Relationships between Measured X2 and Equivalent Outflow (cfs) and Salinity (EC) during Low-Flow Conditions

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One of the uncertainties in Delta water management during low-flow conditions is the daily Delta outflow (NDOI). ICF International prepared an independent evaluation of the relationships between daily Delta outflow and X2 and salinity (EC) in WY 2014 to determine if these relationships could be used to provide more certainty in understanding outflow during low-flow conditions. Our evaluation identified a new method for accurately estimating daily Delta outflow based on measured bottom X2 during low flow periods. The method estimates the daily "equivalent" Delta outflow (i.e., outflow which controls the salinity gradient and X2) based on the daily measured X2. The daily measured X2 was linearly interpolated using the bottom EC measurements at western Delta monitoring stations. The application of this method to other water years with a range of Delta outflow would confirm the reliability of the measured X2 and equivalent outflow estimates.

The minimum required Delta outflow is identified in D-1641 and outflow is regulated to control salinity and X2 in February-June. A reliable estimate of daily outflow could allow more accurate regulation of outflow and the salinity gradient (X2 and EC), thereby potentially saving water during low flow periods. This new method for estimating equivalent outflow would be like installing a speedometer to ensure you are driving within the speed limit.

Daily average bottom EC measurements from the western Delta and Suisun Bay monitoring stations (i.e., Benicia, Port Chicago, Mallard Island, Pittsburg, Collinsville, Antioch, and Emmaton) were used to estimate the daily average X2 (km). The equivalent outflow corresponding to the daily measured bottom X2 was calculated, using the "inverse" of the steady-outflow version of the daily X2-log outflow equation (Kimmerer and Monismith 1993):

X2 (km) = 10.16 + 0.945 * X2 (day-1) – 1.487 * log [Outflow (cfs)]
[Kimmerer-Monismith daily X2]

Steady X2 (km) = 185 – 27 * log [Outflow (cfs)]
[steady-outflow to X2 relationship]

Outflow (cfs) = 10 ^ ([185 – X2 (km)]/27)
[daily X2 to equivalent outflow relationship]

The outflow estimate from the bottom X2 measurement is called the "equivalent" outflow. The daily average X2 fluctuates upstream and downstream with changes in daily mean tide and with changes in Delta outflow. Higher daily mean tide increases the average EC at each station and shifts the bottom X2 upstream. The separation of the tidal effects from the daily outflow effects can improve (i.e., stabilize)

Delta operations; the daily outflow can be regulated independently of the tidal variations in X2 and EC to maintain the required Delta outflow. The equivalent outflow can be separated from the tidal effects using this equation:

Measured Bottom X2 (km) = X2 from Equivalent Outflow (cfs) + C (km/ft) x [Daily Mean Tide – Long-term Mean Tide]

The preliminary estimate of the tidal effect coefficient (C) was about 5 km/ft. The measured X2 shifts upstream about 1 km for each 0.2 feet change in the daily average tide.

This method for estimating the daily equivalent outflow was generally confirmed by the accurate estimates of the average daily surface EC measurements at multiple locations in the Delta, calculated using a negative exponential equation with the equivalent outflow for each station, which were introduced as the second part of the G-model formulation (Sullivan and Denton 1994).

EC (uS/cm) at Fixed Station = Min EC + A x exp [-b x Effective outflow (cfs)]

Figure 1a shows the daily calculated X2 (blue line) from DAYFLOW, using the Kimmerer and Monismith daily X2 equation with NDOI outflow estimates, compared with the measured bottom X2 (green dots) for 2014. The bottom X2 is defined as 2 ppt bottom salinity (TDS), which is equivalent to an EC of 3,830 uS/cm (USGS conversion). The measured X2 was considerably higher (indicating less outflow) than the calculated DAYFLOW X2 in 2014. The CDEC calculated X2 (gold line), using surface EC measurements (surface EC of 2,640 uS/cm was assumed for a bottom EC of 3,830 uS/cm) from Mallard Island (75 km) and Collinsville (81 km) is shown for reference. The daily average tidal variations at Jersey Point are also shown for reference (blue diamonds, right-hand scale).

