Appendix 1: Modeling Analyses

1. Modeling Scope and Approach

RMA was contracted to use modeling tools to investigate the temporal and spatial variations in transport time scales, such as “residence time” (defined below), and in water source in the Delta and in subregions, to explore the sufficiency of the current nutrient monitoring network to capture these variations, and to use the modeling results and analyses to make recommendations on locations where additional monitoring may be useful or current monitoring is redundant.

1.1. Time Frames Selected for Analysis

All modeling analyses were accomplished using three time frames that are representative of Delta flow conditions. **Table 1** below shows the three time frames selected, as well as the monthly average values of the inflows and exports considered. The three time frames are roughly described as Average flow conditions, Lower flow conditions, and Higher flow conditions, and were chosen as a single month and year for each condition.

Table 1. Summary table of the representative time periods that were selected for the analysis. Average inflows were calculated from daily average flow data estimated with the Dayflow computer program (http://www.water.ca.gov/dayflow/). Abbreviations: SJR = San Joaquin River inflow, SAC = Sacramento River inflow, CVP+SWP = combined Central Valley Project and State Water Project outflows, CALAVERAS = Calaveras River inflow, COSUMNES = Cosumnes River inflow, MOKELUMNE = Mokelumne River inflow, YOLO+LIS = Yolo Bypass/Lisbon Toe Drain, cfs = cubic feet per second.

Time period	Flow Condition	Estimated average inflows and outflows (cfs)						
		SJR	SAC	CVP+SWP	CALAVERAS	COSUMNES	MOKELUMNE	YOLO+LIS
September 2008	Low	801	10,461	4,930	32	3	33	110
September 2010	Average	1,713	16,451	10,403	21	13	163	158
June 2011	High	10,529	41,397	9,676	103	947	1,786	655

The recommended time frames were selected using a statistical analysis of monthly average flows into and out of the Delta for the period May – October, 2000 - 2013. The main inflow and outflows considered are:

- Sources: Sacramento River , Yolo Bypass/Lisbon Toe Drain inflow, San Joaquin River, Mokelumne River, Cosumnes River, Calaveras River;
- Exports: combined State Water Project (SWP) and Central valley Project (CVP) exports

Together, these flows largely determine the Net Delta Outflow. For each of the three month/year times selected, the Sacramento and San Joaquin inflows and the combined SWP+CVP export flows were the primary conditions considered, while the other inflows were used to select among potential candidate time/year combinations.

Although there were several candidate month/year combinations possible, several factors were used to discriminate or select between alternatives:

- Whether the Mokelumne and/or Cosumnes Rivers were flowing
- Whether the combined flow from the Yolo Bypass plus the Lisbon Tow Drain was enough to create flow through the Cache/Liberty Complex area
- How far the value of the three major factors was from either the maximum or minimum values of the three factors over the analyzed time frame (e.g., September 2008 was very close to the minimum of the San Joaquin set of monthly average flows)
- The opening and closing times of the various gate and barrier operations (**Table 2**)

The months May – October were used in calculating statistics as a subset of all possible months as the highest flows occur during late fall through winter, and these extremely high flows yield little information as they essentially illustrate very short residence times and a couple of obviously dominant source water contributions.

Table 2. Status of Delta gates and barriers during the time periods selected for the particle tracking simulations with the RMA2 model.

Time period	Delta Cross Channel	Head Old River Barrier	Old River Barrier	Middle River Barrier	Grant Line Barrier
September 2008	Open	Open	Closed	Closed	Closed
September 2010	Open	Open	Closed	Closed	Closed
June 2011	Closed	Open	Closed part of the month	Closed part of the month	Closed

1.2. Delta Subregions Selected for Analysis

Figure 1 shows the major subregions that were initially chosen for the modeling analyses: Sacramento River, North Delta (Yolo region and Liberty Island), Eastside (Mokelumne and Cosumnes River inflows), Central Delta, South Delta (San Joaquin River inflow), Confluence, and Suisun Bay. As the Central Delta region encompasses a large area of the Delta, this region was split into two smaller segments in order to examine potentially interesting sub regions (see **Figure 2**).

