, 3, and 4. In all cases, whether the parameter is outflow, X2 or a runoff index, the trend is driven by four points with much higher outflows and values of FMWT/STN than in the other points, and those four points correspond to the only above normal and wet years in the 2002-2014 record.

The drier years (below normal, dry, and critically dry) show no significant correlations with outflow, X2, or runoff index. All coefficients of determination, r^2, are very small (0.1 or less), and the slopes of the trends are also very small in absolute value (and sometimes have a trend that would suggest *less* outflow would increase survival). From Figures 1, 3, and 4, it seems that the trend seen in Figure 1 is not necessarily indicative of a summer phenomenon (*i.e.*, more summer outflow leads to better survival), but rather that wetter years, which tend to have higher outflows for many months, result in better summer to fall survival for Delta smelt.

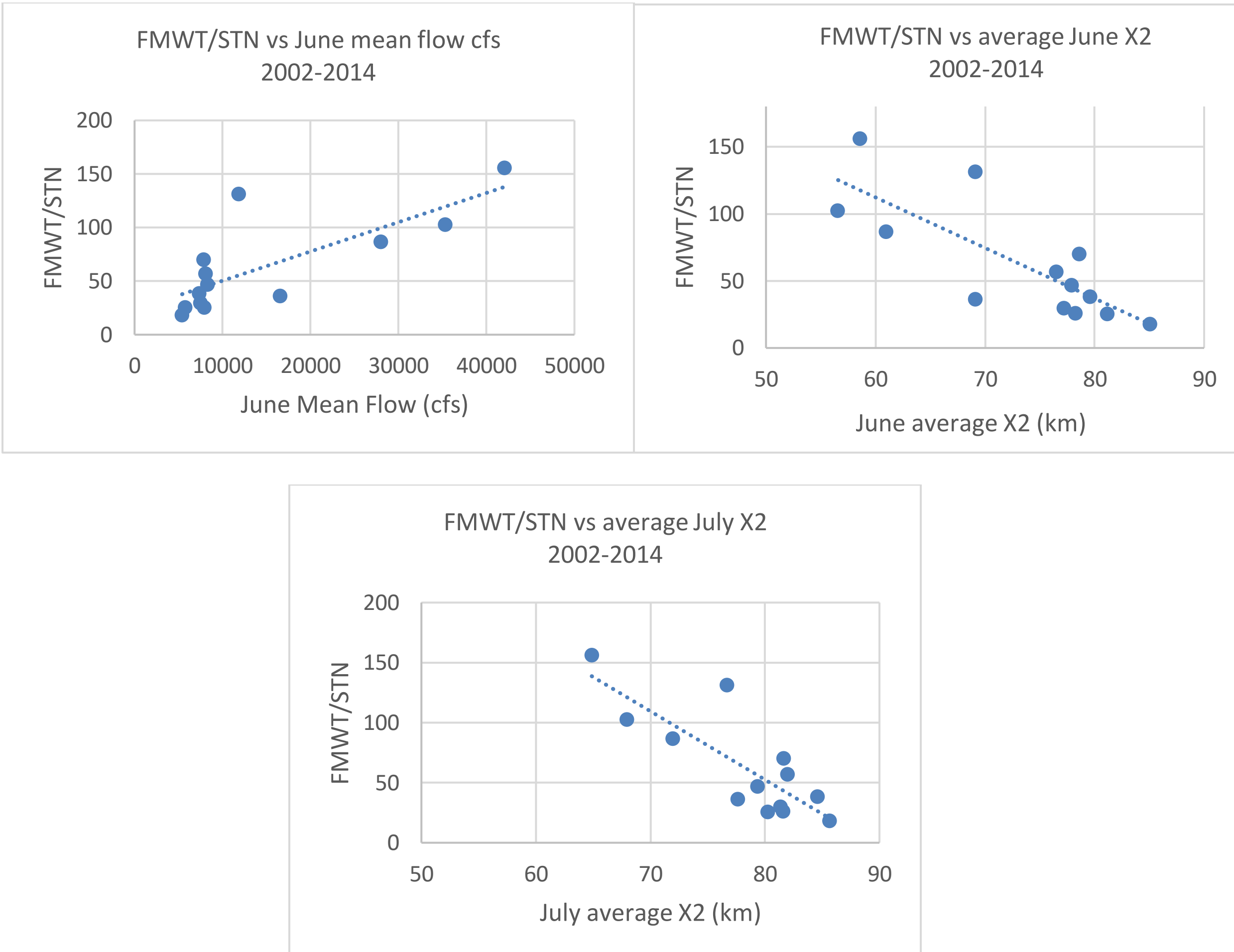

Figure 3. FMWT/STN plotted against: June mean outflow (upper left), June X2 (upper right) and July X2 (bottom). The respective values of r^2 are 0.59, 0.63, and 0.67.

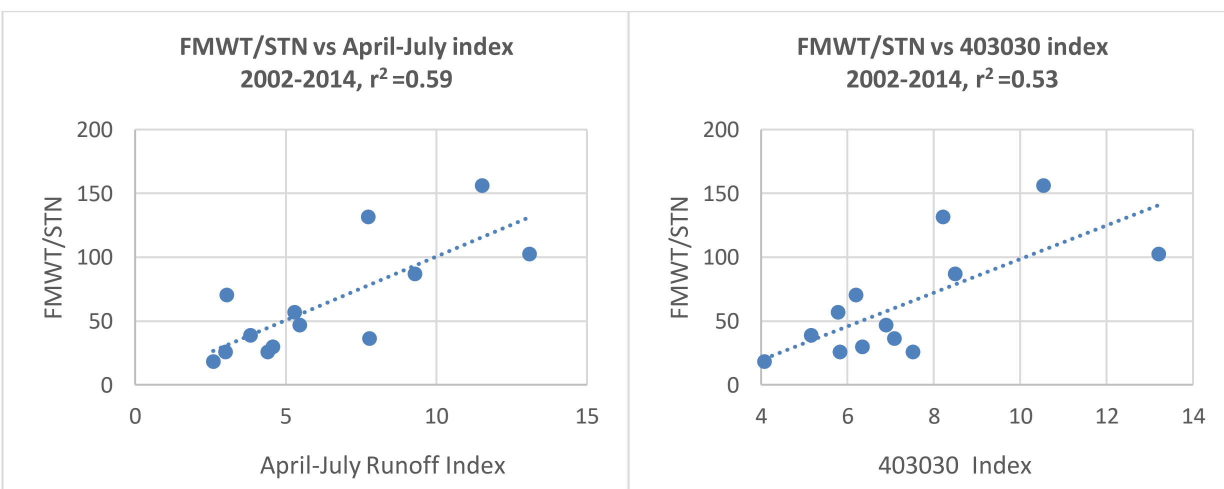

Figure 4. FMWT/STN plotted against the A-JI and the 403030 Index, with trend lines.

The outflows in above normal and wet years in the spring and summer tend to be very much higher than the minimum required outflows. These wetter years are distinguished by large, uncontrolled, or “surplus” flows, as these flows are, very often, beyond the control of usual project operations. In the previous section, the autocorrelation in outflow (and X2) and the correlations of the runoff indices with both outflow and X2 was established, so one expects to see such large outflows, not in isolated months, but over seasons.

While one can hypothesize a relationship between FMWT/STN and the ensemble of outflows (spring and summer) or with general runoff conditions from these data, there is no obvious way to break things apart to a particular month or few months. Just as an example, Figure 3 would indicate that moving X2 in July from 75 to 70 km (an increase in outflow on the order of 6000 cfs) would increase the FMWT/STN from about 80 to 109 (assuming July X2 is causal, and survival follows the trend line). Figure 4 would indicate that increasing the A-JI by 2.9 million acre-feet (MAF) would accomplish the same thing. There is quite a difference between 6000 cfs in a month (or even three summer months, which is about 1.1 MAF) and 2.9 MAF. Given the scatter in the data in Figures 1, 3, and 4, it is difficult to have confidence in the exact outcome of such an action in any particular year: the field data show a trend, but they do not line up on the trend line. The variation of the data around the trend line can be much greater than an incremental increase found in FMWT/STN by moving along the trend line slope.

It was found that adding one year to the record (2001) changed the coefficient of determination r^2 considerably (for example, for July X2, it dropped to 0.3), yet the general trend is still seen in a graph. The question arises: are these trends of survival as measured by FMWT/STN with outflow, X2, and runoff in the spring and summer found only in the post-2002 data, or are they apparent in longer time sequences? This is explored further below.

IV.B 2002-2015, FMWT as It Relates to Outflow, X2, and Runoff Indices

Figure 3 of the CDFW Rationale paper shows the logarithm of FMWT plotted against average July-September X2, showing a potential relationship for the period 2002-2015 (reproduced as Figure 2 in this paper). As one might expect from the discussion above on autocorrelations, relationships with average X2 or runoff indices might also be found. It turns out this is the case, as seen in Figure 5, which shows the log of FMWT plotted against average July through September X2, average April through June X2, and April through July runoff index. Coefficients of determination r^2 for the trend lines shown in the graphs are 0.34, 0.33, and 0.30 respectively.

It is well known that a logarithmic graph can hide data scatter, although in some instances there is a rationale for an exponential relationship between variables. As shown in Appendix A, X2 is proportional to the log of the product of prior outflows (raised to decreasing powers), so use of the log of FMWT would imply some power-law relationship between FMWT and past outflows.

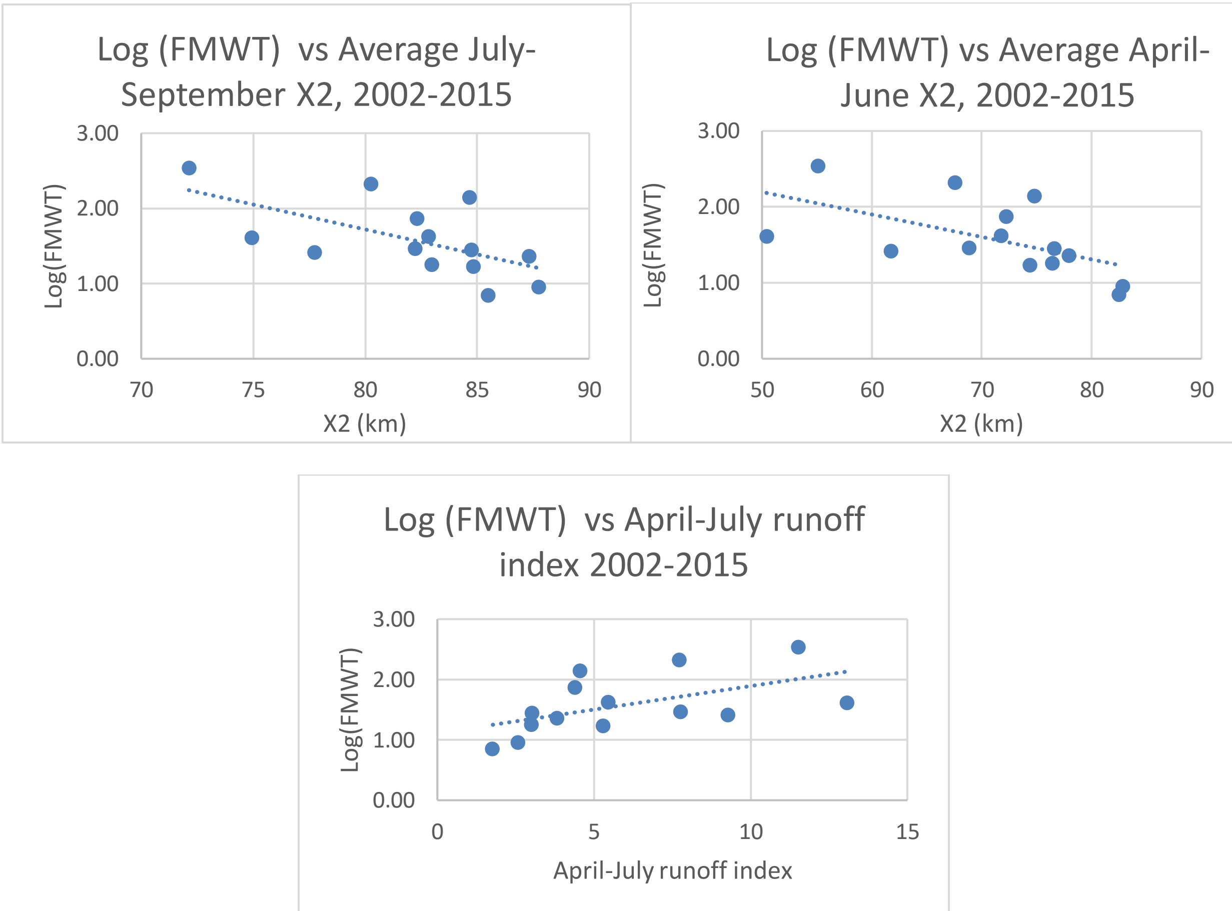

Figure 5. Log(FMWT) plotted against average July through September X2 (left) and against average April through June X2 (right) and the April through July runoff index (A-JI) (bottom). r^2 is 0.34, 0.33, and 0.30 respectively for the trend lines.

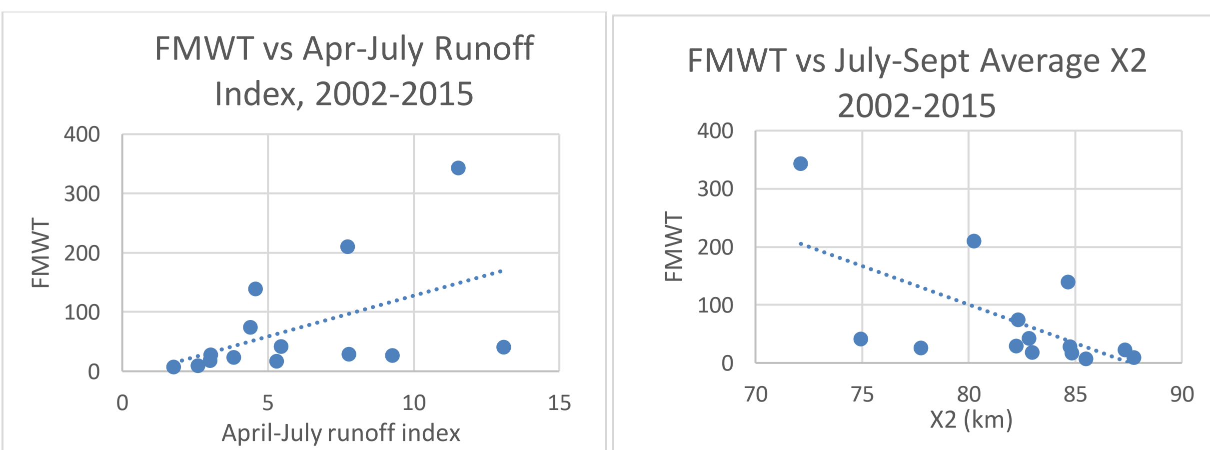

Figure 6. FMWT plotted against A-JI (left) and average July-September X2 (right). r^2 is 0.24 and 0.38 respectively for the trend lines.

To see if a log relationship is needed, Figure 6 shows linear graphs of FMWT plotted against A-JI and average July-September X2, where r^2 for the shown trend lines is 0.24 and 0.38 respectively. Figure 6 obviously shows the variation in data that is not so apparent when using a log transformed variable. In both Figures 5 and 6, the trends are all strongly influenced by the four wetter years, though not to the same extent as was found in the last section for FMWT/STN, as only two years drive the trend for FMWT.

One might wonder why FMWT should be a function only of flow parameters (be they April-July runoff, April-June X2, or July-September X2); one would expect FMWT in one year to be related to the FMWT in the prior year. Furthermore, one might ask if there is there a relationship evident with years prior to 2002. This is explored below.

IV.C FMWT/STN and FMWT as They Relate to Outflow, X2 and Runoff Indices, Starting in 1987 and 1992

It was found that reasonably strong relationships between the FMWT/STN survival indicator and various outflow and runoff-related factors exist for the period 1992-2014 (*i.e.*, the relationships are not limited to 2002-2014). This can be seen in a number of different cases involving outflow and X2 in various months as well as the runoff indices; a few examples are presented in Figure 7. Figure 7 shows FMWT/STN plotted against July average X2, the April-July runoff index, and the 403030 runoff index. The trend lines in the graphs have r^2 values of 0.43, 0.40, and 0.32 respectively. Also noted in the graph are the water year types (wet, above normal, below normal, dry, and critically dry).

As was seen in the limited data set of 2002-2014, the wetter years dominate the trend and give the highest levels of FMWT/STN for the 1992-2014 period (and there are many more wet periods in this record). However, a trend is still not found in the drier years, as seen in Figure 8.

Several conclusions can be drawn from Figures 7 and 8. First, the trend found in Figure 1 (Figure 4 of the CDFW Rationale paper) is not limited to 2002-2014, but extends back as far as 1992. Second, the trend cannot simply be ascribed to a summer outflow trend; rather it is a trend that manifests itself through the amount of runoff in a season, whether measured by the 403030 index or the A-JI. Finally, the trend is driven by wetter years, with no trend seen in the other years, which would suggest a threshold effect related to runoff: in lower runoff years, survival is not obviously dependent on X2, outflow, or runoff index, but is likely driven by other factors. Once above the threshold in runoff, the effects of high runoff become apparent.

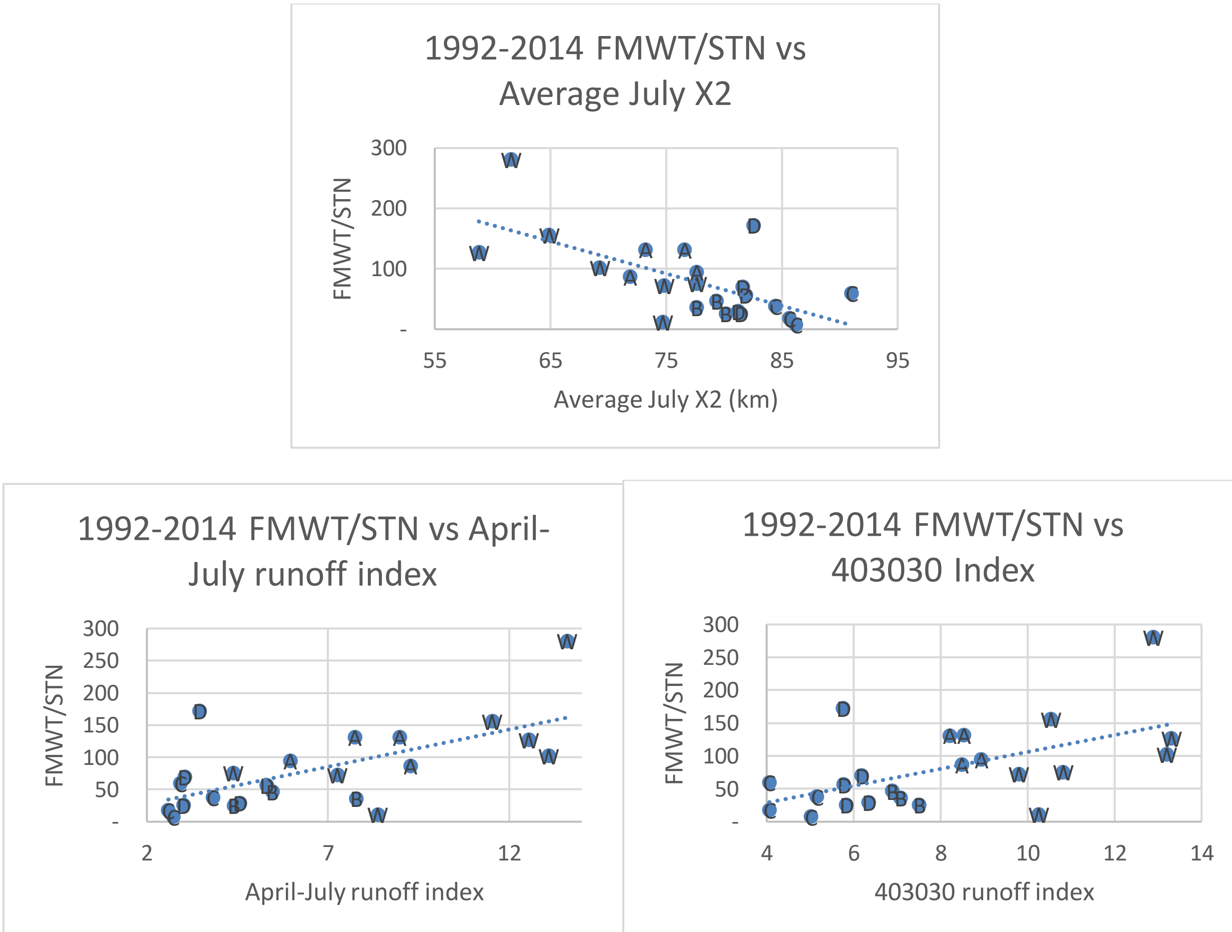

Figure 7. FMWT/STN plotted against average July X2 (top), April-July runoff index (bottom left), and 403030 runoff index (bottom right) for 1992-2014. Letters indicate water year type. r^2 for the trend lines shown is 0.43, 0.40, and 0.32, respectively. The water year types align with the 403030 graph from right to left, since the value of the 403030 index determines the water year type.

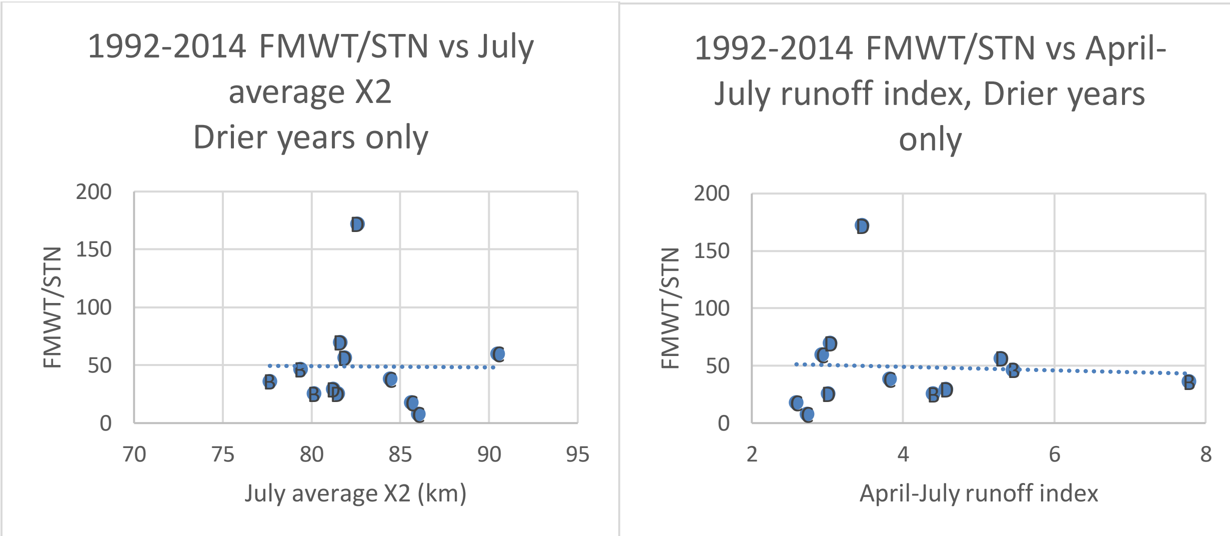

Figure 8. FMWT/STN plotted against July average X2 (left) and April-July runoff index (right) for below normal, dry, and critically dry years, 1992-2014. Trends are not significant ($r^2 < 0.1$).

Finally, a question arises: what happens if one tries to extend this back to 1987, when *Corbula* established a presence in the Delta? This is shown in Figure 9, where FMWT/STN is plotted against July average X2 and A-JI for 1987-2014. There is, in both graphs, a cluster of points for 1987-1991 in an upper quadrant, at the high X2 or low runoff ends of the respective graphs. Why these particular years just prior to 1992 may not fit the trend since 1992 is discussed in more detail later, but this was a period that was very dry, except for two very wet "miracle March" periods in 1989 and 1991 (which resulted in a somewhat extended freshening of the Delta in the early spring), and it was a period when the clam *Corbula* was being established. It has been argued by Kimmerer[4] that the effect of the clam invasion rippled through the ecosystem, and its effects varied and built over several years as the ecosystem responded to the invasion.

Other factors may also be involved. In addition to being a period in which the clams were becoming well established, 1987-1991 was certainly a period with less predation risk[8] than there has been more recently and with an absence of *Microcystis* blooms.

In 1992, there was a large drop in FMWT for Delta smelt, indicating a large population decline. This was after 6 years of drought and at a time after the clam *Corbula* became well established. Listing of Delta smelt came in 1993. After 1991, there appears to be a relationship between FMWT/STN and total runoff, driven by the wettest of years, but the five years just prior to 1992 do not seem to fit the same pattern.

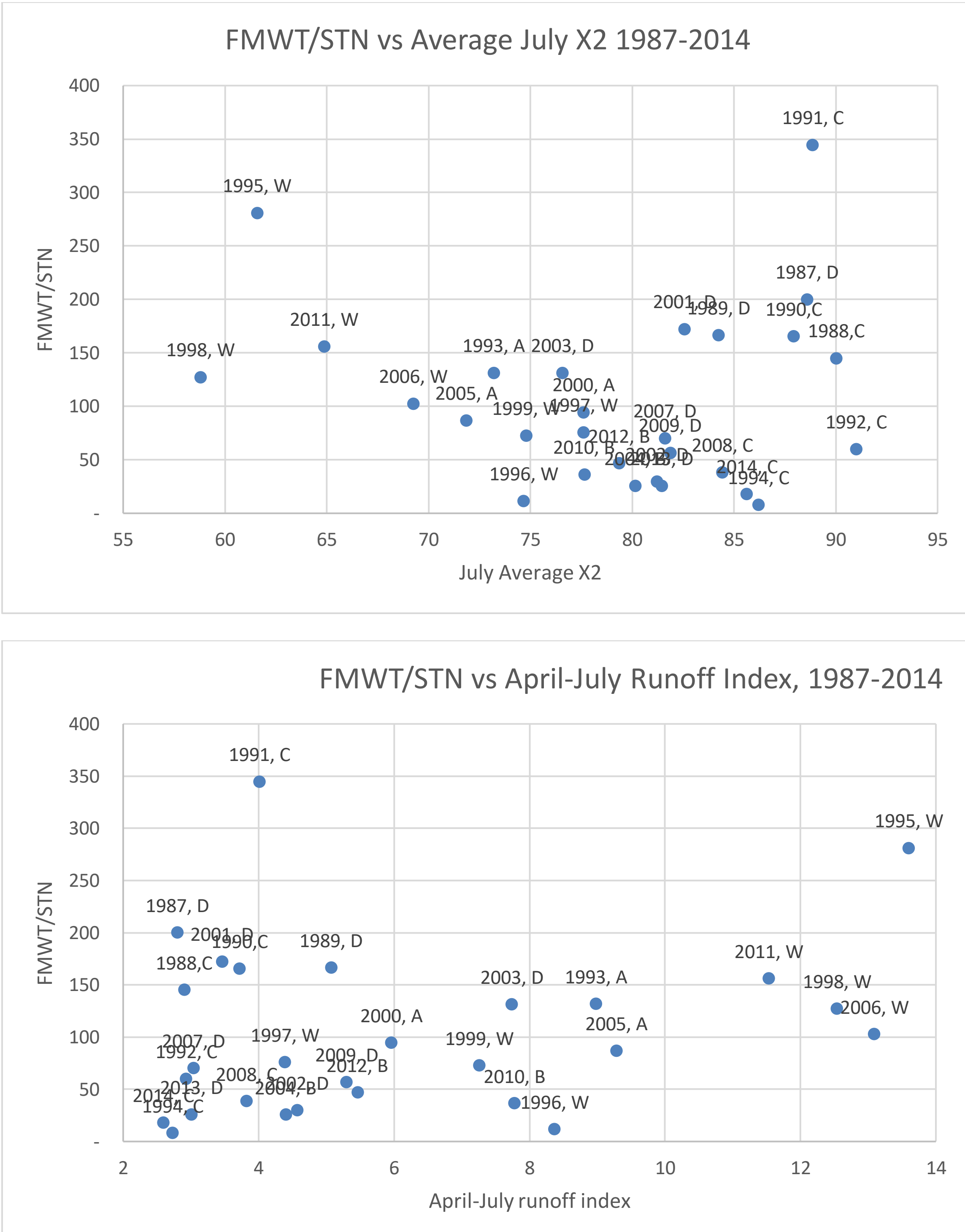

Figure 9. FMWT/STN plotted against July average X2 (top) and April-July runoff index (bottom) for 1987-2014. Data from 1987-1991, all drier years, are found in the upper right quadrant in the top graph, and upper left quadrant in the bottom graph. Years for each data point are indicated, along with letters indicating water year type.

The CDFW Rationale paper also suggested that, for 2002-2015, there is a relationship between the log of FMWT and average July through September X2. It was shown previously that this relationship is seen for other parameters, notably runoff parameters (Figures 5 and 6). A strong relationship is not seen if the data are extended back to 1987 (r^2 on the order of 0.1 or less, with no significance to the correlations). However, one might think that FMWT normalized to its prior year value might be related to the amount of runoff in a year (*i.e.*, the FMWT in one year might be proportional to the FMWT in the prior year, and related to the current year runoff). FMWT normalized to its prior year value is plotted in Figure 10, which shows the data for 1987-2015.

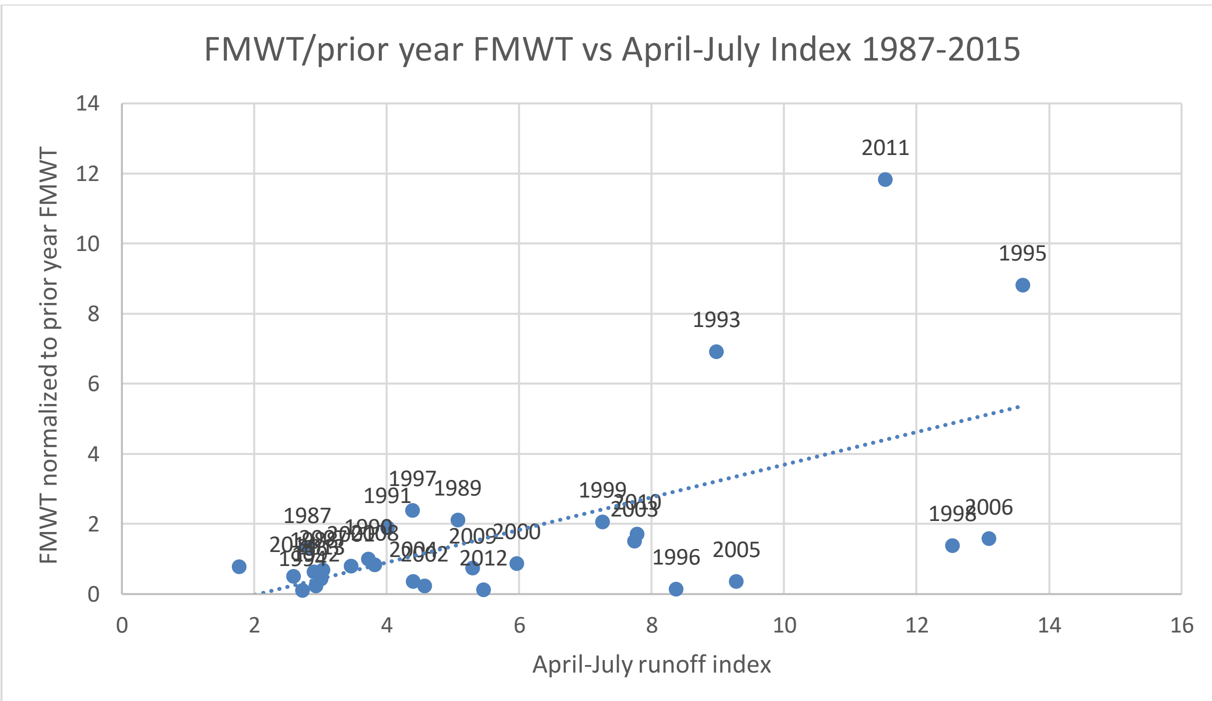

Figure 10. FMWT normalized by the prior year FMWT, plotted against the April-July runoff index. r^2 for the trend line is 0.35, significant at the 0.002 level, but wide scatter is apparent, and the trend is driven by a few wet years. (See Figure 11 for non-wet years only).

