Assessment of Methylmercury Contributions from Sacramento-San Joaquin Delta Farmed Islands

Final Report

By

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Executive Summary

Concern over mercury (Hg) pollution in the Sacramento-San Joaquin Delta (Delta) has resulted in posting of fish advisories recommending limited human consumption of sport fish (OEHHA, 1994). The Hg species of greatest concern to human health is monomethylmercury (MeHg). Human exposure to MeHg occurs primarily through the consumption of contaminated fish (Fitzgerald et al., 1998). Mercury cycling in the Delta is complicated. Ongoing studies in the Delta have begun to increase our understanding of Hg sources, sinks, and processes.

Farmed islands account for 70 percent of the total area of the Delta and utilize water from Delta channels for irrigation. The large surface area, high soil organic matter content, and irrigation that alternately wets and dries the soils facilitates *in situ* production of MeHg and subsequent discharge of drainage water with elevated MeHg concentrations. Farmed Island drainage water MeHg concentrations are high compared to concentrations in river channels surrounding the islands indicating farmed islands are a source of MeHg.

Prior to this study relatively little work has been done to quantify MeHg discharges from Delta farmed islands. This report presents results of a study aimed at answering the following key questions: 1) Are Delta farmed islands net producers or consumers of MeHg? and, 2) If farmed islands are producers, what are the contributing MeHg loads to Delta channels? This study had the following objectives: a) measure MeHg concentrations in drainage water exported from farmed Islands, b) estimate the volume of water exported via pumps from farmed islands, c) estimate MeHg loads from farmed Islands, and d) investigate the relationship between land management practices, island characteristics, MeHg concentrations, and loads. We present results showing the quality control program for the project, MeHg concentrations in drainage water exported from selected Delta farmed Islands, comparisons of land use, soil types, and surface and groundwater interactions as related to MeHg concentrations and loads, present water budgets, and estimate MeHg loads from farmed islands. Finally, using data collected during this study we make an estimate for MeHg loads from Delta farmed islands and compare loads to other sources and sinks in the Delta.

The following is a summary of key points from this study:

- MeHg concentrations collected from farmed islands where mineral soils predominate were lower than islands where organic soils predominate.

- There is substantially greater variability in MeHg concentrations collected from organic-soil islands compared to mineral-soil islands.

- Temporal variation in MeHg concentrations occurred at all islands and at organic-soil sites seasonal peaks were larger compared to mineral-soil sites.

- At the 95 % confidence level, we determined that MeHg concentrations were significantly correlated with DOC concentrations and that flushing of shallow zone groundwater (porewater) by the addition of new water is a probable mechanism explaining MeHg concentrations in subsurface drains on Delta islands.

- MeHg concentrations in the 2-m deep well in the corn field (0.196 ng L^{-1}) were much lower than in the rice field (3.42 - 8.54 ng L^{-1}). The redox potential for the corn field well indicated oxidizing conditions while the rice field well data indicated reducing conditions.

- Water management practices that minimize exports from wetlands such as limiting drain flow and recirculation of drainage water will probably minimize subsurface loads from wetlands and result in lower or equivalent loads to current Delta agricultural conditions.

- Observation well data for T2 and B2 are generally consistent with the subsurface drainage concentration data and the hypothesis that MeHg is produced in surficial organic sediments (within 5 feet of land surface) and may be flushed to the drainage ditches via subsurface flows during flooding of fields.

- Wetland surface water MeHg loads were substantially greater than the subsurface loads and concentrations indicating MeHg production is occurring within surficial sediments and not at depth.

- Winter flooding and holding water on cropland appears to be a factor in increased MeHg concentrations in drainwater.

- Farmed islands with organic dominated soils had higher net MeHg loads than islands with mineral dominate soils.

- Annual Delta wide farmed island MeHg load is 0.1 g day^{-1} with a range of -0.5 to 0.6 g day^{-1}. During high flow periods the MeHg load is 0.4 g day^{-1} (range = -0.5 to 1.3 g day^{-1}) while during low flow periods the MeHg load was -0.1 g day^{-1} (range = -0.6 to 0.3 g day^{-1}).

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Introduction

Concern over mercury (Hg) pollution in the Sacramento-San Joaquin Delta (Delta) has resulted in posting of fish advisories recommending limited human consumption of sport fish (OEHHA, 1994). The Hg species of greatest concern to human health is monomethylmercury (MeHg). Human exposure to MeHg occurs primarily through the consumption of contaminated fish (Fitzgerald et al., 1998) as MeHg is the dominant form of Hg in fish (Bloom, 1992). In aquatic systems MeHg production is typically mediated by microbes including sulfate-reducing bacteria (Berman and Bartha, 1986; Compeau and Bartha, 1985; Gilmour et al., 1992). The primary site of Hg methylation occurs in sediments at the oxic/anoxic interface (Mason et al., 1998). MeHg is moved into overlying or drainage water from the sediments by diffusion and advection processes (Choe et al., 2004). In surface water, MeHg is readily bioaccumulated by phytoplankton and zooplankton and biomagnified up the food web, ultimately posing a threat to fish consumers (Hall et al., 1997).

Mercury cycling is complicated and extensive studies in the Delta have begun to increase our understanding of transformative processes, sources, and sinks of Hg (Choe and Gill, 2003; Choe et al., 2003; Choe et al., 2004; Heim et al., 2007; Davis et al., 2008; Foe, 2003; Marvin-DiPasquale and Agee, 2003; Foe et al., 2003). An integrated mass balance model approach has been used to quantify the magnitude of MeHg sources and sinks in the Delta. This model indicates tributary inputs are the major source of MeHg to the Delta (Foe et al., 2008) followed by open water and marsh sediment water exchange (Gill, 2008b; Heim et al., 2008). Lesser sources of MeHg to the Delta are from rainfall (Gill, 2008a), and waste water returns and urban runoff (Foe et al., 2008).

The Delta receives runoff from 40 percent of California's land and covers 300,000 hectares with thousands of kilometers of waterways within its boundaries making it the largest estuary on the west coast of the United States. Historically, seasonal wetlands and marshes were predominate habitat features in the Delta (Atwater et al., 1979). Today, the majority of these seasonal wetlands and marshes have been reclaimed for agricultural uses (Lucas et al., 2002; Nichols et al., 1986). Research shows that the water and sediment in the remaining Delta marsh habitat has elevated MeHg concentrations relative to other habitat types (Choe et al., 2004; Heim et al., 2007).

The reclaimed marshes (farmed islands) are now fertile agricultural land primarily composed of organic (peat), highly organic mineral, and mineral soils. Farmed islands account for 70 percent of the total area of the Delta and utilize water from Delta channels for irrigation. Given the large surface area of the Delta farmed islands, high soil organic matter content, presence of Hg in soils, and irrigation that alternately wets and dries the soils, *in situ* production of MeHg in agricultural fields and subsequent discharge of drainage water with MeHg to Delta channels is a concern.

Episodically high MeHg concentrations (greater than 1 ng L^{-1}) have been observed in drainage water from farmed islands in the Delta (Foe et al., 2008). These concentrations are high compared to concentrations in river channels surrounding the islands suggesting the farmed islands are a source of MeHg (Foe, 2003). Agricultural fields have been shown to be a source of

MeHg in other locations as well (Babiarz et al., 1998; Balogh et al., 2003; Balogh et al., 2005; Hurley et al., 1995). However, prior to this study relatively little work has been done to quantify MeHg discharge from farmed islands in the Delta. Key questions are: 1) Are Delta farmed islands net producers (i.e. "sources") or consumers (i.e. "sinks") of MeHg? and, 2) If farmed islands are producers, what are the contributing MeHg loads to Delta channels? This study had the following objectives: a) measure MeHg concentrations in drainage water exported from farmed Islands, b) estimate the volume of water exported via pumps from farmed islands, c) estimate MeHg loads from farmed Islands, and d) investigate the relationship between land management practices, island characteristics, MeHg concentrations, and loads.

Methods and Materials

Site selection

We compiled a list of seventy-three farmed islands with information on total acreage, soil type, number of irrigation diversions, number of agricultural drainage returns, crop types, and land uses. Eight farmed islands were selected from this list to represent the Delta. These farmed islands all had a limited number of agricultural drainage returns which reduced efforts to quantify MeHg loads as it was necessary to measure discharge and MeHg concentrations at each return.

Four of the farmed islands had organically dominated (peat) soils and four had mineral dominated soils. Soil type of farmed islands also corresponds to location within the Delta. The central Delta is dominated by organic rich soils while the perimeter farmed islands are dominated by mineral soils. Dividing the sites by soil type also divided sites spatially within the Delta; four islands were located around the northern perimeter of the Delta and four islands were located in the center or central western Delta. The soils, hydrology, and land- and water-management practices for the eight islands were representative of most farmed islands in the Delta.

The farmed islands selected for this study are listed in Table 1. In exchange for access to the properties it was agreed that the common names and locations of the farmed islands would not be used in this report. Furthermore, island names and specific locations have been eliminated from all presentations of the data. Results of MeHg loading obtained from these farmed islands were used to estimate MeHg loads for Delta farmed islands.

In addition to determining MeHg loads from farmed islands, detailed work was done to identify factors affecting MeHg concentrations on farmed islands having peat soils. This work was conducted at farmed islands T2 and B2. We collected samples from drainage ditches and observation wells, and at T2 also collected samples from a demonstration wetland constructed on a field formerly planted to corn (see Appendix for description of demonstration wetland). In this way, we compared agricultural and wetland MeHg loads for the same type of area. At T2 data collection occurred at the southeastern area (TS) and the northwestern area (TN) (Figure 1). At B2 we collected surface and subsurface samples (shallow well samples) in rice, corn and tomato fields.

Table 1. Site code, soil type, acreage, irrigation diversions, drainage returns, and crop types for the eight farmed islands sampled in the Delta.

Site Code	Dominate Primary Soil Type	Total Acreage[1]	Number of Irrigation diversions[1]	Number of Agricultural drainage returns[1]	Crops
N1	Mineral	26000	57	9	Alfalfa, Grapes, Corn, Tomatoes
M1	Mineral	4740	41	2	Alfalfa, Grapes, Tomatoes, Wheat
W1	Mineral	1654	7	2	Wheat, Tomatoes, Corn, Safflower
S1	Mineral	3100	7	2	Alfalfa, Safflower, Beans, Tomatoes
St2	Organic	9600	40	2	Corn, Wheat, Alfalfa
T2	Organic	3630	30	1	Corn, Wheat, Alfalfa
B2	Organic	6006	34	1	Corn, Rice, Tomatoes
J2	Organic	3471	31	1	Corn

1. from Sacramento San Joaquin Delta Atlas, http://baydeltaoffice.water.ca.gov/DeltaAtlas/index.cfm

Water sampling for determination of farmed island methylmercury concentrations and loads

Water was collected on thirty occasions, about monthly, between September 2005 and March 2008 for the purpose of determining MeHg concentrations and loads. Water grab samples were collected using ultra clean sampling techniques (Gill and Fitzgerald, 1985). Samples were collected using a bottle grab sampler. The grab sampler was constructed by attaching large plastic ties to the end of a fiberglass pole positioned in a manner to hold a 250 ml glass sampling bottle securely in place while sampling.

At each site, water was collected from the main drainage ditches that flowed to drainage pumps. The samples were collected just under the surface of the water. Samples were collected in a double bagged 250 mL pre-cleaned borosilicate bottle and the bottle and cap were triple rinsed with ambient water just prior to collecting a sample. Samples were immediately placed on ice and kept in the dark for transportation back to the laboratory. Samples were preserved within 48 hours of collection with 0.5 percent hydrochloric acid.

Figure 1. Map of site T2 showing sampling locations at the TN and TS areas.

Water sampling for factors affecting methylmercury at T2 and B2

At farmed island T2 from Fall 2005 to Fall 2006 we measured flow and collected samples at three drainage ditches, DR1, DR2 and DR3 prior and post flooding of a managed demonstration wetland (Figure 1). We measured flow when samples were collected using a Marsh-McBirney flow meter (at DR2) and with a vessel of known volume and stop watch at DR1 and DR3. At all three locations, weirs were installed and we measured flow at the weir. Prior to May 5, 2006 measurements and samples collected at DR1 and DR2 reflected agricultural conditions. After, May 5, DR3 measurements and samples reflected the effects of flooding organic soils for a managed demonstration wetland (see Appendix for description of demonstration wetland). Flow in DR3 was exclusively subsurface drainage from the wetland. At each site, water was collected from the main irrigation drains that feed the Agricultural drainage returns. Grab water samples for MeHg were collected, transported, and preserved as described above. We also collected samples for DOC and major ions as described in Deverel et al., (2007a). Additionally, dissolved oxygen, electrical conductivity, pH and redox potential were measured as described in (Deverel et al., 2007a).

We sampled selected shallow wells on T2 in the TN area during winter and summer, 2007 for MeHg, DOC, and major ions and cations using methods described in Deverel et al., (2007a)(Figure 1).

During winter and summer 2007, we collected water samples from shallow wells, drainage ditches, and surface runoff from three fields consisting of corn, rice, and tomatoes on farmed island B2. We also measured inflow and outflow for the three crops during irrigation using a flow meter as described above.

Quality assurance / quality control program

Quality assurance and quality control (QA/QC) included a field component and laboratory component. On each field trip a source water blank, field blank, and field duplicate were collected. The source water was collected directly from the 18 Megaohm water source in the laboratory in the same container as used for the field blank water carried for the collection of field blanks. The source water was used to verify the field blank water had undetectable levels of MeHg. The field blank was collected by transporting laboratory water with undetectable amounts of MeHg into the field and processing a sample with this water in an identical manner as the field samples. The field blank data was used to verify a contamination free collection process. Thirty-two field blanks were collected for unfiltered MeHg and two for filtered MeHg. Field duplicates were collected randomly and simultaneously along with the drain water (native) sample at one site on each trip. Thirty-two field duplicates were collected for unfiltered MeHg. The relative percent difference between native and duplicate field samples was used to determine field variability. Laboratory QA/QC samples included spike recoveries of MeHg preformed on native samples and analytical duplicates of native samples. Seventy-two native/duplicate and spike/spike duplicate pairs were measured. These measurements provided information about the accuracy and precision of the MeHg analysis.

Methylmercury analysis

Water samples for MeHg analysis were distilled to remove interferences. Typically, 50 mL of acidified sample was used in aqueous-phase distillation. Distilled samples were analyzed for MeHg by aqueous-phase ethylation, trapping on a carbotrap® column, gas chromatography separation, thermal decomposition to elemental mercury, and detection by cold vapor atomic fluorescence spectroscopy (Liang et al., 1994). Analytical recovery was checked regularly with the certified reference material DORM-2 (dogfish muscle, 4,470 ± 320 ng MMHg g^{-1} dw tissue, 101.7 ± 9.2 % recovery (n = 72)), purchased from the National Research Council of Canada. The detection limit determined from was 0.02 ng L^{-1} as determined by replicate measurements of low level water samples.

Dissolved organic carbon analysis

Dissolved organic carbon (DOC) was analyzed by the University of California at Davis using a Shimadzu TOC-5000A total organic carbon analyzer using methods described in Bird et al., (2003).

Major ion analysis

Weck Laboratories in City of Industry, California and Sequoia Laboratories of Sacramento, California utilized EPA methods 200.7 and 300 to determine calcium, magnesium, potassium, sodium, chloride, and sulfate concentrations in filtered samples.

Water and methylmercury load calculations

Outflow calculations

Except for St2, we estimated outflow from farmed islands using power records and pump test results. For St2, Department of Water Resources provided monthly flow estimates from flow meters placed on the discharge pipes. Power consumption records at M1 were incomplete and no water budget was calculated for this island. For the estimates using power consumption in kilowatt-hours, we used power records obtained from Pacific Gas and Electric and the results of pump-efficiency tests. Pump tests[1] were conducted since 2004 for all discharge pumps. The pump tests provided a value for acre feet pumped per kilowatt-hour. Therefore, we multiplied the monthly power consumption by acre-feet/kilowatt-hour to obtain monthly flow estimates.

The uncertainty in these calculations are due to 1) changing water levels in the adjacent channels which affect the pump lift and 2) the effect of operation of multiple pumps at island drainage stations. Relative to the first uncertainty, Templin and Cherry, (1997) provided some insight as they compared flows measured with in-pipe propeller meters with power-estimated flows for the two drainage pumps on T2. Flows were measured and estimated individually for the two pumps and then summed and compared. Therefore, the differences for the estimated and measured flows were due primarily to changes in the hydraulic gradient. Their data indicated that uncertainty associated with this effect for monthly data ranges from -3.5 to 19.5 percent of measured values; the average was about 9 percent for the monthly values. In the second case, the uncertainty can be substantial if the variation in the pump test results are significant for the pumps at the pump station. For this study, where there were multiple pumps, we used the average of all pump test values for estimating loads which resulted in an uncertainty of 10 to 25 percent. To calculate MeHg loads we multiplied water outflow estimates by MeHg concentrations measured in the drainage water for that month.

