APPENDIX D –
FLOW SCIENCE SOUTH DELTA WATER AGENCY DIVERSIONS, JUNE 2008

9427

TECHNICAL MEMORANDUM

DATE: June 9, 2008

TO: Tim O'Laughlin, O'Laughlin & Paris LLP

FROM: Susan C. Paulsen, Ph.D., P.E., Gang Zhao, Ph.D.

SUBJECT: **Re: SDWA Diversions**
FSI 048007

On June 2, 2008, Tim O'Laughlin of O'Laughlin and Paris requested that Flow Science Incorporated (Flow Science) prepare a brief summary of available information regarding water flows in the South Delta. This draft response is divided into three sections, which address the following primary questions:

- How does freshwater leave the Sacramento-San Joaquin Delta?
- How do hydraulic gradients work in the South Delta, even with the tide?
- How do flow patterns and in-Delta activities affect salinity within the Delta?

1. How freshwater leaves the delta

The Sacramento-San Joaquin Delta has a large network of river channels and smaller sloughs, and it is connected to the San Francisco Bay through Suisun Bay and the Carquinez Strait (see Figure 1). Many of the channels within the Delta are below sea level and the flows in these channels are affected by tides. Figure 2 shows three days of measured river stage and flow rate at the station Jersey Point on San Joaquin River (station ID SJJ, see Figure 1 for location). At high tides the direction of the flow is into the Delta (negative flow rate) and the river stage increases. At low tides, the river water flows out of the Delta and the river stage falls.

The volume of water flowing into the Delta during high tides and the volume of water flowing out of the Delta during low tides can be calculated by integrating the flow rate curve, and generally these two volumes are not equal. The net outflow volume can be computed by subtracting the volume flowing into the Delta from the volume flowing out of the Delta. For the tidal cycle (about 25 hours) marked in green and blue in Figure 2, the net outflow volume is approximately 10,000 ft^3. This is an example that shows the existence of a net outflow over a tidal cycle. Furthermore, this concept is applicable to the entire Delta. For the time period 1980-1991, the average annual Delta outflow was 21,020 thousand acre-feet (*Delta Overview*, California Department of Water Resources). The Delta outflow must be supplied by the fresh water inflow to the Delta to satisfy mass balance. Most fresh water inflow to the Delta comes from the rivers around the Delta. Rivers flow into the Delta, and they continue flowing through the Delta into the Suisun Bay, the San Francisco Bay, and eventually into the Pacific Ocean. Water is also exported from the Delta and diverted within the Delta. As water travels through and ultimately out of the Delta, it mixes with waters from other sources. It is well established that “Delta outflow is the primary source of fresh water for Suisun Bay and Suisun Marsh” (California Department of Water Resources, Environmental Services Office, 2001, pp. 6). San Francisco Bay receives nearly all of its freshwater from the Sacramento-San Joaquin River system (Kimmerer, 2002). Water is not retained within the Delta in perpetuity, but rather is flushed from the system by both tidal action and by replacement with new inflows. The average residence time within the Delta varies from weeks to about three months in wet and dry years, respectively (see Fischer et al., 1977; or Mierzwa, undated).