Figure 1b shows the measured bottom X2 (purple dots) and the tidally adjusted X2 (red dots) along with the DAYFLOW X2 (green boxes) and three different estimates of the antecedent outflow, calculated using the G-model formulation with different volumetric averaging coefficients. A smaller volume coefficient allows greater fluctuations (and less lag) in the antecedent or effective outflow.

Figure 2 shows the daily antecedent Delta outflow (blue line) calculated using the G-model formulation from the daily NDOI (gold line) with a volume coefficient of 125,000 cfs-days compared to the equivalent outflow calculated from the daily measured X2 for 2014 (green line). There is no moving average (i.e., lag in effective outflow) included in the measured bottom X2 method. The equivalent Delta outflow (from measured X2) was considerably less than the DAYFLOW estimates of NDOI and effective outflow for most of the low flow periods in 2014. The effective outflow calculated from the USGS measured daily average outflows (tidal filtered) was similar to the equivalent outflow (for measured X2) in the months of October-January, but was considerably lower than the other outflow estimates in the second half of the year. The measured bottom X2 provided a daily effective outflow that ranged from a minimum of 2,000 cfs at the end of January to a maximum of 15,000 cfs during the March storm. The average effective outflow (based on the measured X2) was about 3,000 cfs during October, November, and December, and again from June-September. These are relatively large differences in the estimated channel depletions used for estimating NDOI. Although the EC at each of the monitoring stations can be estimated directly from the measured bottom X2, calculating the equivalent outflow for the tidal adjusted X2 allows the Delta operations (exports) to more accurately match the Delta outflow objective.

Figure 3a shows the comparison between the measured daily average EC at several western Delta EC stations and the estimated EC calculated from the daily equivalent outflow (based on the measured bottom X2). The equivalent outflow was used in the negative exponential equation for each station to calculate the daily average EC. Because the measured daily X2 and daily salinity both change rapidly with tidal fluctuations, moving the salinity gradient upstream or downstream, the short term daily EC changes are more closely matched using the measured bottom X2. The relationship between the equivalent outflow and X2 is assumed to be the same as indicated in the original X2-log outflow equation. For example, an outflow of 7,000 cfs corresponds to X2 at 81.1 (near Collinsville), an outflow of 3,000 cfs corresponds to X2 at 91.1 km (1 km downstream from Emmaton), an outflow of 2,500 cfs corresponds to X2 at 93.25 km, and an outflow of 2,000 cfs corresponds to X2 at 95.9 km (near Threemile Slough). Although the bottom X2 is measured and the surface EC is measured, the assumed X2-effective outflow is an assumed "scale" between the two. The measured surface EC patterns in 2014 closely followed the measured X2 patterns, but there was no independent evidence that the assumed relationship between X2 and outflow is accurate (at these relatively low outflows). An outflow of 3,000 cfs may correspond to X2 at 90 km or at 92 km.

Figure 3b shows the measured and calculated daily average surface EC at Mallard Island, Collinsville, Antioch, Emmaton, Threemile Slough, and Rio Vista for 2014. The very similar fluctuations at each EC station correspond to the daily variations in the bottom X2. This demonstrates the accuracy of the proposed method for measuring the bottom X2, estimating the daily equivalent outflow, and calculating the daily average surface EC at each station in the western Delta. **Figure 3c** shows the measured and calculated daily average surface EC at the western Delta stations as a function of the measured daily average EC at Mallard. This provides a slightly different summary of the salinity gradient for any selected daily average Mallard EC. For example, when the Mallard EC was 10,000 uS/cm, the measured Collinsville EC was about 6,000 uS/cm, the measured Antioch EC was about 3,000 uS/cm, the measured Emmaton EC was about 1,500 uS/cm, and the Threemile Slough EC was about 1,000 uS/cm.

Additional evaluations using the method and data described above could be performed to inform water management within the Delta during low-flow conditions. These include:

- Evaluate several water years with a range of Delta outflows to confirm the reliability of the measured X2 and equivalent outflow and EC estimates
- Prepare a daily salinity data file (i.e., DAYSALT) as a companion to DAYFLOW. Include the surface and bottom EC measurements at each Delta station and the bottom X2 estimates and the tidal-adjustment of bottom X2 in DAYSALT. The equivalent outflow calculations could be added to DAYFLOW (for 1999 to 2014) as a more accurate estimate of the salinity-gradient (X2 and EC) patterns in each year.

