Mercury Open Water Final Report for Compliance with the Delta Mercury Control Program

Chapter 5. Delta-Mercury and Methylmercury Modeling Studies

Submitted by the Open Water Mercury Modeling Workgroup

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List of Acronyms and Abbreviations

Bureau	Bureau of Reclamation
CalFed	CalFed Bay-Delta Program, former state and federal consortium focused on Delta issues
CVP	Central Valley Project
cfs	Cubic Feet per Second
Delta	Sacramento-San Joaquin Delta
D-MCM	Dynamic Mercury Cycling Model
DMCP	Delta Mercury Control Program (DMCP)
DSM2-Hg	Delta Simulation Model, version 2, Mercury Model
DWR	(California) Department of Water Resources
fHg	Filter-passing Mercury
fMeHg	Filter-passing Methylmercury
Hg	Mercury
Hg(II)	Inorganic mercury with an oxidation state of +2
Hg(0)	Elemental mercury
Inorganic Hg	Sum of inorganic Hg(II) and Hg (0)
MeHg	Methylmercury
PEST ++	Parameter Estimation Software
SSC	Suspended Sediment Concentration
SWP	State Water Project
SWRCB	State Water Resources Control Board
Hg	Total Mercury (sum of inorganic mercury and MeHg)
uHg	Unfiltered (aqueous) mercury
uMeHg	Unfiltered (aqueous) methylmercury
USGS	United States Geological Survey
WWTP	Waste Water Treatment Plant
WY	Water Year(s)

Introduction

The Delta Mercury Control Program (DMCP) requires the California Department of Water Resources (DWR) to reduce methylmercury (MeHg) open water sediment flux from areas out of compliance in the Delta and Yolo Bypass (See Chapter 1). An existing hydrodynamic and water quality model was extended to include features needed to simulate mercury (Hg) in the Delta. This included the addition of a compartment to represent surface sediments, the ability to simulate suspended sediments in the water column and sediment bed, and the ability to simulate inorganic Hg and MeHg in the water column and sediment bed. The updated model is called Delta Simulation Model, version 2, Mercury Model (DSM2-Hg). This effort was complemented by modeling, field, and laboratory studies in the Yolo Bypass. The approach was approved by the Central Valley Regional Water Quality Control Board (Regional Board) to evaluate the potential effects of operational changes on Hg cycling and MeHg supply.

The objective of Chapter 5 is to summarize and provide key findings of interest to management and policy makers associated with the application of DSM2-Hg. Details are provided in Technical Appendix I which focuses on the Hg module, and Technical Appendix J which focuses on the suspended and bed sediment modules. When packaged for public release, DWR will publish model source code, executable files, and other information on the DSM2 website (DWR, 2020a).

Site Description

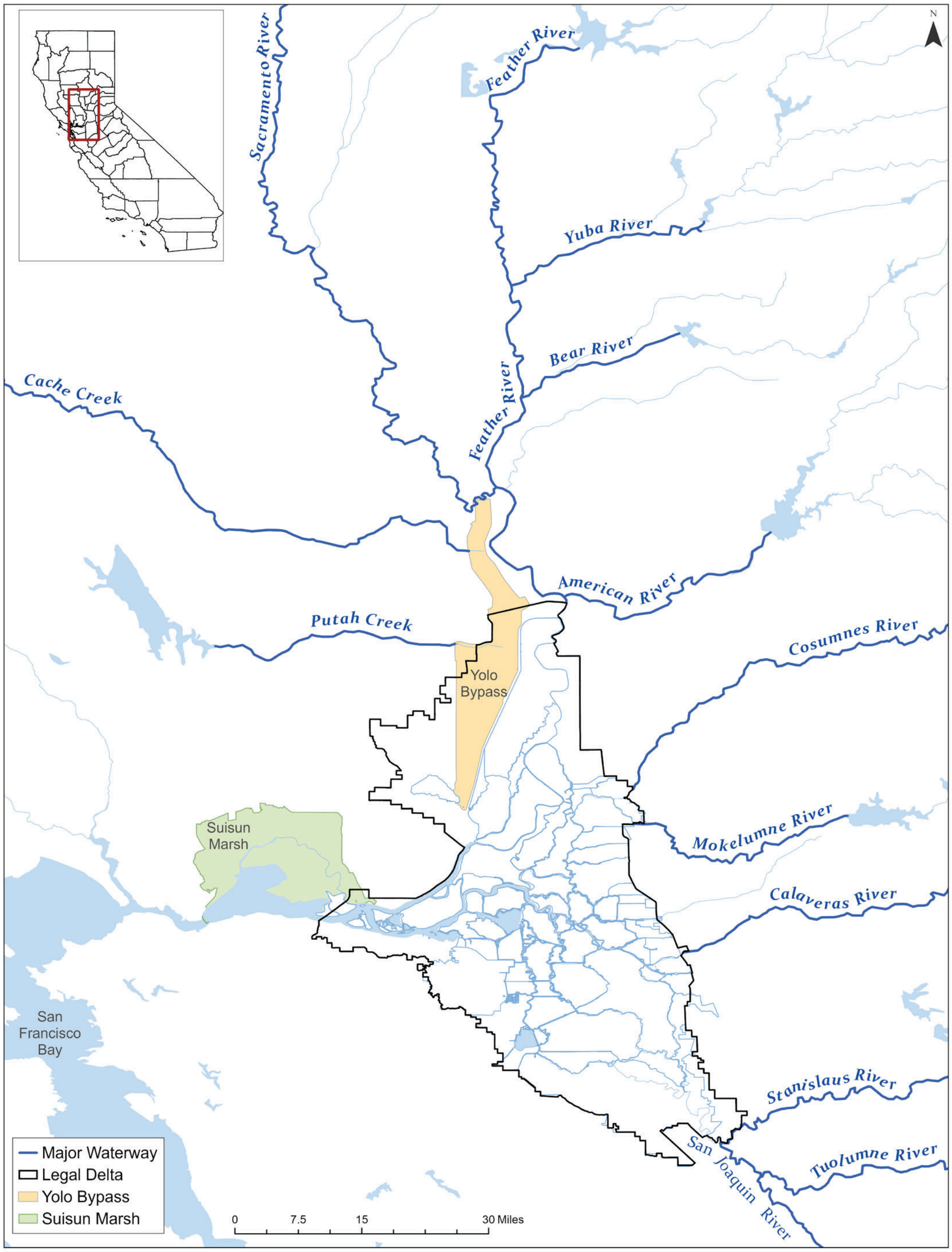
The Delta

The Sacramento-San Joaquin Delta (Delta) is the largest freshwater tidal estuary on the west coast of the United States. It is formed by the confluence of the Sacramento and San Joaquin Rivers and lies just east of where the rivers enter Suisun Bay (Figure 5-1). The Delta is the hub of California's two largest surface water delivery projects, the State Water Project (SWP), operated by DWR, and the Central Valley Project (CVP), operated by the Federal Bureau of Reclamation (Bureau). The Delta provides a portion of the drinking water for 29 million Californians and irrigation water for agriculture. The Delta comprises a 700-mile maze of sloughs and waterways surrounding more than 60 leveed tracts and islands. The estuary provides habitat critical to the survival of many fish and wildlife species.

The operation of the Delta is subject to a complex array of water rights, flow criteria, and endangered species laws. In terms of water rights, the SWP and CVP are subject to several water right permits issued by the State Water Resources Control Board (SWRCB). In addition to setting water quality criteria that translate into operational standards within the Delta and the Delta watershed, the SWRCB also sets in-stream flow standards. DWR and the Bureau must obtain authorization for any taking of threatened or endangered species. Together this complex set of regulations impose strict constraints on how and when the SWP and CVP can move water.

The Yolo Bypass (Figure 5-1) provides flood control protection for Sacramento and other riverside communities. During high flows, water is diverted from the Sacramento River north of Sacramento into the Yolo Bypass. Water flows through the Bypass and back into the Delta just north of Rio Vista. These Yolo Bypass flows are a source of sediment and Hg in the Delta.

Figure 5-1 **Boundaries of the Legal Delta**



Sediment and Hg transport in the Delta are driven by the combination of tidal flows from San Francisco Bay and freshwater inflows from the Sacramento and San Joaquin Rivers, some minor tributaries and during flood events from the Yolo Bypass. Freshwater inflows into the Delta are highly variable but are modulated by upstream reservoir operations (Table 5-1). For the 2000-2006 study period, median flows for the Sacramento and San Joaquin Rivers are around 18,000 cfs and 2,200 cfs respectively. Median exports from the State Water Project and Central Valley Project were 4,800 cfs and 4,200 cfs respectively. When operating, median Yolo Bypass flows were around 730 cfs with maximum flows in excess of 250,000 cfs. The Yolo Bypass and Delta Hg models described in this report provide tools for exploring how hydrologic variability, SWP and CVP operations, and other factors may affect Hg and sediment transport and fate, including MeHg loads, in the Delta.

Table 5-1 Ranges of Major Delta Inflows and Exports Oct 1, 1999 to July 31, 2006

	Inflows			Exports	
	Sacramento River (cfs)	San Joaquin River (cfs)	Yolo Bypass (cfs)	State Water Project (cfs)	Central Valley Project (cfs)
Maximum	92,790	34,767	256,214	(9,120)	(4,678)
Median	17,805	2,181	0 or 732**	(4,801)	(4,201)
Minimum	4,705	950	(40)*	0	0

Source: California Data Exchange Center *upstream tidal flows at toe drain during summer

**Flows from the Yolo Flood Control Bypass into the Delta are episodic. The median flow of the entire time period is zero. The median value for when the Yolo Bypass is flowing is 732 cfs.

Study Objectives and Approach

Objectives

The primary objectives associated with the development and application of DSM2-Hg were to:

- Create a numerical model that can simulate concentrations, fluxes, transport and fate of inorganic Hg and MeHg in water and surface sediments in the Delta.
- Use the model to evaluate processes governing MeHg supply to the Delta.
- Use the model to help evaluate whether there are operational changes or other strategies that can be implemented to reduce ambient MeHg concentrations in the Delta.

Development of the DSM2-Hg model also provides a tool to explore additional questions in the future, beyond the direct scope of the current analysis. As an open source model, interested stakeholders could also use and refine the model to include other desired inputs.

As discussed in Chapter 1, due to resource, time, and technical constraints, a manually calibrated Delta Hg model fulfills DWR's Delta open water portion of the DMCP. Additional Delta sensitivity and scenarios proposed in the workplan were not conducted[1]. All changes from the original Workplan were approved by the Central Valley Regional Water Quality Control Board (Technical Appendix A).

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[1] After report submittal, Delta sensitivity runs were conducted and can be found in Technical Appendix K.

Model Selection

It was clear during the design phase of the project that Hg cycling in the Delta is strongly influenced by hydrodynamics and sediment transport. Furthermore, conditions can change rapidly in the Delta, and can vary spatially over relative short distances. A model framework was needed that could represent not just Hg, but also freshwater and tidal flows and sediment transport, including temporal and spatial variability. Another feature important for Hg simulations was to explicitly include a sediment bed compartment in the model framework. This is because MeHg production often occurs in the surface layer of the sediment bed, and because legacy inorganic Hg contamination in surface sediments can affect MeHg production and supply to overlying waters.

No single model existed at the outset of the study with all the features needed to simulate Hg cycling, and the primary influences on Hg cycling, in the Delta. An effort was therefore undertaken to extend an existing DWR hydrodynamic model for the Delta, the Delta Simulation Model version 2 (DSM2) (DWR, 2020a), to include a sediment bed module, suspended sediment transport and fate, and Hg cycling in water and the sediment bed. A separate effort unrelated to Hg replaced the water quality module in DSM2 with an updated General Transport Module (GTM) (Hsu and others, 2014) that is modular to allow additional constituents, such as Hg, to be added to the model. The resulting DSM2-Hg model simulates hydrodynamics, sediment transport, and the cycling and fate of three major forms of Hg (MeHg, Hg(II), and elemental Hg(0)) in the water column and surface sediments of the Delta (Figure 5-2).

DSM2 is a one-dimensional (1-D) model, suitable for applications where gradients occur in one direction (along the flowpath in this case) but are assumed to be the same (well-mixed) vertically and horizontally perpendicular to flow. This is a reasonable assumption for the Delta's open water channels but becomes a limitation once conditions have significant variability in two or three dimensions, such as downstream in San Francisco Bay which has conditions that also vary with depth and across the width of the bay. Thus, the downstream limit of DSM2 was set at Martinez (Figure 5-3) to keep the model domain primarily in the channelized part of the Delta. Martinez is also the location of a long-term tidal gage which provides data for modeling tidal flows into and out of the Delta. Since greater confidence in 1-D conditions occurs in areas upstream of Chipps Island (Figure 5-3) and since Chipps Island is closer to the downstream boundary of the legal Delta than the model's downstream boundary at Martinez, modeled exports of mercury and suspended sediment to San Francisco Bay presented in this report were calculated at Chipps Island.

Tributary inflows represented in DSM2 include the Sacramento, San Joaquin, Cosumnes, Mokulmne, and Calaveras Rivers and the Yolo Flood Control Bypass (Yolo Bypass). Water supply exports in DSM2 include the State Water Project (SWP), the federal Central Valley Project (CVP), and Contra Costa Water District. Consumptive use of water on the 142 Delta islands is also represented in DSM2 (DWR, 2020b). Ongoing development of DSM2 is documented in annual reports to the State Water Resources Control Board (CNRA, 2020).

An overview of DSM2-Hg follows. Additional information on the development of the Hg, suspended sediment, and sediment bed modules is provided in Appendix I and Appendix J, respectively.

Figure 5-2 Key Features of the Delta Mercury Model (DSM2-Hg)

Delta Mercury Model (DSM2-Hg)

Forms of Mercury Modeled

- Methylmercury (MeHg)
- Hg(II)
- Elemental Hg (Hg(0))

Model Domain and Study Period

- Open water channels in the Sacramento San Joaquin Delta between Sacramento, Venalis and Martinez. Emphasis on results upstream of Chipps Island.
- Mercury calibration period: October 1999 to July 2006
- Simulation time step 15-minutes

Connection to the Yolo Bypass

- Flows and constituent loads from the Yolo Bypass enter the DSM2-Hg model near Liberty Island
- Yolo Bypass flow and concentrations can be provided by the Yolo Bypass Hg model, field data if available, or synthetic data

Potential Future Model Applications

- Scenario testing (options to reduce MeHg supply). Scenarios may involve running other models and require other resources.
- Refined model analysis along with field program to address data and knowledge gaps
- Improved characteriziation of spatial and temporal patterns for Hg and MeHg cycling and supply in Delta
- Replicate historical conditions
- Sensitivity of Delta Hg/MeHg concentrations to changes in flows, etc--(may involve running other models and require other resources).