The drivers in the apparent trend are a few wet years. If all the wet years are removed, the remaining data show no trend, as seen in Figure 11.

From the data presented in this section, it is apparent that very wet years can result in improved FMWT normalized to the prior year FMWT (though there is a great deal of variation in the data) and a large FMWT/STN response. For non-wet years, the normalized FMWT and FMWT/STN response to outflow level is poor. Even in the wet years, however, there is a great deal of variation, indicating other factors, besides simply runoff, are at play.

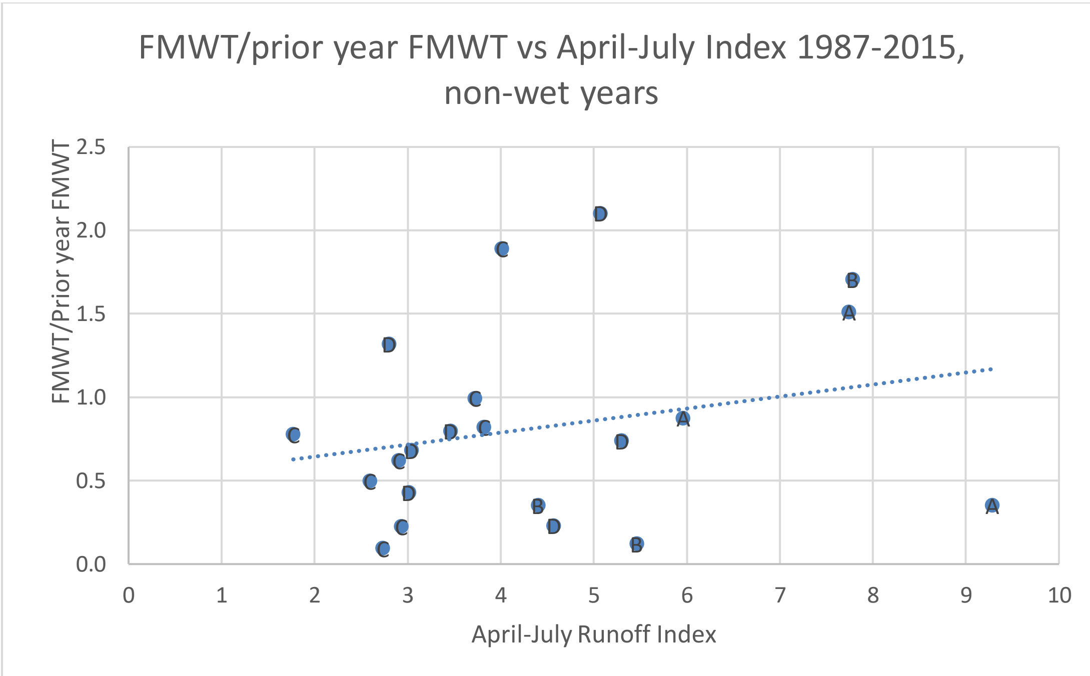

Figure 11. FMWT normalized to the prior year FMWT, plotted against the April-July runoff index, for above normal, below normal, dry, and critically dry years only, 1987-2015. The trend line shown is not significant (r^2 of 0.06).

V. POSSIBLE CONCEPTUAL MECHANISM FOR THE RUNOFF RELATIONSHIPS WITH FMWT AND FMWT/STN

It should be clear that the relationships discussed in the prior sections are driven by years with very large outflows. What is it about these years and outflows that distinguishes them from other years (aside from the magnitude of the outflows)? Inspection of the outflow data reveals that in wet and above normal years, outflows are very often not just above the minimum required outflows but well above the ability of current facilities to control them: the runoff exceeds reservoir capacity, pumping capacity, and water demand, and the resulting outflows are "uncontrolled" or "surplus." This can be seen in Figure 12, which illustrates Delta outflow conditions as classified by the State Water Project Operations Control Office (graph courtesy of Deanna Sereno, Contra Costa Water District[5]). It is clear that wetter years often have "surplus" (excess) outflows that extend from spring well into summer.

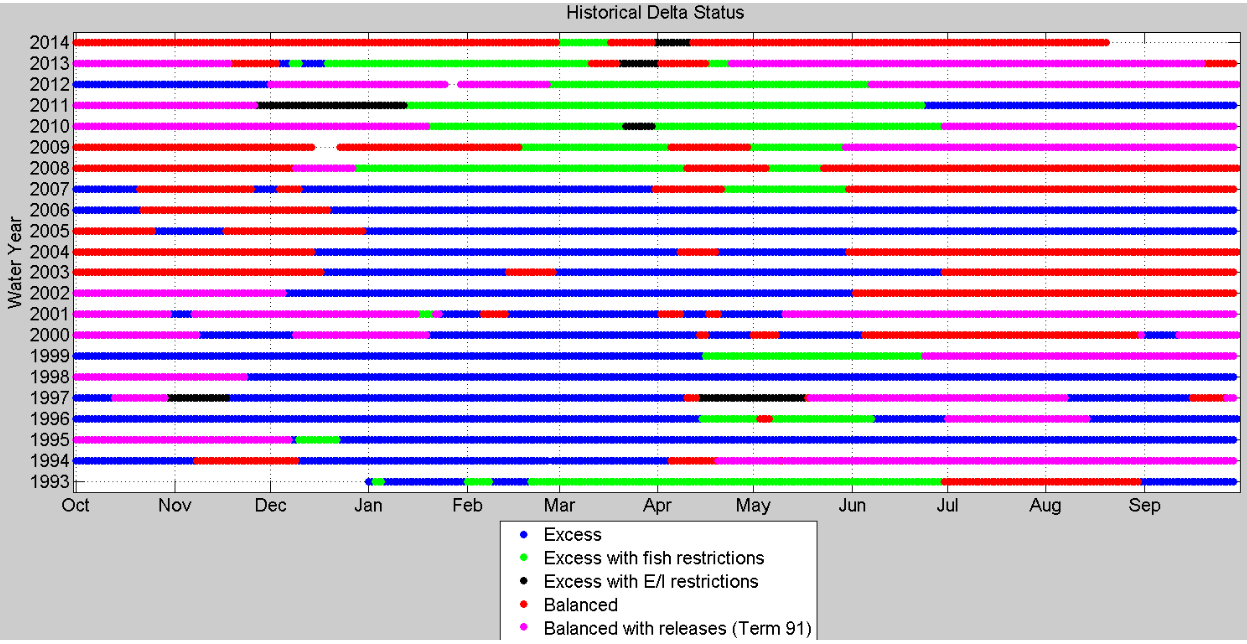

Figure 12. Delta outflow conditions from 1993-2014. Wet years are 1995-1999, 2006, and 2011. Above normal years are 1993, 2000, 2003, and 2005.

A graph from a study of historical Delta salinity levels provides some insight into the differences in the characteristics of wetter and drier years. Figure 13 is reproduced from Figure 3-9 (page 31) of the Contra Costa Water District report "Historical Fresh Water and Salinity Conditions in the western Sacramento-San Joaquin Delta and Suisun Bay."[6] Figure 13 was produced to indicate the change in salinity patterns in the Delta since the beginning of the 20th century. It shows three separate 11-year periods, with similar overall hydrologic conditions (although the sequence of wet and dry years is different, and the two more recent periods actually have somewhat wetter overall hydrological conditions than does the early 20th-century period).

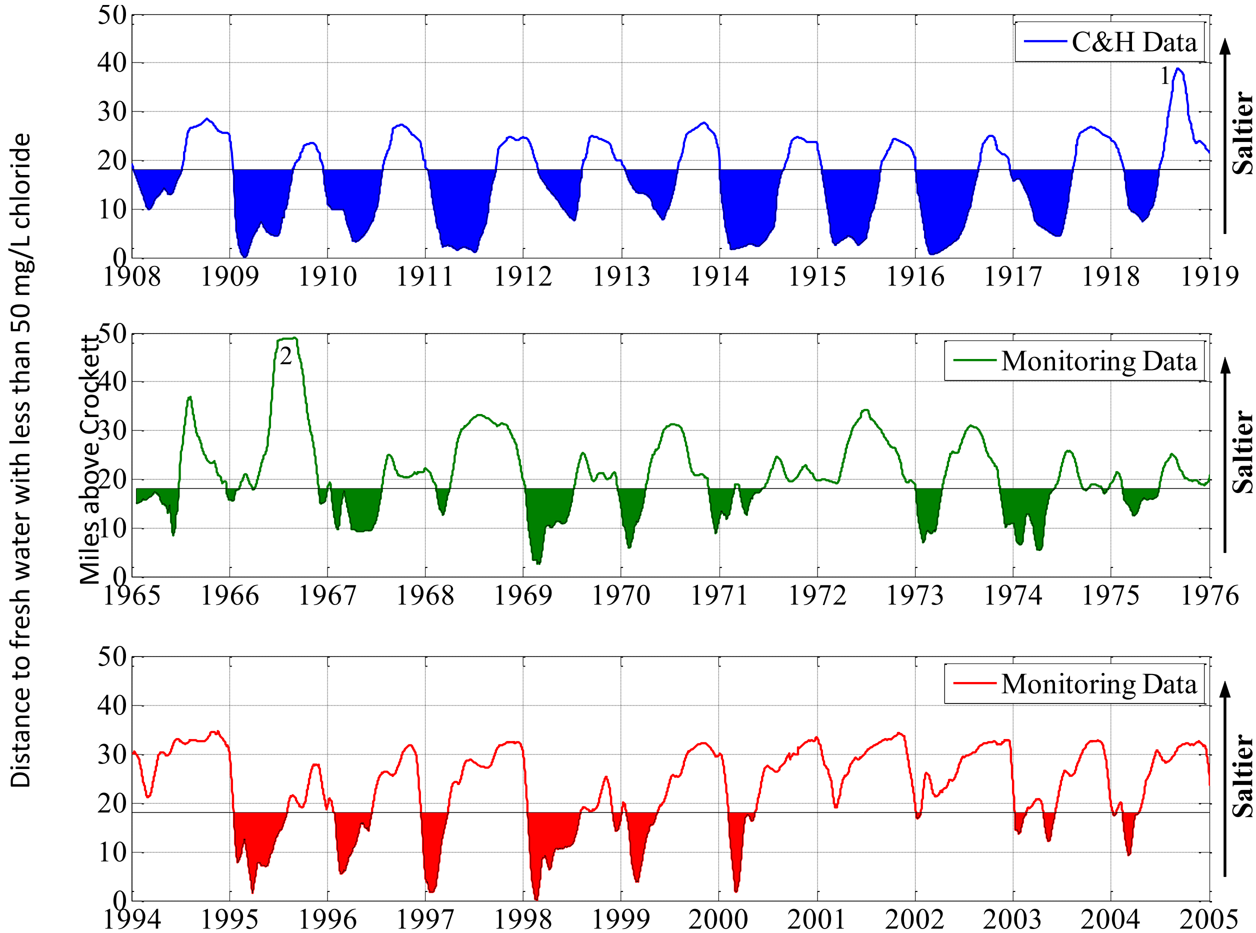

Figure 13. Reproduced from Figure 3-9, page 31 of reference 6, and described in that report as **"Distance to fresh water from Crockett**: Distance to fresh water is defined as the distance in miles upstream of Crockett to water with less than 50 mg/L chloride concentration. The horizontal line, at approximately 18 miles, is the distance from Crockett to the Delta [75 km from the Golden Gate]. The shading represents the spatial extent and duration of the presence of fresh water within Suisun Bay, downstream of the Delta." See reference 6 for data notes.

Figure 13 shows the distance in miles from Crockett in the Carquinez Strait to a point where the surface salinity is about 350 µS/cm (about 50 ppm chloride, or about 0.2 psu, *i.e.*, around the "X0.2" location, but measured in miles from Crockett). The line marking the shading is near Chipps Island, about 18 miles from Crockett, and about 75 km from the Golden Gate. It turns out that X0.2 of 75 km means that X2 is about 62 km, for reference. One notices immediately that even in dry years, Suisun Bay was fresh for a considerable period of time in the early 20th century, prior to the construction of the large dams and the large water diversions upstream of and in the Delta.

However, what this graph shows so remarkably are the conditions in the Delta and Suisun Bay from 1994-2005: the wet years in which the FMWT for Delta smelt greatly increased (the "Pelagic Organism Recovery," years if one might use that term) from 1995 to 2000 were marked by long periods of fresh water and low salinity in Suisun Bay. The Pelagic Organism Decline (POD) period starting in 2002 is distinguished by a lack of fresh water in Suisun Bay.

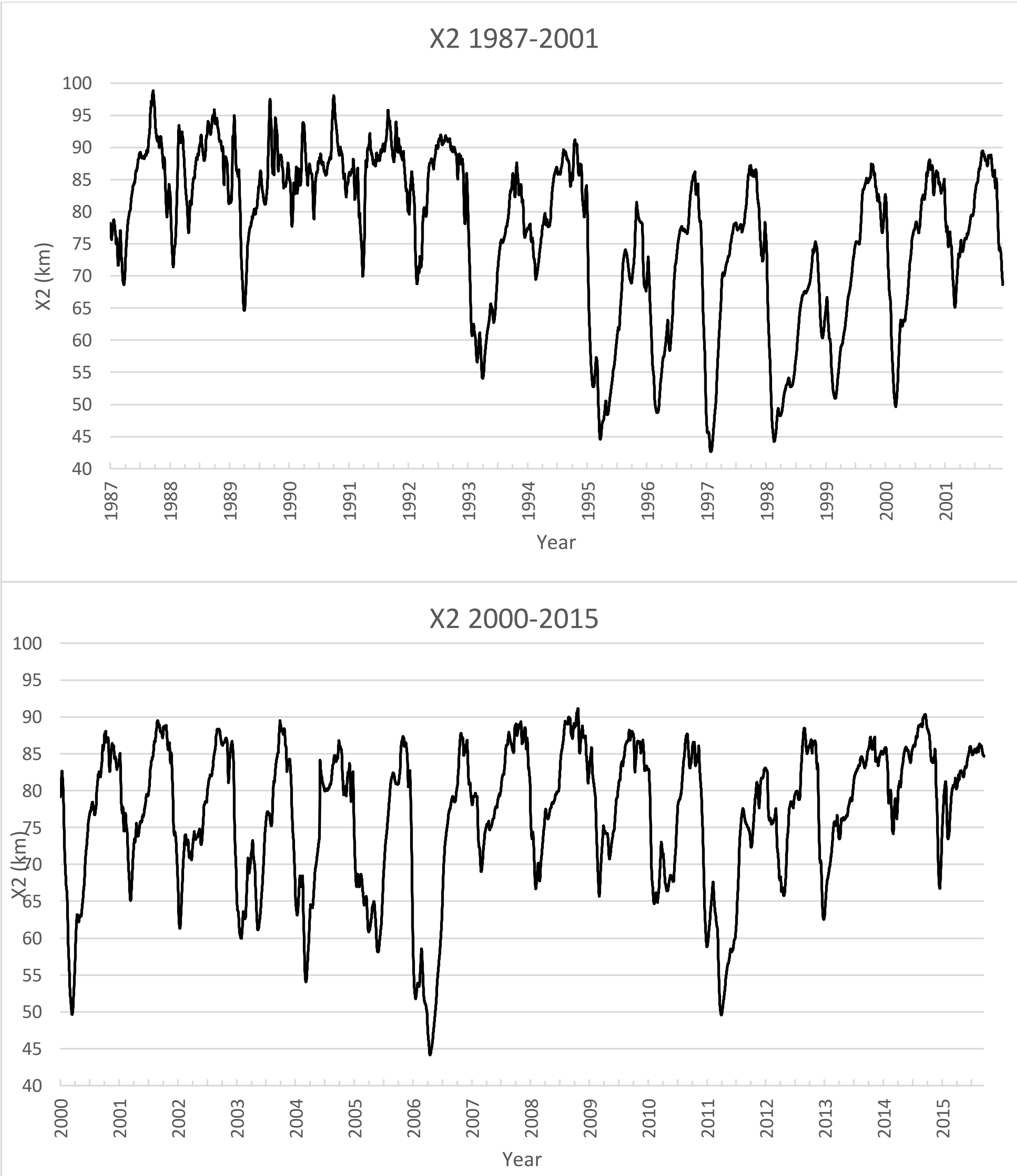

Figure 14. X2 for 1987-2001 (top) and 2000-2015 (bottom). When X2 < 62 km, there is fresh water at Chipps Island (~0.2 psu).

Figure 14 expands upon the data in Figure 13 by showing X2 for 1987-2015. When X2 is less than 62 km, there is very fresh water at Chipps Island (salinity about 0.2 psu). Thus, when X2 is 62 km or less, there is very fresh water in a considerable portion of Suisun Bay and, of course, in the western Delta. The periods when there is considerable fresh water west of Chipps Island in Suisun Bay for several months are exactly the same years which are the drivers for the relationships found between runoff indices (and outflow and X2 as well) with FMWT and FMWT/STN in the last section.

Thompson and Parchaso[7] show data (their Figure 3) that demonstrates, when compared to Figure 14, that the clam population of *Corbula* dramatically drops when fresh water is present in the western Delta and Suisun Bay for significant periods. As described in their paper, reproduction and recruitment of the clam is limited when water is below 2 to 5 ppt salinity. Lower clam abundance would mean reduced competition between smelt and clams for food during these periods (albeit indirect, as clams primarily consume phytoplankton, but there is generally a concurrent drop in food for smelt).

Reduced clam population and improved food supplies are not the only things that come with high runoff periods. Inflows are greatly increased (and since large outflows require large inflows, inflows will also be correlated with normalized FMWT and FMWT/STN). Large inflows dilute pollutants and increase organic loading into the Delta, both dissolved (as any operator of a treatment plant using Delta water knows well) and particulate (including "particles" of large sizes, as any boater who has dodged logs in the Delta during these periods knows as well). Turbidity also greatly increases with high runoff. These are all conditions that can benefit smelt, and they all arrive during wetter periods that are associated with improved FMWT/STN.

On the other hand, in the drier periods there is no apparent relationship of normalized FMWT or FMWT/STN with runoff or outflows, and those periods are characterized by a completely different situation (no freshening of Suisun Bay and the western Delta, low inflow, low outflow). Clearly, factors other than runoff become important during dry years, since FMWT/STN shows no apparent relationship with runoff in drier periods: these are the years that Suisun Bay does not freshen for extended periods (that includes almost all the drier years, with a few exceptions like 1989 and 1991, which had "miracle March" flows). Increasing or decreasing outflows in summer months of those years may be of limited value: increasing X2 could simply put smelt further east, where high temperatures, *Microcystis* blooms, and higher predation reduce survival, and decreasing X2 could move them further west where food production is degraded because of an abundant clam population. Smelt are effectively in a vise in drier years, with little good habitat anywhere. Thus it would appear that there is a reason for the threshold response: if runoff is low, there is no apparent relationship between survival and runoff, as Suisun Bay never freshens and there is no good habitat in the late spring and summer. When runoff is sufficiently high to freshen Suisun Bay for an extended period, clam population declines, inflows bring nutrients and dilute pollutants and a decent habitat becomes available in the western Delta.

Why don't the FMWT/STN data for the 1987-1991 drought period fit in with the trend seen since 1992? Quite possibly, as discussed by Kimmerer[4], the total effects of the clam invasion had not yet completely rippled through the system. X2 was well to the east in those years (with the exception of short periods in the "miracle Marches" of 1989 and 1991), but predation rates were likely much less than they are today (as evidenced by the reduced salvage of largemouth bass and bluegill, which greatly increased starting around 1993, as seen in Reference 8, Page 58, Figure 27), and *Microcystis* blooms were not occurring in the Delta interior, possibly allowing better survival prior to 1992, despite the arrival of clams in 1987. Quite possibly, lower predator populations in the early 1990's, in combination with the *Corbula* invasion, changed the ecological dynamics around 1992, leading to very poor habitat conditions except in the very wet years.

VI. NOTE ON THE RELATIONSHIP OF THE SMELT 20mm INDEX AND PRIOR FALL X2 AVERAGE

The Interagency Ecological Technical Report 90[8] shows a figure (page 159, Figure 81b) relating the log of the 20mm index for Delta smelt with the prior year September through December average X2. This figure is reproduced below, with data from 2014 and 2015 added (Figure 15, upper). Once again, it is not clear why a log relationship is used, as Figure 15 (lower) shows an equally good relationship without resorting to a log transformation (in fact, it is better when the recent years are added).

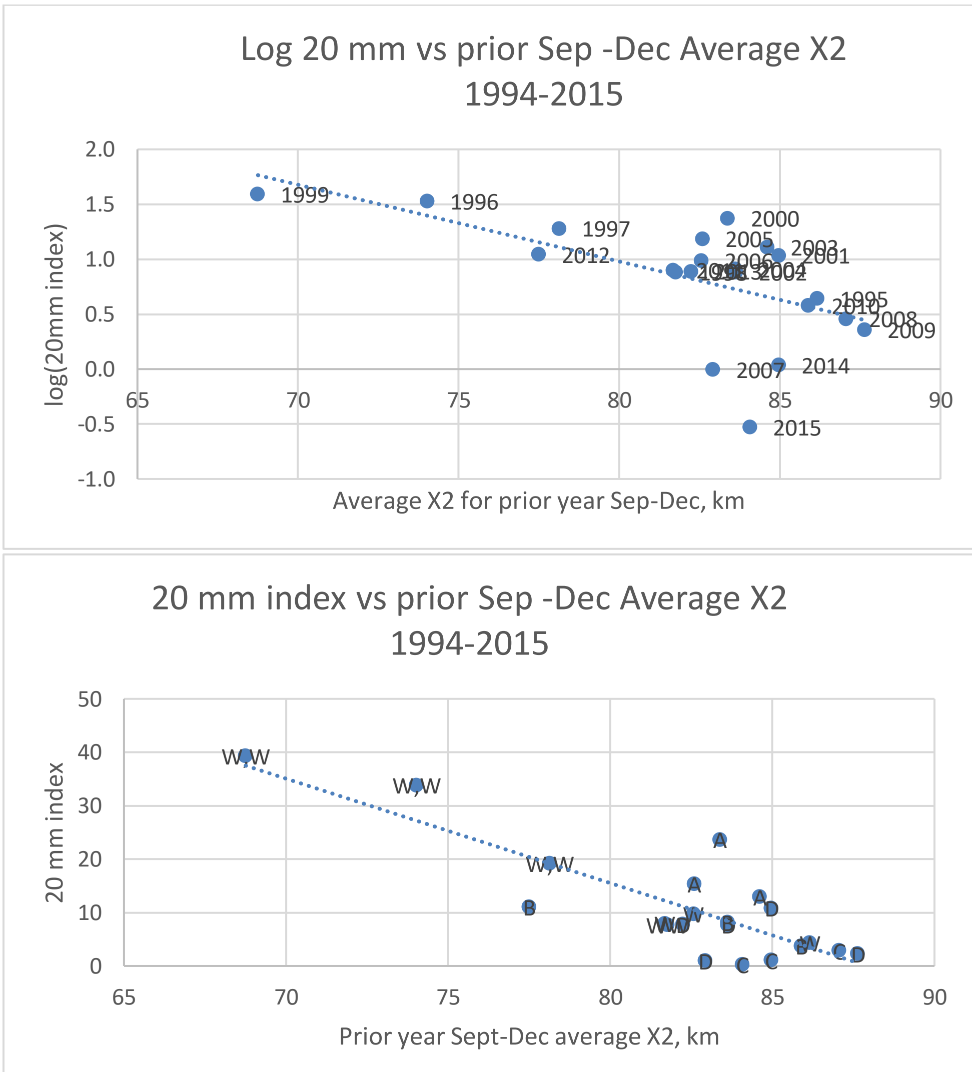

Figure 15. Log (20 mm index), upper graph, and 20 mm index, lower graph, plotted against the prior year September through December average X2. r^2 values are 0.35 and 0.7 respectively. Upper graph includes the year for the 20 mm index, the lower year the water year type.

It is readily apparent from the lower graph in Figure 15 that the trend line is driven by three years, in this case not just wet years, but three wet years that followed wet years (designated W,W). The possibility that this relationship was driven solely by the prior year April-July runoff index was explored (Figure 16). There is more variation in the data than was found in Figure 15.

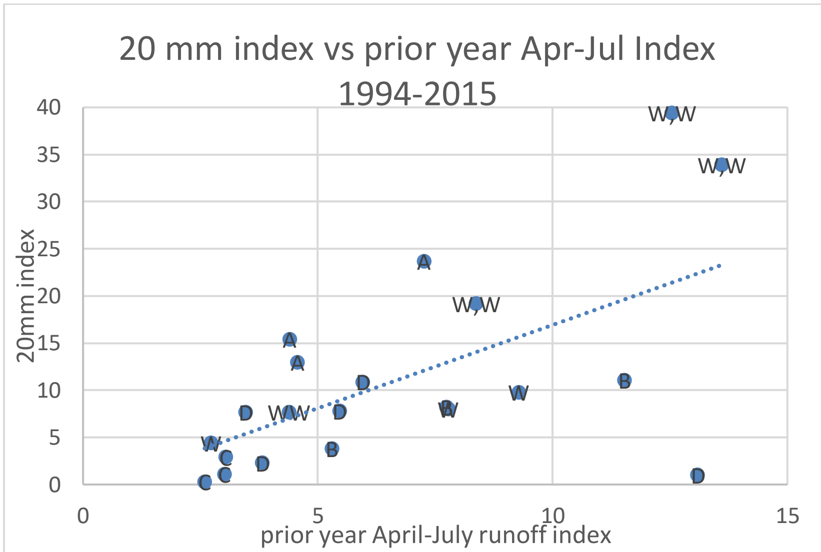

Figure 16. 20 mm index plotted against the prior year A-JI. r^2 for the trend line is 0.37.

Inspection of the data shows that the three years driving the relationship had common characteristics: a high prior year A-JI and high runoff in the late fall or early winter. This possibly suggests that high spring runoff (A-JI) in the prior year leads to a high FMWT/STN and FMWT normalized to prior year FMWT (Figures 7 and 10), and then a large late fall/early winter runoff helps promote a healthy population the following spring. On the other hand, if the back-to-back wet years are removed, there is no significant correlation (r^2 of 0.15 at the $p<0.13$ level), which once again suggests a threshold level effect.

To explore the possibility that the apparent relationship is driven by high runoff in the prior year (leading to a high FMWT/STN), followed by a high runoff the following year, a multivariate regression was done for the 20 mm index as a linear function of the prior year A-JI and the current year October-March runoff index (O-MI). The results are shown in Figure 17. Again, the regression is driven in large part by the three years that were back-to-back wet years. These results are not entirely satisfactory, and more analysis is recommended along these lines. However, it seems clear that the apparent correlation is driven by the back-to-back wet years, which again suggests a threshold effect.

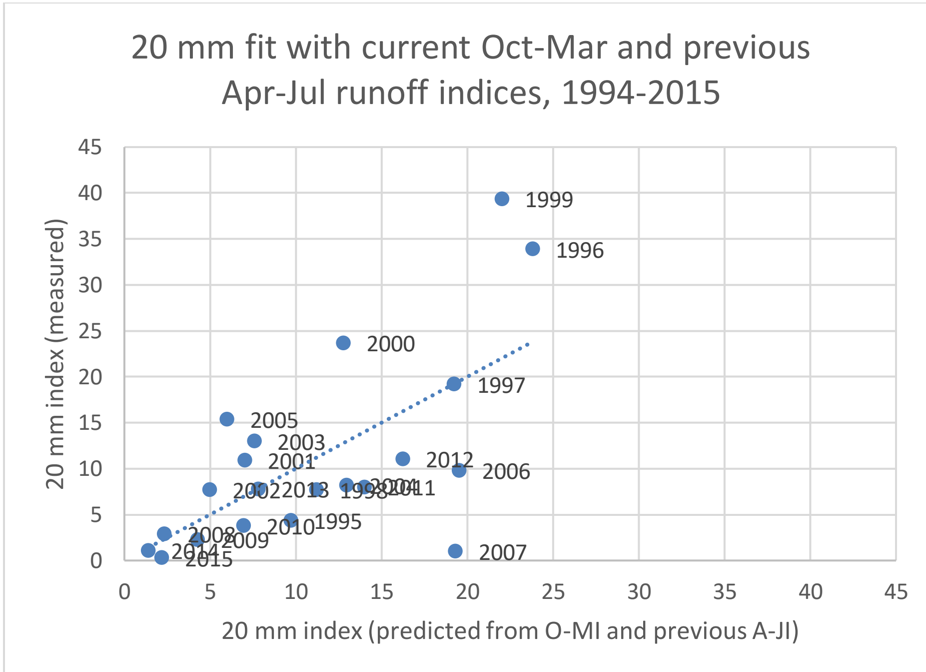

Figure 17. Results of a linear regression of 20mm index with the prior year April-July runoff index and the current year October-March runoff index. r^2 for the regression is 0.43

VII. CONCLUSIONS

The analysis presented above started with concepts presented in the CDFW Rationale paper[1] and further developed those concepts. This study finds that:

1) Delta outflow and X2 are autocorrelated, and there are strong correlations of outflow and X2 among the months of April through September, for the period 1987-2014 (Tables 1 and 2).
2) The relationships between FMWT/STN and runoff indices are driven by wetter years; no relationship is seen when only the drier years are considered (Figure 8), which suggests a threshold in runoff for improved survival.
3) A possible mechanism is explored as to the cause of these relationships. Figures 13 and 14 indicate that the wet years driving the relationships include high runoff that leads to significant periods where the western Delta and Suisun Bay become fresh. These periods also include high inflow, which tends to bring in dissolved and particulate organic matter and high turbidity, and the freshening of the western Delta and Suisun Bay that has been found to suppress the population of *Corbula*. In drier years, the western Delta and Suisun Bay do not get fresh for long periods of time, and there are no large inflows for long periods of time. It is quite possible that in those drier years, moving X2 (and Delta smelt) to the west puts them in an area with a higher density of clams that reduces food levels, and moving X2 (and Delta smelt) east puts them at risk for higher predation, temperatures, and *Microcystis* blooms (effectively, there is no good habitat in the western or central Delta in drier years). This supports the possibility that a threshold in runoff may be important.
4) Examination of the 20 mm index shows that, for 1994-2015, there is a relationship with average September-December X2 that appears to be good, and that a log transformed 20 mm index is not needed to see a relationship. However, the relationship is strongly influenced by three back-to-back wet years. There is no significant relationship for years that are not back-to-back wet years. There are some indications that the prior year April-July runoff and current year October-March runoff indices are drivers, but more work is needed.
5) Delta outflow and X2 in the months of April through September are strongly correlated with the April-July runoff index and the 403030 runoff index for the years 1987-2014 (Tables 3 and 4).
6) For 2002-2014, the period examined in the CDFW Rationale paper, the correlations found between FMWT/STN and summer outflows are shown not to be limited to those months. FMWT is also correlated with spring outflow, spring and summer X2, and the April-July and 403030 runoff indices (Figures 3 and 4).
7) For 2002-2014, FMWT has an apparent relationship with the April-July runoff index (Figures 5 and 6).