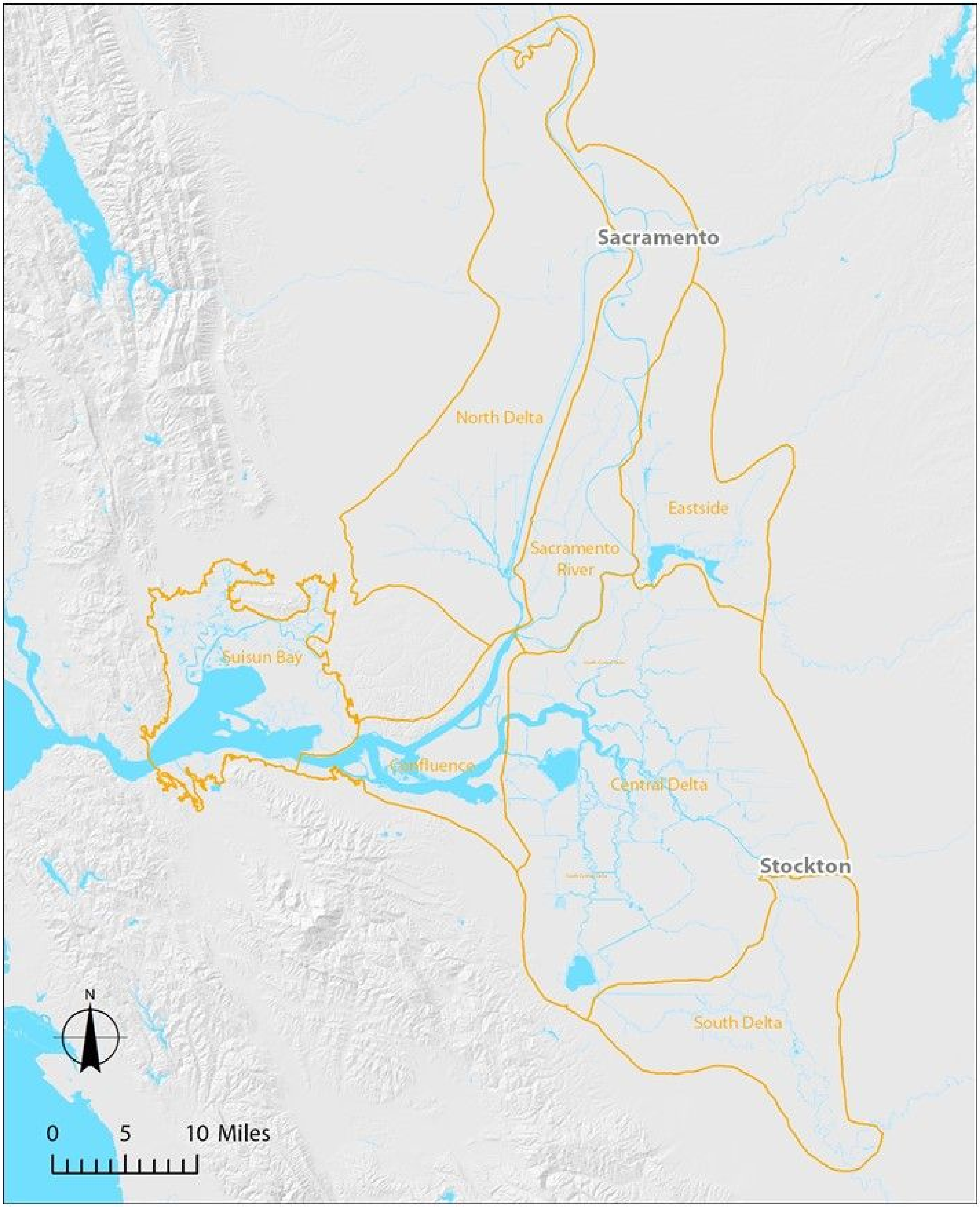

Figure 1. Delta subregions, as proposed in Jabusch et al. (2016).

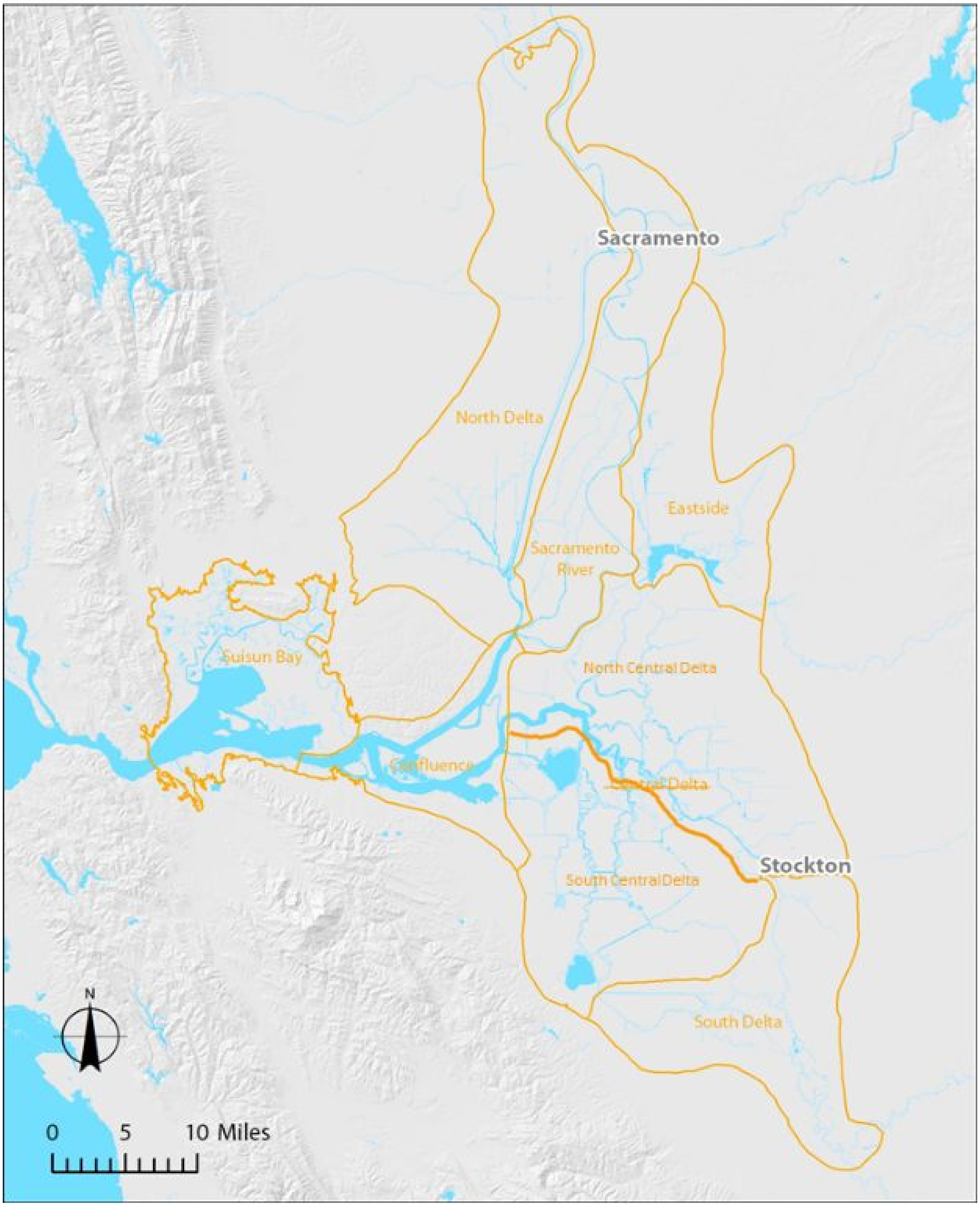

Figure 2. Final subregions used in the modeling analyses.

1.3. Model Analyses and Outputs (Graphics and Calculations)

The model analyses essentially fall into three categories:
DSM2 model calculations:

1. Volumetric water source analysis

RMA Particle tracking modeling

2. Residence time
3. Age and exposure time

1. *Volumetric Water Source Analysis* – DSM2 model calculations provide volumetric source water information for selected individual locations to represent the variation within each subregion. In addition, these locations were used to calculate regional averages for each of the Delta subregions for each time period. Results from individual locations within subregions were compared to evaluate similarities and differences in the mix of source waters. Since the modeled locations include monitoring stations, the result of this evaluation will inform decisions about where stations are missing or redundant.