Figure 5-3 **Delta Mercury Model (DSM2-Hg) Domain, Inflow and Outflow Locations.**

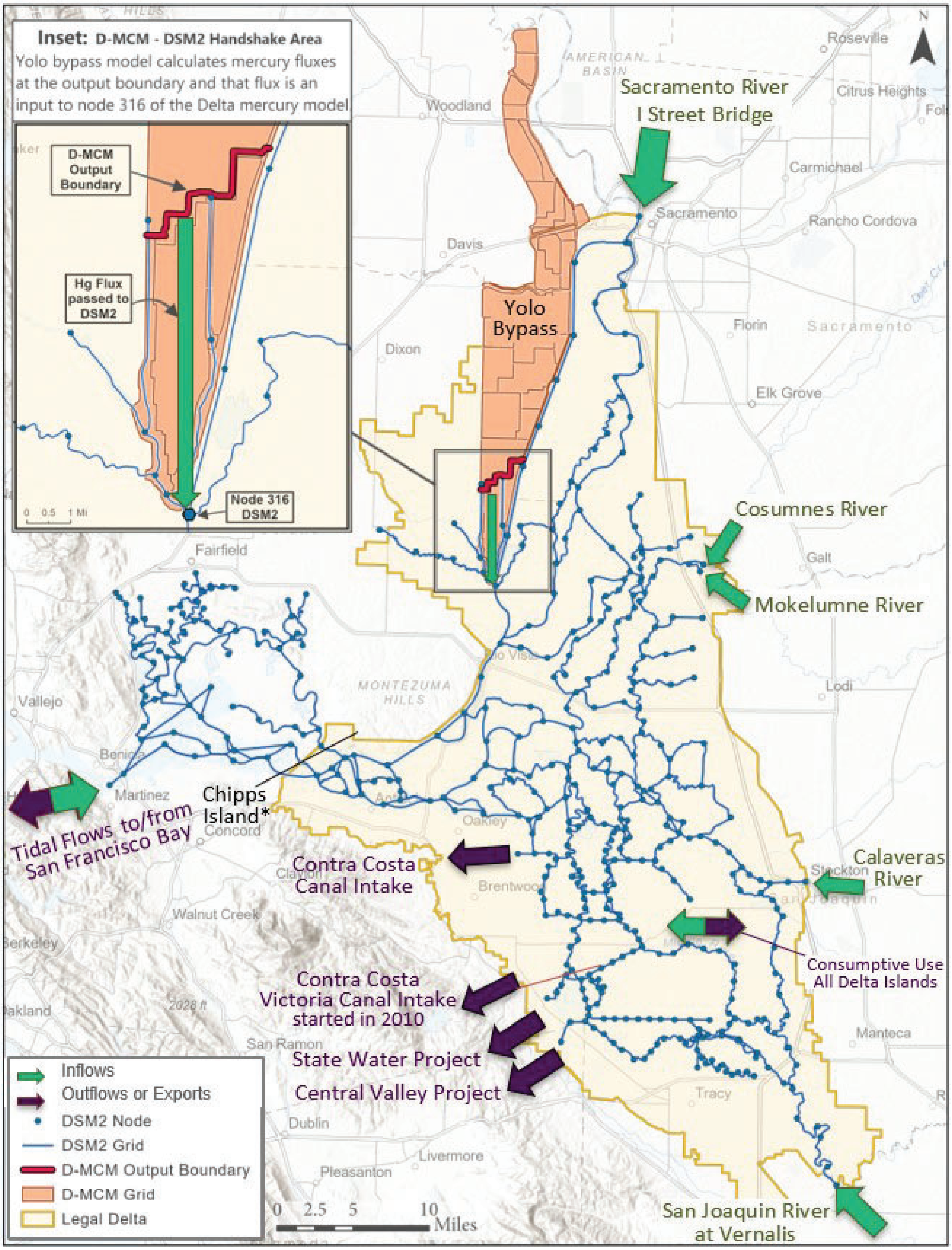


Figure Note: Separate Yolo Bypass model domain also shown in orange. Inset shows how outputs from Yolo Bypass model (D-MCM) were passed as loads to DSM2-Hg model.

**Flux calculations at Chipps Island are computed as the sum of three channels indicated by the black line.*

Major Components of Delta Hg Model Analysis

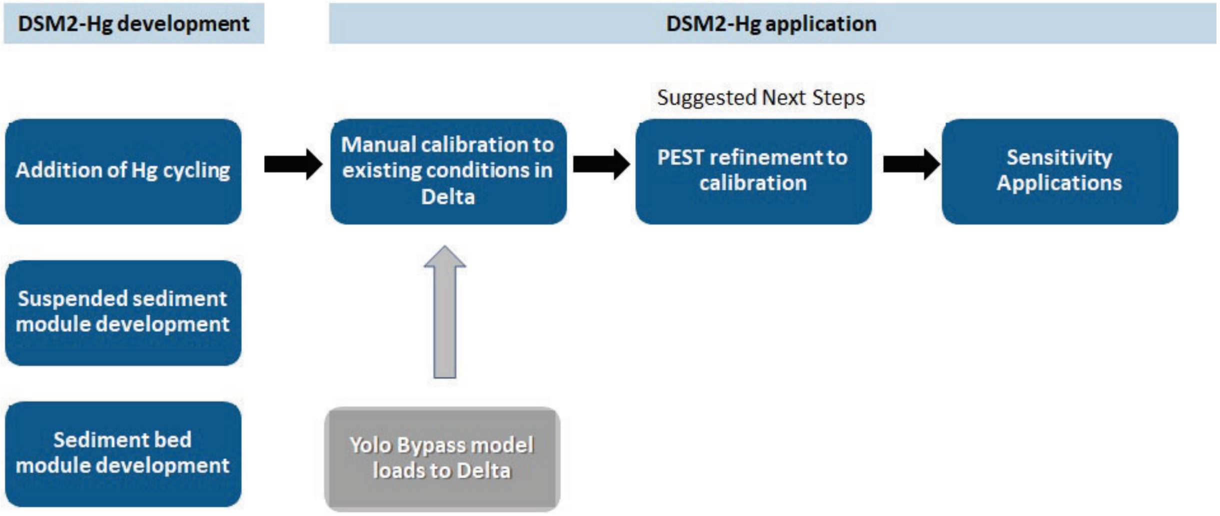
Application of DSM2-Hg to the Delta included the following major steps

1. Data assembly and review
2. Identification of best data years for model calibration
3. Simulation of hydrology for calibration period October 1999- July 2006 (completed prior to this study)
4. Simulation and calibration of suspended sediment loads, transport and fate in open water channels and sediment bed of the Delta.
5. Manual calibration of DSM2-Hg for inorganic Hg and MeHg in the water column and bed sediments
6. Calibration refinement, sensitivity and uncertainty analysis with parameter estimation software (PEST++, future task)

The Delta model analysis was based on extending the capabilities of an existing model and using existing data. The Delta modeling effort was also supported by a separate model analysis of Hg in Yolo Bypass, described in Chapter 4. The Yolo Bypass model provided estimates of suspended sediment, inorganic Hg and MeHg loads to the Delta model.

Similar to the Yolo Bypass model analysis, the calibration goal was ultimately to refine the manual calibration and carry out a sensitivity/uncertainty analysis of the Delta Hg model using PEST++. Time constraints prevented including this approach in this report, however, it is anticipated that work will continue to calibrate the model using PEST++, with results available as a future addendum.

Figure 5-4 Components Associated with the Development of the DSM2-Hg Model



Approach to Hydrology

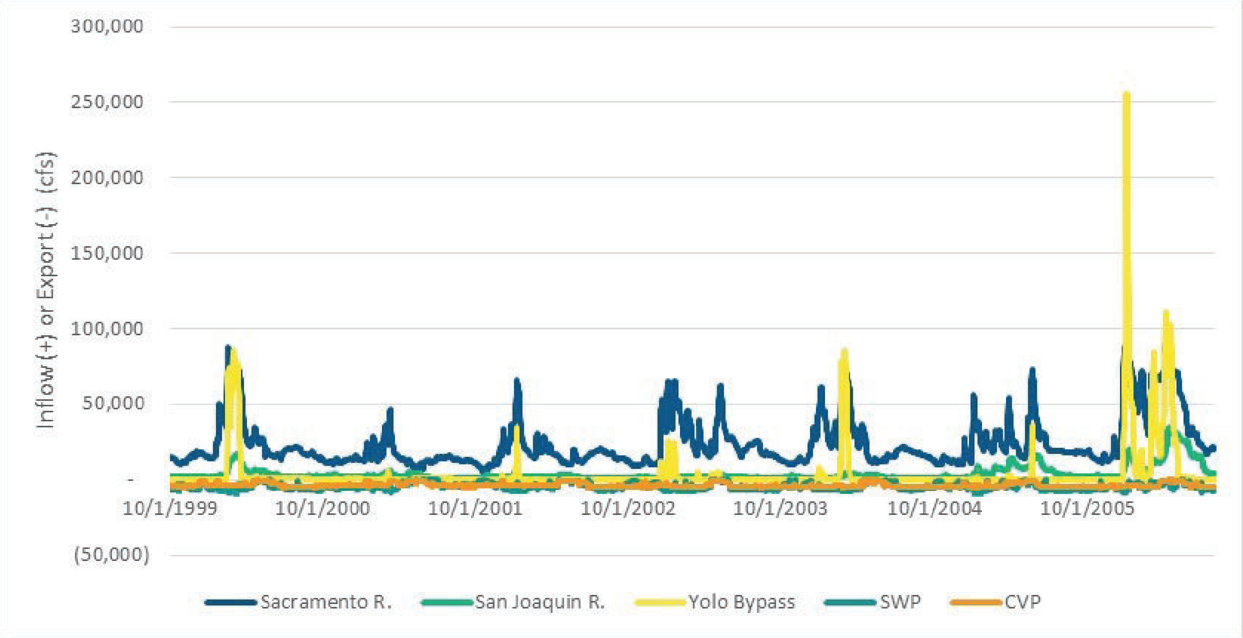
A review of data needed for simulations indicated that the best data years for Hg model calibration were during water years 2000-2006 (October 1999-July 2006). DSM2 had previously been applied and calibrated for water flow for this time period during other studies (Finch, 2014; Liu and Sandhu, 2012, Liang, 2018). As shown in Table 5-2 and Figure 5-5, the Hg calibration period captured a wide range of flow conditions, including some of the wettest years on record with sustained flooding in the Yolo Bypass and some drought years. The best data period for calibration of the suspended sediment component of the model analysis was 2010-2013. DSM2 had also previously been applied and calibrated to simulate water flows for this period. All simulations were carried out using short time steps (15 minutes) needed for estuarine conditions with tidal flows.

Table 5-2 Hydrologic Year Types for Hg and Suspended Sediment Simulation Periods

Water Year	**Year Type**	
	Sacramento Valley	**San Joaquin Valley**
Hg Calibration Period		
2000	Above Normal	Above Normal
2001	Dry	Dry
2002	Dry	Dry
2003	Above Normal	Below Normal
2004	Below Normal	Dry
2005	Above Normal	Wet
2006	Wet	Wet
Suspended Sediment Calibration Period		
2010	BN	Above Normal
2011	W	Wet
2012	BN	Dry
2013	D	Critical

Table Note: https://info.water.ca.gov/cgi-progs/iodir/WSIHIST

Figure 5-5 **Delta Mercury Model (DSM2-Hg) Boundary Inflows and Exports Oct. 1999 to July 2006**



Approach to Represent Suspended and Bed Sediments

DSM2-Hg represents both suspended sediments in the water column and bed sediments using 3 particle types:

a. Coarse inorganics (e.g. sand)
b. Fine inorganics (e.g. silt and clay)
c. Organic matter

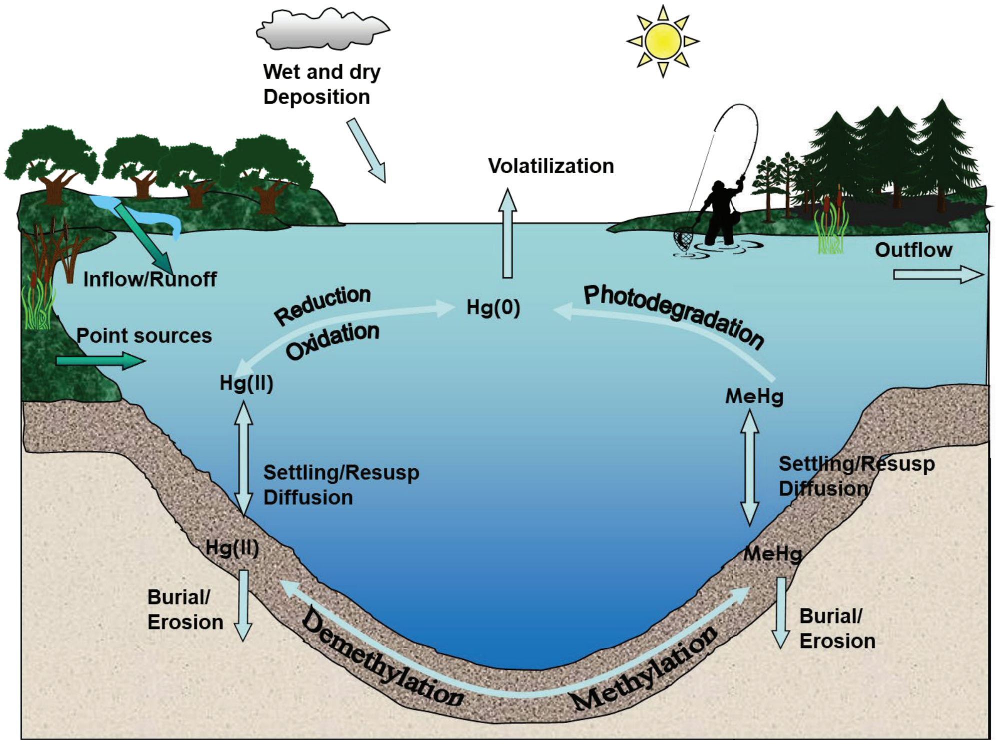
Each particle type has unique properties in terms of particle densities, settling velocities, resuspension rates, and Hg partitioning (ratio of solids:dissolved concentrations). The model has a 2-layer sediment bed to represent erosion and settling of sediments at the channel bed.