8) The relationships between FMWT/STN and X2 or runoff indices are not limited to 2002-2014, but extend back to 1992 (Figure 7). The data for the period 1987-1991 do not fit the pattern for FMWT/STN as a function of X2 and runoff indices (Figure 9) that is seen for 1992 to the present.
9) There is a possible relationship between FMWT normalized with its prior year FMWT value and the April-July runoff index (Figure 10). This relationship is driven by a few wet years and is not significant when just drier years are considered (Figures 10 and 11), again suggesting a threshold effect.

The title of this paper poses the question: "Will increasing outflow in the summer increase Delta smelt survival?" From the data examined, one can say the data support the notion that wet years with significant outflow that freshens Suisun Bay for extended periods are beneficial to smelt survival and its population. However, summer outflows alone cannot be taken as a primary causal factor from the data. The high summer outflows that drive the apparent relationships seen in Figures 1 and 2 belong to periods in which runoff is high for the spring and summer. Summer outflow is one part of an ensemble of effects that come with high runoff. It cannot be concluded that summer outflow *per se* is a driving factor from the data: it could well be that the driver is spring runoff (X2 for example, which has been shown to be important previously[9]).

In effect, when the autocorrelation of flow is taken into account, Figures 1 and 2 tell us very little more than what we already know. Wet periods result in high, uncontrolled flows that extend through the summer (Figure 12). Wet periods move X2 seaward in spring, and low X2 in spring is associated with an improved population of Delta smelt (Jassby *et al.*[9]). High spring flows in wet years result in freshening of Suisun Bay and the western Delta for substantial periods[6], which in turn reduces the *Corbula* population[7].

The CDFW provides some reasons why increasing summer outflow in 2016 (and moving X2 seaward) would be beneficial, but correctly notes that a modest increase in outflow might not be detectable. Among the arguments is that food availability in 2016 should be better as a result of the high flows in the spring of 2016, and that is entirely possible.

However, a carefully designed experiment must consider the dynamic nature of the location of X2. Like a broken watch, which is accurate twice per day, X2 is at its mean daily location only four times per day as the tides move X2 8 to 10 km per cycle. If, for example, X2 is at 70 km on average, it is moving between 65 and 75 km twice per day over the tidal cycle (and it would be a much greater range on a monthly averaged basis). Increasing outflow 2,500 cfs or so to move X2 2 km to the west would actually move the range from 63 to 73 km. Thompson and Parchaso[7] found that while high flows suppressed *Corbula*, they did not eradicate them; their numbers and mass recovered rapidly in Grizzly Bay (their Figure 3). By moving X2 westward in the summer, the amount of time X2 spends farther west could simply expose smelt to a higher level of food competition. Consequently, a proposed experiment should consider not just the average X2, but its Lagrangian motion, the *Corbula* population in Suisun Bay, and the availability of food over the X2 range (and the range of smelt around X2).

Given the variation in the data, it is not even clear how one would design an experiment to test the effects of summer outflow on survival. To get a response on the order of the standard error of the estimate in these regressions (Figure 1, for example) would require an increase of outflow on the order of 2,500 cfs or more. Figure 7 suggests it would take an extra 2 MAF in April-July runoff. To get beyond the standard error and have some certainty the result is due to the increased outflow would take much more outflow. The data are clear that in *drier* years, summer outflow (and even April-July runoff) is not an important factor in determining FMWT/STN: the data indicate a possible threshold effect, so to improve survival of smelt in those years, enough outflow is needed to breach the threshold to make Suisun Bay fresh (effectively turning those years into much wetter years).

There are difficulties in doing an experiment in wet years as well, and it would be very difficult to evaluate the results for several reasons. First, in wet years, outflows are often uncontrolled or surplus (see Figure 12), and it would be difficult or even impossible to reduce them. Consequently, one is limited to increasing outflow, if it is possible, but using Delta diversions to vary outflow while not increasing inflow avoids all the possible benefits of increased flux of nutrients and turbidity into the Delta. If inflows are increased, one has all the upstream risks (e.g. loss of storage and cold water for subsequent years).

However, it seems this is not simply an outflow effect but an effect of wet years, and a positive response could well require the concurrent increase in inflows seen in wet years (i.e., changing outflow without changing inflow might well be insufficient or even inconsequential). If inflow is also important in driving these relationships, then the focus on outflow alone could be futile.

A similar difficulty exists for the 20 mm survey: if average X2 from September through December is causal, and the correlation seen in Figure 15 is not simply a manifestation of wetter years, then to get a response on the order of one standard error, a movement of X2 to the east of about 3 km is required, which would take on the order of 3,000 cfs, or 750 TAF, over the four months. To get beyond the standard error and gain some certainty of the outcome would take much more flow, doing artificially what wet years do automatically. Again the role of inflow is likely to be important as well, as is the ensemble of conditions that come in wet years. For the 20 mm index, the driver is back-to-back wet years, further complicating what one might hope for as an outcome by simply focusing on fall months.

APPENDIX A

Calculation of X2 and Its Relationship to Delta Outflow

X2, the location from the Golden Gate in kilometers of the 2 ppt salinity line in the Delta and Bay is generally calculated[9] from an equation of the form:

$$X2(t) = a + b\,X2(t-1) - c\log(\,Q(t)) \qquad (1)$$

where X2(t) is X2 at time t, X2(t-1) is X2 at the prior time step (daily or monthly for example), Q(t) is the Delta outflow at time t, and a, b and c are constants, with |b|<1.

This equation leads immediately to a recursive equation of the form:

$$X2(t) = a(\textstyle\sum_{k=0}^{n} b^k) + \; b^{n+1}\,X2\big(t-(n+1)\big) - \; c\log(\prod_{k=0}^{n} Q(t-k)^{b^k} \quad (2)$$

Where Q(t-k) is the Q at k time steps prior to time t.

Since |b|<1, as n → ∞, this equation becomes:

$$X2(t) = \frac{a}{(1-b)} - \; c\log(\,\textstyle\prod_{k=0}^{\infty} Q(t-k)^{b^k} \qquad (3)$$

Two things should be self-evident:

First, X2 will be autocorrelated since X2 at one time is linearly related to X2 at a prior time, with coefficient b^{n+1} (see Equation 2) and since |b| < 1, this autocorrelation decays with lag time; and second, X2 is logarithmically related to prior outflows (Equation 3).

That the equation is bound is easily shown. Let Q_m and Q_M be the minimum and maximum outflows in the time period. Then

$$\frac{a}{1-b} - \; c\log(\prod_{k=0}^{\infty} Q_m^{b^k}) \le X2 \;\le \frac{a}{1-b} - c\log(\prod_{k=0}^{\infty} Q_M^{b^k})$$

But $\log(\prod_{k=0}^{\infty} Q^{b^k}) \;=\; \frac{1}{1-b}\log Q$, so for |b|< 1, X2 is bounded in the relationship, which means that in this respect, the formula is valid mathematically and does not diverge even when an infinite lag time is applied (n → ∞). Similarly, it can be shown that the relative cutoff error (i.e., truncating the expansion and ignoring the term X2(t-(n+1) term) in calculating X2 with Equation (2) is on the order of $2b^{n+1}$. Thus one can calculate how far back one would expect a strong autocorrelation. If b=0.945 (daily) or 0.3278 (monthly), then with less than 5% relative error, one need only use the last 2 or 3 months of outflow data to get an estimate of X2(t) within 5%. Going back farther than that in time produces smaller and smaller effects on the current value of X2, so the autocorrelation could tail off accordingly. In practice, it is found that X2 is strongly autocorrelated with a lag of more than 3 months, but that is likely because 1) Q is also autocorrelated, 2) seasonal effects replicate from year to year and 3) outflows (and therefore X2) throughout the year are driven to a large extent by runoff for that year.

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DATA SOURCES

Data used in the following analyses can be found in the following locations:

Water year runoff indices (October-March, April-July and 403030 index:
http://cdec.water.ca.gov/cgi-progs/iodir/wsihist

Net Delta Outflow and X2 from Dayflow:
www.water.ca.gov/dayflow
For water years prior to 1997, X2 was calculated from Dayflow outflows, using the Dayflow X2 relationships.

FMWT index
http://www.dfg.ca.gov/delta/data/fmwt/indices.asp

STN index:
http://www.dfg.ca.gov/delta/data/townet/indices.asp?species=3

Water Conditions from the California State Water Project Operations Control Office
http://www.water.ca.gov/swp/operationscontrol/deltaops.cfm

What Dimensional and Lagrangian Analyses Tell Us about Flow Regimes, Flow Indicators and at Fish Salvage Export Facilities in the Sacramento-San Joaquin Delta
December, 2016

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Abstract
It is shown that the use of measured Old and Middle River flow (a dependent variable) compared to simply using exports and San Joaquin River inflow (independent variables) adds noise without adding information when analyzing salvage data. It is further shown, using a Lagrangian analysis, why there is an apparent threshold effect, where salvage increases rapidly with increasing exports. The Lagrangian analysis reveals the correct averaging period for analysis of salvage data, and it reveals why salvage data do not show a relationship with neap-spring tidal effects.

In this paper, dimensional and order of magnitude analyses are applied to variables affecting water flow and velocity in channels near export facilities in the Sacramento-San Joaquin Delta. A quasi-Lagrangian depiction of water movement is used to reveal three flow and velocity regimes that are described as tidal, transitional and riverine-like conditions. A flow index involving only the most important *independent* variables is proposed based on a simple continuity argument and the order of magnitude analysis; the index is then used to evaluate fish salvage data. It is shown that the effects of the different flow regimes are discernible in salvage data and the Lagrangian depiction reveals the correct averaging period for analyzing fish salvage data. It also reveals why there is an apparent threshold effect, on one side of which salvage is relatively unaffected by net flow and on the other salvage rapidly increases.

Comparison of the proposed flow index with the measured Old and Middle River ("OMR") index reveals that the OMR index, which includes neap-spring tidal and other effects, increases noise in the analysis of salvage data without adding discernible information. The quasi-Lagrangian analysis reveals the reason neap-spring tidal effects are not a significant transport mechanism: at high net flows the flow regime is riverine, tidal effects are small and do not significantly affect the travel time along the channel; at low net flows, the regime is tidal and neap-spring tidal effects are averaged out over the many tidal excursions that occur during the travel time down the channel.

It is found that the flow regimes offer an explanation of the observed data such as the observed fish salvage even when net flow is positive (away from the export pump plants), failure of some parameters to predict salvage, and extremely high salvage during riverine conditions. The hypothesis that low-frequency tidal flows (i.e., neap-spring variations) are an important factor in predicting or analyzing fish salvage data is tested; the hypothesis is seen to fail the tests applied. The current use of the measured OMR index (which is a dependent variable and is based on filtered field measurements) increases noise but adds no additional information when compared to proposed index that includes only the key independent variables (export pumping and San Joaquin River flow) in analyzing salvage data.

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Background

The Sacramento/San Joaquin Delta is the largest estuary on the west coast of the United States and is a source of drinking water for 25 million Californians, some of whom are entirely reliant upon it. The Central Valley Project (CVP) Intake and the State Water Project (SWP) Intake at the southwest end of the Delta (Figure 1) are the two largest diversion facilities in the Delta, and can pump as much as 425 m^3/s (15,000 cfs). Pumping at these facilities can have a significant effect on hydrodynamics in the south Delta depending on the magnitude of pumping compared to other factors (Monsen 2007, others). Hydrodynamics in the Delta are complex and largely dependent on tidal action, major river inflows from the Sacramento and San Joaquin Rivers, export pumping at the CVP and SWP intakes, minor tributary flows, wind and barometric pressure, in-Delta agricultural diversions, local minor diversions, agricultural and urban discharges and, in some areas, density driven circulation. Hydrodynamics in turn affect the salinity, temperature, transport of plankton, pollution, sediment and possibly fish behavior. Determining how hydrodynamics and export pumping affect native fish populations has been a major scientific question driving regulations in the Delta for over 40 years.

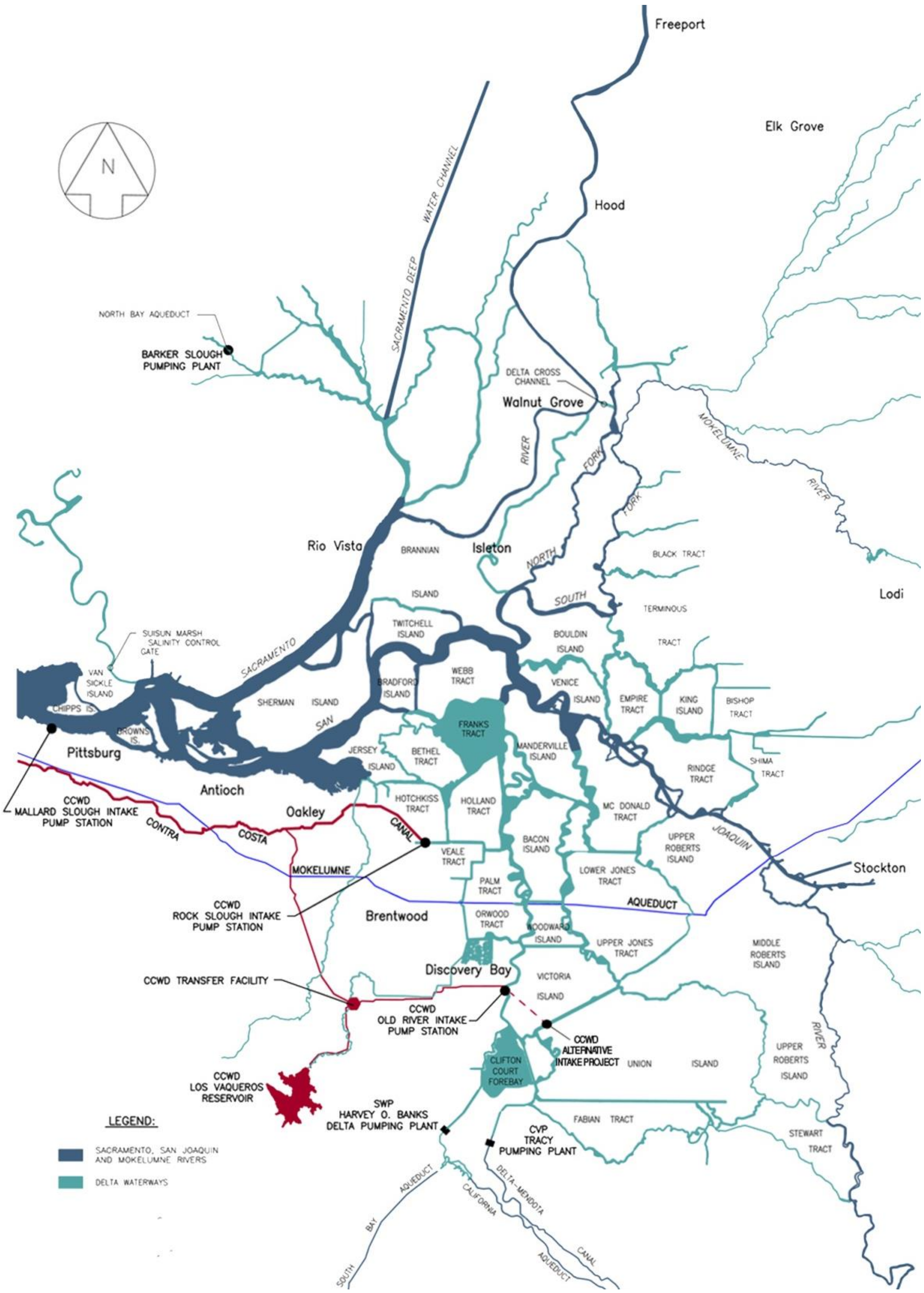


Figure 1. Sacramento-San Joaquin Delta (from California Dept. of Water Resources Delta Atlas)

Given the spatial and temporal complexity of hydrodynamics in the Delta, and the complex interaction of tidal flows with anthropogenic influences (from diversions to tidal barriers) simplified hydrodynamic indicators have been developed from time-to-time in an effort to seek simple mechanistic relationships between hydrodynamics and other variables of concern, such as water quality and fish entrainment at the export facilities. Those efforts have been less than satisfactory, in significant part because the system is so complex it defies explanation by simple parameters whose influence is of limited range. Since the late 1980s, state and federal regulatory agencies have used one or more of these hydrodynamic indicators to test cause and effect relations and to regulate operations of the state and federal facilities with the goal of improving conditions for native fish populations while maintain water supplies that are delivered by those facilities. (A brief historical overview of some of the hydrodynamic indicators developed for the Delta is provided in Appendix 1).

One of the complexities involved in the fluid dynamics of the Delta is that flows generated by tides and weather (principally winds and barometric pressure) often dominate flow patterns. Upstream, flows become less tidal and more riverine. However, factors of anthropogenic origin (reservoir releases to rivers tributary to the Delta, channel barriers and diversions) can play a significant role in the water motion in various areas. Delineating various flow regimes may be helpful in sorting through the complexities and in interpreting data, both field and that from various models of flow and transport.

Various complex models solving some simplified versions of the Navier-Stokes equations, coupled with transport equations, over the complex channel system in the Delta have proved successful in calculating salinity (and other conservative substances) transport in the Delta, but have to date not been successful in evaluating movement of fish which are non-conservative and exhibit their own behaviors, including the ability to move in response to, for example, phases of the tide ("surfing" tidal velocities to move principally in one direction, e.g., see Bennett and Burau, 2014).

Unfortunately, most attempts to analyze data have relied upon dimensional parameters, principally flow. This poses two problems when analyzing data related to fish movement, for example salvage of fish at the export facilities. First, fluid dynamical effects on fish are transmitted via fluid velocity (a local effect) not flow, which is of course related to velocity but not at all the same thing. For example, a net flow of 280 m^3/s (10,000 cfs) may, in the context of Delta flows, seem to be a lot, but in a tidal regime in the western Delta where the tidal flows are 10 to 50 times larger, velocities generated by that net flow might be on the order of 2 cm/s or less. Conversely, in a narrow channel such a flow can generate velocities on the order of 30 cm/s or more, certainly significant for any sizeable object in the water. Clearly, when the local flow regime is tidal, transport will be dominated by tidal effects (tidal dispersion, tidal trapping, etc.) and when riverine conditions dominate, transport will be dominated by advection (including dispersion associated with the velocity profile). In between those two regimes is one where both mean advection and tidal transport are important, which we designate as transitional (between tidal and riverine).

The second problem arises when changes are made to the configuration of the Delta, for example increasing channel widths (and cross-sectional area) or adding tidal habitat. Both of these can change the tidal characteristics in ways that might move conditions in a channel from one regime into another (for example, if habitat restoration suppresses the tidal flow in the south Delta, as models suggest it will, the regime could easily move to riverine or simply a stagnant regime). By properly normalizing the parameters to the proper important quantities, insight is gained on the potential effects of changed conditions. We start, therefore, on using a simple dimensional argument and order of magnitude analysis to form parameters that are useful in the context of Delta conditions and the particular issue being examined: fish salvage at the export facilities.

Flow and Velocity: Magnitudes and Dimensionless Parameters

While local velocity is the important factor directly affecting aquatic species, flow has often been used as a parameter because it is a common measure of water delivery. Flow is nonetheless an incorrect parameter. Because of the relationship between local flow and local velocity, for fixed geometry, local average velocity (averaged over the channel cross-section) is simply flow divided by cross-sectional area. One immediately sees the issue with using flow alone: depending on the local cross-section, the same average flow can result in a meaningful velocity (to a fish) or an insignificant velocity. However, when average flow is properly normalized to a dimensionless parameter, that dimensionless parameter is numerically the same as the normalized average velocity:

$$Q/Qa=V/Va \quad \text{(for a fixed configuration)}$$

where Q is the cross-sectionally averaged flow, Qa is the appropriate flow factor representing the hydrodynamic conditions. V and Va are the local average velocity counterparts to Q and Qa. While self-evident, these non-dimensional factors have not been used in the past to analyze fish salvage in the Delta; as will be seen, non-dimensional parameters free one to move from a flow-centric conceptual model (which often fails in tidally dominated flows) to a conceptual model focused more on the flow regime and the actual transport (which is through velocity). If done properly, non-dimensional parameters allow one to estimate effects of changes to the system configuration. To get the correct Qa (and by extension, Va) one must examine the order of magnitude of the variables of interest.

The flow or fluid velocity in any Delta channel can be characterized by the combined influences of the previously mentioned factors: tides, wind and barometric pressure (which combine to produce in most areas in the Delta the greatest influence on fluid motion, but are all outside human control), river flow (under most conditions, a controllable independent variable, but not in flood conditions), channel barriers and gates, and pumping and discharges (all independent variables under human control). The flow factors, and their associated orders of magnitudes, are given in Table 1 for channels in the south Delta. The orders of magnitude are given for general local conditions in channels near the export pumps because salvage at the export pumps is the dependent variable being considered.

In order of magnitude, three parameters dominate: tides (and weather, which we combine hereinafter to be designated simply as tides), exports and San Joaquin River inflow. Even combined at their higher levels, the other factors (agricultural and minor diversions) are an order of magnitude lower than the “big three”, and under common circumstances in winter and early spring, can be two orders of magnitude less. Consequently, as a first approximation, the focus will be on the tides, exports and San Joaquin River flows and later we will circle back to evaluate the effects of the factors initially ignored.

Table 1: Flow factors and their corresponding magnitudes for channels near export facilities in the southwest Delta

Factor	Designation	Order of Magnitude Range	Typical range Dec-June
Tides, weather in Delta channels (for example, Old River)	Qa	+/-400 m^3/s (+/-15,000 cfs) in any one channel (Old and Middle Rivers)	Same
Export pumping	Qexp	30-400 m^3/s (1,000-15,000 cfs)	Same
San Joaquin River inflow	Qsjr	15-300 m^3/s (500-10,000 cfs) Can be higher in flood conditions	30-300 m^3/s
Agricultural diversions, south Delta	Qag	-15 – 30 m^3/s (-500 to 1000 cfs) Can be negative during precipitation events, varies over irrigation season	Lower, (higher in summer, lower in winter)
Minor diversions (CCWD, ECCID)	Qm	0-7 m^3/s (0-250 cfs) (each), varies seasonally	Same, ECCID lower in winter

As to a representative flow and velocity, Qa (or Va), for normalization, there are many choices and several can be tested, but the obvious ones to start with are the tidal amplitude and the exports. The former is fixed by nature, the latter independent and directly related to salvage, and will be tested against its affects on salvage. Hence tidal flow (or velocity) should be chosen, but which one?

Flow to the export facilities moves through Indian Slough, Old River, Middle River and several channels to the east leading from the San Joaquin River. The latter may transport fish (principally salmon and steelhead from the San Joaquin River) but it is less important for other species (delta smelt for example) and largely controlled most of the year. Indian Slough is a smaller (but not necessarily insignificant) channel but is not metered and for those reasons has been ignored compared to the emphasis placed on Old and Middle Rivers. Measurements located near Bacon Island[3] have been used because they have a longer record, although stations located closer to the export pumps would include flow that comes via Indian Slough. The stations near Bacon Island show a significant tidal flow (Old River tidal flows are on the order of +/- 350 m^3/s, Middle River tidal flows are on the order of +/-380 m^3/s). Because of the emphasis on the combined *net* flows as measured at these stations (net as determined by filtering out the higher frequency tidal components), we will use as **Qa** a value of **700 m^3/s (25,000 cfs)**, which is derived from the approximate magnitude of the combined flow amplitudes at these two stations (half the full tidal flow range). Later, it will be shown that to determine the flow regime at a

[3] Old River (OBI) is a USGS station 11313405. Middle River MDM , USGS station 11312676.

particular location, one should use the local tidal velocity amplitude and compared to the local net velocity.

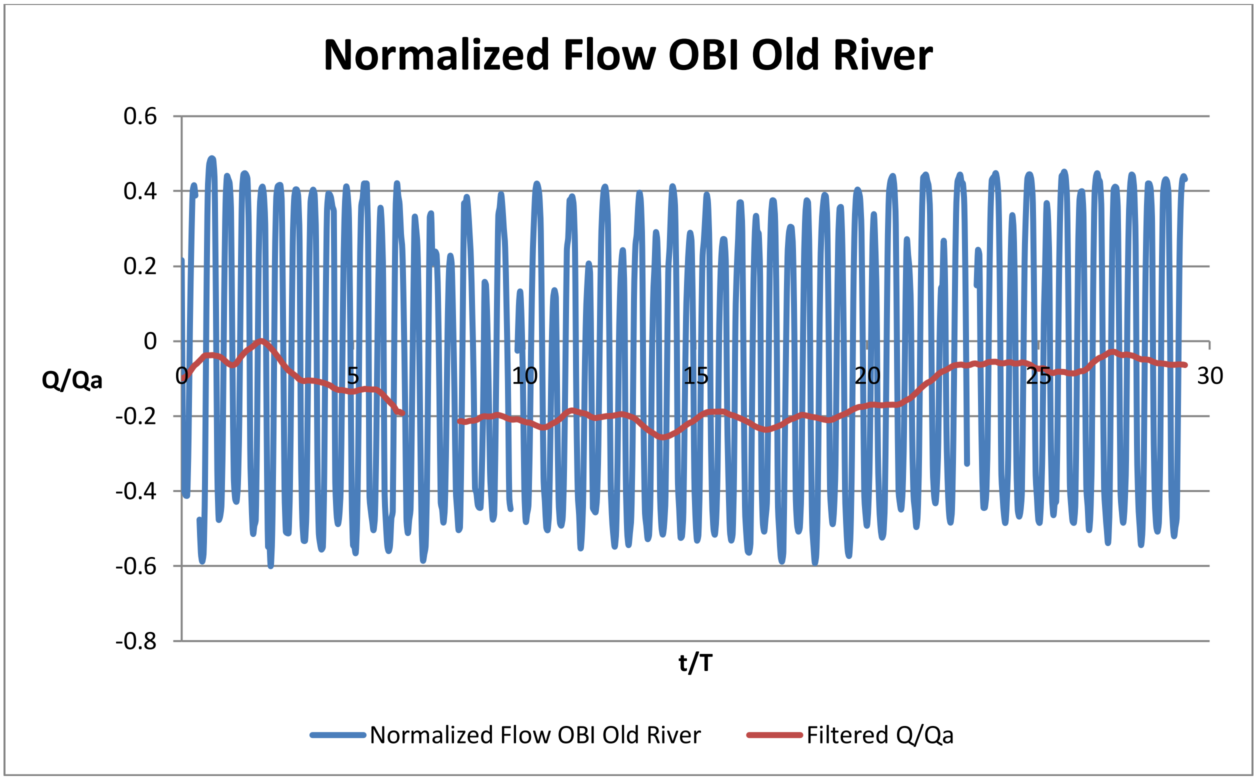
Flows and velocities normalized with Qa or Va derived above are of course being compared to conditions at those combined locations, which is not necessarily representative of locations in general in the Delta, not even of other locations along Old and Middle Rivers. However, other locations along Old and Middle River generally respond to tidal and net flows in a similar fashion as these locations but are subject to local conditions and to variations due to the wave nature of the tides. For example, even along Old River one location may exhibit predominately tidal conditions and at the same time other locations several miles away may experience predominately riverine conditions because the tidal amplitude declines significantly in that short distance. It will be seen that this particular Qa is adequate for the purposes used here, but it is not the only one possible or even necessary.

To give an idea of the conditions in Old and Middle Rivers, normalized flows and velocities in Old (OBI) and Middle Rivers (MDM) for recent (2014) conditions are shown in Figures 2 and 3 for a period in March 2104 (time in the figure is normalized to the average tidal period). Export flows varied during the period from a high end of about 200 m^3/s (7000 cfs) to a low of about 30 m^3/s (1000 cfs). Compare these to conditions downstream (Figures 4 and 5) in Old River (OH4) and Victoria Canal (VCU[4]) through which flow from Middle River connects to the export pumps. Note the different normalized flow and velocity characteristics at these locations (shown in Figures 4 and 5) compared to the more northerly stations shown in Figures 2 and 3, especially the reduced ebb flows evident in Figures 4 and 5.

Tidal flow at OBI (or MDM) is much greater than tidal flow at OH4 (or VCU) because some of that flow has gone to raising the stage between the respective locations (continuity). However, the flows at VCU and OH4 combined carry more net flow to the pumps than MDM and OBI because they include the flow that has come in via Indian Slough[5], but the tidal flow is decidedly lower than at the more northerly stations. In this example, OBI and MDM exhibit what appears to be tidally dominated flow throughout the period, while VCU and OH4 are more riverine in the early period between tidal day 7 and tidal day 11 when exports were higher as the periods of positive flow to the north are short and totally absent on some phases of the tides.

[4] OH4 and VCU are also USGS stations 11313315 and 11312672 respectively.

[5] One complication here is that Middle River continues to the east, and some net flow may go in that direction away from the export pumps, particularly in the irrigation season; at other times some flow may come from the San Joaquin River into Middle River; the meters at OBI and MDM do not include these flows either. In any event, it can be argued OH4 and VCU meters are more representative of the net flow to the export pumps than OBI and MDM, but they have shorter records of operations.



