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Technical Memorandum

DATE: January 25, 2010

TO: NRC Committee on Sustainable Water and Environmental Management in the California Bay-Delta

FROM: Greg Gartrell, PhD, PE[1]

SUBJECT: **Technical Issues Related to Delta Fall Salinity, Delta Hydrodynamics and Salvage of Delta Smelt in the Sacramento-San Joaquin Delta**

INTRODUCTION

The purpose of this Technical Memorandum is to provide the Committee with a concise summary regarding three specific topics within the scope of the Committee's review of scientific questions, assumptions, and conclusions underlying water-management alternatives in the Biological Opinions. The focus here is on technical aspects that will help the Committee to better understand the dynamics behind the data and its analysis. In that spirit, recommendations are made on what to examine, and how to best formulate conceptual models to explain the data and analysis; no recommendations are made on specific findings or conclusions that should be made from the data. In the interest of brevity, references to more detailed information are provided.

SUMMARY

- Fall salinity levels in the western Delta dramatically shifted about 25 years ago, with an increase in the salinity levels in the fall. Although other seasons did not exhibit a similar shift from conditions that prevailed since the late 1960's, the winter salinity regime has changed since the 1920's, indicating reduced flushing of the system during dry years. Changes in the salinity regime alter the distribution of aquatic species, including protected native species as well as their food and predators, and the residence time of the system. The number of *Corbula* found in the western Delta increases as salinity increases. The location of delta smelt in the fall shifts eastward as salinity moves eastward into the Delta. Delta smelt numbers increased (1997-1999), overlapping a period of fresher conditions associated with a five-year wet period (1995-2000) when *Corbula* numbers in the western Delta declined. While the Pelagic Organism Decline (starting in 2002) corresponds with a period of increased fall salinity and increased numbers of *Corbula* in the western Delta, most (although not all) correlations are weak and other explanations are reasonable (for example, the increased salinity is caused by decreased outflow, and decreased outflow increases the residence time of pollutants discharged into the Delta).

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- Tidal flows dominate the Delta. Conceptual models of the dynamics of salinity or fish behavior based on flow averages, rather than the full tidal flow, generally fail.

- The relationship between salvage and exports can be better understood in the context of 1) a relationship with the independent variables (exports and San Joaquin River flow) and 2) tidal flow amplitude. Use of the dimensional, dependent variable, average Old and Middle River (OMR) flow introduces uncontrollable variables (i.e., noise) that provides no better information and obscures the physical dynamics. Use of the non-dimensional, independent variables provides the correct conceptual model and suggests an approach that the Committee may wish to examine to maintain protection of delta smelt and salmon with less impact on water supplies.

WESTERN DELTA SALINITY

Salinity in the western Delta and Suisun Bay has been greatly altered over the past 150 years by human activities, ranging from elimination of tidal freshwater marsh and channelization in the Delta to reduction of outflow due to upstream water use and Delta diversions.[2] Since the mid-1960's (the extent of continuous monitoring), the salinity regime in the Delta during the winter, spring and summer has remained largely unchanged. Evidence of this is presented in Figure 1, where average spring salinity at a location in the western Delta (in the San Joaquin River at Jersey Point) is plotted against total Sacramento basin runoff[3] for the same year, the latter being a measure of the water available. Similar results are found for winter and summer[4].

Figure 2, however, shows evidence of a large shift in the salinity regime since about 1985: high salinity levels have been found in the western Delta in the fall in all but the wettest years since the mid-1980's. This is the result of reduced outflow from the Delta, which allows more salinity intrusion. Several factors reduce Delta outflow, including increased upstream water consumption (including that due to current forestry practices); a change in rice farming practices (fields are flooded in the fall rather than drained and burned); and an increase in diversions from the Delta.

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[2] Contra Costa Water District (2010). "Historical Freshwater and Salinity Conditions in the Western Sacramento-San Joaquin Delta and Suisun Bay: A summary of historical reviews, reports, analyses and measurements" and Appendices. http://www.ccwater.com/salt.asp

[3] Annual unimpaired flow for the Sacramento River provided by the Department of Water Resources (http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST), which is the total flow on the four major upstream tributaries: the Sacramento River at Bend Bridge, the Feather River at Lake Oroville, the Yuba River at Smartville, and the American River at Folsom Lake.

[4] Ibid 2, Appendix E-1.6

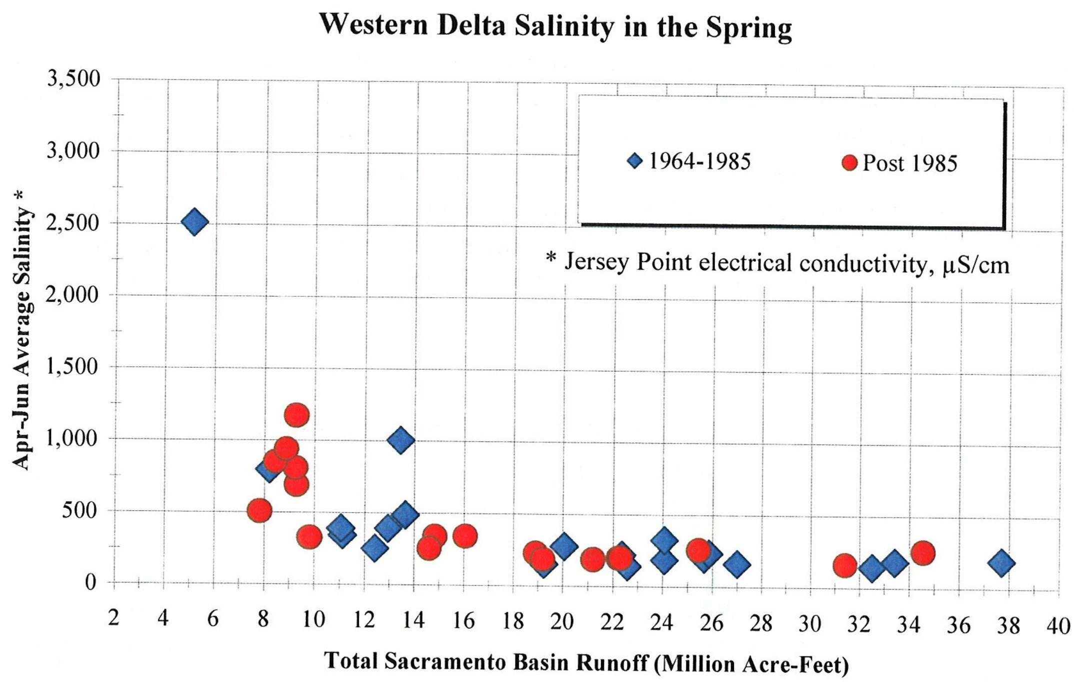

Figure 1: Average spring salinity in the western Delta plotted against total Sacramento basin runoff since 1964. Both pre-1985 and post-1985 data follow the same trend. (The point at 13.4 MAF and 1000 µS/cm was affected by a levee failure in 1972).