Tributary suspended sediment loads to the Delta for most locations shown in Table 5-4 were based on data collected by the United States Geological Survey (USGS). The exception was the Yolo Bypass where loads to the Delta were based on D-MCM simulations of Yolo Bypass. Specifically, Yolo Bypass sediment export was estimated at the stairsteps and passed to DSM2- Hg at node 316 below Liberty Island (see insert in Figure 5-3). Therefore, this modeling exercise did not fully capture the role of Liberty Island on Hg cycling and transport.

Approach to Represent Mercury Cycling

Hg cycling was added to DSM2, based on the approach used in the D-MCM model for the water column and sediment bed (Figure 5-6). Three major forms of Hg were simulated: MeHg, Hg(II), and elemental mercury (Hg(0)). Given that Hg(0) is also inorganic, the sum of Hg(II) and Hg(0) is referred to in the report as inorganic Hg. MeHg production was assumed to occur primarily in the surface sediment bed.

Figure 5-6 Representation of Mercury cycling in DSM2-Hg. Based on D-MCM (EPRI, 2013)



Atmospheric wet deposition of inorganic Hg was estimated using data from the nearest Mercury Deposition Network (MDN) site, CA72, near San Jose. The site was operated from January 11, 2000 through December 27, 2006. Weekly data were used to estimate overall monthly averages for the entire period of record, for use in the DSM2-Hg analysis. Dry Hg deposition was assigned a constant value of 19 ug/m2/yr, the mean value reported by Tsai & Hoeneike (2001) for the San Francisco Bay Estuary from August 1999 through November 2000.

Tributary loads of inorganic Hg and MeHg were based on empirical relationships between Hg concentrations and flow or SSC, for most locations shown in Table 5-4. This was done using tributary-specific data to the extent possible. Yolo Bypass loads to the Delta for inorganic Hg and MeHg were estimated with the D-MCM model (Chapter 4).

The DMCP identified numerous sources of MeHg to the Delta, including fluxes from sediments to open waters. DSM2-Hg included 3 fluxes at the sediment water interface: settling, resuspension of sediment and diffusion, that combined to produce the net flux out of or into sediments (Figure 5-7).

Figure 5-7 Sources and Sinks of MeHg in Delta Waters

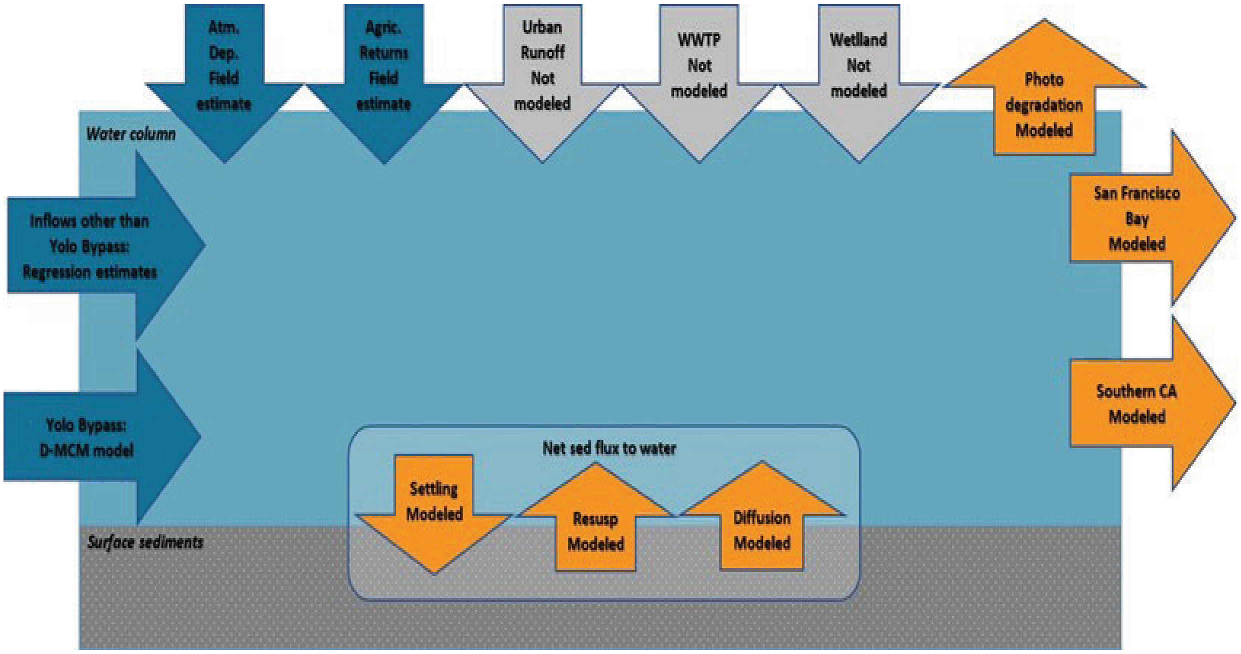


Figure Note: D-MCM = Dynamic Mercury Cycling Model, WWTP = Wastewater Treatment Plant. Modeled fluxes are shown in orange. Boundary fluxes were estimated externally (blue). Fluxes not included in the model analysis are shown in grey.

Approach to Model Calibration for Suspended Sediments and Mercury

Model calibration was required for suspended sediments, inorganic Hg and MeHg. The calibration for suspended sediments was carried out first, followed by inorganic Hg, then MeHg. Suspended sediments and Hg used separate calibration periods that corresponded with the best available field data for each constituent (Table 5-3). Most of the analysis presented in this chapter is for the Delta Hg model calibration period from October 1999 to July 2006.

Table 5-3 **Calibration periods for suspended sediment and mercury**

Constituent	Calibration Period
Suspended Sediment	Calibration Oct 2010-Sept 2013 Validation Oct 2013-Sept 2016
Mercury	October 1999 – July 2006

Table Note: CalFed = CalFed Bay-Delta Program, DMCP = Delta Mercury Control Program

The suspended sediment module was calibrated and validated using 15-minute suspended sediment concentrations provided by the U.S. Geological Survey based on field observations of turbidity and flow (Figure 5-8) (Morgan-King and Wright, 2013). The calibration period was from October 2010 to September 2013 (wet, below normal, and dry years) and the validation period was from October 2013 to September 2016 (critical, critical, and below normal years. The calibration variables were the erosion coefficient and the particle size for each sediment type. Additional information on the suspended sediment calibration and observed data can be found in Appendix J and Hsu and others, 2019.

The calibrations of inorganic Hg and MeHg concentrations were based on observations in surface waters at thirteen locations shown in Figure 5-8. Observations of uHg, fHg, uMeHg and fMeHg were available for comparisons. Due to the limited overall availability of Hg data, all observations within the Hg calibration period from October 1999-July 2006 were used to calibrate the model (as opposed to using some of the data for validation). Details on information used for calibration are provided in Technical Appendix I. The calibrations for inorganic Hg and MeHg were done manually, varying selected model inputs to improve the fit between the model and observations. Model calibration results were evaluated graphically. Ultimately the calibration will be refined using parameter estimation software (PEST++), similar to the approach used for the Hg model analysis for Yolo Bypass (Technical Appendix H). At the time of preparation of this report, only the manual DSM2-Hg calibration was available.

Figure 5-8 Stations used for DSM2-Hg Calibrations of SSC, Inorganic Hg and MeHg in Surface Waters

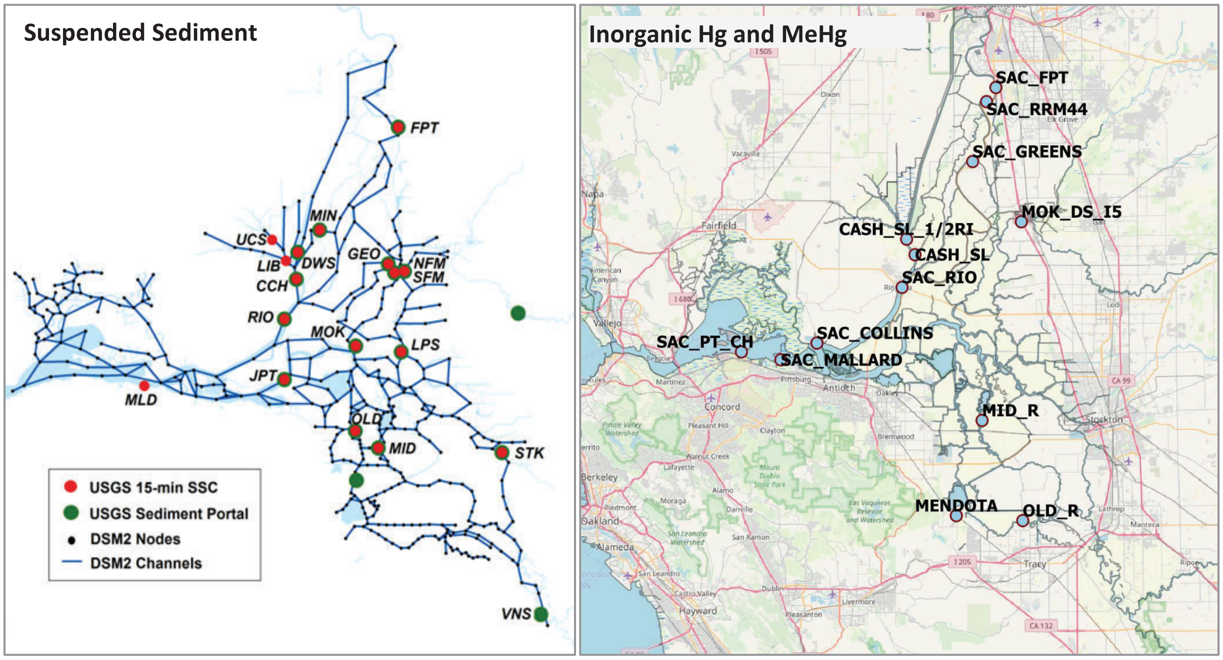


Figure Note: Suspended sediment locations are defined in Table 4-1 of Hsu and others 2019 included in Appendix J. Mercury monitoring locations are defined in Appendix I. Figures in this chapter that refer to these locations identify the locations in a figure note.

Table 5-4 Locations used for DSM2-Hg Inflow and Export Calculations

Location	Inflow or Export	DSM2 Node	Latitude/Longitude
Sacramento River at I Street	Inflow	330	38.5864, -121.5064
San Joaquin River at Vernalis	Inflow	17	37.6638, -121.2501
Yolo Bypass at Liberty Island	Inflow	316	38.2313, -121.6741
Cosumnes River at Michigan Bar	Inflow	446	38.2546, -121.4215
Mokelumne River at Woodbridge	Inflow	447	38.2483, -121.4255
Calaveras River at Stockton	Inflow	21	37.9667, -121.3697
State Water Project	Export	Clifton Court/Banks Pumping Plant	37.8019, -121.6202
Central Valley Project	Export	181/Jones Pumping Plant	37.7970, -121.5852n
Chipps Island	Tidal Flows	Channel 437 Channel 442 Channel 511	38.046494°, -121.888239° 38.046494°, -121.888239° 38.067735°, -121.853877°

Table Note: Combined flows through DSM2 channels 437, 442, and 511 near Chipps Island were used in tidal import and export calculations between the Delta and San Francisco Bay. These locations were selected to reduce the uncertainty associated with the concentrations assigned at the downstream boundary at Martinez. Note that latitude/longitude information is provided for reader reference but is not used in the Delta Hg model.

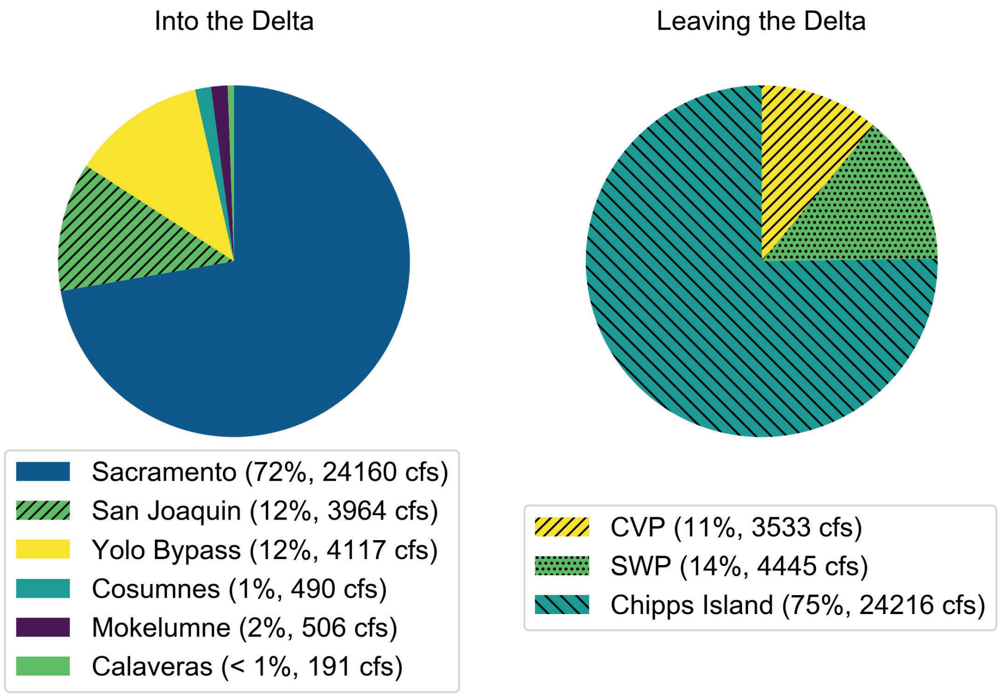
Delta Hg Model Simulation and Calibration Results

Hydrology Results

The largest tributary source of water to the Delta in simulations was the Sacramento River, representing 72% of inputs for the overall period from October 1999 – July 2006 (Figure 5-9). The largest simulated loss of water from the Delta for the same period was net export (adjusting for tidal flows) to San Francisco Bay (Figure 5-9). As noted earlier, the model analysis carried out here included a wide range of hydrologic conditions ranging from dry to wet years (Table 5-2).

