MEMO

To: Delta Methylmercury TMDL Technical Advisory Committee

Cc: NPS Workgroup

Date: August 17, 2012

Subject: Nonpoint Sources Workgroup – Methylmercury Control Study Workplan Outline

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Overview

This memorandum, which is a product of the Nonpoint Sources Workgroup (NPS Workgroup), presents a methylmercury control study workplan “outline.” The control study is a requirement imposed by the Central Valley Regional Water Quality Control Board (Regional Board) on wetlands and irrigated agricultural dischargers in the Delta and Yolo Bypass under the Delta Methylmercury Control Program. The program includes a Total Maximum Daily Load (TMDL) for methylmercury discharges in the Delta. The audience for this outline is the Technical Advisory Committee (TAC), as a tool to provide early review and comment on the technical and logistical approaches. Much of the technical information presented here constitutes and refers to the NPS Workgroup’s knowledge base.

Funding for this project is being provided in part through an agreement with the State Water Resources Control Board and the U.S. Environmental Protection Agency under the Federal Nonpoint Source Pollution Control Program (Clean Water Act Section 319). Cooperating Entities participating in this effort are characterized in Table 1.

The NPS Workgroup is submitting this outline on behalf of all Cooperating Entities. The complete Workplan will provide a prioritized set of management practices (MPs) for the six land use categories considered by the NPS Workgroup. The workplan will prioritize studies based on issues of concern among stakeholders. NPS Workgroup participants, who either manage the lands themselves or represent coalitions, have pledged to find volunteers for Phase 1 Control Study sites. The Workplan will include the knowledge base, along with guidance on developing sampling and analysis plans for future studies. The Workplan also will include guidance on developing a holistic cost-benefit analysis to consider impacts on all beneficial uses. Because of
the diversity of funding sources and land ownership and management, site-specific project proponents are responsible for developing project-specific workplans. In addition to this outline submitted by the NPS Workgroup, two site-specific project proposals are also being submitted for TAC review by various NPS Workgroup participants: (1) USGS and BLM will address a potential management practice affecting three land use categories (permanent managed wetlands, seasonal managed wetlands, and flooded agricultural lands); and (2) DWR and DFG will address a fourth land use category (tidal marshes).

Table 1. NPS Workgroup Cooperating Entities indicating land use categories.

<table>
<thead>
<tr>
<th>Land Use Category</th>
<th>Federal Agencies</th>
<th>State Agencies</th>
<th>Non-profit Organizations</th>
<th>Private</th>
</tr>
</thead>
<tbody>
<tr>
<td>Managed Wetlands – Permanent Wetlands</td>
<td>USBR</td>
<td>USFWS</td>
<td>BLM(2)</td>
<td>DWR</td>
</tr>
<tr>
<td>Managed Wetlands – Seasonal Wetlands</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Agricultural Lands – Flooded Agricultural Land(5)</td>
<td>X</td>
<td>X(1)</td>
<td>X</td>
<td>X(1)</td>
</tr>
<tr>
<td>Agricultural Lands – Irrigated Crop Lands</td>
<td>X</td>
<td>X(1)</td>
<td>X</td>
<td>X(1)</td>
</tr>
<tr>
<td>Natural Hydrology Systems – Floodplains</td>
<td>X</td>
<td>X(1)</td>
<td>X</td>
<td>X(1)</td>
</tr>
<tr>
<td>Natural Hydrology Systems – Brackish-Fresh Tidal Marsh</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

(1) Irrigated agricultural discharges are monitoring assessed via two coalitions (Sacramento Valley and San Joaquin County & Delta). While they also monitor wetlands and rice fields in the Delta, they primarily represent non-rice farmland in the Delta.

(2) BLM manages the Cosumnes River Preserve.

(3) Westervelt is not currently involved in this land use category in the Delta, but could be during Phase 1.

(4) DWR participates in both coalitions (see footnote #1)

(5) Flooded agriculture includes any lands used for agriculture that get flooded at some point of the year, whether during or after crop growth.

This outline is organized by the sections recommended in the Regional Board’s Control Study Guidance dated May 15, 2012. The full workplan will include two additional sections: (1) Quality Assurance Procedures and (2) Project Evaluation and Data Sharing Plan.

Problem Statement

The project area includes the entire legal Delta and the Yolo Bypass (see Appendix A – Land Use Analysis). Large MeHg load reductions are required for contributing sources in most subareas (except Central Delta and West Delta). Percent reductions required vary, ranging from 44% (Sacramento River) to 82% (Marsh Creek).

Wetlands and irrigated agricultural lands are existing activities in each subarea. According to the TMDL, the major land uses in the Delta are agriculture (~60% of the Delta area but 2% of its MeHg load) and wetlands (~6% of the Delta area but 19% of its MeHg load). Wetland acreage in the Delta is expected to increase in the future according to these efforts:

- The US Fish and Wildlife Service’s biological opinion (BiOp) on the Long-Term Operational Criteria and Plan for coordination of the Central Valley Project and State Water Project calls for the state’s Department of Water Resources to implement a program to create or restore a minimum of 8,000 acres of intertidal and associated subtidal habitat in the Delta and Suisun Marsh.
• The Bay Delta Conservation Plan (BDCP) could ultimately require on the order of 60,000 acres of tidal wetland restoration in the Bay-Delta estuary. Currently, on the order of 31,000 acres remain of the original 544,000 acres.
• Up to 200,000 acres of land surrounding the Bay-Delta estuary will be below mean sea level with moderate estimates of future sea-level rise.

The TMDL is based on loads to the Delta's open waters, but wetlands are part of the Delta. Many of the MPs that aim to reduce MeHg loads discharged from wetlands and irrigated agricultural lands may inadvertently increase MeHg concentrations in sediment and biota on site. Because these land and water uses have many important beneficial uses for birds and other wildlife (including threatened and endangered species), some MPs that reduce MeHg discharges to open water may simply redirect mercury problems to seasonal and permanent wetlands. Some MPs that are expected to reduce MeHg discharges from wetlands (e.g., grazing, vegetation removal, changing water levels) may also negatively impact the quality of the habitat (e.g., loss of fall forage for waterfowl) which conflicts with the wetland management goals.

Objectives

The overall objective of the NPS Workgroup’s Control Study is to identify, characterize, and prioritize a suite of potential MPs for implementation in the Delta that would meet or exceed the wetlands and irrigated agriculture load allocations. Our overall goal is to test the hypothesis that a broad suite of practical and cost-effective MPs could achieve each TMDL subarea’s allocated load reduction (or more) with insignificant negative consequences. For each NPS land use category, we will evaluate a suite of MPs which have the potential to reduce MeHg production, bioaccumulation, and discharge. The workplan, serving as a strategic guidance document, will be implemented by site-specific project proponents and their workplans.

Mechanisms Underlying the Study

The NPS Workgroup recently synthesized the scientific understanding of MeHg production, bioaccumulation, and export in the Sacramento-San Joaquin Delta (see Appendix B – Mercury Science Synthesis). Section 6 of the Synthesis lists the important understanding (and lack thereof) based on experiences to date. The key finding is that hydrologic control (e.g., holding water on site) and carbon control (e.g., limiting surface organic litter), rather than inorganic Hg control (i.e., controlling inorganic Hg sources or loads), are primary mechanisms that may limit MeHg production, bioaccumulation, and discharge. The synthesis goes on to suggest that monitoring designs must be broadened to incorporate natural temporal variability and biosentinels as tools to monitor effectiveness of MPs. Recognizing that wetlands, including flooded agricultural lands, are predisposed to MeHg production and bioaccumulation, management of hydrology and carbon during “hot moments” (times and places where MeHg production is highest) may provide the most efficient field-based mechanism to reduce MeHg production and bioaccumulation within wetlands, and MeHg loads in discharges. Some events of concern include early season flood-up (release of stored MeHg pools), winter flooding of agricultural lands and seasonal wetlands, frequency of wetting and drying agricultural and seasonal wetlands, and wet harvesting of (wild) rice fields.
Aqueous MeHg loads from wetlands and irrigated agriculture in the Delta are assessed in the TMDL as two aggregated source types rather than the six land use categories used to organize this Workplan.

## Proposed Control Measures

Based on the most current research results, the NPS Workgroup identified and characterized potential MPs by six land use types (see Appendix C – Wetlands and Irrigated Agriculture Management Practices). The MPs fall within three broad categories aimed at reducing MeHg loads from the NPS land use categories: (1) biogeochemistry [6 MPs]; (2) hydrology, [14 MPs]; and (3) vegetation and soils [4 MPs]. The MPs were also specifically identified for the six land use categories for which they are best implemented (see Appendix C Tables 1-6 for the complete list of identified MPs).

NPS Workgroup participants, in particular, the land owners, land managers, and agricultural coalition representatives, separately and then collectively evaluated the MPs. The primary intent was to reduce the initial potential list of MPs based on feasibility, relative MeHg load reduction potential, competing land management goals or regulatory requirements, and costs. The evaluation criteria applied to each MP were as follows.

**Costs and Benefits:**

- **Scientific Certainty** – The relative level of scientific certainty, based on the available science, that the MP will be effective
- **Costs** – The relative financial cost of implementing the MP, generally on a per unit area basis (e.g., agricultural production losses, labor & pumping costs, additional infrastructure)
- **MeHg Reduction Potential** – The relative potential for reducing MeHg production, bioaccumulation, or discharge that the MP could affect
- **Spatial Applicability** – The relative area of the Delta on which the MP could be implemented

**Practical Challenges:**

- **Technical Capacity to Implement** – The level of willingness and technical capability of land managers to implement the MP
- **Beneficial Use Impacts** – How the MP may positively or negatively impact beneficial uses of the wetland or irrigated agricultural field and downstream receiving waters
- **Other Requirements** – Whether the MP may conflict with other objectives (e.g., vector control, livestock grazing, climate change resiliency, response to sea level rise, salinity management, ecological diversity/mosaic)

This qualitative evaluation by the NPS Workgroup is documented in Appendix D – Management Practices Evaluation. Note that this evaluation by the NPS Workgroup of the potential MPs is intended to focus the potential list of MPs based on the specific conditions and requirements of land owners and managers in the Delta. The overall results represent general consensus. However, some wetlands or agricultural lands may have site-specific conditions and interests by land managers that exclude or include an MP for specific consideration.
Table 2 presents the list of MPs that the Delta NPS Workgroup considered most promising for wide-spread application in the Delta and should have higher priority for control studies, where applicable. Broadly, hydrologic controls are more promising for managed wetlands and flooded irrigated agriculture while carbon controls are more promising for floodplains. Also note that:

- Several studies already completed or in progress evaluate some of these MPs in the Delta. The table will be enhanced by identifying which MPs have been or are being studied.
- The NPS Workgroup considers the available information used to calculate the irrigated agricultural loads in the TMDL to be limited and that some areas, particularly those with mineral soils such as the South Delta, may be MeHg sinks. Thus, the most important first step for irrigated agriculture is to characterize loads on and off irrigated crop lands in the Delta on which various MPs are already being implemented.
- There are no MPs for wildlife even though most Delta wetlands and winter-flooded rice and corn fields exist for the express purpose of providing wildlife habitat, especially for migratory birds. Consequently, the same wetlands and flooded agriculture lands that are often MeHg sources to the Delta also provide productive habitat and attract large densities of fish and wildlife. Whereas the TMDL focuses on loads discharged to the Delta’s open waters, the important effects of MeHg on fish and wildlife largely occur on these sites rather than in the Delta’s open waters. Discharging wetland water into the Delta may actually dilute MeHg concentrations and may lessen net bioaccumulation on site. MPs that reduce MeHg loads into Delta open water but increase MeHg bioaccumulation on site should be discouraged. Broad wildlife management should consider a "Bioaccumulation" category with MPs such as "promote or discourage foraging habit", "promote or discourage bird nesting", "install fish screens to reduce passage or promote fish passage". Such MPs could be applied in every land use category.

Table 2. Potential MPs for NPS Workgroup control studies. “√” indicates general consensus that the MP is promising for application; “+” indicates that the MP may be applicable in particular instances, but only after further research.

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<tbody>
<tr>
<td>Apply coagulant in treatment ponds</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase water residence time</td>
<td>√</td>
<td>+</td>
<td>√</td>
<td>+</td>
<td></td>
<td></td>
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<tr>
<td>Increase water depth</td>
<td>√</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase water velocity</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Timing water discharge</td>
<td>√</td>
<td>√</td>
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<tr>
<td>Pre-flood wetland</td>
<td>+</td>
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<tr>
<td>Flood and hold</td>
<td>√ +</td>
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<tr>
<td>Delay fall flood up</td>
<td>+</td>
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<tr>
<td>Stagger flood/drain events</td>
<td>+</td>
<td>+</td>
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<td></td>
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<tr>
<td>Recirculate drainage water</td>
<td>+</td>
<td>+</td>
<td>√ +</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Use permanent wetlands as treatment ponds</td>
<td>√ +</td>
<td>√ +</td>
<td>√ +</td>
<td>+</td>
<td></td>
<td></td>
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<tr>
<td>Manipulate flooding period</td>
<td>√ +</td>
<td>+</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Irrigate fields in series versus parallel</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Raise depth of drainage ditches</td>
<td>+</td>
<td></td>
<td>√ +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irrigate fields with drip irrigation systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>√ +</td>
</tr>
<tr>
<td>Burn vegetation and soil</td>
<td>+</td>
<td>+</td>
<td></td>
<td>√ +</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Till vegetation below soil surface</td>
<td>+</td>
<td>+</td>
<td></td>
<td>√ +</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bale and remove vegetation</td>
<td>+</td>
<td>+</td>
<td></td>
<td>√ +</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graze fields with livestock</td>
<td>+</td>
<td></td>
<td></td>
<td>√ +</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design of new/ restored tidal wetlands</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

<sup>[1]</sup> Characterization studies are first needed for this land use, which may be a MeHg sink.

<sup>[2]</sup> Control study for these land uses could focus on pre- and post-implementation or with-vs-without monitoring to compare designs.

Study sites for these MPs would ideally represent a range of water regimes (e.g., flooding conditions, irrigation cycles, tidal influence), crop/vegetation types, source water characteristics, soil characteristics, and surface sediment mercury concentrations. Considerations for prioritizing where to conduct control studies are provided in Table 3 by Delta subareas and in Table 4 by land uses. Ideally studies would be conducted in subareas that need greater load reductions and on land uses that appear to have greater MeHg production rates. However, studies will require precise land management; thus, studies should be located where managers are agreeable and able to manipulate their land for scientific research.
Table 3. Delta subarea sizes, MeHg loads, and load allocations.

<table>
<thead>
<tr>
<th></th>
<th>Subarea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor</td>
<td>Central Delta</td>
</tr>
<tr>
<td></td>
<td>Sacramento River</td>
</tr>
<tr>
<td></td>
<td>San Joaquin River</td>
</tr>
<tr>
<td></td>
<td>Yolo Bypass</td>
</tr>
<tr>
<td></td>
<td>West Delta</td>
</tr>
<tr>
<td></td>
<td>Cosumnes/Mokelunme River</td>
</tr>
<tr>
<td></td>
<td>Marsh Creek</td>
</tr>
<tr>
<td>Acres</td>
<td>149,694</td>
</tr>
<tr>
<td>% of NPS Area</td>
<td>31%</td>
</tr>
<tr>
<td>TMDL Load</td>
<td>668</td>
</tr>
<tr>
<td>TMDL Req’d MeHg Load Allocation</td>
<td>668 1,385 195 235 330</td>
</tr>
<tr>
<td>TMDL Req’d MeHg Load Reduction</td>
<td>0% 44% 63% 78% 0%</td>
</tr>
</tbody>
</table>

Table 4. Risk of MeHg production, bioaccumulation and export, and percentage of area of each land use category in the Delta.

<table>
<thead>
<tr>
<th>Land Use Category</th>
<th>MeHg Risk (1-5 scale)</th>
<th>% of Total NPS Acres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Managed Wetlands – Permanent Wetlands</td>
<td>Low – High*</td>
<td>0.2%</td>
</tr>
<tr>
<td>Managed Wetlands – Seasonal Wetlands</td>
<td>High</td>
<td>4%</td>
</tr>
<tr>
<td>Agricultural Lands – Winter Flooded</td>
<td>High</td>
<td>2%</td>
</tr>
<tr>
<td>Agricultural Lands – Irrigated Crops</td>
<td>Low</td>
<td>89%</td>
</tr>
<tr>
<td>Natural Hydrology Systems – Floodplains</td>
<td>High</td>
<td>1%</td>
</tr>
<tr>
<td>Natural Hydrology Systems – Brackish-Fresh Tidal Marsh</td>
<td>Low</td>
<td>4%</td>
</tr>
</tbody>
</table>

* The relative risk varies between deeper ponds and shallower vegetated wetlands.

Monitoring and Data Collection Plan

The NPS Workgroup’s approach is to evaluate MPs that reduce MeHg loads into the Delta to meet TMDL load allocations and to maintain or improve the beneficial uses of the Delta wetlands and flooded agricultural lands for wildlife. Therefore, each control study will monitor MeHg discharges from study sites and bioaccumulation within those sites.

We will measure the effectiveness of our MPs using two basic approaches. The first approach will measure MeHg concentrations in inflows and outflows in order to calculate net MeHg loads (load out – load in). This approach is often complicated by (1) MeHg concentrations in water fluctuating dramatically with time of day, flow changes, and season; and (2) unconstrained flood flows and groundwater seepage, especially on floodplains and sunken Delta islands. Surrogates for hydrology, such as conservative tracers like chloride, should be monitored where feasible. Surrogates for MeHg in water, such as chromophoric dissolved organic matter, should also be used where appropriate. This approach would be most applicable in highly controlled wetlands and in irrigation ditches collecting discharge from many uniform fields.
The second approach will monitor biosentinels for MeHg exposure. Biosentinels provide a time-integrated indication of MeHg concentrations in water and also provide an assessment of MeHg exposure to wildlife. This technique has been used successfully in the Yolo Bypass and Cosumnes River Preserve with caged mosquitofish stationed at inlets and outlets of wetlands to indicate net changes in MeHg exposure. MeHg concentrations in bird eggs and blood can be used to test differences between wetland habitat types and associated MPs. Examples of this tool include ongoing studies at (1) Cosumnes River Preserve where artificial nest boxes in different types of managed wetlands gage which MPs reduce MeHg in bird eggs and MeHg risk to wildlife, (2) within the Cache Creek Settling Basin where birds are being captured live and their blood sampled for MeHg concentrations, and (3) South Bay Salt Pond Restoration Project in San Francisco Bay where MeHg concentrations in bird eggs and fish are being used to monitor the restoration of salt ponds to tidal marsh.

These approaches are similar to those employed in recent studies funded by the Central Valley Regional Water Quality Control Board. Typically, a nested analysis of covariance can be used to compare MeHg concentrations among land use types, among MPs, and over time. Importantly, it is necessary to acquire baseline monitoring data before implementing any MPs and to use a fully replicated study design. We recommend a minimum of a 3-year study, with 3 replicates per management treatment, to compare with 3 control treatments (no manipulation), per land use category.

Furthermore, each study should characterize and account for the financial and ecological costs associated with implementing each MP. Financial costs result from increased water pumping; increased labor, materials, equipment for active management; and reduced crop production. Ecological costs could result from reduced wildlife habitat value for foraging and nesting birds. We recommend that funding also be used to track collateral impacts of MPs on goals other than reduction of MeHg. Additional benefits, such as tidal marshes being carbon sinks, should also be accounted for.
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1 Introduction

This report provides a brief summary of the irrigated agriculture and managed wetlands in the Sacramento-San Joaquin Delta, subdivided by eight subareas delineated in the Sacramento – San Joaquin Delta Estuary TMDL for Methylmercury Total Maximum Daily Load (TMDL). These two general land uses are the focus of the Nonpoint Sources (NPS) Workgroup that was formed to develop a collaborative Control Study workplan consistent with requirements in the TMDL. A full listing of the federal, state, private and other non-governmental cooperating entities can be found on the NPS workgroup’s website (http://delta-mercury-nps.org/). The geographic scope of this report is the legal Delta and the northern part of Yolo Bypass up to the Fremont Weir. Encompassed in the eight subareas is a diverse area of nearly 750,000 acres of waterways, agricultural fields, urban areas, managed wetlands and unmanaged wetlands, of which irrigated agriculture and managed wetlands cover approximately half a million acres.

Funding for this project has been provided in full or in part through an agreement with the State Water Resources Control Board and the U.S. Environmental Protection Agency under the Federal Nonpoint Source Pollution Control Program (Clean Water Act Section 319(h)). The contents of this document do not necessarily reflect the views and policies of the State Water Resources Control Board, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

2 Geography

The eight subareas of the TMDL were described by the Central Valley Regional Water Quality Control Board in a staff report (Wood et al., 2010). A brief overview of each subarea and major landmarks that define its boundaries is given in this section, in order geographically from north to south. Each subarea has a corresponding map in Appendix A.

2.1 North Yolo Bypass

This subarea contains the bypass from the Fremont Weir down to the confluence of Putah Creek with the Toe Drain. This area also includes the Sacramento Weir, just north or West Sacramento, which connects the Sacramento River with the bypass one mile north of interstate 80. Major west side tributary inputs include the Knights Landing Ridge Cut, Cache Creek, Willow Slough and Putah Creek.

2.2 South Yolo Bypass

The south end of the bypass includes the south half of the Yolo Bypass Wildlife Area at Putah Creek down the Toe Drain to Liberty Island. This area contains the entire portion of the Cache Slough system north of the Montezuma Hills that is inside the legal Delta.

2.3 Sacramento River

The Sacramento Deep Water Ship channel forms the western boundary of this subarea with its eastern boundary defined by the legal Delta. The eastern line roughly follows interstate 5 down towards Lodi where Highway 12 approximates the southern boundary of the subarea.
2.4 Mokelumne-Cosumnes Rivers
This area roughly defines the confluence area of the Cosumnes River with the Mokelumne River with its eastern boundary defined by the legal Delta boundary. This subarea stretches to the west as far as the Delta Cross Canal. This subarea boundary was drawn at a course resolution and currently bisects much of the lower Cosumnes River Preserve and its managed wetlands. In future publications, the boundary could be moved north of Twin Cities Road to more accurately show how water flows in the area.

2.5 West Delta
This subarea has the boundary between the Central Valley and San Francisco Bay Regional Water Control Boards where the Sacramento River meets the San Joaquin River. Islands in this subarea include Sherman Island, Jersey Island and Hotchkiss Tract. This subarea is currently in compliance with its TMDL allocations.

2.6 Marsh Creek
The namesake creek dominates this subarea which includes portions of this creek above the tidal influence and still within the Delta. This subarea includes the city of Brentwood.

2.7 Central Delta
This large subarea includes portions of Stockton in the Delta down to the federal and state water pumps in the southeast at Clifton Court Forebay. This subarea is currently in compliance with its TMDL allocations.

2.8 San Joaquin River
This subarea includes the San Joaquin River from Stockton upriver to the confluence of the Stanislaus River at the boundary of the legal Delta. The other major waterways in this subarea include Old River, Fabian Canal and Bell Canal that link the San Joaquin River to the state and federal water pumps in the Central Delta.

3 Agriculture in the Delta

3.1 Sources

3.1.1 Land Survey Program
For this analysis the primary source for agricultural acreages was from the Department of Water Resources’ (DWR) Land Use Survey of the legal Delta that was compiled during crop year 2007 and converted to a geographic information system layer. This Delta layer was supplemented by DWR’s 2008 Yolo County Land Use Survey for the section of the North Yolo Bypass region that is north of I-80 and outside of the legal Delta. The data is collected by DWR staff that first delineates field boundaries from digital aerial photos in a computer mapping application. This digital field boundary map is then populated with crop information when DWR staff goes out into the field and visually identifies the land use on over 95 percent of the developed agricultural fields in a survey area (DWR, 2012).
The two main reasons that this data source was used are that it was less than five years old and that it was spatially explicit. Having a spatial dataset rather than county-level records empowered this analysis to show the crop classes by TMDL subarea. The recent crop data from 2007 allows the analysis of a relatively average crop cycle and excludes some of the price spikes and short term acreage shifts in the following two years.