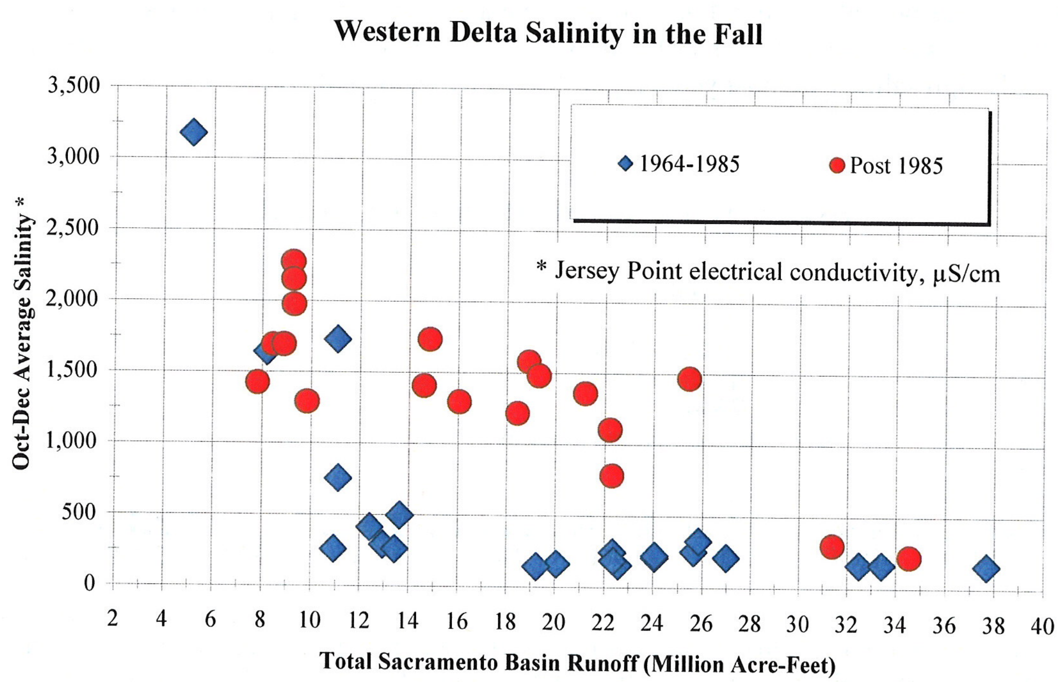

Figure 2: Average fall salinity in the western Delta plotted against total Sacramento basin runoff since 1964. Pre-1985 data follow a distinctively different trend from post-1985 data: higher salinities are found since 1985 for similar hydrological conditions.

The longest salinity record available in the western Delta is at Collinsville, near the confluence of the Sacramento and San Joaquin Rivers. That record (Figure 3) reveals the long term trends: high fall salinity was evident during the 1928-1934 drought, and again during the 1976-1977 drought. Subsequent to the construction of major reservoirs in the 1940's, salinity levels generally remained low in the fall in all but the driest years up until the mid-1980's. Figure 3 also reveals the shift seen in Figure 2: most recent years exhibit high fall salinity regardless of hydrological conditions. In fact, since 1985, 21 out of 25 years experienced high salinity levels in the fall.

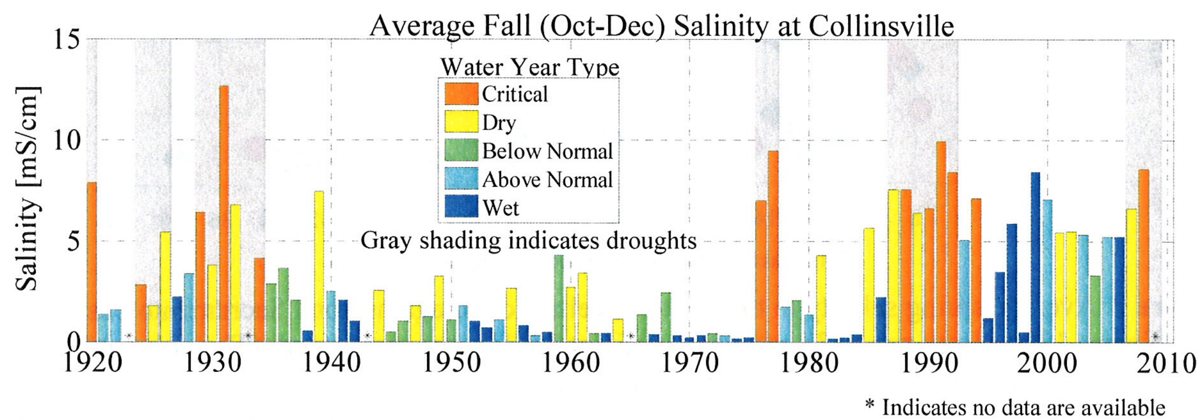

Figure 3: Average fall salinity trend near the confluence of the Sacramento and San Joaquin Rivers. Reservoirs constructed after 1940 allowed salinity control; however, the post-1985 period reveals high salinity in most years regardless of hydrological conditions.