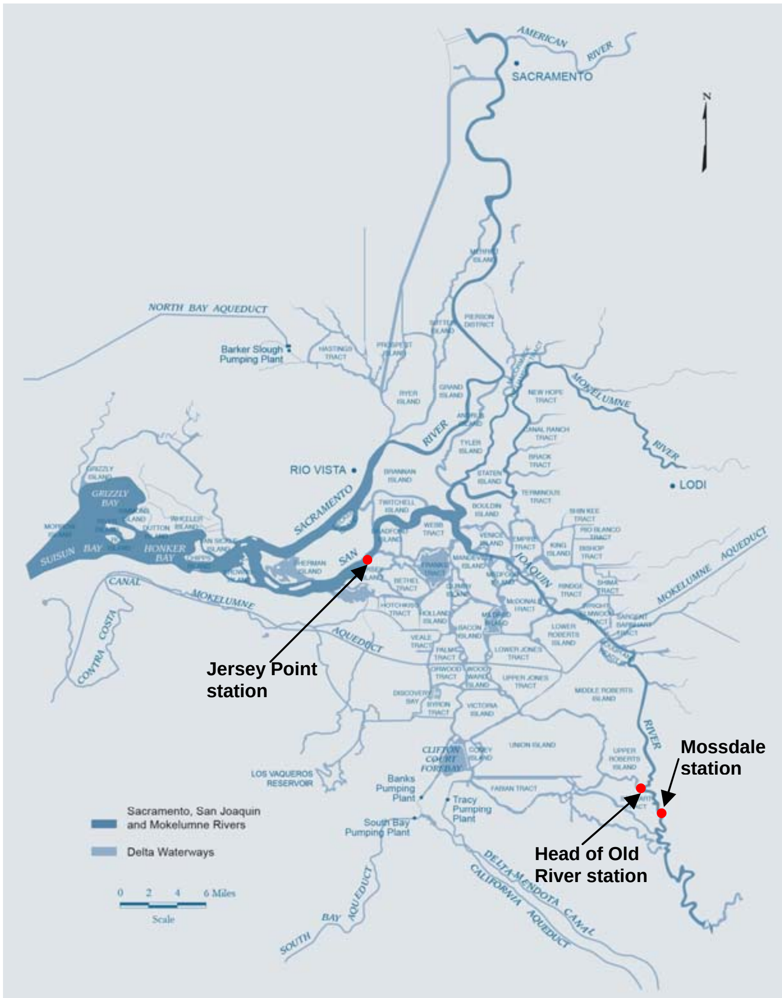

Figure 1. Map of Delta

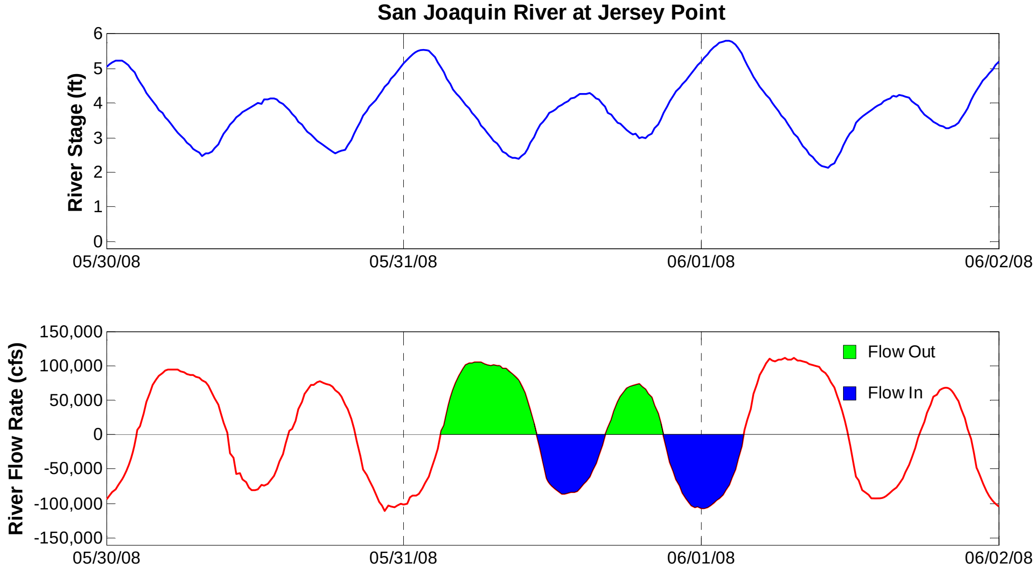

Figure 2. Measured San Joaquin river stage and flowrate at Jersey Point station (data from http://cdec.water.ca.gov/).

2. Hydraulic gradients in the South Delta

The hydraulic gradient between two points is defined as:

$i = (h_B - h_A)/L_{AB}$

where:
i = the hydraulic gradient between points A and B.
h_B, h_A = hydraulic heads at points B and A, respectively.
L_{AB} = the length between points A and B.

The hydraulic head at a point is defined as:

$h = h_p + h_v + z$

where:
h = hydraulic head.
h_p = pressure head.
h_v = velocity head.
z = elevation at the point.