Inflow calculations

There are three primary sources of MeHg loads onto Delta islands; irrigation supply via siphons from adjacent channels during April through September, winter flooding during fall and winter and year-round seepage through the levee. Water flowing onto the islands moves through the subsurface to the drainage ditches and is then pumped off the island to adjacent channels. Because of the low groundwater hydraulic conductivities and gradients, groundwater flow to drainage ditches is slow; less than a foot to several 10's of feet per year (Deverel et al., 2007a). This results in a decadal lag time between the inflow and the subsequent outflow. As a result, calculations of inflow loads are solely for numerical comparison with the outflow loads.

[1] Pump tests were conducted by Power Services, Inc., 6301 Beardon Lane, Ca. 95357

For most Delta islands studied (S1, W1, N1, B2, and St2) we estimated siphon flow onto the islands during late spring and summer (April – September) by estimating crop consumptive use. First, we obtained monthly average reference evapotranspiration (ET_0) values from the California Irrigation Management System (CIMIS) station on 2, assuming them to adequately represent reference ET in the whole Delta. Then we used county land use maps from the California Department of Water Resources to tally the number of acres for each crop. We then used Allen et al., (1998) to estimate the following for each crop represented in the study area:

i. The month or period of the year in which the crop is planted (we assumed planting in the middle of the given time range);
ii. The duration, in days, of each growth stage (initial, development, mid, late) for the crop;
iii. The crop coefficient (K_c) for each growth stage (except development, during which we assumed there is no irrigation).

Using this information, we estimated K_c for each day of the year and crop, and then averaged values by month. This provided a monthly K_c estimate that varies throughout the growing season. We used these monthly K_c and ET_0 values to estimate monthly evapotranspiration (in feet) for each crop, according to the equation:

$$ET = K_c \times ET_0$$

For each island, we multiplied these ET values by the estimated crop areas to obtain the volume of water consumed by each crop during each month. These were tallied to estimate total water consumed by all crops and therefore siphoned onto the island in each month.

After identifying three likely sources of uncertainty (reference ET, planting times, and land use change) in our consumptive use estimates for St2, N1, S1 and W1, we analyzed each for its possible monthly (April - September) and total effects as described below.

i. *Reference ET*. Reference ET values as reported by CIMIS have an error range of about ±15 percent due to climatic spatial variability (Burt et al., 2002). Since ET_0 is a factor multiplied by final K_c estimates, the total effect of ET_0 variation on consumptive use is also ±15 percent.
ii. *Planting times*. Since the planting season for each crop is reported in "Crop evapotranspiration" as a one- or two-month period, we estimated the effects of planting at different times within the time period (middle ±10 days). These affected total consumptive use estimates by less than ±2.5 percent on all islands; individual months were subject to greater errors, in most cases staying within ±100 percent and never exceeding 140 percent. We took planting schedule into account in the form of timing the beginning of each year's consumptive use according to the wetness of that year. Since 2006 was such a wet year, we assumed late planting. Likewise, since 2007 and 2008 were very dry, we assumed early planting. We assumed average planting for 2005.
iii. *Land use change*. Some of the DWR land use maps used to estimate crop acreages were from as early as the mid-1990s. To account for possible land use changes since the maps were created, we examined the effects of converting all corn (a relatively low-demand crop) acreage to alfalfa (a significantly higher-demand crop), and vice-versa. Since on

most islands these were among the two most heavily represented crops by area, and their water requirements differ so greatly, these estimates represent somewhat extreme land use change scenarios.

These affected inflow estimates as follows:

a. St2. The portion of the island represented in the study did not contain any alfalfa. Thus, there was no effect from alfalfa conversion to corn.
b. N1. Corn and alfalfa were major crops but did not dominate the island. Conversion of alfalfa to corn resulted in an annual decrease of 16 percent and individual monthly changes not exceeding 55 percent. Conversion of corn to alfalfa resulted in an annual increase of 6 percent and individual monthly changes not exceeding 20 percent.
c. S1. Conversion of alfalfa to corn resulted in an annual consumptive use decrease of 5 percent and monthly decreases not exceeding 23 percent. Conversion of corn to alfalfa resulted in an annual consumptive use increase of 28 percent and monthly increases mostly under 100 percent.
d. W1. Conversion of alfalfa to corn resulted in an annual consumptive use decrease of 8 percent and individual monthly decreases not exceeding 26 percent. Conversion of corn to alfalfa resulted in an annual consumptive use increase of 18 percent and individual monthly increases not exceeding 56 percent.

In addition to the above factors, the actual volume of water siphoned onto the island is affected by irrigation efficiency and consumptive use of groundwater. For B2, W1, N1, St2, and S1, we assumed that the volume of water siphoned onto the island was equal to the consumptive use. Because all islands are below sea level, groundwater levels are shallow and there is seepage onto the island which can be used by crops. Based on past observations on islands T2 and J2, the volume of water applied may be less than consumptive use. Considering the relevant factors, we estimated the error associated with our monthly consumptive use estimates for siphon inflow to be ± 65 percent.

For island T2, we estimated summer irrigation based on data provided by Templin and Cherry, (1997) for 1994 - 1996. Templin and Cherry, (1997) measured flow in 12 of the 21 siphons on T2 using in-pipe propeller flow meters. We calculated the average monthly flow per siphon and multiplied this by the total number of siphons. The total estimated volume of siphoned water was 3,335 acre feet for April – September. This is about 40 percent of the estimated consumptive use for corn which was the predominant crop at the time. However, our observational experience on T2 indicates that crops are usually under-irrigated relative to other islands and therefore we believe that our estimates for T2 are probably reasonable within ± 40 percent as there is uncertainty associated with the fact the pasture and alfalfa currently occupy a substantial percentage of the island. Much of this acreage remains under-irrigated relative to other islands. For example, conversations with the primary grower on T2 indicate that corn is rarely or never irrigated. Other locations where alfalfa and pasture predominate on more mineral soils are irrigated more frequently.

For Island J2, we relied on information from the land manager about siphon use. Pasture is almost the exclusive land use on J2. About 20 % of the island pasture is irrigated and water is also siphoned for drinking water for cattle. We estimated inflow for J2 Island for April – September as 1,720 ± 860 acre feet.

On islands B2 and St2, managers siphon water onto the island for winter flooding. In both cases, water is siphoned onto the island in the late fall and flooding is maintained through drainage control and precipitation. Based on conversations with the land manager and aerial photos, we estimated the volume of water siphoned onto B2 in the part of island that contributes to the southwest drainage pump that was sampled during this study. We assumed siphoned water would first fill the unsaturated zone which is about 3.3 feet in depth and has a total porosity of about 86 percent and an unsaturated porosity of about 15 percent. We assumed a flooding depth of about 1 foot on 1,293 acres based on aerial photos and field observations. This resulted in an estimated volume of water of 2,400 acre feet. Using similar information about acreages of flooding from the land manager for St2, we estimated a volume of 2,500 acre feet for 1,350 acres (the area drained by the discharge pipe that was sampled during the study).

Seepage calculations

To estimate the seepage rate, Q ($ft^3\ d^{-1}$), through the levees onto each Delta island, we used Darcy's law, which states:

$$Q = AK\frac{\Delta h}{\Delta x},$$

in which A is the cross-sectional flow area (ft^2), K is hydraulic conductivity of the levee material ($ft\ d^{-1}$), and $\Delta h/\Delta t$ is the head gradient across the levee (dimensionless).

i. Hydraulic conductivity. For all the island levees, we used an estimate of 0.6 $ft\ d^{-1}$ for hydraulic conductivity. We derived this estimate from results obtained during the development of a groundwater flow model of T2 (Deverel et al., 2007b). Since there is a significant degree of spatial variability in hydraulic conductivity of Delta levees, we assumed the estimate of 0.6 $ft\ d^{-1}$ had an error of ± ½ order of magnitude which resulted in about -80 to 400 percent uncertainty in monthly seepage estimates.
ii. Head gradient. We estimated head gradients using LIDAR elevation data for the islands, monthly mean stage data for adjacent river channels, and levee width estimates obtained from aerial photos. From the LIDAR data we calculated average elevation for each island, and then assumed the average depth to the water table to be 3 feet below land surface. We estimated the head decline (Δh) across the levee as the elevation difference between water table elevation and adjacent average stream stage elevation. We used the levee widths for horizontal lengths across the levees (Δx), to calculate monthly hydraulic gradients.
iii. Cross-sectional flow area. For cross sectional flow area, we used the product of each levee's length and the depth of subsurface flow through the levee. We took levee lengths of each island from the DWR *Sacramento-San Joaquin Delta Atlas* and GIS. For flow depth we used hydraulic head difference (the numerator of the head gradient term) plus 30 feet to account for underflow, based on data collected on T2.

To estimate MeHg seepage loads onto the island, we multiplied the estimated seepage and siphon flows onto the islands by the MeHg concentrations for the nearest channels. Seepage loads are generally significantly less than the estimated inflow loads for irrigation and winter flooding; differences ranged from 20 percent to 60 percent less on J2 and T2, 2.5 times less on St2 and over an order of magnitude less on B2, N1, S1, and W1. Because the seepage estimate is lower than the consumptive use inflow estimate, the uncertainty in the monthly inflow estimate is primarily due to the uncertainty in the consumptive use inflow estimate or about 65 percent.

Results and Discussion

Quality assurance quality control program

For the thirty-three source water blanks collected only one (3.0 percent) had detectable amounts of MeHg (0.031 ng L^{-1}). The isolated contamination was less than two times the method detection level (MDL) of 0.02 ng L^{-1} and should not have affected the results. A total of thirty-four field blanks were collected and all but two (5.9 percent) were less than the MDL. Two field blanks had detectable amounts of MeHg but were less than two times the MDL. The first was collected at M1 in May 2007 and the second at T2 in August 2007. The contamination should not have affected the accuracy of MeHg concentration results, with the exception of the August 2007 sample at T2.

To assess the repeatability of field sampling a total of thirty-two native and field duplicate pairs were collected during the study. The average relative percent difference (RPD) between native and duplicate pairs was 21 percent.

In the laboratory a total of seventy-two native and duplicate pairs were analyzed and typical reproducibility was 15 percent. This includes measurements of pairs less than ten times the MDL which are typically greater than the data quality objective of ± 25 percent. The RPD of field duplicates was greater than laboratory duplicates suggesting the variability observed in field duplicates was more attributable to natural variation. Matrix spike recovery averaged 99.2 ± 10.5 percent (n = 144) and the RPD between matrix spike and matrix spike duplicate pairs was 6 percent (n = 72) indicating good precision and accuracy for the laboratory method.

Farmed island methylmercury water concentrations

All MeHg concentrations for unfiltered drainwater are shown in Table 2. Water was collected from the main drains of each island just prior to entering the pumps which discharge drainage water to adjacent channels. The lowest median MeHg concentration was measured at N1; the median was 0.088 ng L^{-1} and the average concentration was 0.122 ± 0.018 ng L^{-1} (s = 0.092, n = 27). The highest MeHg concentrations were measured at B2; the median was 1.66 ng L^{-1} and the average was 3.26 ± 0.74 ng L^{-1} (s = 3.99, n = 29). The median concentration for B2 was 18 times greater than the median concentration for N1. Using the Mann-Whitney median comparison test for all samples, the median MeHg concentration of drainwater collected from islands where mineral soils predominate, N1, M1, S1, and W1, (0.256 ng L^{-1}) was significantly

lower (alpha = 0.05) than the median (0.355 ng L^{-1}) for the islands where organic soils predominate (T2, J2, B2, St2).

Table 2. Methylmercury (MeHg) concentrations measured monthly at eight farmed island agricultural returns. Data is listed showing water year as well as average and median concentrations, standard error (SE), and standard deviation (s) of measurements.

Water Year	Date	Station ID and MeHg (ng L^{-1})							
		W1	N1	S1	M1	T2	J2	B2	St2
04-05	9/13/05		0.046	1.090	0.425	0.213	0.058	0.205	
05-06	10/13/05	0.875							3.440
	11/1/05	0.616	0.046	0.335	0.157	0.204	0.310	5.020	2.930
	11/29/05	0.262	0.087	0.257	0.097	0.137	0.062	10.600	0.829
	1/10/06	0.255	0.187	0.407	0.068	0.162	1.450	7.840	1.040
	2/14/06	0.417	0.160	0.525	0.090	0.134	0.304	7.080	5.440
	3/14/06	0.507	0.115	0.453	0.086	0.189	0.651	1.330	0.222
	4/25/06		0.107	0.492	0.098	0.245	0.709	0.556	0.179
	5/23/06	0.924	0.484	0.699	0.124	0.220	0.401	0.315	0.310
	6/28/06	0.801	0.268	1.030	0.448	0.509	1.041	0.898	0.168
	7/25/06	4.690	0.110	1.040	0.600	4.180	4.190	2.83	0.130
	8/22/06	0.260	0.080	0.840	0.240	0.320	0.140	0.64	0.160
	9/12/06	1.170	0.048	0.912	0.156	0.548	0.113	0.71	0.395
06-07	10/24/06	0.505	0.063	0.283	0.195	0.113	0.055	0.436	0.232
	12/5/06	0.375	0.020	0.174	0.125	0.111	0.039	0.384	1.880
	1/8/07					0.137		2.51	
	1/30/07							5.57	
	2/27/06		0.075	0.310	0.065	0.152		2.91	1.110
	3/27/07		0.095	0.307	0.174	0.120		1.16	0.413
	4/30/07	0.438	0.085	1.290	0.441	0.257	0.282	1.66	0.538
	5/22/07	0.293	0.164	1.350	1.060	0.537	0.188	0.557	0.213
	6/26/07	0.401	0.088	1.270	1.520	0.342	0.246	0.697	0.141
	7/24/07	0.591	0.069	1.040	0.441	0.658	0.355	2.6	0.230
	8/21/07	0.977	0.050	0.579	0.185	0.293	0.221	0.544	0.358
07-08	10/1/07	0.377	0.030	0.328	0.057	0.198	0.136	0.306	0.230
	11/5/07	0.992	0.061	0.753	0.106	0.073	0.116	17.7	3.790
	12/3/07	0.148	0.103	0.129	0.135	0.081	0.224	9.13	0.977
	1/9/08		0.155	0.134	0.082	0.116	0.253	4.36	0.947
	2/4/08	0.099	0.123	0.119	0.085	0.160	0.396	3.75	0.978
	3/3/08	0.345	0.114	0.269	<MDL	0.074	0.509	2.17	0.052
Average		**0.709**	**0.112**	**0.608**	**0.279**	**0.374**	**0.498**	**3.258**	**1.012**
Median		**0.438**	**0.088**	**0.492**	**0.146**	**0.194**	**0.253**	**1.660**	**0.395**
SE		**0.191**	**0.018**	**0.076**	**0.065**	**0.144**	**0.167**	**0.741**	**0.259**
s		**0.916**	**0.092**	**0.395**	**0.339**	**0.762**	**0.836**	**3.991**	**1.348**

Figure 2 shows the comparison of concentrations for samples collected from farmed islands with mineral and organic soils. In addition to the higher median for the samples collected from organic-soil islands, there is substantially greater variability relative to the mineral islands. Figure 3 shows MeHg concentrations represented with boxplots for the individual islands. The

higher median concentrations and variability observed at B2 and secondarily at St2 relative to other sites substantially influence the comparison of the organic and mineral islands illustrated in Figure 2.