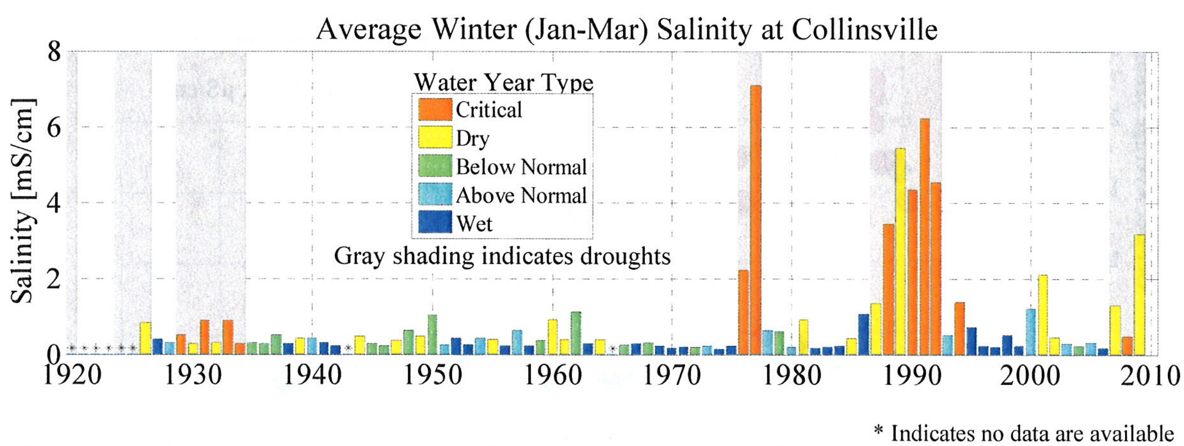

Figure 4: Average winter salinity trend near the confluence of the Sacramento and San Joaquin Rivers. Filling of reservoirs constructed after 1940 reduced flows to the Delta, especially in dry years; however, the post-1995 period reveals the effects of the X2 Standard in dry years (reduced winter salinity compared to the prior two droughts).

The long-term record also reveals another change of interest: reduction in winter freshening of the Delta in very dry years. The 1928-34 drought was likely the driest 6 year period in the past 1,000 years[5]. Salinity intrusion at that time was already affected by channelization and loss of tidal marsh in the Delta (both of which increase salinity intrusion[6]) and diversions for irrigation (minimal in winter). Nonetheless, the record shows the western Delta freshening in the winter during this drought (Figure 4). By contrast, the Delta did not freshen in the winters of the 1976-77 and 1987-92 droughts. In 1995, the "X2 standard"[7] was implemented; subsequent to 1995, average winter salinity is less in dry years than it was in the prior two droughts, but still higher than the 1928-34 drought. Consequently, the potential exists for extended periods of high salinity in the western Delta, especially when the winter period is dry.

DISCUSSION

The clam *Corbula* was introduced into the system around 1987; this species thrives in brackish and saline water, but not in fresh water. As shown in Figure 5, *Corbula* numbers in the western Delta increased during the drought of 1987-92 when salinity levels were high in the western Delta, declined during the 1995-2000 wet period (especially in 1995 and 1998 which had very high runoff and long periods of low salinity), and returned as salinity conditions rose again starting in 2000. During this period, Delta smelt population levels as measured by the Fall Midwater Trawl (FMWT) fluctuated from 1987-1996, rose sharply starting in 1997 to 1999, and declined sharply in 2002 (the start of the Pelagic Organism Decline). Most (though not all[8]) correlations between delta smelt FMWT levels and salinity or *Corbula* numbers are weak or insignificant.

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[5] Meko, D. M., M. D. Therrell, C. H. Baisan and M. K. Hughes. 2001. Sacramento River Flow Reconstructed to A.D. 869 from Tree Rings. Journal of the American Water Resources Association. 37(4):1029-1039.

[6] Enright, C. and S.D. Culberson. 2009. Salinity trends, variability, and control in the northern reach of the San Francisco Estuary. San Francisco Estuary and Watershed Science, Volume 7, Issue 2, CALFED Bay-Delta Authority, December 2009. http://www.escholarship.org/uc/item/0d52737t

[7] "X2 Standard" refers to a water quality objective to reduce salinity from February through June to improve estuarine habitat, implemented by the State Water Resources Control Board, Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary.

[8] We have found significant correlations between fall salinity and subsequent summer Delta smelt population indices (as measured by the Summer Townet survey), but not subsequent fall indices (FMWT). We have also found that Delta smelt Summer Townet and *Corbula* numbers correlate with subsequent December Midwater Trawl, but not FMWT.

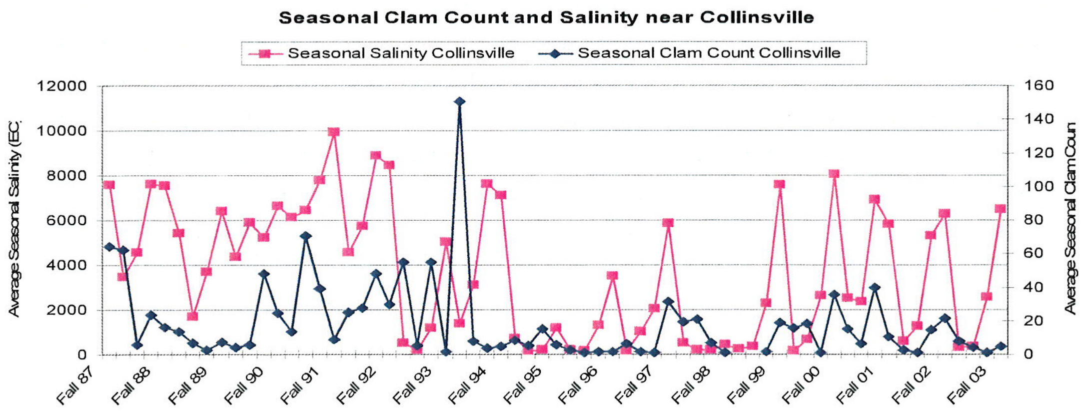

Figure 5: Average seasonal salinity (µS/cm) near the confluence of the Sacramento-San Joaquin River (Collinsville) and *Corbula* number index. Salinity and the *Corbula* index declined in the wet period from 1995-2000.