River flows from locations with higher hydraulic heads to places with lower hydraulic heads (i.e. the down gradient direction). In the Delta system, river stages are measured at a number of stations and reported with a common datum, and river stage is a good approximation of $h_p + z$ for the Delta rivers. River stages and flow data around the Delta can be downloaded from California Department of Water Resources' (DWR) website (http://cdec.water.ca.gov/). From the downloaded data, the hydraulic head can be calculated at a number of stations. Figure 3 shows the hydraulic heads and flow rates of the San Joaquin River at Mossdale and the head of Old River for four days starting at 01/01/08. Positive flow rate means water is flowing from Mossdale to the head of Old River. During the 4 days, the hydraulic head at Mossdale is higher than that at the head of Old River for most of the time, and as a result, the direction of the flow is from Mossdale to the head of Old River for most of the time. For two short periods of time on 01/03/08 and 01/04/08, the hydraulic head at Old River is higher than that at Mossdale, and correspondingly, the flow direction is from Old River head to Mossdale during these periods. This is a clear demonstration, with measured data in South Delta, of the physical laws that govern the river flow.

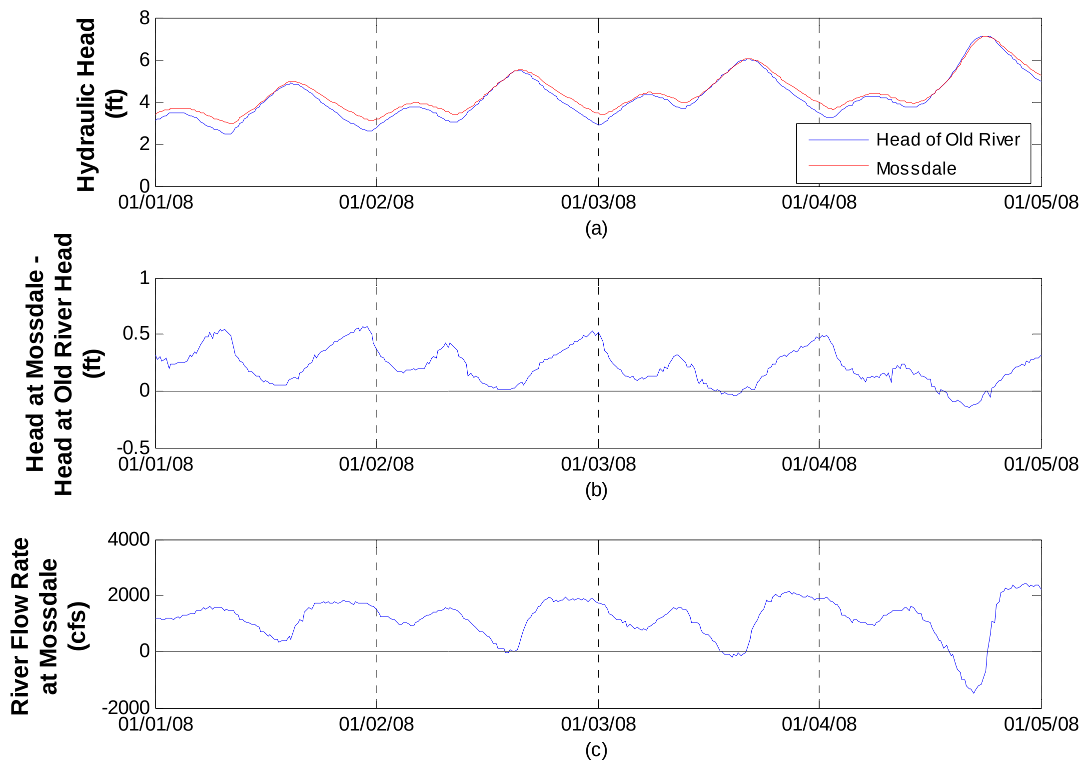

Figure 3. Hydraulic heads and flowrate at Old River head and Mossdale (a)Hydraulic Heads; (b) Difference in Hydraulic Head; and (c) Flow Rate at Mossdale

Hydraulic gradients, such as the gradient in the example shown above, drive flows throughout the Delta. These gradients in surface waters are primarily a function of inflows (as the stage at locations where flows enter the Delta is a function of the flows themselves, with higher stages resulting from higher inflows), tides, and events that may induce gradients locally. For example, pumping water from the export locations induces hydraulic gradients toward the pump locations. Similarly, local diversions via pumps that draw water from Delta channels induce local gradients, such that water flows toward the diversion pumps. Water removed from Delta channels is replaced by water flowing toward the diversion or export locations; in this manner, removing water from Delta channels alters hydraulic gradients throughout the system. The system responds dynamically to changes in inflows, exports, and diversions, as well as to tidal action.