### 3.2 Analysis

#### 3.2.1 Overall Distribution

Delta agriculture was categorized into eight main categories yielding an overall distribution as shown in Figure 1. Detailed descriptions of these main categories will be given in the following section. Figure 1 shows the dominance of pasture, hay and grain crops in the overall Delta. A more detailed look at the map in Figure 2 shows the subarea distribution with this category being the primary land use in the South Yolo Bypass, San Joaquin River and the West Delta. Field crops are the second most common agricultural land use with its prevalence mostly clearly seen in the Sacramento River and Central Delta subarea. Major field crops in the Delta and Yolo Bypass include corn, beans (dry), safflower and sunflowers. Truck and berry crops are shown in Figure 2 along the eastern edge of the Delta with much more significant acreages in the southern portion of the Central Delta and throughout the San Joaquin River subarea. Major contributors to the Truck and Berry category include tomatoes, asparagus, melons and potatoes. The fourth most abundant agricultural land use in the Delta was vineyards with vineyard cultivation primarily taking place in the Sacramento River subarea. Smaller vineyards are in the southeast and northeast corners of the Central Delta as well as pockets of vineyards in the San Joaquin and Mokelumne River. Orchards form the fifth largest category with their growth primarily in Sacramento River subarea and a smaller acreage in the southern part of the San Joaquin subarea.

![Figure 1 Distribution of agriculture in the Delta and Yolo Bypass](image)
Figure 2 Map of major agricultural types in the Delta and Yolo Bypass
### 3.2.2 Crop Categories

#### 3.2.2.1 Field Crops

Field crops in the Delta are geographically dominant in the Central Delta and lower Sacramento River with corn comprising the lion share of the acreage followed by safflower, Sudan grass and dry beans as shown in Figures 4 and 5.

![Figure 3 Specific crops and acreage within the Field Crop category](image-url)

### Table 1 Acreages of major agricultural crop categories by subarea

<table>
<thead>
<tr>
<th>Crop Category</th>
<th>Central Delta</th>
<th>Sacramento River</th>
<th>San Joaquin River</th>
<th>South Yolo Bypass</th>
<th>West Delta</th>
<th>North Yolo Bypass</th>
<th>Marsh Creek</th>
<th>Mokelumne River</th>
<th>Grand Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>PASTURE, HAY &amp; GRAIN</td>
<td>45,394</td>
<td>43,782</td>
<td>32,797</td>
<td>45,846</td>
<td>10,257</td>
<td>1,375</td>
<td>671</td>
<td>1,146</td>
<td>181,266</td>
</tr>
<tr>
<td>FIELD CROPS</td>
<td>59,444</td>
<td>46,279</td>
<td>16,125</td>
<td>10,929</td>
<td>1,788</td>
<td>2,942</td>
<td>1,452</td>
<td>871</td>
<td>139,830</td>
</tr>
<tr>
<td>TRUCK &amp; BERRY CROPS</td>
<td>24,506</td>
<td>7,620</td>
<td>18,696</td>
<td>679</td>
<td>3</td>
<td>2,153</td>
<td>418</td>
<td>996</td>
<td>55,071</td>
</tr>
<tr>
<td>VINEYARDS</td>
<td>4,236</td>
<td>20,774</td>
<td>1,793</td>
<td>19</td>
<td>580</td>
<td>404</td>
<td>1,189</td>
<td>28,995</td>
<td></td>
</tr>
<tr>
<td>ORCHARDS</td>
<td>2,171</td>
<td>8,947</td>
<td>5,385</td>
<td>157</td>
<td>53</td>
<td>285</td>
<td>1,233</td>
<td>239</td>
<td>18,470</td>
</tr>
<tr>
<td>RICE</td>
<td>1,234</td>
<td>1,607</td>
<td>6</td>
<td>7,193</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10,041</td>
</tr>
<tr>
<td>IDLE</td>
<td>1,871</td>
<td>2,020</td>
<td>2,010</td>
<td>1,362</td>
<td>191</td>
<td>1,806</td>
<td>267</td>
<td>242</td>
<td>9,769</td>
</tr>
<tr>
<td>LIVESTOCK</td>
<td>49</td>
<td>163</td>
<td>970</td>
<td>27</td>
<td>32</td>
<td>35</td>
<td></td>
<td></td>
<td>1,277</td>
</tr>
<tr>
<td>TOTAL</td>
<td>138,906</td>
<td>131,192</td>
<td>77,776</td>
<td>59,025</td>
<td>12,904</td>
<td>15,755</td>
<td>4,480</td>
<td>4,682</td>
<td>444,719</td>
</tr>
</tbody>
</table>
3.2.2.2  **Truck and Berry**

Truck and Berry crops are diverse with more than half of its acreage comprised of tomatoes, primarily processing tomatoes. Significant acreages of asparagus, melons, squash, cucumbers and potatoes are
also grown in the Delta (Figure 6). The largest concentration of truck and berry crops is in the southern Delta.

Figure 5 Crop specific acreages of truck and berry crops in the Delta and Yolo Bypass
3.2.2.3  Orchards

Orchards are geographically highly concentrated in the Delta with climatic condition and soil conditions dictating their location. The most orchard acreage is in pears with this crop almost exclusively in the center of the Sacramento River subarea. Almonds are grown principally in the southeast section of the San Joaquin. Cherries, apricots and apples are grown mostly in Marsh Creek and the far western portion of the Central Delta. Notably there are practically no orchards in the middle of the Central Delta where TMDL allocations are currently met.
Figure 7 Distribution of orchard crops in the Delta and Yolo Bypass

- **Pears, 6,402**
- **Walnuts, 3,387**
- **Almonds, 3,147**
- **Cherries, 1,512**
- **General Orchards, 1,587**
- **Apples, 1,048**
- **Olives, 713**
- **Apricots, 674**
3.2.2.4 Grain, Hay and Pasture

The land in this category shows the largest contiguous block of pasture located in the South Yolo Bypass with smaller, mosaics of pasture and alfalfa in many parts of the Delta including the Sacramento River, lower Central Delta and the San Joaquin.

For this analysis the two original DWR classes were combined, Pasture and the Grain & Hay category. This allowed the analysis to look at broad changes over time in subsequent sections of this report. Land
use in this category changes frequently within this broad class and it is unclear how well the original mapping differentiated between the different classes. Since much of the land in this broad class is generically put into a General Grain and Hay category, the meaning of the other categories is diminished.

Figure 9 Distribution of pasture, grain and hay land use in the Delta and Yolo Bypass
Figure 10 Map of pasture, grain and hay land use in the Delta and Yolo Bypass
3.2.3 Crop Increases
In an effort to look at changes to Delta agriculture over time, the 2007 crop layer was compared in a GIS analysis with available DWR Land Use Surveys at the county-level from the mid-1990’s. The major crop shifts above 500 acres are recorded in the following Figure. The biggest shift in crops in the Delta has been the growth of over 15,000 new vineyards. The largest percent gain was from rice which was barely grown in the Delta in the 1990’s and has expanded to over 4,000 acres. This increase includes the growing of rice in places such as the Cosumnes River Preserve and the Yolo Bypass Wildlife Area to help provide habitat for wintering waterfowl and other water birds as well as support the financial sustainability of these public areas. Recently, more rice is being grown on private land in the Delta, presumably prompted by both higher rice prices and the desire of landowners and hunters to hunt over winter-flooded rice. Other large acreage gains were made by Sudan grass for animal forage and turf farms for urban markets. It is unclear whether the higher reported acreages of farmsteads and semiagricultural infrastructure is more due to the higher precision mapping in the more recent survey or an actual increase in homes and facilities in the Delta. Other crop increases of note include orchards such as cherries, olives and almonds. Based on the mapping data, olives appear to be a new crop in the Delta over the last decade.

Table 2 Major crop increases in the Delta and Yolo Bypass 1990’s – 2007

<table>
<thead>
<tr>
<th>CROPS</th>
<th>Change</th>
<th>DELTA</th>
<th>1990s Acres</th>
<th>2007 Acres</th>
<th>CATEGORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vineyards General</td>
<td>15,793</td>
<td>119%</td>
<td>13,234</td>
<td>29,028</td>
<td>VINEYARD</td>
</tr>
<tr>
<td>Rice</td>
<td>4,699</td>
<td>1448%</td>
<td>325</td>
<td>5,024</td>
<td>RICE</td>
</tr>
<tr>
<td>Corn</td>
<td>4,005</td>
<td>4%</td>
<td>99,114</td>
<td>103,119</td>
<td>FIELD CROPS</td>
</tr>
<tr>
<td>Sudan</td>
<td>3,892</td>
<td>220%</td>
<td>1,768</td>
<td>5,661</td>
<td>FIELD CROPS</td>
</tr>
<tr>
<td>Pasture, Grain &amp; Hay</td>
<td>2,974</td>
<td>102%</td>
<td>172,584</td>
<td>175,557</td>
<td>PASTURE + GRAIN and HAY</td>
</tr>
<tr>
<td>Pasture Turf Farms</td>
<td>2,201</td>
<td>192%</td>
<td>1,146</td>
<td>3,348</td>
<td>PASTURE</td>
</tr>
<tr>
<td>Semiagricultural Misc</td>
<td>2,097</td>
<td>1062%</td>
<td>198</td>
<td>2,295</td>
<td>SEMIAGRICULTURAL</td>
</tr>
<tr>
<td>Farmsteads</td>
<td>1,366</td>
<td>37%</td>
<td>3,707</td>
<td>5,073</td>
<td>SEMIAGRICULTURAL</td>
</tr>
<tr>
<td>Truck &amp; Berry General</td>
<td>1,098</td>
<td>63%</td>
<td>1,729</td>
<td>2,827</td>
<td>TRUCK &amp; BERRY CROPS</td>
</tr>
<tr>
<td>Cherries</td>
<td>895</td>
<td>145%</td>
<td>618</td>
<td>1,512</td>
<td>DECIDUOUS FRUITS AND NUTS</td>
</tr>
<tr>
<td>Olives</td>
<td>742</td>
<td>NEW</td>
<td>0</td>
<td>742</td>
<td>CITRUS AND SUBTROPICAL</td>
</tr>
<tr>
<td>Almonds</td>
<td>727</td>
<td>29%</td>
<td>2,520</td>
<td>3,247</td>
<td>DECIDUOUS FRUITS AND NUTS</td>
</tr>
</tbody>
</table>
3.2.4 Crop Decreases
The overall crop decreases in the Delta were larger than the crop increase with safflower shrinking to approximately a quarter of its former acreage. Sugar beets are unique in that they are the only major crop to virtually be eliminated in the Delta in recent times. Other major crop acreage drops include the loss of about a quarter of the tomatoes and one half of the asparagus in the study area. Beans(dry) also lost acreage and may indicate that there is less rotations of crop fields between corn, tomatoes and beans (dry) than in previous decades. Other major decreases include the loss of over 40% of the walnut orchards and over 60% of the sunflower fields. Orchards acreage decreased significantly for apricots, apples and pears with an aggregate loss of almost 3,500 acres.

Table 3 Major crop losses in the Delta and Yolo Bypass 1990's – 2007

<table>
<thead>
<tr>
<th>CROPS</th>
<th>Change</th>
<th>DELTA</th>
<th>1990s Acres</th>
<th>2007 Acres</th>
<th>CATEGORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safflower</td>
<td>-34,388</td>
<td>-72%</td>
<td>48,020</td>
<td>13,632</td>
<td>FIELD CROPS</td>
</tr>
<tr>
<td>Sugar Beats</td>
<td>-12,262</td>
<td>-96%</td>
<td>12,707</td>
<td>445</td>
<td>FIELD CROPS</td>
</tr>
<tr>
<td>Tomatoes</td>
<td>-12,115</td>
<td>-28%</td>
<td>43,325</td>
<td>31,211</td>
<td>TRUCK &amp; BERRY CROPS</td>
</tr>
<tr>
<td>Asparagus</td>
<td>-10,816</td>
<td>-49%</td>
<td>22,163</td>
<td>11,347</td>
<td>TRUCK &amp; BERRY CROPS</td>
</tr>
<tr>
<td>Idle (cropped within 3 years)</td>
<td>-10,339</td>
<td>-55%</td>
<td>18,813</td>
<td>8,474</td>
<td>IDLE</td>
</tr>
<tr>
<td>General Field Crops</td>
<td>-3,537</td>
<td>-41%</td>
<td>8,684</td>
<td>5,147</td>
<td>FIELD CROPS</td>
</tr>
<tr>
<td>Beans(dry)</td>
<td>-2,372</td>
<td>-27%</td>
<td>8,683</td>
<td>6,312</td>
<td>FIELD CROPS</td>
</tr>
<tr>
<td>Walnuts</td>
<td>-2,178</td>
<td>-41%</td>
<td>5,289</td>
<td>3,111</td>
<td>DECIDUOUS FRUITS AND NUTS</td>
</tr>
<tr>
<td>Sunflowers</td>
<td>-1,732</td>
<td>-63%</td>
<td>2,759</td>
<td>1,027</td>
<td>FIELD CROPS</td>
</tr>
<tr>
<td>Apricots</td>
<td>-1,453</td>
<td>-68%</td>
<td>2,128</td>
<td>674</td>
<td>DECIDUOUS FRUITS AND NUTS</td>
</tr>
<tr>
<td>Apples</td>
<td>-1,107</td>
<td>-51%</td>
<td>2,156</td>
<td>1,048</td>
<td>DECIDUOUS FRUITS AND NUTS</td>
</tr>
<tr>
<td>Grain Sorghum</td>
<td>-988</td>
<td>-60%</td>
<td>1,646</td>
<td>658</td>
<td>FIELD CROPS</td>
</tr>
<tr>
<td>Pears</td>
<td>-945</td>
<td>-13%</td>
<td>7,347</td>
<td>6,402</td>
<td>DECIDUOUS FRUITS AND NUTS</td>
</tr>
<tr>
<td>Melons, squash and cucumbers</td>
<td>-744</td>
<td>-14%</td>
<td>5,190</td>
<td>4,446</td>
<td>TRUCK &amp; BERRY CROPS</td>
</tr>
<tr>
<td>Potatoes</td>
<td>-427</td>
<td>-12%</td>
<td>3,483</td>
<td>3,056</td>
<td>TRUCK &amp; BERRY CROPS</td>
</tr>
</tbody>
</table>

3.2.5 Agricultural Winter Flooding
The active flooding of agricultural fields by land managers can serve many purposes including the decomposition of crop waste, attracting waterfowl use, and irrigating pasture or other crops. As part of the 2007 DWR Land Use Survey for the Delta, DWR staff mapped the amount of agricultural field ponding during a cloud free portion of late November and late December of 2006. For this analysis the late December time period was used since it was early enough in the winter to not have the active management of agricultural ponding not be confused with ponding due to rain events. Based on the precipitation shown in Figure 11, before the mapping performed on November 23, the Delta only had rain events less than 0.5 inches. In December the largest rain event was 1.5 inches and was large enough potentially to cause unmanaged flooding.

The original work by DWR excluded the northern Yolo Bypass. Ducks Unlimited extended the analysis to include the North Yolo Bypass subarea and did one group of additions in the Central Delta on Medford
Island to map active winter flooding of agricultural fields that were missed in the original DWR survey. Due to the temporal nature and varying depth or flooding, it is difficult to map. Additional work is needed to review this dataset to see if other areas in the Delta were missed by the DWR survey. One weakness of this analysis is that flooding was mapped in early winter 2006, rather than in winter 2007. The flooding actually measures the flooding of the harvested 2006 crops rather than the mapped 2007 crops. This method may be driven by available datasets. Ideally, this analysis would be redone so that the crop in winter-flooded fields could be directly determined. For this analysis it was assumed that the crop was the same in 2006 as was mapped in 2007.

Across the Delta and Yolo Bypass, there were a total of 11,000 acres of early winter-flooded agriculture shown in the map in Figure 12 with a breakdown by crop type and region. This flooding was very spatially aggregated with the bulk of the flooding occurring in two main areas, as mapped in Figure 13. The North Yolo Bypass is composed of flooded rice. The northern portion of the Central Delta and the southern portion of the Sacramento River are primarily flooded corn.

Figure 11 Cumulative precipitation at the Stockton Fire Station, winter 2006. CDEC, DWR
Figure 12 Major agricultural land uses with winter flooding, November 2006
Figure 13 Map of agricultural flooded fields, November 2006
3.2.6 Flood, Furrow or Broad Strip Irrigated

The NPS Workgroup requested agricultural information on the prevalence of flood, furrow or borders strip irrigation in the subareas of the Delta. In the DWR Land Use Survey, the irrigation method is listed, if known. The resulting data shows that 65% of the crops in the study area are irrigated with flood, furrow or borders strip irrigation. The crop specific data by subarea are shown in the table in Appendix B. The values range from near 100% use of these methods for rice, beans (dry) and sudan grass to virtually no use of these techniques on turf farms, olive orchards and potatoes. Other crops have low adoption of these techniques and also low demand for water throughout the growing season, such as safflower, wheat and vineyards.

4 Managed Wetlands

4.1 Subarea Distribution

California has lost the highest percentage, more than 91%, of wetlands of any state, with the majority of its loss in the Central Valley (Dahl, 1990). One of the goals of wetland managers is to maximize the number of birds and other wildlife that can be sustained by the existing patches of wetlands and to restore wetlands where possible. Land managers at state and federal refuges as well as private duck clubs now manage much of their wetlands to maximize wetland plant seed production to support the millions of migratory waterfowl and other birds that use local wetlands in the winter months. Managing wetlands includes controlling the application of water to optimize seed germination and to have the wetland flooded when birds arrive in the winter. Managed wetlands are comprised of seasonal wetlands and permanent wetlands. While seasonal wetlands only have water during the winter months, permanent wetlands have water year round or at least until mid-July when ducks and other wetland dependent birds have fledged their young. These managed areas are in contrast to unmanaged wetlands which are along water bodies and which flood episodically either through precipitation, runoff events or tidal action.

This study focuses on mapping managed wetlands for two reasons. First, the NPS Workgroup’s purview is managed wetlands. The open water allocations and floodplain contributions are the responsibility of another workgroup. Secondly, the amount and distribution of managed wetlands has not been uniformly mapped in the Delta and Yolo Bypass over the last decade. Before this study, the Central Valley Regional Water Quality Board used wetland acreages from the National Wetland Inventory (NWI) in their TMDL documents. This inventory misses much of the managed wetlands in the Delta either due to the old base date of the NWI or the lack of looking at the landscape at the right time of year to see seasonal flooding. An example of managed wetlands missed by the NWI is shown for the lower Cosumnes River in Figure 14 which shows managed wetlands in red and the NWI labeled wetlands in green shades.
The current effort to map managed wetlands focused on using the winter of 2011 as the base year with field boundaries primarily extracted from aerial photography in 2009 or 2010. The total acreage mapped was over 18,000 acres of managed wetlands. Current best management practices for wetlands include the goal of keeping 15% of a wetlands complex in semi-permanent or permanent wetlands for breeding birds. Since keeping shallow wetlands wet all year can encourage undesirable vegetation growth over a few years, the location of semi-permanent wetlands is often rotated every couple of years within a larger wetland complex, such as a wildlife area, preserve or refuge. Due to this rotating nature of semi-permanent wetland management, this mapping effort did not directly map semi-permanent wetlands. It is assumed that 10% of the managed wetland base is in semi-permanent wetlands that hold water through the winter and into the early summer. These areas are drained in July and dried out before flooding the following fall. Deeper permanent wetlands are assumed to make up 5% of the managed wetlands and hold water throughout the year.

As shown in Figure 15, the location of managed wetlands is most concentrated in the North and South Yolo Bypass with these two subareas containing approximately two-thirds of the managed wetlands in the Delta and Yolo Bypass. Large managed wetland areas exist in the Sacramento River subarea, including the Stone Lakes National Wildlife Refuge, Cosumnes River Preserve and some private duck clubs on Delta islands. Smaller managed wetlands are also found on private parcels in the Central Delta with few to no large managed wetlands in the West Delta, Marsh Creek or San Joaquin subareas as
shown in Figure 16.

Figure 15 Distribution and map of managed wetlands in the Delta and Yolo Bypass
Figure 16 Map of the major public managed wetland areas in the study area
4.2 Comparison to Unmanaged Wetlands

As part of previous meeting with the NPS Workgroup, members have asked how does the magnitude of managed wetlands relate to the amount of unmanaged wetlands in the Delta. For this comparison, the acreage of unmanaged wetlands was used from the National Wetland Inventory. To remove any double counting of wetland areas, a GIS approach was used to geographically subtract the areas that were mapped as managed wetland from the source NWI data set. The following figure shows that managed wetlands consist of about 43% of the mapped wetlands in the Delta and Yolo Bypass. Geographically, the unmanaged wetlands are more spread out across the study area as they often border many of the waterways that wind throughout the Delta and Yolo Bypass. A large concentration of unmanaged wetlands exists in the West Delta near Lower Sherman Island Wildlife Area. These wetlands would be subject to tidal action. Farther upstream, away from the tides, in the lower part of the South Yolo Bypass, some unmanaged wetlands are mixed with pasture lands. Many of the unmanaged wetlands in the Delta and along the Cosumnes River may also act as floodplains during high water events.

Figure 17 Comparison of the managed wetlands to unmanaged wetlands in the Delta and Yolo Bypass
5 Soil Characteristics

Two soil characteristics were discussed by the NPS Workgroup as correlating to higher methylmercury presence. It is still undetermined whether higher presence of organic matter or sulfur in soils has any causative relationship with methylation (Windham-Meyers and Ackerman, 2012); however, it was requested that this study should examine the mapping resources for these soil characteristics in the Delta and Yolo Bypass. One of the core questions on the effect of organic matter on methylation relates to not only the presence of organic matter, but to what forms organic matter is most labile, whether it is inputs from dissolved matter, particulates in runoff, wetland plants, algae, soil organic matter, or other sources.

The most detailed soil mapping resource collected throughout the Delta and Yolo Bypass is at the county level by the Natural Resources Conservation Service in their soil surveys. From these soil surveys, the percent soil organic matter is recorded or each soil component. This total soil organic percent can be summed by soil depth. Since the soil organic matter would only effect methylation at the soil-water interface, this study mapped the soil organic percent at zero to 10 cm. The following map shows the Delta’s peat soils as the highest concentration of organic matter with concentrations falling off sharply on the mineral soils of the foothills. The Central Delta, which contains the majority of the high organic matter soils, is the only subarea (besides the downstream West Delta) that currently meets its TMDL allocations.

The NPS Workgroup also requested any pertinent mapping resources on soil sulfur content. Some previous studies have shown that mercury and methylmercury can be complexed by thiol groups - sulfur containing groups (Skyllberg et al., 2003; Windham-Myers and Ackerman, 2012). Based on previous research by USGS and others in the Delta, the system does not appear to be sulfur limiting. This is in direct contrast to other ecosystems such as continental systems or high elevation systems (Windham-Myers, personal communication). Although no mapping resources are currently available, further inquiry on this subject could be directed to Carol Kendall at USGS, Menlo Park who has measured sulfate in the surface water throughout the Delta. In the Sacramento Valley upstream of the Delta, the geographic trend tends to be lower sulfate concentrations in water from the Sierras rather than water from the coast range or agricultural areas (Wanty et al., 2009). It is suspected that this west-east trend is muted by the time water is mixed in the Delta.
6 Summary

The Steering Committee of the NPS Workgroup requested a summary table of the main land uses that were reviewed in the workgroup’s knowledgebase document and management practice document that were previously submitted to the NPS Workgroup. These land uses included winter-flooded agriculture, other irrigated agriculture, seasonally managed wetlands, permanently managed wetlands, and unmanaged wetlands which includes tidal marsh. The winter flooded agriculture is dominated by rice and corn that are flooded for the entire winter. This acreage is a low estimate of water on the landscape and needs further research to refine its value.
Wetlands are categorized into three classes in the summary table. Seasonal Managed Wetland is flooded in the fall and the water level is managed to keep the field wet until the spring or early summer. A seasonal wetland is fully dried out over the later part of the summer. This category includes both seasonal wetlands that are drained in the spring to promote seed plant growth and seasonal wetlands where the water level is maintained into the early summer to provide habitat for breeding waterfowl. Permanent Managed Wetland has its water level managed the entire year and stays wet all year. The “Other Unmanaged Wetlands” category was derived from the National Wetland Inventory and contains wetlands that have no actively managed water management. This wetlands category contains tidal marsh and some riparian wetlands, but it rarely counts floodplain habitat. Based on a perfunctory examination of the NWI data, the majority of the acres in the “Other Wetlands (NWI)” category would be tidal marsh that is located along the many waterways throughout the Delta. These acres should be examined by another TMDL workgroup involved with unmanaged wetlands and open water.

