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

Executive Summary

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The Open Water Workgroup

The Open Water Mercury Technical and Modeling Workgroup

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Purpose of This Report

This report and its accompanying Technical Appendices, are submitted to the Central Valley Regional Water Quality Control Board by the Open Water Workgroup in fulfillment of open water reporting requirements for Phase 1 of the Delta Mercury Control Program (DMCP). The Workgroup consists of staff from the California Department of Water Resources (DWR), California State Lands Commission, Central Valley Flood Protection Board, United States Army Corps of Engineers, and United States Bureau of Reclamation.

Open water is defined in the DMCP as the methylmercury load that fluxes to the water column from sediments in open water habitats within channels and floodplains in the Delta and Yolo Bypass. Open water allocations encompass three activities: 1) water conveyance operations that may impact Delta in-channel methylmercury ([e.g., operations of the State Water Project and Federal Central Valley Project]; 2) production of methylmercury in the Yolo Bypass floodplain inundated by managed floodplain flows; and 3) regulatory or management oversight of activities proposed within open water areas. The DMCP lays out an implementation strategy for the control of methylmercury and total mercury in the Delta and Yolo Bypass.

The foundation of this report is based on a workplan and an accompanying technical memorandum approved by the Regional Board in February 2014. A characterization approach was approved due to the complexity of the system and the infeasibility of altering operations of the State and Central Valley Water Projects for control study purposes.

One goal of this project was to develop two mercury models for open water areas of the greater Delta and the Yolo Bypass. An existing proprietary mercury model, the Dynamic Mercury Cycling Model (D-MCM) (EPRI, https://www.epri.com/#/pages/product/3002002518/?lang=en-US, accessed 9/10/19) was applied to the Yolo Bypass. For mercury modeling of the remaining Delta system, the ability to simulate mercury and suspended/bed sediments was added to an existing DWR 1-D model, the Delta Simulation Model 2 (DSM2; https://water.ca.gov/Library/Modeling-and-Analysis/Bay-Delta-Region-models-and-tools/Delta-Simulation-Model-II, accessed 9/10/19). For the Yolo Bypass D-MCM, the parameter estimation software (PEST ++) (Model-Independent Parameter Estimation and Uncertainty Analysis; http://www.pesthomepage.org/, accessed on 7/6/20) software package was used to fine-tune the manual calibration, and optimize parameter estimates. DWR is in the process of making modeling data available publicly. When packaged for public release, DWR will publish model source code, executable files, and other information on the DSM2 website (https://water.ca.gov/Library/Modeling-and-Analysis/Bay-Delta-Region-models-and-tools/Delta-Simulation-Model-II, accessed 7/29/20). The Yolo Bypass D-MCM model source code is not available publicly. However, the approach to mercury cycling in D-MCM has been published (Harris and others, 2012, Hudson and others, 1994). In addition to Technical Appendix G, which provides details on model development, assumptions, calibration, and sensitivity runs, any model input and output information is available on specific request.

Because available mercury data for the Yolo Bypass was limited, a second project goal was to conduct field and laboratory studies to characterize and quantify major mercury and methylmercury sources and flows using a geochemical mass balance approach. This information would provide critically needed parameterization data for the development of the Yolo Bypass D-MCM.