References

Kimmerer, W., S. Monismith. 1993. An estimate of the Historical Position of 2 PPT Salinity in the San Francisco Bay Estuary. (In) Managing Freshwater Discharge to the San Francisco Bay/Sacramento –San Joaquin Delta Estuary: The Scientific Basis for an Estuarine Standard. San Francisco Estuary Project. San Francisco CA.

Sullivan, G. D., R. A. Denton 1994. Report on Clean Water Act X2 Water Quality Standards. Contra Costa Water District. Concord CA.

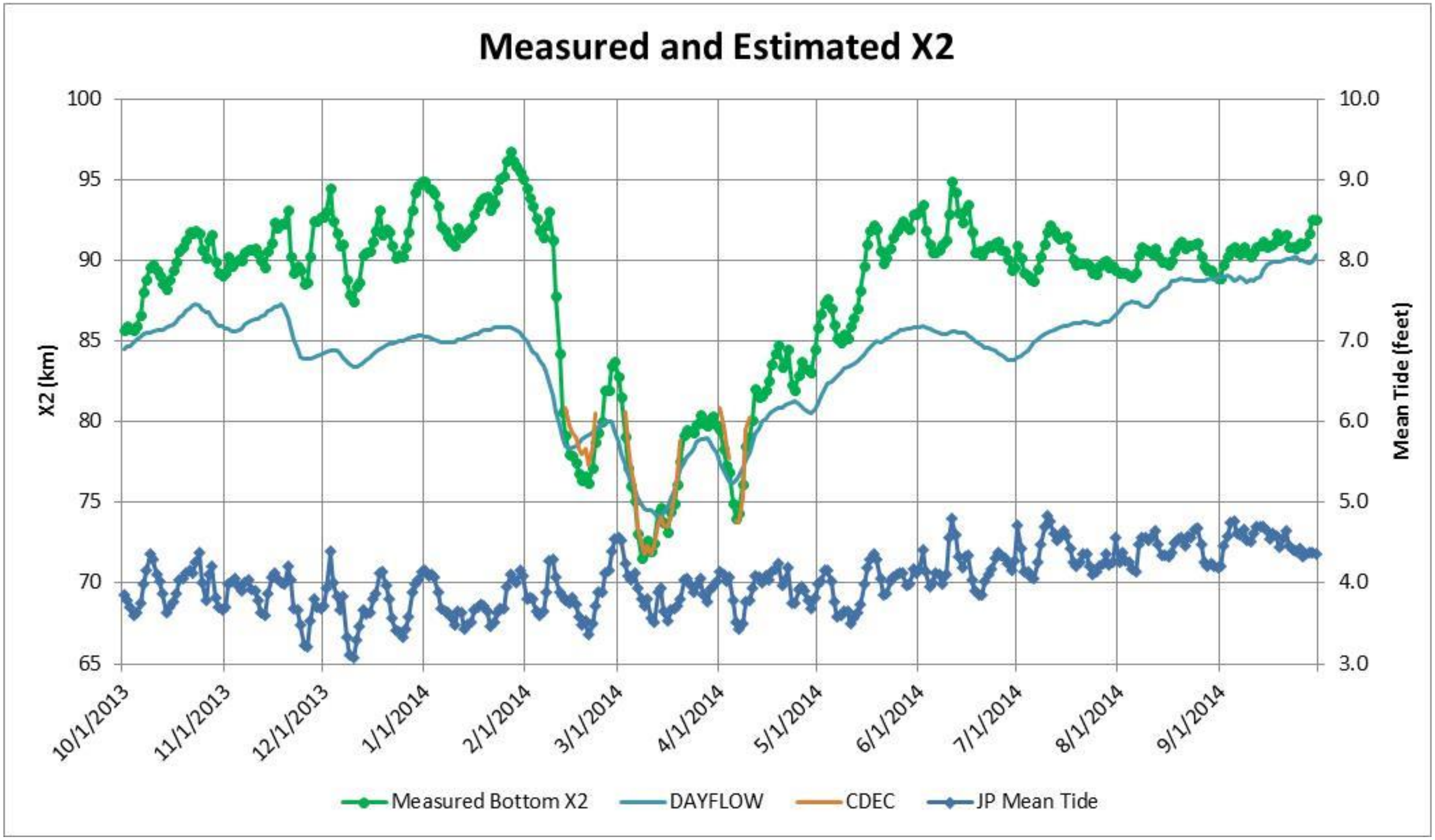

Figure 1a. Measured WY 2014 bottom X2 (green line) was considerably higher than X2 calculated from DAYFLOW outflow, indicating that outflow was less than DAYFLOW estimates. Estimates of X2 from surface EC are also shown (from CDEC for periods when X2 was downstream of Collinsville at 81 km).