Recent analysis of the location of delta smelt in the fall shows that delta smelt move eastward as salinity intrusion increases[9]. Figure 6 shows an example of this: locations of delta smelt from the FMWT are shown for two periods with above normal hydrologic conditions. In the pre-1985 case (upper map), when salinity conditions were lower, delta smelt were found in greater numbers in Suisun Bay; in the later years, when salinity conditions were higher, smelt were found farther east. This is consistent with the work of Feyrer *et al.*[10], who used FMWT data to show that delta smelt populations are concentrated near the 2 part per thousand (ppt) salinity location ("X2") in the fall. Consequently, as the salinity regime in the fall has shifted since 1985, delta smelt have moved eastward in response.

[9] Kawakami, B., Contra Costa Water District (2009). Manuscript in preparation
[10] Feyrer, F., M. Nobriga, T. Sommer and K. Newman, (2009) Manuscript in preparation.

FMWT Delta Smelt Average Catch Percentages (Oct-Dec)

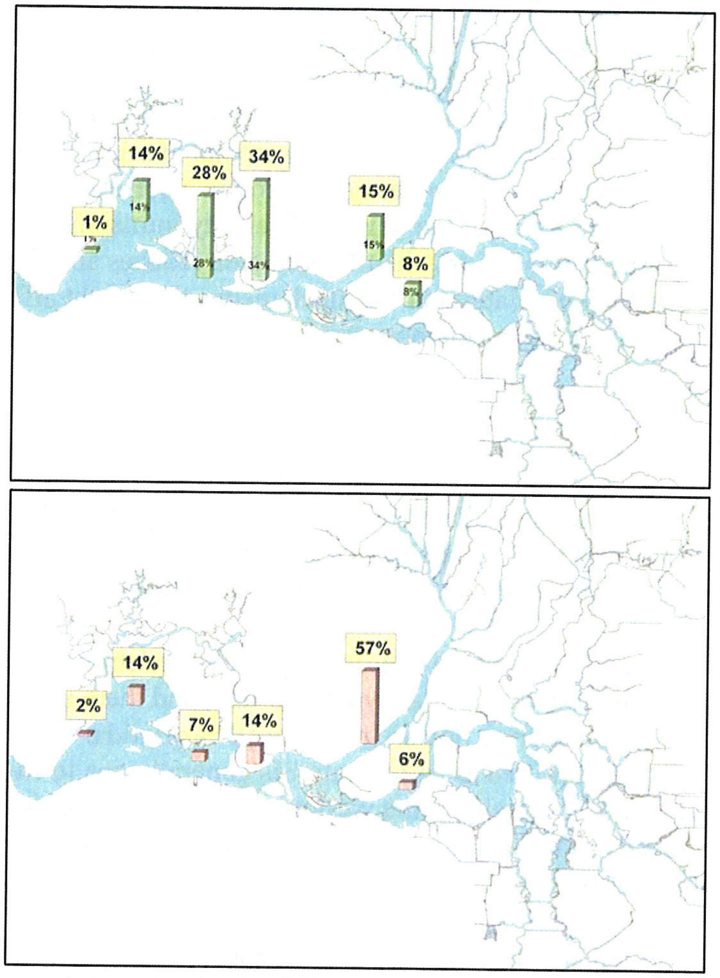

Figure 6: Delta smelt location in the fall for two periods with above normal hydrologic conditions. The upper map shows average delta smelt distribution in the fall following above normal water year runoff for years prior to 1985; the lower map illustrates the same analysis from 1985 to 2009, when salinity in the fall has been higher.

The salinity regime shift also affects residence time of pollutants. Salinity in the western Delta is strongly related to outflow: as outflow from the Delta decreases, salinity intrusion increases. With reduced outflow, residence time increases (at the lowest typical outflows, residence times can be months in the western Delta). Consequently, at low outflow, pollutants can accumulate and reside for relatively long periods of time.

This does not mean, and we do not mean to imply, that the change in salinity regime in the fall is the sole factor or even the major factor in the decline of fish populations. The recent years when fall salinity was low were accompanied by other important conditions, for example, high flows and low salinity levels for extended periods of time. The fall salinity increase is, perhaps, merely a concurrent event with more important factors, or acts in combination with other factors.

While western Delta salinity, *Corbula* abundance, delta smelt location, and residence times are all interrelated, no strong or definitive correlations have been established that explain the relationships between these factors and delta smelt populations. While some statistically significant correlations can be found, they are generally for limited circumstances or involve correlations where mechanisms relating the factors involved are not entirely clear, but nevertheless may be indicators. For example, Feyrer *et al.*[11] found a correlation between suitable habitat area (which is related to X2 or the degree of salinity intrusion) and FMWT. As smelt move east in response to salinity intrusion, their habitat area reduces and the habitat in which they reside changes; one can speculate as to the mechanisms that might affect population but the establishment of direct linkages is much more difficult.

TIDAL FLOWS IN THE DELTA

This is a brief discussion of the importance tidal flows in understanding Delta dynamics, the difference between average flow and tidal flow, and how a "net flow conceptual model" will result in misunderstanding the dynamics or, worse, in incorrect conclusions.

Flows in the San Francisco Bay and Sacramento-San Joaquin Delta are strongly influenced by ocean tides. The tides produce two flood-ebb tidal cycles per day, and there is generally a small net flow west towards the ocean due to river flows. In nearly all cases, tidal flows dominate the dynamics: net flow, though sometimes used as an indicator, is generally one to two orders of magnitude smaller than tidal flows, especially in the western Delta. There are exceptions, but attempts to conceptualize Delta dynamics based on net flows, without regard to the dominate factor of tidal flows, will almost always fail.[12]

Figure 7 demonstrates a typical fall situation with net positive flow (westward, towards the ocean) in the lower Sacramento River, and net negative flow (eastward, away from the ocean) in the lower San Joaquin River. A net flow conceptual model that does not take into account tides or fish behavior would lead one to believe that as delta smelt move eastward, they would be directed into the lower San Joaquin River, rather than the lower Sacramento River, where they are found: the net flow conceptual model gives the exact opposite result of what is seen to be the case in the lower graph in Figure 6.