2. *Residence Time Analyses* – Residence time is defined as the time required for a water parcel at a certain location to migrate out of a water body. The residence time varies with location in the estuary. In our context, residence time is the time it takes a water parcel to leave a pre-specified region in the model calculated from the start of the 28 day simulation period. For this analysis, the RMA model was used to simulate how long it takes individual particles uniformly distributed in the region to exit the region. The model was run for 28 days for the low, average, and high flow conditions for each of the seven subregions. Statistics from the model output were used to estimate the residence time for particles in the subregions under the different flow regimes.

   The variability in residence time within the subregion indicates whether the region is homogeneous or not. Outputs will be used to identify potential high residence time areas within each subregion.

3. *Age and Exposure Time Analysis* - The purpose of this analysis is to understand how long water from different sources typically spends in each of the subregions. Age is the complement of residence time. Age represents the amount of time an individual parcel of water has spent inside of the model domain since it entered the model. So, age applies to parcels of water that enter through an inflow boundary in the Delta model domain. Exposure time is the amount of time a parcel spends within a specified region during a predetermined time period such as the length of a computer simulation, allowing for multiple entries and exits to the region. In comparison, the residence time calculation only considers the time to the first exit. Age/exposure time maps were generated with the RMA model by simulating the near continuous release of particles from a source water for 28 days under low, average, and high flow conditions. The model tracked the movement of these particles through the Delta for 28 days. Statistics on the age of particles in a subregion on day 28 were calculated and qualitatively compared with "Volumetric Water Source" statistics to better define source waters in each of the subregions (Section 3.2. Particle tracking Modeling). For each example, if a region is 80% Sacramento River

water, how “old” or “young” is that water?

2. Background on Hydrodynamic Modeling Applications

2.1. DSM2-QUAL Volumetric Calculations

Table 3 provides a list of the 57 sites for which “Volumetric fingerprints” were estimated, and **Figures 3 - 9** show the geographic location of the sites selected for each subregion.

Table 3. Summary table of DSM2 volumetric output locations. Station = Department of Water Resources (DWR) - Environmental Monitoring program (EMP) monitoring station. Node = DSM2 (Delta Simulation Model 2) node.

Code	Type	Location	Subregion
C3	Station	Sacramento River @ Hood	Sacramento River
Channel428_L	Node	Sacramento River @ Ida Island	Sacramento River
MinerSl	Node	Miner Slough	Sacramento River
RSAC128	Node	Sacramento River @ Delta Cross Channel	Sacramento River
RSAC155	Node	Sacramento River @ Freeport	Sacramento River
SLSBT011	Node	Sutter Slough below Steamboat Slough	Sacramento River
SutterSl	Node	Sutter Slough below Elk Slough	Sacramento River
CacheRyer	Node	Cache Slough @ Ryer Island	North Delta
LibertyIsland	Node	Liberty Island	North Delta
Sac Deep Watr Shp Chl	Node	Sacramento Deep Water Ship Channel	North Delta
SLBAR002	Node	Barker Slough	North Delta
SLCCH016	Node	Cache Slough near Hastings Tract	North Delta
D4	Station	Sacramento River above Point Sacramento	Confluence
D11	Station	Sherman Lake near Antioch	Confluence
D12	Station	San Joaquin River @ Antioch Ship Channel	Confluence
D14A	Station	Big Break near Oakley	Confluence
D15	Station	San Joaquin River @ Jersey Point	Confluence
D22	Station	Sacramento River @ Emmaton	Confluence
D24	Station	Sacramento River below Rio Vista Bridge	Confluence
ThreeMileSlough	Node	Sacramento River @ Three Mile Slough	Confluence
D2	Station	Suisun Bay near Preston Point	Suisun Bay
D6	Station	Martinez	Suisun Bay
D7	Station	Grizzly Bay	Suisun Bay
D8	Station	Suisun Bay off Middle Point near Nichols	Suisun Bay
D9	Station	Honker Bay near Wheeler Point	Suisun Bay
D10	Station	Sacramento River @ Chipps Island	Suisun Bay
NZ032	Station	Montezuma Slough, 2nd bend from mouth	Suisun Bay
S42	Station	Suisun Slough 300' south of Volanti Slough	Suisun Bay
SLMZU011	Node	Montezuma Slough near Beldon’s Landing	Suisun Bay
SLMZU025	Node	Montezuma Slough near Molena	Suisun Bay
DCC	Node	Delta Cross Channel	Eastside
P2	Station	Mokelumne River @ Franklin Road Bridge	Eastside
RMKL019	Node	Mokelumne River @ Snodgrass Slough	Eastside
RSMKL019	Node	Mokelumne River, South Fork, near New Hope	Eastside

D16	Station	San Joaquin River @ Twitchell Island	North Central Delta
D26	Station	San Joaquin River @ Prisoners Point	North Central Delta
MD6	Station	Sycamore Slough near Mouth	North Central Delta
MD7	Station	South Fork Mokelumne River below Sycamore Slough	North Central Delta
MD10	Station	Disappointment Slough @ Bishop Cut	North Central Delta
RMKL005	Node	Mokelumne River @ Georgiana Slough	North Central Delta
RSAN052	Node	San Joaquin River @ Shima Bend	North Central Delta
P8	Station	San Joaquin River @ Buckley Cove	North Central Delta
C9	Station	West Canal @ Clifton Court Intake	South Central Delta
D19	Station	Frank's Tract	South Central Delta
D28A	Station	Old River @ Rancho Del Rio	South Central Delta
P10A	Station	Middle River @ Union Point	South Central Delta
RMID015	Node	Middle River @ Middle River	South Central Delta
ROLD034	Node	Old River near Byron	South Central Delta
CHDMC006	Node	Delta-Mendota Canal near Tracy Pumping Plant	South Delta
CHGRL009	Node	Grant Line Canal @ Tracy Road	South Delta
C7	Station	San Joaquin River @ Mossdale Bridge	South Delta
C10	Station	San Joaquin River near Vernalis @ SJR Club	South Delta
GrntLineDnstrmBar	Node	Grant Line Canal downstream of the barrier	South Delta
OldRatMiddleR	Node	Old River @ Middle River	South Delta
P12	Station	Old River @ Tracy Road Bridge	South Delta
ROLD047	Node	Old River downstream of Mountain House Creek	South Delta
RSAN072	Node	San Joaquin River @ Bowman Road	South Delta