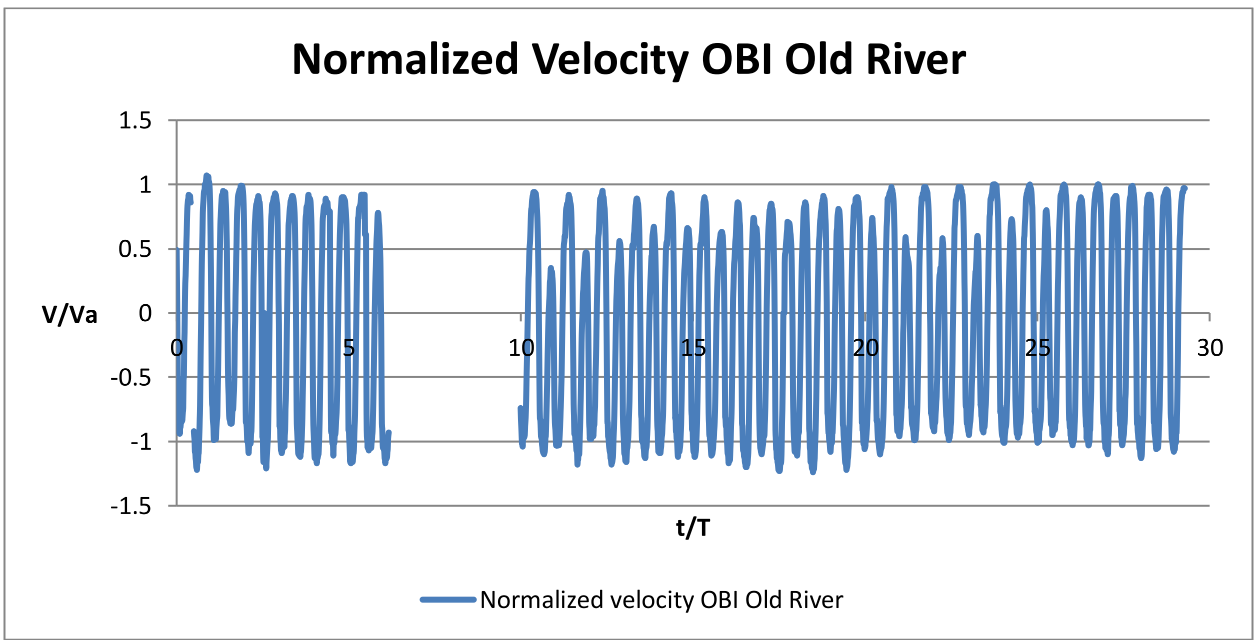
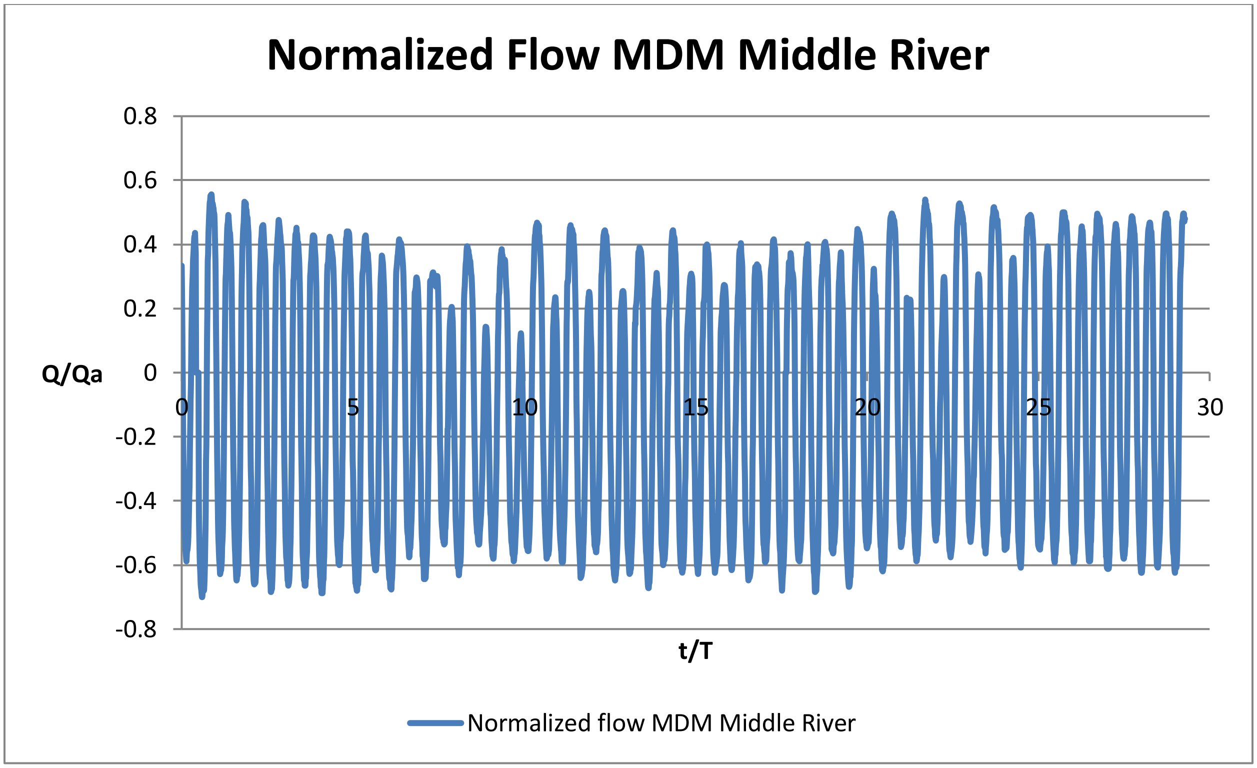


Figure 2: Normalized flow and velocity at OBI, March 2014



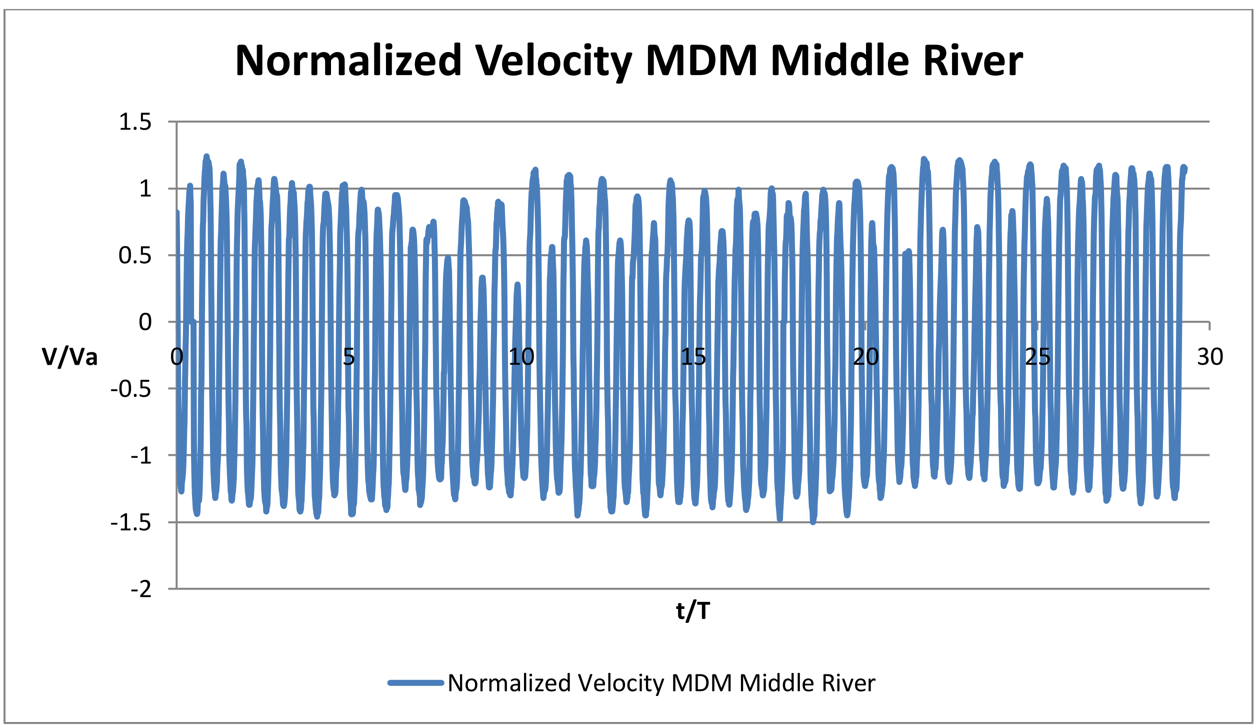
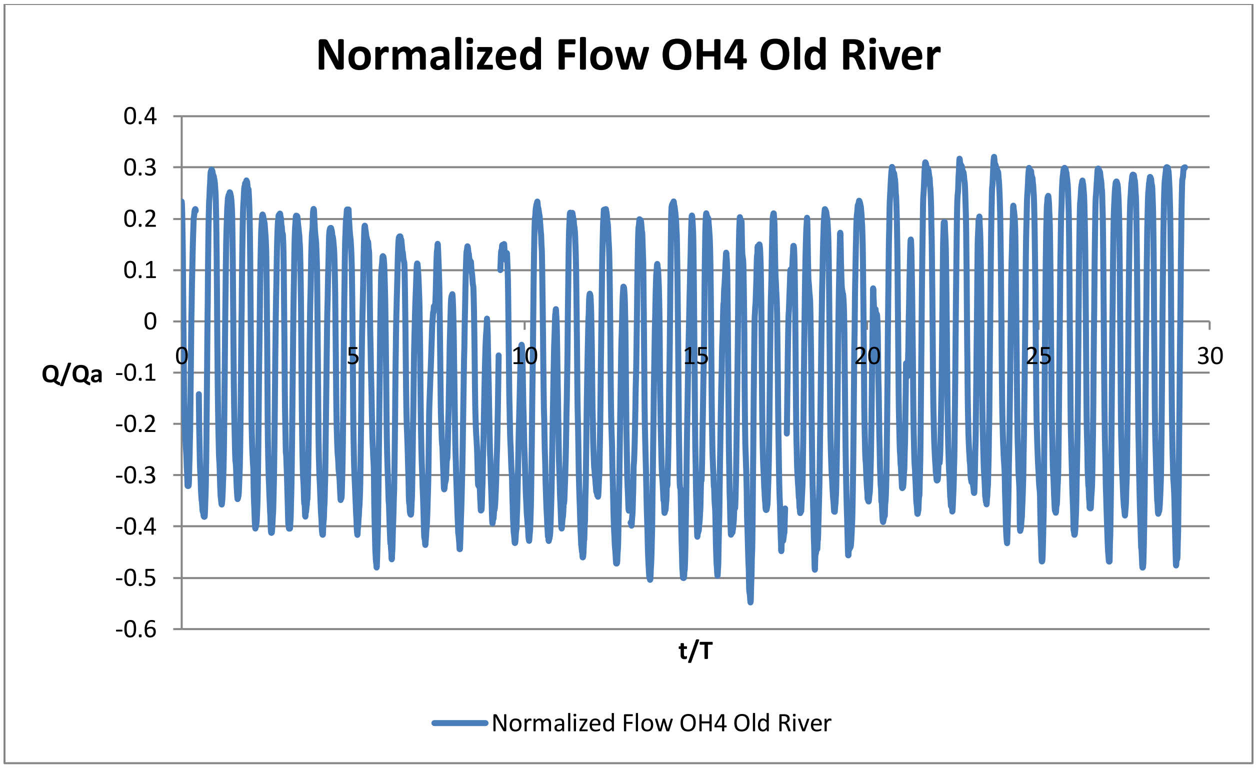


Figure 3: Normalized flow and velocity at MDM, March 2014



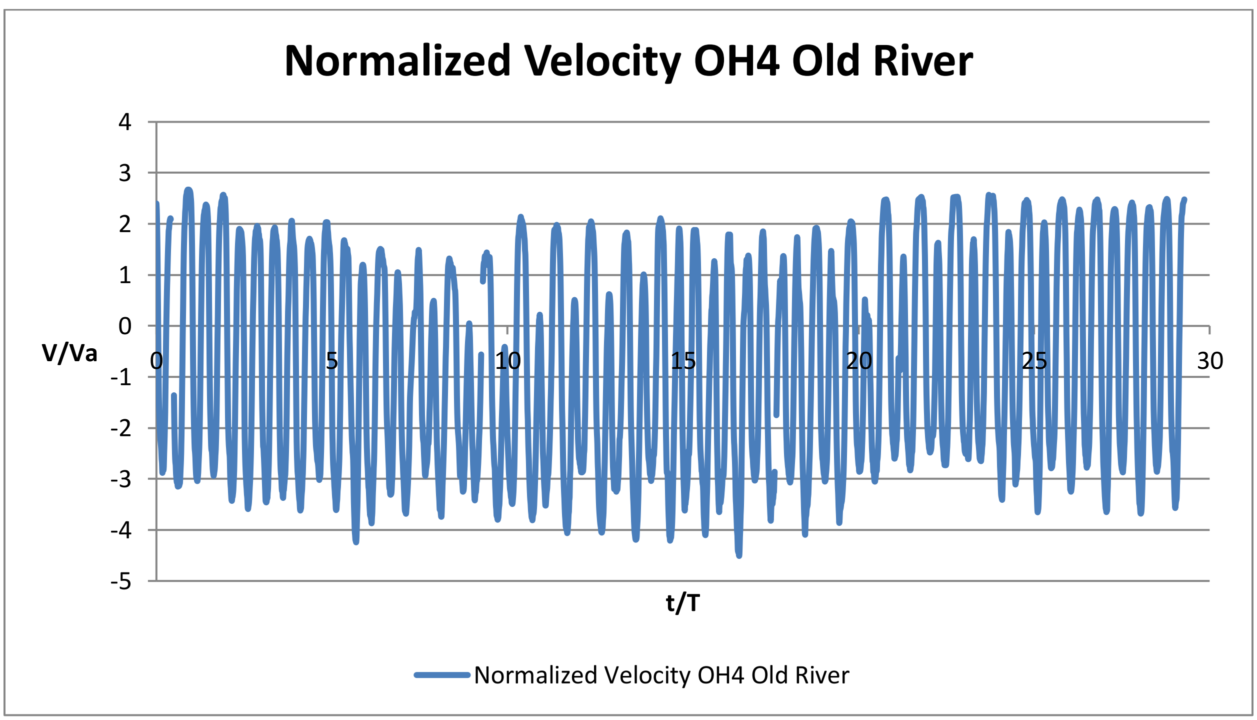
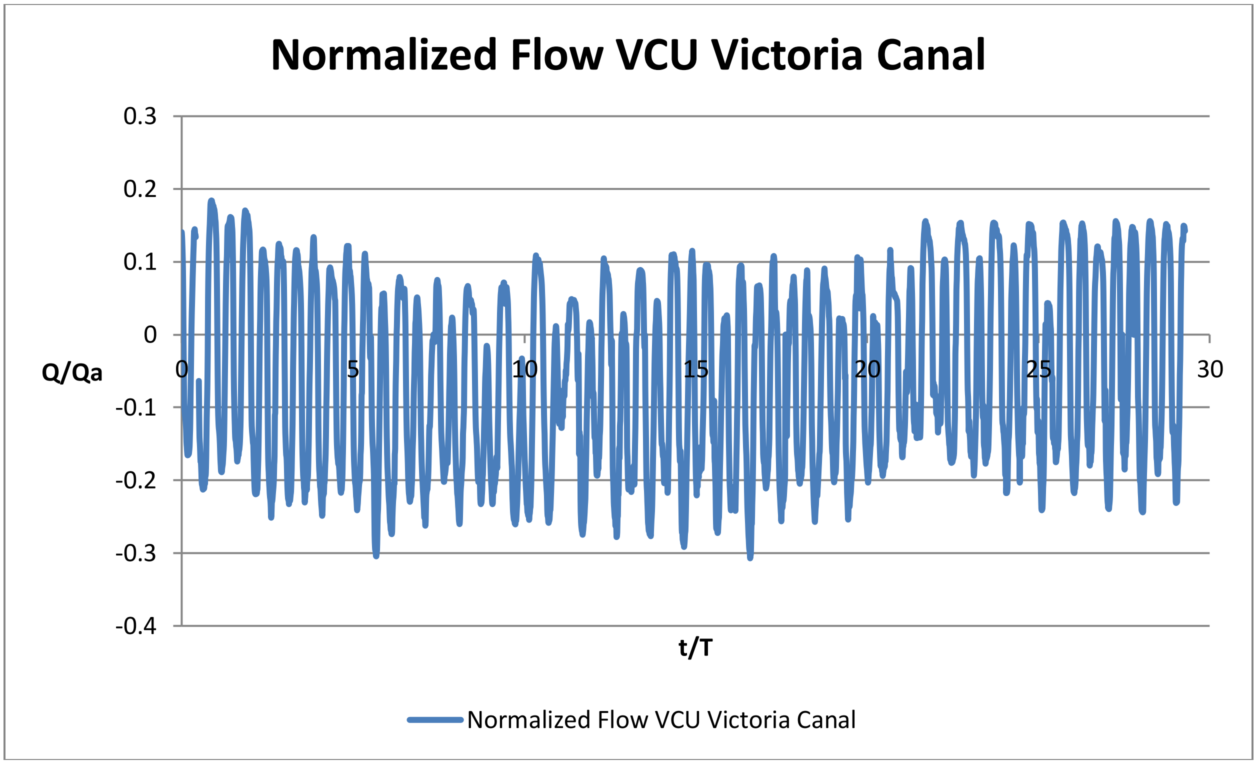


Figure 4: Normalized flow and velocity at OH4, March 2014



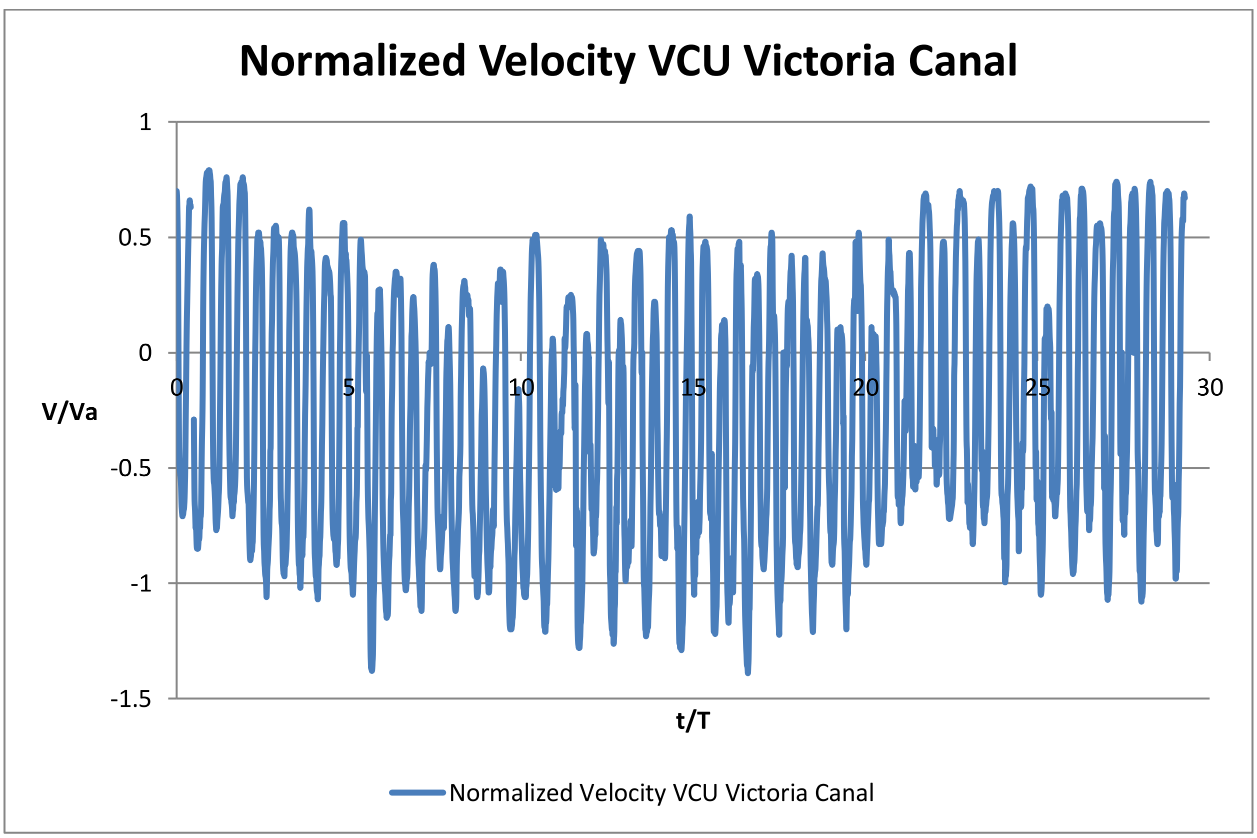


Figure 5: Normalized flow and velocity at VCU, March 2014

Normalized Flow Parameters

We are searching for a parameter that 1) can characterize the flow regime (tidal, transitional, riverine) that is based on the most important *independent* controllable parameters that can be directly related to fish salvage, 2) that can then be used to compare against other parameters that include more variables in order to test the importance of the other variables to fish salvage at the export pumps.

Starting with a continuity argument, one would expect that the (normalized) salvage of fish in a particular time period would be the flow from the north (via Old and Middle Rivers and Indian Slough) times the normalized density of fish from the north, plus the flow from the east (San Joaquin River) times the normalized density from the east. If S the normalized salvage, then it is easily shown that normalized salvage is determined in the following equation:

$$S = Qexp\ \rho_N\ (1+ Qm/Qexp + a*Qsjr/Qexp\ (\rho_E / \rho_N - 1))$$

where Qexp is the export pumping flow rate, Qm are minor diversion flow rates from screened intakes, a*Qsjr is the effective flow from the San Joaquin River (as reduced by agricultural diversions and barriers), ρ_N is the normalized density of fish arriving from the north, ρ_E is the normalized density of fish arriving from the San Joaquin River direction near the head of Old River. One sees immediately for typical conditions, S is highly dependent upon Qexp and that reducing Qexp will reduce salvage over the short term (as expected).

Qm/Qexp is, under most conditions (and especially when salvage is relatively high), on the order of 0.02 or less, and can be neglected.

For San Joaquin River steelhead and salmon, we would expect ρ_E / ρ_N to be on the order of unity, so $(\rho_E / \rho_N - 1)$ would be small, possibly near zero. In the case where a*Qsjr/Qexp* $(\rho_E / \rho_N - 1)$ is small (probably the usual case) then

$$S \approx Qexp\ \rho_E \qquad \text{for } \rho_E \approx \rho_N \text{ and } Qm/Qexp << 1$$

Thus for San Joaquin River steelhead and salmon, one would expect salvage to depend upon Qexp, rather than only on flows in Old and Middle River.

For delta smelt and salmon from the Sacramento or Mokelumne systems, ρ_E is effectively zero, and the relationship reduces to:

$$S = Qexp\ \rho_N\ (1 - a*Qsjr/Qexp) \quad \text{for } \rho_E/\rho_N \text{ and } Qm/Qexp << 1$$

The factor "a" is on the order of 0.5, so, except in times of very high San Joaquin River flows, |a*Qsjr/Qexp| will be less than 0.5, (often less than 0.2). Hence we see again that, when Qexp is reduced, salvage and normalized salvage will drop in response to Qexp.

The normalized density ρ_N is a function of time, but, it is also a function of the "retarded time" or antecedent conditions: density or normalized density of fish near the export pumps at time t is related to the density of fish at a prior time in another location where the fish entered the path way to the export pumps. It is also dependent on the flow conditions over the time of travel, as well as fish behavior and survival over the path travelled.

One immediately sees the need for viewing this problem in a Lagrangian, and not an Eulerian, frame: the travel time is determined by the path of the particle (fish) from its initial location to the export pumps. That travel time is, in turn, determined by the fluid ***velocity along the path*** (as well as fish behavior, which allows movement into adjacent fluid paths and the influence of adjacent paths). Using the fluid velocity as an approximation, one sees immediately that it is necessary to integrate the particle velocity over time to determine the path, and hence velocity is averaged over the length of travel time to get ρ_N at the pumps. Hence, the key term for delta smelt salvage would be expected to be Qexp - a*Qsjr, that is Qexp as reduced by a*Qsjr, averaged over an appropriate time frame.

The term (Qexp – a* Qsjr) is related to but not the same thing as average flow in Old and Middle River. We start with this parameter and then compare it against an average value of the combined net flow at in Old and Middle Rivers as measured at OBI and MDM, commonly referred to as Old and Middle River flow, designated here as <Qomr>[6,7]. Previously, one of us (Gartrell, 2010) found by statistical analysis that the parameter that correlates best to seasonally averaged delta smelt salvage was a parameter composed of daily exports (Qexp) and 3-day averaged San Joaquin River flow (Qsjr). The quantity (0.48 Qsjr) - Qexp[8] was found to have a slightly better statistical regression with normalized delta smelt salvage than use of <Qomr>. If Qsjr and Qexp are regressed against <Qomr>$_1$, the one day average of <Qomr>, the best fit is:

{Estimated best fit of <Qomr>$_1$ no barriers} = Qi = -0.87(Qexp - 0.48Qsjr) (cfs)

It is interesting that the best fit has a factor of 0.87; when the San Joaquin flow is small compared to exports (often the case drier periods), then it means that the flows at OBI and MDM, which provide the value of <Qomr>, are only providing 87% of the exports. The only other place the water can come from is via Indian Slough (unmeasured) which must supply the rest. One could argue that other diversions are not included above; inclusion of agricultural and other local diversions results in factor even *smaller* than 0.87, so that the flows at OBI and MDM are providing at most 0.87 of the export flow when San Joaquin flow is small. The above relationship is valid most of the time in winter and early spring when there are no barriers in the South Delta.

The above analysis suggests the important factor is Qi without the 0.87 factor. We could of course simply use the parameter used by Gartrell (2010) which eliminates the 0.87, but use of this parameter makes it simpler to compare Qi with <Qomr>, as they will be numerically similar (though not identical) and the difference between them can then be compared directly: that

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[6] Brackets <> are used to denote filters or averages. <> denotes a Godin filtered time series to remove higher frequency tidal components. <>1 is a daily average of the Godin filtered data, <>3 is a three day average, etc.

[7] USGS data can be found at CDEC or USGS sites., for example: http://nwis.waterdata.usgs.gov/ca/nwis/uv/?cb_00060=on&cb_72137=on&cb_99409=on&cb_00065=on&cb_00055=on&cb_63680=on&format=gif_default&site_no=11455420&period=&begin_date=2014-08-05&end_date=2014-08-05.

[8] This is valid when no barriers are in place in the South Delta, the usual case from December through March.

allows us to test directly the significance of other factors contained in <Qomr> but not in Qi (agricultural diversions, minor diversions, tidal effects).

When the Head of Old River barrier is in place (blocking San Joaquin River inflow), the relationship used is:

{Estimated best fit of <Qomr>$_1$ HORB in} = Qi = -0.84(Qexp - 0.56Qsjr) - 406 (cfs)

This again indicates Indian Slough flow is about 15% of the export flow. When the Grantline Canal barrier is in place the relationship used is:

{Estimated best fit of <Qomr>$_1$ GCLB in} = Qi = -0.87(Qexp - 0.53Qsjr) - 1290 (cfs)

Qi and <Qomr>$_1$ can be normalized by Qa to analyze the flow regimes and the salvage data.

Quasi-Lagrangian Analysis

In the previous section, it was seen that the tidal flow in Old and Middle Rivers is shifted in the direction of the average flow. This results in an extended time period when the rivers are in the flood portion of each tidal cycle and a reduced time period when the rivers are ebbing. This can be seen more dramatically when a Lagrangian approach is used.

There are insufficient data to perform a proper Lagrangian analysis with the field data: only two velocity meters are on each river, and one finds frequent gaps in at least one. However, there are sufficient data to perform what we designate as a quasi-Lagrangian analysis where velocity at one or two meters is used to illustrate the various conditions: tidal, transitional and riverine.

Two parameters are used to characterize the conditions for the rivers: Qi/Qa (numerically the same as Vi/Va) which denotes the general conditions of the system under consideration, and the individual river conditions <Qor>/Qa-or and <Qmr>/Qa-mr, which are the respective average to flow amplitude ratios for Old and Middle Rivers. The reason for the two parameters will be apparent from the analysis.

To illustrate the movement of fluid particles we integrated (simple trapezoidal method) the velocity in Old River. For velocity we employed a simple scheme that used velocities in the channel as measured at OBI for locations north of OBI, an interpolated velocity for locations between OBI and OH4 and velocities as measured at OH4 for locations south of OH4. As seen in Figures 2 and 4, velocities at OH4 are very much higher than at OBI; this is because of the constriction at the channel near the Highway 4 Bridge, where the OH4 meter is located. Since those velocities are higher than would be found elsewhere in the channel away from the constriction, we experimented with use of a factor to reduce the measured velocities at OH4 for this analysis. It was found that for the purposes of illustration, a factor of 0.5 applied to the velocities made little difference, in large part because over the distance of the integration, from Old River at Franks Tract to the export pumps, the OBI station dominates. At any rate, use of the OBI station alone without the interpolation still illustrates the points.

Figure 6 shows, in an x-t graph, the integrated velocities (yielding distance) against time normalized to tidal cycle (approximately 25 hours). Distance is normalized by the distance from Franks Tract to the export pumps. Conforming to the usual choice of positive and negative directions and velocities, zero is taken at Franks Tract, -1 at the export pumps. This quasi-Lagrangian analysis therefore gives the approximate location of a fluid particle moving at the average channel velocity over a number of tidal cycles. Integration was halted when the normalized distance reached -1 (the export pump location).

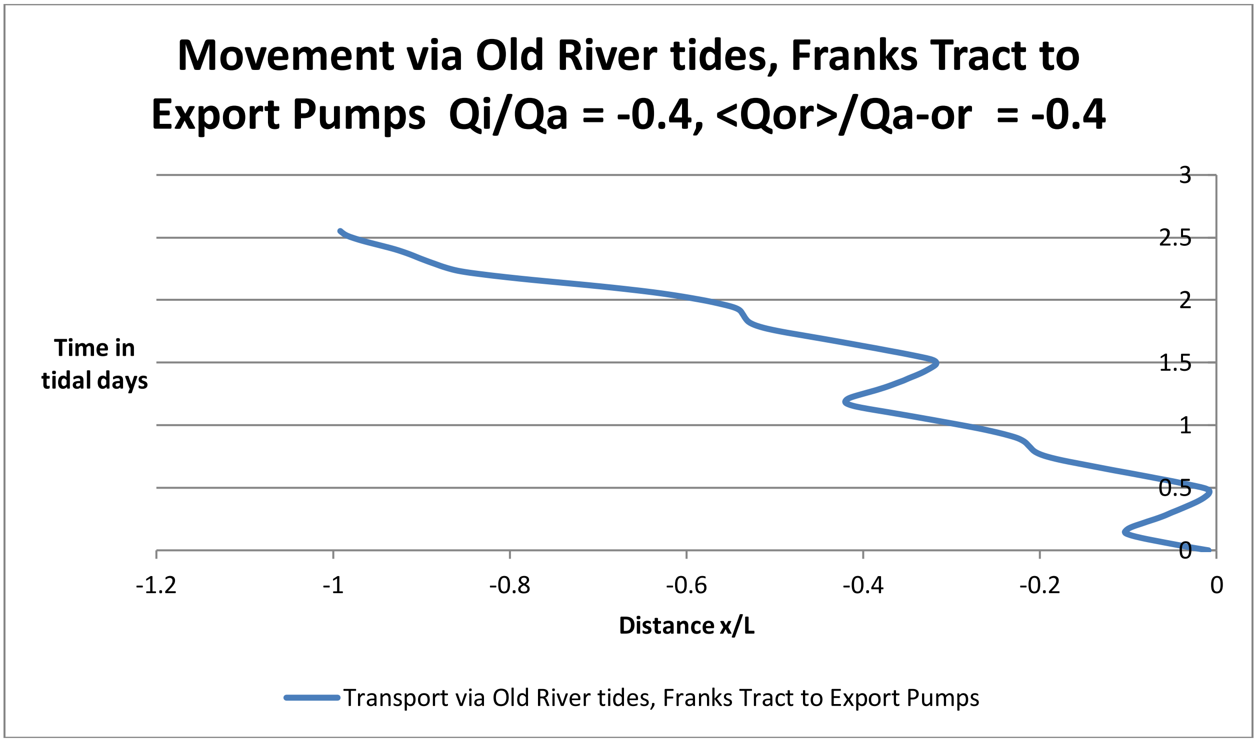


Figure 6. Movement of fluid in Old River, for conditions of Qi/Qa = 0.4, showing riverine-like conditions. L is approximate distance from Franks Tract to export pumps along Old River.