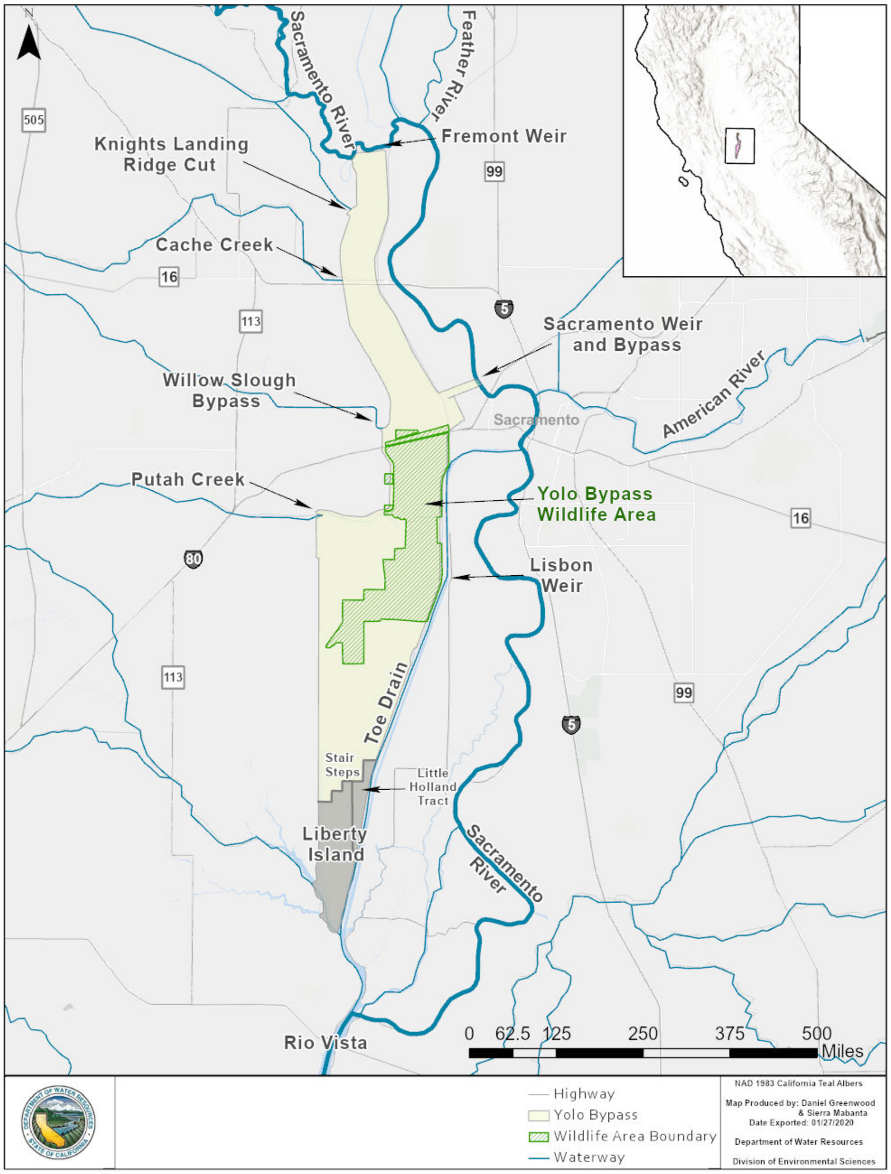
Sediment erosion studies provided the model with erosion values for different land-use types and sediment-water exchange flux experiments were used to estimate mercury diffusive flux into overlying waters for various land types. Vegetation senescence studies of pasture land in the Yolo Bypass during a flood event investigated MeHg contributions from decaying vegetation and led to possible approaches for a future Best Management Practices for pasture lands. Samples collected from import and export sites allowed mass balance calculations for the Yolo Bypass and provided data on the relative contributions of total, filter-passing, and particulate analytes. The mass balance information was not used directly by the model as sampling occurred outside of the modeled time period; however, it provided a valuable check on model patterns.

Key Highlights-Technical Studies in the Yolo Bypass

Over the course of the sampling period, the state of California experienced a severe drought in Water Years (WYs) 2013-2016, however WY 2017 was the second wettest year in a 122-year record. For the mass balance study, only one small event in 2014 and one larger event in 2016 was captured; nine events were sampled in 2017. Therefore, mass balance results focus on samples collected in WY 2017.

Mass balance sampling built upon previous sampling efforts by sampling unfiltered mercury (Hg) and methylmercury (uMeHg), filter-passing Hg (fHg) and MeHg (fMeHg) and particulate Hg (pHg) and MeHg (pMeHg). This allowed greater exploration of patterns associated with floodwater dynamics. This included examining MeHg and Hg dynamics by dividing the Yolo Bypass into two sections—the upper reach, from the top of the Fremont Weir to the stairsteps and the lower reach from the stairsteps to the base of Liberty Island (Figure EX-1).