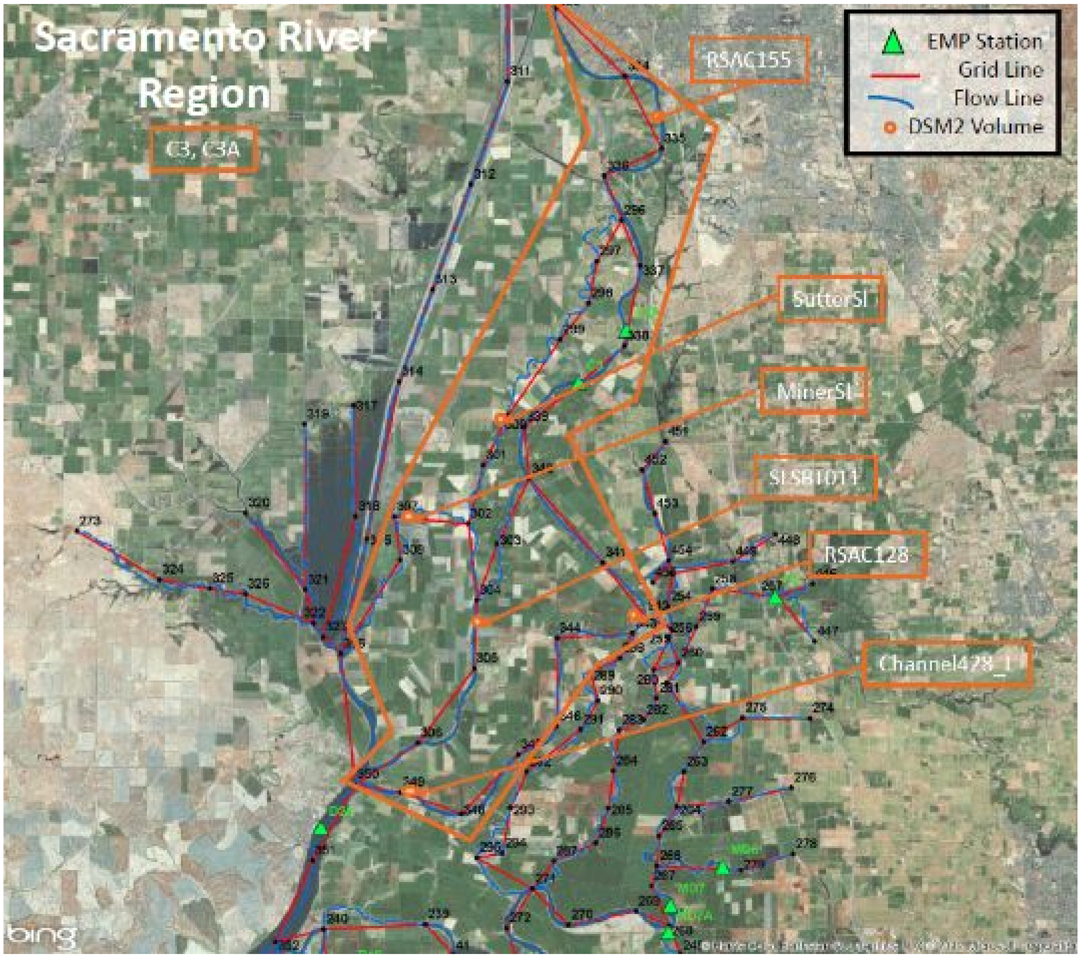

Figure 3. DSM2 volumetric output locations in the Sacramento River subregion.