For the condition in which Qi/Qa is about -0.4 shown in Figure 6, the Lagrangian analysis reveals a distinctly riverine-like behavior: movement is largely unidirectional and with brief periods in which the movement is back towards Franks Tract. As pointed out previously, velocities at OH4 exhibit much less ebb flow than flood flow than is seen at OBI, and the "acceleration" towards the export pumps is evident for x/L < -0.8. The movement ends at x/L = -1 (export pumps) at about 2.5 tidal periods, or about 63 hours.

In contrast, Figure 7 shows a similar plot of movement for Qi/Qa = -0.1 (<Qor>/Qa-or = -0.08). In this case a more tidal-like movement is seen with a "drift" caused by the net velocity. Again, an "acceleration" is seen at x/L = -0.8 as the flow becomes more riverine-like near that location. Travel time is about 14 tidal days.

One might expect that in between for -0.4 < Qi/Qa < -0.1, one would find a somewhat "transitional" type behavior in the movement in each river, but this is not the case. Instead, one sees a switch to tidal-like flow first in Old River, while Middle River remains riverine-like[9]. This split between the rivers is apparent in comparing mean flows between the rivers: at OBI and MDM for Qi/Qa near -0.4, <Qor> and <Qmr> are somewhat more equal; the same is true for Qi/Qa around -0.1. However, more net flow travels by MDM when the Qi/Qa is near -0.25 as demonstrated in Figures 8 and 9.

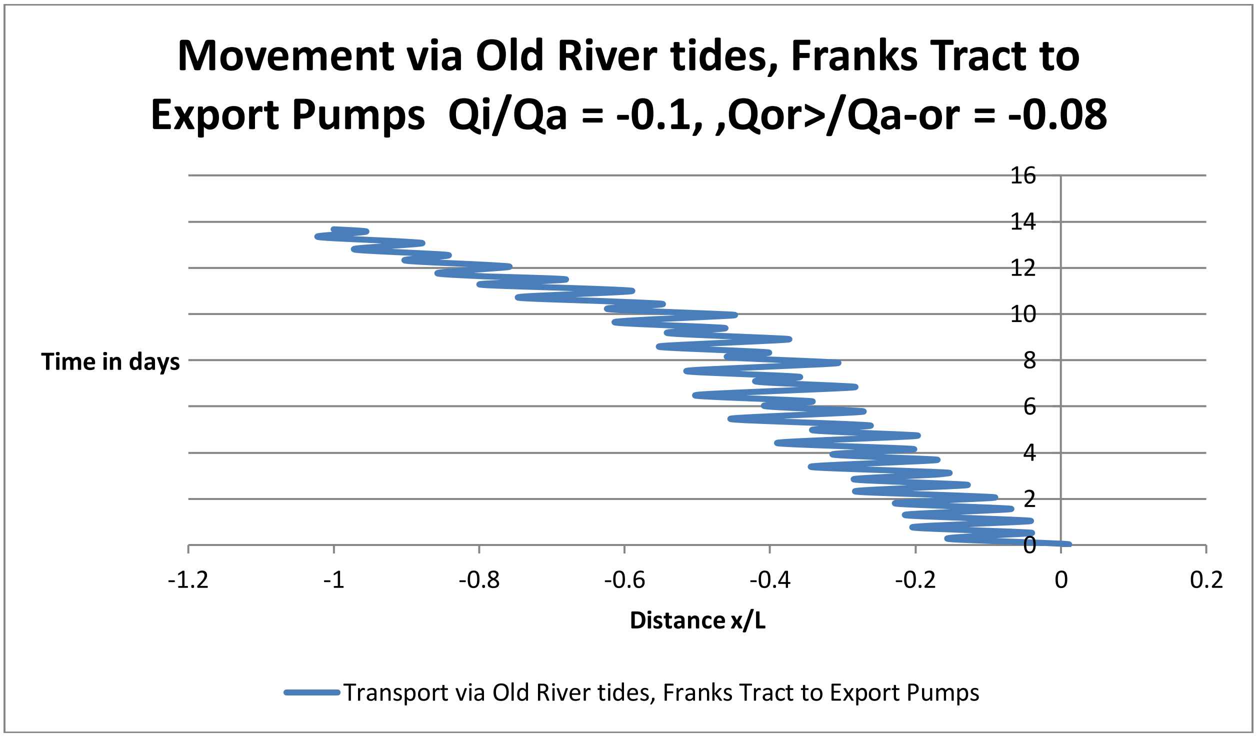


Figure 7. Movement of fluid in Old River, for conditions of Qi/Qa = 0.1, showing tidal-like conditions. L is approximate distance from Franks Tract to export pumps along Old River.

[9] At least at OBI and MDM, but those conditions are likely to dominate until x/L is less than -0.7 for both channels; recall that Middle River water arrives at the export pumps via Victoria Canal which has a more restricted capacity and via Woodward Cut to Old River.

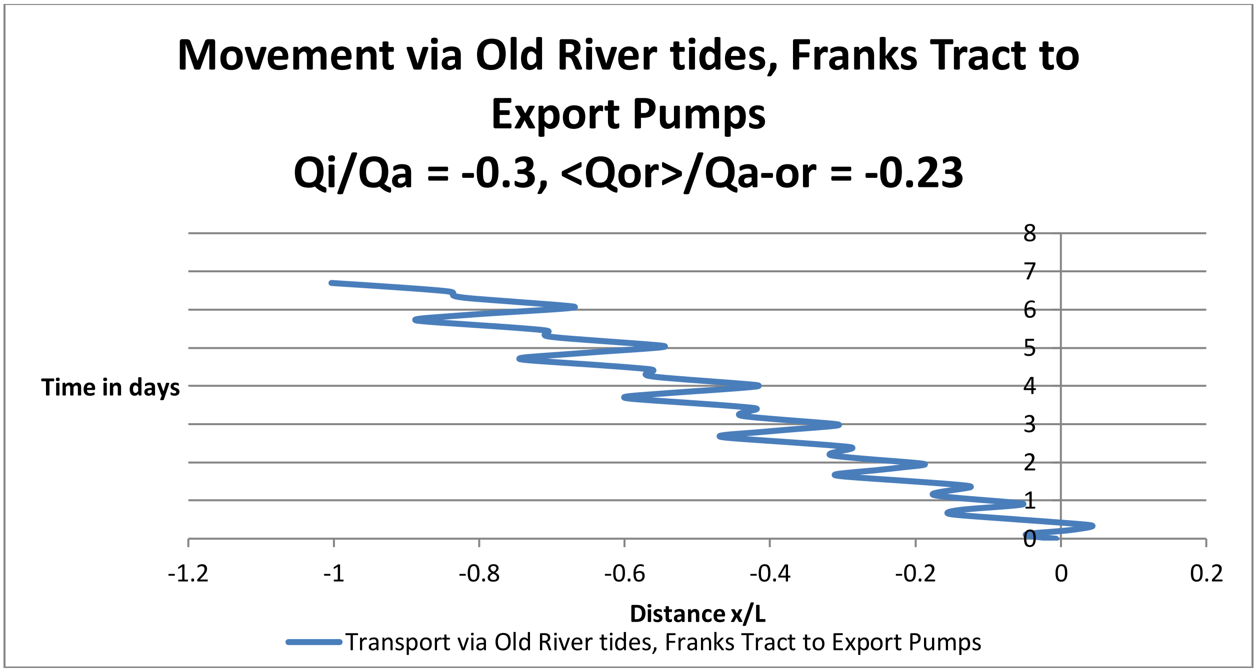


Figure 8. Movement of fluid in Old River, for conditions of Qi/Qa = 0.3, showing tidal-like conditions, same period and conditions as Figure 9.

Figure 8 shows movement in Old River (OBI) and Figure 9 shows movement in Middle River for the same time period with Qi/Qa = -0.3. While Old River exhibits tidal-like conditions, Middle River is decidedly riverine-like.

While Qi/Qa is -0.3, the individual river indices are quite different: <Qor>/Qa-or = -0.23 and <Qmr>/Qa-mr = -0.35; thus for this system, the "transitional" state can be a true mix of riverine conditions in one channel and tidal in the other. The travel times are to be noted as well: for this case, the travel time is 7 tidal days in Old River, but only about 2 in Middle River.

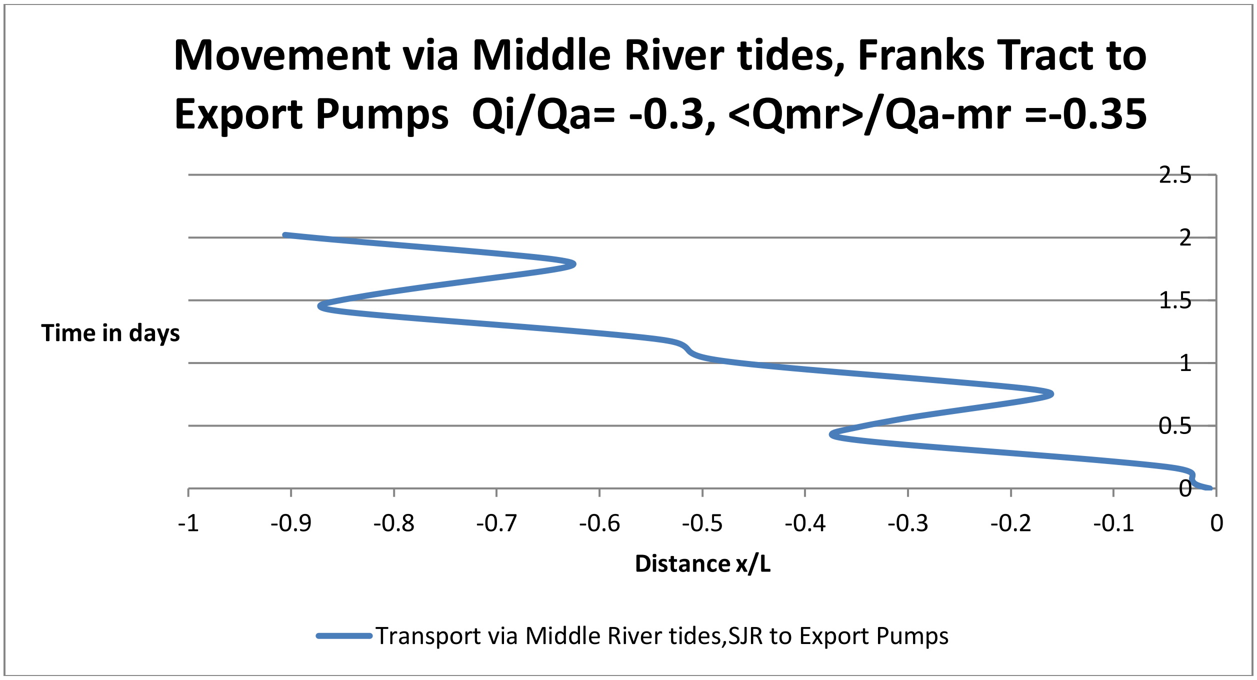


Figure 9. Movement of fluid in Middle River, for conditions of Qi/Qa = 0.3, showing riverine-like conditions, same period and conditions as Figure 8

To summarize, riverine conditions exist when |Qi/Qa| = |Vi/Va| are greater than about 0.3 and tidal when they are less than about 0.2 and transitional in between.

Flow Index, Flow Regimes and Fish Salvage

In this section we explore fish salvage as related to the flow index Qi/Qa, in part to interpret the results in terms of flow regimes, and in part to compare with <Qomr> in the sections that follow to see if there are significant differences between an index that uses only Qexp and Qsjr, which are the largest factors, the only factors capable of changing flow regimes and, for Qexp, the only factor directly linked to salvage at the export pumps. We follow methods that have been used previously in biological opinions and biological assessments in attempts to relate <Qomr> with salvage.

To explore the risk of entrainment under varying Delta hydrodynamics conditions, studies have utilized a particle tracking model (PTM), which simulates the transport and fate of neutrally buoyant particles in the Delta channels and estimates the probability that a parcel of water starting at one location will arrive at another location in a given time frame. The use of PTM for entrainment risk analysis and the modeling assumptions used for this report are discussed in Appendix 2.

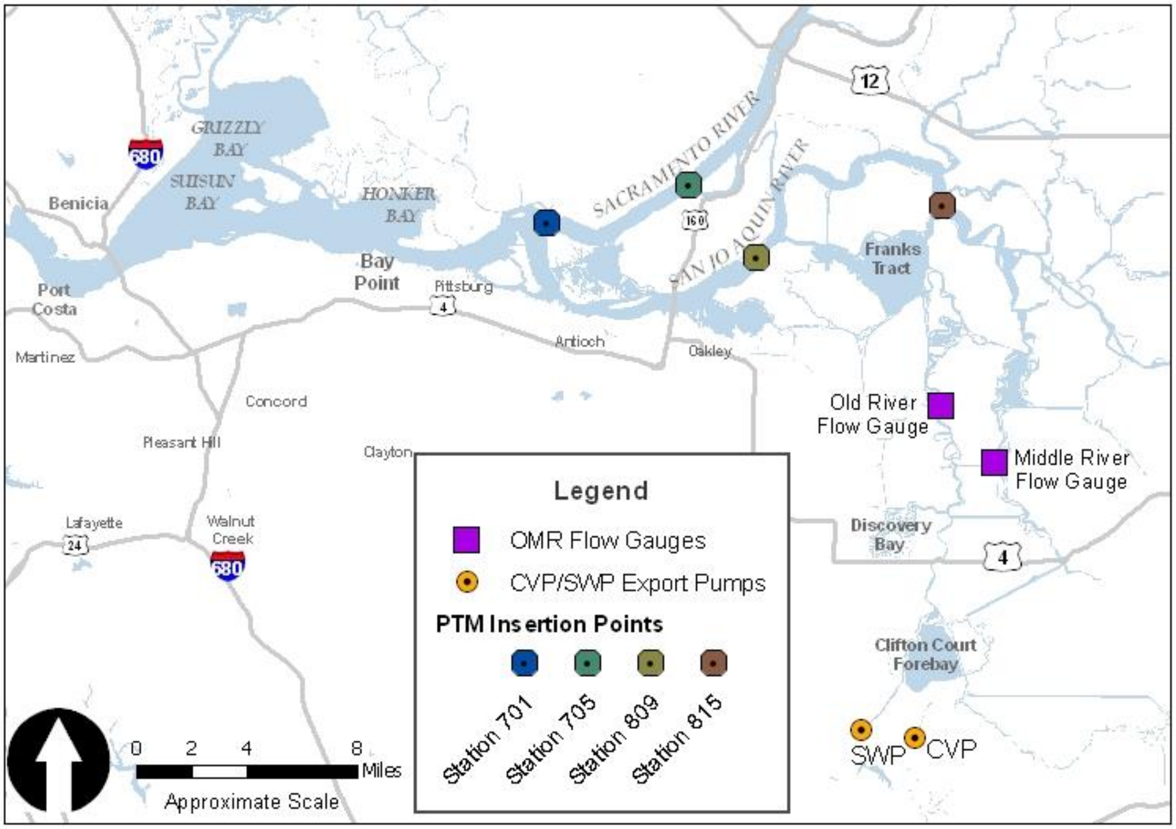


Figure 10: Map of PTM insertion locations

Particle tracking modeling is used to determine the movement of neutrally buoyant particles after release from specific locations within the Delta (Stations 701, 705, 809, and 815 shown in the map above). After release, particle movement is simulated with tidal hydrodynamics and the final particle fate (e.g. where the particle ends up after a defined amount of time) is determined.

Results from hundreds of PTM simulations are summarized below to illustrate the variation in particle arrivals at the export pumps as a function of flow index Qi. For these studies, particle releases were simulated with the PTM model at select fish survey locations within the Delta as shown in Figure 10. Particle movement was tracked throughout the simulation, and the total percentage of particles entrained at the SWP and CVP export facilities in the south Delta was determined for 28 day periods after each simulated particle release. In Figure 11, total percent entrainment is plotted against the average Qi/Qa during the simulation period to illustrate how well OMR predicts entrainment risk. Qa shown here is the local Qa (based on local tidal amplitude).

As expected, the entrainment risk is highly dependent on the starting location for the particles[10]. For instance, no more than 5% of the particles released near the confluence of the Sacramento and San Joaquin River were entrained during any of the simulations (panel A), yet nearly 90% of

[10] Implementation of the current OMR regulations allows for consideration of the spatial distribution of delta smelt and longfin smelt to some extent; this is typically done currently through application of judgment of fishery experts in the adaptive management process. However, the regulations include a minimum value of <Qomr> (-5,000 cfs) that cannot be exceeded regardless of spatial distribution.

the particles released on the San Joaquin River near mouth of Old River were entrained during a few simulations (panel D). Note that especially for the locations with low entrainment, the particles are released in areas clearly in tidal conditions, and it is only when conditions approach riverine in Old and Middle Rivers is there significant entrainment and only for particles released nearby.

The entrainment risk varies for different levels of average Qi/Qa, with considerable scatter in the results. For instance, for particles starting on the San Joaquin River near the mouth of Old River (panel D), at Qi/Qa equal to -0.12, entrainment varies from 8% to 24%, and at Qi/Qa about -0.2, entrainment varies from 4% to 64%. So while Qi/Qa clearly reflects some characteristics of Delta hydrodynamics, the value of Qi/Qa alone is not sufficient to predict particle movement, even in the idealized case of a numerical model.

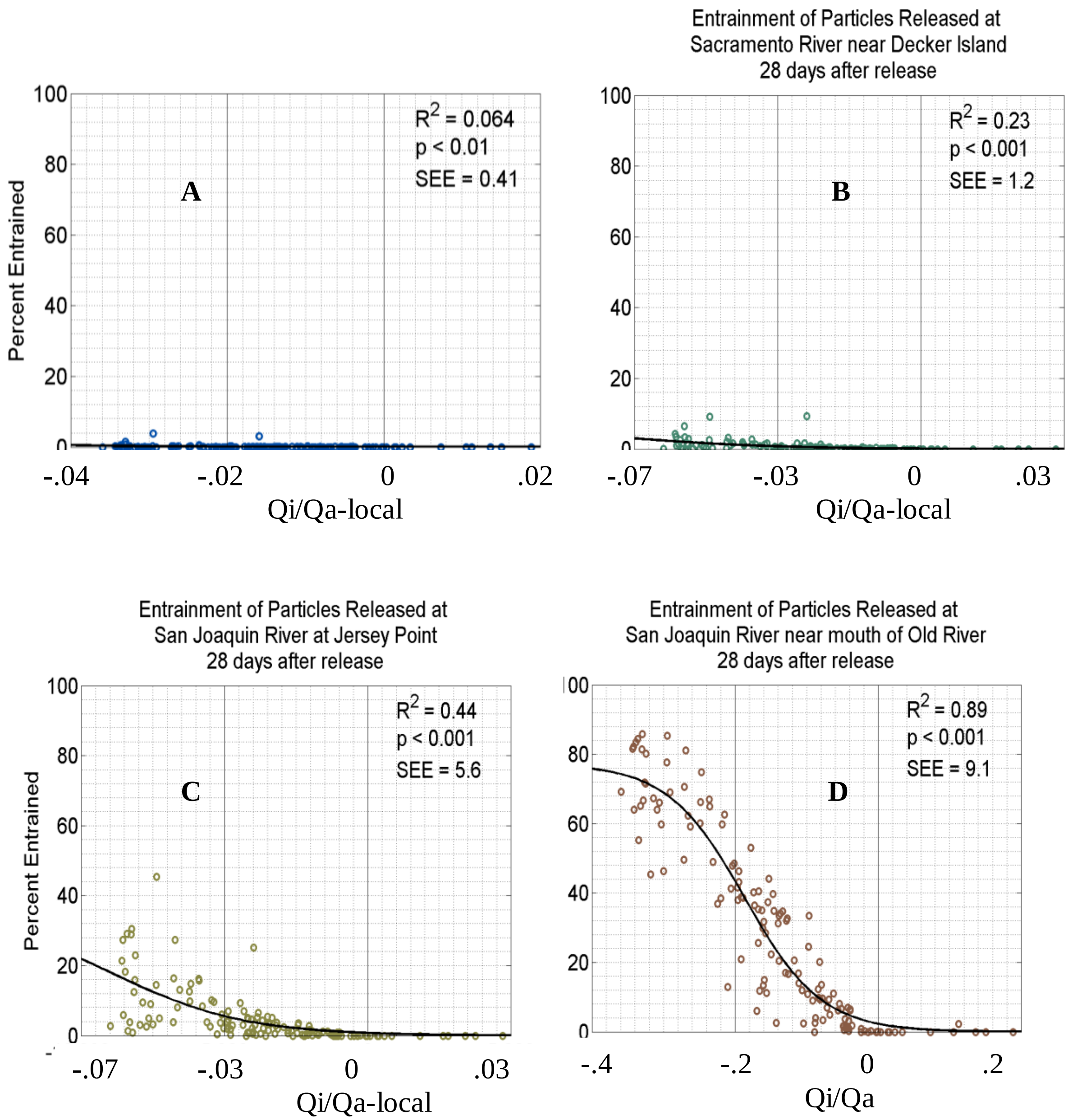


Figure 11: **Entrainment of Particles as a function of Modeled OMR and the Flow Index**
Percent of particles entrained at the CVP and SWP export facilities can be represented flow index. Particles were released at (A) the confluence of the Sacramento and San Joaquin Rivers (station 701), (B) the Sacramento River at Decker Island (station 705), (C) the San Joaquin River at Jersey Point (station 809), and (D) the San Joaquin River near mouth of Old River (station 815). See Figure 10 for a map of these locations. Qa-local is the local tidal amplitude for the release point. Graph D uses Old and Middle River Qa (25,000 cfs).

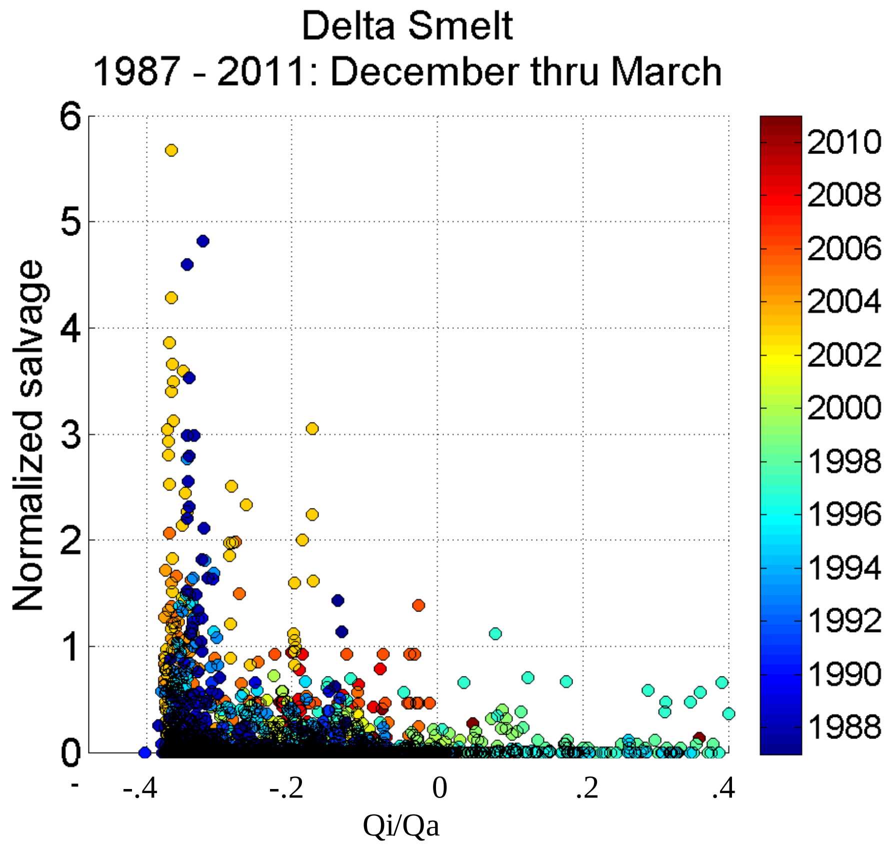
The pattern in Figure 11D will be seen in all the following presentations of data: the highest levels of salvage (and normalized salvage) at for Qi/Qa<-0.3, the regime with riverine-like flow, followed by much lower levels as the flow conditions become more tidal-like. In Figure 11, the data are from passive tracers; what will be seen for field data for fish is that the levels in the tidal condition range of -0.2<Qi/Qa<0.1 the fall off in salvage is much slower and remains non-zero even for Qi/Qa>0 (tidal with net flow away from the export pumps.

Figure 12 shows field data for delta smelt salvage from 1988 to 2010 in the upper graph and color coded with the turbidity levels in the lower graph, following a method used in the most recent biological opinion. The data reveal several points. Again, the data show a strong peak at the most riverine type conditions. The other observation that can be made from Figure 12 is that in the tidal range -0.2<Qi/Qa<0.2, there is a slow tapering of salvage, especially as the index becomes positive, but it remains at times significantly non-zero. This would indicate that transport is occurring even with positive net flow in the tidal regime. Clearly, net advection has a much smaller effect as |Qi/Qa| becomes small; for tidal conditions transport depends more on dispersion than net advection as seen here.

The data also show a curious spike near Qi/Qa = -.2 which is from the same period as the yellow points near Qi/Qa = -0.4 (December 2002-January 2003). In fact, these were all from the same event, which started in December, 2002 with a storm event in which the pump plants suddenly turned up pumping to the maximum allowable of about 300 m^3/s (11,000 cfs). Salvage of delta smelt started shortly after the pumping levels were raised and went to very high levels within a few days. San Joaquin River flow remained relatively low in the neighborhood of 40 to 60 m^3/s (1500 to 2200 cfs). During the three month period of high flows in 2002-2003, there were several short periods lasting from 2 to 8 days in which pumping was reduced, but salvage was at high levels the entire period. Considering these data with flow regimes in mind, most of the time the regime was strongly riverine but when pumping was reduced for short periods, the regime changed to transitional (but likely remained riverine in at least one channel). The lower graph reveals that turbidity levels were high during the entire period as well, which has been associated with salvage levels.

The lesson here is to be cautious about over-interpreting the data: the fact that there is an isolated spike at a level of Qi/Qa in this case is probably more related to the high pumping rates for months and it is speculative whether that should be attributed to the lower level of Qi/Qa=-0.2 without the context of the overall conditions. (Later it will be seen that use of an average is more appropriate than the same day Qi for salvage because of the travel time, which shifts the 2002-2003 spike to the left on the graph). In no other case are high salvage levels seen in the tidal flow regime. In fact, the lowering of pumping rates just reduced the salvage level because the pumping level was reduced: the fish were already in the system and their effective transit time was slowed, but not stopped. Pumping less for a short time reduced the daily salvage but not the overall situation (the reduction in daily numbers in proportion to pumping rate reduction can be seen in the data). Since the periods were brief when pumping was reduced (on the order of a transit time or less), the overall regime in the period was more riverine than transitional.

The quasi-Lagrangian analysis would also suggest that an important parameter is related to the time or travel, determined by the velocity integrated over the time it takes for movement along the entire channel. A complication is of course that the integrating time is a function of velocity so the integrating time gets longer as |Qi/Qa| reduces (moves to zero).



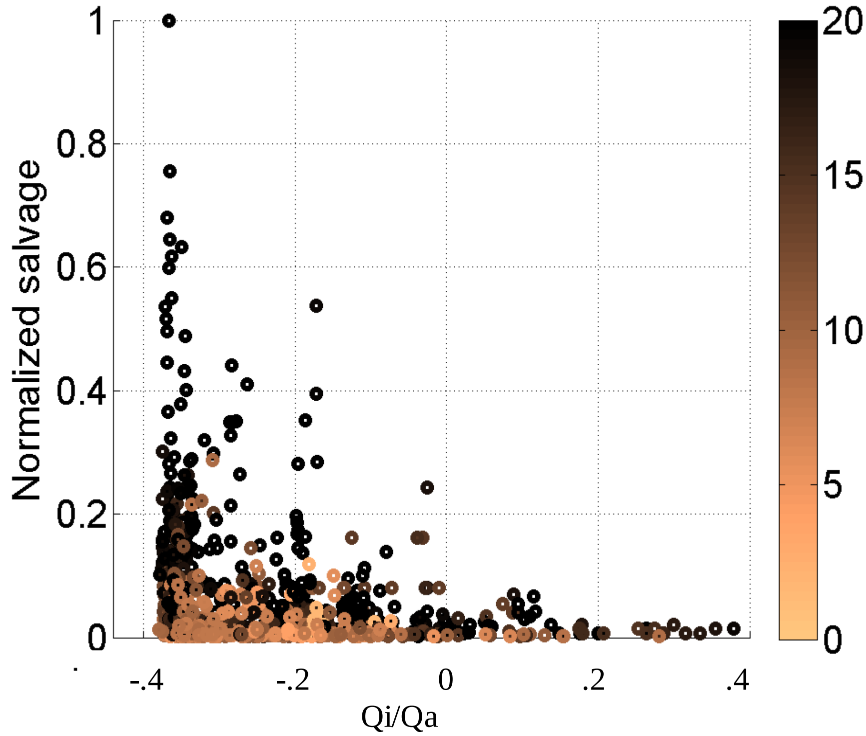


Figure 12: Normalized Delta smelt salvage with Qi/Qa. Upper graph: by year.Lower by turbidity

Figure 13 shows normalized delta smelt salvage averaged from December through March plotted against Qi/Qa averaged over the same time period. Again high normalized salvage is found in upper transitional to riverine conditions while it tapers off in the tidal conditions. Note that averaging over long time periods risks missing smoothing the data so much that important features might be lost. At the same time, short averaging risks not capturing the effects of the length of time for movement (that is, it fails to integrate velocity that is actually responsible for movement over the time the movement takes place).