Table 4 Major agricultural and wetland land uses in the region (*Unmanaged Wetlands, National Wetland Inventory)

<table>
<thead>
<tr>
<th></th>
<th>Central Delta</th>
<th>Sacramento River</th>
<th>San Joaquin River</th>
<th>Yolo Bypass South</th>
<th>Yolo Bypass North</th>
<th>West Delta</th>
<th>Cosumnes/Mokelumne River</th>
<th>Marsh Creek</th>
<th>Grand Total</th>
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<tbody>
<tr>
<td>Agriculture (Winter-Flooded)</td>
<td>4,322</td>
<td>1,916</td>
<td>8</td>
<td>757</td>
<td>4,236</td>
<td>35</td>
<td></td>
<td></td>
<td>11,274</td>
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<tr>
<td>Other Irrigated Agriculture</td>
<td>137,672</td>
<td>129,585</td>
<td>77,776</td>
<td>59,018</td>
<td>8,562</td>
<td>12,903</td>
<td>4,682</td>
<td>4,479</td>
<td>434,677</td>
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<td>Seasonal Managed Wetland</td>
<td>1,615</td>
<td>2,755</td>
<td>6,460</td>
<td>5,890</td>
<td>190</td>
<td>475</td>
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<td>Permanent Managed Wetland</td>
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<td>145</td>
<td>340</td>
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<tr>
<td>Other Unmanaged Wetlands *</td>
<td>6,000</td>
<td>2,600</td>
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<td>3,700</td>
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7 References


8 Appendix A Subarea Boundary Maps

Figure 19 North Yolo Bypass subarea
Figure 20 South Yolo Bypass subarea
Figure 21 Sacramento River subarea
Figure 22 Mokelumne/Cosumnes River subarea
Figure 23 West Delta and Marsh Creek subareas
Figure 24 Central Delta and San Joaquin subareas
9 Appendix B  Flood, Furrow or Broad Strip Irrigation
### Table 5 Flood, furrow or broad strip irrigation percentages by crop by subarea

<table>
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<tr>
<th>Crop Type</th>
<th>Grand Total</th>
<th>Central Delta</th>
<th>Sacramento River</th>
<th>San Joaquin River</th>
<th>Yolo Bypass-South</th>
<th>Yolo Bypass-North</th>
<th>West Delta</th>
<th>Cosumnes/Mokelumne</th>
<th>Marsh Creek</th>
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<tbody>
<tr>
<td>PASTURE, GRAIN AND HAY</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pasture Alfalfa &amp; mix</td>
<td>86%</td>
<td>94%</td>
<td>57%</td>
<td>100%</td>
<td>89%</td>
<td>97%</td>
<td>100%</td>
<td>100%</td>
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<td>Pasture Mixed</td>
<td>75%</td>
<td>75%</td>
<td>70%</td>
<td>84%</td>
<td>80%</td>
<td>100%</td>
<td>44%</td>
<td>55%</td>
<td>60%</td>
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<td>General Grain and Hay</td>
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<td>56%</td>
<td>41%</td>
<td>20%</td>
<td>5%</td>
<td>0%</td>
<td>18%</td>
<td>20%</td>
<td>5%</td>
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<tr>
<td>Pasture Native</td>
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<td>6%</td>
<td>96%</td>
<td>14%</td>
<td>47%</td>
<td>31%</td>
<td>11%</td>
<td>56%</td>
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<td>Wheat</td>
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<td>Pasture Turf Farms</td>
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<td>General Pasture</td>
<td>69%</td>
<td>35%</td>
<td>75%</td>
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<td>75%</td>
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<td>TOTAL</td>
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# Table 6 Crop specific irrigation types, frequency and water needs

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<th>Avail</th>
<th>Region</th>
<th>Irrigation Type*</th>
<th>Irrig2</th>
<th>Irrigation Start</th>
<th>Irrig End</th>
<th>Frequency</th>
<th>Total Water (AcIn)</th>
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<td>Yes</td>
<td>Delta</td>
<td>Flood</td>
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<td>September</td>
<td>1</td>
<td>54</td>
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<td>October</td>
<td>March</td>
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</tr>
<tr>
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<td>Drip</td>
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<td>Bi-weekly</td>
<td>42</td>
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<td>Sacramento Valley</td>
<td></td>
<td>May</td>
<td>May</td>
<td></td>
<td></td>
<td>6</td>
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<tr>
<td>Sudan</td>
<td>No</td>
<td>San Joaquin Valley South</td>
<td>Sprinkler</td>
<td>June</td>
<td>August</td>
<td></td>
<td>5</td>
<td>20</td>
</tr>
<tr>
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<td>Sacramento Valley</td>
<td>Furrow</td>
<td>May</td>
<td>August</td>
<td></td>
<td>7</td>
<td>32</td>
</tr>
<tr>
<td>Tomatoes, processing</td>
<td>Yes</td>
<td>Sacramento Valley</td>
<td>Sprinkler</td>
<td>April</td>
<td>July</td>
<td></td>
<td>9</td>
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</tr>
<tr>
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<td>Furrow</td>
<td>March</td>
<td>December</td>
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<td>Melons, squash, cucumbers</td>
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<td>Potatoes (sweet)</td>
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<td>August</td>
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</table>

Source: Crop specific surveys from University of California Cooperative Extension - Sample Costs to Produce. [http://coststudies.ucdavis.edu/](http://coststudies.ucdavis.edu/) (assessed May 7, 2012)

* Type = sprinkler, microsprinkler, drip, flood, furrow
A Synthesis of Mercury Science to Support Methylmercury Control Studies for Delta Wetlands and Irrigated Agriculture

Prepared by: L. Windham-Myers\textsuperscript{1} and Josh T. Ackerman\textsuperscript{2}

\textsuperscript{1}U.S. Geological Survey – National Research Program, \textsuperscript{2}U.S. Geological Survey - Western Ecological Research Center

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### 4. Agricultural Lands

#### 4.1 Case studies in flooded agricultural lands (rice, wild rice, summer fallow)

- **Yolo Bypass Wildlife Area (SWRCB, Prop 40)**
- **Twitchell Rice Project (DWR TW-08-03)**
- **Cosumnes River Preserve (EPA 319h and ERP-10-014)**

#### 4.2 Case studies on lands with irrigated crop lands

- **Farmed Islands (CVRWQCB)**

#### 4.3 Seasonal and spatial processes

### 5. Natural Hydrology Systems

#### 5.1 Floodplains

- **Cosumnes River Preserve (USGS, ERP-02-P40)**

#### 5.2 Brackish-Fresh Tidal Marsh

- **Browns Island (ERP-00-G01)**
- **Liberty Island (BREACH III, ERP-97-C05)**
- **Tidal Marshes of the Petaluma River (ERP-02-P62)**
- **Suisun Marsh (ERP-99-B06)**

### 6. Synthesis - Knowledge Base, Knowledge Gaps, and Summary

#### 6.1 Knowledge Base

#### 6.2 Knowledge Gaps

#### 6.3 Possibilities for post-processing data to infer MeHg loads

#### 6.4 Summary

### 7. Application of Knowledge Base toward Development of Methylmercury Control Studies

### 8. Acknowledgments

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Executive Summary
The Sacramento-San Joaquin Delta (Delta) provides habitat for warm and cold-water species of fish and their associated aquatic communities along with valuable wildlife habitats. Significant beneficial uses of the Delta, including wildlife and fish habitat and recreation, are impaired due to elevated methylmercury (MeHg) levels in fish. Mercury (Hg) is a toxic metal that has no known beneficial function in living organisms. MeHg is a form that bioaccumulates in food webs and is a potent neurotoxin. State regulators recently developed a total maximum daily load (TMDL) regulatory control program to insure that discharges into all waters of mainstem rivers and tributaries entering the Sacramento-San Joaquin River Delta, and all waters of the California Delta, have acceptable or lower concentrations of aqueous MeHg. Recent efforts in conceptual modeling of mercury cycling (e.g. Delta Regional Ecosystem Restoration Implementation Plan, DRERIP-MCM, Alpers et al. 2008) and in literature produced since DRERIP suggest some patterns and pathways that may be important in controlling MeHg production and export in managed wetlands, agricultural lands and naturally flooded wetlands of the Delta. Key findings include:

1) Within-wetland storage and degradation of MeHg can be increased by limiting water flowthrough.
2) Restricted flow may be used to effectively limit export of MeHg, but may enhance in situ bioaccumulation in aqueous foodwebs.
3) The wetting of previously dried wetlands promotes the concurrent availability of geochemical precursors to microbial MeHg production – reactive Hg(II), ferric iron (Fe(III)), sulfate (SO$_4^{2-}$), and labile carbon (e.g., acetate).
4) The wetting of previously dried wetlands often generates an initial pulse of MeHg release from sediments to surface waters.
5) In seasonally flooded wetlands, annual budgets of MeHg export are dominated by pulsed, sequential events that lead to “hot moments” of MeHg production and release.
6) Beyond patterns of MeHg production, aqueous MeHg concentrations show both diel and seasonal temporal variability, due to photochemical processes and vegetation-driven transpiration.
7) MeHg concentrations in biota also vary significantly with season, and the breeding season is when wildlife populations are most vulnerable to the effects of MeHg.
8) Temporally, available carbon may be the ultimate regulator of MeHg production in seasonal wetlands, as availability of Hg, S, and Fe can cycle with environmental conditions but the carbon-based energy available for microbial activity is consumed and lost.
9) Sites of high THg in water and sediment are not necessarily sites of high MeHg in water and sediment.
10) Quantification of particulate and filter-passing phases of aqueous MeHg, and correlation of these analytes with other geochemical parameters provide insight into the processes controlling MeHg concentrations.
11) Wetlands tend to have higher MeHg concentrations in biota than in surrounding water bodies, indicating that wetlands are primary sites of MeHg production and bioaccumulation.
12) MeHg concentrations in biota breeding within the San Francisco Bay and Delta are considered elevated compared to related populations, and effects of MeHg on avian reproduction, body condition, and behavior have been documented.
Data, reviewed herein, from multiple field studies in the Delta over the past decade suggest that wetland habitats with episodic wetting and drying (such as rice crops, seasonal wetlands, winter-flooded agricultural fields and wetland floodplains) are likely to promote MeHg production and export. Rather than widespread regional source reduction for inorganic mercury, management of hydrology and carbon during pulsed flooding events may provide the most effective reduction of MeHg contamination to water bodies and biota. The MeHg control measures described herein focus on decreasing within-wetland MeHg production, increasing MeHg degradation and sequestration, and reducing aqueous export of MeHg loads in tailwater. Herein we synthesize current knowledge of Delta MeHg dynamics suggest effective management practices in managed wetlands, irrigated agriculture, and naturally flooded wetlands. We further identify knowledge gaps that are necessary for quantitative modeling approaches (e.g. Dynamic Mercury Cycling Model, D-MCM; EPRI 2009) and should be addressed in accordance with future monitoring plans and control studies.
1. Overview

This synthesis is a natural extension of the Delta Regional Ecosystem Restoration Implementation Plan (DRERIP) Mercury Conceptual Model (hereafter DRERIP-MCM; Alpers et al. 2008). Recent process-based studies and monitoring data (2003-2011) have improved our understanding of processes that influence methylmercury (MeHg) dynamics in the Sacramento–San Joaquin Delta (Delta) and larger San Francisco Bay (SFB) ecosystem. The DRERIP-MCM (Figure 1) provides a mechanistic approach to understanding MeHg abundance and biotic impacts using a driver-linkage-outcome approach. Because the primary goal of this synthesis is to support identification, development, and study of management practices that reduce MeHg loads to the Delta, we focus on processes that influence MeHg concentrations in sediment and water. Thus, this synthesis focuses on DRERIP-MCM’s Submodel 1 Mercury Methylation, which includes both a) delivery and formation of reactive (inorganic) mercury and b) microbial transformation of reactive, inorganic mercury (hereafter “reactive Hg(II)”) to organic methylmercury (MeHg) (Figure 2). Principal intermediate outcomes of DRERIP-MCM’s Submodel 1 are MeHg concentrations in water and sediment. While useful for monitoring MeHg dynamics, these outcomes are only important because of their influence on biota. The subsequent submodels in DRERIP provide a mechanistic conceptual model by which water and sediment MeHg concentrations influence bioaccumulation (Submodel 2), and how resulting biotic concentrations may have health effects in humans and wildlife consuming those biota (Submodels 3 and 4, respectively).

Figure 1. Linkage of submodel compartments of the DRERIP-MCM from net MeHg production (Submodel 1) to MeHg bioaccumulation (Submodel 2) to MeHg impacts on humans and wildlife (Submodels 3 and 4, respectively). From Alpers et al. 2008.

Because the focus of this document is on scientific knowledge associated with management practices for reducing aquatic loading of MeHg from specific habitats to Delta waters, there is only limited discussion of the effect of management practices on biotic MeHg concentrations. Biotic MeHg impacts are the primary driver for setting TMDL allocations (Wood et al. 2010), and thus we recognize the narrow focus of this synthesis for guiding control studies.

In keeping with the process-based approach of DRERIP, we focus first (Section 2) on peer-reviewed published literature on mechanistic understandings of MeHg production, transport, and
degradation pathways. We provide background on biotic MeHg uptake and impacts, and further, we recommend including biotic endpoints for a comprehensive monitoring study plan. Sections 3-5 focus explicitly on recent literature from Delta habitats that include managed wetlands, agricultural lands, and naturally flooded lands (floodplains and marshes). The purpose of Sections 3-5 is to illustrate patterns and pathways observed through recent Delta studies, and through this summary, guide readers towards specific studies of interest regarding habitat types and/or processes of concern. DRERIP-MCM (Alpers et al. 2008) remains the primary source of information – this synthesis builds on DRERIP with new peer-reviewed literature available since 2008, new data from regional monitoring and process-based studies (2003-2011), and a specific focus on MeHg production and fluxes in managed wetlands and irrigated agriculture.

The uncertainty and importance of stated processes are also highlighted where possible, for use in developing a science plan to evaluate the landscape-scale decisions and the effectiveness of site-specific management practices. After synthesizing the main findings and implications in Section 6, we take a first step at applying this knowledge base to specific questions posed by the SWRCB, to suggest how the findings herein may be useful to planning efforts (Section 7).

Figure 2. Drivers, linkages (processes) and outcomes for mercury methylation and export for the Sacramento-San Joaquin Delta. DRERIP-MCM Submodel #1 from Alpers et al. 2008.
2. Methylmercury Production, Transport, and Degradation

The DRERIP Mercury Conceptual Model (DRERIP-MCM, Alpers et al. 2008) was developed, along with a broad range of conceptual ecosystem models, to aid in determining management options for limiting MeHg exposure in response to Delta wetland restoration practices (http://www.dfg.ca.gov/ERP/conceptual_models). In this literature review and synthesis, we apply the principles of DRERIP-MCM and new knowledge from literature and recent field studies for use in designing MeHg control studies. We seek to assess the current understanding and future research needs for development of effective management practices in managed wetlands, irrigated agriculture, and naturally flooded wetlands proposed for restoration. We recognize that “one size does not fit all”, and that the effectiveness of a given strategy will be influenced by current conditions and adaptive management. We also recognize the need of regulators to apply parcel-based strategies rather than a watershed approach within this hydrologically complex river-estuary continuum. As such, here in Section 2 we discuss the extent to which fundamental processes of MeHg production, import, and export are understood and how they may vary among different land use types, different management scenarios and different environmental conditions. Taking a holistic approach, we examine the relative influence of hydrologic, chemical, and biologic interactions that may be altered by management practices.

As the importance of wetlands in the biogeochemical cycling of Hg has become more widely recognized in recent years (see Selin et al. 2009), attention has turned towards examining the contribution of specific wetland types to overall Hg cycling and how this mosaic of wetland types affects Hg cycling at the scale of the entire Delta ecosystem (Slotton et al. 2002; Slotton and Davis 2008; Marvin-DiPasquale et al. 2003, 2007; Yee et al. 2007). Variations in salinity, hydrology, and vegetation result in a diverse mosaic of wetland types and make the Delta both interesting and challenging to study. Dense communities of emergent vascular plants are a typical feature of wetlands. Sediments in these habitats tend to be comparatively organic rich, due to the continuous input of above- and below-ground biomass from primary production, and often exhibit high rates of microbial activity associated with the ongoing decay of senescent vascular plant material. As such, microbial processes associated with the cycling of trace metals are often elevated in wetlands, compared to nearby non-wetland aquatic habitats such as open waters (Marvin-DiPasquale et al. 2003). There is a growing recognition that wetland environments can be particularly active zones for the conversion of inorganic divalent mercury (Hg(II)) to the more toxic organic MeHg form (Zillieux et al. 1993, Krabbenhoft et al. 1999), a process largely mediated by sediment bacteria (Gilmour et al. 1992). Although biological and geochemical controls on this process are understood in broad terms, the specifics are less clear, and the variation in mercury speciation and MeHg production rates expected across different wetland types is largely unknown. Further, an unexpected preliminary result of recent research is the finding that not all wetlands in San Francisco Bay or the Delta are elevated in biotically derived methylmercury (Davis et al. in review). Further, a Delta-wide geospatial analysis of available data has indicated that there may not be an overall correlation between wetlands and elevated methylmercury in biota (Melwani et al. 2007).

The San Francisco Bay and Delta has undergone extensive research on temporal and spatial patterns of mercury contamination in sediment, surface waters, and biota, largely through organized efforts (SWRP 1997, Wiener et al. 2003). At local scales, patterns of sediment MeHg concentrations have been less temporally variable than water concentrations, and have not
significantly predicted fish tissue or surface water MeHg concentrations (Heim et al 2007, Marvin-DiPasquale et al 2007). Fish tissues, which can serve as an integrated measure of Hg exposure, have shown a spatial pattern of lower values in the central and western Delta and greater values in tributaries such as the Cosumnes and Mokuleme Rivers (Slotton et al 2002, Slotton and Davis 2008, Melwani et al 2009). Aqueous MeHg concentrations in surface water of the central Delta are also often lower than Delta tributaries and neighboring subbasins, including the Yolo Bypass and Cosumnes River (Foe 2003, Marvin-DiPasquale et al 2007). Despite expectations that Hg methylation would be promoted in slow shallow waters of the Delta, preliminary mass balance calculations suggest that only 40% of the Delta’s MeHg load comes from within the Delta – roughly 20% from wetlands and 20% from open water sediments. The bulk of MeHg in the Delta appears to be supplied through river flows, especially the Sacramento River (Foe et al. 2008). Further, this mass balance indicated a net loss of methylmercury in water as it flows through the Delta (Foe et al. 2008), suggesting that the Delta serves annually more as a sink for MeHg than as a source. The main causes of the MeHg loss are thought to be photodemethylation and sedimentation (Byington et al 2007, Stephenson et al. 2008), with varying importance across the Delta. Particle tracking suggests that photodemethylation is more important in the central Delta (Stephenson et al. 2007), but given the seasonal variability (Gill 2008a,b) and extreme complexity of the SFB-Delta flows, further measurements are warranted. Another possible contributing factor to the lower levels of methylmercury in the central Delta is high concentrations of reduced sulfur in benthic sediments, which may serve to make reactive forms of Hg less available to the methylation process (Marvin-DiPasquale et al. 2007).

A growing set of literature on Hg cycling processes across diverse watersheds is indicating a range of important environmental conditions that influence MeHg transport and transformation – including hydrologic exchanges, organic compounds, particulate binding and biogeochemical precursors. Actual transport and transformation processes for MeHg have been measured in several studies in the Delta, as reported herein. By comparing processes among habitats and between different temporal and spatial scales, some dominant patterns and pathways are emerging for Delta wetlands. We report below basic expectations of the DRERIP conceptual model and incorporate newly published research from the Delta, San Francisco Bay (hereafter SFB), and other relevant ecosystems.

2.1. Methylmercury Production within Delta

2.1.1 Inorganic Mercury Inputs

The transport of HgT (total Hg, all chemical forms) to and within the Delta is a unique case study compared to other mercury-impaired water bodies. In order of greatest HgT load contribution first, the mix of Hg sources to the Delta over the last century include 1) sediment and runoff from Sierran drainages contaminated with legacy Hg from gold mining activities, 2) sediment and runoff from bedrock-derived Hg and mineral springs, and 3) atmospheric Hg deposition from a wide range of sources, both natural and anthropogenic (e.g. forest fires, industrial combustion; see Domagalski 2001). As shown in Table 1, these sources are likely to range widely in their role as precursors to MeHg formation in the Delta. The isotopic signature of HgT has recently been used to assess the dominant sources of Hg in sediments along the Delta-to-SFB continuum, and through time by depth (Gehrke et al. 2010). Upstream mines, whether for mercury or gold, are the dominant source of sediment Hg from the Delta tributaries down to the Delta and SFB. Hg
released through placer-mining of gold dominates the sediment HgT pool in Cosumnes River habitats, whereas in the Yolo Bypass, δ²⁰²Hg isotope signatures suggest a combination of this metallic placer-mining source with Coast Range cinnabar sources (30% versus 70%, respectively). Regions of high HgT also appear to be sourced from natural erosion of sediments rather than from local industrial sources. Further, the depth profiles observed are consistent with other historic datasets and with expected mining sources (Conaway et al. 2008), supporting the fidelity of depth profiles as historical records of Hg loading (Suchanek et al. 2008).

2.1.1.1 Watershed Supply
Sedimentary transport of Hg is historically and currently the greatest source of Hg to the Delta ecosystem (Domagalski et al. 2000; Foe et al. 2008; Louie et al. 2008). Watershed monitoring of suspended sediment concentrations (DTMC 2002), and patterns of deposition and resuspension in the Delta suggest that over 90% of Delta sediment is en route from Sierra Nevada tributaries to the ocean (Conomos et al. 1977; Singer 2008), but that erodible pools have been declining since major dams trap sediments in most drainages (Schoellhamer 2011). Fine grained sediment fractions are disproportionately associated with high HgT concentrations (Domagalski 1998), and their movement may be the primary ongoing source of Hg within the Delta. In the Yolo Bypass, Sacramento River overflows dominate suspended sediment loads, but Cache Creek dominates the HgT load (Louie et al. 2008; Domagalski et al. 2004a). Episodic deposition and resuspension of sediment in the Yolo Bypass show that pulsed sediment storage and erosion (Springborn et al. 2011) have a regional influence on tributary HgT inputs to the Delta.

2.1.1.2 Atmospheric Sources
Atmospheric sources of mercury are poorly understood in the Delta, but recognized as an input to the Sacramento River Basin and SFB-Delta (Domagalski et al. 2000). No atmospheric deposition stations are sited in the Delta proper, but air-water flux has been measured (Gill 2008b) and patterns of deposition can be notable at selected locations (Conaway et al. 2005, 2008). While the east coast of the U.S. is dominated by wet deposition, the west coast is dominated by dry deposition, which is more difficult to model and measure (Gill 2008b). Further, Weiss-Penzias et al. (2012) demonstrated highly elevated MeHg concentrations in fog, 34-fold greater than expected from rainwater alone. Modeled deposition using EPA’s Community Multi-scale Air Quality shows high, and previously unaccounted for, rates of deposition in western states (Jaffe et al. 2005). Conversion to reactive gaseous mercury (RGM) by the presence of ozone can double deposition rates. This pool of Hg(II) may be transported into the Delta in aqueous or particulate phases. In the absence of local geologic sources, fish MeHg concentrations in Sierra Nevada lakes may be driven by atmospheric deposition (Davis et al. 2008). Atmospheric contributions from local versus regional (refineries and power plants) versus global sources are speculative, and currently only represented in open-air deposition measurements, neglecting the role of vegetation-facilitated deposition, a well-defined vector in many eastern U.S. studies (Grigal 2002).