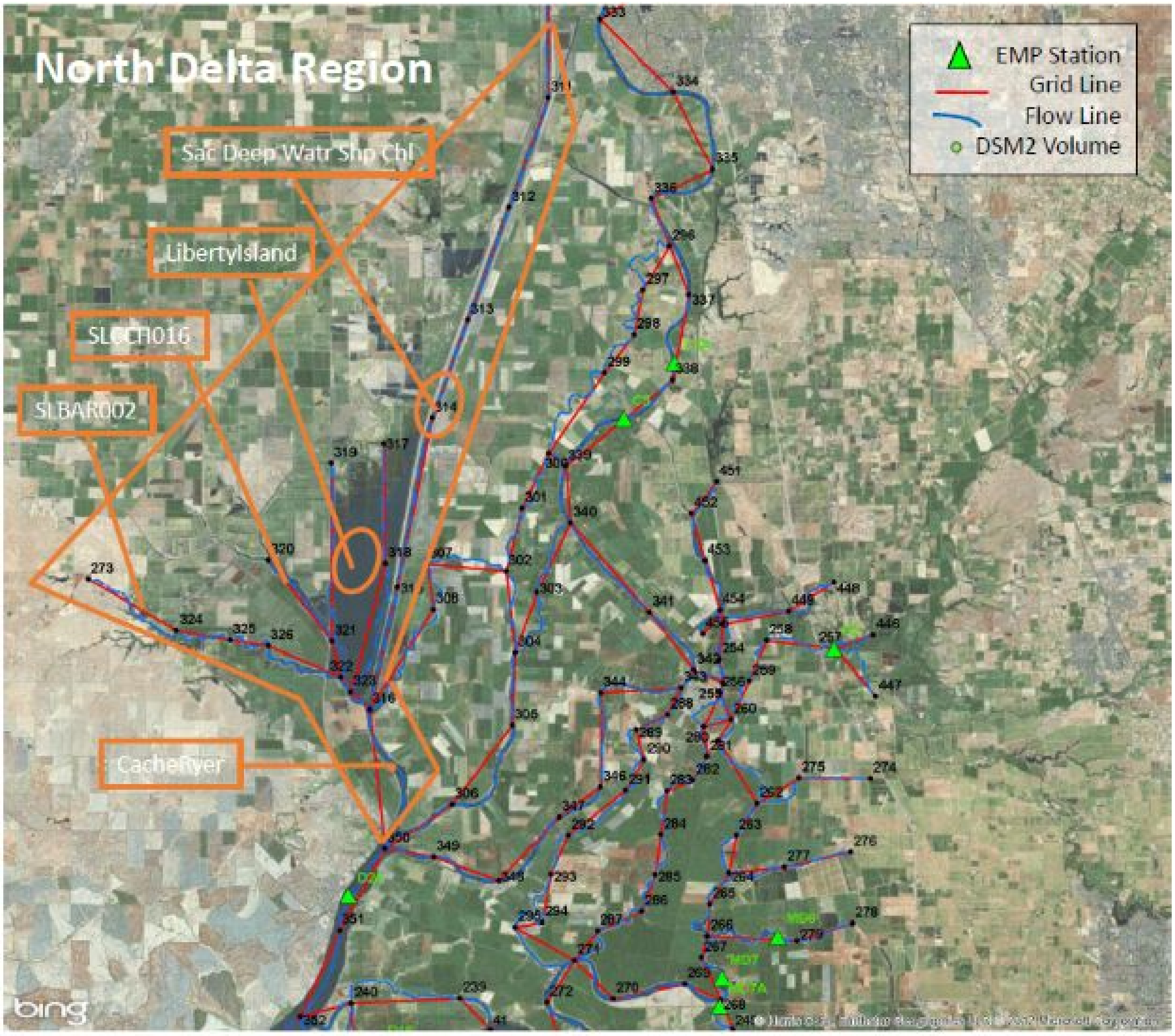

Figure 4. DSM2 volumetric output locations in the North Delta subregion.

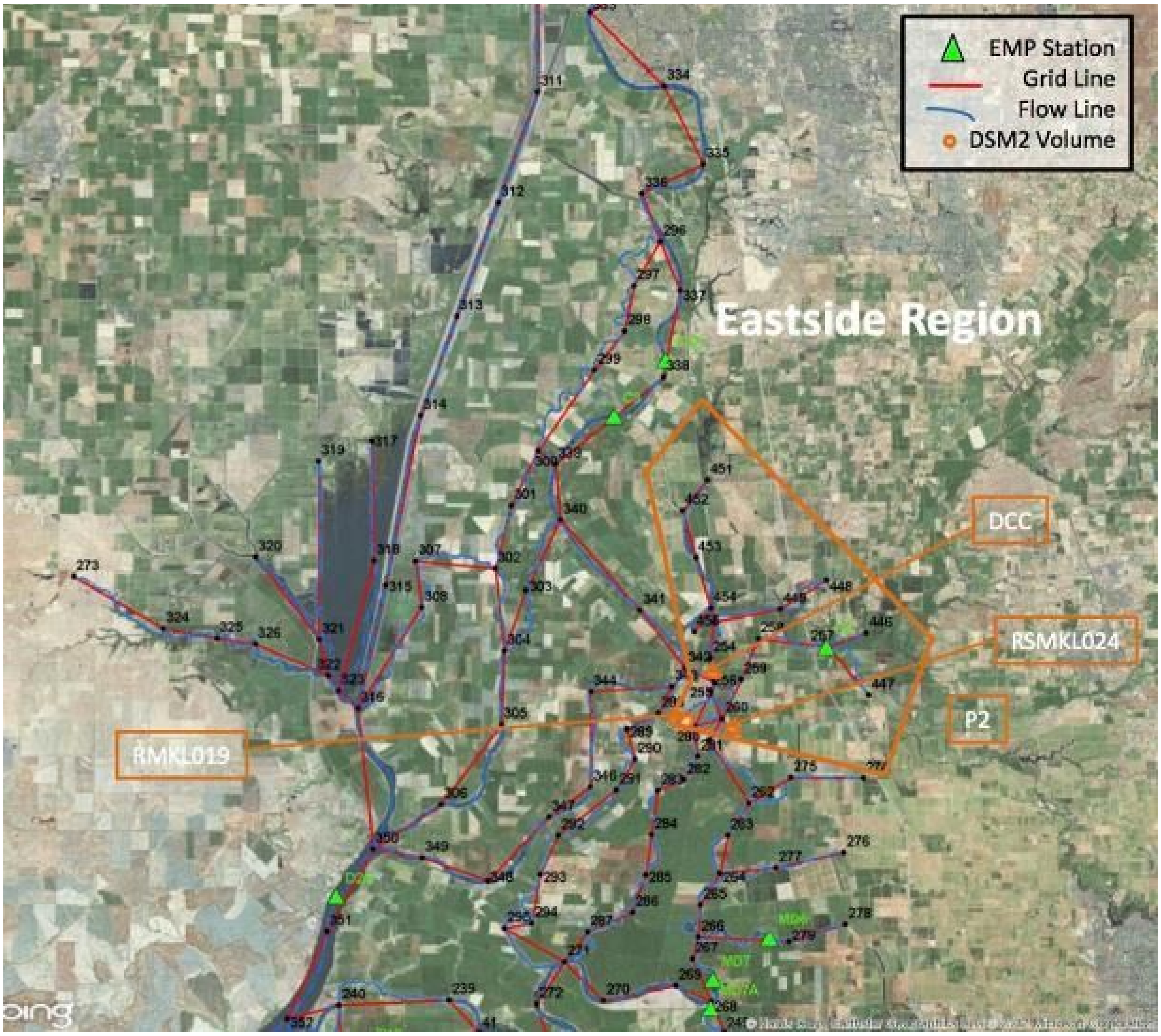

Figure 5. DSM2 volumetric output locations in the Eastside subregion.