Figure EX-1 **Yolo Bypass Schematic Map**



Mass balance work corroborated previous work that the Yolo Bypass was a net source of MeHg, but also showed that most of the generation of MeHg occurred in the upper reach of the Yolo Bypass. On average, the upper reach of the Yolo Bypass was a net sink for all fractions of Hg and a net source for all fractions of MeHg. The entire Yolo Bypass was a net sink for uHg and a net source for uMeHg (Figure EX-2). The upper reach between the inlets and the stairsteps supplied 79% of the total amount of MeHg produced within the Bypass, the majority being in the particulate form; the majority of Hg was also in the particulate form. When the Fremont Weir was spilling, it was the dominant tributary input of water flow and loads of all parameters to the Yolo Bypass, though some uncertainty in the individual load estimates impedes our ability to close with certainty the mass balance. Nevertheless, given this caveat, the mass balance shows reasonable closure, suggesting that the major loads have been identified.

Figure EX-2 Mass Balance of MeHg (g/day) in the Yolo Bypass for WY 2017

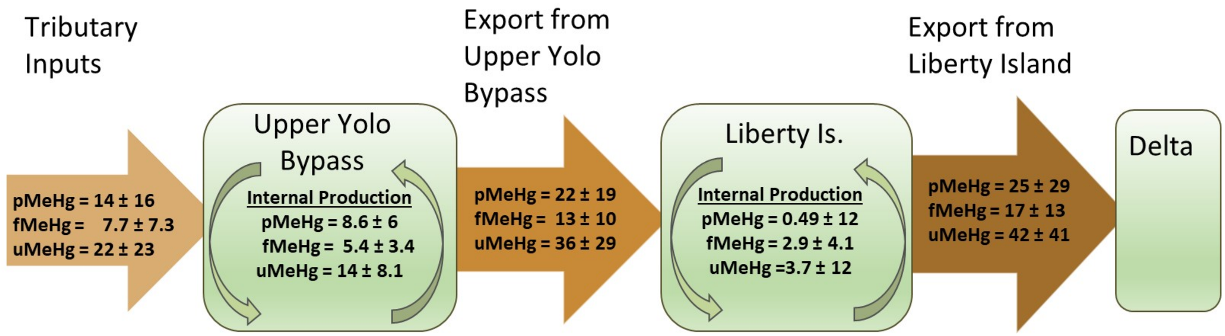


Figure Notes: pMeHg = particulate methylmercury. fMeHg = filter-passing methylmercury. uMeHg = unfiltered methylmercury. Internal production fluxes were determined by averaging the net difference (output – input) determined for each individual sampling event. Thus, the average flux for the internal production does not simply represent the difference between the average output flux minus the average input flux.

Spatially, MeHg concentrations increased as water moved from the Fremont Weir in the north, to the stairsteps in the south. No such increase was observed for Hg or other analytes. Additionally, the quality of the MeHg changed as water moved from north to south, with more MeHg becoming associated with particles and the particles becoming more organic in nature.

Several notable temporal trends emerged. First, for samples collected from the Fremont Weir and Putah Creek, a first flush effect was observed for uMeHg concentrations. This was not observed at other tributaries. First, at Fremont Weir, increased loads in the first flush event were driven both by high flows and high concentrations. Second, at the Cache Creek Settling Basin (CCSB), the highest concentrations were observed at the lowest flows. The results at the CCSB mirrored those observed in a previous CalFed study (see Chapter 3 and Technical Appendix B, Foe and others, 2008). Third, over the course of the 2017 sampling season (from the beginning of January through the end of April 2017), the dominant fraction of MeHg changed from being predominantly filter-passing to predominantly particulate with time. Fourth, the quality of the MeHg appeared to shift from less organic to more organic as water moved south.

Of the 14 ± 8.1 g/day of net internal MeHg production observed in the upper reach of the Yolo Bypass (Figure EX-2), approximately 5.04 ± 1.56 g/day can be accounted for by open water sediment-water exchange flux of filter-passing methylmercury. Note that this sediment-water flux estimate was determined based on short duration (~ 1 day) experiments and therefore they may not represent the flux over a 4-month flood event, such as occurred in WY 2017. Additionally, a number of assumptions went into upscaling the experimental value to sediment-water flux for the full Yolo Bypass. Given these caveats, this estimate of open water sediment flux leaves approximately 9 g/day of internal methylmercury production within the upper Yolo Bypass unaccounted for, strongly suggesting that there is another unidentified internal source. Note that our experiments were unable to translate MeHg contributions from erosion or consider possible increased shear forces associated with post-first flush flooding events or resuspension and deposition of external sediment loads. Therefore, the contributions from these sources were not included and require further study. However, sediment erosion studies determined that there was little erosion associated with pasture lands, the largest land use in the Yolo Bypass, therefore this component was not added to our conceptual model of sources.