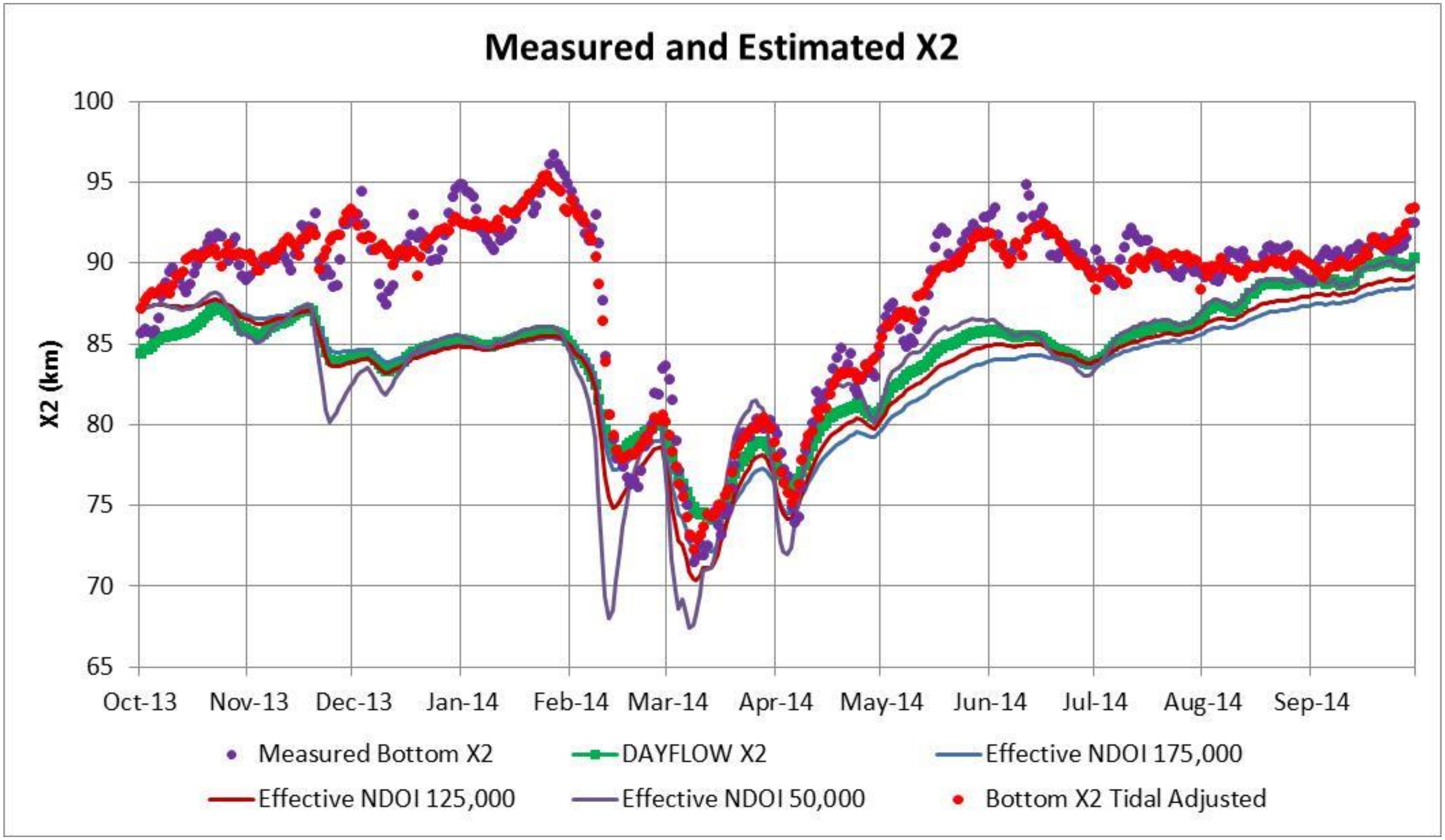

Figure 1b. Measured bottom X2 (purple dots) and X2 adjusted for tidal effects (red dots) compared to X2 calculated from effective NDOI (with several lag coefficients) using the G-model formulation and with DAYFLOW X2 (K-M daily equation) for WY 2014.