The importance of atmospherically deposited Hg in MeHg bioaccumulation within the Delta is unclear but potentially important. One anomaly for the Delta was isotopic Hg signatures in silversides. While d¹⁹⁹Hg signatures were consistent with local sediment sources in SFB subhabitats, this relationship became less consistent in Suisun Bay and toward the Delta (Gehrke et al. 2011), suggesting a mix of Hg sources to biotic MeHg uptake other than local sediment.
Table 1. Relative magnitude, reactivity, and importance of mercury sources to methylmercury production to the Delta, revised from DRERIP-MCM (Alpers et al., 2008)

<table>
<thead>
<tr>
<th>Source</th>
<th>Hg Speciation</th>
<th>Magnitude of Total Hg Load to Delta</th>
<th>Reactivity (susceptibility to methylation)</th>
<th>Importance to MeHg Production in Delta</th>
<th>Uncertainty</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRIMARY SOURCES</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atmospheric</td>
<td>Hg(II)</td>
<td>L</td>
<td>H</td>
<td>M</td>
<td>H</td>
<td>1</td>
</tr>
<tr>
<td>Urban runoff</td>
<td>Various</td>
<td>L</td>
<td>M</td>
<td>L</td>
<td>H</td>
<td>1,2</td>
</tr>
<tr>
<td>Wastewater</td>
<td>Various</td>
<td>L</td>
<td>M</td>
<td>L</td>
<td>L</td>
<td>1,2</td>
</tr>
<tr>
<td>Mercury mines</td>
<td>HgS</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>M</td>
<td>1,3</td>
</tr>
<tr>
<td>Gold mines</td>
<td>Hg(0)</td>
<td>H</td>
<td>L – M</td>
<td>H</td>
<td>M</td>
<td>1,3</td>
</tr>
<tr>
<td>SECONDARY SOURCES</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resuspension</td>
<td>Various</td>
<td>H</td>
<td>L – M</td>
<td>H</td>
<td>M</td>
<td>1,4,5</td>
</tr>
</tbody>
</table>


2.1.2 Inorganic Mercury Speciation within the Delta

The relative importance of different inorganic Hg pools to MeHg production may be a function of reactivity (susceptibility to methylation). Not all Hg is equally available to cross bacterial cell membranes and thus be subject to methylation. Availability for biologic uptake is affected by speciation of the Hg atom, chemical binding sites associated with matrix properties (water, sediment, and organic matter), the temporal dynamics of speciation (diel, annual, and episodic), and the kinetics of chemical versus physical transport mechanisms. High rates of MeHg production and aqueous MeHg export can be found in sites of high or low HgT; speciation of Hg may be a primary determinant of MeHg dynamics.

2.1.2.1 Mercury Speciation

The primary Hg species found are elemental Hg(0), divalent Hg(II), or bound. Bound species may be either in an organic compound, such as MeHg (monomethylmercury) or dimethylmercury ((CH₃)₂Hg), or an inorganic compound such as HgS (mercuric sulfide). With a low boiling point, Hg(0) vaporizes at naturally occurring environmental temperatures acting as an inert gas with little affinity for bonding. If oxidizing chemicals are present (Br, Cl, ozone), Hg(0) may become charged or oxidized to divalent Hg(II). Hg(II), also known as reactive gaseous mercury (RGM) is considered “sticky” with a strong affinity for binding to negatively charged compounds and is capable of being transported across cell membranes under specific binding conditions. The ability of Hg(II) to cross cell membranes may be enhanced by the formation of neutral sulfides (Benoit et al. 1999; Drott et al. 2007). In contrast, the binding of Hg(II) to sulfide or organosulfur-rich particles may subject Hg to colloidal or particulate fluxes driven by advection. HgS compounds, such as cinnabar or metacinnabar in processed mining ores, are particularly insoluble forms of Hg (see review by Gerbig et al. 2012). The mobility and reactivity of a given Hg atom thus is strongly influenced by its chemical form and kinetic dynamics with the surrounding matrix of sediment and water. Thus, both the source of contamination (e.g., Hg(0) from placer gold mining, HgS from hardrock mercury mines) and the environmental conditions that surround the Hg atom are important to its relative reactivity, and ultimately to its toxicity.
2.1.2.2 Water and Sediment Properties

Mercury speciation in sediments and water varies strongly with biogeochemical conditions such as organic matter quality and redox potential (Ravichandran 2004). The kinetics of binding, flocculation, and precipitation determine phase and availability. Ionic, sulfidic, and organic compounds in aqueous conditions may ultimately limit microbial uptake of Hg. These conditions can change dramatically over time and space, altering the rates at which mercury can be taken up by methylating bacteria, and ultimately converted to MeHg (e.g., Marvin DiPasquale et al., in review). Cinnabar, the primary Hg-sulfide mineral found in Hg mining ores, is particularly insoluble in deionized water, but rates of dissolution can be enhanced in the presence of organic matter (Ravichandran et al., 1998, 1999, Waples et al. 2005) or sulfur-oxidizing bacteria (Adam Jew, pers. comm.).

Speciation processes (such as Hg reduction, oxidation, volatilization, and binding) are strongly influenced by environmental factors such as temperature, radiation, and water quality (organic and inorganic constituents). Reduction of oxidized Hg(II) to elemental Hg(0), the insoluble and volatile form, is an important sink for reducing Hg bioavailability. Biological reduction of Hg has been found in cells through mer-operons (merA; Barkay et al. 2003) and chemically in sediments and pore water through reduced humic compounds (Allard and Arsenie, 1991). In open water environments, however, photochemistry is particularly important, as penetrating ultraviolet wavelengths alter electron transitions and reduce Hg to its gaseous elemental form (Sellers et al. 1996). The rate at which this Hg(0) is reoxidized back to Hg(II) controls its rate of volatilization out of the water column. Reduction and oxidation are in continuous play and the relative direction of Hg speciation can change daily (diel patterns of solar radiation) or seasonally (environmental patterns of redox, including iron availability, etc). Naturally occurring cinnabar, and to a lesser extent calcine metacinnabar (reprecipitated mercuric sulfides) are highly insoluble in deionized water but may be oxidized through chemical (Fe(III) and Cl; Han et al. 2010), physical (solar radiation; Gustin et al. 2002), and biological (Adam Jew, pers. comm.) processes.

2.1.2.3 Organic Matter

The quantity and quality of organic matter plays a critical role in the production of MeHg. Organic matter in wetlands may be sourced from internal productivity of wetland plants and algae, or from inputs of terrestrial runoff. Regardless of organic matter’s provenance, wetland soils are typically high in organic matter due to accretion, slow decay, and fermentative processes. The presence of dissolved organic matter (DOM) strongly affects the inorganic speciation of Hg, which otherwise could be well predicted thermodynamically by state variables such as pH, temperature, and redox status. The influence of DOM on MeHg production is a function of its concentration and quality. High energy spectroscopic studies of light absorption and fine structure (e.g. EXAFS, XANES) suggest that Hg-binding to organic carbon is primarily through thiols and sulfhydryl functional groups (Skyllberg et al. 2006). As reviewed by Gerbig et al. (2012), DOM has a strong affinity for Hg in solution and predominantly increases the mobility of Hg in aqueous environments. Both low molecular weight organic acids (Slowey et al. 2005) and hydrophobic and aromatic carbon compounds (Haitzer et al. 2003) are capable of mobilizing soil Hg as colloidal or dissolved compounds. The strong association of DOM and Hg is common across landscapes – as DOM increases over time or among habitats, aqueous Hg often increases, as well. Whether the relationship between aqueous Hg and DOM is causative or correlative, the relationship can be
exploited to assess aqueous Hg concentration and fluxes at a lower cost than direct monitoring of aqueous Hg.

Solid-phase organic matter (SOM, or soil organic matter) also has strong interactions with Hg speciation and mobility. Binding sites on sulfide and thiol (organic sulfur) groups within organic (Skyllberg et al. 2000) and peat soils (Nagy et al. 2011) may be a long-term sink for Hg under stable conditions. In fact, even as peat diagenesis concentrates Hg pools over time (Biester et al. 2007), depth profiles retain patterns of Hg loading in wetland environments from ombrotrophic bogs (Hermanns and Biester 2011) to riverine peatlands, including the Delta (Alpers et al. 2008b).

Within the Delta, the role of DOM in MeHg cycling was studied with a 2004 amendment to the project *Dissolved Organic Carbon Release from Delta Wetlands: Amounts, Alterations, and Implications for Drinking Water Quality and the Delta Foodweb* (ERP-00-G01) titled *Mercury Release from Delta Wetlands: Facilitation and Fluxes*. In particular, DOM varied strongly in character, between different seasons and subhabitats (e.g. tidal marsh, openwater, tributary), and the nature of the DOM strongly influenced mercury binding and photochemistry. Specifically, aromatic wetland-sourced DOM promoted mercury release from sediments, a process that was enhanced in lower ionic strength waters, as that allowed mobilization of colloidal mercury (Suess and Aiken, unpublished data). Use of high frequency in situ measurements of turbidity and chromophoric DOM to monitor Hg and MeHg are described by Downing et al. (2009) and Bergamaschi et al. (2011).

2.1.2.4 Particulate Transport within the Delta
Transformation between dissolved and solid phases of Hg is critical to Hg mobility. Watershed Hg loads are typically dominated by suspended particulates. Some data suggest that erosion and resuspension of historic sediments provide the greatest pool of Hg to the Delta (Domagalski 1998). In contrast, Stephenson et al. (2008) suggest that less than 3% of the HgT load in the Delta is from sources within the Delta. As coarse-grained sediments may be restricted to river channels and other sites of turbulent flow, fine-grained sediments are more abundant within delta open waters and wetland environments (Schoellhamer et al 2007). Due their relatively high surface area, fine-grained sediments are preferentially laden with Hg (Hunerlach et al. 2004). Based on historic estimates of Hg use in the Sierra Nevada and calculated pools in current mine tailings piles, it appears that a very small fraction of the residual gold mining Hg has made its way out of the Sierra Nevada into the Delta (Michael Singer, personal communication). As incision continues on these historic deposits, Hg on sediment may be a long-term source of Hg to the Delta, and primarily released during episodic flooding (Singer et al. 2008).

Rather than simply a source of Hg, particulates and colloids in the water column also provide surfaces for adsorption of aqueous mercury (e.g. Babiarz et al. 2001), thus possibly promoting sequestration and settling of Hg in particulate forms. This concept is quantified as a partitioning coefficient, which is the ratio of particulate to aqueous phase mass at equilibrium. Ecosystems higher in DOM concentration often have lower partitioning to solids (e.g. Dittman et al. 2010; Brigham et al. 2009), and thus have higher benthic Hg fluxes (Wallschlager et al. 1996). However, the partitioning coefficient can change quickly (Babiarz et al. 2001), even over diel scales in lake water (e.g. Naftz et al. 2011) and between ebb and flood in tidal channels (Bergamaschi et al. 2011).
Short-term hydrologic events can be important drivers, even at the landscape scale (Shanley et al 2005).

Further, particulates can represent a significant flux of MeHg through the Delta, particularly during turbulent flows in winter. The hydrologic model RMA-2 (see DRMS 2007) and its particle tracking submodel were applied to characterize transport and losses of MeHg within the Delta from its major tributaries. Using a mass balance approach, Stephenson et al. (2008) estimated that particle settling is a dominant loss term for aqueous MeHg exported to SFB, and important to Central and South Delta outflows only in winter months (Oct-Dec), whereas photodemethylation losses of Hg dominated during the spring and summer months.

### 2.1.3 Methylation of Mercury(II) within Delta

The extent to which Hg in the Delta is transformed to MeHg is largely unknown. Mass balance models suggest that less than 40% of the MeHg in the Delta surface waters is produced internally (Foe et al. 2008; see *Transport, Cycling, and Fate of Mercury and Monomethyl Mercury in the San Francisco Delta and Tributaries, An Integrated Mass Balance Assessment Approach* (ERP-02-C06-a), of which approximately half is produced from benthic sediments and half is produced by Delta wetlands. Yet, with high riverine inputs, the Delta is an annual net sink for MeHg as sediment deposition and photodemethylation losses exceed benthic flux and water column methylation (Foe et al. 2008). In this highly leved water system, the currently low rates of tidal and floodplain exchange may reduce the importance of wetlands (DRMS 2007), but they may be particularly important sources in wetland-rich subwatersheds and over time, with ongoing restoration activities (Bergamaschi et al. 2011). Further, row crop agriculture acreage and irrigation practices are subject to change, thus altering their relative role in the Delta MeHg budget. Methylation, a natural process, can occur in any ecosystem, but net methylation requires that rates of MeHg production are greater than rates of MeHg degradation. Further, for a site to export MeHg, it needs to be mobilized through in advection of surface or subsurface waters, which may vary over time.

#### 2.1.3.1 Microbial mercury(II) methylation

Methylation – the process by which an element (in this case, Hg) is bound with a methyl-group (CH₃) – can occur with or without biological intervention. Under laboratory conditions, pH, temperature, and ionic strength regulate the rates of abiotic methylation (Celo et al. 2006), and evidence exists that abiotic Hg(II) methylation is measurable in the water column of some lakes at high altitude (Ribeiro-Guevara et al. 2008) and high latitude (Siciliano et al. 2005). However, abiotic methylation has never been identified in temperate surface waters such as the Delta or SFB, as benthic and wetland sources of MeHg probably far outweigh any abiotic pathways (Choe et al. 2004).

The kinetic and biochemical process by which microbes methylate mercury remains a mystery. This fundamentally important process, in which Hg is attached to a methyl-group (CH₃), may be a passive byproduct of Acetyl-CoA synthesis in microbial respiration (Morel et al. 1998), or a means of detoxification for microbial metabolism (Barkay et al. 2003). Recent work with a well-known methylating sulfate-reducing bacteria species (*Geobacter sulfurreducens*) has shown that Hg(II) is actively taken across cell membranes and actively exported into cytoplasm as MeHg (Schaefer et al. 2011). Under laboratory conditions, only a subset of sulfate-reducing bacteria (e.g. Compeau...
and Bartha 1985, Gilmour et al. 1992) and iron-reducing bacteria (Kerin et al. 2006, Fleming et al. 2006) have actually been shown as active methylators of Hg in anoxic sediment. Thus, MeHg production is ultimately controlled by the presence and activity of those Hg(II)-methylating bacteria and the bioavailability of Hg(II) to these bacteria. Further, to have net MeHg production, rates of production must be greater than rates of degradation, either bacterial or abiotic (see section 2.1.3.2). As such, multiple factors are at play in controlling net MeHg production rates.

Bacterial activity is largely determined by temperature and the supplies of electron acceptors (e.g. sulfate and ferric iron) and electron donors (e.g. labile organic matter). Organic matter is particularly important. Luengen et al. (2009) has shown that in SFB, the primary influence of algal blooms on MeHg exposure is not biodilution (lower MeHg concentrations per algal cell and thus lower rates of foodweb bioaccumulation, Chen and Folt 2005), but rather, post-bloom stimulation of MeHg production in benthic sediments due to carbon loading. In addition to laboratory studies, multiple field studies in Delta and SFB show that wetlands can vary over five orders of magnitude in bacterial activity rates between wetland types as well as between seasons (e.g. Davis et al., in review; Marvin-DiPasquale and Agee 2003). In addition to changes in bacterial activity, the susceptibility of Hg(II) to methylation can vary independently of total Hg pools. This availability, a function of redox status and geochemical matrices, is highly sensitive to habitat conditions. Because Hg binds strongly to sulfide and organosulfur groups abundant in carbon-rich, clay-rich reduced sediments, the pool of Hg in play (hereafter “reactive Hg (II)”) generally becomes depleted in permanently flooded wetland soils, as binding and precipitation occur. However, binding to neutral sulfides (Benoit et al. 1999) or thiols (e.g. cysteine; Shaefer and Morel 2009) appears to promote Hg methylation. Assays of this reactive mercury pool include tin-reducible fractions (Marvin-DiPasquale and Cox 2009) as well as sequential extractions (Bloom and Preus 2003), both of which have shown strong fidelity with microbial bioavailability (Bloom et al. 2006; Marvin-DiPasquale et al. 2006).

From Everglades canals (Corrales et al. 2011) to Adirondack meadows (Selvendiran et al. 2008) and German floodplains (Frohne et al. 2011), multiple studies have found that the highest rates of MeHg production are measured under intermediate conditions, in which microbial activity and Hg bioavailability are optimized. Optimization of these two factors is transitional and thus uncommon, as the conditions that promote microbial activity (abundant sulfate and labile carbon) also limit over time the pool of mercury able to be methylated. Intermittent wetting and drying appears to yield periods of high MeHg production by periodically generating these optimal conditions (Gustin et al. 2006). Vegetation may optimize these conditions physiologically through rhizosphere exchanges (oxygen and organic acids) and litter production (Kieu 2004, Windham-Myers et al. 2009). At the landscape scale, many studies show clear windows of time and transitional landscapes that are more prone to being MeHg production “hot spots” or “hot moments”. More simply, within the whole range of wetland types from open water to dried fields, those at the extreme ends are the least likely places for net MeHg production, and those in the middle of the spectrum (e.g. intermittently flooded ecosystems) the most likely places - due to availability of both electron donors (labile carbon) and electron acceptors (oxidized iron and sulfur). Carbon availability (food energy for bacteria) may be the ultimate regulation of MeHg production in seasonal wetlands, since energy is lost during microbial activity, whereas total pools of Hg, S, and Fe are fairly consistent but speciation cycles with environmental conditions.
2.1.3.2 Degradation/demethylation of methylmercury

Degradation (or demethylation) of MeHg – the physical cleaving of the methyl group (CH$_3$) and Hg atom – is considered a sink for MeHg. There are two main categories of MeHg degradation: microbial processes and solar radiation. Microbial degradation comes in two forms – the dissimilatory cleaving of CH$_3$ from Hg with an organomercurial-lyase (e.g. MerB operon) and the oxidative consumption of CH$_3$ as an electron donor. Both processes have been observed in sulfate-reducing bacteria and methanogens (Marvin-DiPasquale and Oremland 1998) in field studies, and their relative importance varies with microbial community structure (Marvin-DiPasquale et al. 2000).

Photodegradation is largely a radiative process by which formation of oxygen or hydroxyl radicals physically cleaves the bond between the methyl group and Hg (Suda et al. 1993). Driven primarily by sunlight, it is a dominant process in open waters with high ultraviolet penetration (UVA and UVB, e.g. Sellers et al. 1996) and is generally inhibited in turbid or DOC-rich surface waters (Krabbenhoft et al. 1998). Rate measurements suggest that MeHg photodemethylation may account for 17% of the loss of MeHg from the Delta water column (Gill 2008a). This is equal to nearly half of estimated sedimentation losses (34%), as determined by mass balance and particle tracking approaches (Stephenson et al. 2008), whereas the remaining ~50% of MeHg is lost from the Delta through hydrologic export. While ultraviolet radiation can also directly reduce Hg(II) to Hg(0), the volatile inert form, in natural waters this Hg(0) is often re-oxidized before diffusion to the atmosphere, and thus volatilization may not be a reliable sink for Hg (Gill 2008b, Conaway et al. 2008).

Improved analytical capabilities have made it possible to estimate rates of both methylation and demethylation, as well as the relative influence of demethylation on net MeHg production. Diffusive gradient in thin films (DGT; Clarisse et al. 2011) provides a means of in situ deployments for seasonal and spatial comparisons under field conditions. Multi-collector mass spectrometry on mercury isotope fractions has illustrated significant Hg fractionation during photodegradation as a nuclear-related, mass-independent process (Bergquist and Blum 2007) and microbial degradation as a mass-dependent process (Kritee et al. 2009). An important finding using $\delta^{199}$Hg signatures in Delta forage fish (silversides) is that the MeHg they contain has undergone photodegradation, perhaps multiple times over (Gehrke et al. 2011b). By a literature comparison they estimate that 10%-30% of the MeHg in the Delta is likely lost to photodemethylation. These isotopic data support calculations by Gill (2003a), and provide a novel technique to assess internal cycling rates of MeHg that may be useful for designing effective management practices.
Table 2. Expected habitat-specific relative methylmercury concentrations in sediment and overlying water in the Delta and San Francisco Bay. From DRERIP (Alpers et al. 2008) [L, low; M, moderate; H, high; NA, not applicable]

<table>
<thead>
<tr>
<th>Habitat</th>
<th>MeHg Overlying water</th>
<th>MeHg Sediment</th>
<th>Flooding Characteristics</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Managed Wetlands</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permanently Flooded Wetlands (Submerged Aquatic Vegetation)</td>
<td>L – H</td>
<td>M</td>
<td>Perennial All All All</td>
<td>1</td>
</tr>
<tr>
<td>Permanently Flooded Wetlands (Emergent Vegetation)</td>
<td>L – H</td>
<td>M</td>
<td>Perennial All All All</td>
<td>1,8</td>
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<tr>
<td>Permanently Flooded Wetlands: Floating Vegetation</td>
<td>M ?</td>
<td>Perennial All All All</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Seasonal wetlands, winter flooded</td>
<td>H H</td>
<td>Seasonal Oct-Mar Cool</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Seasonal wetlands, spring and winter flooded</td>
<td>H ?</td>
<td>Seasonal May-Aug Cool to Warm</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Agricultural Lands</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agricultural wetlands: seasonally flooded (rice, wildrice, fallow)</td>
<td>M – H</td>
<td>M – H</td>
<td>Seasonal Apr-Sep Warm to Hot</td>
<td>5,6</td>
</tr>
<tr>
<td>Row Crops, winter flooded</td>
<td>M M – H</td>
<td>Irrigated Oct-Mar Cool</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Row Crops</td>
<td>NA L</td>
<td>Irrigated NA NA</td>
<td>9</td>
<td></td>
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<tr>
<td>Natural Hydrology Wetlands</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brackish-Fresh Tidal Marsh: High Elevation</td>
<td>M L-H</td>
<td>Episodic (2x/month) All All</td>
<td>2,3,4</td>
<td></td>
</tr>
<tr>
<td>Brackish-Fresh Tidal Marsh: Low-Med Elevation</td>
<td>L – M L – M</td>
<td>Episodic (2x/day) All All</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Floodplains</td>
<td>H H</td>
<td>Episodic (seasonal) Jan-May Cool to Warm</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

2.2. Methylmercury Hydrologic Transport and Fate

2.2.1 Watershed sources of methylmercury (draining into the Delta)
Monitoring of unfiltered MeHg concentrations and a resulting mass balance model (Foe 2003, Foe et al. 2008) suggest that ~60% of the MeHg within the Delta comes from its major tributaries. Depending on season, the Sacramento River is responsible for 50-85% of the MeHg inputs and ~75% of hydrologic flow. At ~25% of Delta water supply, the smaller flows of the San Joaquin River supply less than half of the total MeHg load from the Delta’s tributaries, but due to limited circulation, are an important source in the south Delta. MeHg loads to the Delta are dominated by the Yolo Bypass when it is conveying floodwaters, usually in winter and spring months. While the mass balance and monitoring approach has bounded the patterns and poolsizes of MeHg in the Delta, we still lack key information about MeHg sources, transport and transformations (production/degradation/storage) in its tributary watersheds.

Analyses of patterns of MeHg flow at water monitoring stations along the Sacramento and San Joaquin Rivers provide some insight into the processes regulating MeHg loading (Foe et al. 2008). Studies from across the U.S. have identified seasonal and/or event-driven relationships between flow rates and MeHg transport (Balogh et al. 2006, Brigham et al. 2009), but MeHg concentrations in Delta waterways were independent of flow at all stations except Prospect Slough. Episodic flooding in Prospect Slough is suggested as a primary driver of MeHg loading, as it is connected to the mercury-enriched Yolo Bypass. Further, monthly estimated amounts of MeHg in unfiltered water were independent of suspended sediment concentrations (as measured by turbidity sensors), except at Freeport. Because Freeport is sourced broadly from the upper Sacramento, American and Feather Rivers, MeHg loads are difficult to attribute to a particular source without further mass balance or isotopic tracking studies.