Net flow models versus a tidal view of the Delta

[11] Ibid

[12] Reliance solely on average flow in the Delta proved problematic in the past. For example, average flow in the lower San Joaquin River was first used in a model that attempted to describe how salinity intrusion in the Delta increased with increasing exports (increasing exports can result in a net "reverse" flow in the lower San Joaquin River). That model simply failed: the hydrodynamics were not captured by the model and therefore the predicted salinity levels and flows were wrong, with little, if any, relationship to field measurements.

Net flow (whether considering Old and Middle Rivers or any other tidal channel) is a mathematical construct, not a physical factor experienced by aquatic organisms which are actually affected by local water velocities.[13] Net flows are averages of flows measured at a point (an Eulerian view), effectively the view of water movement from a stationary position. This mathematical construct simplifies a complex flow field, but in the case of fish movement, can confuse the picture considerably. Fish experience local velocity as they move around (their Lagrangian view).

Net Flow Direction during the Fall

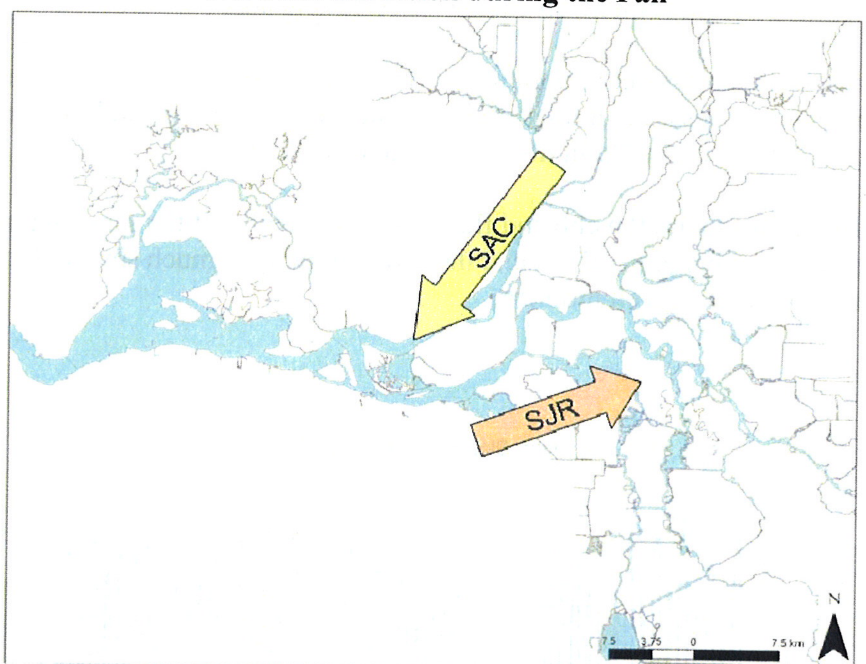

Figure 7: Typical direction of net (average) flow in the lower Sacramento River (SAC) and San Joaquin River (SJR) in the fall.

The movement of water and fish in a tidal environment is very different than the average movement projected by net flows. To examine the problems of a conceptual model based on average flows (Eulerian or Lagrangian average) in a tidal environment, consider the following:

a) Tagged salmon released north of Rio Vista have been caught after just a few days at Chipps Island, moving through an area where tidal flows are very high but net flows are very small. If the salmon moved with the average flow, they would require one to two months to arrive at Chipps Island.

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[13] Flow in a channel is the average velocity times the cross-section. The velocity in a channel varies across the width and depth of the channel. Fish will experience the local velocity (in space and time), not the cross-sectionally averaged velocity, nor the overall flow in the channel.

b) An aquatic organism could start the day in Old River, travel with the instantaneous local velocity up the river on the flood tide, move across Woodward Cut to Middle River and travel down Middle River on the ebb tide. The daily average movement (in this case Lagrangian average) would be pointing from Old River to Middle River, leading to the false conclusion that the organism walked across the island. All information about the intermediate movement of the organism is lost in the averaging. On the other hand, using the (Eulerian) average of the measured water velocity at one location in the channel (the USGS velocity meter for example) could give an average velocity of a few millimeters per second (or about 300 meters per day), leading to only a small net movement, an equally false conclusion.

Clearly, averaging flows throws out important information necessary in understanding the physical and biological processes in a tidal environment. The following graphs of instantaneous flows[14] at various locations in the Delta illustrate these problems.

Figure 8 shows Delta flows with the ebb and flood flows generally of the same magnitude in opposite directions. The average net flow, and therefore velocity is much smaller than any velocity affecting the fish at a given moment.

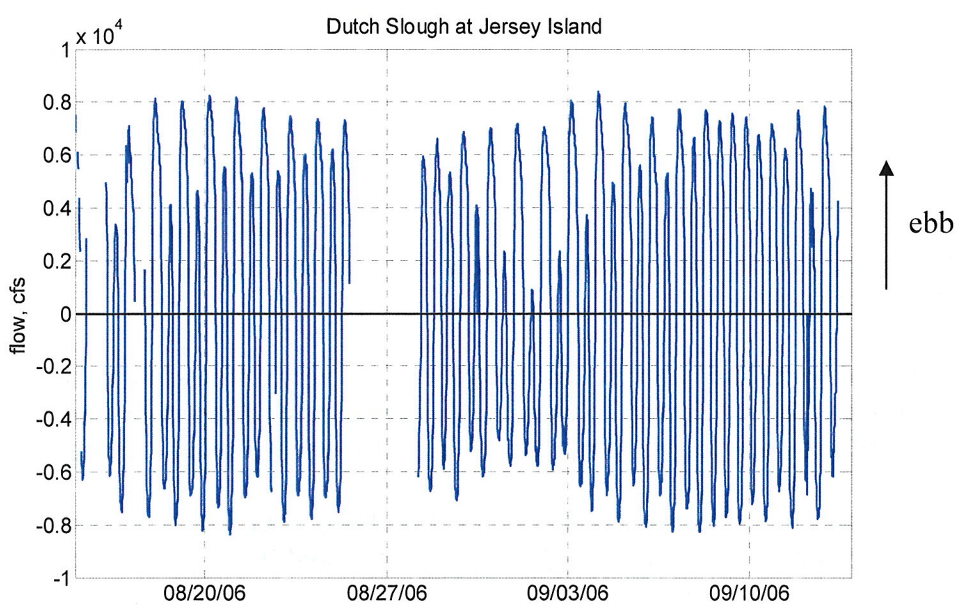

Figure 8. Tidal flow in the Delta with flood (negative) and ebb (positive) flows nearly balanced. 1 = 10,000 cubic feet per second

[14] Data are from the California Data Exchange Center (http://cdec.water.ca.gov). Data shown in Figures 8, 9 and 12 are for the period August 15 to September 14, 2006.