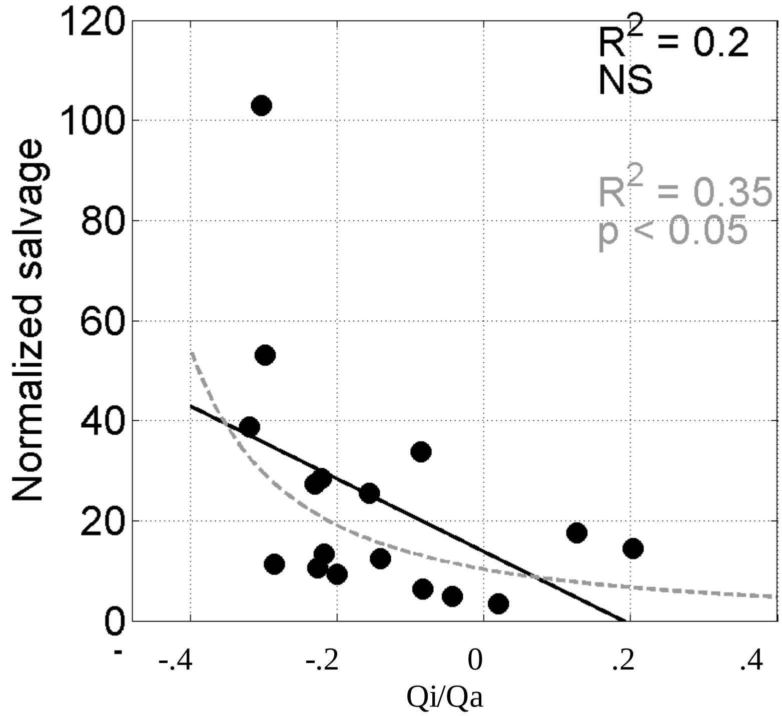


Figure 13: Normalized delta smelt salvage totaled over the December-March frame (both salvage and Qi/Qa are averaged.

Comparison of Qi with <Qomr>

In this section we compare <Qomr> as it relates to salvage, with Qi, which depends only on exports, San Joaquin River flow and (through the linear relationship used) the presence or absence of the Head of Old River Barrier (HORB) or Grantline Canal Barrier (GLCB). As discussed in Appendix 3, <Qomr> is a filtered flow rate based on velocity measurements in Old and Middle River, except when data are missing, in which case it is based on regressions (Old River flow estimated from Middle River, Middle River flow estimated from Old River, or, when both are missing, <Qomr> is based on exports and San Joaquin River flow in a similar fashion to Qi. <Qomr> is estimated about 30% of the time (see Appendix 3).

Although <Qomr> excludes Indian Slough flows, which, as previously shown, contribute at least 13% of the net flow from the north, it includes the agricultural and minor flows ignored by Qi, and it includes variations in flow caused by the neap-spring cycle and weather effects. If the information missing from Qi (namely, Qag, Qm and tidal effects) are important to fish salvage, one would expect that salvage would be somewhat higher when <Qomr> - Qi is negative and lower when it is positive. This was tested and is presented in Figure 14, which shows the unnormalized and normalized results.

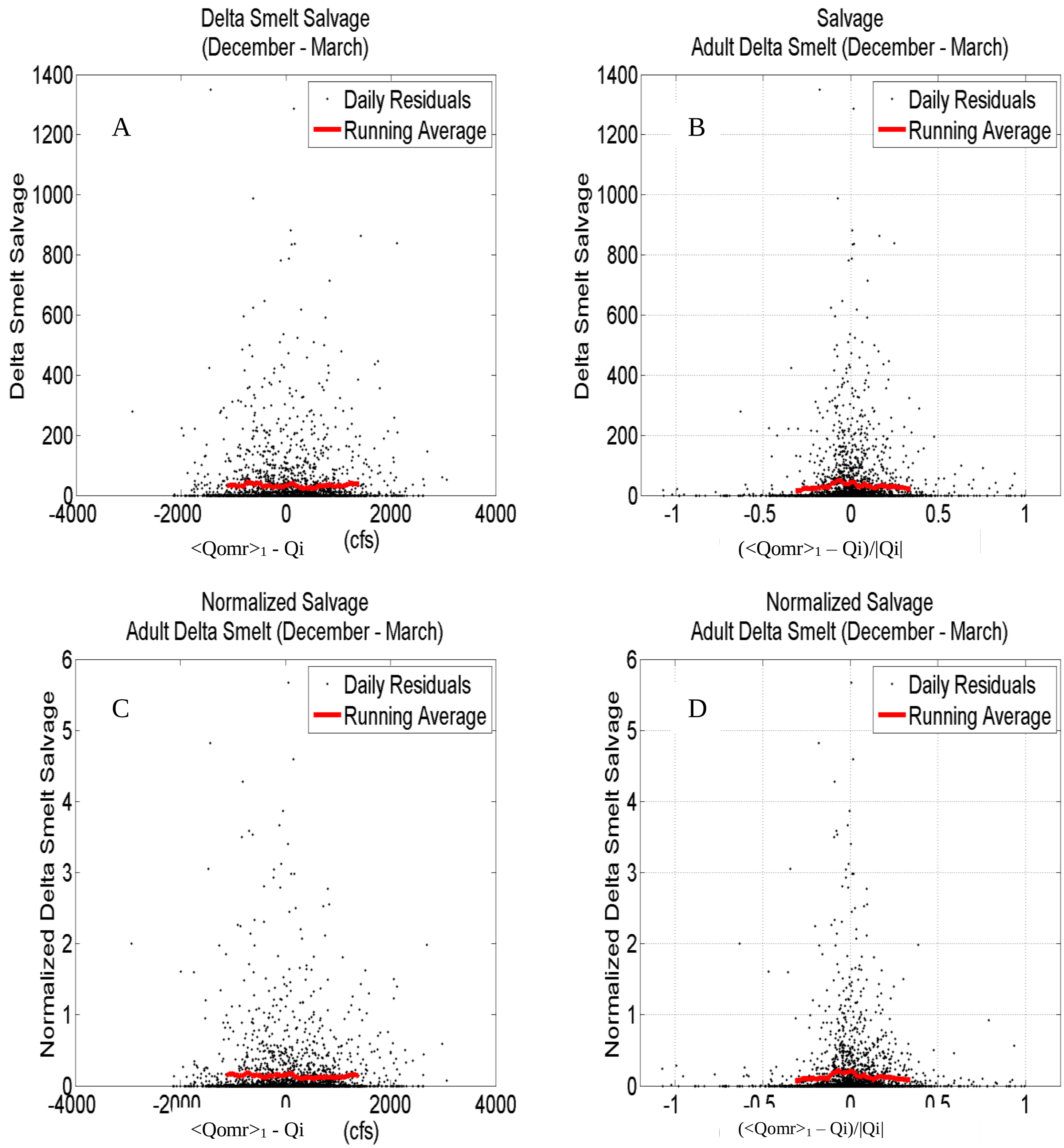


Figure 14: Salvage and normalized salvage of delta smelt plotted against the difference between <Qomr>$_1$ and Flow Index Qi (with and without normalization by the absolute value of Qi).

Figure 14 shows black dots for the daily salvage plotted against <Qomr>$_1$ - Qi, and a running average shown with a red line. None of the four graphs exhibit an obvious trend towards more salvage (or normalized salvage) as a function of the difference between <Qomr>$_1$ and Qi (whether normalized or not). The only possible trend that might be seen in graph C of Figure 14, where more normalized salvage is evident when <Qomr>$_1$ - Qi is *positive* and near 2000 cfs: this would be entirely counter-intuitive since it would suggest when Qi is more negative than <Qomr> by more than 1000 cfs, there is more normalized salvage. This trend is also possibly seen in salvage (graph B) when the normalized {<Qomr>$_1$ - Qi}/|Qi| is between + 0.5 and +1.

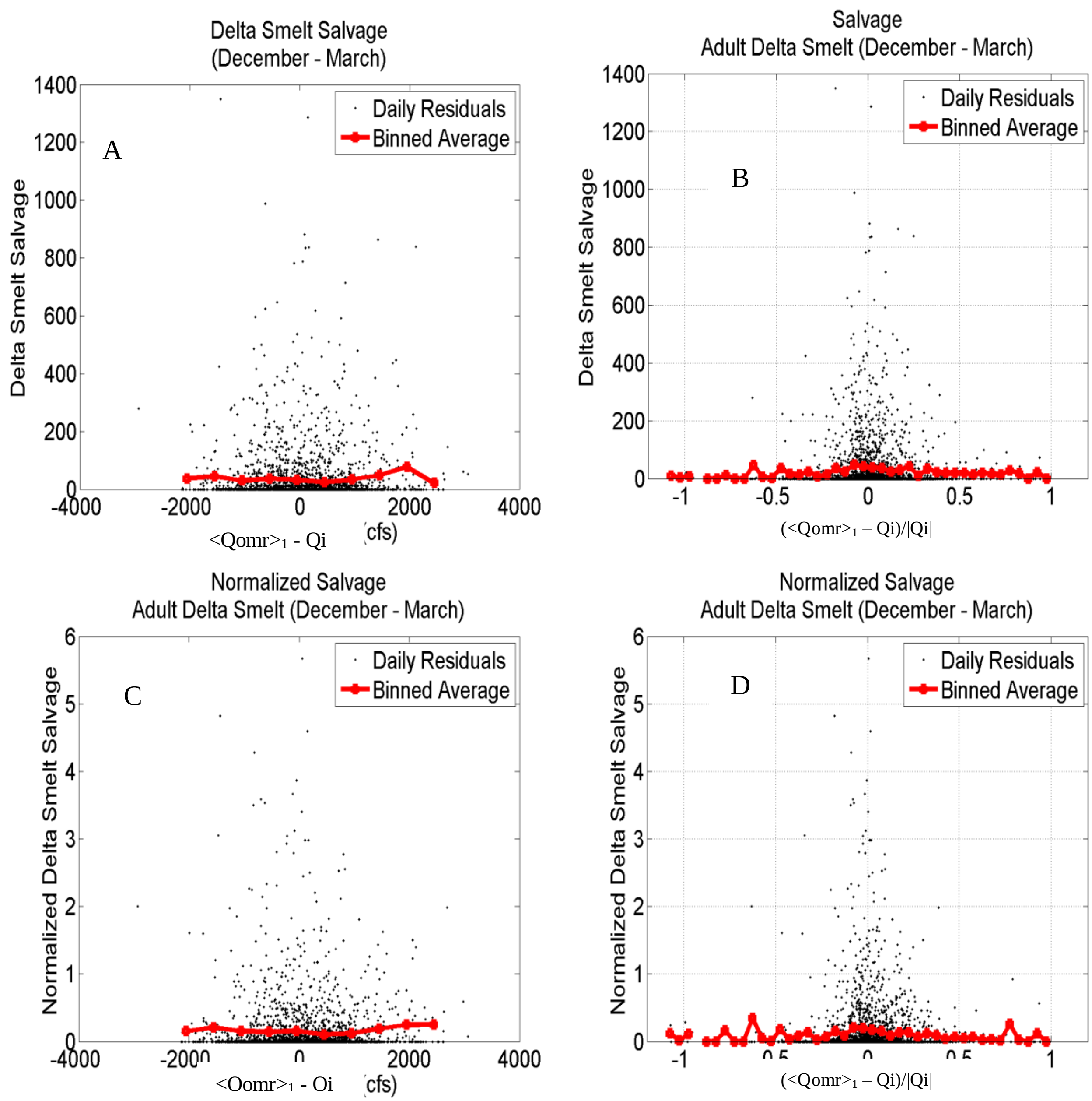


Figure 15: Salvage and normalized salvage of delta smelt plotted against the difference between <Qomr>$_1$ and Qi (with and without normalization by the absolute value of Qi) with binned averages. Figure 14 had running averages, as opposed to binned used here.

Figure 15 is similar to Figure 14 except that the red line is binned averages (binned at 500 cfs intervals). In both Figures 14 and 15, graphs B and D show the data with the flow difference normalized by |Qi|. The absolute value is used to avoid changing the sign of $<Qomr>_1$ - Qi. Normalization by 1/|Qi| allows one to see the data when the difference is of the same order as the absolute value more clearly (when $|<Qomr>_1$ - Qi|/|Qi| is greater than 0.5 where one might expect to see the largest effects; however none are seen in either salvage or normalized salvage. On the other hand, normalization of the flow difference puts the data with the largest |Qi| closer to zero. Large negative Qi corresponds to the largest amount of salvage (see figures 12 and 13 and that is reflected here.

*No apparent information is discerned in these graphs as function of $<Qomr>_1$ - Qi; the graphs would suggest that for salvage, measured **$<Qomr>_1$ does not provide new information compared to Qi (other than noise on the signal)***. The reasons for this are discussed below.

First, Qag and Qm in this period (December through March) are much smaller than Qi, Qexp and Qsjr by an order of magnitude or more (Table 1); in fact Qm is always much smaller than Qexp. The effect of Qm and Qag on travel time is not large, at most about 10% at the lowest levels of |Qi| (Qexp is seldom less than 1500 cfs, about an order of magnitude larger than Qag and Qm for December through March). While the tidal component in <Qomr>-Qi can be large compared to Qi (on the order of 2000 cfs and even larger with weather effects) *the tidal component is transitory and quasi-periodic*; over several tidal days the effect is largely integrated out. When Qi/Qa is about -0.4 (riverine), $|<Qomr>_1$-Qi| will be small compared to |Qi| and will make little difference in the transit time; when |Qi|/Qa is small (order of 0.15 or less) the integrating period is 8 to 15 days, so even though $|<Qomr>_1$-Qi/Qi| might be 0.5 to 1 on any one day, when averaged over the travel time it will be much smaller and have a smaller impact. This is seen in Figures 16, 17 and 18

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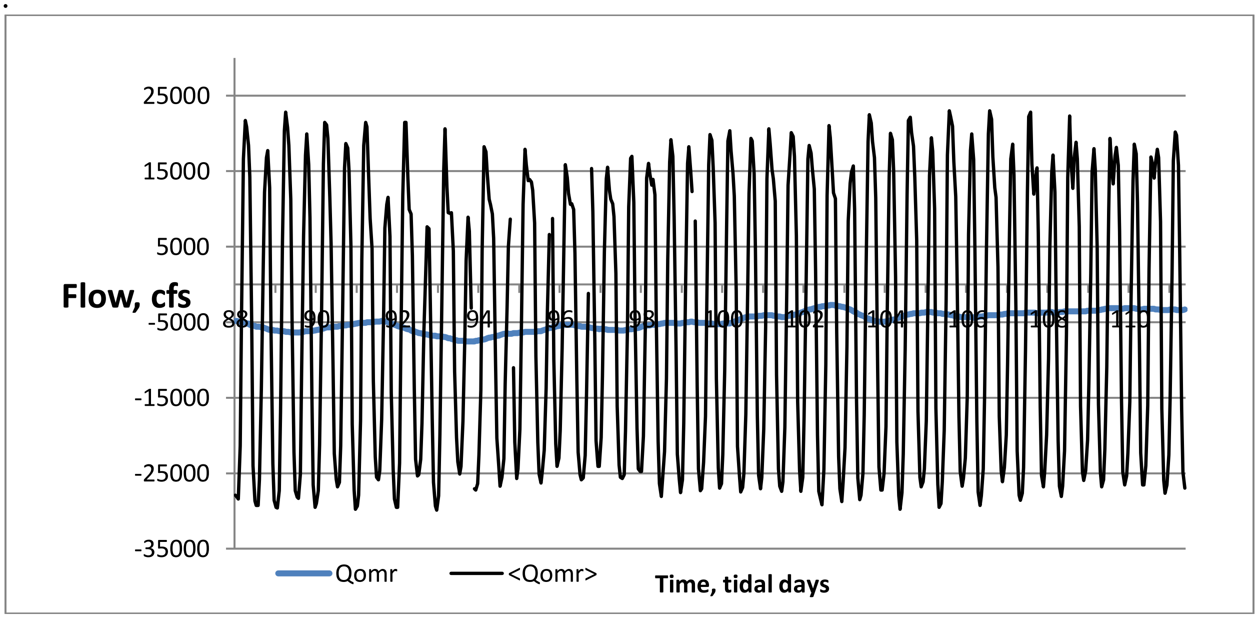

Figure 16. Qomr (sum of Old and Middle River flow) showing measured data at 15 minute intervals, and filtered <Qomr>.

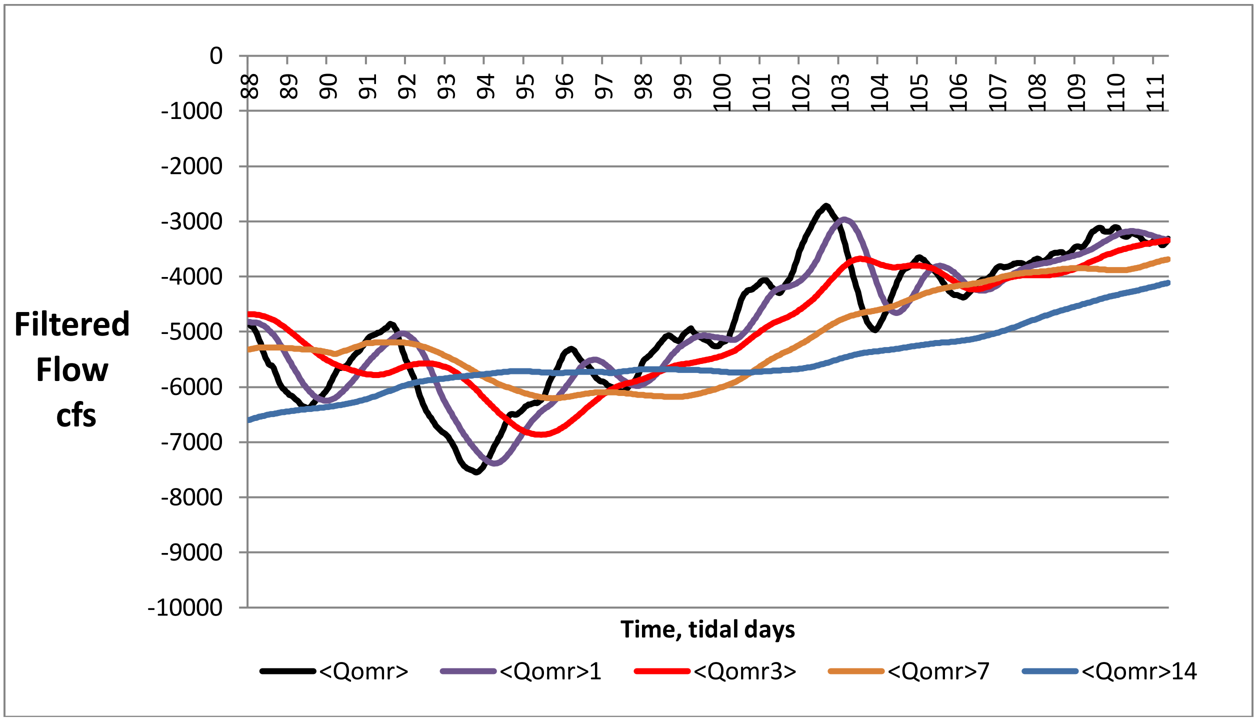

Figure 17. Same as Figure 16, showing only filtered values with running averages of 1, 3, 7 and 14 days.

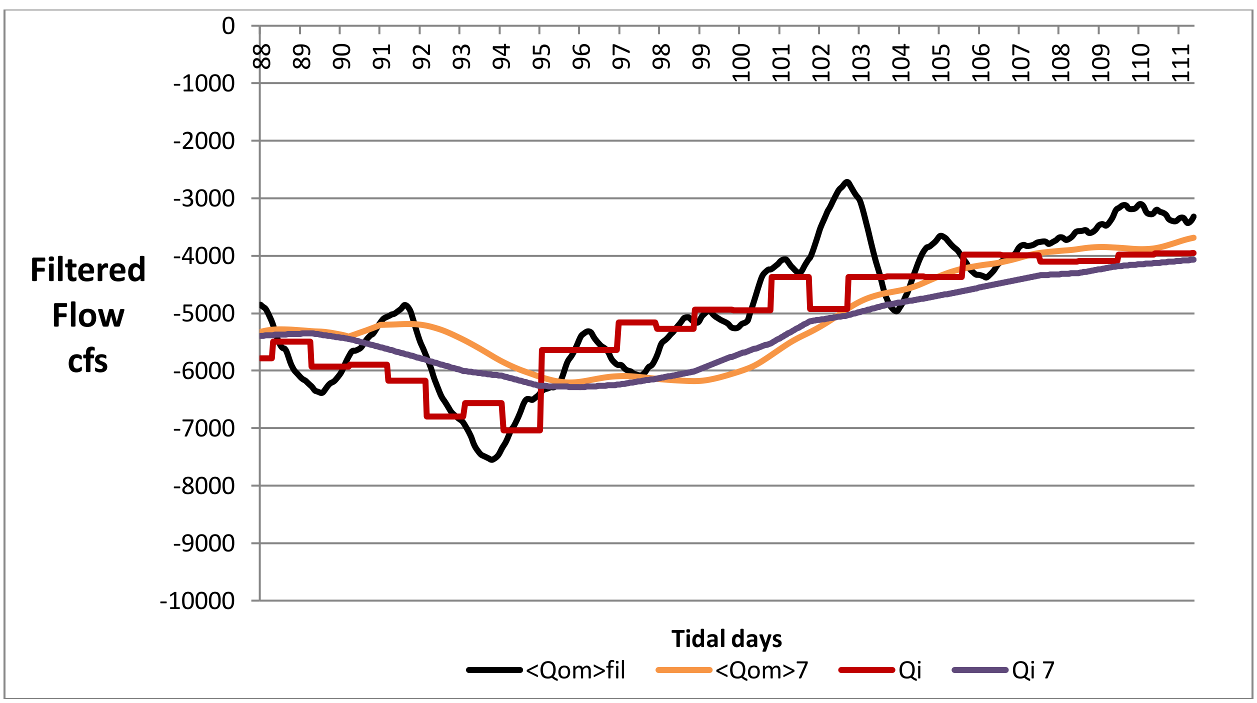

Figure 18. Same as Figures 16 and 17, but showing <Qomr>, <Qomr>7, Qi and Qi filtered with a 7 day running average.

Figure 16 shows flow data for a period (9/14/2013-10/14/2013) with Qi/Qa ranging from the transitional regime to tidal. It is presented here, along with Figures 17 and 18, which cover the same period, as an illustration of how the level of averaging of Qomr affects the variation and range of <Qomr>. Figure 16 shows combined Old and Middle River flow, Qomr along with the tidally filtered <Qomr>. While focus for regulatory purposes is on <Qomr>$_1$ (the subscript designates a one-day average of <Qomr>), the flows (actually the associated velocities) that affect aquatic species are many times larger and Figure 16 helps to illustrate just how great the difference is.

Figure 17 shows <Qomr> further filtered with using a running average (back filtering) of 1, 3, 7 and 14 days. For the time of movement in the period shown, 3 to 10 days is probably the most relevant, but the effects of filtering are easily seen: even a 3 day running average removes much of the tidal components not removed by the tidal filter; there is little difference between 7 and 14 day filtering (except for the obvious phase shift of 7 days as expected).

Figure 18 shows <Qomr> and Qi (which is a daily value), along with a 7 day running average of each. The 7 day averages are very similar and further offer evidence of exactly why no particular pattern is found in Figures 14 and 15, which show salvage plotted against <Qomr>-Qi. *The tidal variations do not appear to be a significant factor in determining salvage because the tidal variations are integrated out over the movement along the rivers*. The other factors in <Qomr> but missing in Qi are either too small for an effect to be observed or too small to have a significant effect.

Thus, by inclusion of only the largest factors Qexp and Qsjr in Qi, with exclusion of the always smaller Qag and Qm, and the exclusion of the tidal variations found in <Qomr>, Qi retains the important features that describe salvage. Based on these arguments and the data shown in Figures 14 and 15, one would expect salvage data presented as a function of <Qomr> to look "noisy" compared to the same presentation using Qi for short term averaging (for example, daily salvage) and the presentations should look largely the same for long period averaging (for example, December-March total salvage against average <Qomr> or Qi). These types of graphs are presented in the next section.

Comparison of Salvage with <Qomr> and Qi

To evaluate how well the flow index Qi reflects Delta hydrodynamics affecting salvage as compared to <Qomr>, we return to the PTM example provided earlier. In the following figures we use dimensional values for Qi and <Qomr>$_1$ so they are easily compared with work as used in biological opinions and assessments. Figure 19 the percent of particles entrained at the export facilities as a function of two indices: the first index (left column: panels A1, B1, C1, and D1) is the average <Qomr>$_1$[11] during the simulation period. The second index (right column: panels A2, B2, C2, and D2) is the flow index Qi.

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[11] For the analyses presented in this section, "<Qomr>" includes both the calculated flows from the USGS website whenever available and estimates of the values using the USGS estimation methods for the periods when data is missing (Appendix C).

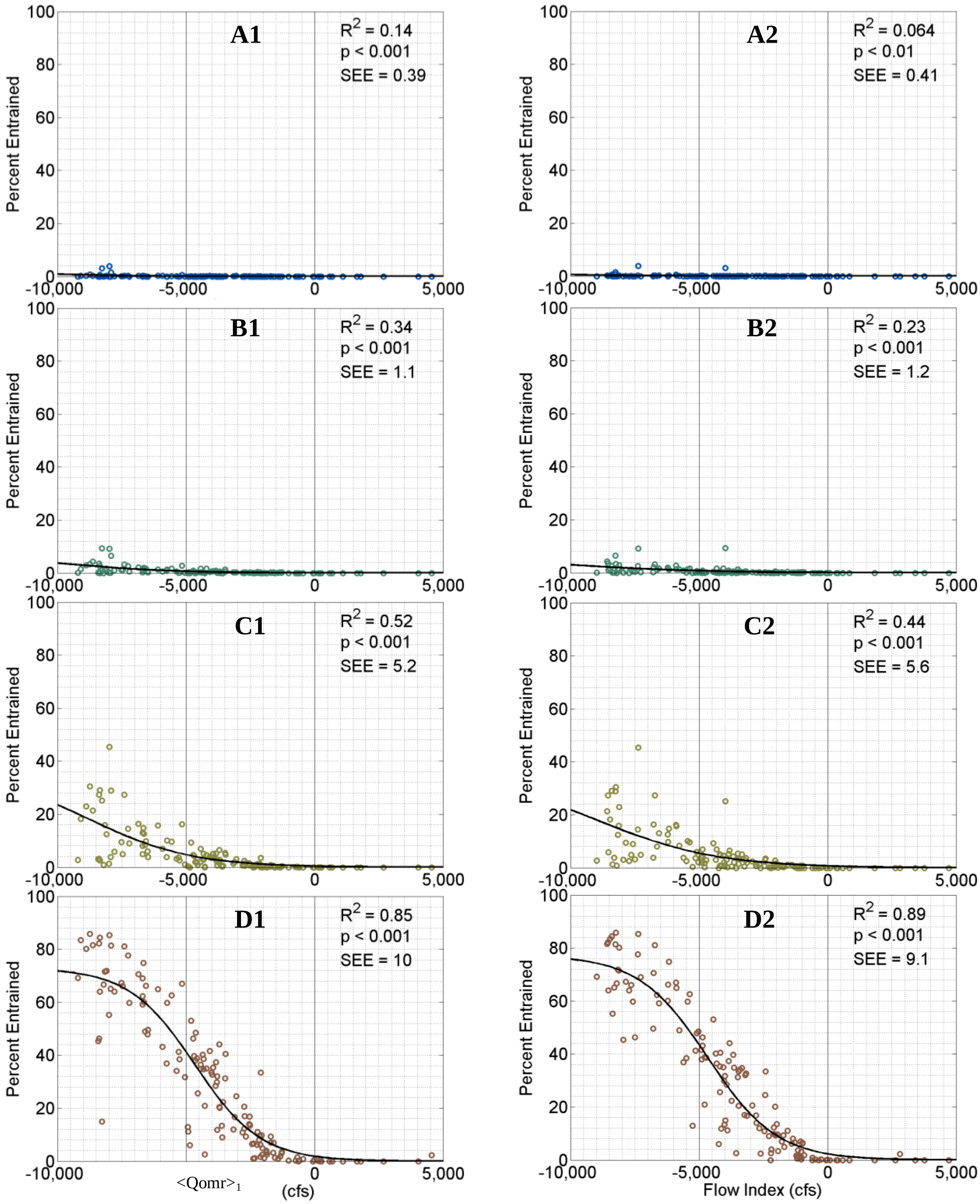


Figure 19: Entrainment of Particles as a function of Modeled <Qomr>$_1$ and the Flow Index Qi
Percent of particles entrained at the CVP and SWP export facilities can be represented by the <Qomr>$_1$ (panels A1, B1, C1, and D1) and the flow index Qi (panels A2, B2, C2, and D2). Particles were released at (A) the confluence of the Sacramento and San Joaquin Rivers (station 701), (B) the Sacramento River at Decker Island (station 705), (C) the San Joaquin River at Jersey Point (station 809), and (D) the San Joaquin River near mouth of Old River (station 815). See Figure 10 for a map of these locations.

Particle entrainment is used here as an indicator of hydrodynamic conditions that predict fish salvage at the export pumps. The use of PTM for entrainment risk analysis and the modeling assumptions used for this report are discussed in Appendix B.

Entrainment of particles released at the San Joaquin River near the mouth of Old River shows a strong response to both Qi values (panel D2) and the <Qomr>$_1$ values (panel D1). As particle release points move farther from the export pumps the entrainment response decreases, until there is almost no response during the 28 day simulation period for particles released at the confluence of the Sacramento and San Joaquin Rivers. The correlations and SEEs for the relationships between entrainment and the alternative index are similar to those for the relationships between entrainment and <Qomr>$_1$; R^2 is slightly higher for Qi for the particle release point with the strongest entrainment response, and slightly lower for Qi for other particle release points. Note that for the release points for A, B and C, the local tidal amplitude is such that any particle released at these locations will spend a large fraction of travel time tidal conditions. Any conclusions or operational recommendations drawn from these relationships would not be materially different whether <Qomr>$_1$ or the Qi is used.

To further evaluate Qi compared to <Qomr>$_1$ for protection of listed fish species in the Delta, analyses similar to those in the existing biological opinions and technical workgroup presentations were performed for both Qi and <Qomr>$_1$. As new analyses are developed to support hydrodynamic indices for the remanded biological opinions or in other venues, they can be similarly used to evaluate the flow index Qi and <Qomr>$_1$.