2.2.2 Hydrologic transport of methylmercury within the Delta
Active movement of MeHg within the Delta likely occurs through advective, event-driven erosion, deposition, and resuspension (Schoelhammer 2002, Topping et al. 2004, Ganju et al. 2005), as well as benthic fluxes (Choe et al. 2004) and DOC-related flocculation and adsorption of dissolved and colloidal phases (Choe and Gill 2003). Tidal exchanges with wetlands may serve as MeHg sinks when particulate MeHg dominates the MeHg load (Stephenson et al. 2008, Bergamaschi et al. 2011). When wetlands are the primary MeHg source, aqueous MeHg can be dominated by dissolved (a.k.a. filter-passing) fractions (<0.45 μm; Hill et al. 2009). Because dissolved MeHg pools are more subject to physical and biological transformations, monitoring of dissolved MeHg may provide a better indication of MeHg uptake dynamics (e.g. Chasar et al. 2009; Marvin-DiPasquale et al. 2009). The fluorescent fraction of DOM (FDOM, a subset of chromophoric DOM, also known as CDOM) has been shown to be tightly coupled with dissolved MeHg fluxes in wetlands (Downing et al. 2009, Bergamaschi et al. 2011, Fleck et al. in review, a, in review, b). Fleck et al. (2011) have shown that this relationship breaks down when sources of MeHg and DOM are uncoupled, such as in Delta locations where surface water is a mixture of multiple sources (e.g. Liberty Island). The relative pool of particulate versus dissolved phase MeHg affects seasonal, inter-annual, tidal and event-driven transport, and thus needs incorporation in monitoring approaches, especially as water quality and particle transport is predicted to change over the next century (Schoelhammer 2002, Cloern et al. 2011).
2.3. Methylmercury in Biota

2.3.1. Methylmercury bioaccumulation within Delta

Multiple datasets are in support of ingestion as the primary route of exposure in biota to MeHg, from algal to avian pathways. Some advancement in this understanding comes from Delta and SFB studies. Isotopic experiments by Luengen et al. (2011) suggest that regardless of origin, DOM generally inhibits MeHg uptake into diatoms, a dominant class of Delta algae. These results were similar to Tsui and Finlay (2011) in Minnesota streams. On the other hand, linked studies on small fish (biosentinels) in south SFB have seen that high DOC promotes partitioning of MeHg into dissolved phases, which appears to enhance foodweb MeHg bioaccumulation (Ackerman et al. 2010). Stewart et al. (2008), and as reported in Marvin-DiPasquale et al. (2007) found that bioaccumulation factors are fairly consistent between different food webs, and that the initial uptake of MeHg into the base of the food web is the primary driver of the MeHg tissue concentration of a given trophic position. Further, pelagic food chains (algal-based) versus benthic or epiphytic-based food webs are generally more enriched in MeHg, due primarily to food chain length and dietary segregation (Grimaldo et al. 2009).

Another interesting bioaccumulation development since 2007 is the abundance of studies showing elevated MeHg in rice grains of mining regions (e.g. Feng et al. 2008). Although their Hg and MeHg concentrations were generally too low to have a significant impact on humans, husked rice and wildrice grains from the Yolo Bypass were elevated in MeHg beyond other native emergent plants (*Typha spp*, *Schoenoplectus acutus*), and may be an important source of MeHg to migrating birds visiting winter-flooded rice fields (Windham-Myers et al. in review). Finally, the linkages between sediment MeHg production and water concentrations of MeHg and biotic MeHg uptake and effects remains poorly understood. Although the TMDL’s allocations are derived from target MeHg concentrations in fish tissue (Wood et al. 2010), MeHg availability and biotic uptake pathways for MeHg into the base of the food web (phytoplankton) and through dynamic food chains are still unpredictable.

2.3.2. Methylmercury Impacts to Fish and Wildlife

MeHg concentrations in biota within the Delta, as well as the Central Valley and SFB, are considered elevated. Biosentinel fish (Slotton et al. 2002), sportfish (Slotton and Davis 2008), and birds (Eagles-Smith et al. 2009a) have indicated that the central Delta and open waters of SFB have among the lowest MeHg concentrations in biota whereas their tributaries and adjacent wetlands contain the highest MeHg concentrations in biota. Most data suggest that wetlands are hot-spots for MeHg bioaccumulation, due to the fact that frequent wetting and drying of habitats tends to promote MeHg production and also tends to be highly productive biologically which attracts large numbers of fish and wildlife (Ackerman and Eagles-Smith 2010). Although it is extremely difficult to demonstrate toxicological effects of MeHg on fish and wildlife in the wild, recent data demonstrate that current mercury concentrations in SFB and the Delta are causing reproductive and other impairment in birds (Ackerman et al. 2007). MeHg concentrations in several species of birds breeding in the Delta and SFB were associated with demethylation of mercury in bird livers (Eagles-Smith et al. 2009b), reduced body condition (Ackerman et al. 2012), reduced egg hatching success (Ackerman and Eagles-Smith 2008), reduced nest survival (Schwarzbach et al. 2006, Eagles-Smith and Ackerman 2010), increased likelihood of an embryo being malpositioned within the egg (Herring et al. 2010), and increased mortality of young chicks (Ackerman et al. 2007).
Altogether, these results suggest that mercury contamination may be currently impairing bird reproduction with the Delta and SFB, and impacts to fish and wildlife should be incorporated into TMDL target criterion values.

### 2.3.3. The Need to Incorporate Methylmercury Impacts to Fish and Wildlife in Wetland TMDLs

Currently, the State Water Board either regulates or seeks to regulate discharge from sources through the TMDL process whereby sources must reduce their TMDL below a target level. This TMDL process regulates only the potential pollution that is discharged from sources but does not consider pollution within sources. Because wetlands are known to be sites of elevated MeHg production, wetlands are considered sources by the regulatory process. Wetland managers, and land managers in general, will therefore have to comply with a regulatory process that evaluates only the discharge from wetlands outlets. This regulatory framework may be harmful to fish and wildlife since management actions that seek to reduce loads from wetlands into downstream habitats (the waterways of the Delta), may be elevating pollution within wetlands. For example, a simple way to reduce loads from wetlands is to restrict water flow out of wetlands. This management strategy to reduce export of MeHg could be applied to rice fields or reverse-cycle seasonal wetlands which are irrigated during the summer growing season and have high rates of evaporation. Yet, this strategy of limiting flow through and evaporating water from wetlands would likely have a negative effect on local fish and wildlife which rely on wetlands and rice fields for foraging habitat. Seasonal wetlands and flooded rice fields in particular are known to have among the highest concentrations of MeHg in biota relative to other water bodies (Ackerman and Eagles-Smith 2010, Windham-Myers et al. 2010). Therefore, fish and wildlife are already at considerable risk to mercury contamination in wetlands, and management actions that seek to reduce export to the Delta could exacerbate this problem. We urge a more comprehensive approach to the regulatory process that considers more than just exports from wetlands via the TMDL process. Wetlands should be considered a unique case where their great value to fish and wildlife is explicitly recognized, and the regulatory process focuses less on wetland exports and more on health of the complete wetland ecosystem.

### 3. Managed Wetlands

The Delta has lost more than 95% of its historic wetland acreage since the mid-1800s (for more details, see [http://www.sfei.org/DeltaHEStudy](http://www.sfei.org/DeltaHEStudy)). Managed wetlands (naturally vegetated but hydrologically managed, both seasonally and permanently flooded) occupy 43% of the Delta’s current wetland acreage. The location of wetlands that are kept permanently flooded varies between years, but based on best management practices for wildlife, it is estimated that a total of 15% of all managed wetlands are permanently flooded at any one point in time. Thus at 18,500 acres for all managed wetlands, approximately 2800 acres are permanently flooded wetlands (such as wildlife management areas and shallow impounded ponds, such as the restored wetlands on Twitchell Island). At 15,700 acres, managed seasonally flooded wetlands are generally either gate-controlled floodplain environments, wildlife management areas (i.e. duck ponds) or flood conveyance systems. Managed wetlands are less abundant in the Delta than naturally flooded wetlands (24,500 acres) which are found predominantly along tributary edges, and in the West Delta (Petrik 2012). However, because managed wetlands have some marginal control of flooding regimes, they are amenable to hydrology-related control options for reducing MeHg export. Chapter 5 in CDFG (2010; authored by C.N. Alpers) summarizes the results of multiple ERP and
CALFED funded studies that address managed wetland mercury dynamics, especially the Yolo Bypass sub-watersheds (including the Yolo Bypass Wildlife Area and the Cache Creek and Putah Creek watersheds). Additional studies discussed here on permanent wetlands in the Delta include Twitchell Island and ongoing data from the Cosumnes River Preserve. Additional studies discussed here on seasonally flooded wetlands include Suisun Bay and the Cosumnes River Preserve (discussed under flooded agriculture).

### 3.1 Case studies in permanently flooded wetlands

#### 3.1.1 Cache Creek Settling Basin (ERP-99-B06)

The project *Transport, Cycling, and Fate of Mercury and Monomethyl Mercury in the San Francisco Delta and Tributaries, An Integrated Mass Balance Assessment Approach* (ERP-02-C06-a), studied a broad range of habitats, with permanent wetlands of the Cache Creek Settling Basin among them. Sediment MeHg concentrations were generally lower in permanently flooded wetlands than in seasonally flooded wetlands. The primary sediment covariate with MeHg was sediment organic matter. Efforts to assess biogeochemical influences suggested that indices of sulfate reduction (e.g., hydrogen sulfide) were not associated with MeHg concentrations in pore water profiles.

#### 3.1.2 Cache Creek and Yolo Bypass Wildlife Area (SRWP Prop. 50)

With the project *Special Water Quality and Sediment Studies* (Prop 50), USGS scientists pursued short-term research in 2005-6 within the Yolo Bypass Wildlife Area (YBWA) and the Cache Creek Settling Basin (CCSB) in cooperation with the Sacramento Regional County Sanitation District, the Sacramento River Watershed Program, and the United States Environmental Protection Agency. Of the two permanently flooded wetlands sampled, surface sediment HgT concentrations were greater in the CCSB but MeHg concentrations were greater in the YBWA (n=1 wetland per site). Surface water MeHg was low in both permanently flooded wetlands, especially compared to the paired seasonally flooded wetlands. Between seasons and sites, the correlation between unfiltered MeHg concentrations in surface waters and sediment MeHg (0-2 cm depth) suggested *in situ* sediment flux as the local source. Field observations and amendment experiments suggested that permanent wetlands were poised for sulfate reduction, having limited pools of oxidized iron available, and also limited pools of reactive Hg(II). Carbon pools, not HgT pools, were better predictors of MeHg production between habitats. Therefore permanent wetlands showed evidence of MeHg production and flux into the water column but the spatial patterns of MeHg production were more likely a function of organic carbon concentrations, not HgT concentrations.

#### 3.1.3 Yolo Bypass Wildlife Area (SWRCB, Prop 40)

The project *Methylmercury cycling, bioaccumulation, and export from agricultural and non-agricultural wetlands in the Yolo Bypass* (SWRCB 06-232-555-0) included process-based measurements of MeHg production, export, and bioaccumulation from May 2007- May 2008 in two permanently flooded wetlands, and three habitat types: open water, cattail-dominated, and tule-dominated. The biogeochemical variability between emergent marshes (cattail or tule dominated) on the edge of the permanent wetland and open water sites (>1m depth, n=2) were striking. Sediments of open water sites were among the lowest in MeHg concentrations, with the lowest measured rates of microbial methylation throughout the annual study. In contrast, the emergent marsh surface sediments, which were also highly reducing with no measurable oxidized iron and limited pools of sulfate, had significantly higher MeHg concentrations. Microbial
methylation rates were maximized in these emergent marsh habitats, where soil organic carbon and pore water acetate were among the highest measured. Compared to nearby seasonal wetlands, MeHg production, however, was kept in check by the low pools of Hg(II) in the emergent marsh soils. Experimental devegetation in both cattail and tule stands reduced sediment MeHg concentrations, with the largest effect on pore water acetate. High carbon supplies rather than Hg(II) appear responsible for the high microbial methylation rates and reducing conditions in the emergent wetland. Concentrations of MeHg and HgT in surface water were lower near outlets than inlets of permanent wetlands; when corrected for dilution, these patterns suggest that YBWA permanent wetlands were a net sink of aqueous MeHg and HgT. Similarly, MeHg body burdens and tissue concentrations in mosquitofish were decreased near outlets of permanent wetlands as compared with inlets with incoming water from nearby seasonal wetlands. In contrast, notonectid invertebrates were more elevated in MeHg near outlets. These data illustrate that invertebrate exposure routes may be different than mosquitofish, and that full food web monitoring is necessary to successfully interpret biotic impacts of MeHg exposure.

3.1.4 Yolo Bypass Wildlife Area (SWRCB, DFG)

The project Methylmercury Concentrations and Exports from Seasonal Wetlands in Yolo Wildlife Area, California (DFG) measured surface water MeHg concentrations in multiple seasonal wetlands and permanent wetlands through the 2007-8 and 2008-9 winter flooding seasons, to assess potential controls on MeHg production and export. Using a permanent wetland as a “polishing pond” or “settling basin”, the study showed that permanent ponds had 8- or 10-fold lower concentrations of unfiltered aqueous MeHg than tailwater from seasonal wetlands. This reduction in MeHg concentration is ascribed to internal removal mechanisms, such as particle settling and photodemethylation, based on the relatively short residence times (22-36 days) of water in the permanent wetlands and assuming complete mixing of inflows. Under these conditions, dilution effects would be <25% after the first month and would exponentially diminish over time (Heim et al., in review). Given the diminished solar radiation of the winter season, particle settling is proposed as the dominant removal process during winter periods.

3.1.5 Twitchell Island (ERP-02-C06-a)

The project Transport, Cycling, and Fate of Mercury and Monomethyl Mercury in the San Francisco Delta and Tributaries, An Integrated Mass Balance Assessment Approach (ERP-02-C06-a) measured surface water MeHg concentrations at inlets and outlets of two peat-building permanent wetlands established to reverse Delta subsidence (for more, see Miller et al. 2008). In contrast with permanent wetlands in the Yolo Bypass and Cache Creek watershed, these wetlands were estimated to export MeHg at roughly 3-5 μg m⁻² yr⁻¹, similar to estimates from Browns Island (Bergamaschi et al. 2011), a natural tidally-flooded peat-based ecosystem in the Delta dominated by emergent marsh (especially tule, Schoenoplectus acutus). Two reasons to explain this net export include 1) very low MeHg concentration in source water (<0.08 ng L⁻¹), promoting a net benthic flux of MeHg and 2) highly organic peat soils (>90% loss on ignition), suggesting an abundant carbon supply for microbial MeHg production. Seasonally, both wetlands had similar low concentrations of MeHg during fall and winter months (~0.3 ng L⁻¹), but in spring and early summer months, the shallower, more completely vegetated west pond exported water of greater MeHg concentrations than the deeper, less vegetated east pond (0.3-3 ng L⁻¹ versus 0.1-0.9, respectively). HgT and MeHg concentrations in the peat substrate were similar between ponds. Sassone et al. (2008) suggest that the lower MeHg aqueous concentrations in the east pond may
be dilution-based, due either to larger volume of water present or to photodegradation in the large open water subhabitats.

3.2 Case studies in seasonally flooded wetlands

3.2.1 Cache Creek and Yolo Bypass Wildlife Area (SRWP Prop. 50)
Seasonally flooded wetlands were also studied in the 2005-6 project Special Water Quality and Sediment Studies (Prop 50), described in section 3.1.2. and focusing on the Yolo Bypass Wildlife Area (YBWA) and the Cache Creek Settling Basin (CCSB). Seasonal wetlands of both drainages were elevated in surface water MeHg (unfiltered) compared with permanently flooded wetlands, especially at the end of spring flooding (May). The YBWA seasonal wetland was prone to greater MeHg in surface waters. Flooding of the YBWA seasonal wetland resulted in a rapid and significant (five-fold) rise in sediment MeHg concentration within 3-4 weeks following inundation, which may include diffusion of MeHg produced during a previous time period. Temporal changes in sediment sulfur and iron speciation suggest that rates of both microbial sulfate reduction and Fe(III)-reduction were significantly higher at YBWA, compared to CCSB, during the period between flooding and drying. A subsequent soil incubation and amendment experiment suggested that the YBWA seasonal wetland soils were poised for higher rates of microbial MeHg production upon flooding than CCSB seasonal wetland soils, due to greater availability of carbon, iron and sulfur, as well as pools of reactive Hg. HgT concentration in filtered water was positively correlated with both total Fe and dissolved organic carbon (DOC) in the wetlands, offering additional support for the role of these constituents in the partitioning of HgT between particulate and dissolved phases, but ultimately HgT concentrations were not positively correlated with aqueous or sediment concentrations of MeHg.

3.2.2 Yolo Bypass Wildlife Area (SWRCB, Prop 40)
The project Methylmercury cycling, bioaccumulation, and export from agricultural and non-agricultural wetlands in the Yolo Bypass (SWRCB 06-232-555-0) included process-based measurements of MeHg production, export and bioaccumulation in a large seasonal wetland during the 2008 winter-spring flooding season. Rates of measured microbial MeHg production in winter flooded wetlands were 3- to 5-fold lower than summer-flooded wetlands; however, %MeHg concentrations in surface sediments were similar (Median = 1.4%). Surface water MeHg concentrations rose quickly upon floodup, likely due to diffusive flux of previously produced MeHg. Furthermore, as the flooding continued through the winter, MeHg concentrations in sediment and surface water continued to rise as did pore water DOC, pore water acetate (labile carbon), and pore water iron (reduced Fe(III)). These data suggest that the organic soils of seasonal wetlands were geochemically poised to release and produce more MeHg quickly upon flooding, and rates were enhanced by increasing concentrations of labile carbon from decaying plant matter (e.g. swamp timothy, Crypsis schoenoides). The importance of carbon supplies was also illustrated by the decrease in microbial methylation rates and associated decrease in pore water acetate with the experimental removal of photosynthetic inputs (devegetation treatment). Finally, in contrast with the permanent wetland, the majority of MeHg pools were associated with the filter-passing fraction (<0.45 μm) rather than the particulate fraction.
3.2.3 Yolo Bypass Wildlife Area (SWRCB, DFG)

The project *Methylmercury Concentrations and Exports from Seasonal Wetlands in Yolo Wildlife Area, California* (DFG) measured surface water MeHg concentrations in multiple seasonal wetlands and permanent wetlands through the 2007-8 and 2008-9 winter flooding seasons, to assess potential controls on MeHg production and export. Upon flooding, concentrations of MeHg in surface waters rose quickly, to greater than 20-fold the incoming water concentrations (6-15 ng L\(^{-1}\) v. 0.3 ng L\(^{-1}\)). Evapoconcentration was limited to <5% due to low potential ET and rapid flow through (<30 days). No differences were observed in surface water MeHg between fields which had been partially mowed and those that had been disked. However, the wetland on which cattle were allowed to graze in years 3 and 4 saw an order of magnitude decrease in surface water MeHg concentrations (from peak concentrations of 12 ng L\(^{-1}\) to 1.3 ng L\(^{-1}\)). The significance of carbon removal on MeHg production was assayed with a slurry experiment using plant litter (swamp timothy) and sediment from YBWA seasonal wetlands. Whereas all incubated sediment slurries showed increases in filtered MeHg concentrations over the 30-day incubation, the plant+sediment treatment resulted in MeHg concentrations 10-fold greater than either sediment or plant incubations alone. Replicate treatments with molybdate (an inhibitor of bacterial uptake of sulfate) implicated sulfate reduction as the primary driver of MeHg production in the slurry experiment. The PI’s suggest two possible management pathways: labile carbon control to inhibit MeHg production, and tailwater routing of seasonal wetland surface waters to permanent ponds to remove aqueous MeHg through settling and photodemethylation (Heim et al. in review).

3.2.5 Grizzly Island and Suisun Bay (ERP-99-B06)

The project *Transport, Cycling, and Fate of Mercury and Monomethyl Mercury in the San Francisco Delta and Tributaries, An Integrated Mass Balance Assessment Approach* (ERP-02-C06-a), included a large range of habitats, with some limited studies in managed seasonal wetlands of Grizzly Island (western Delta). A comparison of MeHg concentrations in drainages from natural tidal wetlands and seasonally managed wetlands on Grizzly Island found high concentrations of MeHg in export waters from both habitats, with greater average concentrations in the tidal wetland (0.8 v. 0.17 ng L\(^{-1}\)). Siegel et al (2011) found that changes in timing of flooding and or hydroperiod management could be used to decouple periods of flooding from conditions that enhance microbial activity (abundant litter, higher temperatures), which may have led to lower MeHg production.

3.3 Seasonal and spatial processes

Across all studies reported above, we see some promising evidence that MeHg export may respond to wetland management by either 1) reducing MeHg production rates, 2) increasing MeHg degradation and sequestration rates, and/or 3) controlling the rate and timing of hydrologic flows off wetlands into receiving waters. Determining the extent to which MeHg dynamics may be modified by management, and which methods are most appropriate and effective will require field demonstration or coupled hydrological/biogeochemical modeling. Due to potential collateral impacts of flow restriction to limit export, the most favorable control methods are likely to be those that focus on limiting MeHg production and enhancing aqueous MeHg removal.

Process-based studies have illustrated some commonalities of MeHg production among managed wetlands, whether they are permanently or seasonally flooded. First, the primary ingredients necessary for MeHg production are present over time in nearly all wetlands studied (methylating bacteria, organic C, S, Fe, and Hg). Thus, it is the dynamic availabilities of those ingredients,
whether supplied from outside or inside the wetland, which regulate the relative MeHg production. Second, stimulation of MeHg production at a given site can occur from either a rise in the abundance of electron acceptors (sulfate and/or ferric iron) or a rise in the abundance of electron donors (organic C), depending on initial limitations. Reaction rates may also be influenced by temperature, pH and ionic strengths that regulate the kinetics of availability.

Results from field studies largely point toward seasonal wetlands as having greater net MeHg production and greater MeHg export than permanently flooded wetlands. The periodic drying that occurs in seasonally flooded wetlands (but not in permanently flooded wetlands) is a key factor its relative abundance of reactive Hg(II), as Hg(II) can be released oxidatively from reduced sulfur, whether inorganic or organic. However, the actual rates of MeHg production vary little among the wetlands, differing primarily in the relative importance of different drivers. Specifically, permanent wetlands had extremely high microbial activity but limited amounts of Hg(II) available for methylation. In contrast, all seasonal wetlands had significantly greater availability of reactive Hg(II), which decreased as microbial activity ramped up during winter flooding. It is important to note that while open-water, non-vegetated sites in permanent wetlands were low in MeHg production throughout annual cycles, MeHg production was not completely inhibited, and microbial methylation of Hg along the vegetated edges was among the highest measured.

Amendment experiments to assess MeHg production show mixed results, due to the tight interactions and feedbacks among Hg, C, S, and Fe chemistry. Some laboratory experiments have shown that addition of ferrous iron can limit MeHg production, presumably through reduction of Hg availability by limiting neutral sulfide formation (Mehrotra and Sedlak 2005). Heim et al. (in review) found that direct additions of plant litter and sulfate increased MeHg pools in slurry incubations from a YBWA seasonal wetland, but Marvin-DiPasquale et al. (2009) found that both seasonal and permanent wetlands in YBWA were at capacity for MeHg production, responding minimally (if at all) to any Fe, S, and C amendments. In contrast, while the CCSB had a limited capacity for MeHg production, soils from both seasonal and permanent wetlands responded positively but inconsistently to various Fe, S, and C amendments. The pathways of increased MeHg production are often difficult to identify in amendments due to comingled chemical influences and non-equilibrium conditions.

We note that the patterns observed in MeHg dynamics of managed wetlands, whether they are permanently or seasonally flooded, are functions of the same MeHg production, degradation, and transport processes. The net effect of interacting physical, chemical or biological processes however may be very different across space and time depending on the relative magnitude of different transport and transformation rates. For example, the surface waters of permanent wetlands have deeper water and longer residence times, which can generate conditions of net aqueous MeHg removal – in which rates of photodemethylation and particle settling exceed MeHg production and benthic flux. However, this net balance may be altered by initial or temporally variable conditions (e.g. solar radiation). Note that despite similar water flow management, the permanent wetlands on Twitchell Island – with cleaner input water, highly organic peat soils, and dense vegetation cover – were found to be sources of MeHg to receiving waters while as those in the Yolo Bypass were sinks for MeHg. The relative importance of these different processes is thus subject to change between locations and over temporal scales (daily, seasonally, yearly, and longer) under potential climate changes.
Three primary mechanisms have emerged as promising methods by which to limit MeHg export:
1) Limit MeHg production by limiting carbon supplies;
2) Promote MeHg removal by increasing residence time, and/or routing tail water toward treatments (e.g. open-water polishing pond or coagulation by metal-based salts); and
3) Limit MeHg outflow during “hot moments” (e.g. initial diffusive flux to flooding waters).