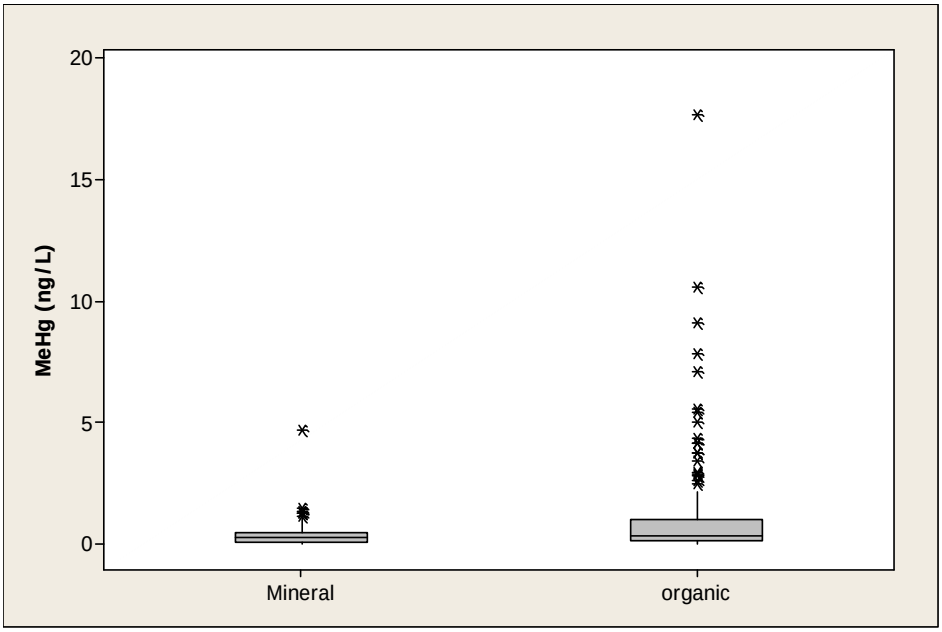

Figure 2. Boxplot showing methylmercury (MeHg) concentrations for drainage water samples collected from the four islands predominated by mineral soil and four islands predominated by organic soils. The boxes represent the inner quartile range and the asterisks represent data outliers.

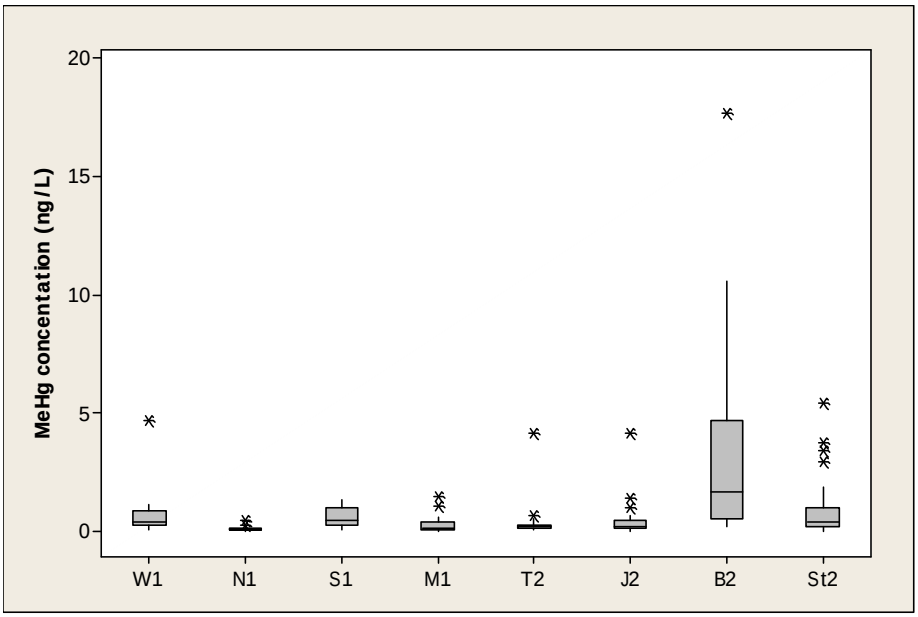

Figure 3. Boxplot showing methylmercury (MeHg) concentrations for drainage water samples collected from the eight islands. The boxes represent the inner quartile range and the asterisks represent data outliers.

This study spanned four water years (October 1 – September 30); sampling began at the end of water year (WY) 2005 and was completed half way through WY 2008. Interannual and seasonal comparisons were made between WY 2006 and 2007 as we had complete monthly sampling for these two years.

According to Department of Water Resources, (2006) WY 2006 was a wet year with precipitation in the Sacramento River Basin at 150 percent of average, 145 percent of average in the San Joaquin Basin, and 140 percent of average state wide. Although precipitation was 140 percent above normal, the month of September was drier than normal. Two significant flood events occurred during WY 2006: a New Year's Eve flood event extending into January 2006 and an early April flood on the San Joaquin River. In contrast, WY 2007 was the 18th driest year for the Sacramento River Basin during the 102 year record of stream flow measurements and the 8th driest year for the San Joaquin region (Department of Water Resources, 2007). During WY 2007, January and March were drier than average. In contrast, the other large precipitation months of December and February were above normal at 101 percent and 170 percent of average, respectively. WY 2008 was also a drier than normal year during which statewide precipitation was 85 percent of average; runoff 55 percent of average; and reservoir storage 85 percent of average (Department of Water Resources, 2008).

Using the data in Table 2, we compared MeHg concentrations in unfiltered drainwater samples by water year. First, using the Mann-Whitney test, for sites dominated by mineral soils (W1, N1, S1, & M1), we determined that the median concentration for WY 2007 (0.300 ng L^{-1}, inner quartile range = 0.0873 to 0.5235) was not significantly different from the median concentration for WY 2006 (0.268 ng L^{-1}, inner quartile range = 0.0873 to 0.5235). However, at sites S1 and M1 the seasonal increase in MeHg, discussed in detail below, appeared to be elevated in WY 2007 relative to WY 2006. Second, for sites dominated by organic soil (T2, J2, B2, St2), the median MeHg concentration was higher for WY 2006. However the difference was not statistically significant at alpha = 0.05. The medians of MeHg concentrations for the samples collected at sites dominated by organic soil were 0.398 ng L^{-1} (inner quartile range = 0.193 to 1.258) and 0.302 ng L^{-1} (inner quartile range = 0.193 to 0.608) for WY 2006 and WY 2007 respectively. Data for WY 2006 and 2007 were combined to test for differences in MeHg concentrations between soils types over both years. There was no significant difference between the two soil types ($t = 1.98$, $df = 158$, $p < 0.05$). Additionally, comparisons of MeHg concentrations within water years of averages from sites of similar soil type were not significantly different but seasonal peaks were much higher at sites with organic dominated soils (Figure 4).

Seasonal variation in MeHg concentrations was observed at all sites but the timing and magnitude of the variation differed between sites (Table 2, Figure 4). The mineral soil dominated sites (W1, N1, S1, & M1) all generally showed elevated MeHg concentrations during summer months relative to winter months. At site W1, the measured July 2006 MeHg concentration (4.69 ng L^{-1}) was an outlier. The average MeHg concentration of unfiltered drain water collected from W1 was 0.709 ng L^{-1} and the median was 0.438 ng L^{-1}.

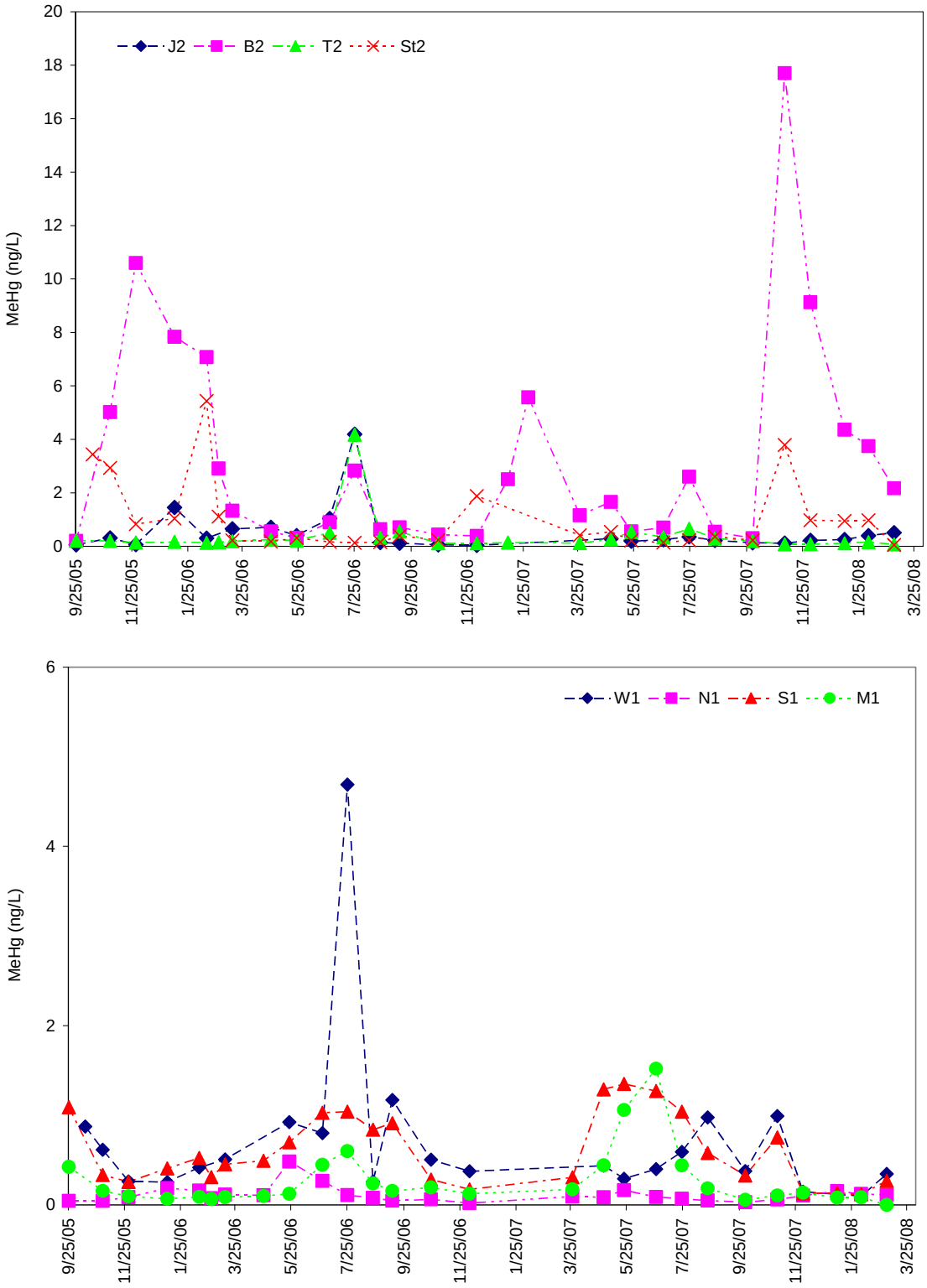

Figure 4. Seasonal variation in drainwater methylmercury (MeHg) concentrations for organic and mineral islands. Data for the organic islands are illustrated in the top graph and for the mineral islands in the bottom graph. Note the different scales for the Y-axes.

Similar to W1 in timing but at much lower concentrations, at site N1 a maximum of 0.484 ng L^{-1} was measured in May 2006 and the following year the seasonal peak was less (May 2007, 0.164 ng L^{-1}). The average concentration at N1 was 0.112 ng L^{-1} and the median was 0.088 ng L^{-1}. In contrast to sites W1 & N1, water collected from S1 showed strong seasonality during both water years with maximums of 1.04 and 1.35 ng L^{-1} occurring July 2006 and May 2007 respectively. MeHg concentrations were ~4 times higher at S1 during spring and summer compared to fall and winter. The average MeHg concentration at S1 was 0.608 ng L^{-1} and the median was 0.492 ng L^{-1}. Observations on the timing and magnitude of seasonal peaks in MeHg concentrations measured at M1 were similar to S1. A seasonal peak in MeHg concentration of 0.600 ng L^{-1} occurred during July 2006 and during the following June 2006 was 1.520 ng L^{-1}. The seasonal peaks at M1 were greater than two times the average MeHg concentration of 0.279 ng L^{-1} (median = 0.146 ng L^{-1}).

The farmed islands with predominantly organic soils (T2, J2, B2, & St2), also showed seasonal changes in MeHg concentrations (Table 2, Figure 4). However, the seasonal variation was not the same on all islands with organic dominated soils. At two of the islands (J2 and T2) observations were similar to those for the mineral dominated islands W1 and N1 with increased MeHg concentrations during summer and of greater magnitude during 2006 than 2007. At T2, the maximum MeHg values occurred during summer with the highest concentration measured July 2006 (4.180 ng L^{-1}). The following summer concentrations were much lower (0.658 ng L^{-1}, July 2007). The summer peaks in MeHg concentrations are substantially larger than the average MeHg concentration of 0.374 ng L^{-1} and median concentration of 0.194 ng L^{-1}.

On island J2, we observed a similar pattern as at T2 during 2006 but summer 2007 MeHg concentrations were not elevated. The highest MeHg concentration was measured during July 2006 with a value of 4.190 ng L^{-1}. At J2, no seasonal trend was evident during 2007; the average MeHg concentration was 0.498 ng L^{-1} and the median concentration was 0.253 ng L^{-1} for the entire study period.

Although islands T2 and J2 are predominated by organic soils or highly organic mineral soils, MeHg concentrations measured at the drains are similar to those measured from islands with predominantly mineral dominated soils. This is an important point to consider as these concentrations are used to calculate MeHg loads and these loads were extrapolated to estimate loads for all farmed islands in the Delta. Although soil types on islands T2 and J2 are primarily organic, the farming practices are similar to that of islands studied having mineral dominated soils.

The low MeHg concentration at islands J2 and T2 is probably due to the nature of the soils relative to the soils on B2 and St2. The soils on J2 and T2 vary in organic matter content from about 15 to 35 percent. However, highly organic mineral soils are present on a large part of both islands. In contrast, the organic soils on B2 are 40 to 60 percent organic matter and there are very small areas of mineral or highly organic mineral soils. Soils on St2 are reported to be similar to those found on B2 (McElhinney, 1992). The higher organic matter content and the greater predominance of the organic soils on B2 and St2 likely contribute to the higher MeHg concentrations for these two islands relative to T2 and J2.

Winter flooding on B2 and St2 also contribute to the larger MeHg concentrations measured in the drain water samples from these islands. Specifically, MeHg concentrations in samples collected from sites B2 and St2, showed a different seasonal pattern (Table 2, Figure 4) relative to the other islands. These two islands showed a strong seasonal trend of elevated MeHg concentrations during winter months. Concentrations at B2 were always highest during winter months. The drier water year 2007 coincided with lower winter MeHg concentrations at both B2 and St2. The average MeHg concentration at B2 was 3.258 ng L^{-1} and the median concentration was 1.660 ng L^{-1} and winter MeHg concentrations were 10 to 20 times higher than other times.

Concentrations at St2 were not as high as B2 but similar to B2 peak concentrations occurred during winter (Table 2). The St2 winter concentrations were elevated relative to the average MeHg concentration of 1.012 ng L^{-1} and the median concentration of 0.395 ng L^{-1}.

Islands B2 and St2 are deeply subsided and practice winter flooding which makes much of the island a seasonal wetland. It is likely that these practices result in the significant increases in MeHg concentrations relative to other sites studied which do not practice winter flooding. Winter flooding and holding water on cropland is isolated to a few farmed islands in the Delta. Given the MeHg concentrations measured at B2 were significantly higher than other islands studied, the loads calculated at B2 during this study should only be extrapolated to other organic-soil islands which also practice winter flooding. Higher MeHg concentrations observed at sites practicing winter flooding may pose a problem for wildlife independent of the magnitude of the MeHg load. This is particularly important if the island is being used as a wildlife refuge for fish eating animals. High MeHg concentrations in main drains of the islands should elevate small fish MeHg concentrations and increase MeHg exposure of fish eating animals.

Foe, (2003) measured an average MeHg concentration of 0.35 ng L^{-1} in samples collected from five farmed island main drain agricultural returns in the months of June and July 2000 and noted the MeHg concentrations were variable but high compared to concentrations in river channels surrounding the islands. The average MeHg concentrations measured in this study are in general agreement with (Foe, 2003). A comparison made between MeHg concentrations of source water for each island and concentrations at the agricultural returns suggest MeHg production is occurring *in situ.* Table 3 shows a comparison of average concentrations of MeHg source water and the average concentrations of the return water. With the exception of site N1, drainwater from the farmed islands in this study had higher MeHg concentrations by a factor of 2 to 16 indicating that the farmed islands produce MeHg. Comparison of MeHg loads is required to determine if the islands are a net source of MeHg to Delta surface waters.

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Table 3. Comparison of average methylmercury (MeHg) concentrations in farmed island source water and farmed island agricultural return water and the factor between averages.

Station ID	Source Water MeHg (ng L^{-1})	Agricultural Return MeHg (ng L^{-1})[5]	Factor
W1[1]	0.415	0.709	2
N1[2]	0.104	0.112	1
S1[3]	0.116	0.608	5
M1[2]	0.104	0.279	3
T2[4]	0.207	0.374	2
J2[4]	0.207	0.498	2
B2[4]	0.207	3.258	16
St2[4]	0.207	1.012	5

1. Data for source water collected at Cosumnes River at I5 (Foe et al., 2008).
2. Data for source water collected at Sacramento River at Freeport (Foe et al., 2008).
3. Data for source water collected at Sacramento River at Rio Vista (Foe et al., 2008)
4. Data collected this study from irrigation supply, source San Joaquin River at T2.
5. Data collected this study.