Mass balance patterns suggested that organics could be one source of the unaccounted 9 g/day of internal MeHg production in the upper reach. Vegetation senescence mesocosm experiments, simulating floodwater inundation of pasture lands (the largest managed vegetation source in the Yolo Bypass), consistently showed that disking vegetation into the sediment resulted in significantly less fMeHg production than sediments with standing rye grass vegetation.

Integrating the results from mass balance and sediment-water flux studies with the vegetation senescence experiments provided a conceptual model for the contributions of decaying vegetation to MeHg production under floodwater inundation. This suggested that vegetation senescence effectively balanced the internal production of uMeHg determined from the mass balance study (within the uncertainty of the load calculations).

Production of methylmercury in decaying emergent vegetation released an estimated 7.8 ± 1.8 g/day of filter-passing (3.0 ± 0.7 g/day) and particulate (4.8 ± 1.1 g/day) methylmercury to flood waters. The sum of pasture sediment-water flux of filtered (1.4 ± 0.8 g/day) and particulate methylmercury (2.2 ± 1.3 g/day), combined with the release of methylmercury from decaying vegetation, introduced 11.4 ± 7.8 g/day of methylmercury. Our work could not adequately quantify the pMeHg contributions of erosion, deposition, and resuspension of solids and could only estimate the pMeHg contributions from sediment-water exchange and vegetation senescence. The importance of pMeHg in the Yolo Bypass is not currently understood or quantified.

Our work also highlighted the distinction between fresh and senescent vegetation in producing MeHg. One vegetation senescence experiment estimated that fresh vegetation produced a higher flux of fMeHg to overlying water than the dry vegetation even though the fresh vegetation biomass was only 40% of the dried vegetation. This example illustrates the compounding difficulty of understanding the effects of removing vegetation via grazing and the potential differences associated with vegetation age/condition on MeHg production and the flux of fMeHg to overlying waters.

Vegetation senescence study results suggest that reducing the amount of standing winter vegetation may play an important role in reducing methylmercury loads. Removing the decaying vegetation in all the pasture lands of the Yolo Bypass, estimated to produce 1710 ± 560 g for the 2017 flood event, could decrease methylmercury loads more than the 833 g/year load reduction required by the DMCP. However, given the assumptions associated with experimental values, more study is required to fully quantify vegetation numbers.