4. Agricultural Lands
Flooded agricultural fields, generally those in rice or wild-rice crop-rotations, may be hotspots for bioaccumulation, as suggested by short-term caged fish experiments (Ackerman and Eagles-Smith 2010). Studies in the Yolo Bypass, Twitchell Island, and ongoing studies on the Cosumnes River Preserve suggest patterns for MeHg production and export.

4.1 Case studies in flooded agricultural lands (rice, wild rice, summer fallow)

4.1.1 Yolo Bypass Wildlife Area (SWRCB, Prop 40)
The project Methylmercury cycling, bioaccumulation, and export from agricultural and non-agricultural wetlands in the Yolo Bypass (SWRCB 06-232-555-0) included process-based measurements of MeHg production, export and bioaccumulation in three agricultural field types: white rice (Oryza sativa, n=2), wild rice (Zizania palustris, n=2) and fallow fields flooded to control weeds by premature germination (mixed vegetation, n=2). Detailed hydrology, chemistry and isotopic tracers provided a great resource of data upon which to understand the processes behind the MeHg concentrations and loadings. Because these fields were fully dried prior to flooding in May 2007 (rice and wild rice) and July 2007 (fallow), seasonal biogeochemical responses were profound. After an initial pulse of MeHg into surface waters upon flooding, MeHg concentrations remained high at outlets, primarily due to evapoconcentration. Further, MeHg was predominantly in the filter-passing fraction (<0.45 μm, median > 50%). Agricultural wetlands, however, were not necessarily exporting MeHg during the growing season. Rather, high influent MeHg concentrations (northern block fields) were reduced while low MeHg concentrations (southern block fields) were increased such that all discharges tended toward similar and highly elevated MeHg concentrations, due to extremely high evaporative and transpirative concentration (Bachand et al. in review, a). Ultimately, the MeHg concentration of source water, rather than crop type or water management strategy, tended to determine whether a field was a net source or sink of MeHg. (Bachand et al. in review, b).

MeHg production in sediments increased during the growing season but little evidence of flux from soils to surface waters was observed. The two factors most likely to have inhibited greater observed MeHg concentrations in surface waters during the growing season were 1) photodemethylation, and 2) inhibited benthic flux due to plant transpiration. Photodemethylation in the shallow water column, as observed through diel and seasonal comparisons, may have removed nearly 50% of dissolved MeHg during the growing season. Transpiration, the dominant water flux in summer, represented 75% of applied water in agricultural fields (Bachand et al. in review, a). As supported by seasonal Cl and δ34SO4 data, as well as diel MeHg and algal flux patterns, densely vegetated fields may exert a net downward advective flux of water, thus preventing significant diffusive flux of MeHg from surface sediments. These data suggest that clear understanding and quantification of hydrologic paths are essential to calculating loads, as are
sampling designs poised to capture diel differences. In other words, aqueous MeHg at peak daylight hours may represent minimum concentrations and thus underestimate average loads.

Agricultural fields were distinctly different from managed wetlands in the YBWA, both in seasonal patterns and initial conditions. Agricultural fields were much lower in sediment organic content and much higher in reactive mercury and oxidized iron pools (Fe(III), both crystalline and amorphous). Rapid release and continued high concentrations of MeHg in surface waters of agricultural fields led to high Hg uptake in caged and resident mosquitofish. After 60 days, 82% of caged fish and 59% of wild fish had HgT concentrations exceeding the 0.2 \( \mu g \) g\(^{-1}\) wet weight sublethal effects threshold. The practice of holding water on the fields to promote water usage and limit MeHg export had an unintended consequence of elevating short-term bioaccumulation \textit{in situ} by elevating surface water MeHg concentrations.

In contrast to expectations, MeHg production in rice fields was not stimulated by the addition of sulfate-bearing ammonium fertilizer ((NH\(_4\))\(_2\)-SO\(_4\)). While sulfate reduction was measurable year-round, the dominant carbon-flow pathway in the flooded fields was through reduction of ferric iron (Marvin-DiPasquale et al. in review). Whereas iron-reduction appears to play some role in the enhanced MeHg production on agricultural wetlands, the authors cannot identify whether that role is direct or indirect. Further, in contrast to expectations of temperature-driven maxima for MeHg production, winter conditions led to the greatest rates of sediment MeHg production, sediment MeHg pools and MeHg concentrations in surface water on the agricultural fields. These patterns were correlated with detrital pools of rice residue and pore water concentrations of acetate (Windham-Myers et al. in review, b). Further, lower rates of photodemethylation due to low sun angles and more turbid flooding waters may account for the higher surface water MeHg concentrations in winter.

### 4.1.2 Twitchell Rice Project (DWR TW-08-03)

The project \textit{Subsidence Mitigation through Rice Cultivation on Twitchell Island} (TW-08-03) focused on carbon and water flows, but in addition, documented surface water MeHg concentrations and loads at six locations from October 2008-November 2009. Unfiltered MeHg concentrations were 2- to 20- fold greater than inflowing San Joaquin River water, and the highest values were found in rice drains relative to corn and oat drains. Further, the highest MeHg concentrations occurred in drains when rice fields had no standing surface water, and the lowest concentrations occurred upon flooding, illustrating the role of advective flow in displacing or diluting MeHg concentrations during the growing season. The redistribution of MeHg-enriched water back on to rice fields, however, appears to have promoted MeHg removal and prevented export of MeHg from the rice fields. This recycling of water was likely responsible for the elevated Hg levels in caged mosquitofish, of which 97% were over the TMDL target during the six-month sampling effort. Additional data from wetland restoration on Sherman Island may be useful for further studies on MeHg responses to hydroperiod on peat soils.

### 4.1.3 Cosumnes River Preserve (EPA 319h and ERP-10-014)

The projects \textit{Wetland Management and Agricultural Organic Matter Reduction to Decrease Methylmercury Loads from the Cosumnes River Preserve} (EPA) and associated project \textit{Wetland and Rice Management to Limit Methylmercury Production and Export} (ERP-10-014) are ongoing from 2010-2012. Rice fields (n=9) have been subjected to one of three scenarios for rice residue
management – swath and bail (removal), chop and disk (burial), and chop only (control). Also with three hydrologic treatments, managed wetlands (n=9) have been kept permanently flooded, spring flooded only or fall and spring flooded. In addition to MeHg concentrations in biota (caged mosquitofish) and surface water, the net effect of these on management practices on sediment processes are being measured, including indices of carbon and mercury availability. Data are forthcoming.

4.2 Case studies on lands with irrigated crop lands

Over 90% of land use in the Delta is agricultural, ranging from row crops to turfgrass to pasture. As an important sink for Delta water, a source of labile carbon, and a potential contaminant source, irrigated crops are a significant landuse with likely implications for MeHg loading in the Delta.

4.2.1 Farmed Islands (CVRWQCB)

The project Assessment of Methylmercury Contributions from Sacramento-San Joaquin Delta Farmed Islands (CVRWQCB 2009) assessed the relative importance of Delta farmed islands to MeHg cycling from 2005-2008. By focusing on water flow rates and MeHg concentrations in drainage channels from a wide range of farmed islands (“polders”), Heim et al. (2009) estimated MeHg loads from farmed islands and investigated their relationship with land management practices and island characteristics such as soil organic content and groundwater hydrology. Of 73 potential farmed islands with agricultural drains, eight were selected for monitoring – four with predominantly mineral soils and 4 with more organic soils. Overall, organic soils had greater average and greater peak seasonal MeHg concentrations in drainage channels. Strong correlations between MeHg and DOC in drainage channels suggest that both are sourced from shallow pore waters advectively driven into subsurface drains during irrigation. Using 2-m deep wells in saturated soils, MeHg concentrations were significantly greater in subsurface vadose zones under flooded rice fields than in deeply drained fields (3-9 ng L\(^{-1}\) v. 0.1-0.4 ng L\(^{-1}\) respectively). Limited water throughput may limit the advective movement of MeHg-rich groundwater into drains, thus limiting MeHg loading to the Delta. Another practice found to enhance MeHg loading into agricultural returns was winter flooding (common in 20% of Delta lands), which promoted subsurface export and presumably MeHg production at the soil surface. Although the drains studied are confidential, farmed islands known to undergo winter flooding and/or rice agriculture (T2 and B2, http://bayDeltaoffice.water.ca.gov/DeltaAtlas/index.cfm) showed greater MeHg flux from surface flow than from subsurface flow, suggesting that MeHg production occurs predominantly at the soil surface. Despite the abundance of farmed fields, their net daily loading from agricultural returns to the Delta was minimal (ranging from -0.5 to 0.6 g d\(^{-1}\)). Nonetheless, local enrichment of MeHg concentrations may have adverse effects on biota present in or near drainage channels.

4.3 Seasonal and spatial processes

The predominance of agricultural land use in the Delta, the variety of agricultural crops and field management, and the range of initial soil and drainage conditions mandate a process-based approach to assessing the most effective management practices for MeHg control. Mineral-based irrigated agricultural fields were not found to discharge large MeHg loads through agricultural returns, but winter flooding may raise MeHg concentrations in surface water to levels detrimental for resident biota. Deltaic organic soils (peat islands) had similar responses among agricultural treatments. Primarily, the onflow of water (irrigation) for rice or row crops appears to promote the
advective flow of DOC and MeHg-laden pore water into drains. MeHg production in agricultural fields and associated wetlands appears to take place only under flooded conditions, and predominantly at the surface where fresh labile carbon is abundant.

While hydrology is clearly important in controlling MeHg fluxes in agricultural fields, it is specifically the advective flows that require clear understanding in order to assess loads. Reducing outflows during the growing season was an effective way of limiting MeHg export from agricultural wetlands in the YBWA. Internal removal processes were promoted but MeHg exposure was high for resident biota. Further, for rice management, a long residence time with minimal water export might be detrimental. Minimum water depths are needed during critical periods of the rice life cycle (so that flower buds are protected from low evening air temperatures which can cause sterilization). Further, unless input waters are initially freshly sourced from the Sacramento River, such as for Twitchell Island, input water conductivity may be elevated during the growing season, and additional evaporation can cause salt (osmotic) stress on the crop plants. Only the minimal amount of water that is needed should be flowed through the rice fields to minimize MeHg export. More attention to water management to optimize water use might require more resources. Further, with all other processes being equal, source water characterization may determine ultimately whether a field is importing or exporting MeHg.

One cultural practice – leaving outflows open and flowing during the wet harvesting of wildrice – led to the highest exports of MeHg in the YBWA study, due primarily to particulate phase MeHg. Appreciation for the effect of physical disturbance on particulate MeHg loads may yield a management practice that allows for settling prior to export. Because particulate MeHg was the dominant phase of aqueous MeHg in permanent wetlands of the YBWA study, settling was likely a primary removal process. Still, dissolved MeHg can sometimes be the dominant aqueous form in permanent ponds (M. Stephenson, pers. comm.). Promotion of this process, by adding tailwater cleaning ponds into the design of agricultural drains, may be a simple cost-effective method to reduce hydrologic export and biotic exposure, especially outside of the wetland boundaries.

The role of carbon is underscored in all the aforementioned agricultural studies. Because crops are genetically predisposed to generate large amounts of easily degradable carbon-based energy, they necessarily promote microbial processes, both during the growing season through root exudates and in the post-growing season through litter decay. Peat soils may be less amenable to carbon management, but, for mineral soils, easy methods of crop residue removal will likely limit MeHg production during post-season flooding. In particular, the residual surficial layer of rice straw remaining in the YBWA and Twitchell Island are likely at play in the high concentrations of sediment MeHg during winter months. Disking or bailing for removal, which are being tested now in the Cosumnes River Project may be reasonable methods of controlling this source of labile carbon that fuels anaerobic microbial metabolisms under flooded conditions. Collateral effects of these control methods on sediment quality are also being assessed.

Finally, as seen in rice and wild rice fields of both the minerotrophic Yolo Bypass soils and the more organic soils of Twitchell Island, fish MeHg bioaccumulation is high in agricultural wetlands with a slow or cyclical throughput of water. Increasing residence time may be valuable for water conservation and reducing MeHg exports, but with the elevated Hg concentrations in Delta soils, those conditions create “hot-spots” for MeHg bioaccumulation. Monitoring should include higher
trophic level predators, such as waterbirds, to insure that resident or migratory avian populations are not seeing declines or inhibited reproduction.

5. Natural Hydrology Systems
The Delta waterways are so highly manipulated that few habitats can be classified as having “natural hydrology”. Nonetheless, for the purpose of informing future decisions on wetland restoration and design, we describe here some results of recent studies from unmanaged, naturally vegetated wetlands subject to episodic and tidal influences.

5.1 Floodplains

5.1.1 Cosumnes River Preserve (USGS, ERP-02-P40)
The CALFED project Evaluation of Mercury Transformations and Trophic Transfer in the San Francisco Bay/Delta: Identifying Critical Processes for the Ecosystem Restoration Program (ERP-02-P40) is evaluating six hypotheses with regard to mercury methylation and demethylation processes at two primary field sites: 1) the Cosumnes River and its floodplain and 2) Franks Tract, a flooded island in the central Delta. Compared to openwater and Egeria-dominated habitats of the central Delta (Franks Tract), the Cosumnes River Preserve site had higher MeHg in water and biota but similar values in sediment (Marvin-DiPasquale et al 2007). Experimental comparison of algal MeHg uptake in these water bodies suggested greater uptake rates in Franks Tract water (Pickhardt and Fisher 2007), even though Franks Tract fish were notably less elevated in MeHg. Initial sediment and water HgT concentrations were not notably different between regions, but reactive Hg(II) pools were greater at the Cosumnes River and its floodplain. The hypothesis most consistent with the observed patterns in the rich dataset of biogeochemical conditions is that the higher rate of sulfide production in the central Delta limited the availability of reactive Hg(II), and thus limited MeHg production. The Cosumnes River floodplain, in particular, is a subhabitat with a rapid and strong response to flooding. Cosumnes River floodplain soils showed elevated MeHg in surface sediments during flooding. While surface water MeHg concentrations did not increase between January and June, caged larval fish showed high levels of MeHg bioaccumulation over the course of spring flooding.

5.2 Brackish-Fresh Tidal Marsh

5.2.1 Browns Island (ERP-00-G01)
The CALFED project Measurement of Mercury Release for Delta Wetlands: Amounts, Alterations, and Implications (ERP-00-G01) added mercury measurements to a previously funded project on organic carbon loads within the Delta. By measuring mercury fractions (filtered and unfiltered MeHg) on the same splits of surface waters being assayed for organic carbon constituents (dissolved organic matter, or DOM, and absorbance profiles) this project helped develop organic matter proxies for MeHg concentrations, thus allowing a continuous record of fluorescent DOM to be used to infer continuous MeHg concentrations. Coupled with continuous flow rate data, the 12-month study estimated fluxes from measured and modeled data. This study is among the first to clearly show a tidal wetland as a net source of MeHg to the estuary in all seasons, with an annual loading of 2.5 mg m⁻² yr⁻¹. At 4-40 times previous estimates, the loading from this wetland type alone represented ~3% of river loading, or 80 g⁻¹ yr⁻¹. Though tidal wetland fluxes are not a large component of the Delta MeHg mass balance, in situ biota may be exposed to high concentrations.
of dissolved MeHg, which dominated aqueous MeHg pools. Particulates, however, varied the most between flood and ebb and thus were the most significant component of net flux on an annual basis. Thus, hydrologic variations may yield source or sink dynamics, as the magnitude of MeHg fluxes was the result of complex interactions of tides, geomorphic features, particle sorption, and random episodic events such as wind storms and precipitation. The study also made a strong case for long-term, high-frequency in situ measurements to develop tidal flux budgets for MeHg, to quantify the small changes between inflow and outflow concentrations.

5.2.2 Liberty Island (BREACH III, ERP-97-C05)

The restoration of intertidal habitat on Liberty Island (BREACH III) shows evidence of carbon and sediment flow from the Cache Slough drainage. The relative importance of these flows for MeHg is poorly understood, and no evidence currently exists to support or refute enhanced bioaccumulation following tidal marsh restoration on Liberty Island. The CALFED project Assessment of Ecological and Human Health Impacts of Mercury in the San Francisco Bay-Delta Watershed (ERP-97-C05) produced a comprehensive MeHg process and monitoring dataset to assess pre-restoration conditions. Biosentinel data from 1999-2000 (Slotton et al. 2002) suggest that waters surrounding Liberty Island were fairly low in MeHg concentration. Further, methylation potential was greater in the organic soils of Liberty, but far below rates measured at Venice Cut and Cosumnes River, again suggesting that Liberty Island has not been historically high in MeHg production. Given the multiple environmental datasets being currently monitored, tracking MeHg dynamics in response to this restoration through time would be a convenient and useful way to test effects of floodplain restoration on MeHg production in the Delta.

5.2.3 Tidal Marshes of the Petaluma River (ERP-02-P62)

The project Mercury and Methylmercury Processes in North San Francisco Bay Tidal Wetland Ecosystems (ERP-02-P62) compared methylmercury production rates and concentration in a variety of tidal marsh environments under fresh-brackish-saline conditions, including sloughs, low tidal marsh, and high tidal marsh (which is only wetted at extreme high tides, approximately 2–6 days per month). The highest concentrations and production rates of MeHg in sediments occurred in the high marsh interiors, rather than in channels or channel edges. This pattern appears to be due to greater availability of reactive Hg(II) and higher activity of Hg(II)-methylating bacteria in densely vegetated, poorly draining organic soils. Bioaccumulation in the resident black rail was correlated with sediment MeHg concentrations. Tidal export in surface waters was measurable but fluxes were inconclusive. Further, photodemethylation was determined to exert only a small influence on MeHg concentrations in surface water, due to high turbidity.

5.2.4 Suisun Marsh (ERP-99-B06)

The project Transport, Cycling, and Fate of Mercury and Monomethyl Mercury in the San Francisco Delta and Tributaries, An Integrated Mass Balance Assessment Approach (ERP-02-C06-a), included a large range of habitats for validation, with two tidal marsh sites continuously monitored for MeHg flux with auto samplers over 25-hour deployments. For the First Mallard station in Suisun Marsh, four of the five studied tidal cycles showed a loss of MeHg, with export from the marsh into the channel (>15% ebb dominated). In Suisun Slough, the loading was dominantly positive (>15% flood dominated), with the marsh being a sink for particulate MeHg.

This section represents a synthesis of previously described, current literature on Hg cycling in the Delta’s wetlands and agricultural fields. The synthesis is presented in two complimentary ways: first listing the knowledge base (what we now know), second listing the knowledge gaps (what we still need to know to answer key management questions), and third listing the datasets that may be amenable to further analysis to infer MeHg load estimates.

6.1 Knowledge Base

Below are listed some consistent observations from the studies described above.

- Permanently flooded wetlands on mineral soils are generally net sinks of MeHg, because net removal (particle settling and photodemethylation) exceeds net production and export.
- The removal of MeHg from surface waters of permanently flooded wetlands can lead to lower in-situ fish MeHg concentrations.
- Sulfate reduction is the dominant energy flow pathway in surface sediments of permanently flooded wetlands, whereas iron reduction dominates seasonal wetlands.
- Sediment MeHg production is enhanced by organic matter and reactive mercury availability, but these pools are rarely optimized under the same conditions.
- The nature and abundance of dissolved organic matter (DOM) is an important variable to monitor as it exerts strong controls on MeHg mobility and speciation, and fluorescent-DOM is a strong proxy for dissolved MeHg in surface water.
- The tight coupling of Hg, C, S and Fe biogeochemical cycles prevents a clear understanding or prediction of how alterations in one or more of these elements will affect Hg methylation rates.
- Holding water longer (lower throughput, longer residence time) can reduce MeHg by promoting photodemethylation and particle settling.
- Due to concentration dependent processes of diffusion and/or degradation, source water, rather than management practices, can determine whether a particular wetland is a net MeHg source or sink.
- Upon flooding, previously dried soils (seasonal wetlands) often release an initial pulse of MeHg, which was likely produced under previously flooded conditions.
- Evaporative and transpirative water loss can lead to a >90% concentration of Hg and related constituents, such as in the shallow water column of a slow-flowing agricultural field.
- Because plant transpiration in rice and wild-rice fields draws 50-75% of surface water through soil, the resulting downward advective flux may limit diffusion of pore water MeHg into surface waters during the growing season and during daylight hours. Diffusive benthic flux of MeHg into the water column of rice fields thus may be limited to nighttime hours and seasonal leaf-off.
- Winter may be the most significant month for MeHg loading from wetlands and agricultural fields, because 1) water flows increase and become less controllable and 2) managed or episodic winter flooding of litter-strewn habitats promotes MeHg production rates.
- At local scales, total Hg concentrations are not often correlated with MeHg concentrations in water or sediment. Therefore, sites of high HgT are not necessarily sites of high MeHg.
- Sub-lethal effects of MeHg exposure on wildlife populations are difficult to identify, but in several SFB and Delta habitats studied, the potential exists for impaired avian reproduction.
6.2 Knowledge Gaps

Despite all that has been learned about mercury cycling from scientific research, the key drivers of MeHg production and fate remain unclear within the Delta and in many other ecosystems globally. Depending on the scale of inquiry, there remains a great deal of uncertainty in how and why environmental MeHg concentrations change across the Delta. Rather than focus on site-specific datagaps (of which there are many), we identify below some key questions that inhibit our current management of Delta resources include:

1) Is atmospherically deposited Hg an important source for MeHg production?
2) Are carbon-rich peat soils more prone to MeHg production than mineral soils?
3) Do different types of DOC throughout the Delta have different influences on MeHg uptake into the base of the foodweb?
4) Does winter-flooding of agricultural fields enhance MeHg exposure among migrating bird populations?
5) How important is bacterial demethylation to limiting MeHg abundance?
6) What are the collateral effects of different land management practices, such as restricting water flow, removing plant litter, or adding coagulating salts?

For these questions, our primary gap in knowledge is a data gap. While site specific work on Hg cycling will be necessary to develop appropriate management practices, ancillary environmental parameters will need to be measured as well to apply the research more broadly and to understand why any given MeHg response is either seen or not seen. Further, quantified rate measurements that could be applied in a modeling framework are essential to extrapolating field data across changing landscape conditions. As we have suggested above, the net patterns of MeHg abundance and bioaccumulation are a balance of multiple processes (or linkages). Recent literature, sampling methods, and technologies have greatly advanced our knowledge of the key physical, chemical, and biological processes to be understood. The next phase of research requires a quantitative multivariate approach to these processes, so that we can understand why a given management strategy may have different outcomes in different sites.

Because Hg transformations and transport through the Delta are influenced by a great many variables – both strong and weak – and because wetlands are not independent from their neighboring habitats, a modeling approach will be necessary to bracket the possible outcomes of different management practices. Without quantification, the net effects of a given management practice will be difficult to understand and apply elsewhere. Although the DRERIP-MCM is helpful in directing research goals, it is a conceptual model, not quantitative, and thus unable to be used to quantify the relative benefits of different management approaches. The Dynamic Mercury Cycling Model developed by Reed Harris (D-MCM; EPRI 2009) provides an ecosystem framework to quantify the pathways of Hg transformation in wetland and aquatic environments. Thus, D-MCM may be a useful tool to test the sensitivity of different wetland types to management alterations.

6.3 Possibilities for post-processing data to infer MeHg loads

While all of these aforementioned studies have value in developing the temporal, spatial, and experimental design of load-reduction studies for a MeHg TMDL, a great limitation among the studies is 1) detailed hydrologic measurements, and 2) ancillary geochemical data that may be used to infer hydrology. MeHg concentrations alone are valuable monitoring data but they are only half of the equation to estimate loading. As was learned in the Yolo Bypass (Sections 3.2.2
and 4.1.1), high MeHg concentrations were generally a function of evapo-concentration rather than net MeHg production, and thus net export was very low, if not negative (MeHg was imported). Further, higher MeHg concentrations were not indicators of MeHg export, but were associated with higher *in situ* bioaccumulation in fish. Although hydrology wasn’t specifically measured during 15 of the 17 aforementioned studies, post-processing of the MeHg concentration data into relative loads may be possible where 1) hydrologic tracer data are available (conductivity, chloride, temperature) or where 2) the hydrology management data are similar among years and are available from management agencies. This could include the Cache Creek Settling Basin, the Twitchell Island rice fields and permanent wetlands, and the Grizzly Island seasonal wetlands.