Detailed studies of factors affecting methylmercury at T2 and B2

As part of an effort to understand processes and factors affecting MeHg concentrations on Delta peat islands, we collected samples from drainage ditches and observation wells on T2 and B2. The part of T2 studied and B2 are similar in their hydrology and soil characteristics. Both are deeply subsided (over 6 m) and the organic soils in the areas where samples were collected were similar and have similar organic matter contents (25 to 50 percent). In contrast to B2, T2 is not intentionally flooded during the winter but there is frequently standing water during the winter in the area studied. Corn is the primary crop planted in the study area on T2. However, we also collected samples from a temporary managed non-tidal wetland constructed on a field formerly planted to corn. In this way, we compared agricultural and wetland MeHg loads for the same area. On the central Delta farmed island (B2), we collected surface and subsurface samples in rice, corn and tomato fields.

We also collected selected groundwater and drain samples in the northwestern area (TN) of T2 which has been extensively studied for DOC and Hydrology by Fujii et al., (1998) and Deverel et al., (2007a). Deverel et al. (2007) described in detail physical data for drain flow, groundwater levels, aquifer parameters, and chemical data for these two areas. During 2000 – 2003, they measured drain flow, estimated groundwater movement, collected and analyzed water samples from wells and drainage ditches for inorganic and organic constituents, and developed a conceptual model for processes affecting DOC.

Previous researchers have reported the carbon composition of T2 soils. Fujii et al., (1998) reported that the northern (TN) island soils ranged from 18.3 to 27.7 percent carbon, and Fleck et al., (2007) reported that the TN and southern (TS) island soils ranged from about 18 to 24 percent and 20 to 28 percent carbon, respectively.

There is some geohydrologic data for B2 which shows that it is similar to T2. Specifically, water flows onto the island from adjacent channels through and under levees and is pumped off the island via a system of drainage ditches and discharge pumps. However, the organic deposits are generally shallower on B2 (Deverel and Leighton, 2009). The organic deposits on T2 are 5 to 7 m thick whereas they are generally less than 5 m thick on B2.

Chemical and physical data collected at T2 have been used to create a conceptual model illustrating the relationship of hydrologic conditions, groundwater flow and agricultural drain flow, chemistry, and carbon loads (Figure 5)(Deverel et al., 2007a). The following is a summary of Deverel et al., (2007a):

> *Groundwater flows from the San Joaquin River onto the island primarily via underlying mineral deposits. San Joaquin River water is also the source of irrigation water. Drain flow is seasonal with maximum flow corresponding to maximum groundwater levels during winter. Peak flows generally correspond to winter precipitation. During low flow conditions during late spring through fall, deep groundwater flows to drainage ditches from chemically reduced permanently saturated deposits. Groundwater age dating and tritium analysis of drain water samples indicated that the drainage water is substantially influenced by water that recharged twenty years prior to the study.*
>
> *Drainage DOC loads vary seasonally and spatially. During the high-flow period relatively high DOC concentrations from oxidized shallow soils and high groundwater levels result in large drain flows and loads relative to the low-flow period. Agricultural drainage DOC loads are generally lower than wetland drainage loads. Using groundwater chemical data and a groundwater flow model, Burow et al., (2005) estimated subsurface DOC loads from a non-tidal constructed wetland on T2 as 1,233 to 3,671 g/ha-day. Fleck et al., (2007) reported an annual average DOC load of 2,566 g/ha-day for the wetland in the TN area (Figure 1).*

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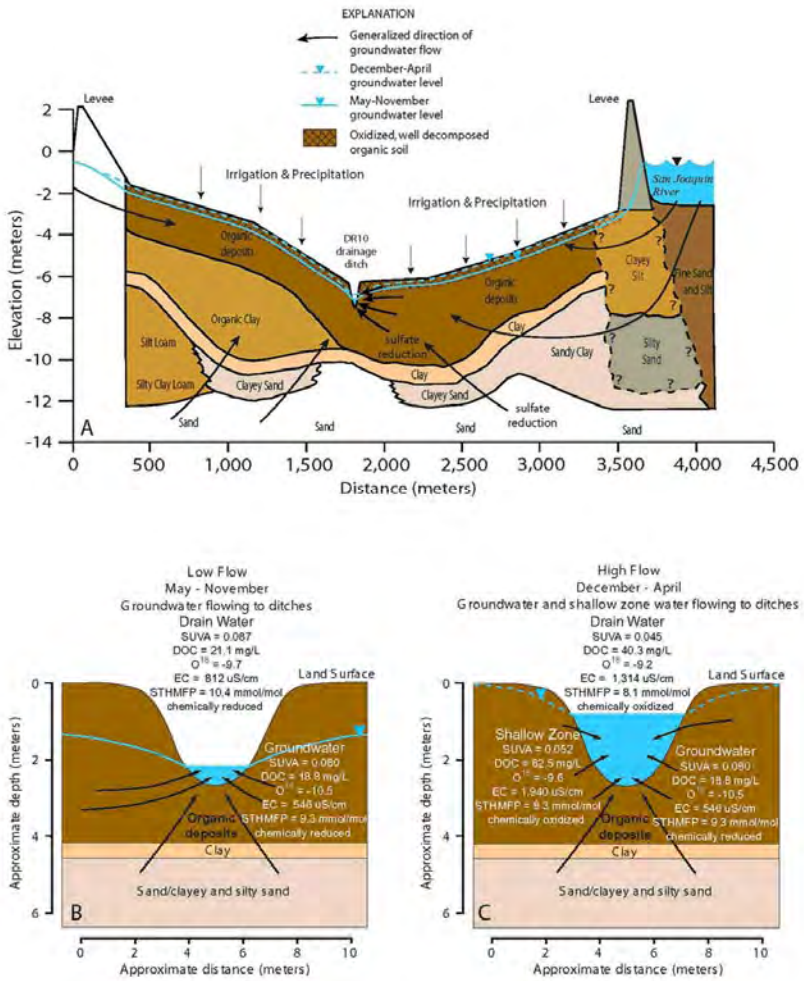

Figure 5. Conceptual model of groundwater and drain flow for T2 (from Deverel et al., 2007a).

Relation of methylmercury to chemical constituents in subsurface drainage on T2

Figure 6 shows temporal variation in MeHg concentrations for DR1 and DR2 from November 1, 2005 to December 5, 2006. Prior to flooding of the demonstration wetland in early May 2006, MeHg concentrations were relatively low through January 2006. During February through April, concentrations increased to over 1.8 ng L^{-1}. After wetland flooding, concentrations increased further to over 2.4 ng L^{-1} and then declined in early winter to about 0.2 ng L^{-1}. The May peak and subsequent declines in MeHg concentrations corresponded to temporal variability in MeHg concentrations in DR3. The water collected at DR3 is subsurface drainage from the demonstration wetland but the high MeHg concentrations are likely due to flushing of porewater by the addition of "new" water to the wetland. Similar temporal variability has been observed at seasonal wetlands around Mud Slough were high MeHg concentration occur after flood up followed by decreases over a period of several months (Foe et al., 2008). These measurements have a practical value given the possibility of conversion of deeply subsided farmed islands into shallow wetlands to prevent further subsidence. From this data it is unclear what long term (six month plus) consequences flooding would have to either MeHg concentrations or loads.

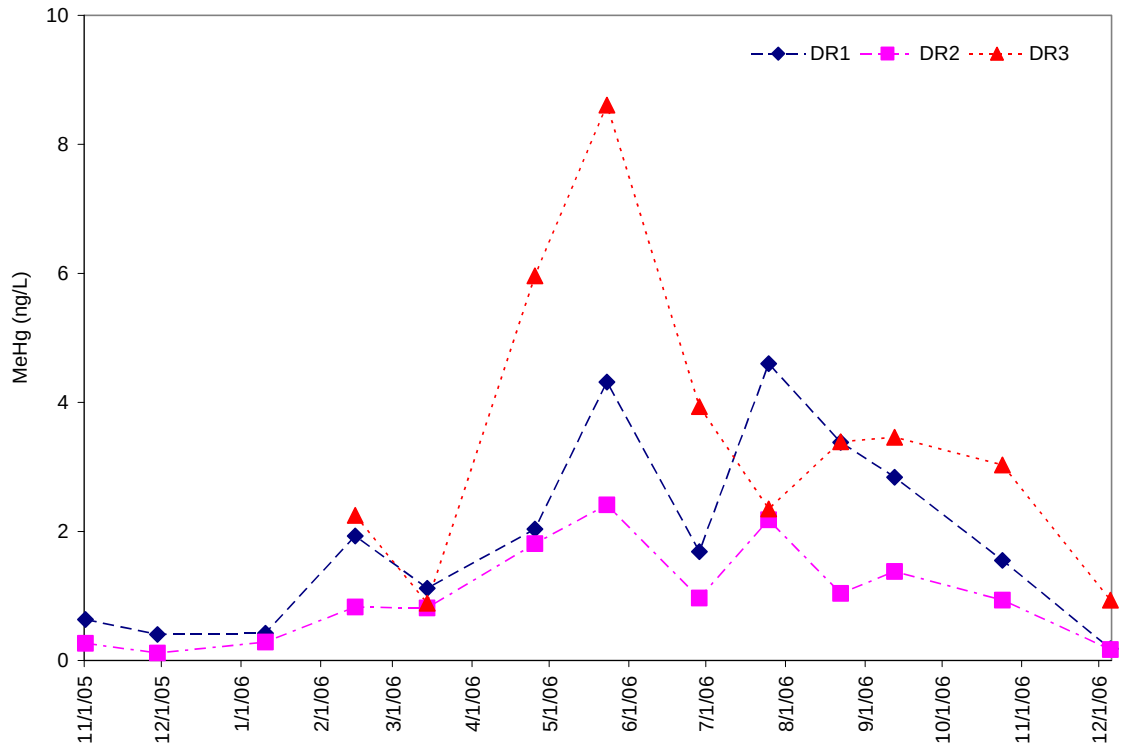

Figure 6. Temporal variability in methylmercury (MeHg) concentrations in DR1, DR2 and DR3.

The relation of MeHg concentrations to concentrations of other constituents provides insight about processes affecting MeHg concentrations. We analyzed samples for DOC and sulfate and determined redox potential in the field for DR3 drainwater. Figure 7 shows that the DR3 MeHg concentration peak of almost 9 ng L^{-1} corresponded to the DOC peak concentration of 212 mg L^{-1} in late May 2006, soon after wetland flooding. Data and analysis presented in Deverel et al., (2007a) and Fleck et al., (2007) demonstrated that the high drainage water DOC concentrations are the result of flushing of DOC in the shallow variably saturated zone. This reservoir of DOC is the result of organic soil oxidation. Application of San Joaquin River water flushed the high DOC water in the shallow organic soils to the DR3 drainage ditch and the same process appears to mobilize MeHg to the subsurface drainage water.

Concomitant with DOC flushing, we measured the onset of reducing conditions. Prior to flooding in fall 2005, we measured low sulfate and low redox potential values associated with flow to the drainage ditches of deep groundwater in contact with relatively less decomposed organic deposits. As the groundwater level rose with the winter rains, shallow, variably saturated zone water began to flow to the drainage ditch and flush stored DOC and salts (including sulfate) from organic matter oxidation. This resulted in an increase in sulfate concentrations from less than 5 mg L^{-1} in mid December to 250 mg L^{-1} in early February. Continued flushing during the wet 2006 winter (2006 was the 4th wettest year on record since 1906) and spring continued to remove DOC and sulfate and resulted in reducing conditions with redox potential values dropping to -50 mV and below in February – April (Figure 8). Lower redox potential values were measured during May through July as the result of wetland flooding. DOC and MeHg concentrations also decreased during this time period. Presumably due to

continued flushing with oxidized San Joaquin River water which was applied to the demonstration wetland, drainage ditch redox potentials increased but sulfate, DOC and MeHg concentrations remained relatively low through October 2006. The reason for maintenance of lower MeHg concentrations is unclear. However, low sulfate concentrations indicate sulfate reducing conditions in pore waters. The absence of sulfate may indicate lack of sulfate reducing bacteria for MeHg production.

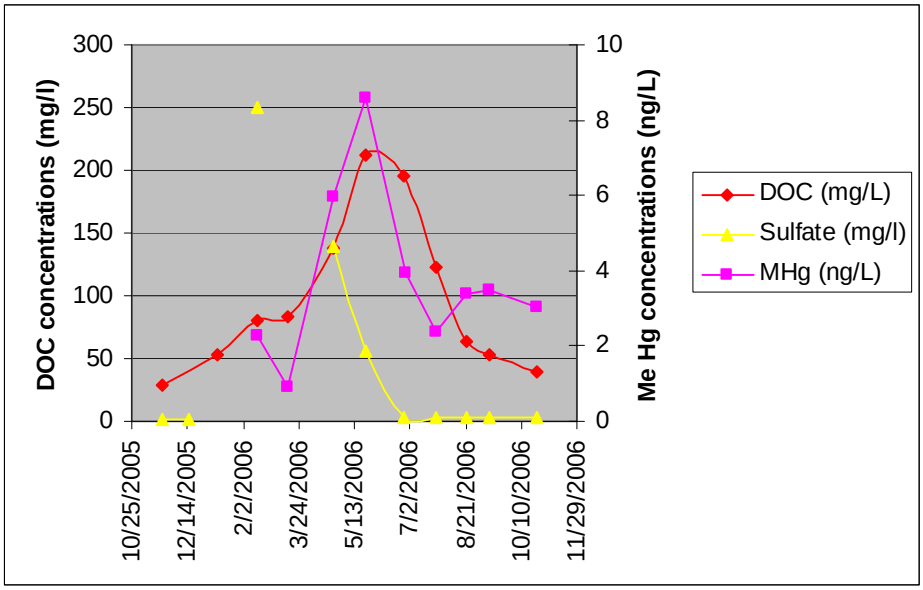

Figure 7. Temporal variability in dissolved organic carbon (DOC), sulfate, and methylmercury (MeHg) at DR3.

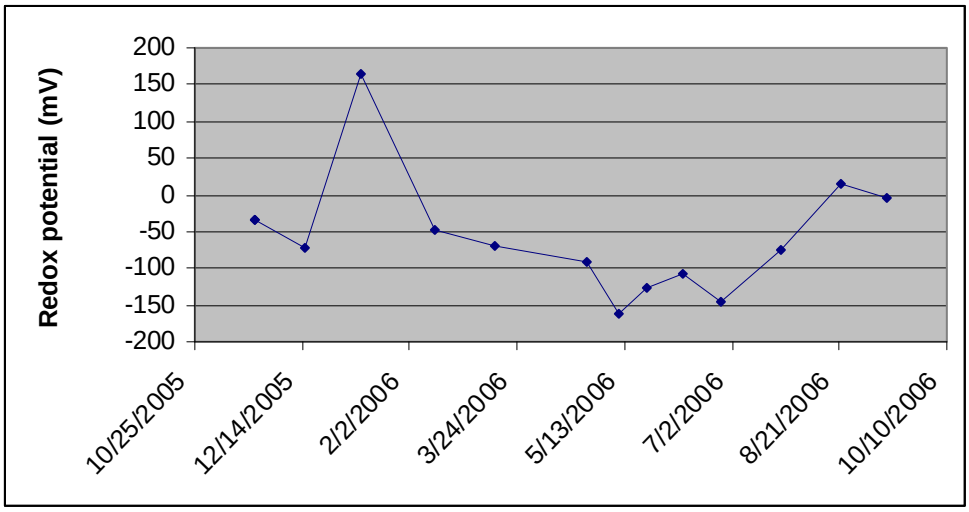

Figure 8. Temporal variability in redox potential at DR3.

Figure 9 shows a significant correlation at the 95 % confidence level of MeHg and DOC concentrations indicating that flushing of shallow, variably saturated zone groundwater is a probable mechanism explaining MeHg concentrations in subsurface drains on Delta islands. MeHg concentrations are also influenced by redox potential. Lower redox potential values result

in lower MeHg concentrations. Regression analysis of MeHg on DOC concentrations and redox potential for DR3 explains 75 percent of the variance in MeHg concentrations with the following equation: [MeHg] = -1.41 + 0.0598(redox potential) + 0.0787 [DOC].