As is well-documented, large export flow rates can induce hydraulic gradients within the Delta that are large enough to make rivers flow “backwards” or “upstream.” In this way, the distribution of water within the Delta is altered dramatically. For example, most of the water diverted from the South Delta export locations (CVP and SWP) originated in the Sacramento River (Paulsen 1997). If the export pumps did not remove large quantities of water from the south Delta, very little Sacramento River water would be present at these locations.

Another significant point is that the pressure head at the same depth of flow may be different at different locations because of the difference in salinity within the water column. Under these conditions it is possible to have saline water flowing upstream near the bed and fresh water flowing downstream near the surface. This commonly occurs downstream of Rio Vista.

3. Salinity in the Delta

The highest salinity source of water to the Delta is ocean water [“The primary source of salinity in Delta water is the ocean itself” (CALFED Water Quality Program, 2007, pp. 9)]. At high tides, ocean water intrudes into the Delta, bringing in high salinity water. The high salinity ocean water mixes with low salinity water brought into the Delta mainly by river flows, and, as noted previously, saline water may flow upstream near the bottom of the river while freshwater flows downstream near the surface; these are termed density driven flows The actual horizontal and vertical distribution of salinity in the

Delta is affected by many factors such as the tides, freshwater inflow, Delta exports, diversions, agricultural return flows, and barriers and gates operations. Among these factors and particularly in the western Delta, tides and Delta outflow have the most significant impacts on the Delta salinity. As noted by CALFED, "Tidal movement and density-driven flow are the engines that move seawater into the Delta. Delta outflow (dependent on Delta inflow and diversions) pushes salinity out of the Delta. These two forces working against one another determine how much and how far salinity from seawater intrudes into the Delta" (CALFED Water Quality Program, 2007, pp. 40). Based on this simplified conceptual model and assuming a uniform vertical distribution of salinity in the Delta (which is questionable in portions of the Delta downstream of Rio Vista), a salt balance equation (Fischer et al., 1979, pp. 267) can be used to estimate the Delta salinity.

$$S = Q_0 S_0 / (Q_0 + Q_f - Q_e)$$

where:
Q_0 = the circulating flow of ocean water.
Q_f = the tributary discharge from all upstream tributaries.
Q_e = diversion of water.
S_0 = ocean salinity.
S = estuary (the Delta) salinity.

In this equation, it is assumed that the salinity of inflows is negligible, which is a questionable assumption, as will be shown below. Even though this is a rather simplified model, it reasonably explains the relationship among some of the most important Delta parameters. The equation above shows that increasing river inflow Q_f (e.g., wet years) lowers Delta salinity; decreasing river inflow Q_f (e.g., dry years) results in higher Delta salinity. Also increasing diversion Q_e will increase Delta salinity. In the extreme case when $Q_e = 0$ and $Q_f = 0$ (i.e., no river inflow, no diversion), Delta salinity will be the same as ocean salinity.

Historical data also clearly show the results of changes in freshwater inflows. When freshwater inflows decrease, salinity within the Delta increases, as freshwater flows are insufficient to "push out" seawater that enters the Delta with the tides (see, e.g., historical isohalines for various years, such as 1931).

The simplified equation provided above assumes that all freshwater inflows to the Delta have negligible salinity. However, certain inflows have much higher salinities than river inflows. Agricultural drainage, in particular, can have salinity values ranging as high as 4,000 uS/cm, and salinity levels in channels adjacent to large volume or large flow rate agricultural return flows can increase dramatically. Thus, in-Delta agricultural diversions can have a "double impact" on Delta salinity: first, they remove freshwater flows from the system decreasing the NDO; and second, the volume of water that they return to Delta channels is both smaller and saltier than the volume that was withdrawn.

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