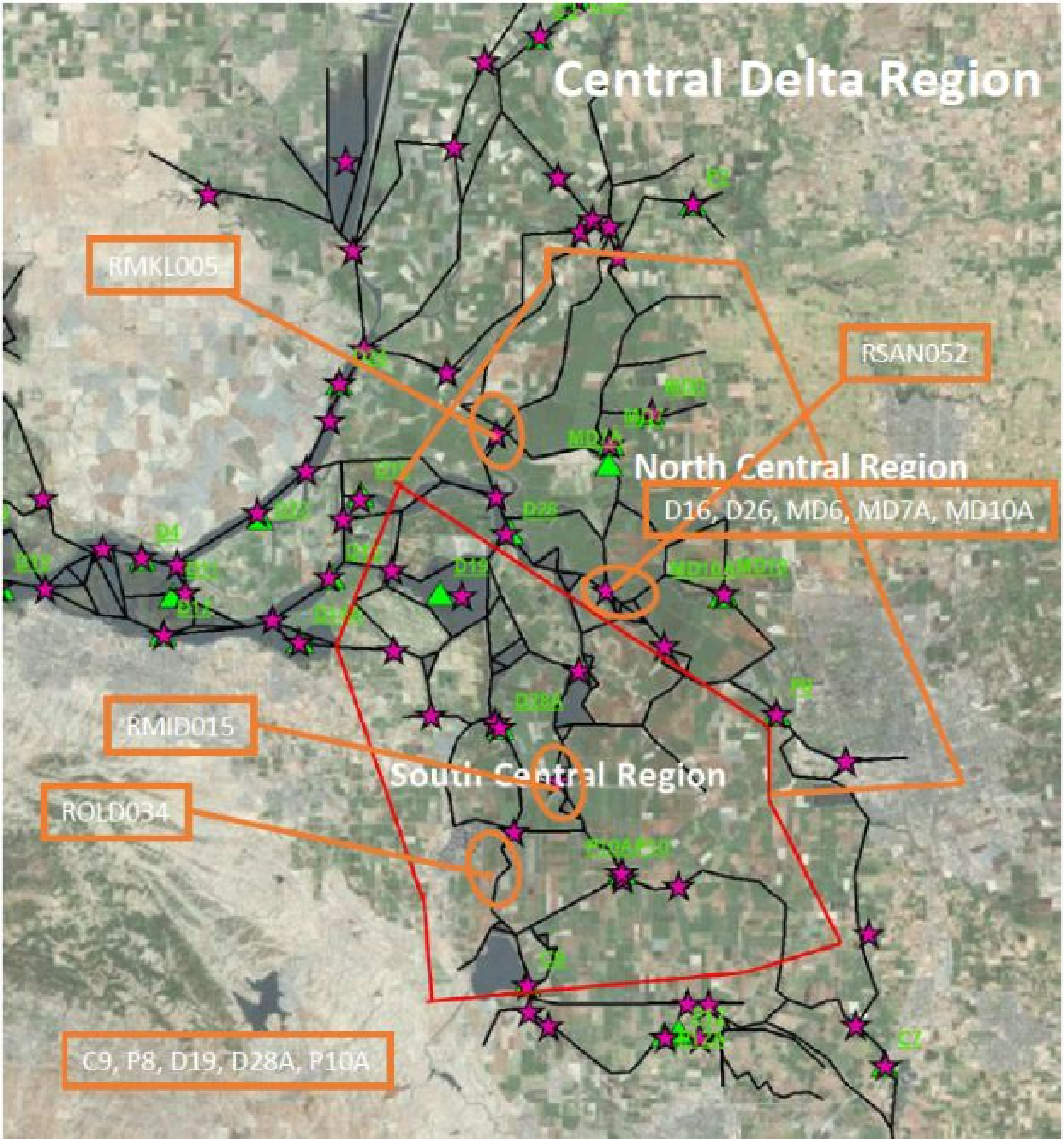

Figure 6. DSM2 volumetric output locations in the North Central and South Central subregions.