Figure 9 shows tidal flows with a stronger flood than ebb. An aquatic organism at this location may still move in the opposite direction from the average flow if it changes its position across the channel or with the depth (i.e., if it gets into the high velocity part of the channel on the ebb, and stays near the channel sides on the flood[15]). On the other hand, an organism in the high velocity part of the channel on the flood tide will move a long way south in one excursion, much farther than the net flow would have them move.

The point of this discussion is not to ignore net flows, but rather to caution against over-reliance on averaging that over simplifies key dynamics. Tidal flows are responsible for salinity intrusion and moving organisms around. Net flows alter the tides, sometimes substantially, but often not. Both must be considered carefully as is seen in the next discussion.

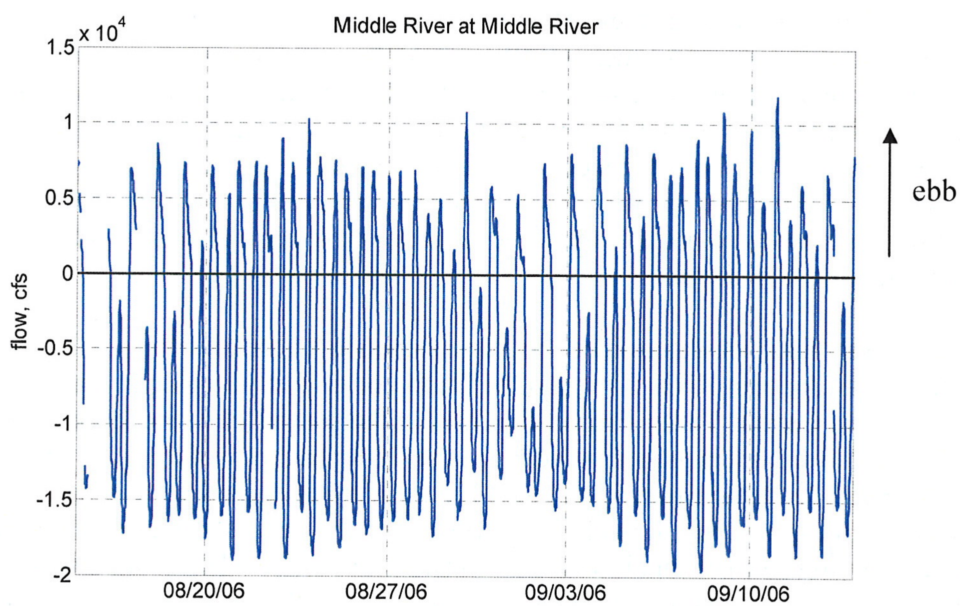

Figure 9. Flow with strong flood tide compared to ebb (positive flow), 1 = 10,000 cubic feet per second

[15] Salmon clearly have the ability to pick the right tide based on cues, or they could not get from north of Rio Vista to Chipps Island in just a few days.

FISH SALVAGE, EXPORTS AND TIDAL FLOWS

To minimize entrainment and salvage of fish at the State Water Project and federal Central Valley Project export facilities in the South Delta, the 2008 FWS BO and 2009 NMFS BO include water-management alternatives to limit net flow in Old and Middle River. However, as discussed above, the net flow at a specific location may obscure the physical processes in the system and lead to incorrect conclusions.

The relationships between salvage at the export facilities and total combined pumping at the exports can be better understood in the context of a relationship with 1) the independent variables (exports and San Joaquin River flow) and 2) tidal flow amplitude.

Old and Middle River (OMR) flows are determined by tides, exports, San Joaquin River inflows, wind and barometric pressure (as they affect tides), physical barriers within channels, and hundreds of small diversions. As such, OMR average flow is a *dependent* variable (salvage of delta smelt is also a dependent variable). Use of the dimensional, dependent variable, average OMR flow, in relationships with delta smelt introduces uncontrollable variables (noise), provides no better information than the independent variables, and obscures the actual dynamics driving the process. Use of the non-dimensional, independent variables provides the correct conceptual model and suggests a way to provide the same or better protection of delta smelt and salmon with less impact on water supplies.

By examining field data, we determined the key independent variables for predicting salvage of delta smelt are San Joaquin River flow into the Delta and export pumping at the State Water Project and federal Central Valley Project facilities in the south Delta (the location of salvage). No statistical improvement is gained by adding other independent variables, in part because they are poorly known. As demonstrated in Figure 10, a statistical regression to predict OMR net flow (y-axis) from exports, San Joaquin River flows and the best estimates of other diversions and unknown (or ungaged) channel flows has considerable noise when plotted with field measurements of OMR (x-axis). As illustrated in Figure 10, the uncertainty in the range of interest (OMR < 0 cfs) is on the order of +/- 1,500 cfs or more. (This is not the case when a comparison is made with a numerical model that has those same best estimates as input[16]: there is very little scatter in the model, but both models are using the same input data, so it would only be surprising if they did not agree well.)

[16] Hutton, P. (2008) "A Model to Estimate Old and Middle River Flows", Metropolitan Water District of Southern California.