### 6.4 Summary

Data currently available from field studies in the Delta, and from findings in published literature, suggest hydrologic control (e.g. holding water on site) and carbon control (e.g. limiting surface organic litter), rather than Hg control (e.g. controlling Hg supply), as primary mechanisms to limit MeHg production and export. These data also suggest that monitoring designs must be broadened to incorporate natural temporal variability and biotic responses to MeHg control measures. Further, these data suggest that wetland and agricultural lands are predisposed to MeHg production. Rather than attempting broad Hg source reduction, management of hydrology and carbon during “hot moments” may provide a more efficient field-based mechanism to reduce MeHg production on wetlands, and MeHg loads in tailwater. Some events of concern include early season floodup (release of stored MeHg pools), winter flooding of agricultural and seasonal wetlands, and wet harvesting techniques on rice fields.

This review suggests a positive outlook on attaining the MeHg TMDL targets, by appreciating that not all irrigated and flooded Delta landscapes are MeHg hotspots for production, export and bioaccumulation. Much of the Delta is currently managed, both hydrologically and in agricultural and pastoral landuse, and may be amenable to simple changes in cultural practice.

### 7. Application of Knowl edge Base toward Development of Methylmercury Control Studies

The RWQCB seeks to use previous knowledge to design control studies for existing land uses and water management practices to meet MeHg allocations. Many of the questions in the posted guidance document (updated 5/15/12) are based on site-specific control options, and most address the question of whether a practice might be feasible and/or effective. A few questions were selected and addressed below to begin the process of addressing these decisions.

1. Of the below factors that affect methylmercury production, fate, and transport, which could be adjusted?
   a) concentration of total mercury in source water and in sediment?
      a. Not feasible except at regional scale
   b) organic material (dissolved and sediment-based) available to methylating bacteria?
      a. Feasible where vegetation is managed (e.g. croplands)
      b. Potential negative consequences
   c) degree and extent of anaerobic conditions?
      a. Feasible where water depths and quality are managed (e.g. mechanical aeration)
b. Potential negative consequences
d) cycle of wetting and drying of land surface?
   a. Feasible where water control structures allow management
   b. Potential negative consequences
e) residence time, clarity, and depth of water (affect rates of photodemethylation and loss through particle settling)?
   a. Not feasible without changing landuse goals
f) extent of wetted surface
   a. Not feasible without changing landuse goals
g) management of water (includes extent of wetted surface; flow, seasonality and extent of inundation)
   a. Feasible in managed wetlands
   b. Potential negative consequences
h) concentrations and forms of chemicals that affect reactivity of mercury (for example, ferrous ion, selenium, nitrate, sulfide and sulfate)
   a. Only feasible by chemical dosing in perpetuity
   b. High likelihood of negative consequences

2. Would reducing total mercury in your source water result in reducing methylmercury levels in your discharge?
   a) The general abundance of mercury within Delta soils and annual riverine inputs reduces the importance of HgT as a driver for MeHg production and export.
   b) Rather than HgT, the pool of reactive Hg(II) is more dynamic in time and space and more mechanistically associated with sediment MeHg production.

3. Which management options would enable effluent methylmercury concentrations to be reduced to equal to or less than the implementation goal for ambient Delta water (an annual average of 0.06 ng/l)? Or, if source water methylmercury concentrations are above 0.06 ng/L, which management options would enable discharge methylmercury concentrations to not exceed source water methylmercury concentrations?
   a) The magnitude of MeHg degradation or sequestration that is necessary to meet the implementation goal varies widely with source water, which varies by site and season.
   b) Management options that enhance degradation and sequestration processes (photodemethylation, particle settling, downward advection through plant transpiration) all may have a generally positive effect on reducing source water concentrations. The primary driver has to be that MeHg degradation exceeds production and release.

4. What are the negative and positive environmental effects of the management practices or activities being tested? Do they counter current practices for pollution control and other issues of environmental quality?
   a) The practice of restricted water flow may enhance water use efficiency within land uses, but may lead to negative impacts on crops and native biota (salinity, alkalinity, dissolved oxygen) as well as inhibiting mosquito control techniques.
   b) The practice of post-harvest litter control may reduce both methane and methylmercury production, but may lead to negative impacts on over-wintering biota and/or sediment quality (e.g. loss of organic matter, compaction).
5. Is there sufficient information to be able to apply the management practices or activities in an adaptive manner?
   a) The feasibility of management practices is subject to site-specific conditions which may change over time.
   b) A modeling approach – conceptual and quantitative – allows efficient targeting of necessary data collection. Further, mechanistic models allow better use of monitoring data to understand why changes are observed over time and space.

8. Acknowledgments

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Potential Management Practices to Control Methylmercury in Discharges from Non-point Sources within the Sacramento-San Joaquin Delta

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Introduction

The Sacramento-San Joaquin Delta (Delta) provides a beneficial recreational use area to humans as well as valuable habitats to fish, birds, and wildlife. Significant beneficial uses of the Delta are impaired due to elevated methylmercury (MeHg) levels in fish and wildlife. MeHg is a potent neurotoxin and is a mercury species that readily bioaccumulates and biomagnifies in foodwebs. State regulators recently developed a total maximum daily load (TMDL) to reduce MeHg concentrations in Delta fish to protective levels.

In this report we discuss a variety of management practices (MPs) intended to reduce aquatic loading of MeHg from non-point sources (NPS) of differing land use types within the Delta. Windham-Myers and Ackerman (2012) present a synthesis of mercury science to support the development of Delta NPS control studies to implement the Delta TMDL. That synthesis and other research, published or on-going, was used to identify these MPs.

Land Use Types

The MPs are grouped by NPS land use types reported by Windham-Myers and Ackerman (2012) as follows:

- Managed Wetlands (permanently flooded\(^1\) and seasonally flooded)
- Agricultural Lands (flooded and irrigated)
- Natural Hydrology Systems (floodplains and brackish-fresh tidal marsh).

MPs are discussed for each of these land use types (Photos 1-6), recognizing how differing land uses and management, water sources and management, soil types, and other factors will influence the effectiveness and/or viability of a given MP. Nonetheless, there may be MPs that are useful at reducing MeHg loads across multiple categories of NPS.

A synthesis of current knowledge of MeHg cycling in the Delta suggests that wetlands and certain agricultural lands are predisposed to MeHg production (Windham-Myers and Ackerman, 2012). Windham-Myers and Ackerman (2012) suggests that rather than attempting broad source

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\(^1\) Permanently flooded wetlands are defined as being inundated with water and their bottom sediments not allowed to dry out between seasonal cycles.
reduction in organic mercury across a broad range of land use types, management of hydrology and carbon during “hot moments” [times and places that are more prone to intense MeHg production] may provide a more efficient mechanism to reduce MeHg production on fields, bioaccumulation, and MeHg loads in tail water. This report focuses on the following three broad categories of MPs aimed at reducing MeHg loads from NPS: Biogeochemistry, Hydrology, and Vegetation and Soils. We describe MPs in each category below and summarize these MPs in the context of the land use and land management for which they are best implemented (Tables 1-6).

Management Practices

Biogeochemistry

Apply Coagulant

The use of metal-based coagulants (e.g. ferric chloride, ferric sulfate, aluminum sulfate, PACs – polyaluminum chlorides) is routinely used by the drinking water industry to remove particles, dissolved organic matter and phosphorus from drinking water. Because inorganic Hg and MeHg are closely associated with particles and DOM, addition of these coagulants to natural waters is expected to sequester the Hg in the organo-metal precipitate, termed flocculate or floc (Henneberry et al., 2011; 2012). This MP would involve applying coagulants to natural waters and letting the resulting material settle out of solution, thereby reducing water column total and MeHg concentrations. In some cases, the resulting flocculate could be retained and removed from the natural environment. Questions related to this MP include Hg related questions and logistical / implementation related questions. Hg related questions include (1) Is the Hg retained in the flocculate subject to bioaccumulation and/or transport? (2) Are there any adverse toxicity effects to fish and wildlife related to the addition of specific types of coagulants? (3) What are the biogeochemical effects resulting from coagulation? (4) Do iron-based flocs change near redox conditions to suppress mercury methylation rates, predominantly from sulfate reducing bacteria, providing a mechanism to suppress or prevent the upward movement of MeHg from wetland sediments? The low-intensity chemical dosing project on Twitchell Island is investigating logistical questions related to required infrastructure, system operation, operations & maintenance, and economics. Some questions on implementation and robustness of this technology may remain. This MP may be most appropriate for a single point of discharge (e.g. island drains) and sites associated with a treatment wetland.

Aerate

This MP involves aeration of wetlands to increase redox potential in the water column and in surficial sediments. The rationale behind this MP is that oxic conditions will suppress the production of MeHg by iron- and sulfate-reducing bacteria and decrease MeHg flux from the sediments into overlying water. However, sediments contain many aerobic bacteria that use oxygen already present, thereby creating and maintaining the anaerobic conditions necessary for

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2 USGS Agreement Number CL8WRAG0001 (Prime Agreement) with DWR for research project entitled "Investigating In Situ Low Intensity Chemical Dosing to Decrease Delta Waters DOC Concentrations and OBP Precursors While Accelerating Wetland Peat-Accretion Rates and Reducing Flood Risks".
the methylation of Hg (Mailman et al., 2006). Also, studies have shown that oxygenation didn’t stop MeHg supply but rather created oxic conditions that enticed zooplankton to migrate lower in the water column and thus bioaccumulate greater amounts of MeHg than they would have if the anoxic boundary had remained in place (Dent *et al.*, 2011).

*Add Nitrate*

This MP involves adding nitrate to wetlands during suboxic conditions. The rationale behind this MP is that adding nitrate during low DO conditions may reduce the flux of MeHg from sediments by providing additional electron acceptors to microbial reactions allowing other bacteria to outcompete sulfate reducers thereby decreasing MeHg production (Auer *et al.*, 2008). There are several potential negative impacts for this MP. First, addition of nitrate would change water chemistry with unknown results. Second, increasing nitrogen supply would likely increase organic carbon supply and result in an increase in MeHg production (Luengen and Flegal, 2009).

*Increase Fish Population*

This MP involves using fish to sequester MeHg and then harvesting the fish. The rationale behind this MP is that MeHg will move from the water column into plankton, zooplankton, and then small fish at a rate sufficient to remove a large percentage of MeHg from the water column resulting in decreased MeHg loads from the wetland. Fish typically contain on the order of one million fold higher concentrations of MeHg than the water in which they live. The fish would then be harvested to remove MeHg from the system. This is analogous to current practices of aquaculture, and also occurs in Asia where subsistence farmers farm both rice and fish that use rice paddies simultaneously. There are several questions concerning the application of this MP: (1) Will biomagnification of MeHg remove a large fraction of MeHg from the water column? (2) Will local piscivores be adversely impacted? (3) How and where will the harvested fish be disposed? (4) What species and density of fish is needed to effect a significant removal of MeHg from the system? (5) What potential adverse water quality issue might arise?

*Amend Soil with Iron*

This MP involves adding ferrous iron to soil prior to flooding. The rationale behind this MP is that MeHg production will be decreased by decreasing the formation of Hg-sulfide complexes which is thought to be the form of Hg which is methylated by bacteria (Mehrotra and Sedlak, 2005). Currently, this MP has not been shown to be effective at landscape scales. The questions concerning this MP are: (1) How much iron to add to a wetland? (2) Would the amount of iron added need to be determined for each location this practice is used? (3) How often do applications need to be done? (4) What does the addition of iron do to soil quality? (5) What are the unintended consequences of soil amendments?

*Amend Soil with Sulfate*

This MP involves adding sulfate (CaSO$_4$) to wetland soil prior to flood-up. The rationale is to make inorganic Hg unavailable for methylation by the formation of insoluble HgS. In reality, the addition of sulfate has been shown to increase the methylation of remaining Hg (King *et al.*, Appendix C – Wetlands and Irrigated Agriculture Management Practices
Furthermore, sulfate concentrations in many Delta wetlands already have been elevated as a result of applied fertilizers and soil conditioners (gypsum) and MeHg concentrations and production have not been decreased (Marvin-DiPasquale et al., In review; Heim et al., unpublished data from current Yolo Project). This MP would not be effective at reducing MeHg loads from wetlands.

**Hydrology**

*Recirculate Drainage Water*

This MP eliminates MeHg discharge by holding more water on site and applying new water as needed. The rationale behind this MP is that eliminating discrete drain events between the wetlands and adjacent water ways will eliminate MeHg loads. Heim et al., (2009) recommended recirculating drainage water for irrigation as a way to reduce MeHg loads from Delta farmed islands. For Twitchell Island rice fields, recycling rice and island drain water onto the rice fields during irrigation season has enabled those fields to be a net sink for water quality constituent loads, including Hg (Deverel et al., 2012). Potential negative impacts may include poorer water quality for some constituents of concern on the wetland, increased salinity, increased bioaccumulation and risk to fish and wildlife, and reduced wetland area for drainage recovery. This MP might be best suited for certain periods of time when MeHg concentrations are elevated. Islands in the deep Delta continuously pump water to enable growing terrestrial crops on those islands. The Agriculture and Food Research Initiative (AFRI) project is investigating using crop mosaics of terrestrial crops, rice and wetlands to recycle and recirculate island water to more efficiently utilize water and reduce exports of water quality constituents of concern. Technical questions associated with recycling include 1) how does recycling affect MeHg concentrations across different soil types and organic content in the Delta; 2) what are potential impacts on bioaccumulation, toxicity, and bioexport; 3) what configurations and cultural practices most affect in-field MeHg concentrations and their impact on the timing of recycling; and 4) what are the economic issues at the local, regional and state scale. Additional logistical questions relate to understanding approaches at the island scale, accommodating subsurface flow paths and loading, and addressing seasonal issues affecting recycling approaches.

*Increase Water Residence Time*

This MP decreases MeHg loads by allowing natural processes to reduce water column MeHg concentrations. The rationale behind this MP is that increasing the amount of time water is held on site allows for MeHg removal processes to occur such as photodegradation and removal to the sediments by particle settling (Fleck et al., In review; Byington, 2007; Heim et al., In review). Photodegradation rates are a function of MeHg concentrations, intensity of solar irradiation, and light penetration. Particle settling rate depends on water depth and turbulence, and amount and size of particulates. There are several questions concerning the application of this MP: (1) Will MeHg production at a site offset the MeHg destruction processes? (2) How will increased water residence time affect water quality? (3) What residence time is most beneficial to MeHg removal and how is it affected seasonally? (4) How do you manage a wetland to promote
photodegradation while encouraging more open water and discouraging thick vegetation cover and algal growth?

**Increase Water Depth**

This MP decreases MeHg by discouraging the growth of emergent vegetation. The rationale is that keeping water in permanent wetlands deeper than 1 m will discourage growth of emergent vegetation and decrease available carbon and habitat shown to promote MeHg production. This MP would only be applicable to habitats were water levels could be maintained year round. The following questions concern the application of this MP: (1) Will ecosystem productivity be decreased? (2) Will habitat value be decreased?

**Increase Water Velocity**

This MP decreases exposure of water to MeHg hotspots within shallow wetlands by increasing water velocity. The rationale behind this MP is that if you decrease exposure of water to areas of emergent vegetation and higher MeHg production by moving water through the wetland in high velocity channels there will be a decrease in MeHg load off of the wetland. This MP is best suited for locations that have low MeHg concentrations source water to the wetland. There are several questions concerning the application of this MP: (1) Can wetlands be effectively short circuited without diminishing other water quality parameters? (2) Will bioaccumulation in the wetland be increased? (3) What will be the effect on habitat value?

**Pre-flood Wetland**

This MP consists of a flood-up cycle involving flooding, draining, and immediately re-flooding the wetland. The rationale behind this MP is that flooding the wetland surface will initiate the vegetation decomposition process, saturate the soils, and establish flow paths within the wetlands, which should help to reduce the production of low DO hotspots and methylmercury production. Siegel et al. (2011) found in Suisun Marsh duck clubs in 2007 that this practice resulted in large spikes of DOC and MeHg discharged into the adjacent sloughs during the first flush.

**Flood and Hold**

This MP eliminates the discharge of wetland water into adjacent water. The rationale behind this MP is that eliminating discrete drain events between the wetlands and adjacent water ways will eliminate all MeHg load. It would also allow for photodemethylation and microbial degradation of DOC to take place in wetland waters rather than deteriorating water quality of adjacent water ways (Siegel et al., 2011). This MP is different from “recirculate drainage water” described above in that no new water is applied to the wetland and pumps are not used to move water. This MP could potentially be used if wetland management issues can be resolved. These issues include deteriorated water quality and impairment to water fowl habitat and other wildlife, and increased salinity.

**Timing Water Discharge**
This MP decreases the exchange of wetland water with adjacent water during times of poor water quality on the wetland. The rationale behind this MP is that eliminating discrete drain events and reducing exchange between the wetlands and adjacent water ways will reduce MeHg loads (Windham-Meyers et al., 2010). It is similar to “flood and hold” described above but does allow for a limited amount of discharge to adjacent water ways. It would also allow for photodemethylation and microbial degradation of DOC to take place in wetland waters rather than deteriorating water quality of adjacent water ways. There is potential for deteriorated water quality and increased bioaccumulation within the wetland.

**Delay Fall Flood Up**

This MP involves flooding wetlands as late as possible in advance of the fall waterfowl management and hunting season. The rationale behind this MP is to flood-up when water temperatures are as low as possible in order to reduce temperature-dependent microbial activity as water temperatures decrease into the fall season. Siegel et al. (2011) reported temperature was not limiting BOD rates and that, although biogeochemical processes are exponentially affected by temperature, this effect is still relatively small during the fall period. A major disadvantage of this MP is that it would compress the time period over which a suite of wetlands at a given location divert water. It may also hinder normal wetland management operations and reduce habitat available for early migrating waterfowl and shorebirds.

**Stagger Flood/Drain Events**

This MP involves staggering in time the flooding and draining of multiple wetlands connected to one waterway. The rationale behind this MP is that decreasing the number of wetlands flooding at any one time will decrease the magnitude of net-upstream flow and thereby decrease the magnitude of MeHg load to the receiving water. In effect, the MP is a ‘temporal’ dilution approach (Siegel et al., 2011). Questions remain as to what effect this MP would have on water quality within the wetland while waiting to discharge. Implementation of this MP would require close coordination among wetland managers. Wetland management could be complicated due to a shortened time period for initial flood-up management for those wetlands flooded later.

**Use Permanent Wetlands as Treatment Ponds**

This MP involves routing high MeHg concentration tailwater from seasonal wetlands through permanent wetlands. The rationale behind this MP is that seasonal wetlands are producers of MeHg and generally have high MeHg concentrations relative to permanent wetlands (Heim et al., In review). Moving water from the seasonal wetlands into permanent wetlands prior to discharging allows removal processes such as photodegradation and particulate settling to decrease MeHg concentration. In addition, bioaccumulation in permanent wetlands is lower relative to other wetland types (Ackerman and Eagles-Smith, 2010). This MP is most effective in locations where permanent wetland receiving water has high MeHg concentrations. If source water is low in MeHg loads from permanent wetlands may be a net source.

**Manipulate Flooding Period**

Appendix C – Wetlands and Irrigated Agriculture Management Practices
This MP involves controlling the time a field is flooded. One rationale behind this MP is that shortening the period of inundation on a field will limit the amount of vegetation grown during the summer and thereby limit the amount of organic matter in the wetlands when they are flooded in the winter (Windham-Meyers et al., 2010). The end result would be less MeHg production by bacteria due to carbon limitation. A study using this MP on agricultural fields is in progress on the Cosumnes Reserve and results may apply to non-agricultural seasonal wetlands as well (Eagles-Smith, 2012). Another rationale for this approach could be the timing of flooding. In the Yolo Bypass, flooding of rice fields in the fall increased MeHg concentrations in the water column and this was presumed to be because of the high available organic content (from rice harvesting) at the time of flooding (Bachand et al, 2012a in progress, Bachand et al, 2012b in progress). Thus, timing flooding to periods of time with lower available organic carbon could reduce MeHg production and export. Questions remain about effect of this MP on habitat value and vegetation selection.

Irrigate Fields in Series Versus Parallel

Similar to recycling of irrigation water, the routing of water through rice fields and managed wetlands, where one field or wetland discharges into another at its inlet, may reduce MeHg loading through several mechanisms including increasing water loss to evapotranspiration (ET) thus reducing the loading to channel waters and sequestering the MeHg within the wetland, reducing the diffusive flux of MeHg from the soil into the overlying water column by reducing the concentration gradient throughout much of the managed area and ultimately creating a longer residence time for the water from initial irrigation draw to ultimate discharge. This approach likely reduces MeHg exports at the cost of increasing MeHg concentrations within the wetlands and rice fields where evapoconcentration and MeHg production occur but may reduce MeHg concentrations where removal mechanisms are dominant. This approach is dependent upon island configuration, topography and other logistical factors.

Raise Depth of Drainage Ditches

Within subsided Delta islands where peat soils dominate, water exports and contaminants derived from soil processes (including MeHg) are largely determined by the hydraulic gradient between the wetland or rice water level and drainage ditch water level. Drainage ditches in the Delta are maintained at low water levels to promote an aerated root zone for much of the island which is controlled by island pumps. Raising the water level in drainage ditches within areas where rice or wetlands are established on these islands will reduce the water flow through the soils to the drains thus reducing the island load. The raising of ditch water levels lowers the hydraulic gradient through the soils creating a surface water dominated system that is more in balance with ET using less water, reducing loads to the drains and ultimately reducing loads from the islands. The effectiveness of this approach is likely limited to drainage systems in peat soils of the Delta. The change in hydrologic flow paths on the exchange of MeHg between the surface soil and overlying water in these systems that is not well understood or studied, therefore in situ effects are unknown.

Irrigate Fields with Drip Irrigation Systems
This MP limits advective drainage to ditches from irrigated agricultural fields by utilizing drip irrigation systems to supply water at agronomic rates (i.e., no excess water to run off or seep below the root zone). The rationale behind this MP is that eliminating excess water will eliminate discharges from the agricultural fields to adjacent waterways thus eliminating MeHg loads. Periodic flooding would be required on many of the Delta islands to flush out accumulated salts from the root zone.

**Soils and Vegetation**

**Burn Vegetation and Soils**

This MP involves burning above ground vegetation and exposing soils to high temperatures prior to flooding. The rationale behind this MP is that MeHg production will be decreased as inorganic Hg and organic material is removed by combustion making them unavailable to methylating bacteria. Negative impacts of burning are decreased air quality as particulates and elemental Hg are released to the atmosphere. This MP is also limited to more mineral soils. Peat and highly organic soils in the Delta can burn and result in catastrophic problems. There also may be local restrictions to burning that would limit this MP’s utility. Furthermore, this practice would run counter to “conservation agriculture” principles of leaving organic material on site.

**Till Vegetation Below Soil Surface**

This MP involves tilling soil to move vegetation below the layer of soil where methylation occurs. The rationale behind this MP is that MeHg production will be decreased as organic matter used by methylating bacteria is moved below the soil horizon where methylation occurs. This MP is not appropriate for organic, peaty soils. A negative impact of this MP is that it may remove desired food sources for waterfowl. This MP is currently part of a study on agricultural fields but results may apply to non-agricultural seasonal wetlands (Eagles-Smith, 2012).

**Bale and Remove Vegetation**

This MP involves baling vegetation and hauling it off-site for disposal. The rationale behind this MP is that removing vegetation will remove a major source of labile carbon and thus reduce MeHg production following flood-up. Laboratory tests verified the role of vegetation residue as a source of enhanced MeHg production (Heim et al., Submitted). The benefit of this practice is that it physically removes surficial organic matter from the system (above-ground biomass but not the below-ground root system biomass) as opposed to leaving it within the wetland to be broken down by microbial activity. The MP is anticipated to reduce MeHg production within managed wetlands. This MP is currently being used as part of a study on agricultural fields but results may apply to non-agricultural seasonal wetlands (Eagles-Smith, 2012). Several questions would need to be addressed for this MP: (1) How does baling and removal of vegetation affect growth and establishment of new vegetation? (2) What are the potential adverse environmental impacts to a sustainable Delta, specifically as related to subsidence and managing hydrologic risks to the islands? (3) What are the economics behind this practice and how do you make it
sustainable (4) Is disturbance resulting in MeHg pulses during vegetation removal? and (5) What are its effects on food value, habitat and soil quality?