The simulation period included a wide range of annual freshwater inflows, varying 4.3X from 17,956 cfs in water year 2001, to 77,930 cfs in water year 2006 (averages). The relative importance of different water sources also varied among years. The Yolo Bypass, for example, ranged from 1-25 % of the overall tributary supply of water among the years simulated.

Figure 5-9 Estimated Average Water Inflows and Outflows for the Delta from October 1999 to July 2006



Suspended Sediment Calibration and Results

An example of simulated and observed suspended sediment concentrations (SSC) is shown Figure 5-10. Overall, the modeled results capture observed trends and extreme events for Delta suspended sediment concentrations. These results reflect the suspended sediment calibration and validation period from 2010-2013. The calibrated suspended sediment model was then used for the mercury study period of October 1999 to July 2006.

Figure 5-10 Observed and Simulated Suspended Sediment Concentrations in Delta Waters.

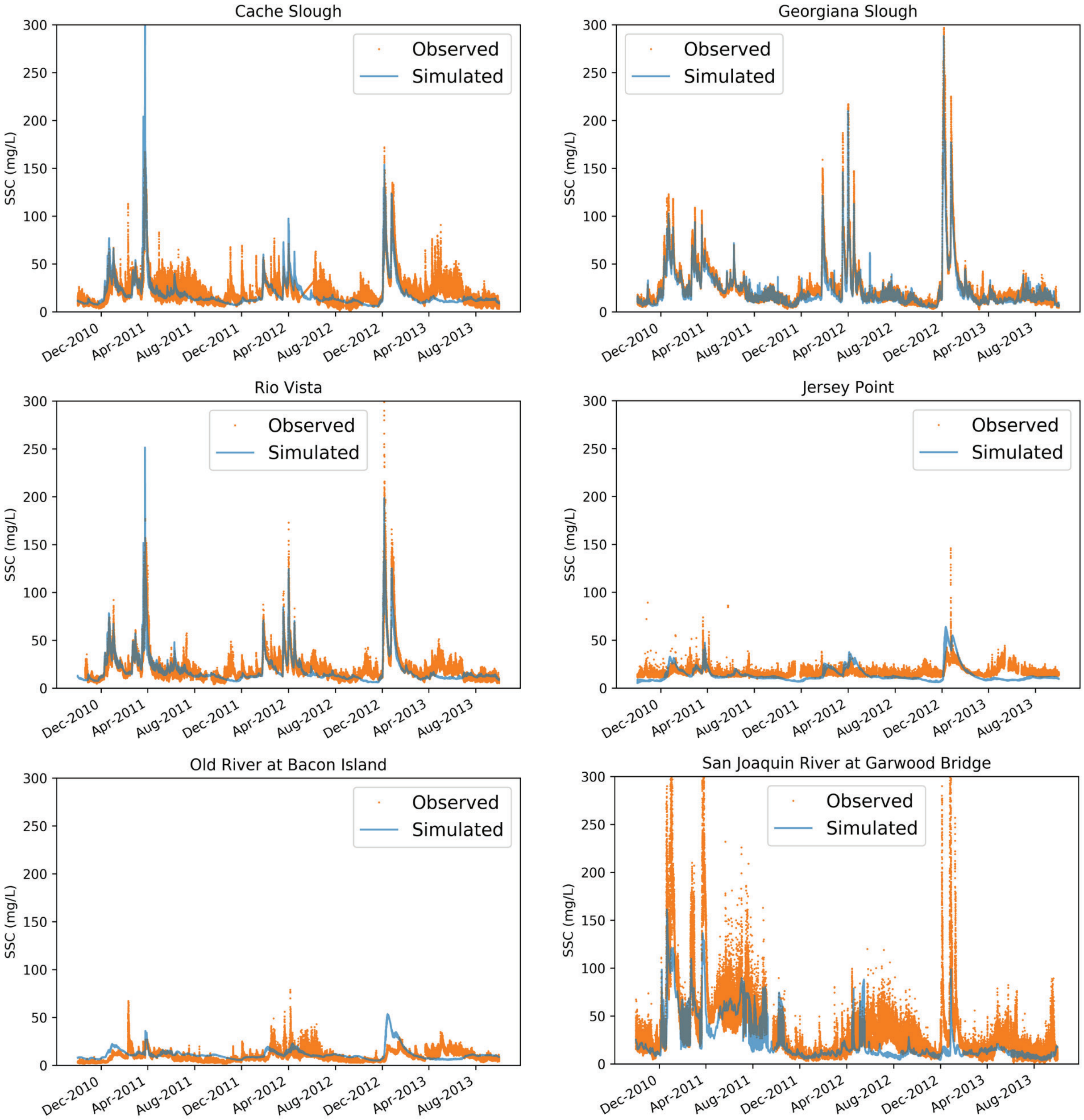


Figure Note: See Figure 5-8 for a map of the observation locations: Cache Slough at Ryer Island (CCH), Georgiana Slough(GEO), Rio Vista (RIO), Jersey Point (JPT), Old River at Bacon Island OOLD) and San Joaquin River at Garwood Bridge (/STK). Data from USGS (Morgan-King and Wright, 2013).

The largest estimated suspended sediment loads to the Delta from October 1999 to July 2006 were from the Sacramento River (72%) (Figure 5-11, Table 5-5). The Yolo Bypass and San Joaquin Rivers contributed 15% and 12% respectively. Nearly 90% of the suspended sediments that flowed out of the Delta, exited the Delta at Chipps Island and flowed into San Francisco Bay. The State Water Project and federal Central Valley Project exported 6% and 4% of the suspended sediment loads respectively in simulations. The relative proportions of the sediment loads from different sources are consistent with a 2003 Delta sediment budget (NHC, 2003).

Consistent with previous findings (Louie and others, 2008), DSM2-Hg model results simulated the Delta as a net sink for sediment. The export of suspended sediment at Chipps Island was roughly half of the inflowing supply for the overall simulation period (Table 5-5). The greatest suspended sediment loads occurred during the winter months (Figure 5-12). The Delta remained a net sink for suspended sediments for all months during the simulation (Figure 5-13).

Figure 5-11 Estimated Average Delta Suspended Sediment Inflows and Outflows for October 1999 to July 2006

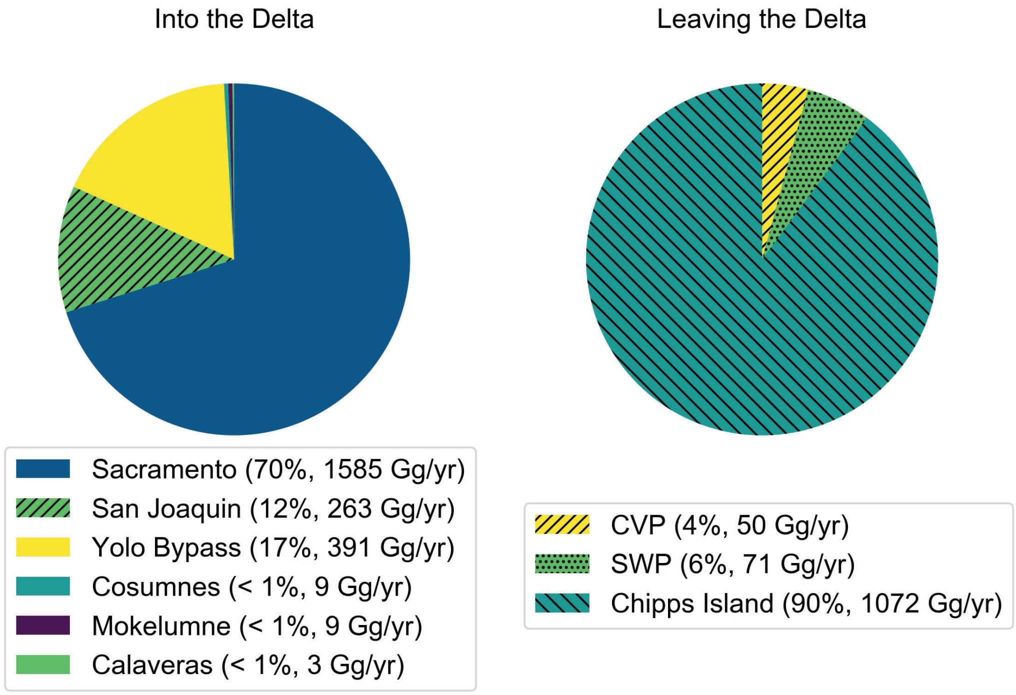


Figure Note: Inflow loads based on Outflow fluxes simulated with DSM2-Hg.

Data from USGS (Morgan-King and Wright, 2013).

Table 5-5 **Estimated Average Inflows and Outflows of Suspended Sediment, uHg(II) and uMeHg for the Delta from October 1999 - July 2006**

Location	**Load**					**Average concentration**		
	Flow	**SSC**	**uHg(II)**	**uMeHg**		**SSC**	**uHg(II)**	**uMeHg**
Inflows:	**cfs**	**Gg/yr**	**kg/yr**	**g/yr**		**mg/L**	**ng/L**	**ng/L**
Sacramento	24160	1548	270	2897		72	12.5	0.13
San Joaquin	3964	257	30	594		73	8.5	0.17
Yolo Bypass	4117	382	69	1908		104	18.7	0.52
Mokulumne	506	8	2	31		19	3.9	0.07
Calaveras	191	3	4	23		20	22.2	0.14
Cosumnes	490	9	4	143		20	8.5	0.33
All inflows	33428	2207	378	5597		74	12.7	0.19
Outflows:								
CVP	3533	49	12	305		16	3.9	0.10
SWP	4445	69	16	379		17	4.2	0.10
Chips Island	24216	1047	237	3785		48	10.9	0.18
All outflows	32194	1165	265	4469		41	9.2	0.16
Outflow/inflow		0.53	0.70	0.80				

Table Note: Loads are estimated using tributary-specific regressions of parameter concentrations as a function of flow or SSC, except for the Yolo Bypass, which was based on results from the D-MCM model. Outflows were based on DSM2-Hg results. Average concentrations are the constituent loads divided by the flows. Outflow/Inflow values are dimensionless ratios.

Figure 5-12 Monthly Modeled Suspended Sediment Loads in the Delta by Location from October 1999 through July 2006

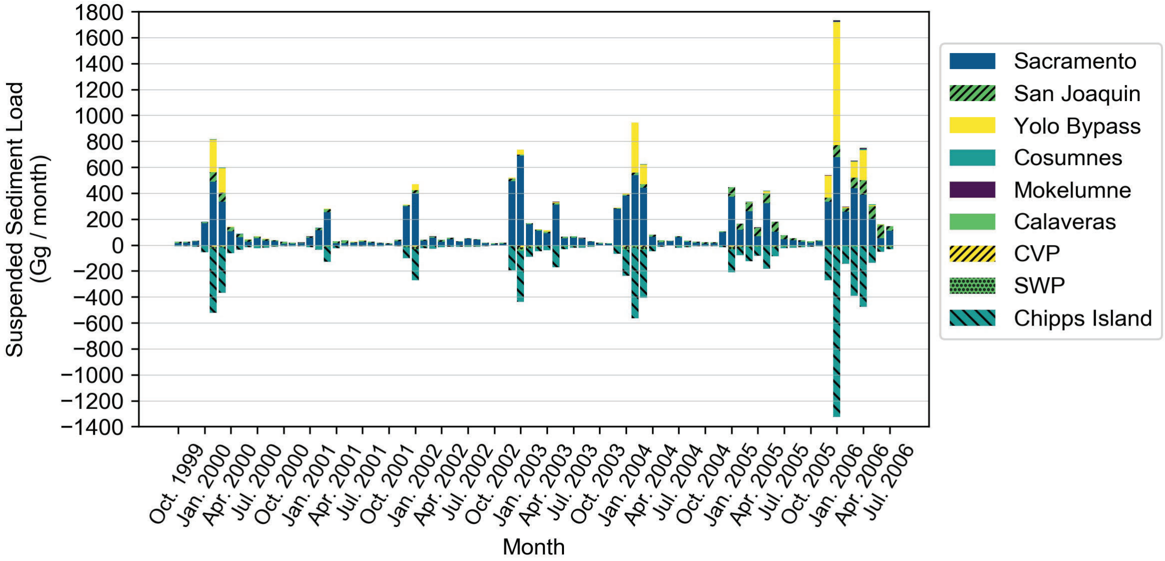
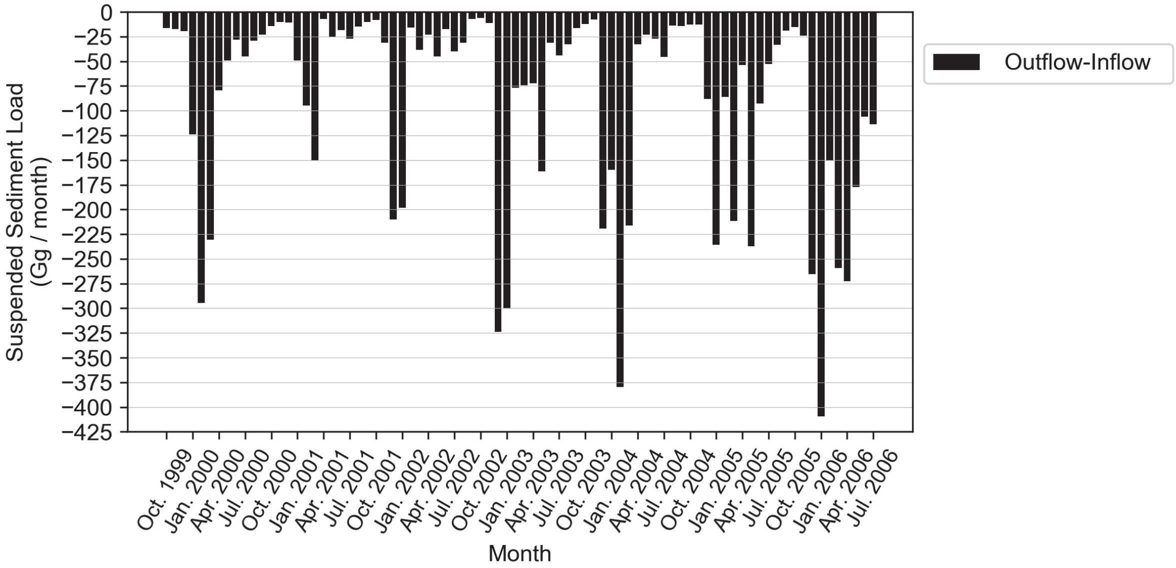


Figure Note: Positive values indicate inputs. Negative values are exports.