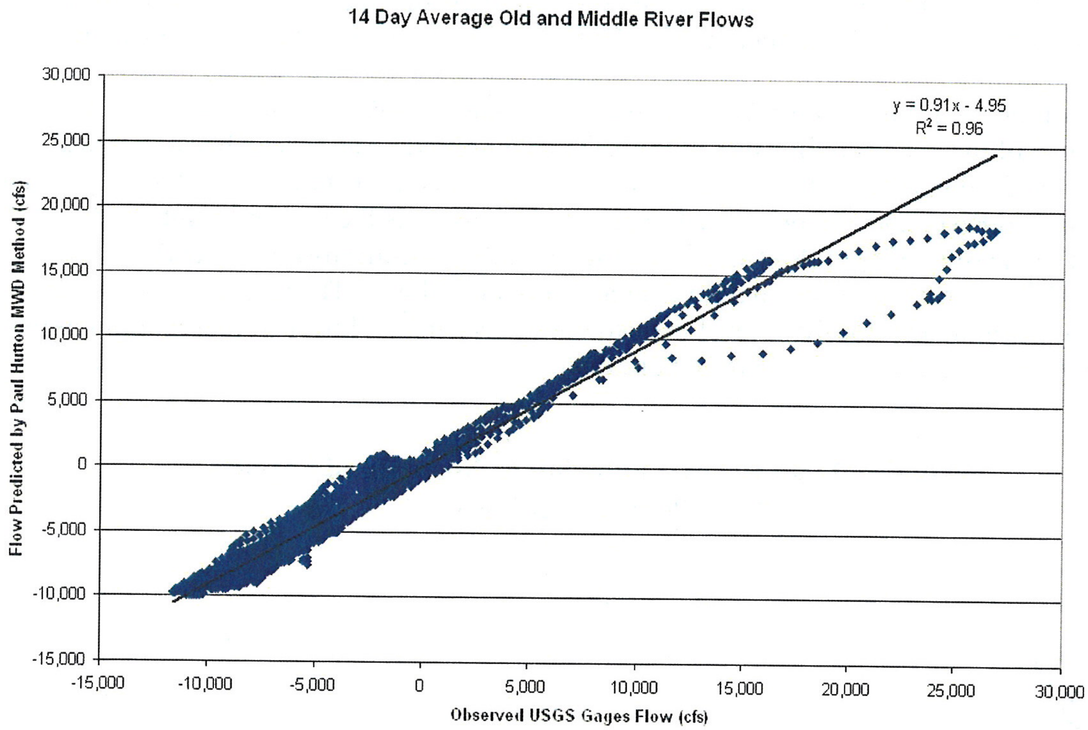

Figure 10: Demonstration of uncertainty in field measurements and estimates of 14-day average flow from 1993 to 2009. Predicted values (y-axis) incorporate estimates of diversions affecting OMR net flow, yet considerable uncertainty remains, particularly in the range of interest (negative levels).

It is found statistically that salvage is largely influenced by exports and San Joaquin River flows[17]. Consequently, there is little, if any, statistical advantage to using the dependent variable of OMR net flow.

Desiro[18] correctly pointed out that the salvage index (cumulative salvage from December through March normalized by the most recent FMWT index) is the correct parameter to use for the biological data: it provides a dimensionless variable and correctly scales salvage of a species to its population index. He did not, however, correlate against a hydrodynamically independent variable, nor did he normalize that variable to obtain a non-dimensional quantity.

Statistical analysis determined that the parameter (Exports – 0.5 San Joaquin River inflow)[19] is the most significant variable. Use of this parameter rather than OMR net flow also has the

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[17] Statistical correlations using exports and San Joaquin flows in the correlation with salvage are numerically better than those using OMR net flow, but very similar. $r^2 = 0.663$, $p=0.0004$. Graphical representations are indistinguishable.

[18] Desiro, R.B. (2009). Declaration of Dr. Richard B. Desiro, Case 1:09-cv—00407-OWW-DLB, p16ff

[19] The factor for San Joaquin River inflow is actually 0.49; this is rounded to 0.5 here.

advantage of limiting the absurd result of predicting non-zero salvage when exports are zero, which is possible when the dependent variable OMR net flow used, but impossible in actuality.

A measure of the tidal flow amplitude was chosen to normalize this "reduced export" level (reduced by ½ of the San Joaquin River inflow). Tidal amplitude was chosen because it is a measure of the driving force in the hydrodynamics of the system; local tidal amplitude (i.e., tidal amplitude in Old River and Victoria Canal) was used because it is the most relevant local quantity. The measure of tidal flow amplitude used was the root-mean-square (RMS) of the residual tidal flow (instantaneous tidal flow minus daily tidal flow). The results are shown in Figure 11, illustrating the threshold level pointed out by Deriso[20]. However, presentation in this format provides insight as to *why* there is a threshold.