**Graze Fields with Livestock**

Grazing would replace mowing and herbicide application as the method for removing unwanted vegetation from the wetlands during the summer dry-land management period. The rationale behind this MP is that plant consumption by grazing will remove a major source of labile carbon from the system and thus reduce MeHg production (Heim et al., In review). The benefit of grazing is that it actually removes organic matter from the system as opposed to leaving it within the wetland to be broken down by microbial activity, as is the case with herbicide and mowing treatments. The main concern with grazing is that animals could consume the plant seeds that make for quality waterfowl forage. Several questions are associated with grazing including: (1) Does grazing reduce seed production or disbursement of preferred vegetation? (2) What type of livestock is best suited for grazing? (3) Will certain livestock such as cattle have footing issues or damage the habitat through trampling? (4) What is the contribution of cattle waste (i.e., manure) to organic carbon, ammonia, and pathogens?

**Management Practices Tables**

A summary of MPs for each land use and management type are listed in Tables 1-6 below. A unique identification (MP No.) is given for each MP. Each MP is categorized into one of three management types/focus (Biogeochemistry, Hydrology, and Vegetation and Soils) for easy reference and detailed descriptions for each MP are found above by matching management practice name. The mechanism by which the MP reduces MeHg load is identified under the mechanism heading. Finally, the rank of these MPs assigned by the NPS workgroup is presented in the Knowledge Base Memo.

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Abbreviations

Agriculture and Food Research Initiative (AFRI)
Biological oxygen demand (BOD)
Dissolved organic carbon (DOC)
Dissolved oxygen (DO)
Evapotranspiration (ET)
Management practices (MPs)
Mercury sulfide (HgS)
Meter (m)
Methylmercury (MeHg)
Non-point sources (NPS)
Sacramento-San Joaquin Delta (Delta)
Total maximum daily load (TMDL)
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<th>Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW-pw-1</td>
<td>Biogeochemistry</td>
<td>Apply coagulant</td>
<td>Addition of metal based coagulant binds DOC and associated inorganic Hg and MeHg</td>
</tr>
<tr>
<td>MW-pw-2</td>
<td>Biogeochemistry</td>
<td>Aerate</td>
<td>Maintain DO levels in water column that prevent MeHg production and sediment flux</td>
</tr>
<tr>
<td>MW-pw-3</td>
<td>Biogeochemistry</td>
<td>Add nitrate</td>
<td>Denitrifying bacteria out-compete sulfate reducers to decrease MeHg production</td>
</tr>
<tr>
<td>MW-pw-4</td>
<td>Biogeochemistry</td>
<td>Increase fish population</td>
<td>Small fish accumulate MeHg and then are harvested</td>
</tr>
<tr>
<td>MW-pw-5</td>
<td>Biogeochemistry</td>
<td>Amend soil with iron</td>
<td>Reduce Hg methylation rates by decreasing Hg-sulfide complexes</td>
</tr>
<tr>
<td>MW-pw-6</td>
<td>Hydrology</td>
<td>Recirculate drainage water</td>
<td>No discharge of water results in no discharge of MeHg</td>
</tr>
<tr>
<td>MW-pw-7</td>
<td>Hydrology</td>
<td>Increase water residence time</td>
<td>Photodegradation and particle settling</td>
</tr>
<tr>
<td>MW-pw-8</td>
<td>Hydrology</td>
<td>Increase water depth</td>
<td>Eliminate habitat shown to promote MeHg production</td>
</tr>
<tr>
<td>MW-pw-9</td>
<td>Hydrology</td>
<td>Increase water velocity</td>
<td>Decrease exposure of water to areas of higher MeHg production by moving water through wetland in high velocity channels</td>
</tr>
<tr>
<td>MW-pw-10</td>
<td>Hydrology</td>
<td>Timing water discharge</td>
<td>Reduce load of MeHg by limiting water discharge</td>
</tr>
<tr>
<td>MP No.</td>
<td>Management Type/Focus</td>
<td>Management Practice Name</td>
<td>Mechanism</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------</td>
<td>--------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>MW-sw-1</td>
<td>Biogeochemistry</td>
<td>Apply coagulant</td>
<td>Addition of metal based coagulant binds DOC and associated inorganic Hg and MeHg</td>
</tr>
<tr>
<td>MW-sw-2</td>
<td>Biogeochemistry</td>
<td>Aerate</td>
<td>Maintain DO levels in water column that prevent MeHg production and sediment flux</td>
</tr>
<tr>
<td>MW-sw-3</td>
<td>Biogeochemistry</td>
<td>Add nitrate</td>
<td>Denitrifying bacteria out-compete sulfate reducers to decrease MeHg production</td>
</tr>
<tr>
<td>MW-sw-4</td>
<td>Biogeochemistry</td>
<td>Amend soil with iron</td>
<td>Reduce Hg methylation rates by decreasing Hg-sulfide complexes</td>
</tr>
<tr>
<td>MW-sw-5</td>
<td>Biogeochemistry</td>
<td>Amend soil with sulfate</td>
<td>Bind inorganic mercury making it unavailable for methylation</td>
</tr>
<tr>
<td>MW-sw-6</td>
<td>Hydrology</td>
<td>Pre-flood wetland</td>
<td>Briefly wetting the marsh plain stimulates aerobic breakdown of organic matter and decreases subsequent MeHg loads</td>
</tr>
<tr>
<td>MW-sw-7</td>
<td>Hydrology</td>
<td>Flood and hold</td>
<td>Eliminating discrete drain events and reducing exchange between the wetlands and sloughs isolates poor quality water within the wetlands</td>
</tr>
<tr>
<td>MW-sw-8</td>
<td>Hydrology</td>
<td>Delay fall flood up</td>
<td>Flood up occurs when water temps are lower to reduce microbial activity and production of MeHg</td>
</tr>
<tr>
<td>MW-sw-9</td>
<td>Hydrology</td>
<td>Stagger flood/drain events</td>
<td>Eliminate multiple discharges to one location at one time to reduce MeHg load to adjacent waterways</td>
</tr>
<tr>
<td>MW-sw-10</td>
<td>Hydrology</td>
<td>Increase water residence time</td>
<td>Photodegradation and particle settling</td>
</tr>
<tr>
<td>MW-sw-11</td>
<td>Hydrology</td>
<td>Recirculate drainage water</td>
<td>No discharge of water results in no discharge of MeHg</td>
</tr>
<tr>
<td>MW-sw-12</td>
<td>Hydrology</td>
<td>Increase water velocity</td>
<td>Decrease exposure of water to areas of higher MeHg production by moving water through wetland in high velocity channels</td>
</tr>
<tr>
<td>MW-sw-13</td>
<td>Hydrology</td>
<td>Use permanent wetlands as treatment ponds</td>
<td>Particle settling; photodegradation; uptake by biota</td>
</tr>
<tr>
<td>MW-sw-14</td>
<td>Hydrology</td>
<td>Manipulate flooding period</td>
<td>Limits organic matter in wetlands when flooded in the winter and decreases MeHg production</td>
</tr>
<tr>
<td>MW-sw-15</td>
<td>Vegetation and Soils</td>
<td>Burn vegetation and soil</td>
<td>Decrease MeHg production by removing methylating bacteria food source and inorganic Hg used to form MeHg</td>
</tr>
<tr>
<td>MW-sw-16</td>
<td>Vegetation and Soils</td>
<td>Till vegetation below soil surface</td>
<td>decreases methylating bacteria activity</td>
</tr>
<tr>
<td>MW-sw-17</td>
<td>Vegetation and Soils</td>
<td>Bale and remove vegetation</td>
<td>decreases methylating bacteria activity</td>
</tr>
<tr>
<td>MW-sw-18</td>
<td>Vegetation and Soils</td>
<td>Graze fields with livestock</td>
<td>decreases methylating bacteria activity as organic carbon is repackaged into less reactive form</td>
</tr>
</tbody>
</table>
Table 3. Agricultural Lands – Flooded Agricultural Lands

<table>
<thead>
<tr>
<th>MP No.</th>
<th>Management Type/Focus</th>
<th>Management Practice Name</th>
<th>Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL-fal-1</td>
<td>Biogeochemistry</td>
<td>Apply coagulant</td>
<td>Addition of metal based coagulant binds DOC and associated inorganic Hg and MeHg</td>
</tr>
<tr>
<td>AL-fal-2</td>
<td>Biogeochemistry</td>
<td>Add nitrate</td>
<td>Denitrifying bacteria out-compete sulfate reducers to decrease MeHg production</td>
</tr>
<tr>
<td>AL-fal-3</td>
<td>Biogeochemistry</td>
<td>Amend soil with iron</td>
<td>Decrease Hg methylation rates by decreasing Hg-sulfide complexes</td>
</tr>
<tr>
<td>AL-fal-4</td>
<td>Biogeochemistry</td>
<td>Amend soil with sulfate</td>
<td>Bind inorganic mercury making it unavailable for methylation</td>
</tr>
<tr>
<td>AL-fal-5</td>
<td>Hydrology</td>
<td>Increase water residence time</td>
<td>Photodegradation and particle settling</td>
</tr>
<tr>
<td>AL-fal-6</td>
<td>Hydrology</td>
<td>Manipulate flooding period</td>
<td>Limits organic matter in wetlands when flooded in the winter and decreases MeHg production</td>
</tr>
<tr>
<td>AL-fal-7</td>
<td>Hydrology</td>
<td>Recirculate drainage water</td>
<td>No discharge of water results in no discharge of MeHg</td>
</tr>
<tr>
<td>AL-fal-8</td>
<td>Hydrology</td>
<td>Stagger flood/drain events</td>
<td>Eliminate multiple discharges to one location at one time to reduce MeHg load to adjacent waterways</td>
</tr>
<tr>
<td>AL-fal-9</td>
<td>Hydrology</td>
<td>Use permanent wetlands as treatment ponds</td>
<td>Particle settling; photodegradation; uptake by biota</td>
</tr>
<tr>
<td>AL-fal-10</td>
<td>Hydrology</td>
<td>Irrigate fields in series versus parallel</td>
<td>Reduces MeHg loading through increasing water loss to evapotranspiration and reducing diffusive flux of MeHg from soil into overlying water column.</td>
</tr>
<tr>
<td>AL-fal-11</td>
<td>Hydrology</td>
<td>Raise depth of drainage ditches</td>
<td>Raising the water level in drainage ditches will reduce the water flow through the soils to the drain thus reducing the load.</td>
</tr>
<tr>
<td>AL-fal-12</td>
<td>Vegetation and Soils</td>
<td>Burn vegetation and soil</td>
<td>Decrease MeHg production by removing methylating bacteria food source and inorganic Hg used to form MeHg</td>
</tr>
<tr>
<td>AL-fal-13</td>
<td>Vegetation and Soils</td>
<td>Till vegetation below soil surface</td>
<td>Decreases methylating bacteria activity</td>
</tr>
<tr>
<td>AL-fal-14</td>
<td>Vegetation and Soils</td>
<td>Bale and remove vegetation</td>
<td>Decreases methylating bacteria activity</td>
</tr>
</tbody>
</table>

Appendix C – Wetlands and Irrigated Agriculture Management Practices
<table>
<thead>
<tr>
<th>MP No.</th>
<th>Management Type/Focus</th>
<th>Management Practice Name</th>
<th>Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL-icl-1</td>
<td>Biogeochemistry</td>
<td>Apply coagulant</td>
<td>Addition of metal based coagulant binds DOC and associated inorganic Hg and MeHg</td>
</tr>
<tr>
<td>AL-icl-2</td>
<td>Biogeochemistry</td>
<td>Amend soil with iron</td>
<td>Decrease Hg methylation rates by decreasing Hg-sulfide complexes</td>
</tr>
<tr>
<td>AL-icl-3</td>
<td>Biogeochemistry</td>
<td>Amend soil with sulfate</td>
<td>Bind inorganic mercury making it unavailable for methylation</td>
</tr>
<tr>
<td>AL-icl-4</td>
<td>Hydrology</td>
<td>Recirculate drainage water</td>
<td>No discharge of water results in no discharge of MeHg</td>
</tr>
<tr>
<td>AL-icl-5</td>
<td>Hydrology</td>
<td>Stagger flood/drain events</td>
<td>Eliminate multiple discharges to one location at one time to reduce MeHg load to adjacent waterways</td>
</tr>
<tr>
<td>AL-icl-6</td>
<td>Hydrology</td>
<td>Use permanent wetlands as treatment ponds</td>
<td>Particle settling; photodegradation; uptake by biota</td>
</tr>
<tr>
<td>AL-icl-7</td>
<td>Hydrology</td>
<td>Irrigate fields with drip irrigation systems</td>
<td>Limited water discharge results in lower MeHg loads</td>
</tr>
<tr>
<td>AL-icl-8</td>
<td>Vegetation and Soils</td>
<td>Burn vegetation and soil</td>
<td>Decrease MeHg production by removing methylating bacteria food source and inorganic Hg used to form MeHg</td>
</tr>
<tr>
<td>AL-icl-9</td>
<td>Vegetation and Soils</td>
<td>Bale and remove vegetation</td>
<td>Decreases methylating bacteria activity</td>
</tr>
<tr>
<td>MP No.</td>
<td>Management Type/Focus</td>
<td>Management Practice Name</td>
<td>Management Practice Name</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------</td>
<td>--------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>NHS-f-1</td>
<td>Biogeochemistry</td>
<td>Amend soil with iron</td>
<td></td>
</tr>
<tr>
<td>NHS-f-2</td>
<td>Biogeochemistry</td>
<td>Amend soil with sulfate</td>
<td></td>
</tr>
<tr>
<td>NHS-f-3</td>
<td>Vegetation and Soils</td>
<td>Burn vegetation and soil</td>
<td></td>
</tr>
<tr>
<td>NHS-f-4</td>
<td>Vegetation and Soils</td>
<td>Graze fields with livestock</td>
<td></td>
</tr>
<tr>
<td>NHS-f-5</td>
<td>Vegetation and Soils</td>
<td>Till vegetation below soil surface</td>
<td></td>
</tr>
<tr>
<td>NHS-f-6</td>
<td>Vegetation and Soils</td>
<td>Bale and remove vegetation</td>
<td></td>
</tr>
</tbody>
</table>
## Table 6. Natural Hydrology Systems – Brackish-Fresh Tidal Marsh

<table>
<thead>
<tr>
<th>MP No.</th>
<th>Management Type/Focus</th>
<th>Management Practice Name</th>
<th>Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>NHS-bftm-1</td>
<td>Biogeochemistry</td>
<td>Add nitrate</td>
<td>Denitrifying bacteria out-compete sulfate reducers to decrease MeHg production</td>
</tr>
<tr>
<td>NHS-bftm-2</td>
<td>Biogeochemistry</td>
<td>Apply coagulant</td>
<td>Addition of metal based coagulant binds DOC and associated inorganic Hg and MeHg</td>
</tr>
<tr>
<td>NHS-bftm-3</td>
<td>Biogeochemistry</td>
<td>Increase fish population</td>
<td>Small fish accumulate MeHg and then are harvested</td>
</tr>
<tr>
<td>NHS-bftm-4</td>
<td>Hydrology</td>
<td>Stagger flood/drain events</td>
<td>Eliminate multiple discharges to one location at one time to decrease MeHg load to adjacent waterways</td>
</tr>
<tr>
<td>NHS-bftm-5</td>
<td>Hydrology</td>
<td>Increase water residence time</td>
<td>Photodegradation and particle settling</td>
</tr>
<tr>
<td>NHS-bftm-6</td>
<td>Hydrology</td>
<td>Design of new/restored tidal wetlands</td>
<td>Implement simple design measures such size of primary, secondary, and tertiary channels to better trap sediment on wetland, and reduce proportion of highest methylating habitats</td>
</tr>
</tbody>
</table>
Photo 1. Permanently flooded wetland on the Fic Fazio Yolo Wildlife Area.
Photo 2a. Seasonal wetland on the Fic Fazio Yolo Wildlife Area during dry period.

Photo 2b. Seasonal wetland on the Fic Fazio Yolo Wildlife Area during wet period.
Photo 3. Flooded agricultural land on the Fic Fazio Yolo Wildlife Area.
Photo 4. Irrigated agricultural lands situated north and south of Sycamore Slough in the Delta.
Photo 5. Floodplains (Yolo Bypass) during a winter flood (photo credit Chris Austin).
Photo 6. Brackish-fresh tidal marsh (Browns Island) located north of Antioch Ca.
### Potential Management Practices

<table>
<thead>
<tr>
<th>MP #</th>
<th>Management Type</th>
<th>Management Practice</th>
<th>Costs</th>
<th>Benefits</th>
<th>Technical Challenges</th>
<th>Other Notes</th>
<th>Management Type or Nature Category</th>
<th>Cost Category</th>
<th>MP #</th>
<th>Management Practice</th>
<th>Costs</th>
<th>Benefits</th>
<th>Technical Challenges</th>
<th>Other Notes</th>
<th>Management Type or Nature Category</th>
<th>Cost Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Biogeochemistry</td>
<td>Add Nitrates</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Nitrates will be added</td>
<td>Nitrates</td>
<td>2</td>
<td>Increase Fish Population</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Nitrates will be added</td>
<td>Nitrates</td>
</tr>
<tr>
<td>3</td>
<td>Biogeochemistry</td>
<td>Increase Soil with Iron</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>Iron will be added</td>
<td>Iron</td>
<td>4</td>
<td>Biogeochemistry</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>Iron will be added</td>
<td>Iron</td>
</tr>
<tr>
<td>5</td>
<td>Hydrology</td>
<td>Reverse Osmosis</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Reverse Osmosis will be added</td>
<td>Reverse Osmosis</td>
<td>6</td>
<td>Hydrology</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>Reverse Osmosis will be added</td>
<td>Reverse Osmosis</td>
</tr>
</tbody>
</table>

### Summary

- **Flow Velocity**: Increasing flow velocity can increase the rate of sediment transport, which can be beneficial for habitats that are sensitive to changes in flow regime.
- **Residence Time**: Increasing residence time can enhance nutrient removal, but it also increases chemical exposure and can affect the habitat for specific species.

### Notes

- **Operational Costs**: Higher costs associated with increased operational requirements for flow and chemical management.
- **Environmental Impact**: Potential for increased chemical exposure and habitat disturbance.

### References

### Potential Management Practices

<table>
<thead>
<tr>
<th>MP #</th>
<th>Management Type</th>
<th>Management Practice</th>
<th>Spatial Applicability</th>
<th>Costs</th>
<th>MeHg Reduction Potential</th>
<th>Spatial Applicability</th>
<th>Tech. Capacity to Implement</th>
<th>MEC</th>
<th>Other Required Inputs</th>
<th>Summary</th>
<th>Other Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW-pw-11</td>
<td>Hydrology</td>
<td>Timing water discharge</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>DWR: This is already done in permanent wetlands. More saline parts of Delta may suffer from buildup - could inhibit methylation through sulfide buildup but may negatively affect species diversity and ecosystem function.</td>
</tr>
</tbody>
</table>

**Notes:**
- This is already done in permanent wetlands.
- More saline parts of Delta may suffer from buildup - could inhibit methylation through sulfide buildup but may negatively affect species diversity and ecosystem function.
- DWR: Management Practices Evaluation
- The Nature Conservancy Study.
- Likely successful on mineral soils, not likely to work on peat soils.

**Other Notes:**
- Likely successful on mineral soils, not likely to work on peat soils.
- DWR: Management Practices Evaluation
- The Nature Conservancy Study.

---

**Appendix D - Management Practices Evaluation**

**Notes:**
- This is already done in permanent wetlands.
- More saline parts of Delta may suffer from buildup - could inhibit methylation through sulfide buildup but may negatively affect species diversity and ecosystem function.
- DWR: Management Practices Evaluation
- The Nature Conservancy Study.
- Likely successful on mineral soils, not likely to work on peat soils.
## Appendix D - Management Practices Evaluation

### Table: Potential Management Practices

<table>
<thead>
<tr>
<th>MP #</th>
<th>Management Type</th>
<th>Management Practice</th>
<th>Applicability</th>
<th>Costs</th>
<th>Certainty</th>
<th>Potential</th>
<th>Applicability</th>
<th>to Implement</th>
<th>Req'mts</th>
<th>Other</th>
<th>General Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Biogeochemistry</td>
<td>Apply coagulant</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>Costs could vary as a function of water chemistry. Generally, a cost-effective method to clean up wastewater; however, may not be cost-effective for all waste streams.</td>
</tr>
<tr>
<td>2</td>
<td>Biogeochemistry</td>
<td>Acid mine drainage</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>Costs could vary as a function of water chemistry. Generally, a cost-effective method to clean up wastewater; however, may not be cost-effective for all waste streams.</td>
</tr>
<tr>
<td>3</td>
<td>Biogeochemistry</td>
<td>Amended with sulfate</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>Costs could vary as a function of water chemistry. Generally, a cost-effective method to clean up wastewater; however, may not be cost-effective for all waste streams.</td>
</tr>
<tr>
<td>4</td>
<td>Biogeochemistry</td>
<td>Amended with iron</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>Costs could vary as a function of water chemistry. Generally, a cost-effective method to clean up wastewater; however, may not be cost-effective for all waste streams.</td>
</tr>
<tr>
<td>5</td>
<td>Biogeochemistry</td>
<td>Add nitrate</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>Costs could vary as a function of water chemistry. Generally, a cost-effective method to clean up wastewater; however, may not be cost-effective for all waste streams.</td>
</tr>
<tr>
<td>6</td>
<td>Biogeochemistry</td>
<td>Aerate</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>Costs could vary as a function of water chemistry. Generally, a cost-effective method to clean up wastewater; however, may not be cost-effective for all waste streams.</td>
</tr>
<tr>
<td>7</td>
<td>Biogeochemistry</td>
<td>Reversal + drain</td>
<td>-</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>Costs could vary as a function of water chemistry. Generally, a cost-effective method to clean up wastewater; however, may not be cost-effective for all waste streams.</td>
</tr>
<tr>
<td>8</td>
<td>Biogeochemistry</td>
<td>Delayed drain</td>
<td>-</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>Costs could vary as a function of water chemistry. Generally, a cost-effective method to clean up wastewater; however, may not be cost-effective for all waste streams.</td>
</tr>
<tr>
<td>9</td>
<td>Hydrology</td>
<td>Drain and flood</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>Costs could vary as a function of water chemistry. Generally, a cost-effective method to clean up wastewater; however, may not be cost-effective for all waste streams.</td>
</tr>
<tr>
<td>10</td>
<td>Hydrology</td>
<td>Hydro logic drainage</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>Costs could vary as a function of water chemistry. Generally, a cost-effective method to clean up wastewater; however, may not be cost-effective for all waste streams.</td>
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The Nature Conservancy

Lisamarie Windham-Myers (USGS)

Wes Heim, CA Rice Commission, DWR

Jacob Fleck (USGS)

The Nature Conservancy

Appendix D - Management Practices Evaluation
## Appendix D - Management Practices Evaluation

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<tr>
<th>MP 7 Agriculture/ Lands</th>
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### Practices Evaluation Notes

- **CRC**: CRC: costs and benefits, but likely to be beneficial to some extent.
- **Notes**: Notes on potential benefits and drawbacks.
- **Applying**: Applying these practices in the field.
- **General Management**: General management recommendations.
- **Notes**: Notes on potential benefits and drawbacks.
- **Notes**: Notes on potential benefits and drawbacks.
## Appendix D - Management Practices Evaluation

<table>
<thead>
<tr>
<th>Management Practice</th>
<th>Possible Benefits</th>
<th>Costs and Benefits</th>
<th>Practical Challenges</th>
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<th>Management Domain</th>
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<td>Improved water quality</td>
<td>Easy to apply in drains, likely to work</td>
<td>Could be applied only during flood events, may not be cost-effective for in-stream applications</td>
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<td>Increased production of beneficial bacteria</td>
<td>Could be used at the inlet or outlet, depending on goal. Could be applied only during flood events.</td>
<td>Could be applied only during flood events.</td>
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<td>Subsided islands with ag return flows are where this was proposed initially</td>
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### Appendix D - Management Practices Evaluation

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### Appendix D - Management Practices Evaluation

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See descriptions of criteria in text.

**Criteria values:**

- + = Criterion encourages use of the MP
- 0 = Criterion neutral on use of the MP
- - = Criterion discourages use of the MP

**Scores:**

- Low range of scores given
- High range of scores given

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Natural Hydrology Systems ̶ Brackish-Fresh Tidal Marsh

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Full range of scores given