We measured MeHg concentrations for DR11 in TN area on T2 (Figure 1). Due to very low flows, we were unable to measure drain flow. MeHg concentrations ranged from 0.088 to 0.206 ng L^{-1} during January and February 2007 and are generally consistent with the drain-water concentrations measured in DR1 and DR2 during fall 2005 and early winter 2006 prior to flooding of the demonstration wetland. However concentrations are higher than the nearby wells 21AA, 21A and 21B which probably represent the source water (see discussion below under observation wells). This may indicate that processes in or adjacent to the drainage ditch result in higher concentrations relative to the groundwater. But MeHg production is not limited to the drainage ditches as data from DR1 and DR2 shows elevated concentrations which must have originated on the fields.

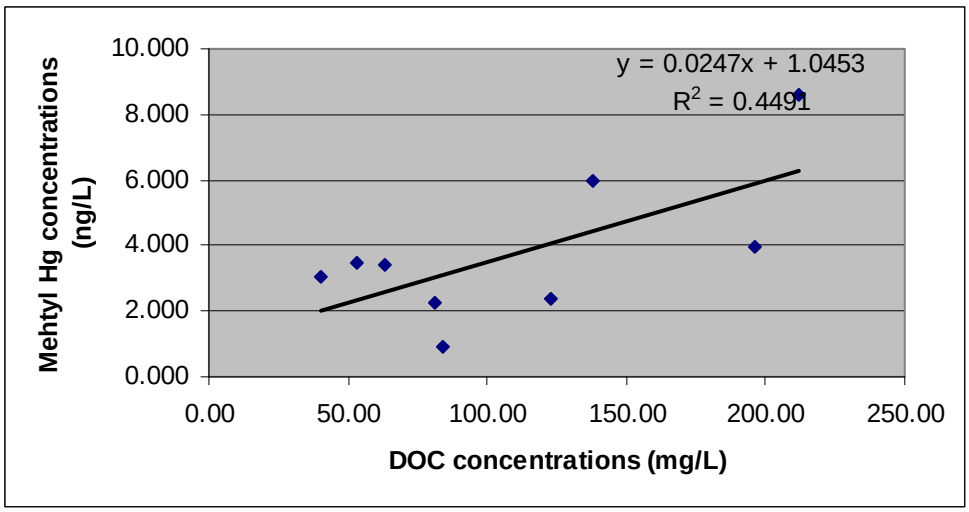

Figure 9. Relation of methylmercury (MeHg) concentrations to dissolved organic carbon (DOC) concentrations (significant at 95 % confidence level).

Subsurface drain flows and methylmercury loads for DR1, DR2 and DR3 on T2

We measured drain flow at DR1, DR2 and DR3 when samples were collected and pressure transducers recorded stage at 15 minute intervals after January 2006. We used a flow/stage relation to estimate flows from the transducer data. Figure 10 shows the results of those measurements and precipitation at the T2 weather station operated by California Department of Water Resources. During fall 2005 and early winter 2006, flows were relatively low and less than 0.5 m^3 min^{-1}. Substantial precipitation in February and March resulted in high subsurface drain flows following storm events. During April, we observed a return to pre winter base flows. Flows over 0.02 m^3 min^{-1} during May through December in DR3 resulted from flooding of the demonstration wetland.

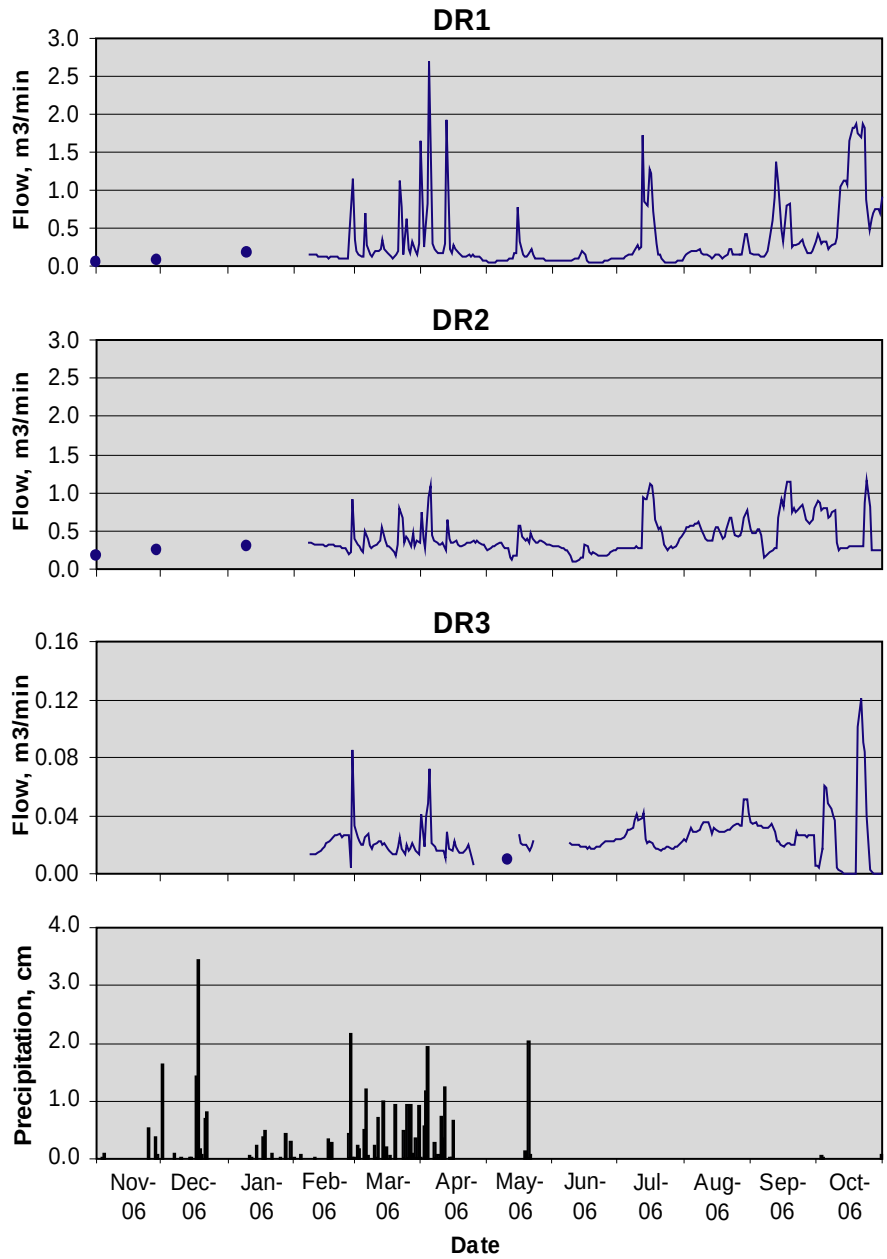

Figure 10. Flows at DR1, DR2 and DR3 and precipitation at the T2 weather station.

Figure 11 shows the subsurface MeHg loads in g/day-A for DR1 + DR2 and DR3. Prior to wetland flooding, MeHg loads ranged from less than 13 x 10^{-7} to over 140 x 10^{-7} g/day-A. Agricultural MeHg loads in DR1 and DR2 occurred from fall 2005 through April 2006 and ranged from 10 x10^{-7} to 142 x 10^{-7} g/day-A. Wetland loads occurred in DR3 from early May through October and ranged from 52 x 10^{-7} to a high of 297 x 10^{-7} g/day-A in late October 2006. The actual contributing area to the DR3 is less than the total area of the wetland because there is some subsurface flow towards DR1 and DR2. Using groundwater elevations measured in observation wells and piezometers, we delineated and calculated the contributing area as 1.1 ha or 2.7 acres (Figure 12). The contributing area was constant within plus or minus 100 m^2 during the study.

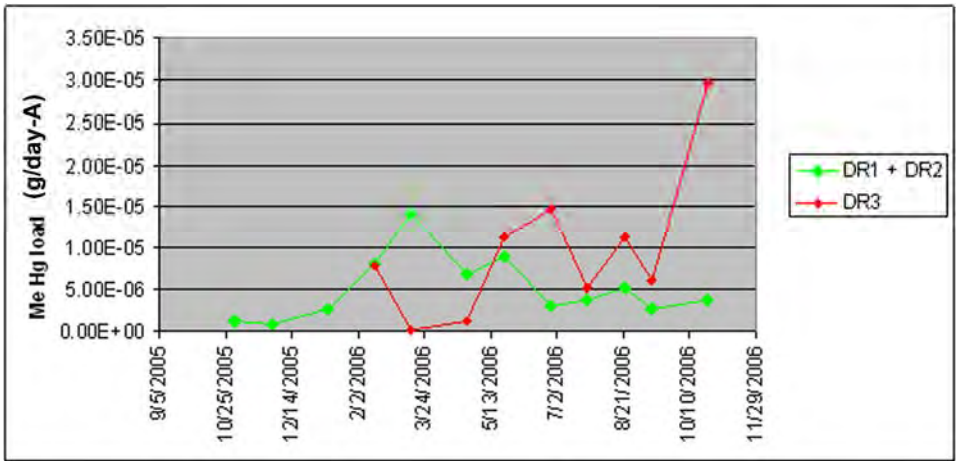

Figure 11. Subsurface methylmercury (MeHg) drain loads for DR1 + DR2 and DR3.

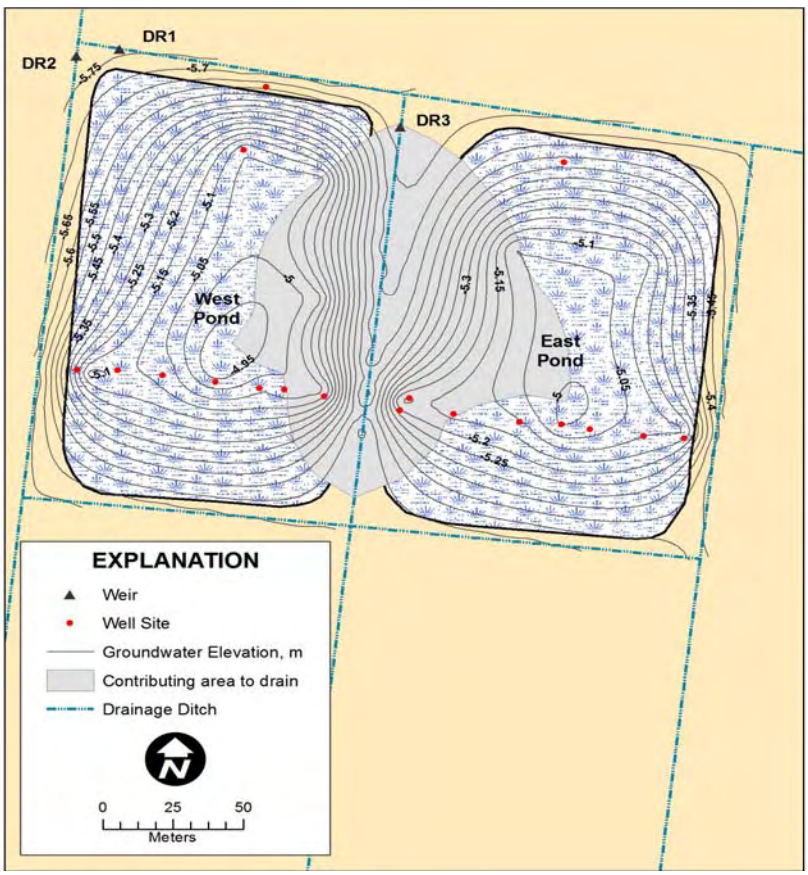

Figure 12. September 12, 2006 groundwater levels (0.5-m wells) and contributing area to DR3.

Figure 11 indicates that wetland subsurface per area loads were slightly higher than agricultural loads. We compared the two data sets (agricultural and wetland load values) using boxplots and the Mann-Whitney comparison test (Figure 13). The wetland median load of 113 x 10^{-7} g/day-A was higher than the agricultural load of 47 x 10^{-7} g/day-A. However, the Mann-Whitney comparison test indicated no significant difference between the two data sets consisting

of six data points each. Figure 6 indicates that MeHg concentrations decreased with time after wetland flooding. Current management practices which create peat oxidation and lead to subsidence also facilitate the production and mobilization of MeHg. Best management practices which keep water on an island may limit the loads to Delta surface waters. Increasing residence times for water on an island may increase MeHg removal mechanisms such as photodemethylation and limit production of MeHg to an initial pulse. However, holding water will also create conditions that continually regenerate organic carbon and may facilitate MeHg production by supplying new carbon sources for sulfate reducing bacteria. Water residence time on an island may be increase by using recirculation methods. However, it is important to consider that a reduction in MeHg load may not translate to a reduction in biota exposure. High concentration water held on an island may increase exposure to foraging wildlife.

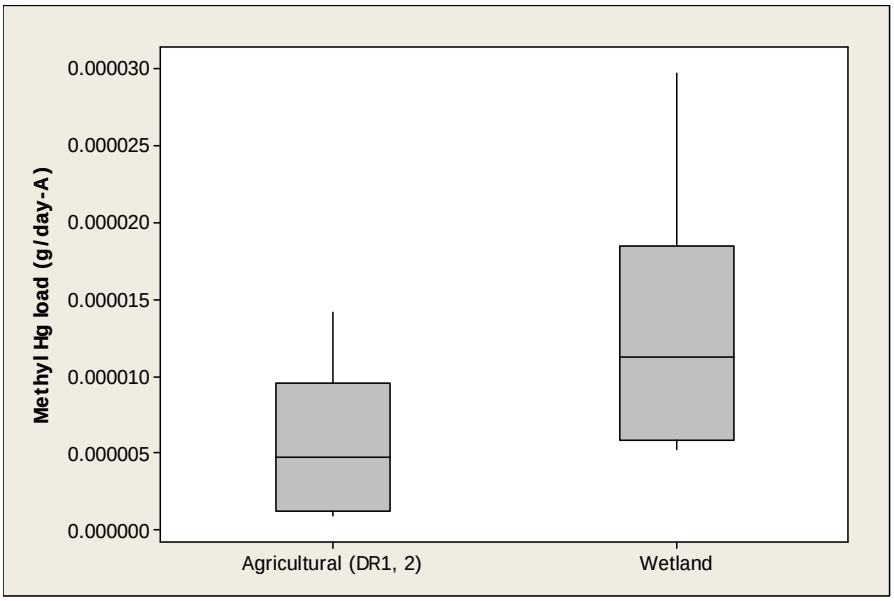

Figure 13. Boxplots of subsurface drain methylmercury (MeHg) loads from wetlands and agricultural conditions. The horizontal line crossing the gray box are the median values. The gray box represents the inner quartile range of the data. Vertical lines extending from the gray box represent the extent of the data.

Wetland surface water flows, methylmercury concentrations and loads on T2

There was a single outflow at the northwest corner of the demonstration wetland that collected all surface water outflows. Figure 14 shows the instantaneous measurements for surface inflows and outflows for the wetland. Inflows varied from 0.4 to 0.5 m^3 min^{-1} during the first two months of wetland flooding. We reduced inflows during August - October to 0.3 to 0.28 m^3 min^{-1}. Outflows were generally less than 0.2 m^3 min^{-1}. We measured excessively high flows during late May of 0.37 m^3 min^{-1} during the flow adjustment period.

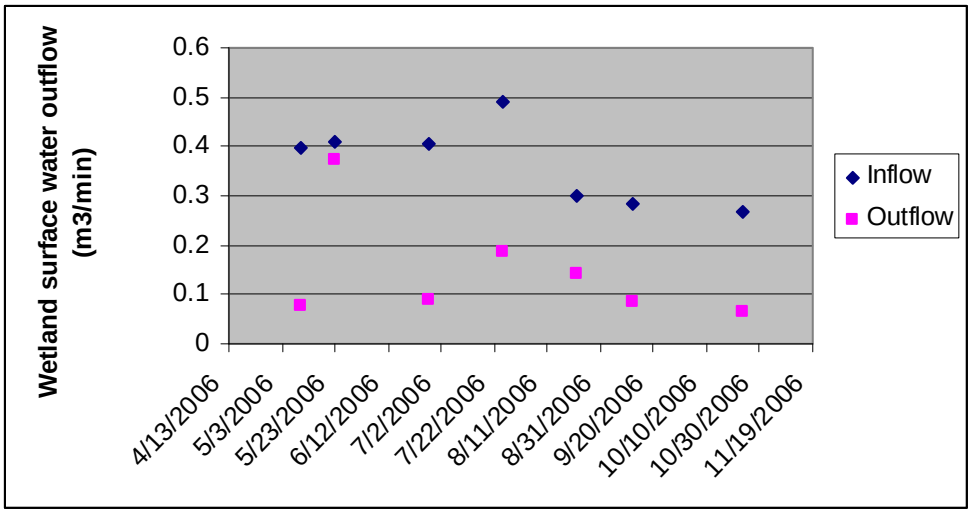

Figure 14. Surface inflow and outflow measurements at the T2 demonstration wetland.