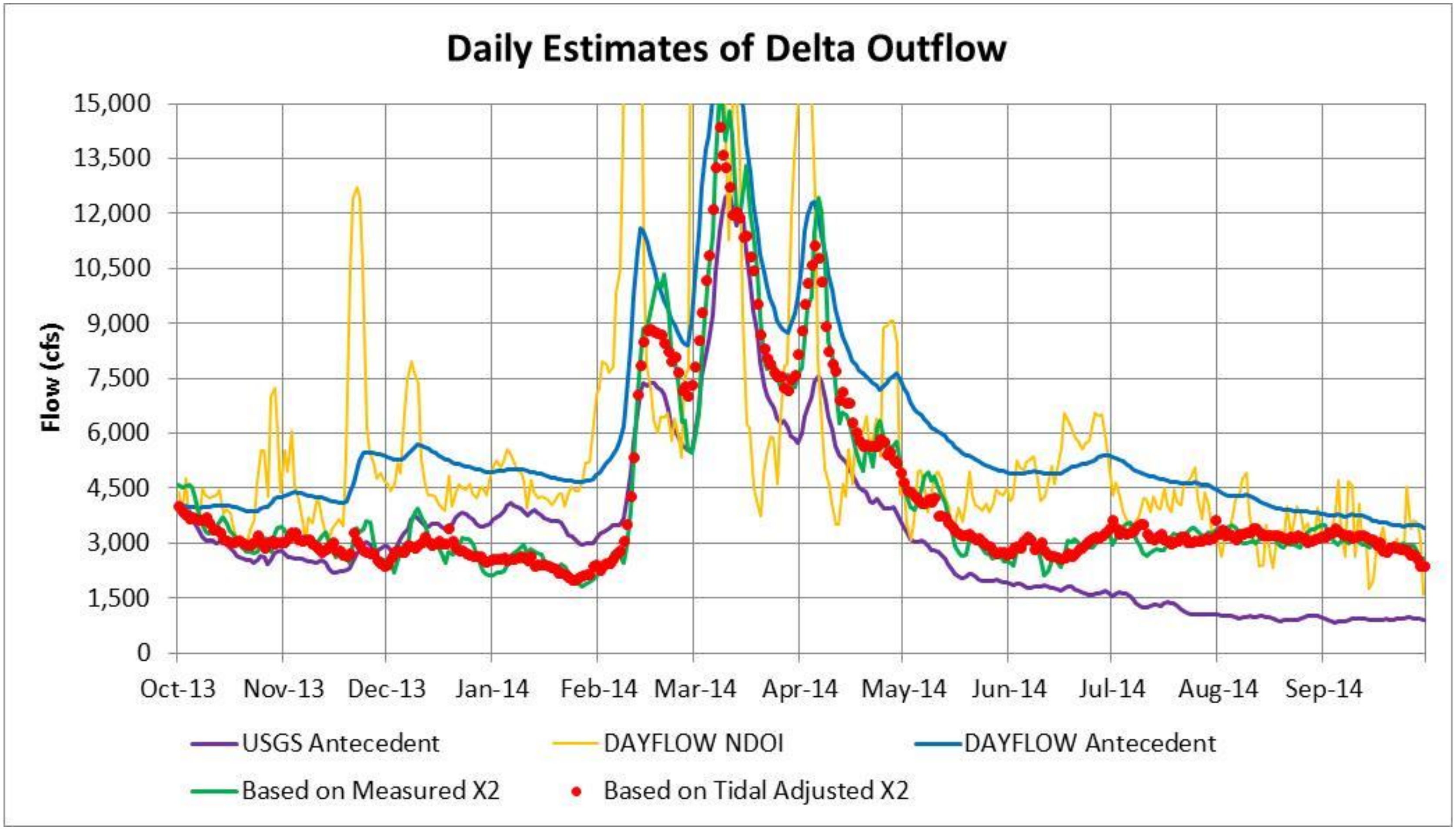

Figure 2. Effective Delta outflow based on measured bottom X2 and based on tidal-adjusted X2 compared to antecedent outflow (G-model) for DAYFLOW NDOI and antecedent outflow for USGS daily outflow measurements for 2014.