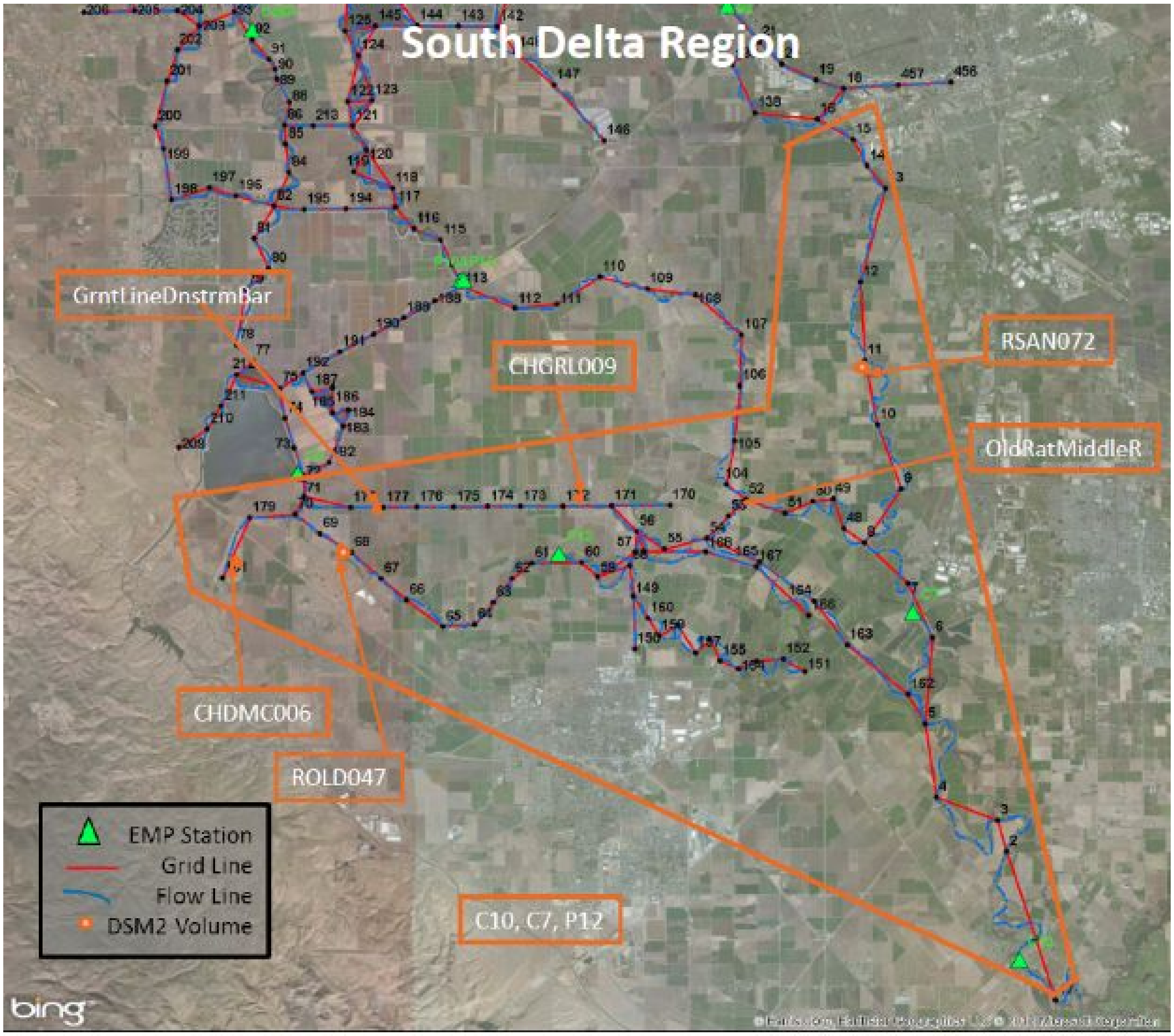

Figure 7. DSM2 volumetric output locations in the South Delta subregion.

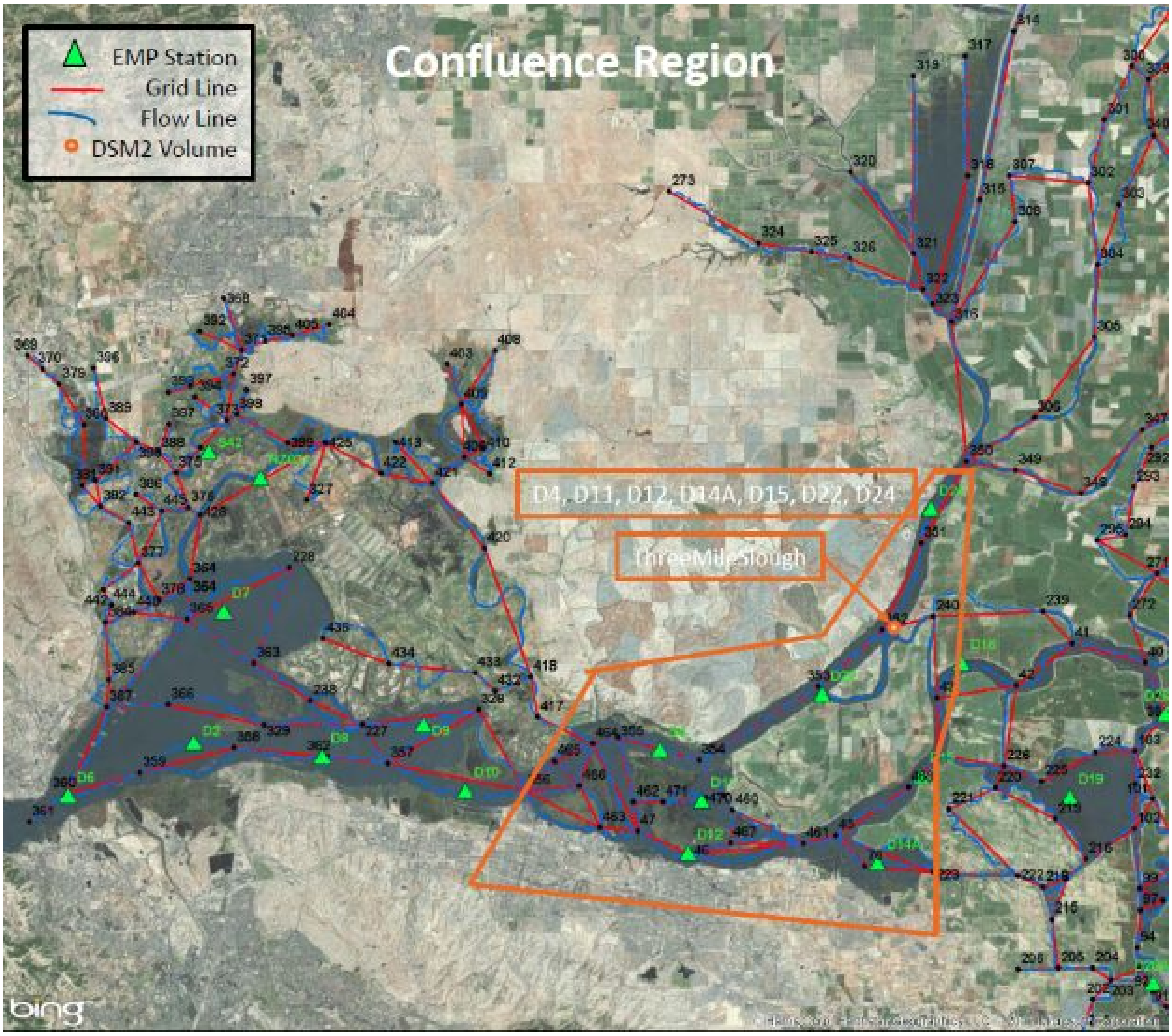

Figure 8. DSM2 volumetric output locations in the Confluence subregion.