Figure 5-13 Monthly Modeled Net Suspended Sediment Loads in the Delta by Location from October 1999 through July 2006. Negative values indicate a net sink (outflows less than inflows)

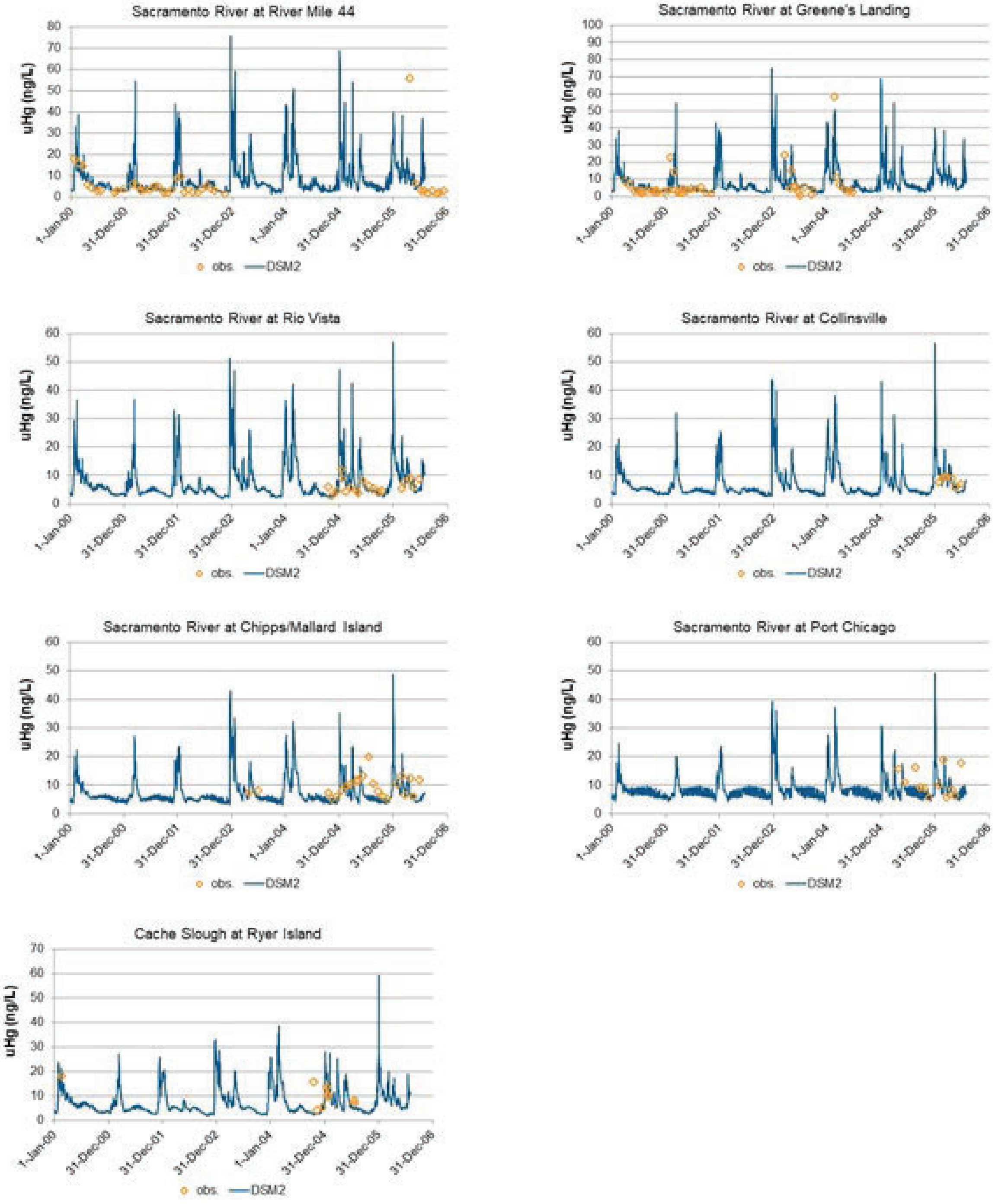


Mercury Calibration

Mercury Concentrations in Delta Surface Waters

Examples of observed and calibrated model results for uHg and uMeHg in surface waters on the west side of the Delta are shown in Figure 5-14 and Figure 5-15. The model calibration reasonably matched observations. The model simulation from October 1999-July 2006 was characterized by highly dynamic conditions and rapid simulated changes in water column concentrations of Hg and MeHg. Observations did not display the same variability, but this may have been partly related to short term events potentially not captured during sampling. Alternatively, the model may have overestimated temporal variability. Additional model results for the calibration of Hg and MeHg in surface waters are provided in Technical Appendix I.

Figure 5-14 Observed and Simulated uHg Concentrations in Delta Surface Waters (west side locations) 2000-2006


Sacramento River at River Mile 44

Sacramento River at Greene's Landing

Sacramento River at Rio Vista

Sacramento River at Collinsville

Sacramento River at Chipps/Mallard Island

Sacramento River at Port Chicago

Cache Slough at Ryer Island

Figure Note: See Figure 5-8 for a map of the observation locations: Sacramento River at Greene's Landing (SAC_Green's), Rio Vista (SAC_RIO), Collinsville (SAC_COLLINS), Chipps/Mallard Island (SAC_MALLARD), and Port Chicago (SAC_PT_CH) and Cache Slough at Ryer Island (CASH_SL). Observed data from Louie and others, 2008, except Sacramento River at River Mile 44 from Coordinated Monitoring Program, 2004. Sacramento River at Greene's Landing from Foe, 2003 and SRWP, 2004.

Figure 5-15 Observed and Simulated uMeHg concentrations in Delta Surface Waters (west side) locations, 2000-2006

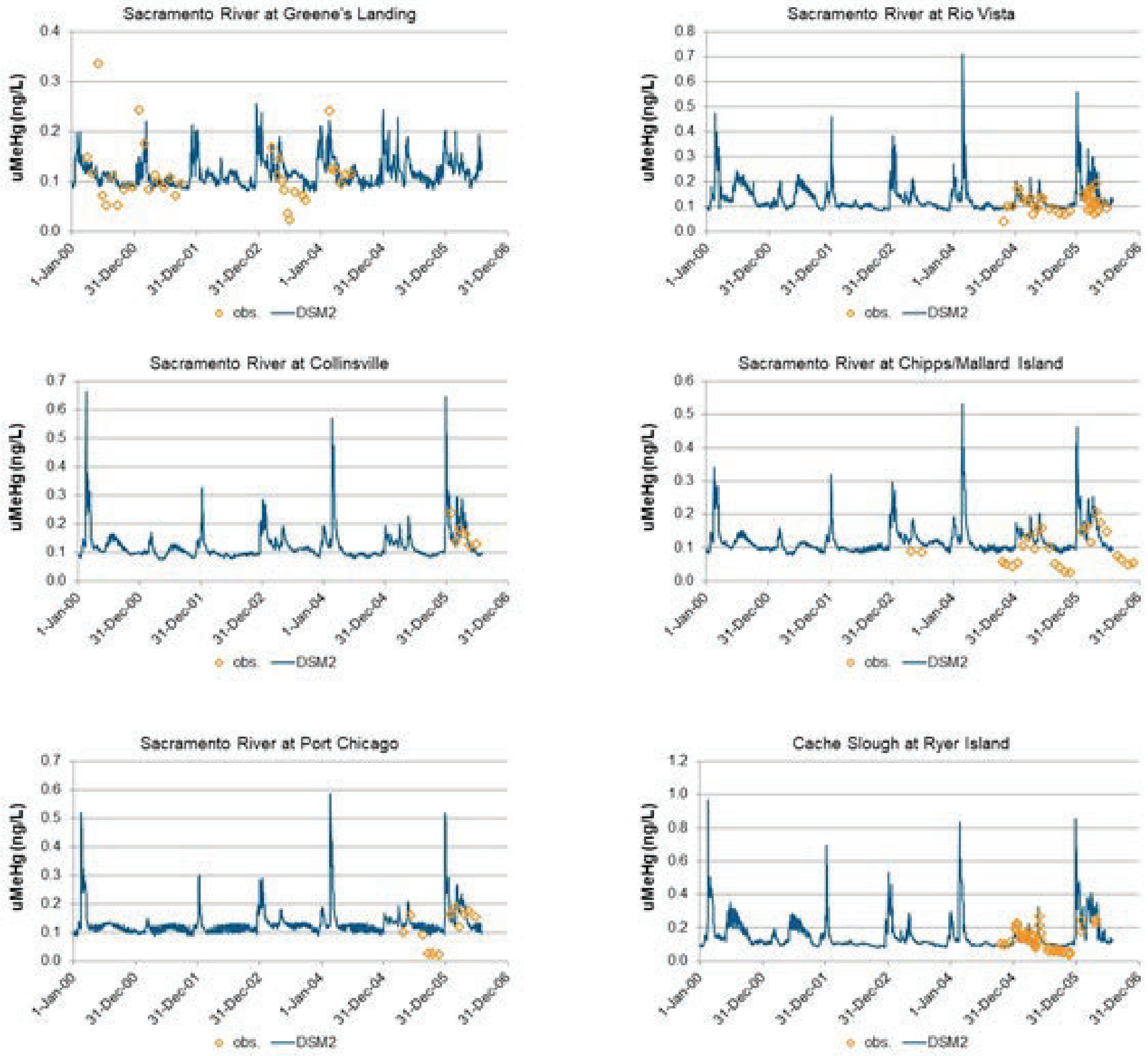


Figure Note: See Figure 5-8 for a map of the observation locations: Sacramento River at Greene's Landing (SAC_Green's), Rio Vista (SAC_RIO), Collinsville (SAC_COLLINS), Chipps/Mallard Island (SAC_MALLARD), and Port Chicago (SAC_PT_CH) and Cache Slough at Ryer Island (CASH_SL). All observed data from Foe and others, 2008. Additionally, data also used from Foe, 2003 for Sacramento River at Greene's Landing and SRWP, 2004.

Spatial Concentration Patterns

Water Column Spatial Concentration Patterns

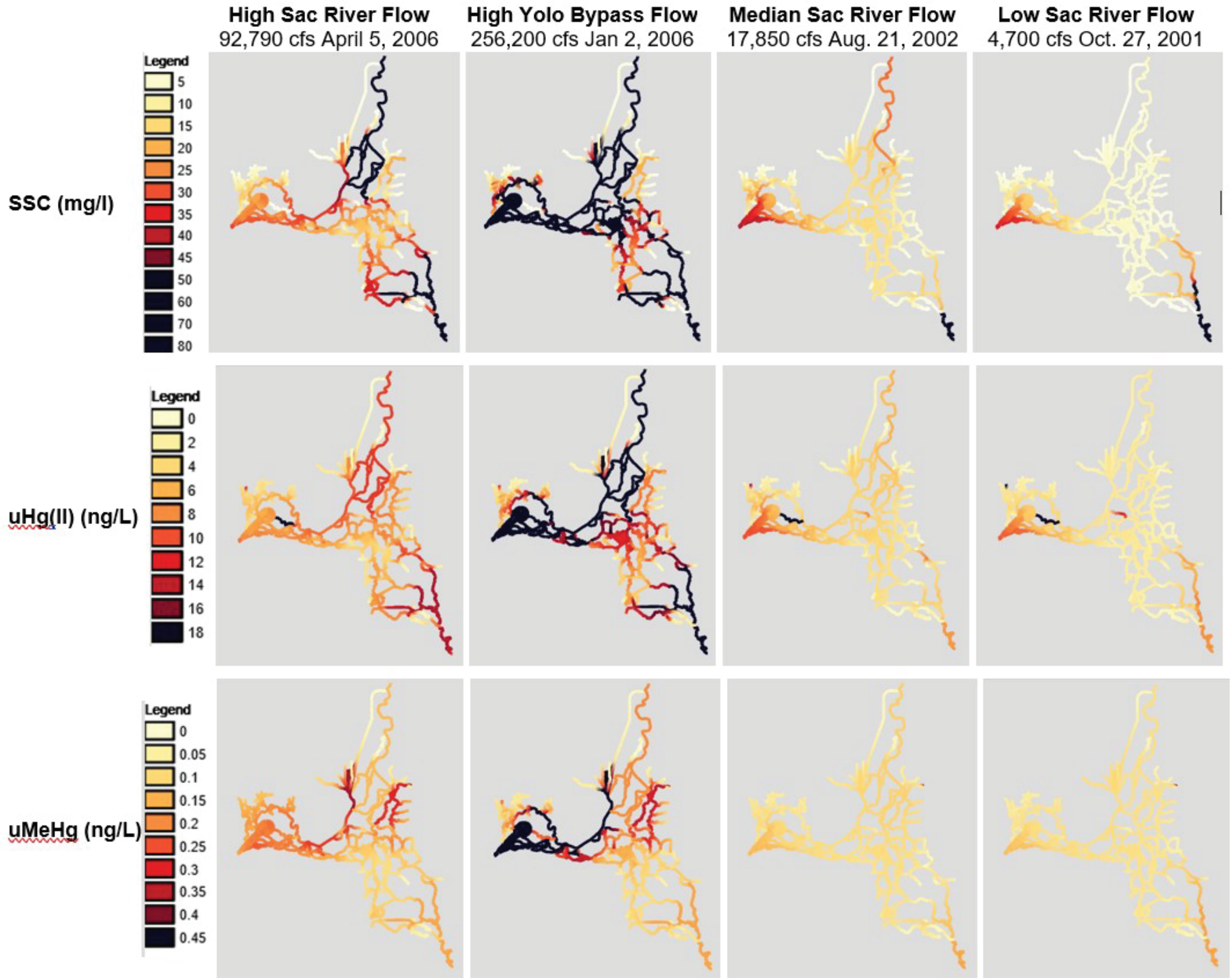
Simulated spatial patterns for high, median and low flow conditions during the Hg calibration period (October 1999 to July 2006) are shown in Figure 5-16. Some spatial features of the simulation included the following:

- When the highest flow occurred in the Sacramento River, (~92,000 cfs), SSC and uHg(II) concentrations were higher on the periphery of the Delta and lower in the Central Delta. This pattern was not evident for uMeHg. Similar trends occurred when the highest flow occurred in Yolo Bypass (256,200 cfs), but concentrations of SSC, uHg(II) and uMeHg were generally higher than when the Sacramento River flow was highest.