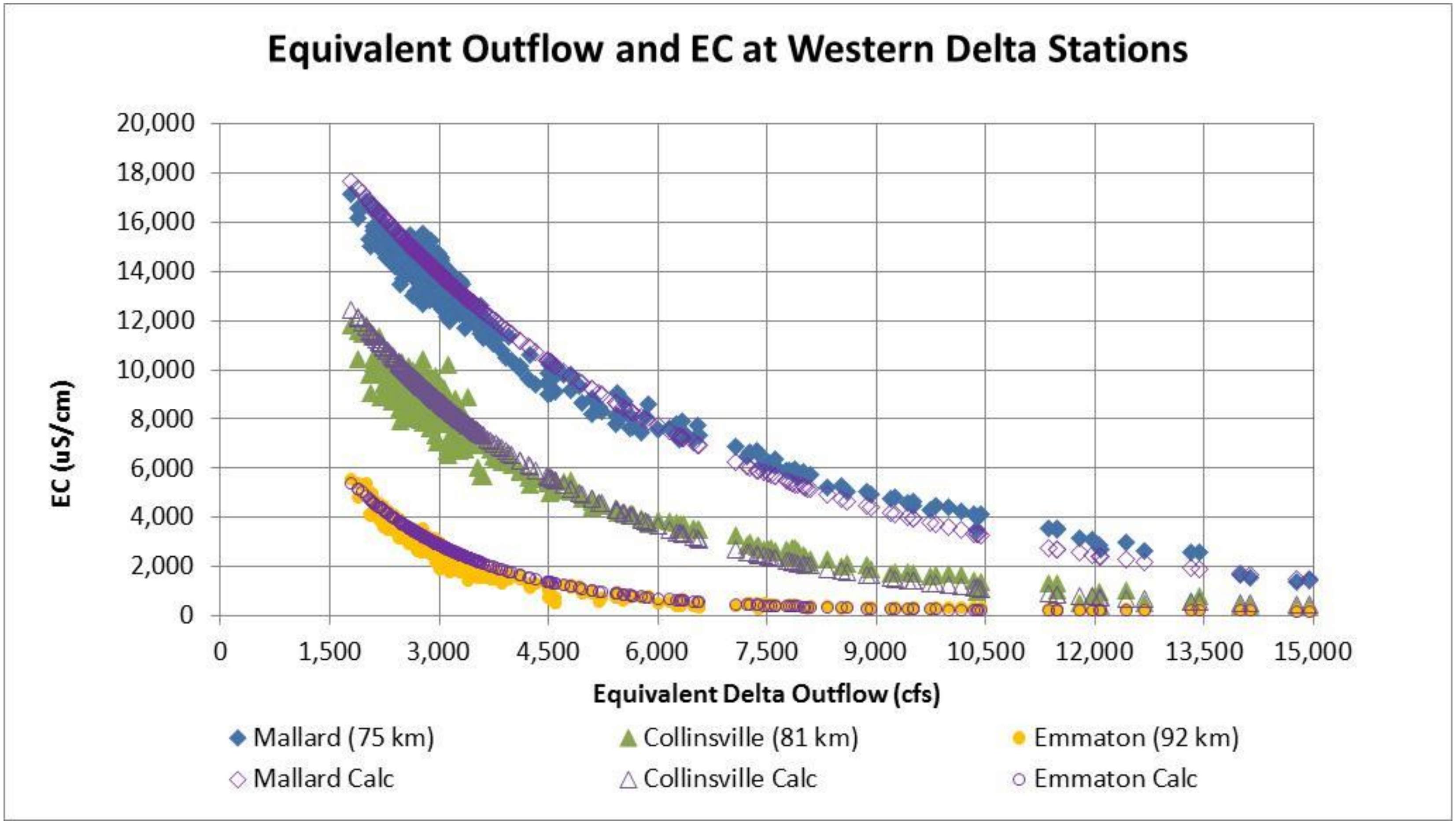

Figure 3a. Daily measured surface EC at Mallard Island, Collinsville, and Emmaton compared to the calculated EC using negative exponential equations with the equivalent outflow estimated from the measured bottom X2 for 2014.