Key Highlights- Modeling Studies

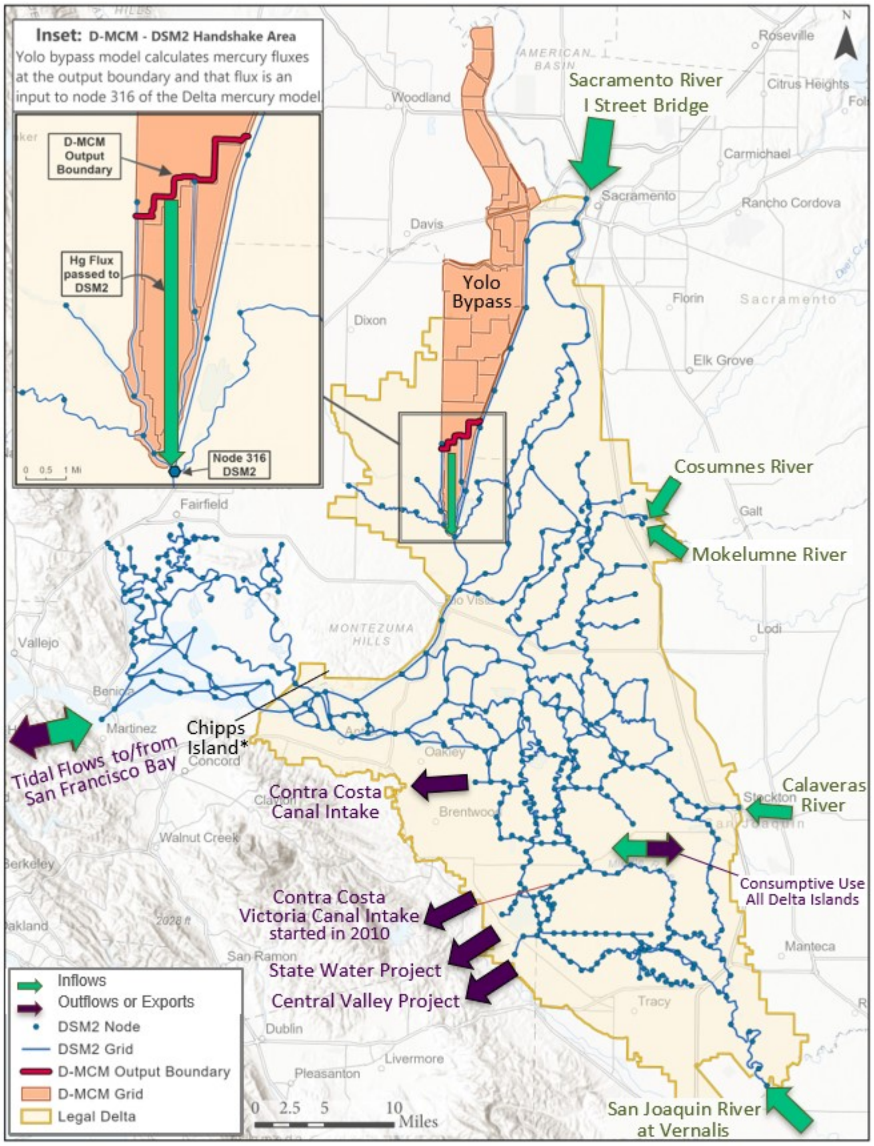
An overview of key points and model capabilities is provided below in Table EX-1. While the model domains of the two models are provided in Figure EX-3.

Table EX-1 Synopsis of Key features of the Yolo Bypass D-MCM and Delta DSM2-Hg Model Analyses

	Yolo Bypass Mercury Model	Delta Mercury Model
Model name	Dynamic Mercury Cycling Model (D-MCM)	Delta Simulation Model version 2 (DSM2-Hg)
Forms of Mercury Modeled	Methylmercury Hg(II) Elemental mercury	Methylmercury Hg(II) Elemental mercury
Model Domain	Yolo Bypass from Fremont Weir to the base of Liberty Island Focused on areas upstream of stairsteps	Open water channels in the Sacramento - San Joaquin Delta between Sacramento, Vernalis and Martinez. Emphasis on results upstream of Chipps Island
Study Period	October 1996 to May 2012	Oct 1999 to July 2006
Time Step	Seconds to hours	15-minutes
Connection between Yolo Bypass and Delta	Simulated export of sediments, Hg(II) and MeHg from Yolo Bypass at stairsteps used as input to the Delta Hg model	Simulated export of sediments, Hg(II) and MeHg from Yolo Bypass at stairsteps used as input to the Delta Hg model
Potential Future Applications	Examine sensitivity of Delta Hg concentrations to changes in flows, climate, boundary concentrations, etc. Replicate historical conditions, fill data gaps, explore spatial patterns.	Scenario testing (options to reduce MeHg supply) Address data gaps using coordinated field and modeling studies Improved characterization of spatial and temporal patterns for Hg and MeHg cycling and supply in Delta Sensitivity of Delta Hg/MeHg concentrations to changes in flows, etc.

Note: future studies require other resources and may involve running other models, such as reservoir operations models

Figure EX-3 Model Domains for the Yolo Bypass and Delta Models and Inflow and Outflow Locations for the Delta Model. Inset shows location of data transfer at the stairsteps (bold red-line in insert) from the Yolo Bypass model to Delta Model.