Figure 15 shows the temporal variability in MeHg and DOC concentrations in the wetland surface water outflow. MeHg concentrations ranged from a high of 9 ng L^{-1} in July to a low of 0.89 ng L^{-1} in late October. Similar to the subsurface results (Figure 6), concentrations were high during the early months of flooding and were similar in magnitude to the subsurface concentrations. Concentrations decreased substantially and leveled off during the last three sampling events. DOC concentrations showed a similar trend reaching a maximum concentration of 50 mg L^{-1} in July and decreasing in August through October. Field parameters remained relatively stable during the wetland flooding period: pH ranged from 5.7 to 6.3, electrical conductivity ranged from 282 to 374 microS cm^{-1} and dissolved oxygen ranged from 0.2 in May to 2.08 mg L^{-1} in June. Temperature ranged from 18.7 ^{o}C in May to a high of 27 ^{o}C in July. During August through October water temperatures ranged from 19 to 21 ^{o}C. Similar to the subsurface flows, there appears to be a flushing of the shallow soils and diffusive flux of MeHg and DOC into the wetland surface water.

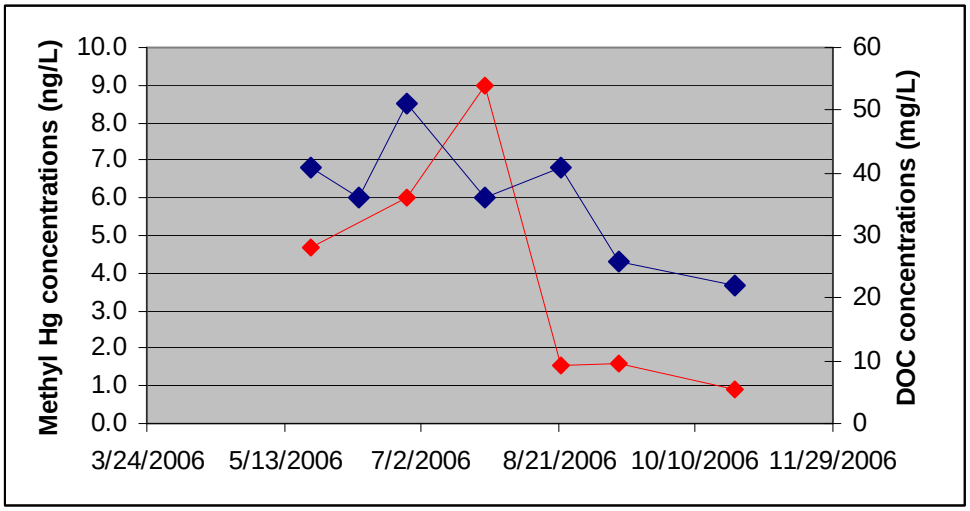

Figure 15. Wetland surface water outflow methylmercury (MeHg) (-♦-) and dissolved organic carbon (DOC) (-♦-) concentrations.

Because of the large surface water outflows and high concentrations, MeHg loads were relatively large during the first 3 months of wetland flooding. Loads decreased to lower levels in August through October. Figure 16 shows that MeHg loads ranged from over 30.0 x 10^{-5} g/day-A in May to 3.91 x 10^{-5} g/day-A in August. September and October loads were 2.41 x 10^{-5} and 1.03 x 10^{-5} g/day-A, respectively. We measured the inflow MeHg concentration and the average was 0.17 ng L^{-1}. The inflow MeHg load to the wetland averaged 9.0 x 10^{-5} g day^{-1}. Therefore, net loads were only slightly lower than the uncorrected outflow loads. The large surface water loads are responsible for the large total (subsurface + surface) MeHg loads from wetlands on organic soils. Again, restriction of surface outflows through the use of recirculated water may reduce surface-water loads.

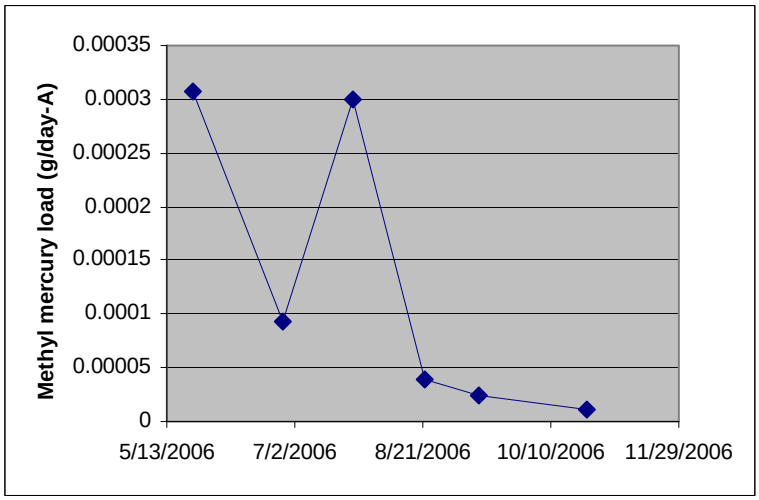

Figure 16. Surface water methylmercury (MeHg) loads from the T2 demonstration wetland.

Surface water methylmercury concentrations and loads for the central Delta island B2

Table 4 shows the inflows and outflows and the respective MeHg concentrations for rice and tomatoes in July and August on B2. Inflows and outflows and concentrations were similar for the two dates. We measured flow and collected samples at the single inlet and outlet for the field. The water was siphoned from the adjacent channel. MeHg concentrations ranged from 0.37 to 0.99 ng L^{-1}. The area of the rice field was 23.5 ha (58 acres). The per area MeHg outflow load was 73 x 10^{-7} g/day-A in July and 33 x 10^{-7} g/day-A in August. During the August measurement, the inflow load was higher than the outflow load resulting in a net deposition of MeHg in the rice field, whereas July saw a net loss of MeHg from in the same field.

For tomatoes, we estimated inflows in the furrows and outflows in the tail water ditches during irrigation for small, well delineated sections of the fields on peat soils. Table 4 shows higher outflow loads for tomatoes relative to rice. Specifically, outflow loads were 560 x 10^{-7} and 297 x 10^{-7} g/day-A in July and August. Net MeHg loads were similar to outflow loads due to the low concentrations in the inflow water. For both dates, inflows were almost identical to outflows. This was probably due to measurement uncertainty as there was almost certainly infiltration along the furrow. Uncertainty was probably the result of our inability to measure flow in all furrows. For example, during the July measurement, we extrapolated measurement

for three furrows to 50 furrows. For both rice and tomatoes, MeHg concentrations increased in the outflow water relative to the inflow water indicating the fields were a source of MeHg.

Table 4. Flows, methylmercury (MeHg) concentrations, and loads for the central Delta island (B2).

Crop	Date	Inflow (m^3/min)	Inflow [MeHg] (ng/L)	Outflow (m^3/min)	Outflow [MeHg] (ng/L)	Area (ha)	Per area MeHg outflow load (g/day-A) (x 10^{-7})	Net per area MeHg load (g/day-A) (x 10^{-7})
Rice	7/31/07	13.59	0.40	6.79	0.99	57.60	73	13
	8/14/07	13.25	0.37	4.08	0.77	57.60	33	-20
Tomatoes	7/31/07	4.25	0.08	4.28	0.63	2.50	560	530
	8/14/07	0.27	0.18	0.28	0.43	0.245	297	177

We measured inflow and outflow concentrations in a 19.3 ha (47.7 acre) corn field on B2 on July 31, 2007. A diesel-engine powered pump removed water from an adjacent subsurface drain to a rectangular ditch about 0.6 foot deep and 3.0 feet wide. Velocity in the ditch was about 2.2 feet per second. The instantaneous flow was about 4 ft^3 s^{-1} onto the field. The inflow water was pumped from an adjacent subsurface drain. The inflow water had a MeHg concentration of 1.09 ng L^{-1}. This resulted in a MeHg load onto the field of about 0.01 g day^{-1}. Irrigation typically lasts for a few days. Water flowed to 60-cm deep "spud" ditches where it was allowed to infiltrate. At the end of the field, spud ditches merged with a collector drain which discharged to the main drain. Due to low flow conditions, we were unable to measure flow in the spud ditches or the drainage ditch. We collected and analyzed samples for MeHg in the 2 spud ditches and the drainage ditch. The drainage ditch collected both surface runoff and subsurface flow. The spud ditch MeHg concentrations were 1.41 and 0.61 ng L^{-1}. The drainage ditch MeHg concentration was 0.076 ng L^{-1}. The corn results are therefore variable and difficult to interpret from the standpoint of outflow loads. Relative to the inflow, we measured concentration decreases in the second spud ditch and the drainage ditch and a slight increase in the first spud ditch. The low outflows and generally low surface and subsurface outflow concentrations indicate low surface and subsurface MeHg drain loads for corn.

Observation well data on the farmed island T2

We collected samples for MeHg analysis from selected observation wells. Deverel et al., (2007a) described the well installation process, construction details and locations (Figure 1). Table 5 shows the dissolved MeHg concentrations for three wells in the TN field. Groundwater MeHg concentrations were very low compared to other samples (surface and subsurface) collected as part of this study. Groundwater flow to the drainage ditches are a mixture of shallow and deep groundwater from shallow decomposed peat and deep less decomposed peat (Deverel et al., 2007a). All well concentrations in Table 5 are substantially lower than the lowest MeHg concentrations in DR1 and DR2 which were about 0.40 ng L^{-1}. There are two possible explanations for this. First, groundwater flowing to DR1 and DR2 may have higher concentrations than groundwater in the TN area. However the data for drain DR11 in the TN area described above indicates similar MeHg concentrations as the DR1 and DR2 drains under

agricultural conditions. It is more likely that the groundwater samples were representative of deeper, chemically reduced groundwater that contributes minimally to MeHg concentrations and loads in drainage ditches. We were unable to collect samples for MeHg analysis from the wells in the TS area prior to wetland flooding. When we sampled the wells during the dry winter of 2007, water levels were deep relative to the study period described in Deverel et al., (2007a). Specifically, the groundwater depth was greater than 1.4 m and redox potential values were generally reducing (Table 5).

Table 5. Methylmercury (MeHg) concentrations in observation wells in the TN field on farmed island T2.

Well ID	Well Depth (m)	Sample date	Dissolved [MeHg] (ng/L)	Oxidation-Reduction Potential (mV)	pH	Electrical Conductivity (micros/cm)
21B	3	8/22/07	0.046	-92	6.5	921
22B	3	8/22/07	<MDL	-100	6.5	960
21A	1	1/8/07	0.037	Not measured	Not measured	Not measured
21A	2	1/30/07	0.030	108	6.1	2380
21A	2	2/26/07	0.064	Not measured	Not measured	Not measured

Observation well data on the central Delta farmed island B2

We installed and sampled two wells on B2, one in the rice field and another in the corn field described above. Both wells were about 2 m deep and similar in construction to the wells on T2. Table 6 shows the analytical results and field parameter data. The depths to water in the wells during winter and summer were about 1.5 m. The MeHg concentrations in the rice well RW-2 were substantially higher than the corn well OWC-1. During the August sampling, we measured chemically reducing conditions in the rice field well and oxidizing conditions in the corn field well. We hypothesize that downward movement of water with high DOC and MeHg concentrations resulted in the high groundwater MeHg concentrations in the rice well. Hydrologic and water-quality data from T2 and Delta rice fields point to the validity of this proposition.

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Table 6. Methylmercury (MeHg) concentrations in corn (OWC-1) and rice (RW-2) fields observation wells on the central Delta island B2.

Well ID	Well Depth (m)	Sample date	Dissolved [MeHg] (ng/L)	Oxidation-reduction potential (mV)	pH	Electrical Conductivity (micros/cm)
OW C-1	2	1/8/07	0.196	172	6.1	972
RW-2	2	8/22/07	8.54	-96	6.2	505
RW-2	2	1/30/07	3.24	Not measured	Not measured	Not measured
RW-2	2	2/26/07	7.45	Not measured	Not measured	Not measured

Methylmercury loads

We estimated net MeHg loads from farmed islands by subtracting calculated monthly inflow loads from outflow loads at each site. Net MeHg loads for each farmed island were evaluated relative to soil characteristics, water management practices, and extent of subsidence. Table 7 lists monthly net MeHg loads in g/acre-day by water year for seven farmed island sites. Discharge data necessary for the calculation of MeHg loads were unreliable for site M1 thus preventing load calculations for this island. Flow measurements were lacking at various times at different locations resulting in an incomplete record of MeHg loads relative to concentration data. Water year 2007 is the most complete record from which to make comparison of loads for all islands. Sites J2, B2, and St2 have the most complete record of monthly load calculations spanning the length of this study.

Figure 17 shows temporal variability in estimated net MeHg loads in g/acre-day. For islands B2 and St2, the highest net MeHg loads occurred during winter 2006 and 2007. Also, relatively high net loads also occurred on J2 during winter 2006. Net MeHg loads for St2 were relatively high during the winter 2006 and 2007 while intervening months showed low or negative values. Relatively high loads occurred during July 2006 at J2 and B2. At J2, MeHg loads during water year 2006 were larger than water year 2007 during which we estimated mostly negative loads. Also, unlike the other predominantly organic-soil islands, net loads on T2 were consistently positive but subject to little seasonal variation. In contrast, W1 had the most negative net MeHg loads during summer months of 2006 and 2007. For the non-organic soil islands, N1, W1 and S1, we estimated net loads that were very low or negative.

Table 7. Net methylmercury (MeHg) loads calculated for seven sites within the Delta (listed monthly and by water year).

Water Year	Date	Station ID and MeHg Load x 10^{-7} (g $acre^{-1}$ day^{-1})						
		W1	N1	S1	T2	J2	B2	St2
04-05	9/13/05						-3.78	
05-06	10/13/05							152.
	11/1/05						156.	96.5
	11/29/05					-2.07		13.9
	1/10/06					138.	1190	79.6
	2/14/06					22.9		459.
	3/14/06					51.7		22.6
	4/25/06					79.3	76.4	10.2
	5/23/06					16.1	-34.7	-15.2
	6/28/06					46.5		7.01
	7/25/06	-76.9	-22.4			157.	112.	-5.27
	8/22/06	-208.	-13.8	-13.1		-8.84	-9.20	-37.1
	9/12/06	-88.9	-9.33	10.8	44.4	2.35	12.9	-8.81
06-07	10/24/06	-29.0	-1.66	4.88	7.10	-.320	4.72	.410
	12/5/06	7.57	.002	4.97	5.29	-2.22	9.88	
	1/8/07				9.07		15.2	
	1/30/07						218.	
	2/27/06		-2.19	-2.18	6.10		237.	385.
	3/27/07		-4.97	-7.13	7.07		32.2	26.4
	4/30/07	-65.5	-8.39	8.70	11.9	6.78	1.96	10.8
	5/22/07	-107.	-17.9	53.1	20.0	-15.8		-41.5
	6/26/07	-248.	-21.5	10.2	9.35	-2.00		-27.1
	7/24/07	-141.	-12.9	14.2	8.72	-19.5		-32.6
	8/21/07	-50.5	-6.46	5.09	33.1	3.65		25.0
07-08	10/1/07	-18.7		1.57	1.72			-10.0
	11/5/07	-3.87		6.35	-2.61			
	12/3/07			2.13	2.45			
	1/9/08			30.7				

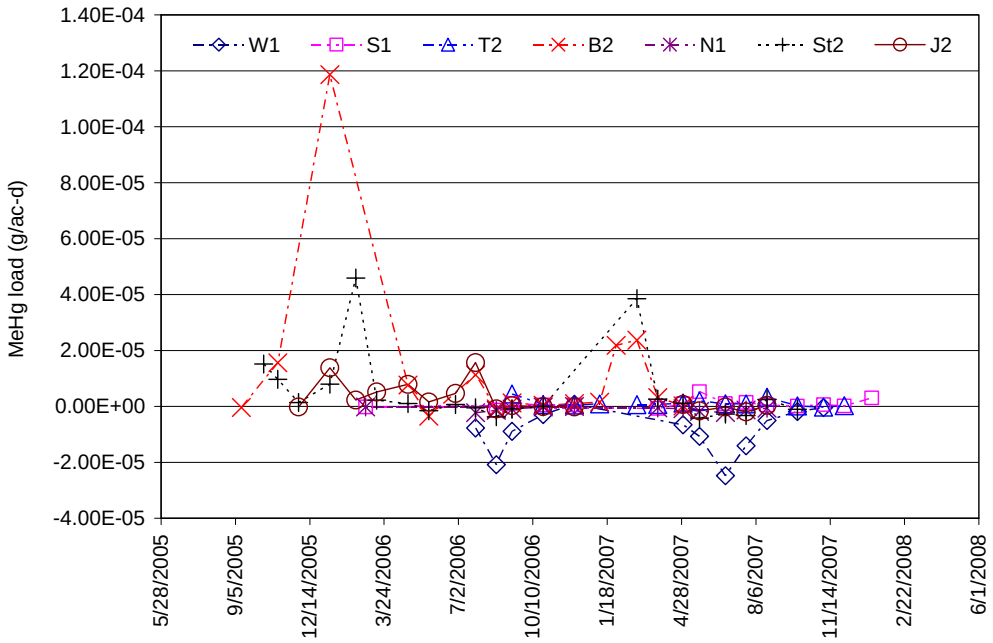

Figure 17. Temporal variability in net methylmercury (MeHg) loads.