- When the median flow for the simulation period occurred in the Sacramento River (17,850 cfs), simulated concentrations of SSC, uHg(II) and uMeHg were less variable and generally lower in magnitude than during the high flow dates presented. Concentrations in downstream areas (Suisun Bay) were simulated to be higher than upstream.

- For low Sacramento River inflows (~4,700cfs), concentrations of all three constituents are lower than in the high flow case, and contributions from the San Joaquin River appear to have more relative influence. These patterns are for the snapshots in time shown in Figure 5-16, and further investigation would be required to see if these patterns are consistent under similar flow conditions. Field data were insufficient to identify Delta-wide spatial trends to compare with model results.

Figure 5-16 Simulated Suspended Sediment, uHg(II) and uMeHg Concentrations for High, Median and Low Flow Conditions During Model Mercury Calibration Period Oct 1999 to July 2006.



Bed Sediment Spatial Patterns

Observations and model results for Hg and MeHg concentrations in surface sediments are shown in Figure 5-17. Due to limited data all observations from 1999-2017 were included, and averages were calculated at locations with multiple samples. Model results are presented for the last day of the simulation period (August 2, 2006).

Observed Hg concentrations in surface sediments were highest in the Yolo Bypass, and were generally higher in downstream Delta areas modeled than the Central Delta. Observed MeHg concentrations in surface sediments were also highest in the Yolo Bypass. In contrast with Hg, MeHg concentrations in surface sediments were higher in the Central Delta than in Detlta areas downstream. It is important to note, especially for MeHg, that the data included in Figure 5-17 were collected during different studies, span multiple years and include samples from all months of the year. Because MeHg concentrations vary seasonally and among years, biases may exist when all data are included in plots. This could lead to the appearance of spatial patterns that are not real, or a lack of patterns where some exist. For these reasons, further analysis of existing data, and likely the collection of additional sediment data, would be needed to more reliably establish spatial patterns for MeHg concentrations in sediments and whether these change with time. The purpose of Figure 5-17 is therefore primarily to demonstrate that simulated concentrations of Hg and MeHg in the surface layer of the sediment bed are comparable in magnitude.

Figure 5-17 **Observed and Simulated Sediment Bed Hg and MeHg Concentrations in the Delta**

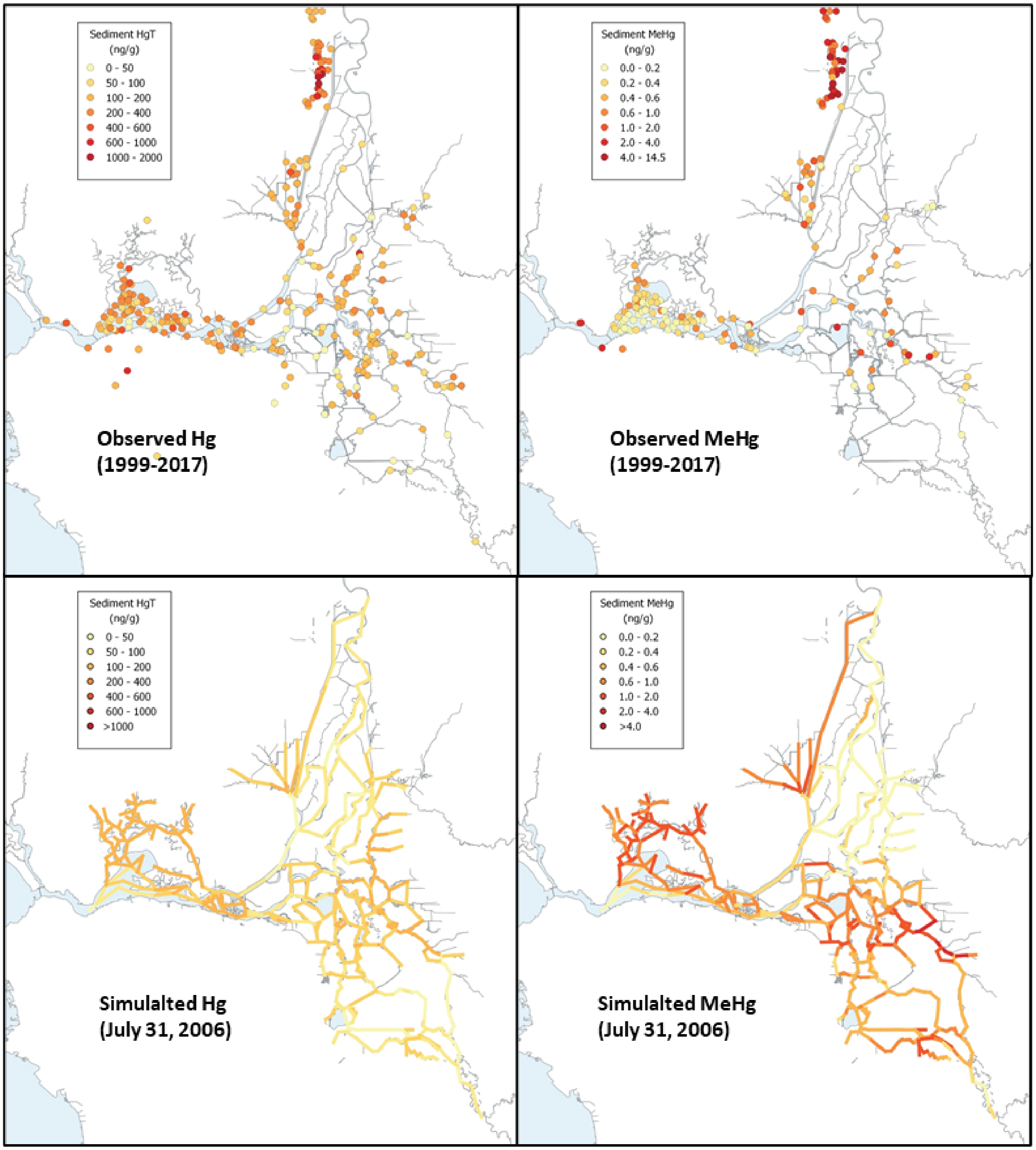


Figure Note: Observations are from 0-5 cm depth, span 1999- 2017 and include all months of the year. Where multiple samples were collected at the same location, values are averaged. Data from Bay and others, 2012; CEDEN, 2018; DiGiorgio, 2018 a,b; Heim and others 2007; Slotton and others; 2002.

Mercury Inflow and Outflow Fluxes

For the overall Hg calibration period October 1999 – July 2006, the Sacramento River was the largest estimated inflowing freshwater source of Hg(II) and MeHg to the Delta (71% and 52% respectively, Figure 5-18. Table 5-5). The magnitude and relative importance of Hg(II) and MeHg loads varied widely among years and months (Figure 5-19, Figure 5-20). Annual freshwater inputs of Hg(II) and MeHg each varied by approximately 6-fold for water years 2000-2006. The relative importance of tributaries as sources of Hg and MeHg also varied from year to year. Yolo Bypass represented about one third of the external supply of MeHg to the Delta for the overall simulation period (Figure 5-18), but this ranged from 3-50% among the years simulated (Figure 5-21). Under some high-flow months, Yolo Bypass was the largest external source of MeHg to the Delta (Figure 5-20).

The largest simulated outflows of inorganic Hg(II) and MeHg were exports at Chipps Island (89% and 85% respectively, see Figure 5-18). The Delta was simulated to be a net long-term sink for Hg and MeHg, exporting roughly half the inflowing load of Hg and 87% of the inflowing MeHg load.

Figure 5-18 Estimated Average Annual Delta uHg(II) and uMeHg Inflows and Outflows for Oct.1999-July 2006. Inflow loads are from regressions based on tributary field data. Outflows are modeled with DSM2-Hg.

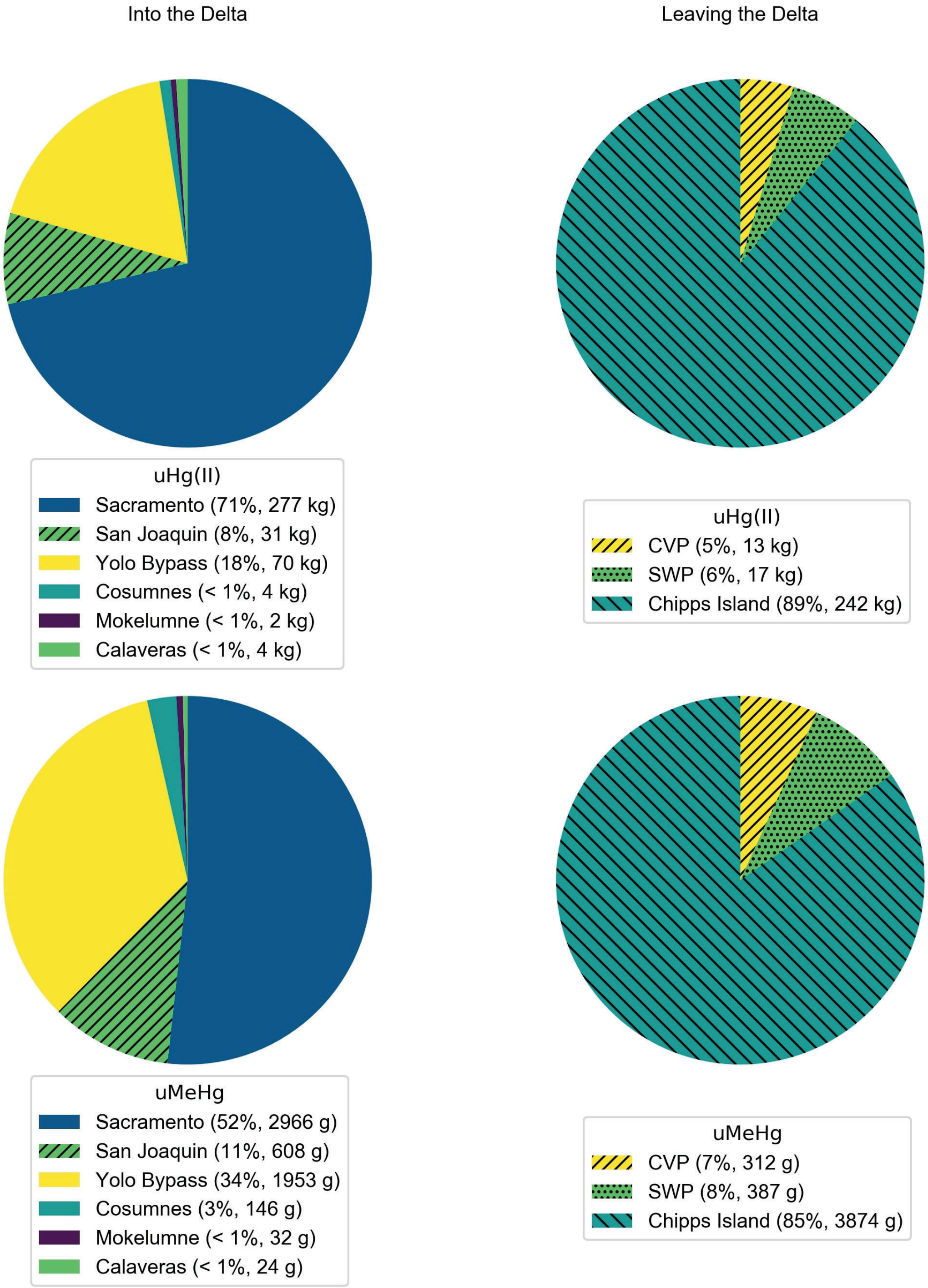


Figure Note: Inflow loads are from regressions based on tributary field data. Outflows are modeled with DSM2-Hg.

Figure 5-19 **Estimated Annual Delta Inflows and Outflows for uHg(II) and uMeHg for Oct. 1999 to July 2006.**

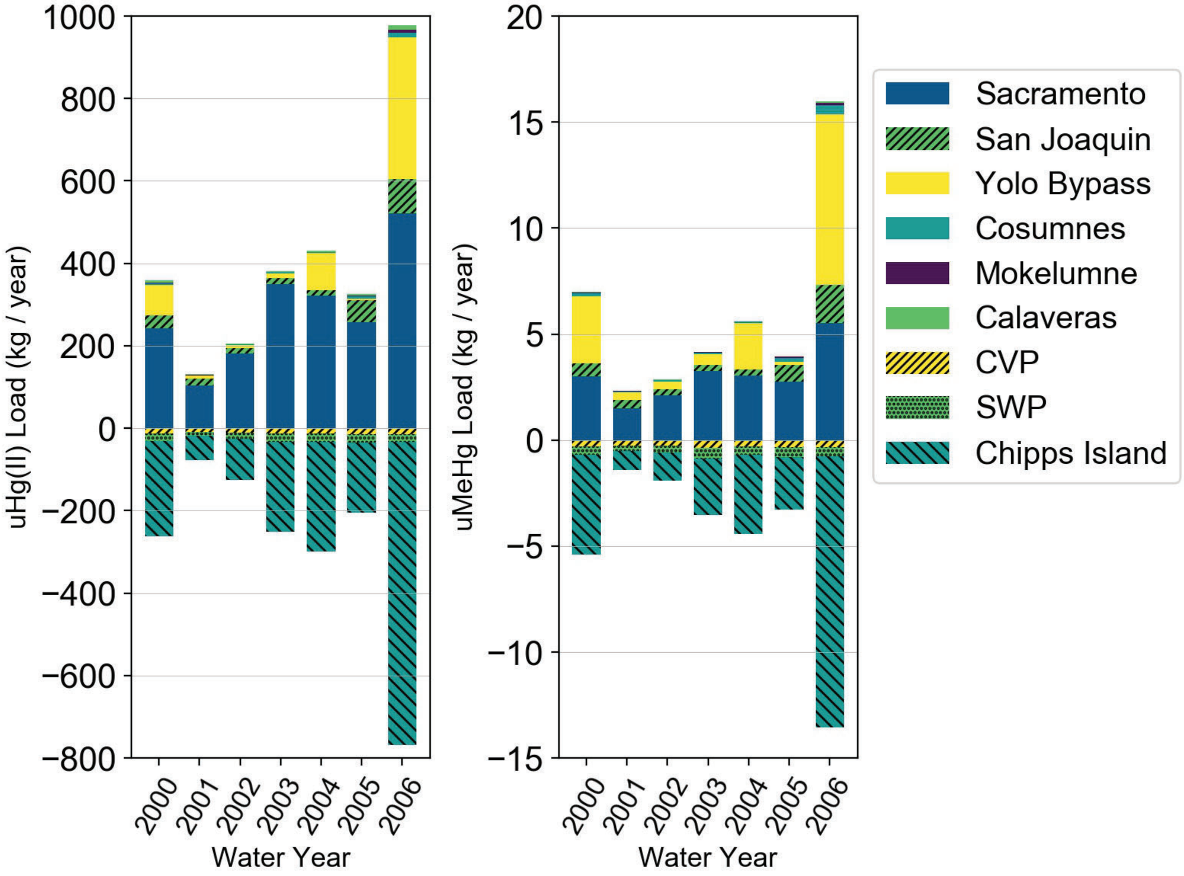


Figure Note: Inflow loads (positive) are from regressions based on field data. Outflows (negative) are modeled with DSM2-Hg.