Yolo Bypass Model Results

The model estimated that the Yolo Bypass was a net source for uMeHg from October 1996-May 2012, via sediment production and the associated flux to overlying waters. Modeled uMeHg export loads at the stairsteps (all exports are reported at the stairsteps) were roughly twice the tributary load for the simulation period. The net load of MeHg to water passing through the Yolo Bypass, i.e. the difference between outflow and inflow fluxes, was approximately 1000 g/yr. Most of this net load occurred during the wet season, when more of the Yolo Bypass was flooded, and flows were greater. The Yolo Bypass model simulations in this study did not include WY 2017, so direct comparisons cannot be made between model results and the mass balance study. However, the model average for the same date range (January

11 – April 25), for years classified as wet (2017 was a wet year), was 18 g/day (range 11-32 g/day among these wet years). For the overall simulation period, the Yolo Bypass was a net trap for inorganic Hg, with 20% less exported at the stairsteps than was loaded from tributaries. Similarly, the Yolo Bypass was a net sink for sediment. Trapping efficiency tended to be greater in drier years.

The total amount of flow and the relative contributions of different water sources varied by an order of magnitude or more among the simulated years. For the simulation period, the Fremont Weir was the largest tributary contributor to water, suspended sediments, and uMeHg, followed by the CCSB. The Fremont Weir contributed approximately half of the uMeHg tributary load, followed by Cache Creek Settling Basin at approximately one third. Together, these two sources represented more than 80% of the total tributary uMeHg load for the simulation period. The CCSB was a slightly larger contributor of inorganic Hg, followed closely by the Fremont Weir (51% vs. 43%, respectively). However, the inorganic Hg load from the CCSB could be overestimated under high flow conditions. In wet years, the largest modeled external sources of suspended sediment were the Fremont Weir and the CCSB, with the Fremont Weir representing two thirds of the suspended sediment input to the Yolo Bypass. In wet years, contributions from the Knights Landing Ridge Cut were small, however, its importance increased in dry years, representing up to 90% of tributary sediment inputs. Direct atmospheric loading of inorganic Hg was small, less than three percent of tributary loads for the simulation period.

To examine potential MeHg reductions, nine simulations, developed in consultation with the Regional Board, were carried out to examine the sensitivity of model results to hypothetical 50% reductions to select model input values. Overall, the simulations reduced the predicted export of MeHg from less than 5% to roughly 20%. The largest decrease in MeHg exports (~20%) occurred by decreasing the conversion efficiencies of Hg(II) to MeHg in Yolo Bypass surface sediments. For some of the simulations, the lack of model response to various sensitivity reductions may have suggested that a simulation period of sixteen years was insufficient to observe a change in response. Simulated removal of all vegetation led to a reduction of approximately 60% in net MeHg production in Yolo Bypass sediments. However, surprisingly, removing vegetation by 50% resulted in less than a 5% decline in MeHg exports. These results reflect competing processes in the model, however, they may also reflect modifications required to allow the model to simulate vegetation effects, which may not fully capture real-world vegetation dynamics. Overall, the simulations and experimental evidence available suggest vegetation can have a strong influence on MeHg production in Yolo Bypass.

Delta Modeling Results

The model was calibrated for suspended sediments, Hg (II), and MeHg. Overall, the model calibration results reasonably fit observations of suspended solids, uHg(II), f(Hg (II), uMeHg, and fMeHg in Delta waters.

During the model study period, the Sacramento River was generally the largest inflowing source of uHg(II) and MeHg to the Delta (71% and 52% respectively). 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, but this ranged from 3-50% among the years simulated. Under some high-flow months, the Yolo Bypass was the largest external source of MeHg to the Delta. Annual freshwater inputs of uHg(II) and uMeHg each varied by approximately 6-fold for water years 2000-2006.

The largest simulated Delta outflows of uHg(II) and uMeHg were exports at Chipps Island (89% and 85% respectively). The Delta was simulated to be a net long-term sink for uHg(II) and uMeHg, exporting roughly half the inflowing load of uHg(II) and 80% of the inflowing uMeHg load (see Chapter 5).

The model was used to explore spatial and temporal patterns of concentrations for suspended sediments, uHg(II) and uMeHg for high, median, and low flow conditions during the Hg calibration period. For the highest flow in the Sacramento River and the Yolo Bypass, suspended sediment 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 patterns were not observed under median and low flows. These patterns represent one snapshot in time; further investigation would be required to see if these patterns are consistent under similar flow conditions.

Estimates of simulated open water sediment fluxes were similar to those developed for CalFed; the model estimated Delta open water sediment flux at 0.42 g/day compared to 0.48 g/day in a 2008 CalFed report (see Chapter 3 and Technical Appendix B, Foe and others, 2008).