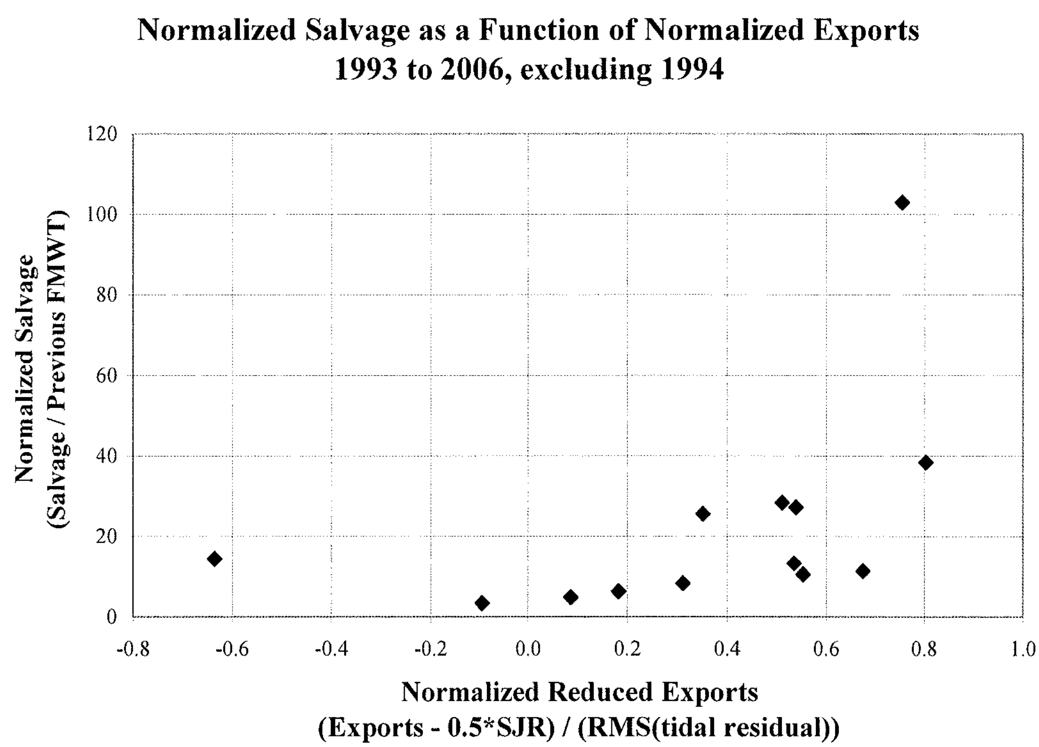

Figure 11: Salvage index (salvage/FMWT) plotted against normalized reduced exports (exports – 0.5 San Joaquin River inflow)/(root-mean-square of the tidal flow with the mean removed). Tidal amplitude is from Old River near Highway 4 and Victoria Canal. Salvage index starts to rise sharply when the normalized reduced exports is about 0.5, a level at which the ebb tide begins to be lost along the channel.

The threshold level for increased salvage begins when the reduced exports reach about half the RMS level of the tidal flow. At this location, the RMS tidal level is about 12,000 cfs, so the reduced export level when salvage begins to rise sharply is about 6,000 cfs. This is consistent

[20] Ibid

with the findings of Swanson[21], who found that salvage of salmon increased rapidly when exports[22] were above a level of about 7,000 cfs.

Figure 12 provides the hydrodynamic reason that this threshold exists: when the normalized reduced exports exceed 0.5, the ebb tide is substantially reduced, or even lost entirely.

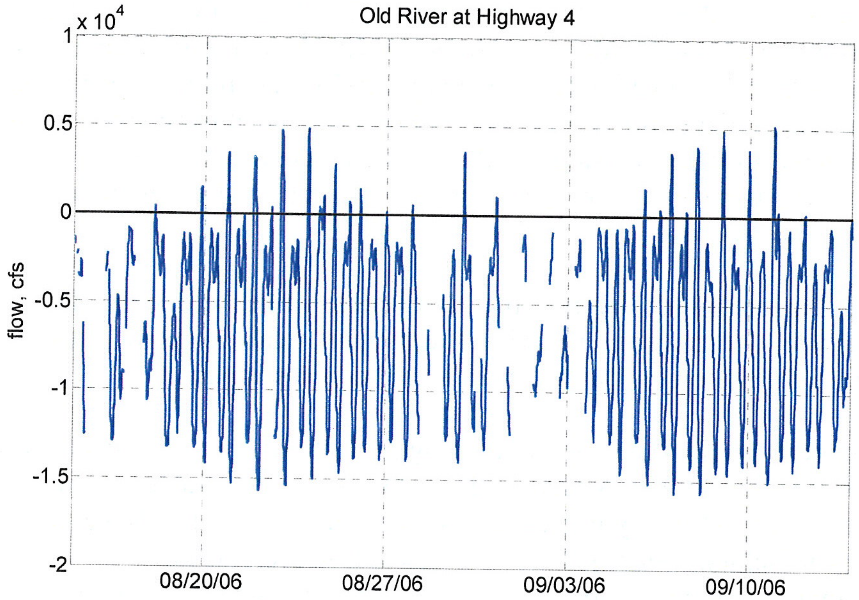

Figure 12: Tidal flow in Old River near Highway 4. Ebb tide is entirely lost for substantial periods over the neap-spring cycle.
(Exports-0.5 San Joaquin inflow)/RMS(Tidal flow residual) ≈ 0.8 during this period.

Figures 8, 9 and 12 are measurements from the same time period. However, they all show different responses, and this is important. An aquatic organism moving in the channel does not experience the flows as represented in these figures: these are Eulerian representations at specific locations and an organism experiences the velocities in its own Lagrangian system (i.e., the velocities as it moves). That Lagrangian excursion can be large (tidal movements are on the order of 4 to 5 miles). Consequently, although an organism may start at a location where there is still a substantial ebb tide, if it moves up the river on the flood tide to a location where the ebb has been substantially lost, it will not "slosh back" as the tides change: the velocities become unidirectional at some point along its path. Figure 11 shows that, for this system, the threshold level for significant (Lagrangian) motion ending in salvage is when the reduced exports reach about 6,000 cfs. Note that it is not necessary for the ebb tide to be substantially lost at each point

[21] Swanson, T. (2008) Personal communication.

[22] Swanson did not account for San Joaquin flows, but given typical inflow levels on the San Joaquin River, the two values are consistent.

in the river, but for the excursion of a particle to reach a point where the ebb tide is substantially lost.

DISCUSSION

The preceding presentation leads to the following observations. The first is the importance of using the independent variables in hydrodynamics and to normalize them to non-dimensional quantities; this is not a new concept[23]. Field data show that the reduced exports (exports reduced by about one-half the San Joaquin River flow) is the important independent parameter. Use of this parameter reduces the noise inherent in using OMR net flow in a real time basis. Statistically, the latter provides no better information; practically, it can cost water supplies without providing any better protection.

The second is to recognize the important tidal dynamics that lead to a threshold level. This requires one to include the tidal dynamics and include a Lagrangian, tidal viewpoint in the analysis. When that is done, the reason for the threshold level becomes apparent.

Finally, this discussion suggests possibilities for maintaining protection of aquatic species while reducing impacts on water supplies through the use of the reduced export variable and the threshold level. Other factors may also play into this; these include turbidity levels and other environmental and biological factors. Consequently, this discussion presents no recommendations on the appropriate level of reduced export or safety factors that might be considered to provide equivalent or better protection.

[23] Buckingham, E. (1914). "On physically similar systems; illustrations of the use of dimensional equations". Phys. Rev. 4: 345–376. doi:10.1103/PhysRev.4.345. http://prola.aps.org/abstract/PR/v4/i4/p345_1.