Figure 5-20 Estimated Monthly Inflows and Outflows for Hg(II) (top panel) and MeHg (bottom panel) in the Delta for Oct. 1999 to July 2006

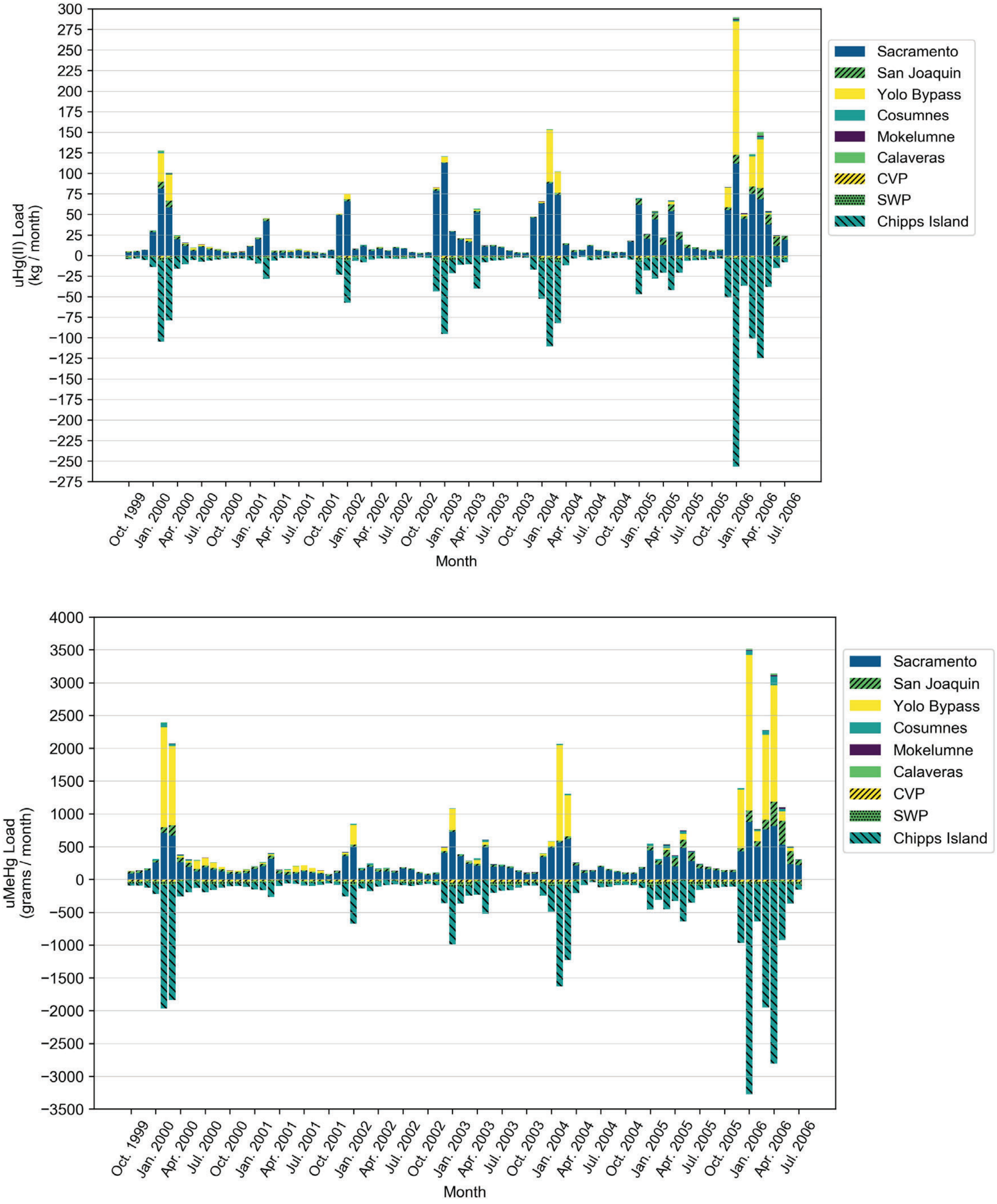
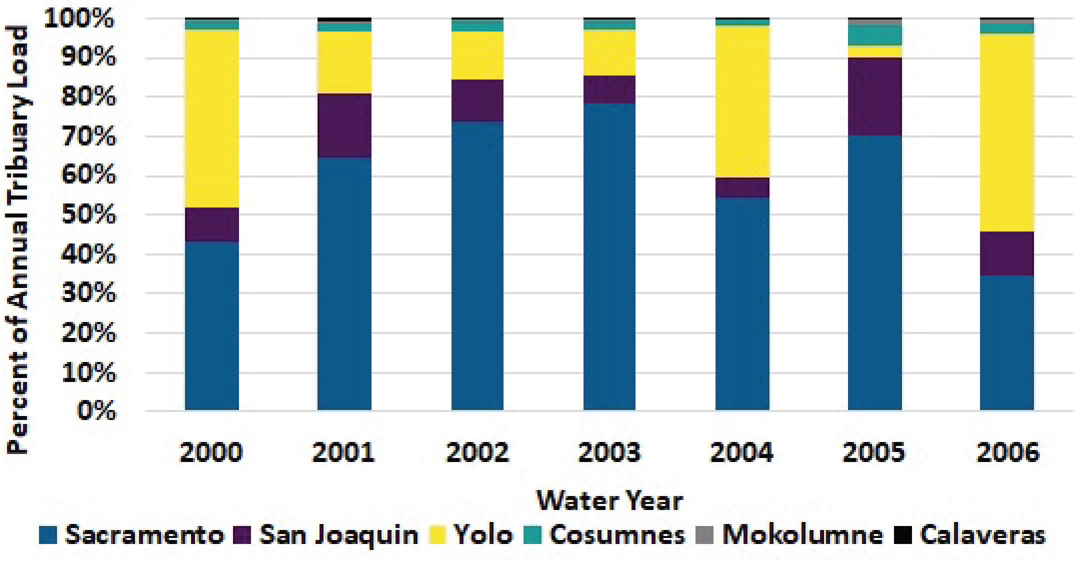


Figure Note: Inflow loads (positive values) are from regressions based on field data. Outflows (negative values) are modeled with DSM2-Hg.

Figure 5-21 Simulated Annual Contributions to the Overall Tributary MeHg Inflow Load for Water Years 2000-2006



Comparisons to Previous Studies

Model results were compared to values reported by CalFed (Stephenson and others, 2008). Data coverage for the CalFed study spanned a twenty-year hydrologic period (WYs 1984-2003) for Hg and suspended sediment (Louie and others, 2008), and between March 2000 and June 2006 (for MeHg) (Foe and others, 2008), for all major freshwater sources and exports.

Modeled and observed MeHg time periods were similar and although Foe and others, 2008 did not collect samples in every month, average MeHg loads between the two studies generally showed good agreement (Table 5-6). For example, average Yolo Bypass MeHg inputs to the Delta were 1.92 kg/year and 2 kg/year for the observed and modeled results, respectively. The time periods between the two studies for Hg and suspended sediment are not directly comparable, especially given the high year to year variability evident in Figure 5-22.

Table 5-6 Comparison of uHg, uMeHg and Suspended Sediment Loads Reported to CALFED and Average Input Loads from the DSM2-Hg Model

	*CalFED 2008 Report			Delta Mercury Model (DSM2-Hg)		
	THg*	**MeHg****	**Suspended Sediment**	**Hg(II)**	**MeHg**	**Suspended Sediment**
Yolo Bypass Input	[1]167.8 kg/yr	[2]1.92 kg/yr	[1]1107.3 Gg/yr	69 kg/yr	2 kg/yr	382 Gg/yr
Sacramento River Input	[1]182.7 kg/yr	[2]2.54 kg/yr	[1]958.5 Gg/yr	270 kg/yr	3 kg/yr	1548 Gg/yr
San Joaquin River Input	[1]28.3 kg/yr	[2]1.27 kg/yr	[1]236.9 Gg/yr	30 kg/yr	0.6 kg/yr	257 Gg/yr
Total inputs to the Delta	[1]416 kg/yr	[2]5.97 kg/yr	[1]2410 Gg/yr	378 kg/yr	5.6 kg/yr	2207 Gg/yr
Delta export to San Francisco Bay	[1]197.9 kg/yr	[2]3.54 kg/yr	[1]801 Gg/yr	237 kg/yr	3.8 kg/yr	1047 Gg/yr
Annual sedimentation rate	200 kg/yr		1497 Gg/yr	116 kg/yr	1.2 kg/yr	1067 Gg/yr
Annual load contribution from Sacramento River and Yolo Bypass	84%		86%	90%	86%	87%

*Table Note: Full CalFED report Stephenson and others, 2008.

[1] Values adapted from Louie and others, 2008, Table 1, Task 2 (Total Hg and Suspended Sediment). Loads calculated for WYs 1984-2003. Input loads for the Yolo Bypass, the Sacramento River and the San Joaquin were calculated for the Yolo Bypass at Prospect Slough, Sacramento River at Freeport, and San Joaquin River at Vernalis, respectively. See Table 1 for all locations used to calculated total inputs to the Delta. Delta exports to San Francisco Bay calculated at Mallard Island

[2] Values adapted from Foe and others, 2008, Table 4, Task 2 (MeHg). Loads calculated for samples collected intermittently between March 2000-June 2006. Loads are for the Yolo Bypass at Prospect Slough, Sacramento River at Freeport, and San Joaquin River at Vernalis. Total Delta inputs represent the sum of the loads from these three sites plus the Cosumnes River and the Mokelumne River. Delta exports to San Francisco Bay calculated at Mallard Island.

For DSM2-Hg, load estimates represent average values over the simulation period from October 1999 through July 31, 2006. Delta exports to San Francisco Bay calculated at Chipps Island.

Figure 5-22 Historical Flows for the Yolo Bypass

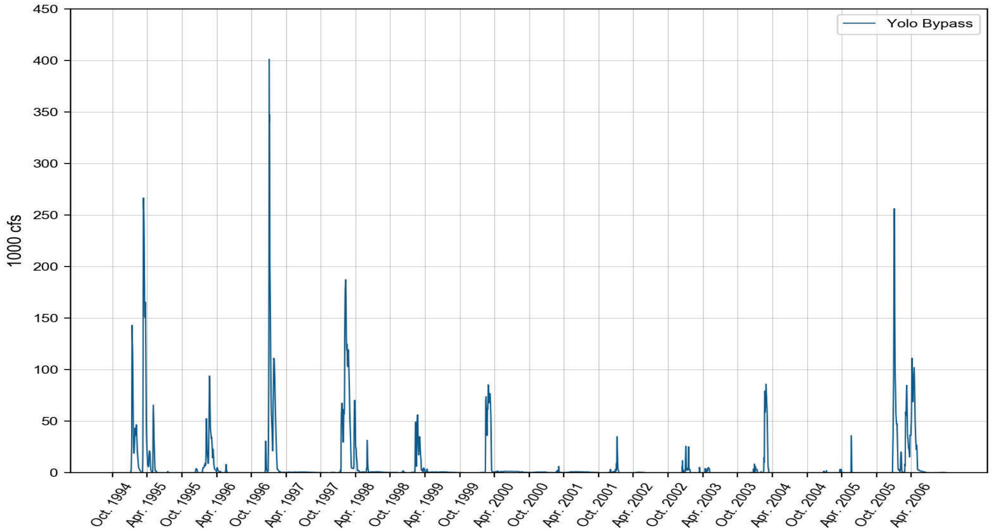


Figure Note: Flows from DSM2-Hydro using data from CDEC station YBY, Yolo Bypass near Woodland. Data available beginning 1989.

Modeled import and export MeHg loads in g/day were similar to those reported by Foe and others (2008) As shown in Table 5-7, the sum of all modeled tributary imports of MeHg into the Delta totaled 15.7 g/day, while MeHg exports totaled 12.5 g/day. In comparison, between March 2000 and June 2006, total tributary inputs reported by Foe and others (2008) were 16.6 g/day, total exports were 11.3 g/day and exports by the State and Federal water projects to Southern California were calculated at 1.5 g/day (Task 2, Figure 9, Foe and others, 2008). Sediment-water fluxes were similar between the two comparisons, however, as shown by the net sediment flux, the Delta was a net sink for MeHg due to the large settling term and the small sediment-water flux term.