Analyses are presented below for delta smelt, longfin smelt, and steelhead; analyses for Chinook salmon are underway but not yet complete. For all three species considered here, the relationships of salvage at the export pumps to the flow index Qi are very similar to the relationship of salvage to the <Qomr>$_1$ flow index[12], with the flow index Qi performing slightly better as a predictor of salvage.

Delta Smelt

Both the daily (Figure 20) and seasonal (Figure 21) normalized salvage of adult delta smelt are plotted against <Qomr>$_1$ and against the flow index Qi. For the daily salvage, visual inspection of the plots shows similar distributions for the two indices. The seasonal salvage plots also indicate the equivalence of the two indices, and have similar values of R^2 and SEE for both log-log and linear data fits. Of note are the 2002-2003 spikes around -10,000 cfs and -5,000 cfs: the spikes in the plots using <Qomr>$_1$ exhibit the expected "noise" compared to those with Qi. Since Qexp and Qsjr were relatively constant in these periods, and there is no reason to believe Qag was large or varying (and Qm is always small compared to Qexp, especially in this period) the variation in <Qomr>$_1$ would be attributed to daily variations caused by tides. Over the travel time, this would be averaged and the variation reduced, but this is not seen when the one-day average of <Qomr> is used. This behavior will be seen consistently and suggests against using

[12] For the analyses presented in this section, "<Qomr>" includes both the calculated flows from the USGS website whenever available and estimates of the values using the USGS estimation methods for the periods when data is missing (see Appendix 3, Section 3.2).

<Qomr>$_1$ and Qi data on a daily basis (as has been common) but rather averaged over a longer period. Note that when total salvage is plotted against the value of <Qomr> or Qi averaged over the season (Figure 21), the plots are nearly identical, suggesting again that the small terms omitted in Qi are not important compared to Qexp and Qsjr.

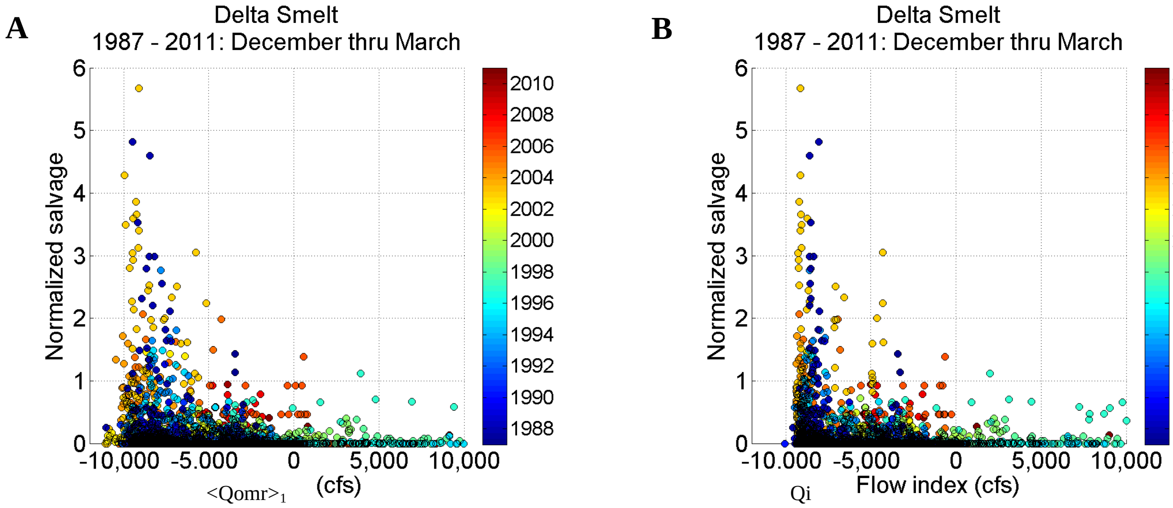


Figure 20: Daily salvage of adult delta smelt normalized by the prior FMWT index

Daily salvage of delta smelt from December through March of 1987-2011 is normalized by an annual population index (i.e. the Fall Midwater Trawl (FMWT) index) for each year and plotted against (A) the <Qomr>$_1$ flow and (B) the flow index Qi. Data points are colored by the water year.

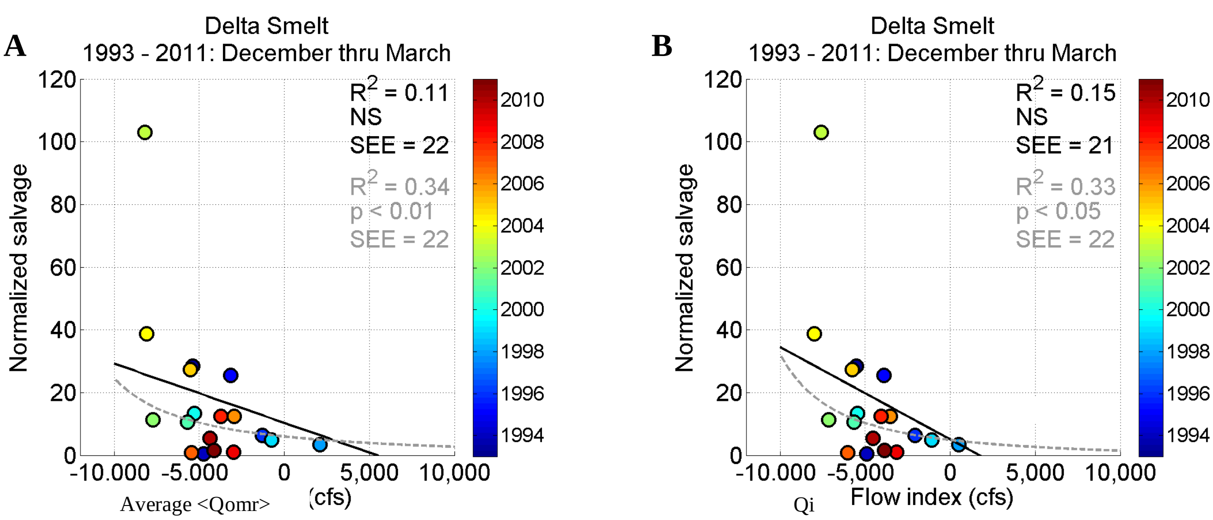


Figure 21: Seasonal (December through March) salvage of adult delta smelt normalized by previous FMWT index

Daily data from Figure 20 are summarized seasonally in this figure by showing the total salvage for December through March, normalized by the annual FMWT index, plotted against (A) the average <Qomr> (USGS data) during the period, or (B) the average flow index Qi during the period. Linear (black line) and log-log (grey dashed line) least squares fits are shown with the statistical parameters listed in the upper right corner of each plot. NS = not statistically significant ($p>0.05$)

USFWS, following the work of Deriso (2011), have developed analyses of delta smelt salvage that include Delta turbidity conditions in addition to south Delta hydrodynamic conditions. This work appears to show a relationship between normalized salvage of adult delta smelt, turbidity conditions measured at Clifton Court Forebay and <Qomr> net flow conditions, as illustrated in Figure 22. Figure 22(A) is reproduced from the USFWS draft biological opinion (2011), in which <Qomr> values are used. Figure 22(B) shows the relationship between adult delta smelt salvage, turbidity and the flow index Qi.

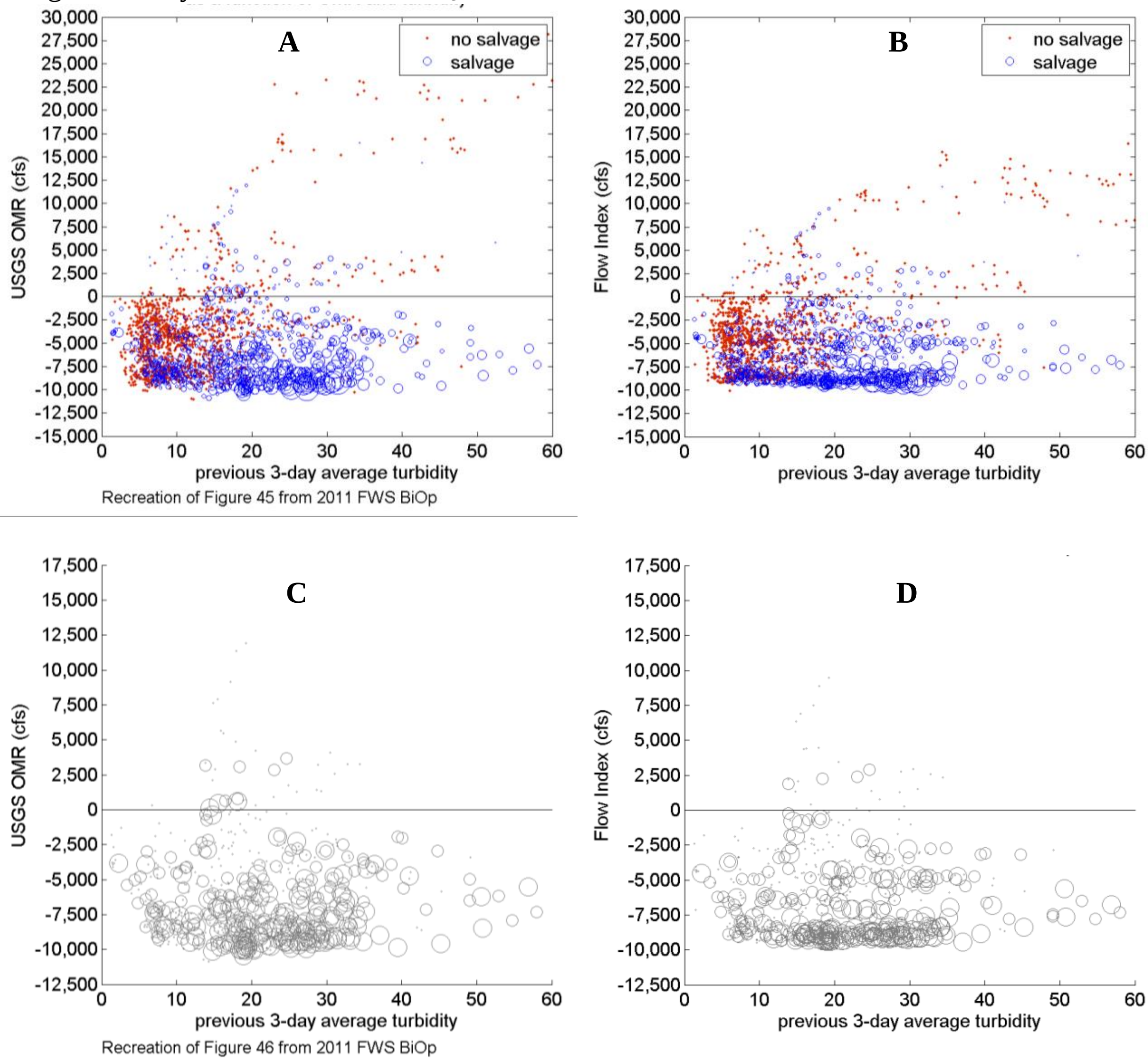


Figure 22: Normalized salvage of delta smelt as a function of turbidity and <Qomr>$_1$ or Qi
Panels A and B show normalized salvage (size of bubble) as a function of 3-day average turbidity at Clifton Court Forebay and either <Qomr>$_1$ (Panel A) or the flow index Qi (Panel B). Panels C and D show normalized salvage (classified into 3 bubble sizes) as a function of 3-day average turbidity at Clifton Court Forebay and either <Qomr>$_1$ (Panel C) or the flow index Qi (Panel D). [Data source: Panels A and C are recreated from the USFWS 2011 biological opinion using data provided by USFWS]

By inspection, the flow index Qi is equally useful in describing the Delta hydrodynamic conditions that contribute to salvage of adult delta smelt. In fact, the vertical scatter appears slightly reduced in Figure 22(B), as expected.

Figure 22(C) is also reproduced from the 2011 USFWS draft biological opinion. This figure presents the same relationship between turbidity, OMR net flows and adult delta smelt salvage, with salvage data points sorted into bins of magnitude relative to the previous Fall Midwater Trawl abundance index. Figure 22(D) presents the same relationship using the flow index Qi. Again, the flow index Qi appears to provide an equivalent utility in predicting adult delta smelt salvage, as compared to <Qomr>$_1$, but with less scatter (as expected).

In Figure 23, a familiar plot format is used to illustrate the data relating turbidity, south Delta hydrodynamics and adult delta smelt salvage. These data are the same presented in Figure 22. Here, turbidity is represented by the color of the data points, as indicated by the color bar on the right side of the plot. Figure 23(A) shows <Qomr> versus normalized salvage, and Figure 23(B) shows the flow index Qi versus normalized salvage. A comparison of these plots illustrates the similar utility of the <Qomr>$_1$ index and the flow index Qi, with added scatter when using <Qomr>$_1$.

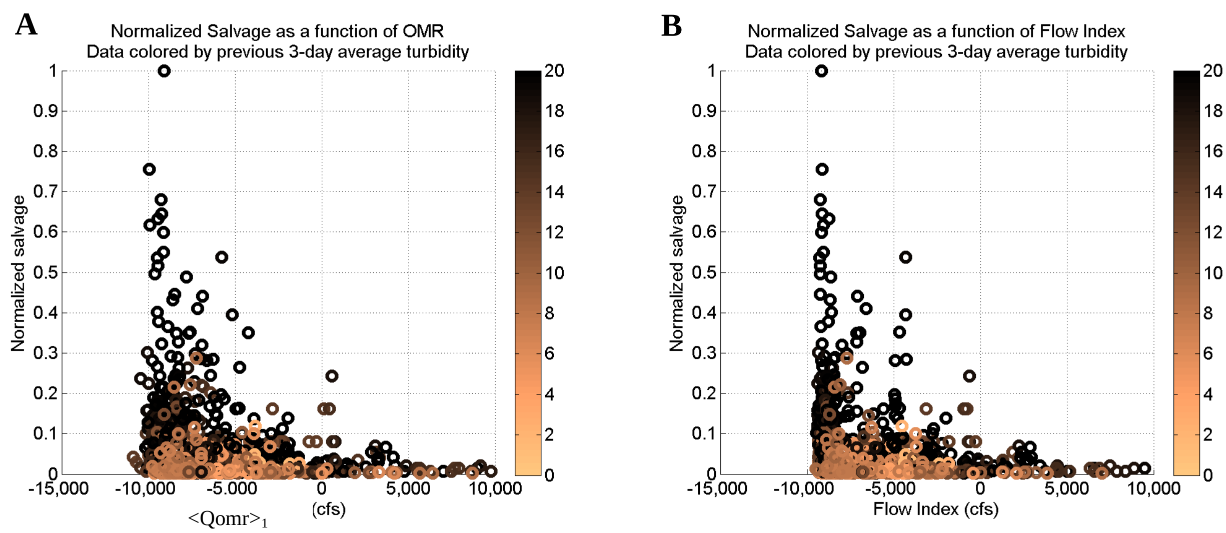


Figure 23: Normalized salvage of delta smelt as a function of <Qomr>$_1$ or Qi and turbidity
Panels A and B recast the same data that was shown in Figure 22 panels A and B into a format similar to Figure 20 The difference between Figure 20 and Figure 23 is that the y-scale here was "normalized" by dividing the normalized salvage in Figure 20 by the maximum normalized daily salvage. The data points are now colored by turbidity instead of water year. [Data source: provided by USFWS]

Longfin smelt

Longfin smelt salvage was examined in the same way as delta smelt salvage: both the daily (Figure 24) and seasonal (Figure 25) salvage of adult longfin smelt is plotted against <Qomr> and against the flow index Qi. For longfin smelt, the plots were done for salvage normalized by prior FMWT, and also for salvage that has not been normalized, since there has been some concern that normalizing the longfin smelt numbers may obscure the true response of salvage to Delta hydrodynamics.

Results for longfin smelt are similar to those for delta smelt: each comparison shows, either visually or through statistics (values for R^2 and SEE), that the flow index Qi is an equally good predictor of salvage at the export pumps as is <Qomr>$_1$ with somewhat less scatter (especially seen in Figure 24, C compared to D). When substantial averaging is done (Figure 25) the results are hardly distinguishable, also as expected. Note that correlations for longfin smelt salvage may not be statistically significant without the incorporation of other variables, so conclusions regarding the relationship between salvage and any flow indices should be judged accordingly. However, the <Qomr>$_1$ and the flow index Qi are both presented to allow comparison of these indices.

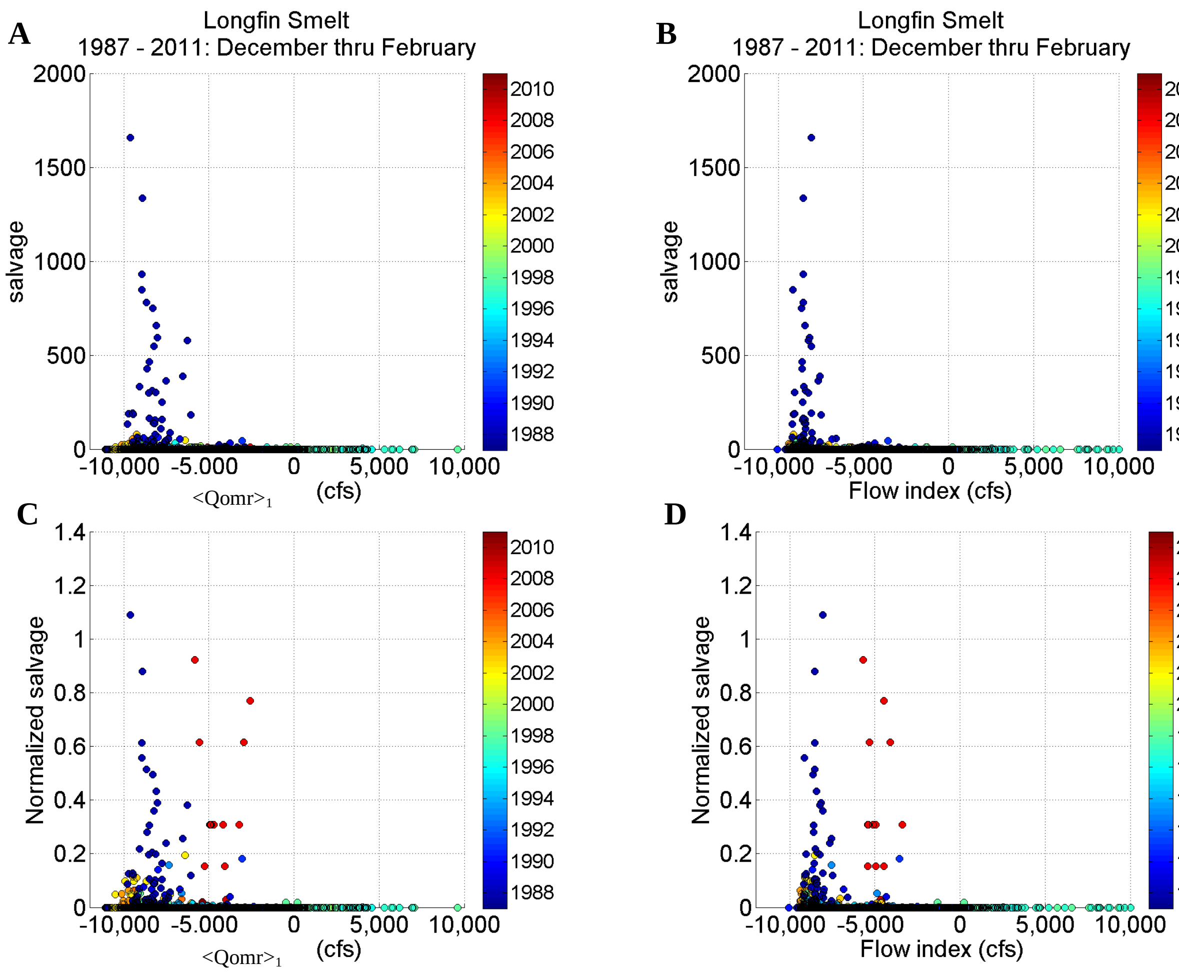


Figure 24: Daily salvage of longfin smelt December through February
Daily salvage of longfin smelt from December through February of 1987-2011 is normalized by an annual population index (i.e. the Fall Midwater Trawl (FMWT) index) for each year and plotted against (A) the <Qomr>$_1$ flow and (B) the flow index Qi. Data points are colored by the water year.

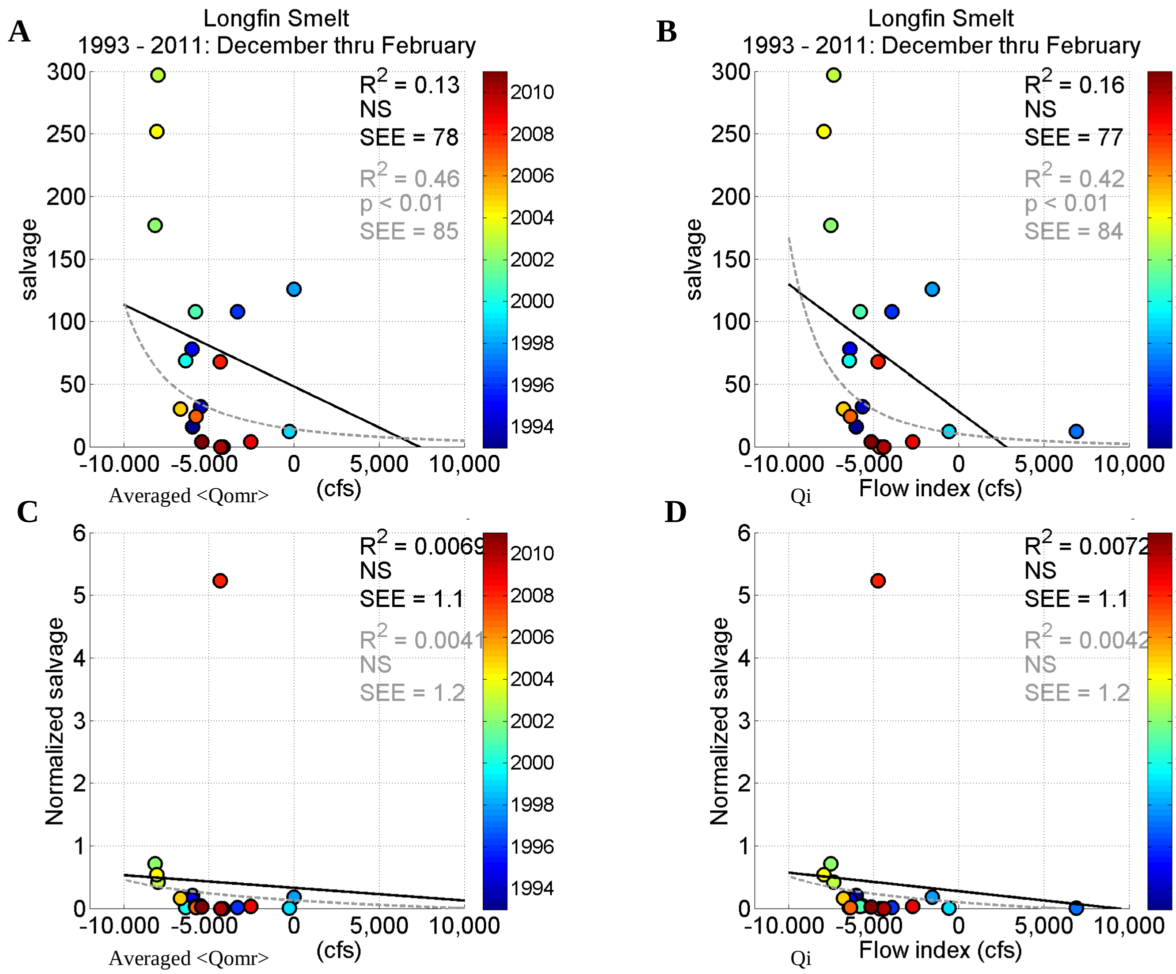


Figure 25: Annual total salvage of adult longfin smelt normalized by previous FMWT index
Daily data from Figure 24 are summarized seasonally in this figure by showing the total salvage for December through February normalized by the annual FMWT index plotted against (A) the average <Qomr> during the period, or (B) the average flow index Qi during the period. Linear (black line) and log-log (grey dashed line) least squares fits are shown with the statistical parameters listed in the upper right corner of each plot.
NS = not statistically significant (p>0.05). Note that only the statistically significant relationship is the log-log function form in panels A and B.

Steelhead

Following technical analyses presented to the IEP steelhead project work team (Grimaldo 2012), Figure 26Figure shows steelhead salvage at the export pumps plotted against the flow index Qi and against <Qomr>$_1$. The top set of plots shows total steelhead salvage, which cannot be normalized because no population estimates are available. The bottom set shows salvage of steelhead with clipped adipose fins, normalized by total hatchery release[13].

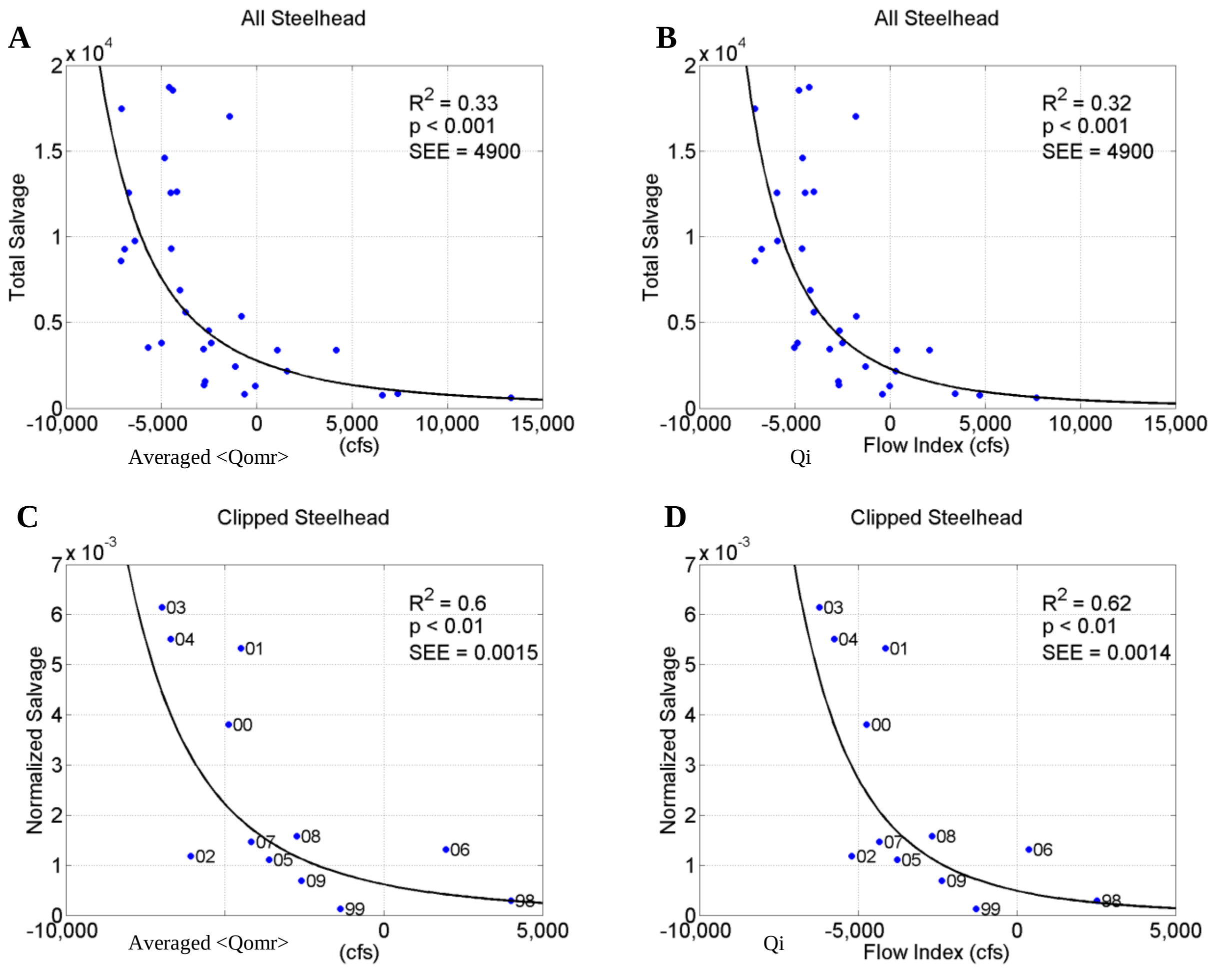


Figure 26: Seasonal Steelhead salvage as a function of OMR flow

Panels A and B show the seasonal (December through June) salvage of all steelhead for all steelhead 1981-2009 as a function of either (A)average <Qomr> or (B) the average flow index Qi. The total steelhead salvage cannot be normalized because no population estimation is available for wild steelhead. Panels C and D show the seasonal (December through June) salvage of steelhead with clipped adipose fins normalized by the total hatchery release for 1998 through 2009 as a function of either average (C) <Qomr> or (D) the flow index Qi.

[13] Daily salvage data and annual hatchery releases were provided by Lenny Grimaldo, Bureau of Reclamation, Bay-Delta Office. The analysis was recreated here for comparison with the flow index Qi.

For both total steelhead salvage and hatchery steelhead salvage, results follow the same pattern as those for delta smelt and longfin smelt: salvage response to the flow index Qi is very similar to salvage response to <Qomr>$_1$. Because these are heavily averaged, they are, as expected, largely indistinguishable.

Note however that steelhead are resident in the San Joaquin River and as such have two routes to get to the export pumps: Old and Middle River and directly via Old River from its head (and Grantline Canal). As such, it might be better to examine steelhead (and San Joaquin salmon) against Qexp directly, rather than Qi or <Qomr>, as argued previously.

Effect of averaging over travel time

The above discussion strongly suggests that salvage is related not only on the conditions at the time the fish are salvaged (i.e., Qexp) but on the velocity conditions over the travel time over the pathway to the export pumps. Ideally, one would use the Lagrangian path to determine the travel time and the averaging time (or more correctly the integrating time); this would be correct for a fluid parcel but not precisely the same thing for a fish, which can inject its own behavior into the pathway. At any rate, examining salvage based solely on the conditions of that day and not on antecedent conditions, which can vary, would introduce unnecessary errors. To examine this, we looked at 7-day running (back) averages of Qi (designated Qi$_7$) and <Qomr> (<Qomr>$_7$) and relate them to salvage at the end of the 7-day average. Figure 27 shows the results for delta smelt adults (compare to Figure 20).