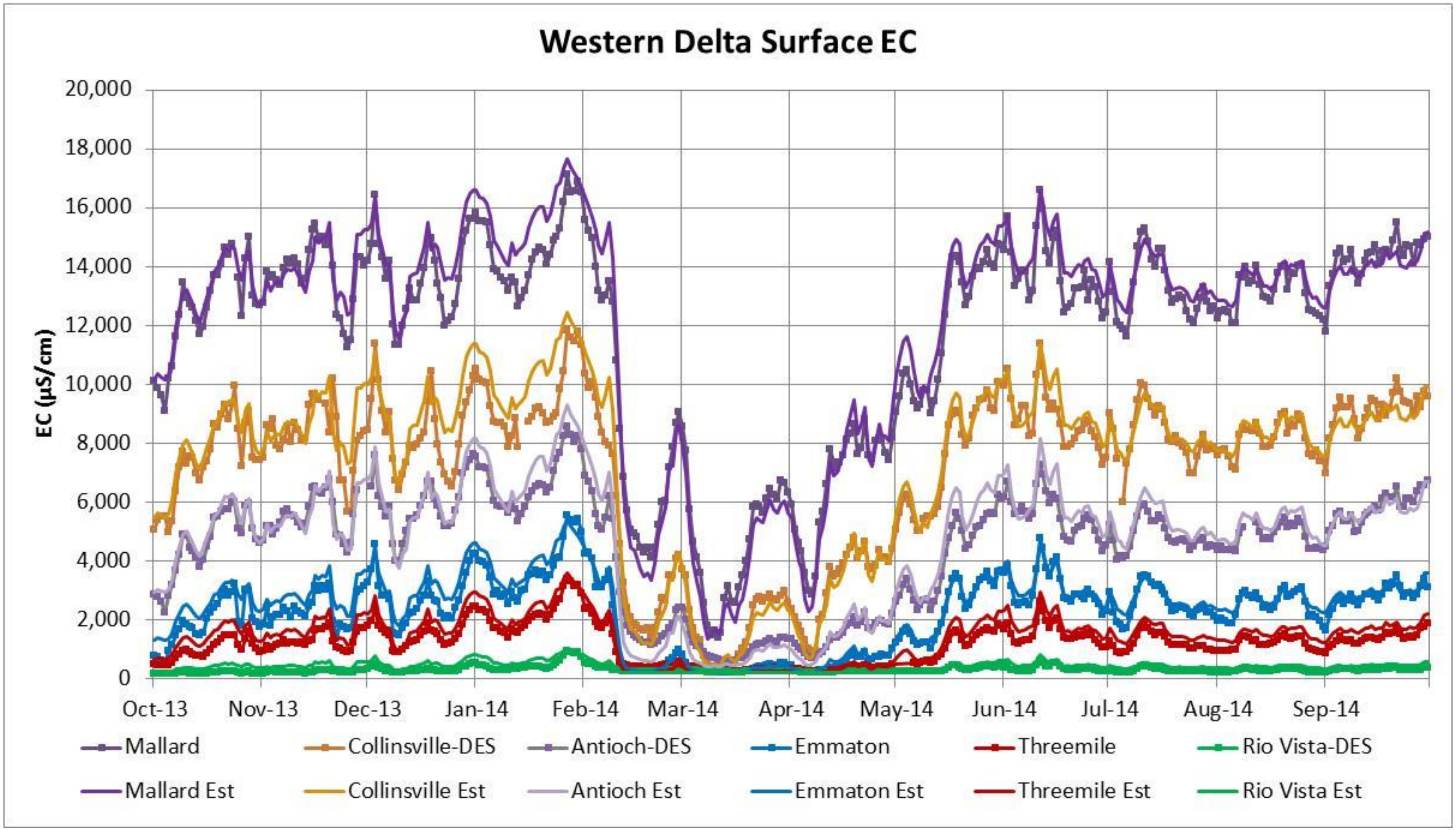

Figure 3b. Comparison of daily average measured EC with calculated EC using negative exponential relationships with effective Delta outflow estimated from measured bottom X2 for WY 2014. All of the EC monitoring stations show a similar response to changes in the effective outflow (and changes in the measured bottom EC).