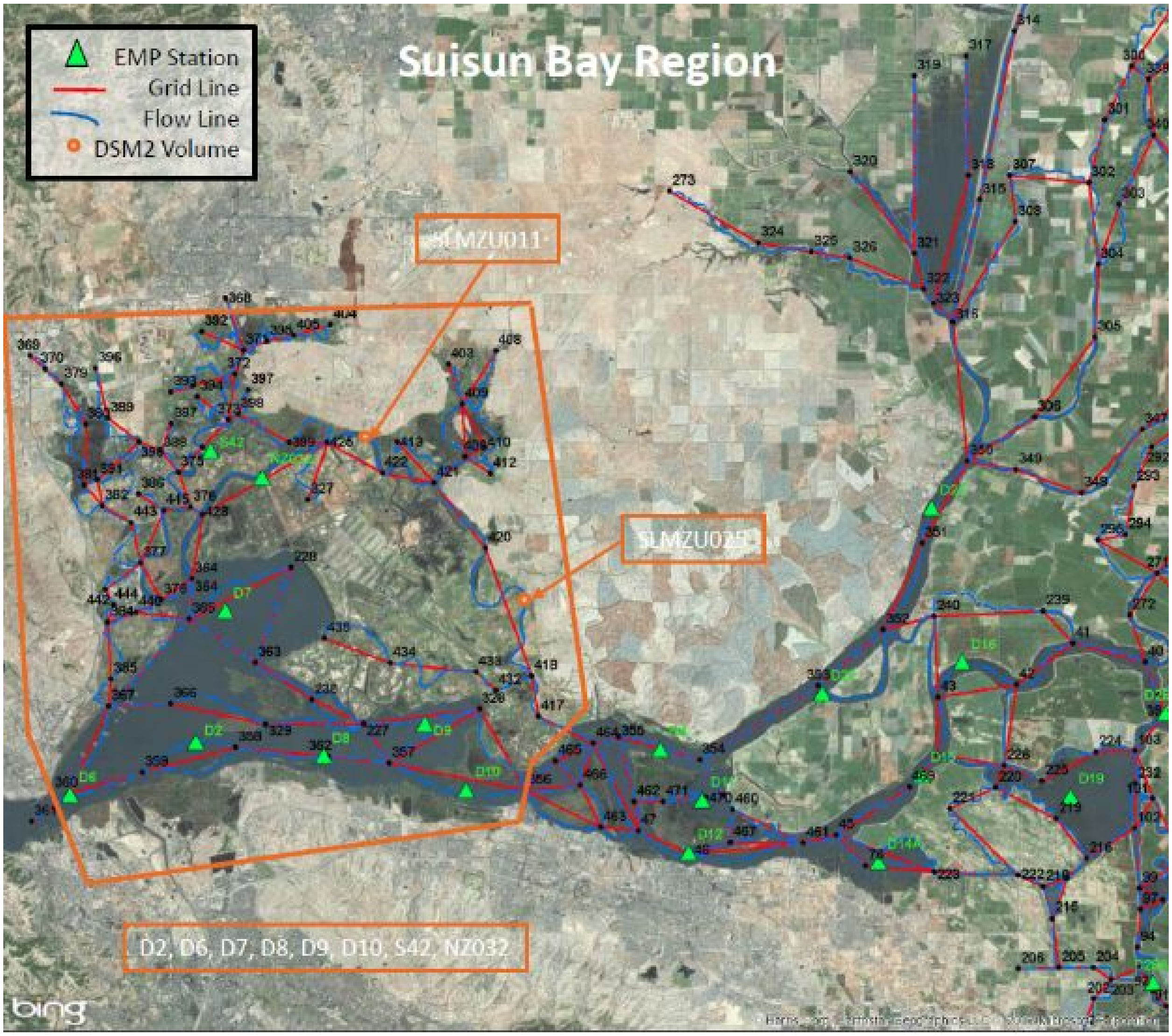

Figure 9. DSM2 volumetric output locations in the Suisun Bay subregion.

The volumetric fingerprints for each location were estimated using output of the hydrologic model Delta Simulation Model (DSM2; see Anderson 2002 and Guerin 2016 for more detail). The volumetric fingerprints estimate the relative contribution of various water sources to the ambient water at specified sites and are presented on a monthly average basis from 2001-2012 Water sources include: Sacramento River; San Joaquin River; tidal source (San Francisco Bay water from downstream of Martinez); Mokelumne and Cosumnes Rivers; Agricultural influences (Delta Island Consumptive Use [DICU] outflow); Yolo Bypass/Toe Drain; Calaveras River, Jones Tract outflow (significant during levee breach in 2004-05 at some sites in South Delta) and wastewater treatment plants (WWTPs).

2.2. *RMA Particle Tracking Modeling*

Hydrodynamics
The RMA2 numerical model of the Sacramento-San Joaquin Delta is a finite element-based program for the simulation of two-dimensional depth-averaged steady and unsteady flow. The program computes water surface elevations and horizontal flow velocity in one or two dimensions. The algorithm solves the shallow water equations in primitive variables to provide temporal and spatial descriptions of velocities and water depths throughout the Delta grid. The time step used for modeling the depth-averaged flow and water quality transport in the Delta is 7.5 minutes. A full description of the governing equations for flow and additional RMA2 model details can be found in RMA (2005).

The RMA2 Delta grid has been sequentially updated and calibrated since its inception. For the current project, details on the grid and the hydrodynamic calibration can be found in RMA documentation prepared for the Prospect Island Restoration Project (Siegel and Carter 2013) .RMA modeling applications used in this project are proprietary.

Particle Tracking Model
The results of the RMA2 flow simulation (x and y velocity components, and depth of water) are saved every time step for all nodal locations to a binary file. These results can then used by the RMA Particle Tracking model, RMATRK, to produce the several types of output, both graphic and statistical.
While all particle tracking simulations use the RMA2 results for advective transport, the calculation of particle dispersion can be calculated in different ways, or not used at all (i.e., simulating pure advection). The settings for calculating dispersion are captured in the screenshot shown in **Figure 10**.

Unlike the hydrodynamics model, calibration data for the particle tracking application is not available. There have been a few small experiments in previous years, but data is generally lacking. The dispersion coefficients selected for the current modeling simulations have been used in many previous applications, and there have been some comparisons with EC data in the Delta as well as comparisons using different sets of dispersion coefficients. The current dispersion set is viewed as reasonable, but statistical results should be viewed as ‘semi-quantitative’.

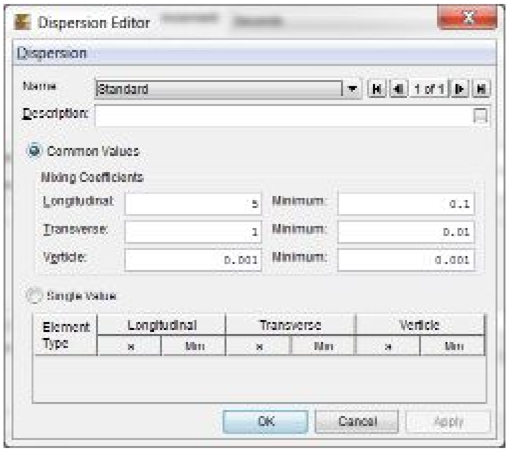

Figure 10. Screenshot of RMA2 model dispersion editor.