Table 8 lists estimated average MeHg loads due to irrigation and seepage and estimated average MeHg outflow loads from the islands, and the resulting average net MeHg load was calculated by the difference. Average net loads are given on a g day^{-1} and g acre^{-1} day^{-1} basis and the average outflow of water and apparent contributing factors are listed. The highest average net MeHg loads originated from B2 where highly organic soils predominate and a large portion of the island is flooded from late fall through early winter as discussed above. Average net loads for the other predominantly organic soil islands J2 and St2 were relatively high while T2 had the lowest average net MeHg load of the organic soil islands. Average net MeHg loads for two of the seven islands studied, N1 and W1, were negative indicating that they were sinks for MeHg.

Figure 18 shows the relation of average island discharge to land surface elevation. The relation explains 63.5 percent of the variance in discharge and is statistically significant at alpha = 0.02. The greater the depth of subsidence, the larger the island discharge due to increased hydraulic gradients onto the island. For all the deeply subsided islands, J2, St2, B2 and T2, larger outflow volumes which ranged from 0.10 to 0.20 foot month^{-1} contributed to higher MeHg loads[2]. For the remaining islands which are less subsided, average outflow was lower and ranged from 0.02 to 0.09 foot month^{-1}. A significant relationship ($p < 0.05$) was observed between the outflow MeHg loads (g day^{-1}) and land-surface elevation ($r^2 = 0.80$) (Figures 19). Moreover, we identified a significant correlation (r^2=0.60, p<0.02) for the logs of average MeHg loads out in grams per day per acre. However, there was no significant correlation found between net MeHg per acre loads and land-surface elevation ($p > 0.05$). Although discharge influences MeHg load there was no statistically significant relation for land surface elevation and MeHg concentrations.

[2] Water discharge values (acre-ft month^{-1}) were normalized by island size (acres) resulting in units of ft month^{-1}.

Table 8. List of average methylmercury (MeHg) loads onto farmed islands (In), average MeHg loads off of farmed islands (Out), average net MeHg loads of farmed islands, average outflow volume of water from farmed islands, and apparent contributing factors.

Station ID	**Average MeHg Load In** (g day^{-1}) x 10^{-3}	**Average MeHg Load Out** (g day^{-1}) x 10^{-3}	**Average MeHg Load Net** (g day^{-1}) x 10^{-3}	**Average MeHg Load Net** (g acre^{-1} day^{-1}) x 10^{-7}	**Average outflow*** (ft month^{-1})	**Apparent Contributing Factors**
W1	16.9	2.72	-14.2	-85.82	0.04	Moderate to highly organic mineral soils on about half of island, mineral soils on other half. Little subsidence.
N1	26.2	0.92	-25.3	-10.12	0.02	Mineral soils predominate. Little subsidence.
S1	1.4	3.1	1.7	8.68	0.09	Mineral soils predominate. Little subsidence.
T2	4.0	8.1	4.1	11.69	0.20	Mixture primarily of organic, highly organic mineral soils. Deeply subsided.
J2	3.2	12.9	9.7	27.84	0.14	Organic soils or highly organic mineral soil on large area of island, very wet conditions during winter, deeply subsided.
B2	5.7	56.1	50.5	134.45	0.10	Organic soils on the entire island, large portion of island flooded during winter, deeply subsided.
St2	6.8	27.6	20.9	50.82	0.19	Predominantly organic soils in area where discharge was measured. Flooding during winter. Deeply subsided.

*Average outflow data was normalized by island size resulting in units of ft month^{-1}.

Figures 18 and 19 show graphical separation between the mineral-soil and organic-soil farmed islands. Examination of the individual islands provides further insight into the differences in loads. Island B2 is the most subsided island with a large area of highly organic soils and stands out with the highest average load. Water is held on B2 for much of the winter and this may explain why B2 falls below the trend line with respect to discharge. Island T2 is deeply subsided but is not intentionally flooded during the late fall and winter. The area on island St2 drained by the drainage and pump station sampled during this study is predominated by organic soils that range from 17 to 52 percent in organic matter content and is flooded during the late fall and winter. Soils on island J2 are predominantly organic or highly mineral and range from 11 to 45 percent organic matter content. Mineral soils are present on a substantial part of the island. Even though J2 is not intentionally flooded during the late fall and winter, because of the drainage system configuration and operation, high groundwater within a few feet of land surface or flooded conditions occurs on much of the island. The islands where mineral soils predominate (S1, W1 and N1) have substantially higher elevations, much less organic matter in the soils and lower outflow loads. Of the three islands studied with predominantly mineral soils and little subsidence, S1 had the highest average net MeHg load (Table 8).

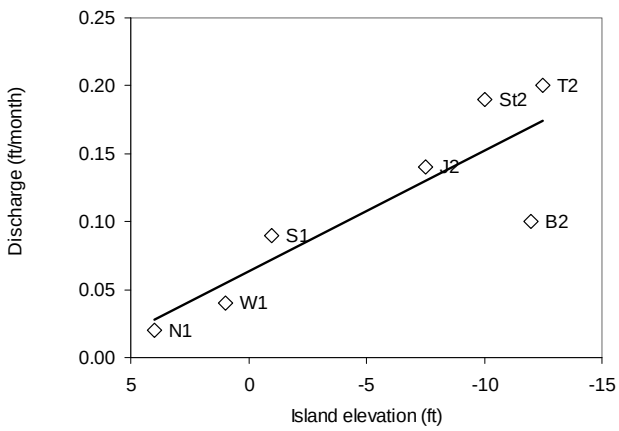

Figure 18. Relation of average discharge to average island elevation. Discharge was normalized to island size and as a result units are ft month^{-1}.

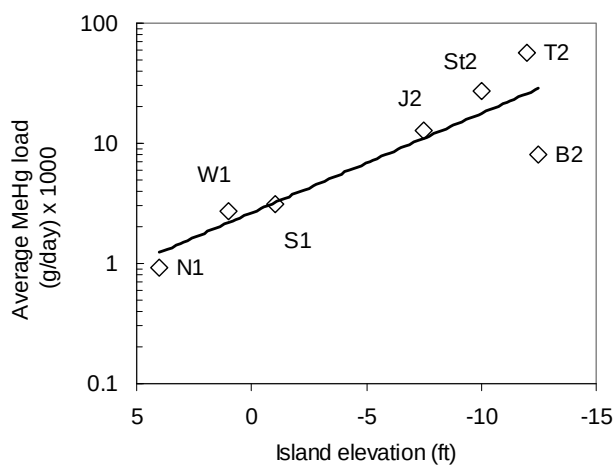

Figure 19. Relation of log of average methylmercury (MeHg) outflow load to average island elevation.

To put into context of other sources of MeHg to the Delta, we used the median net MeHg loads calculated for the farmed islands in this study to estimate Delta wide net MeHg loads from farmed islands. To date, there have been limited studies to quantify net MeHg loads from farmed islands and in the few cases where the attempt has been made the estimates are based on small datasets.

Heim, (2003) estimated MeHg loads from farmed islands by using sediment concentrations correlated to direct measurements of MeHg flux from sediments. The estimated MeHg load from farmed islands was 9.7 g day^{-1} based on eight measurements of MeHg in sediments collected from agricultural return drains. This estimate did not take into account irrigation practices or consider the discontinuity of the agriculture lands with the adjacent waterways likely resulting in an over estimate with large error.

Foe, (2003) estimated a MeHg net production rate of 17-35 grams per month or 10-25 percent of river load in the two-month period for agricultural land use. The estimates were based on samples collected from five agricultural return drains during a two-month period. Foe, (2003) concluded that farmed island loads, while substantial, were beyond the ability of their study to characterize further.

Wood et al., (2008) estimated a net MeHg load of 123 g $year^{-1}$ (~0.34 g day^{-1}) using MeHg concentration data reported by Foe, (2003) and flow estimates from the Delta Island Consumptive Use Model for water year 1999. Wood et al., (2008) also estimated MeHg loads for eight subareas with the Delta using Department of Water Resources land use Geographical Information System (GIS) coverages (1993-2003). However, the MeHg load estimates did not include coolest/wettest months as MeHg concentration data was available only for summer months.

In this study we estimated MeHg loads from farmed islands using two different approaches. The first method uses the median net MeHg loads determined for six of the islands (B2 excluded due to unique winter water management practices) in conjunction with the eight subareas determined by Wood et al., (2008) to estimate the MeHg load from farmed islands in the Delta. This method is useful only for comparison to work done by Wood et al (2008). For each subarea a representative island's net (per acre) MeHg load determined in this study was used to scale up a total MeHg load for the subarea. Finally, loads for all subareas are summed for the net MeHg load from farmed islands (Table 9). The estimated MeHg load from farmed islands determined by this method is 1.09 g day^{-1}. These results are in agreement within a factor of three to values reported by Wood et al., (2008).

The second and preferred method for estimating MeHg loads from farmed islands was done by considering locations, elevations, soil types, and land use practices between non studied farmed islands and islands which were part of this study. As listed in Table 10, one of the seven studied islands (including B2) was matched to each farmed island based on location, soil type, and management practices. As a result, all farmed islands have a proxy MeHg load from which a Delta wide MeHg load (g day^{-1}) is estimated. We estimated farmed island MeHg loads using the median per acre loads of all data for median of high flow months (December – May), and median of low flow months (June – November). Specifically, each farmed island has a proxy

generated from all data, high flow data, and low flow data (from Table 7). A range was calculated for MeHg loads by first calculating the standard error for MeHg load of each island studied and second taking the difference (±) between the median load and standard error. This was done using all data, high flow data, and low flow data. The high and low range values were used as a proxy in the same manner as the median load data to give Delta wide ranges of MeHg loads. Table 11 lists annual, high flow, and low flow net MeHg loads and ranges from Delta farmed islands. The annual Delta wide MeHg load from farmed islands is 0.1 g day^{-1} with a range of -0.5 to 0.6 g day^{-1}. During high flow periods the MeHg load from farmed islands is 0.4 g day^{-1} (range = -0.5 to 1.3 g day^{-1}) and during low flow periods is -0.1 g day^{-1} (range = -0.6 to 0.3 g day^{-1}).

Table 9. A list of TMDL subareas and acreages, farmed island site used to "scale up" loads, average methylmercury (MeHg) load measured at each farmed island site, and MeHg load calculated for subarea.

Sub Area	**Central Delta**	**Cosumnes & Mokuleme**	**Marsh Creek**	**Sac River**	**San Joaquin River**	**West Delta**	**Yolo Bypass North**	**Yolo Bypass South**	**Total**
Acreage	157035	6790	9362	155532	96874	17313	11046	70523	524475
Site used to scale up	T2	W1	J2	St2	T2	J2	N1	Average N1&S1	
Average MeHg Load Measured (g/acre day) (x10^{-7})	11.7	-85.8	27.8	50.8	11.7	27.8	-10.1	-0.7	
MeHg Load Calculated using subarea acreage (g/day)	0.18	-0.06	0.03	0.79	0.11	0.05	-0.01	-0.01	**1.09**

Sub area classification and acreages from Wood et al, 2008

There was a difference of a factor of ten between the two methods we used to calculate MeHg loads. Because the second method used a comprehensive approach to scaling up studied islands to all farmed islands it is the preferred method.

On an annual basis farmed islands appear to be net sources of MeHg to the Delta (Table 11). However, on a seasonal basis farmed islands appear to be net sources of MeHg during high flow periods but net sinks during low flow periods. It is useful to put the farmed island MeHg loads in context with the overall MeHg mass balance for the Delta. Two mass balance models were modified from those presented by Foe et al., (2008) to include the farmed island loads determined in this study (Figure 20). The models presented show MeHg sources and sinks for the wet season (Jan, 2005) and dry season (August, 2005). During high flow conditions sources of MeHg to the Delta include tributary inputs (18.0 g day^{-1}), urban runoff (0.05 g day^{-1}), municipal waste water treatments plants (0.6 g day^{-1}), wetland sediment flux (0.15 g day^{-1}), open

water sediment flux (0.48 g day^{-1}), atmospheric deposition (0.05 g day^{-1}), and farmed island discharge water (0.4 g day^{-1}). Sinks of MeHg are sedimentation (-7.2 g day^{-1}), photodemethylation (-1.0 g day^{-1}), loss to southern California via pumps (-4.1 g day^{-1}), loss to San Francisco Bay (-4.6 g day^{-1}), and dredging (-0.9 g day^{-1}). During low flow conditions, urban runoff, municipal waste water treatments plants, wetland sediment flux, open water sediment flux, and dredging remain unchanged. While tributary (4.3 g day^{-1}) inputs decrease and atmospheric deposition goes to zero. Sinks of MeHg are sedimentation (-1.2 g day^{-1}), photodemethylation (-3.1 g day^{-1}), loss to southern California via pumps (-2.4 g day^{-1}), loss to San Francisco Bay (-0.7 g day^{-1}), and farmed islands (-0.1 g day^{-1}).

Table 10. List of Farmed Islands (Districts), Reclamation number, acres, and site used for the 'scale up' of methylmercury (MeHg) loads.

District Name	**Reclamation #**	**Acres**	**Site Used For Scale-up**
Glide District	765	1400	N1
Lisbon Island	307	6000	N1
Netherlands	999	26000	N1
Liberty Island	2093	4760	B2
Cache Haas Area	2098 & 2068	13200	B2
Merritt Island	150	4740	N1
Ehrheardt Club	813	2300	N1
New Hope Tract	348	12000	N1
Pierson Tract	551	8980	N1
Libby McNiel	369	40	N1
McCormack Williamson	2110	1654	W1
Sutter Island	349	2620	N1
Ryer Island	501	11880	S1
Solano	2084	3100	S1
Prospect Island	1667	1228	B2
Hastings Tract	2060	7150	S1
Grand Island	3	16400	St2
Tyler Island	563	8583	St2
Walnut Grove	554	400	W1
Deadhorse Island	2111	211	S1
Isleton	407	Included in Andrus	T2
Upper Andrus	556	Included in Andrus	T2
Andrus	317	13000	T2
Brannan Island	2067	Included in Andrus	T2
Canal Ranch Tract	2086	3000	T2
Staten Island	38	9600	St2
Twitchell Island	1601	3630	T2
Sherman Island	341	10000	T2
Brack Tract	2033	4873	St2
Terminous Tract	548	10470	St2
Bouldin Island	756	6006	B2
Rio Blanco Tract	2114	705	N1
Bishop Tract	2042	2169	N1
King Island	2044	3260	T2
Empire Tract	2029	3430	T2
Venice Island	2023	3220	T2
Shima Tract	2115	2394	N1

Table 10 continued.