Table 5-7 Comparison of Observed and Simulated MeHg fluxes (g/day) for Selected Locations of Processes

Location	*CalFED 2008 Report	Delta Mercury Model (DSM2-Hg)
Export to SF Bay	-9.8	-10.6
Sum of all Tributary Inputs	16.6	15.7
Sum of S. CA and SF Bay Exports	-11.3	-12.5
Sum of SWP and CVP Exports	-1.5	-1.9
Sedimentation	-4.9	-2.4
Photodegradation	-2.5	-1.4
Open Water Sediment Flux	0.48	0.42
Net sediment-water flux	-4.42	-1.76

*Adapted from Figure 9, Foe and others, 2008

Table Note: Positive values indicate imports into the Delta. Negative values indicate exports out of the Delta. See Table 5-4 for locations used for import and export sites used by DSM2-Hg.

Discussion

Model Development

An existing hydrodynamic model for the Delta, DSM2, was successfully extended to add the capability to simulate Hg cycling in Delta waters and the sediment bed. The model was also enhanced to simulate sediment transport and include the sediment bed as a compartment. These additions were needed for several reasons. First, Hg has a strong tendency to bind to sediments. In systems such as the Delta with significant concentrations of suspended sediment (e.g. >10-20 mg/L), the majority of Hg in surface waters can often be associated with particles. Second, sediment transport and fate become important in terms of determining the remobilization, transport and fate of legacy mercury contamination that occurred in the past. Finally, the surface layer of the sediment bed is important because this is a key zone for the conversion of inorganic Hg into MeHg.

Model Fit to Observations

Overall, the model calibration results reasonably fit observations of suspended solids, uHg and uMeHg in Delta waters. The model simulated suspended sediments well at multiple locations in the Delta (Figure 5-10), both in magnitude and short-term variability over a range of flow conditions. The model fit to observed concentrations of uHg and uMeHg in surface waters was less robust than for suspended sediments but still reasonable in terms of capturing the magnitude of concentrations on dates when observations were available (Figure 5-14, Figure 5-15). The model demonstrated a higher degree of variability for uHg and uMeHg than observations, often changing quickly in simulations. Given the high observed and simulated variability of suspended sediments in Delta waters (Figure 5-10), and the strong tendency for Hg to bind to particles, at least a part of the explanation for greater variability in simulated concentrations of uHg (and uMeHg) could be related to less field information being available for uHg and uMeHg, potentially at times when short term spikes might occur during high-flow events. It is also not surprising that suspended sediment simulation results are more robust than for Hg given both the availability of high resolution (15-min) continuous field observations for SSC at major tributary inflow locations and additional uncertainties that apply to Hg, including limited information to characterize concentrations and variability in tributary Hg loads, and additional processes affecting Hg cycling in the Delta.

The model was also used to examine spatial trends for suspended solids, uHg(II) and uMeHg in the Delta, and whether any such trends varied with time, e.g. as a function of flow. Spatially, relative to other Delta regions, Davis and others, 2008 and Slotten and others, 2002 observed lower Hg concentrations in fish tissue in the Central Delta. In terms of modeled suspended sediment, a snapshot of the highest flows in the Sacramento River and Yolo Bypass showed high concentrations of suspended sediment on the outer areas of the Delta and lower concentrations in the Central Delta (Figure 5-16), likely due to settling as tributary inflows entered the Delta. This pattern was also observed for modeled uHg(II) in Delta waters, as Hg(II) associated with particles may have followed similar sediment settling trends. This trend was not evident in simulations for uMeHg in the water column or bed sediments in the Central Delta (Figure 5-16, Figure 5-17). Surface water and sediment bed observations for Hg and MeHg concentrations were insufficient to establish the accuracy of spatial variability simulated by the model.

Simulated Hg and MeHg Fluxes

The Sacramento River was the largest estimated source of water, suspended sediments, uHg(II) and uMeHg to the Delta for the simulation period (>50% in all cases) (Figure 5-9, Figure 5-11,Figure 5-18). Estimated tributary loads of suspended sediments, uHg(II) and uMeHg were highly variable with time in simulations at time scales from daily to yearly (Figure 5-12, Figure 5-19, Figure 5-20). This was because (1) flow regimes were highly dynamic and spanned a range of wet and dry years, and (2) estimates of most tributary loads for these constituents were based on regressions that ultimately depended on flow as the independent variable, the exception being Yolo Bypass loads which were estimated with the D-MCM model. Annual tributary loads of uHg(II) and uMeHg were estimated to vary six-fold for water years 2000-2006 (Figure 5-19). There was also a strong seasonality to flows and loads, with greater rates during winter (Figure 5-20). This has important implications when using baseline monitoring data to set targets for future MeHg loading, and when monitoring for compliance. A multi-year perspective is needed.

The relative importance of major tributaries as sources of MeHg also varied among and within years and depended on hydrology. For example the Yolo Bypass represented one third of the overall MeHg load from inflows for water years 2000-2006 (Figure 5-18), but ranged from 3-50% annually (Figure 5-21), with greater importance during wetter periods (expected for a flood control structure). The Delta was simulated to be a sink for suspended sediments, inorganic Hg and MeHg. Exports at Chipps Island were roughly 50% less than inflow loads for suspended sediments, 25% less for uHg, and 13% less for uMeHg for the simulation period.

It is important to note that large tributary sources of uHg and uMeHg do not necessarily lead to higher concentrations. The combination of a high flow and low concentration for a tributary could lead to a source being large relative to other tributary inputs but acting to dilute concentrations in receiving waters. If, for example, measures were taken that reduced the flow of a source with lower than the average MeHg concentration for tributaries, it might not lead to lower concentrations in Delta waters. Additional simulations would be needed to explore this concept, but the key point is that it is important to consider concentrations as well as loads for tributaries when evaluating remedial options.

Key Processes

The model analysis confirmed the key roles of hydrodynamics and sediment transport in terms of affecting mercury cycling in the Delta. Increased flow led to increased tributary loads and increased internal mobilization and transport of sediment and associated Hg and MeHg. The dynamic nature of flow in the Delta (and the Yolo Bypass) resulted in a high degree of variability in simulated concentrations of uHg and uMeHg concentrations, inflowing loads and export rates in the short term (e.g. daily) and longer term (e.g. annually).

Uncertainty

Two common sources of uncertainty for model analyses are data and knowledge gaps. While there have been a range of Hg studies in the Delta, they have been undertaken with a variety of objectives and not necessarily designed to quantify Delta-wide fluxes of MeHg and Hg. Therefore more data is desirable to better quantify fluxes over the Delta The large geographic area included in the Delta, wide range of conditions within it, and the high variability of conditions over short periods of time, also add to the challenge of characterizing concentrations, fluxes and key processes affecting Hg and MeHg in the Delta.

In terms of the state of knowledge of mercury cycling in aquatic systems, this continues to evolve, but gaps remain that contribute to model uncertainty. For example, research is ongoing in the scientific community to identify the pool of mercury available for methylation, and whether some sources of Hg(II) to a system are more bioavailable than others. Of relevance to the Delta, which sometimes has high loads of suspended sediment and particulate Hg(II), is whether Hg(II) on suspended sediments is less available for methylation in the system than dissolved Hg(II) loads. This could affect the relative importance of different sources of Hg(II) to the Delta, in terms of contributing to MeHg production. The effects of vegetation on mercury cycling and MeHg production specifically are also topics of recent research (e.g. Chapter 3 in this study and USGS studies by Windham-Myers and others, (2014) are important for the Delta, in terms of affecting MeHg supply from wetland areas and the Yolo Bypass.

Overall, available data and the state of knowledge of mercury cycling were sufficient for the model analysis to proceed but limited the confidence that could be assigned to simulation results. Future application of DSM2-Hg using PEST++ software will help to better identify sources of uncertainty in the model analysis.

Conclusions

The DSM2 hydrodynamic model for the Delta was extended to included sediment transport and mercury cycling in Delta waters and the sediment bed. The model reasonably fit observations of suspended sediment, inorganic Hg and MeHg concentrations in Delta waters. Simulations indicated that flow and sediment transport have a strong influence on Hg cycling, supporting the need to include these processes in the model analysis. The Sacramento River was the largest estimated source of water, suspended sediments, Hg and MeHg to the Delta for the Hg simulation period from October 1999-July 2006 (>50% in all cases). Dynamic flows in the Delta led to high variability in fluxes and concentrations of suspended solids, uHg(II) and uMeHg in inflowing tributaries and in Delta waters during simulations. Annual estimated inflow loads of uHg(II) and uMeHg to the Delta varied by six-fold during the simulated period. Simulations were also characterized by variable concentrations and fluxes on shorter time scales, e.g. months and during events. The Yolo Bypass represented one third of the overall uMeHg load from inflows for water years 2000-2006, but ranged from 3-50% among years, with greater importance during wetter periods (expected for a flood control structure). This temporal variability has important implications when using available data to set targets for uMeHg loading, and when monitoring compliance. A multi-year perspective is needed as well as the ability to capture short term dynamics. The Delta was simulated to be a sink for suspended sediments, uHg(II) and to a lesser extent, uMeHg. Spatially, the model analysis simulated lower concentrations of suspended sediments and uHg(II) in the Central Delta, but not uMeHg. Available data were insufficient to support or refute simulated spatial patterns. Overall, available data and the state of knowledge of mercury cycling were sufficient for the model analysis to proceed and provide meaningful results but limited the confidence that could be assigned to the analysis.

Data/Knowledge Gaps and Next Steps

- **Data gaps**: Available field data were limited in terms of characterizing boundary inflow loads, and concentrations within the Delta, for suspended sediments, uHg(II) and uMeHg. This was partly due to the large geographic area involved. This issue was magnified by the dynamic nature of hydrology in the Delta, leading to a high degree of temporal and spatial variability that could not be captured with limited sampling. This constrains the current ability to quantify mercury cycling in the Delta to a coarser perspective rather than a tightly quantified analysis. Additional data are needed to better characterize inflow loads and within-Delta conditions for a range of hydrologic conditions and a range of years. These data include measurements of inorganic Hg and MeHg in filtered, unfiltered and particulate phases in the water column and sediments, as well as ancillary data such as water chemistry and sediment characterization. Concentration data needs to be collected in a manner allowing the estimation of fluxes at key points in the system, in order to confirm which sources of inorganic Hg and MeHg are most important, and when.
- **Model Development:** The current model analysis included the Delta and Yolo Bypass, using separate models and passing outputs from one model to the other. The model analysis indicated that tributary inflows have a strong influence on mercury concentrations in the Delta. Exports from the Delta may also be an important source of MeHg to downstream areas including San Francisco Bay. Consideration could be given to the merits (and cons) of a model analysis extending beyond the legal Delta.
- **Scientific gaps**: There are scientific gaps that also contributed to uncertainty in the model analysis, including:
    - What pool of Hg(II) is available for methylation? This question has persisted for decades and is challenging to resolve but is especially important at sites with legacy Hg contamination.
    - Is mercury on suspended and bed sediments readily exchangeable or are some sources of inorganic Hg more important that others, in terms of supplying MeHg production? The

    analysis carried out in this study assumed that Hg on solids is readily exchangeable with the dissolved phase.
  - How does vegetation influence MeHg cycling and production? This question is primarily related to loads from the Yolo Bypass, but has important implications for MeHg supply to the broader Delta.
- **Modeling Scope**:
  - <u>MeHg in fish</u>: Given that fish and shellfish MeHg levels are the ultimate end point of interest, the model analysis could be extended to include a food web and bioaccumulation component.
  - <u>Management Scenarios</u>: Time and resources prevented using the developed DSM2-Hg model to evaluate system perturbations to drivers of interest. As approved by the Regional Board, development of the DSM2-Hg model met open water DMCP regulatory requirements, however, future work could apply the model to evaluate how changes to the system would impact MeHg loads and concentrations. Depending on the changes simulated, modifications could be required to the models used and other models may be necessary in order to realistically simulate operational scenarios (discussed further below).
  - <u>Climate change</u> is altering conditions in the Delta that have the potential to affect Hg cycling and bioaccumulation (see for example, Dettinger and others, 2016 and Chapter 6). This issue should be incorporated into future assessments.
  - <u>Sensitivity and uncertainty</u> analyses have not yet been carried out for DSM2-Hg simulations of the Delta, due to time constraints. The future application of DSM2-Hg using PEST++ will provide information on sensitivity and uncertainty, in addition to refining the model calibration.

- **Model Development:** Simulating any changes to operational conditions would require an analysis to estimate Delta inflows and Yolo Bypass operations. Commonly this is done by running the SWP/CVP operations model CALSIM (DWR, 2020c).
  - If Yolo Bypass outflows are used to provide boundary conditions for the Delta model, Delta modeling can only occur during the period and for the management options that have already been run using the Yolo Bypass model. Simulations of different operational scenarios would currently require re-running the proprietary hydrologic model (TUFLOW) and the D-MCM Hg model for the Yolo Bypass. The D-MCM model was also applied to the Yolo Bypass at a coarse spatial resolution. An alternative to these two proprietary models would be to use different simulation software for the Yolo Bypass, for all aspects of the simulations. This could involve using one model for the Yolo Bypass and another (DSM2-Hg) for the Delta, or a single model for the Delta and the Yolo Bypass. Preferably the software would be publicly available software. Within DWR, this platform now exists. If the goal is the long-term use of the Delta model, then consideration should be given to this approach.
  - Model improvements are necessary and important gaps, however, without additional data, the resolution of the model will not improve, therefore it is important that model improvements and increased data gathering efforts happen in parallel.

Program coordination: The ability to quantify and understand sources, sinks, and concentrations of Hg and MeHg in the Delta would benefit from a coordinated Delta-wide program with a specific focus on mercury. In the past and currently, there have been a variety of separate studies, some of which include Delta-wide monitoring for end points of interest such as Hg concentrations in biota (for example the Delta

Regional Monitoring Program), but there is not yet a well-funded, Delta-wide coordinated program to quantify the processes the govern the trends being monitored. The Bay-Delta Hg strategy (Weiner and others, 2003) stated that effective coordination will be crucial for a successful Hg program and suggested that the California Bay Delta Authority recruit or appoint a point of contact on Hg issues. In 2020, this roll could be fulfilled by the Delta Science Program. The coordinating entity would fulfill several duties which include serving as the chief overseer for a Delta-wide effort to identify data and knowledge needs, carry out or oversee studies to address gaps, and create a more robust characterization and understanding of Hg in the Delta and Yolo Bypass.

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