Management Implications

Technical Studies

Managing vegetation as a key component of reducing winter internal Yolo Bypass methylation has important management considerations and provides a starting point for future open water control studies and development of Best Management Practices (BMPs).

Vegetation senescence experiments suggest that controlling above-ground vegetation mass may be an effective mechanism to control methylmercury production and release to overlying waters during a flood event. Disking vegetation into the soil appears to be a promising approach to reduce the internal production of MeHg in the Yolo Bypass. Controlling vegetative biomass by grazing gave mixed results. The dynamics between vegetation quality, quantity, and vegetation type requires further investigation before grazing as a BMP can be proposed. While not examined, selective flooding of pastures in the fall, prior to the winter flood season, may be another approach to reduce or remove the standing biomass of vegetation and reduce methylmercury production from vegetation during a flood event.

With any of these approaches, it is important to note that DWR is not a landowner in the Yolo Bypass, therefore any changes in land use practices are outside its jurisdiction and must be pursued by the Regional Water Quality Control Board. Any proposed BMP will need to be evaluated holistically within the full context of the environment that the BMP would be used. It is recommended that before additional studies are conducted, landowners and agencies, such as the Resource Conservation Districts, will need to be consulted to determine if the ecological and cost-benefit impacts, associated with potential land use management approaches, are reasonable or practical.

Much attention has been placed on the Cache Creek Settling Basin (CCSB) and its contributions of inorganic Hg and MeHg to the Yolo Bypass. However, our coarse estimates of MeHg mass generated from decaying vegetation suggests that reductions in vegetation biomass could substantially help with the Yolo Bypass load allocation reduction required in the DMCP.

Modeling Studies

Modeling frameworks were successfully developed for both the Yolo Bypass and the Delta. Comparison of simulated results to field observations suggest that the models are successfully reproducing patterns and trends, providing a meaningful, but coarser perspectives, rather than a tightly-constrained analysis. The analysis was constrained by a combination of limited data and knowledge gaps regarding some key processes operating in the Yolo Bypass. To extend the models' usefulness and to improve modeling results, additional data is needed to better characterize inflowing loads and within-system conditions in the Delta and the Yolo Bypass for a range of hydrologic conditions and a range of years. Needed data includes measurements of inorganic Hg and MeHg in unfiltered, particulate, and filtered phases in tributaries, the water column, and sediments of the Delta and the Yolo Bypass, as well as ancillary data such as water chemistry (e.g. suspended sediment concentrations, dissolved organic carbon, pH, temperature) and sediment characterization.

The dynamic nature of flow in the Delta and Yolo Bypass resulted in a high degree of variability in simulated uHg(II) and uMeHg concentrations, inflowing loads and export rates in the short term (e.g. daily) and longer term (e.g. annually). This has important implications when estimating present-day baseline loads, assigning load allocations, and monitoring for compliance with regulations in the future. A multi-year perspective is needed, designed to capture year to year variability, but with sufficient resolution to also capture short term variability (or not be biased by it), and show longer term systematic trends that might occur (e.g., via climate change). It is recognized that characterizing the spatial and temporal patterns in a system as large and heterogeneous as the Delta/Yolo Bypass is a large effort. A carefully coordinated program would be required, and options should be considered to use automated or surrogate sampling techniques where possible (e.g. continuous turbidity data to estimate suspended sediment concentrations). In the Yolo Bypass, the spatial coverage of sampling should reflect the various land uses and include vegetation-related parameters where appropriate.

Moving forward, the ability to model a variety of operational scenarios would be improved by developing a single publicly available hydrodynamic and Hg model for both the Delta and the Yolo Bypass. Additionally, given the important role that vegetation appears to play in MeHg production in the Yolo Bypass, model enhancements should include an improved treatment of vegetation where applicable. Since bioaccumulation in fish is the driver of the DMCP, consideration should be given to adding a bioaccumulation component to the model framework. Similarly, since model analysis indicated that tributary inflows have a strong influence on mercury concentrations in the Delta, consideration could be given to the merits and cons of a model analysis extending upstream and/or downstream of the legal Delta. However, the confidence associated with a model analysis carried out with improved tools would still be limited by the level of data currently available. Therefore, model refinements and data collection efforts need to occur in parallel.