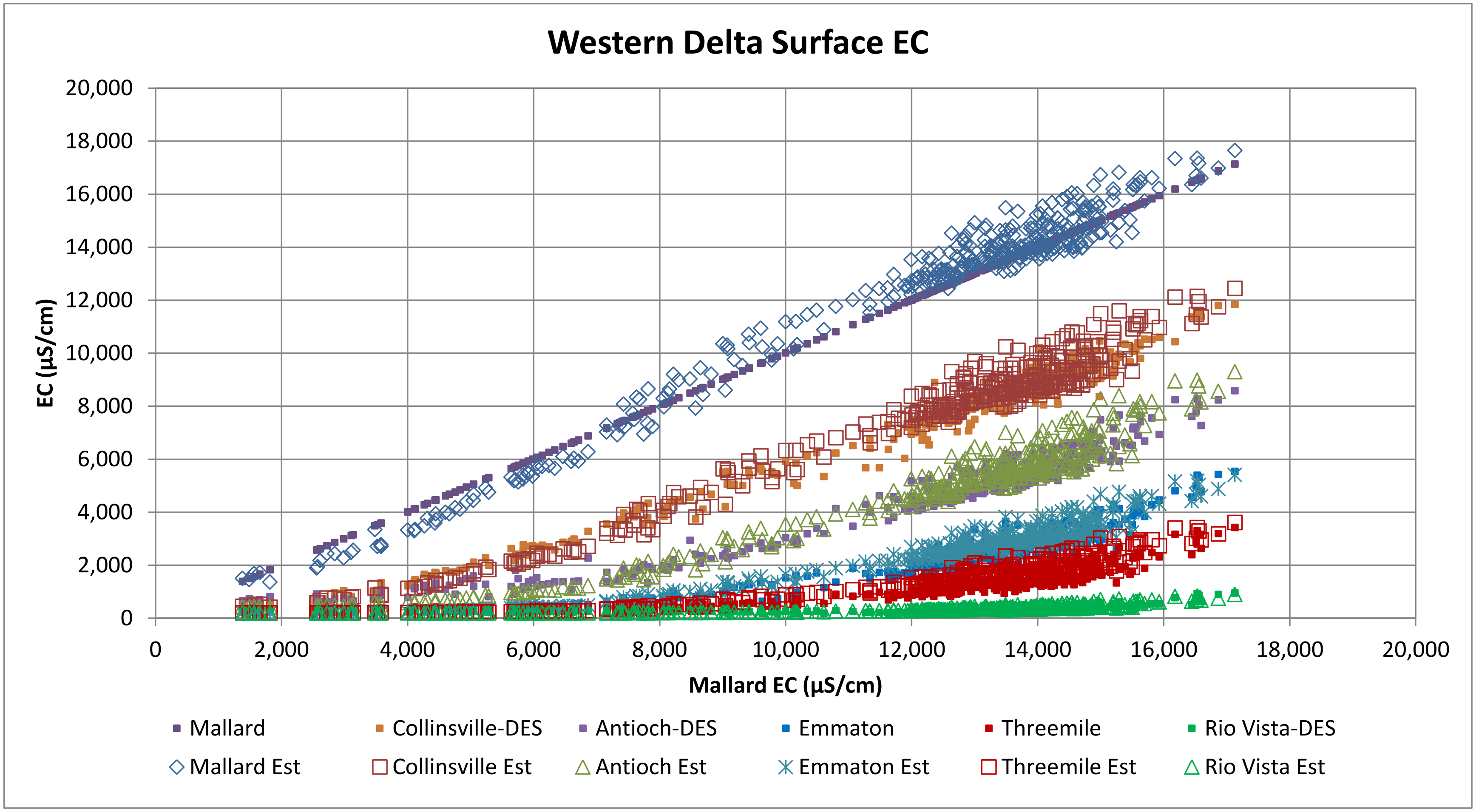

Figure 3c. Comparison of daily average measured EC with calculated EC using negative exponential relationships with equivalent Delta outflow estimated from measured bottom X2 for WY 2014. All of the EC monitoring stations appear to follow a linear salinity gradient (EC increments are constant) at higher Mallard EC (lower outflow) and perhaps a slightly decreasing gradient upstream of X2 (below EC of 4,000 uS/cm).