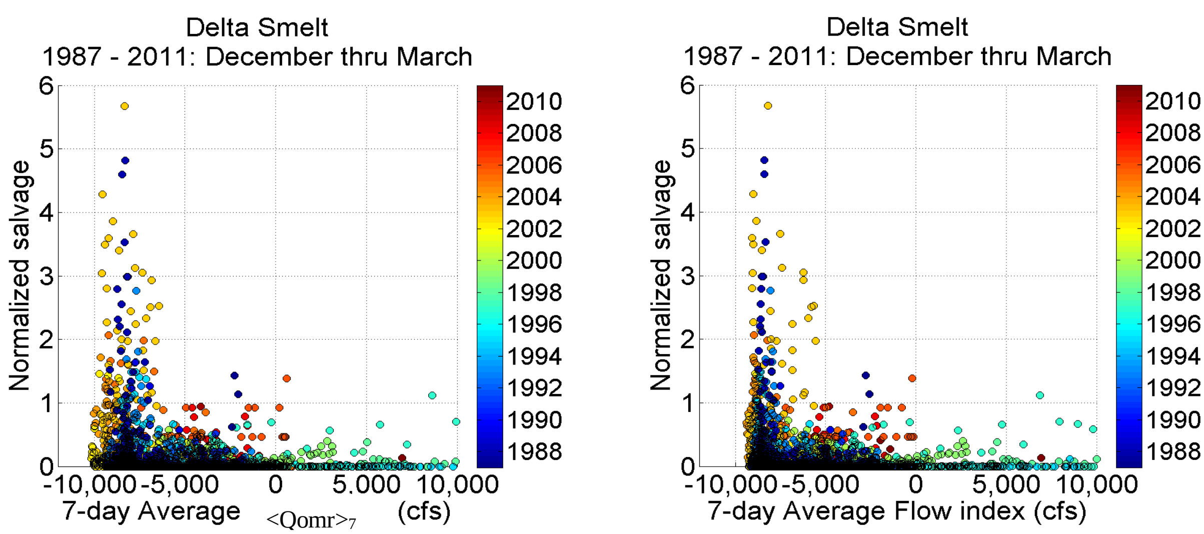
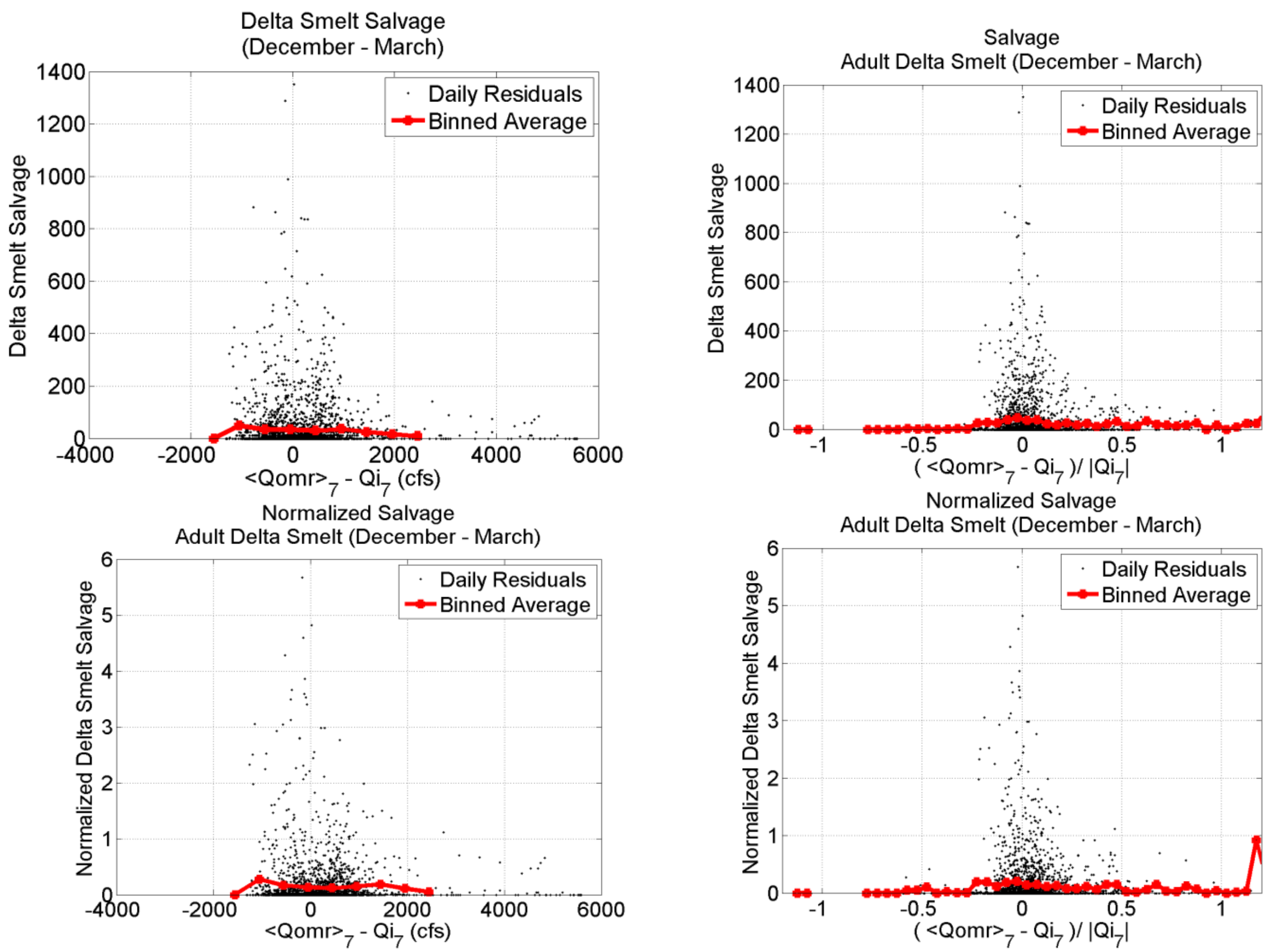


Figure 27: Same data as Figure 20, with 7-day running averages for <Qomr> and Qi

One sees less scatter than in Figure 20, and the 2002-2003 data are much more closely aligned (recall that this was a period of very high pumping with largely riverine conditions, interspersed with relatively short periods of lower pumping).

With an averaging of 7-days one would expect that a good deal of the neap-spring variation would be removed. Previously in Figures 14 and 15, it was seen that the use of <Qomr> compared to Qi seemed to inject noise but not useful information (in other words the variations due to tides, weather, agricultural and minor diversions, or such the variations due to filling Clifton Court Forebay did not have an easily discernible effect on salvage). This is not surprising as these items are either small compared to Qexp and Qsjr (which are contained in Qi) or they the averaging over the travel time reduces their net effect. Figure 28 shows the same data shown in Figures 14 and 15, but instead plotted against $\langle Qomr \rangle_7 - Qi_7$, the seven day averages. These are presented to see if the remaining differences show a trend (i.e., the differences that include the minor flows and other flow effects of longer period than 7 days). No such trends are apparent: even with 7 day averaging, <Qomr> shows no apparent added information compared to Qi. There is no trend that would suggest when $\langle Qomr \rangle_7 - Qi_7$ is negative, there is more salvage (as has been hypothesized but never established); the data suggest again that use of <Qomr> compared to Qi does not provide more information; rather it adds more noise.



This is important for setting a standard: it would suggest the use of Qi (exports and San Joaquin River flow) as the mechanism to control salvage at the export pumps (or simply Qexp for San Joaquin River salmon and steelhead), rather than <Qomr>, which includes flows not controlled by the water projects and not directly related to salvage at the export pumps. This would make sense as part of a balanced approach required by state policy to promote the dual goals of environmental protection and water supply reliability: exports would be regulated on those factors the projects can control (exports, barriers and San Joaquin River flows) and would not be burdened by being regulated by <Qomr> which includes agricultural flows, minor flows and the variations of the tides and weather for which the exporters are not responsible and cannot control. Furthermore, the evidence above indicates there is no loss of protection of species by regulating based on Qi alone. It simplifies compliance, it is more efficient, it allows accurate forecasting of operations and it puts the burden of protection on the party causing the problem.

Conclusions

1. Flow and velocity parameters should be normalized so that when changes occur that affect tides (such as sealevel rise, channel alterations or construction of tidal habitat) regulatory parameters can be adjusted based on similarity considerations.
2. Tidal regimes can be identified (riverine-like, tidal-like and transitional) but their ranges are not precise. The transitional regime can be tidal in one channel and riverine in another at the same time.
3. Normalized salvage and salvage are very much larger in riverine like conditions, but other factors including turbidity are at play as well. Salvage can be low in riverine-like conditions when fish are not present.
4. Normalized salvage and salvage are much lower in the low end of the transitional regime and in the tidal regime, where they are more weakly related to the flow index (i.e., once in the tidal regime, tidal effects are more dominant); when net flow is small compared to tidal flows, salvage is generally small and appears to be independent of the net flow direction.
5. In at least one incident (2002-2003), when riverine conditions dominated, reducing pumping for a few days had no overall effect on conditions: daily salvage reduced because pumping reduced, but the changes to transitional or the high end of tidal conditions did not change the overall presence of delta smelt. Instead the short duration pumping reductions seemed to have simply reduced the numbers of fish salvaged because less water was pumped.
6. A flow index based only on exports and San Joaquin River flow can adequately characterize flow regimes and the risk of salvage or entrainment.
7. Comparison of the flow index with measured <Qomr> does not reveal any additional information is gained from <Qomr> because the movement time is long compared to low-frequency tidal effects (for example, neap-spring cycle variations). <Qomr> adds noise, but no evidence is found to suggest inclusion of neap-spring tidal effects is important in fish salvage rates. Qi retains the largest factors (Qexp, Qsjr and barrier effects); other factors (like Qag and Qm) are an order of magnitude smaller or in the case of tidal effects, are either small or are reduced by integration over the movement time.
8. The use of Qi (exports, barriers and San Joaquin River flow) as the mechanism to control salvage at the export pumps (or simply Qexp for San Joaquin River salmon and steelhead) makes sense as part of a balanced approach, required by state policy, to promote the dual goals of environmental protection and water supply reliability: the exports would be regulated on those items the projects can control (primarily exports but also San Joaquin River flows and barriers) and the projects would not be burdened by being regulated by factors out of their control, includes agricultural flows, minor flows and the variations of the tides and weather. Furthermore, the evidence indicates there is no loss of protection of species by regulating based on Qi alone. It simplifies compliance, it is more efficient, and it allows accurate forecasting of operations. It puts the burden of protection on the party causing the problem.
8. Care must be taken not to over-interpret particular events. Examination of the entire data set shows that the difference between <Qomr> and Qi as related to salvage do not provide any

apparent information, but use of <Qomr> does add noise. Filtering on a 7-day running average or higher for transitional and tidal regimes seems prudent, in which case the two indices appear equivalent as the tidal variations are reduced. Since Qag and Qm are generally much smaller than either Qi or <Qomr> and are not seen to affect salvage at the export pumps, there is no advantage to using <Qomr>.

It has been shown that with filtering, flow indices Qi and <Qomr> provide substantially the same information for salvage data and that averaging over a period of time related to travel time is preferable when relating flow to salvage. Since regulations are directed at the export pumps, use of Qi reduces noise related to other effects that are not seen to be related to salvage but could affect operations unnecessarily (leading to an unnecessary imbalance between the coequal goals). Current issues of using measured field data include the inability to accurately forecast the index value, delay in knowing if regulations are met, and changes in the index values in the QA/QC process that occur well after the timeframe for compliance, or after operational changes to meet compliance. The flow index Qi presented here resolves the above issues and provides protection for fisheries that are as good as the <Qomr> index.

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Appendix 1: Flow Parameters

QWEST. QWEST is defined as the net daily flow past Jersey Point on the San Joaquin River; it is a calculated value. QWEST was originally developed in part as an indicator of seawater intrusion in the western Delta (1978 and 1987 SWRCB Hearings). The model was never particularly successful in predicting flow or salinity as it focused on a net 'reverse' QWEST and ignored tidal and outflow effects. QWEST was included in the State Water Resources Control Board's draft Decision 1630, although neither water quality models nor fish entrainment models based on QWEST have been particularly successful. This draft decision was not adopted by SWRCB and later superseded by SWRCB decision 1641 in 1999 which did not include QWEST regulations. The complete methodology for calculating QWEST can be found on DWR's DAYFLOW website (http://www.water.ca.gov/dayflow/).

E:I ratio. The E:I ratio is defined as the ratio of State and Federal exports divided by the sum of Sacramento River inflow and San Joaquin River inflow measured at Vernalis. In December of 1994 the CALFED Bay-Delta Accord was signed that specified the ratio of exports that could be diverted from the Delta relative to the inflow. This requirement presently limits Delta exports by the State and federal water projects to a percentage of Delta inflow. In July through January, 65% of inflow can be exported. During February through June, months most critical to fisheries, the allowable E-I ratio is reduced to 35% to help diminish reverse flows and the resulting entrainment of fish caused by south Delta export operations. This ratio is included in SWRCB's current D-1641. Kimmerer and Nobriga (2008) found that simulation of particle entrainment at the export facilities was highly correlated with E:I ratio.

<Qomr>. <Qomr> or OMR flow is the tidally filtered (or its daily average) combined flow measured in Old and Middle Rivers at the USGS gages (Figure 10). Flow and water quality in Old and Middle Rivers is highly dependent on export pumping (Monsen 2007). Fish salvage at the export facilities has been correlated with the magnitude of export pumping and 'net reverse' flows in Old and Middle Rivers (Kimmerer 2008, Kimmerer and Nobringa 2008, Grimaldo et al. 2008). <Qomr> is currently a regulated quantity under the 2008 USFWS and NMFS OCAP Biological Opinions.

Qi. Since the implementation of the OMR regulation in the 2008 Biological Opinions, stakeholders have proposed a variety of alternative hydrodynamic indicators (Hutton 2008, CCWD 2010). Qi is similar to <Qomr> but relies only on the significant factors affecting flows in the south Delta: exports and San Joaquin River flow. Qi is defined as a function of total exports at Banks and Jones pumping plant, Qexp, the average San Joaquin River flow measured at Vernalis over the previous 3 days, Qsjr, and the condition of the channel barriers at the head of Old River (HORB) and Grant Line Canal. Qi used here (no barriers) is:

{Estimated best fit of <Qomr>$_1$ no barriers} = Qi = -0.87(Qexp - 0.48Qsjr) (cfs)

When the Head of Old River barrier is in place, the relationship used is:

{Estimated best fit of <Qomr>$_1$ HORB in$_}$ = Qi = -0.84(Qexp - 0.56Qsjr) - 406 (cfs)

When the Grantline Canal barrier is in place the relationship used is:

{Estimated best fit of <Qomr>$_1$ GCLB in$_}$ = Qi = -0.87(Qexp - 0.53Qsjr) - 1290 (cfs)

Appendix 2

Particle Tracking as a Tool

PTM uses velocity, flow, and water elevation information from DSM2-Hydro to simulate the movement of virtual particles in the Delta on a 15-minute time-step throughout the simulation period. If a particle leaves the Delta system by way of an export or diversion or through any other model boundary, this information is recorded for later analysis and termed the “fate” of the particle. Additionally, the percentage of particles remaining within channels in each geographic region is tabulated and analyzed.

Use of PTM for fishery analysis has gained popularity over the last decade; however, the PTM tool has a number of limitations in application to fishery analysis. Chiefly, since the particles simulated in the model are neutrally buoyant (and therefore have no swimming behavior or other independent movement), results of these analyses are most relevant to the planktonic early larval stages of various organisms that do not move independently in the water column. The particles are not considered to reflect movements of juvenile or adult fish within the Delta, or of larvae that are able to move independently in the water column (for example, by varying their buoyancy). Recognizing these limitations, PTM is used in this report as an indicator of Delta hydrodynamics and potential risk for entrainment.

To evaluate hydrologic and operational variability, particle releases were simulated at the start of each month from January 1990 through March 2012, using historical Delta inflows and tides as inputs for the DSM2 model.

One thousand particles were released over a period of 25 hours (to encompass a full tidal cycle). Particle movement was tracked for 120 days; particle location is reported at 28 days and classified as flux past a specific location, potential entrainment at water intakes, or the percent remaining in channels in specific regions of the Delta and Suisun Bay and Marsh.

Appendix 3

"Measured" net flow in Old and Middle Rivers (OMR)

The values that are often referred to as "measured" net flow in Old and Middle Rivers (OMR) are not directly measured quantities. This section reviews the steps taken to calculate the values that are provided by the United State Geologic Survey (USGS) as tidally filtered daily flows. It is demonstrated that the "measured" net flow is an index that contains substantial error, including error induced from bad data and from periods when data are not available. An estimate of the error in the USGS calculation is presented.

3.1 Calculation of "measured" OMR

Since 1987, the USGS has operated and maintained velocity meters in Old River on the west side of Bacon Island (station 11313405) and in Middle River on the east side of Bacon Island (station 11312676). The meters do not directly measure flow; they measure what the USGS terms an "index velocity", which is a measurement of velocity through a portion of each channel. Typically measurements of the index velocity are taken every 15 minutes. A measurement of the water level (i.e. stage) is also recorded at the same time. These are the actual measurements from which an estimate of net daily flow is calculated. The process used to estimate flow is reviewed briefly below to provide background for the error estimates in the following section.

To calculate flow, the USGS utilizes information collected during a limited number of site visits designed to calibrate the station. First, the geometry of the channel is surveyed to develop a relationship between the cross-sectional area and the water level. Second, velocity measurements are collected at many points along the channel cross section over a relatively short time period (typically about 12 or 13 hours) to capture tidal variability. The USGS incorporates the data collected during these field investigations to develop a calibration relationship called a "rating curve". Rating curves allow conversion of the index velocity to a mean channel velocity, which is then used to estimate flow by multiplying by the channel area. Channel area varies tidally with the water level, and is estimated based on stage measurements. (Ruhl and Simpson 2005) These calculations are all performed by the USGS to produce the 15-minute flow values reported to the USGS National Water Information System (NWIS) website.

Once the 15-minute flow is calculated at each station, the USGS applies a mathematical filter to remove the tidal fluctuations. For the Old River and Middle River stations, this is done with a Godin filter, which is a cascaded running mean filter and response function that smoothes the data twice using a 24-hour average and once using a 25-hour average. The USGS uses a centered filter that requires a minimum of 71 hours of continuous hourly data to generate a filtered estimate for one value at the center of that time period. Every filtered value is calculated using data from 35 hours before and 35 hours after that value. Finally, the filtered hourly data are averaged over 24 hours to determine a net daily value.

The USGS reports both the tidal (15-minute) data and the tidally filtered daily data on the NWIS website[14] in near real time, with data updated every 15 minutes. However, since the filter method requires 35 hours of subsequent data to be collected before <Qomr> can be calculated, the most recent filtered data available is generally 2-3 days old. These filtered values are used to determine compliance under the current implementation of the OMR flow regulation.

The final step in the calculation of net flow in Old and Middle Rivers is to add the tidally filtered daily value for Old River and the tidally filtered daily value for Middle River, which is not done on the USGS website[15].

3.2 Error in Estimation of Missing Data

As with all field data collection programs, there are problems with instruments or information transfer that cause loss of data from the Old River and Middle River velocity meters at times. Due to the filtering technique described above, which relies on a 71-hour set of continuous data, small gaps in data time series can create large holes in the record of filtered values. For instance, if tidal data are missing, the filter leaves a gap of 35 hours spanning each side of the missing data. For a single missing data point, the gap is nearly 3 days. Calculating the daily average of tidally filtered values transforms the 3 day gap in the filtered data to a 4 day gap in the daily value, due to the loss of a single data point. Longer periods of data loss are fairly common in the official record, as shown in Figure 3 3-1

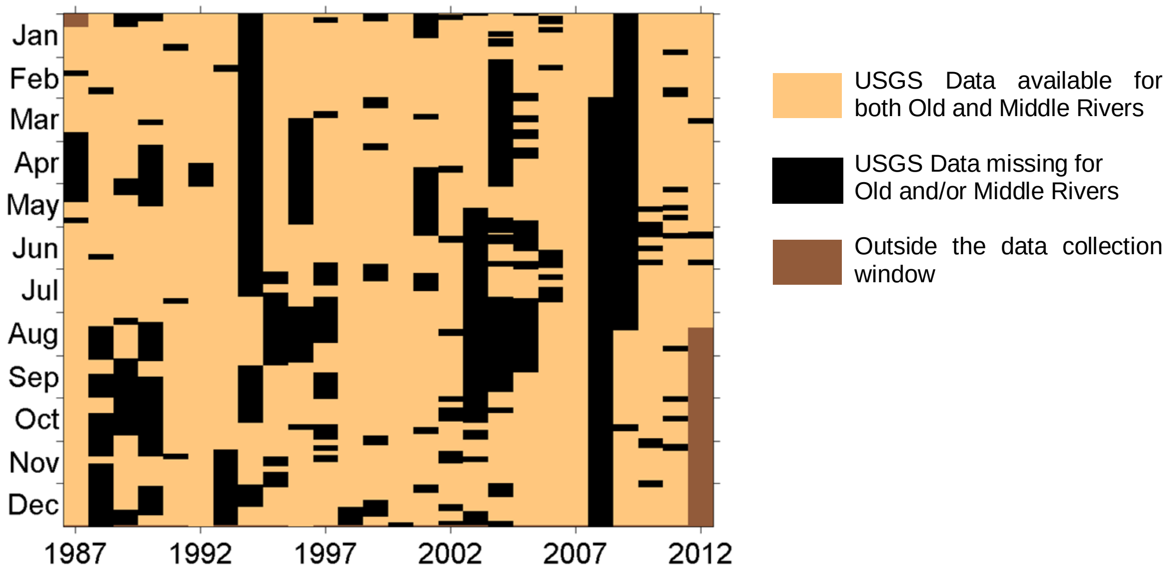

Figure 3-1: Data gaps in the official USGS tidally filtered daily Old River and Middle River data sets
Gaps in data exist throughout the USGS data record. While some gaps (colored in black) last only a few days, many gaps last weeks, months, and even years. [Data source: USGS tidally filtered flow from the NWIS website downloaded August 14, 2012]

[14] http://waterdata.usgs.gov/nwis

[15] Due to the delay in posting of the USGS filtered values and the additional post-processing that is necessary to estimate OMR, DWR posts an estimated value of OMR flow on the California Data Exchange Center (CDEC) website at http://cdec.water.ca.gov/cgi-progs/staMeta?station_id=omr. CDEC values are estimated and are not updated when data are quality controlled.

The USGS NWIS website does not provide estimated values. USGS data are posted as provisional in near real time; USGS subsequently reviews the data and re-posts an approved data set[16], replacing the provisional data. When a value is determined to be incorrect, either in real time or subsequently during the review process, it is simply removed from the website. Figure 3e 3-1 shows when data are missing from the USGS NWIS website, and Table 3-1Tab lists the percentage of time when data are missing for either or both stations.

Table 3-1: Percent of time when data are missing from USGS stations at Old River and Middle River

From the time the sensors started operating in January 1987, a significant portion of the data has been invalid and is now missing values. Prior to analyses, the missing data must be estimated. [Data source: USGS tidally filtered flow from the NWIS website downloaded August 14, 2012]

	USGS "Approved" Data from January 11, 1987 to Feb 29, 2008	All USGS Data from January 11, 1987 to August 11, 2012
Old River	13%	17%
Middle River	21%	24%
Old River or Middle River, but not both	27%	23%
Old River and Middle River	4%	9%
Total time when OMR flow must be estimated	31%	32%

Most scientific analyses require a complete data set, so missing data has been estimated. The USGS developed a data set that incorporated estimates for missing data. This spreadsheet, originally developed in 2006 and updated in 2010, has become widely used in the scientific community. While the spreadsheet clearly indicates when data have been estimated, many scientists have not distinguished between estimated and measured values in their analysis; what is commonly referred to as the "measured" OMR flow data set comprises approximately 70% flows calculated from measured velocity indices and approximately 30% estimated values. The remainder of this section examines the amount of estimation error that has been introduced into the data set.

Typically, when the sensor in either Old River or Middle River is missing data, the tidally filtered daily flow is estimated based on the other river[17]. Figure 3-2 shows a scatter plot of the USGS approved tidally filtered daily flow at Middle River and Old River. The USGS developed piecewise quadratic relationships to estimate flow at one station based on flow at the other station, shown by the blue and red lines in Figure 3-2. The error in using these relationships is shown in Table 3-2.

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[16] As of September 3, 2012, USGS-approved data are only available for the Old River station (11313405) and Middle River station (11312676) through February 29, 2008.

[17] Old River station and Middle River station are located approximately 3 miles apart as the bird flies, but 4 to 6.5 miles apart as the fish swims (through the connecting river channels).

Similarly, Dr. Paul Hutton developed piecewise linear relationships for estimation of tidally filtered flow when one of the two flow values was available; the standard error of estimation (SEE) for Hutton's estimation method is 298 cfs when Middle River is less than -4,000 cfs and 388 cfs when Middle River is greater than -4,000 cfs.

For the 23% of the time when tidally filtered flow in either Old River or Middle River is missing, the value is often estimated based on one of the above correlations.

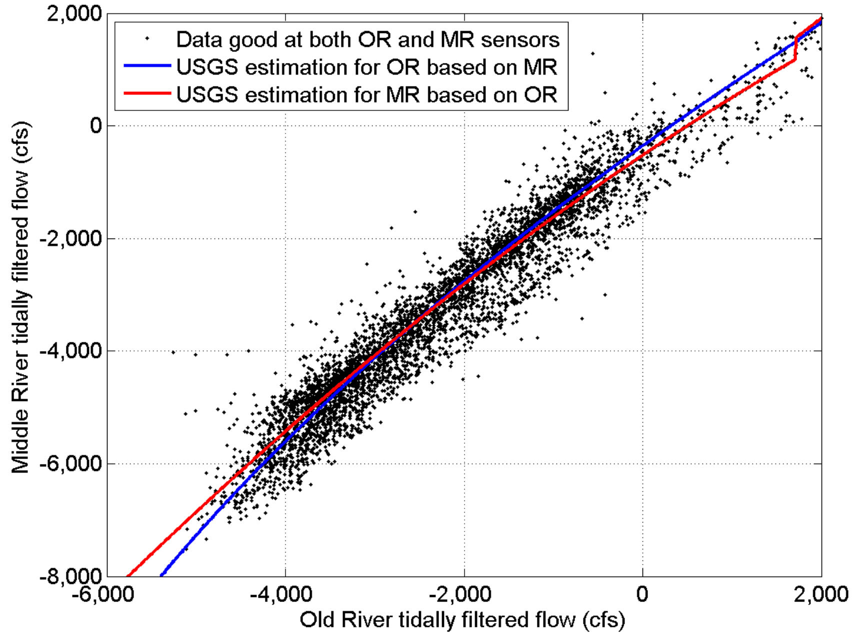

Figure 3-2: Relationship between tidally filtered flow in Old River (OR) and Middle River (MR). When tidally filtered flow from one of the stations is missing, it is common to estimate the value based on the known sensor. Substantial scatter exists in this relationship between the sensors, such that the prediction may be up to 2800 cfs from the actual value. [Data source: USGS tidally filtered flow from the NWIS website downloaded August 14, 2012.]

Table 3-2: Error in estimating flow at either Old River or Middle River
Use of the USGS estimation for tidally filtered daily average flow at either Old River or Middle River. The standard error of estimation (SSE) is a measure of the accuracy of predictions.

Estimation Method	SEE	Maximum Error
Old River based on Middle River	315 cfs	2,040 cfs
Middle River based on Old River	400 cfs	2,840 cfs

For the time periods when both the Old River and the Middle River sensors are missing data, multiple agencies have developed equations to estimate OMR flow based on other system variables. The California Department of Water Resources (DWR) and USGS developed estimates based on the total exports at the SWP and CVP facilities near Tracy, San Joaquin River flow at Vernalis, and the operation of a channel barrier at the head of Old River. The equation parameters and corresponding error estimates are listed in Table 3-3. Similarly, Paul Hutton developed a method to estimate Old and Middle River flows based on the above parameters as well as estimated net south Delta consumptive use and the position of the channel barrier in Grant Line Canal (Hutton 2008).

Table 3-3: Methods to estimate OMR based on Flow at Vernalis and Total Exports, with SEE
DWR and USGS independently developed methods to estimate OMR based on daily flow at Vernalis (Q_{SJR}) and Total Exports (Q_{Exp}) in the form Qomr (cfs) = A * Q_{SJR} (cfs) + B * Q_{Exp} (cfs) + C. The standard error of estimation (SEE) for these estimation methods ranges from 973 cfs to 1,295 cfs. SEE and maximum error for the DWR method is calculated based on the approved <Qomr> data set (as of August 2012). SEE for the USGS method is provided in Ruhl et al (2006), but the maximum error is not reported (NR).

Estimation Author	$Q_{Vernalis}$	Barriers	A	B	C	SEE	Maximum Error
DWR	All	All	0.58	-0.913	0	1,070 cfs	4,360 cfs
USGS	<10,000cfs	In	0	-0.8129	-365	973 cfs	NR
USGS	<10,000cfs	Out	0	-0.8738	1137	1,295 cfs	NR
USGS	≥10,000cfs	All	0.7094	-0.7094	-4619	1,090 cfs	NR

A secondary method to estimate OMR is a simple linear interpolation over the data gaps. The SEE for linear interpolation depends on the number of data points that are missing Table 3-4. As discussed above, the shortest data gap in the tidally filtered daily values is 4 days (due to filter method). As shown in Figure 3-1, many data gaps are much longer than 4 days.

Table 3-1: Error of estimating tidally filtered daily OMR by linear interpolation over gaps in observed data
A viable method to fill small gaps in the tidally filtered daily average USGS values is to linearly interpolate over the data gap. However, the estimation error increases with the length of time that is missing data such that interpolating over more than 4 days can lead to significant maximum error in the estimate.

Length of Gap in Data (days)	SEE	Maximum Error
4	816 cfs	5,600 cfs
10	1,190 cfs	14,300 cfs
20	1,570 cfs	19,400 cfs

In summary, with data missing from the USGS sensors 32% of the time, the <Qomr> data that is typically used for analysis to determine and justify regulations on net flows in Old and Middle River incorporates error due to the necessity of estimating values. As described above, the standard error of estimation ranges from 300 to 1,300 cfs with a maximum error between 2,000 and 6,000 cfs. This error is simply part of what is often termed the “measured” OMR data set.

3.3 “Measured” OMR is itself an index

As discussed in Section 3.1, the values that are often colloquially referred to as “measured” OMR flow (<Qomr>) are calculated based on index velocities that are measured at two point locations in the Delta. The 15-minute OMR flow values are calculated estimates of flow based on the localized measured velocities. USGS then filters and averages the flow values to describe a hydrodynamic parameter that is more useful for fish protection in the Delta than the actual measured values. This type of value is often referred to as an index because it indicates useful information about the system.

As discussed in Section 3.2, “measured” OMR flow is missing for a significant portion of the historical record, and the error of estimating the values is significant. However, even with the estimation error, the <Qomr> index has proven useful to deciphering complicated Delta hydrodynamics. OMR flow has been hypothesized to reflect “the hydrodynamic influence of the water projects’ diversions on the southern half of the Delta and thus the degree of entrainment risk for fishes in that region (Kimmerer 2008; Grimaldo et al. 2009).” (FWS 2011) As pointed out in this document, it is actually velocity that more directly affects fish entrainment. The export pumping directly affects the flow regime (riverine, transitional and tidal) and that in turn bears upon the entrainment.