District Name	Reclamation #	Acres	Site Used For Scale-up
Rindge Tract	2037	6834	T2
McDonald Island	2030	6145	T2
Medford Island	2041	1219	T2
Mandeville Island	2027	5300	J2
Wright Elmwood Tract	2119	2121	J2
Rough and Ready Island		780.5	N1
Lower Roberts Island	684	10600	J2
Lower Jones Tract	2038	5894	J2
Bacon Island	2028	5625	J2
Upper Jones Tract	2039	6259	J2
Woodward Island	2072	1822	J2
Victoria Island	2040	7250	J2
Mossdale	17	12750	N1
Middle Roberts Island	524	13687	J2
Upper Roberts Island	544	11454	J2
Union Island East	1	9622	N1
Union West	2	12580	J2
Fabian Tract	773	7445	N1
Pico and Nagle	1007	6090	N1
Pescadero District	2058	8500	N1
Stark Track	2089	734	N1
Stewart Tract	2062	4800	N1
Paradise Junction	2095	4800	N1
McMullin Ranch	2075	11000	N1
River Junction	2064	7250	N1
Webb Tract	2026	5490	T2
Bradford Island	2059	2051	T2
Jersey Island	830	3471	J2
Bethel Island		3500	J2
Quimbly Island	2090	769	T2
Holland Tract	2025	4060	J2
Hotchkiss Tract	799	3100	J2
Veale Tract	2065	1000	J2
Palm Tract	2036	2436	J2
Orwood Island	2024	4138	J2
Byron Tract	800	6933	J2
Coney Island	2117	935	J2
	Total	416848	

Table 11. Annual, high, and low flow seasons net methylmercury (MeHg) loads and ranges from Delta farmed islands.		
Net MeHg Load ($g\ day^{-1}$)	**MeHg Load Range ($g\ day^{-1}$)**	**Comments**
0.1	-0.5 to 0.6	Based on median MeHg loads for all data (Table 7)
0.4	-0.5 to 1.3	Based on median MeHg loads for high flow months Dec-May (Table 7)
-0.1	-0.6 to 0.3	Based on median MeHg loads for low flow months June-Nov (Table 7)

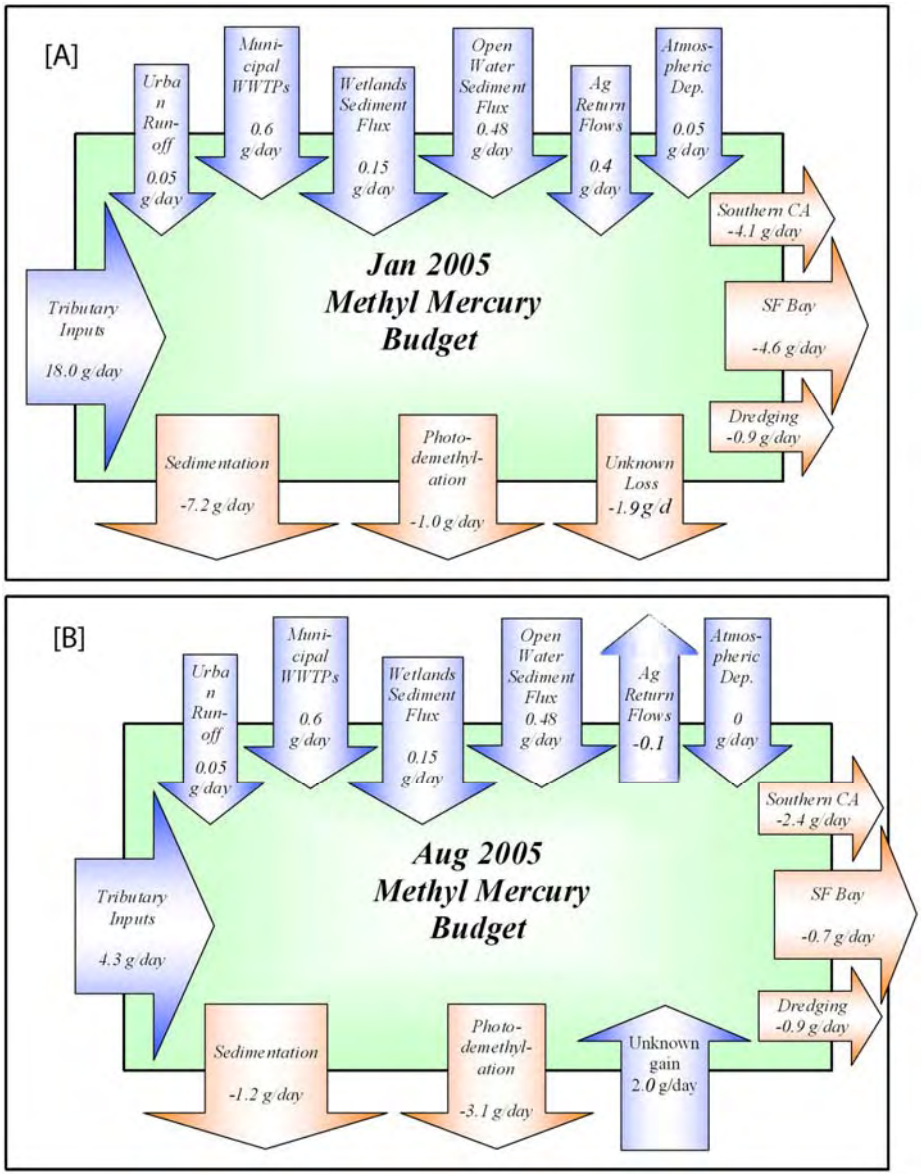

Figure 20. [A] Delta Methylmercury (MeHg) mass balance models for January 2005. [B] Same mass balance for August 2005. Note changes in the relative magnitude of the various processes. This figure was modified from Foe et al., (2008).

Summary and Conclusions

The following bulleted items summarize out key conclusions.

- Median MeHg concentrations determined in samples collected from farmed islands where mineral soils predominate were lower than for islands where organic soils predominate.
- There was substantially greater temporal variability in drain-water MeHg concentrations collected from organic-soil islands compared to mineral-soil islands. There was no significant difference in MeHg concentrations between water years. Seasonal variation in MeHg concentrations was observed at all sites but the timing and magnitude of the variation differed between sites. Seasonal peaks in MeHg concentrations were higher at organic-soil sites compared to mineral-soil sites.
- Concentrations of MeHg in drainage water samples collected on farmed island were typically greater than 0.06 ng L^{-1}. Many of the islands studied had MeHg concentrations greater than 1 ng L^{-1}.
- Winter flooding on cropland appears to be a factor that substantially increased MeHg concentrations in island drain water.
- Elevated MeHg concentrations in main drainage ditches may result in increasing concentrations in small fish and may pose a problem to wildlife. If an island is being used as a wildlife refuge for fish eating animals it is particularly important to determine MeHg levels in biota. This will lead to a better understanding of bioaccumulation and magnification of MeHg on farmed islands.

- Comparison of data from a temporary demonstration wetland on Island T2 prior to flooding (agricultural conditions) and post flooding indicate probable processes affecting MeHg in wetlands and on farmed islands.

    - Fall 2005 subsurface drain-water MeHg concentrations under agricultural conditions were low, reflective of chemically reducing conditions associated with flow of deep groundwater to the drainage ditch during fall. During winter 2006, we measured higher MeHg concentration associated with a rising groundwater table and flushing of DOC and MeHg downward from the shallow soils.
    - During flooding for the wetland in May 2006, MeHg concentrations in subsurface drains increased relative to agricultural conditions as additional MeHg was flushed from the shallow soils. During wetland operation, subsurface drain-water MeHg concentrations declined over time. Similar observations have been made at other locations experiencing seasonal flooding.
    - The relation of MeHg concentrations to concentrations of other constituents provides insight to processes. Prior to flooding of the wetland on T2, we measured low sulfate and low redox potential values associated with flow to the drainage ditches of deep groundwater in contact with relatively less decomposed organic deposits. As the water level rose with the winter rains, shallow, variably saturated zone water began to flow to the drainage ditches

and flush stored DOC and salts (including sulfate) resultant from organic matter oxidation. MeHg concentrations increased with the flooding of the fields and coincided with increases in sulfate concentrations.

- During flooding of the wetland, redox potentials declined with sulfate concentrations and MeHg concentrations presumably due to continued flushing with oxidized San Joaquin River water which was applied to the demonstration wetland.
- At the 95 % confidence level, MeHg concentrations were significantly correlated with DOC concentrations and redox potential values. Downward movement of MeHg in water from shallow soils is flushed to the shallow groundwater and drainage ditches during flooding.

- We used the MeHg concentration and flow data to estimate agricultural and wetland surface and subsurface MeHg loads at the demonstration wetland site on T2.

  - Subsurface agricultural drainage loads ranged from less than 10 x 10^{-7} to over 140 x 10^{-7} g/day-A.
  - Wetland subsurface drainage loads ranged from 52 x 10^{-7} to 297 x 10^{-7} g/day-A. The wetland median load 113 x 10^{-7} g/day-A was higher than the agricultural load of 38 x 10^{-7} g/day-A. However, the Mann-Whitney comparison test indicated no significant difference between the two data sets consisting of six data points each.
  - Wetland surface water MeHg loads were substantially greater than the subsurface loads and concentrations. Concentrations were high during the early months of flooding and then decreased substantially for several months before leveling off during fall 2006.
  - Because of the large surface water outflows and high concentrations, MeHg loads were relatively large during the first 3 months of wetland flooding. Loads decreased to lower levels after several months. Methylmercury loads ranged from over 1667 x 10^{-5} g/day-A in May to 2333 x 10^{-6} g/day-A in August. September and October loads were 1468 x 10^{-6} and 5667 x 10^{-7} g/day-A, respectively.

- On the central Delta island B2, we measured surface water outflow concentrations and estimated loads for rice, corn and tomatoes.

  - Surface water outflows were substantially less than the T2 wetland surface water outflows. For rice, the July and August outflow loads were 73 x 10^{-7} g/day-A and 33 x 10-7 g/day-A respectively. However, during the August measurement the inflow load was higher than the outflow load resulting in a net deposition of MeHg in the rice field.
  - For tomatoes, we measured inflows in the furrows and outflows in the tail water ditches during irrigation for small, well delineated sections of the fields on peat soils. Our data indicated higher outflow loads for tomatoes relative to rice: outflow loads were 560 x 10^{-7} and 297 x 10^{-7} g/day-A in July and

August. Net outflow loads were similar due to the low concentrations in the inflow water.
  - For both rice and tomatoes, MeHg concentrations increased in the outflow water relative to the inflow water indicating production of MeHg in the peat soils during farming is moving into the overlying water.

- Monthly net MeHg loads from farmed islands were estimated by subtracting inflow from outflow loads at each site. Net MeHg loads were temporally variable and islands with predominately organic soils had higher net MeHg loads than islands with dominate mineral soils. The extent of subsidence and soil type appear to be causative factors in determining MeHg loads from farmed islands. Increased organic matter in soils and lower elevations lead to higher per acre MeHg loads.
- Farmed island MeHg loads on a Delta wide scale were estimated using the results of this study to assign proxy loads to all farmed islands based on island similarities. Annual, high flow season, and low flow season loads were calculated. The estimated MeHg load from farmed islands determined by this method was 0.1 g day^{-1} with a range of -0.5 to 0.6 g day^{-1}. During high flow periods the MeHg load from farmed islands is 0.4 g day^{-1} (range = -0.5 to 1.3 g day^{-1}). The low flow MeHg load was -0.1 g day^{-1}, range = -0.6 to 0.3 g day^{-1}). We attempted to assess these farmed island MeHg loads relative to other sources and sinks of MeHg in the Delta.

- Our study results point to the following management practices for reducing MeHg from farmed islands.

  - Reduction in drainage discharge from Delta islands will reduce loads. This can possibly result from recirculating drainage water for irrigation. Longer, on island residence times may help reduce MeHg concentrations through photodegradation.
  - Stopping subsidence will likely reduce MeHg concentrations and loads. Oxidation of peat soils liberates organic carbon and sulfate that is associated with high drainwater MeHg concentrations.
  - Our data indicate that stopping subsidence will stop the increasing drainage volumes that result from lowering land-surface elevations and result in the observed higher MeHg on more deeply subsided islands.
  - The primary mechanism for stopping subsidence is flooding the organic soils for wetlands. Recirculation and restricting export of drainage water from wetlands will be necessary for minimizing MeHg loads from Delta wetlands. Additional investigation of processes and long-term changes in MeHg concentrations in wetlands and associated biota is also warranted.

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Appendix

During 2002 and 2003, HydroFocus constructed a demonstration wetland on approximately 8.25 acres (3.3 ha) of farmed island T2 agricultural land (indicated by the two cells in Figure A1. Our objective during construction was to minimally disturb surface soils so that ground- and drain-water quality measurements would reflect conditions similar to flooding of undisturbed oxidized organic soils. Also, because of the shallow groundwater levels in this area, we were unable to move necessary volumes of soil for berm construction. Therefore, for the core of the berm we placed rice-straw bales (0.9-m high, 1.2-m wide and 2.4-m long) (3 by 4 by 8 feet) wrapped in UV-resistant plastic around the perimeter of each wetland cell. We then scraped soil from within about 4 m of the bales to cover the bales and form a slope.

San Joaquin River water flowed via gravity and underground pipes to the south east corners of both cells starting on May 5, 2006 (Figure A1). Surface water flowed from the east to the west cells via 2 30-cm diameter pipes placed over the DR3 drainage ditch. Surface water exited the wetland system via a single pipe that discharged downstream of weir DR2 in the DR2 drainage ditch. We adjusted flow to the wetland cells based on evapotranspiration estimates from the California Irrigation Management System (CIMIS) weather station on Twitchell Island and seepage estimates.

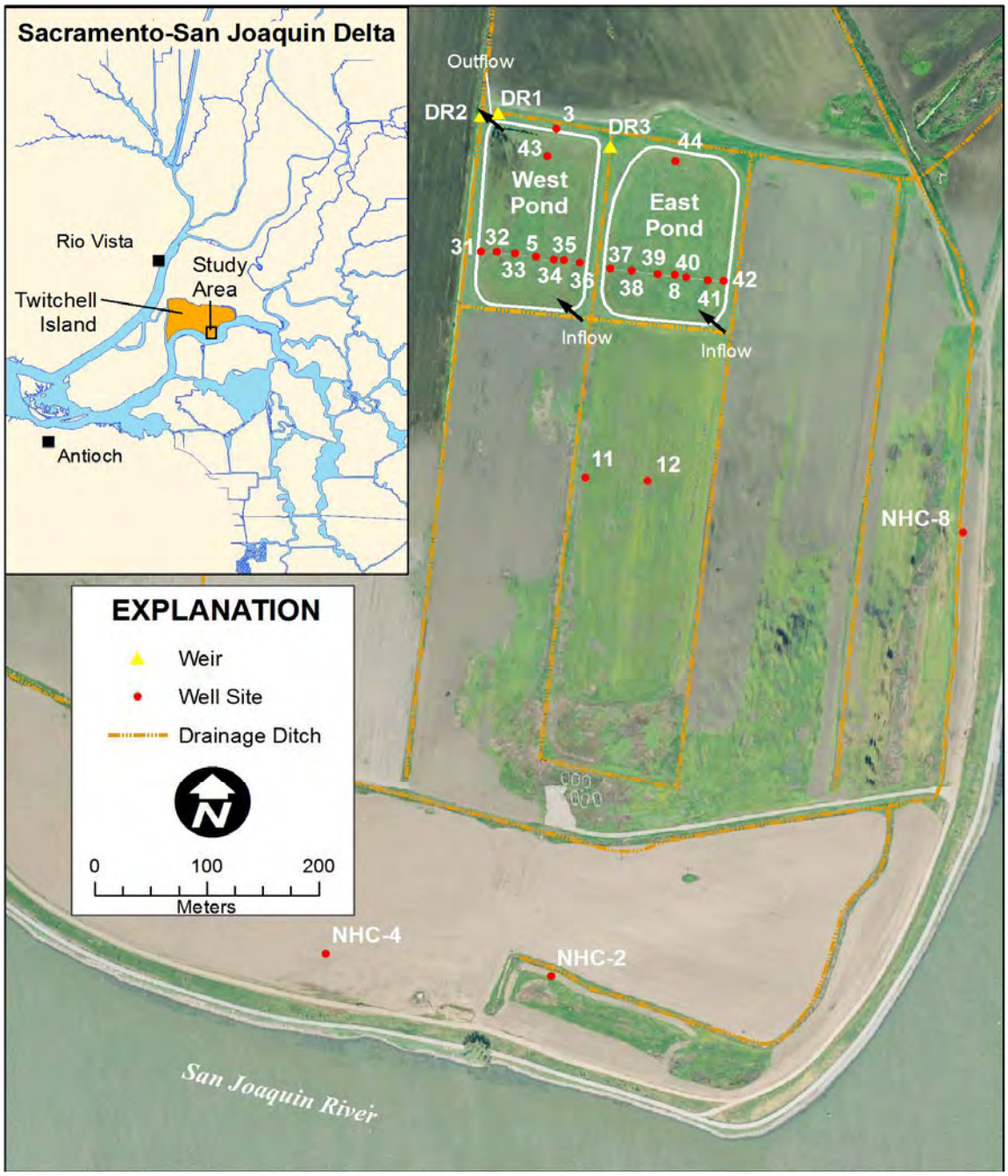

Figure A1. Location of wetland and DR1, DR2 and DR3 drainage ditches and measurement locations on T2.