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

Chapter 6. Climate Change Impacts on Water Operations and Mercury Biogeochemistry in the Yolo Bypass and Delta

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List of Acronyms and Abbreviations

CVP	Central Valley Project
Delta	Sacramento-San Joaquin Delta system
D-MCM	Dynamic Mercury Cycling Model
DOC	Dissolved Organic Carbon
DSM2	Delta Simulation Model 2
DWR	(California) Department of Water Resources
Hg	Mercury
MeHg	Methyl mercury or monomethyl mercury
RCP	Representative Concentration Pathway
SWP	State Water Project

Introduction

This chapter describes the major climate change impacts that are predicted for northern California and the Sacramento-San Joaquin Delta region and how these impacts might alter the net production of methyl mercury (MeHg) and its behavior fate and transport in the Yolo Bypass and Delta region. The impacts follow the drivers outlined in California's Fourth Climate Change Assessment (Bedsworth and others, 2018). Generalized impacts based on our current understanding of the biogeochemistry of mercury (Hg) and MeHg are described first, followed by site specific predictions for the Delta and Yolo Bypass based on a literature understanding of Hg and MeHg biogeochemistry and studies conducted for this report.

Key Findings

Climate change is anticipated to have significant impacts on the Sacramento-San Joaquin Delta system (Delta) and Yolo Bypass which will manifest in also impacting the behavior and fate of Hg and MeHg (Table 6-1). Due to projected increases in volatility of winter rainfall events and periods of drought, predicting long-term Hg trends is problematic. However, we anticipate that the Yolo Bypass will continue to remain a significant net exporter of MeHg to the Delta. It is possible that MeHg exports could increase, driven principally by increases in water temperatures which boost microbial methylation. Enhanced MeHg production could also occur due to more frequent and intense storms delivering more Hg and organic matter to the Delta, resulting in enhanced Hg methylation. Extended periods of drought may also occur. In these circumstances, net Hg and MeHg exports from the Yolo Bypass to the Delta, when compared to the Sacramento River, may become insignificant, but the buildup of vegetation between subsequent flood periods may provide increased organic material for methylation when floodwaters return. It is unclear whether periods of extended drought would enhance or reduce Hg methylation in the Delta. It is currently not clear what impacts declining snowpack, shifts in runoff timing, and rising sea level will have on MeHg production, behavior, fate and transport in the Delta system.

Major Climate Change Impacts and Potential Mercury Response

This section describes in general terms how Hg and MeHg might respond to predicted climate change impacts. These predictions are based primarily on literature references of our general understanding of the biogeochemistry of Hg and MeHg.

Temperature Impacts

Temperature in California is expected to increase statewide between 2 and 7 °C by the end of the century (Pierce and others, 2018). Because MeHg is biotically produced by microbial organisms, microbial activity and MeHg production will be greatly influenced by temperature. While there are several factors influencing microbial activity, in a very general sense, warmer temperatures tend to lead to greater microbial activity, which manifests in greater MeHg production (Desrosiers and others, 2006; St. Pierre and others, 2014; Yang and others, 2016).

Table 6-1 Climate Change Impacts on the Delta, Yolo Bypass and Implications for Mercury Response

Climate Impact	Expected Trend[1]	Delta and Yolo Bypass Response	Mercury Response
Temperature	Warming ↗	Warmer air & water temperatures	Potential enhanced microbial methylation of mercury
Precipitation	More precipitation as rain ↗ Less precipitation as snow ↘ Interannual variability ↗ Precipitation frequency ↘ Atmospheric River storm frequency and intensity ↗ [2]	Impact on Delta/Bypass affected by upstream reservoir operations; Greater interannual flooding variability. Flooding may be more severe- could lead to prolonged flooding when it occurs.	Prolonged and greater aerial extent of flooding of the Yolo Bypass could result in greater MeHg production
Snowpack	Declining ↘	Higher winter stream flows since more precipitation falls as rain than snow,	Unknown
Runoff	Shifting earlier and increasing with warmer storms. ←	Impact on Delta/Bypass affected by upstream reservoir operations	Unknown
Extreme Storms	Increasing ↗	Greater interannual flooding variability. Higher flood flows. Possible increased frequency and duration of flooding in the Bypass	Winter MeHg exports from the Yolo Bypass will likely increase due to increased flood duration and a greater extent of flooded area.
Droughts	Increasing ↗	Lower freshwater inflows will move the salinity mixing zone upriver. Limited discharge of freshwater from the Yolo Bypass into the Delta.	In the winter, there will be no or limited export of MeHg from the Yolo Bypass to the Delta during drought periods. Periods of drought may increase cumulative vegetation biomass in the Yolo Bypass resulting in greater MeHg production in subsequent flood events.
Sea Level	Rising ↗	Sea level rise could move the salinity mixing zone upriver; Levees could overtop if not heightened, and previously dry land could become submerged; Minimal or no impact on northern portion of the Bypass.	Newly submerged lands could result in enhanced MeHg production as has been observed when new reservoirs are impounded.
Wildfires	Increasing ↗	Runoff from burn areas could increase contaminants in water	Mercury content of forest biomass and soils will be released into local air and watersheds, providing additional substrate for mercury methylation.

[1] Adapted from California's Fourth Climate Change Assessment (Thorne and others, 2018)

[2] Overall there are expected to be fewer rainfall events, but storms may be more intense when it rains.

Precipitation and Extreme Storm Impacts

A recent report by Gershunov and others (2019) predicts that climate change along the west coast of the United States will result in greater precipitation variability and greater total precipitation, but with fewer precipitation events and greater intensity of individual events. California's Fourth Climate Change Assessment predicts mean annual precipitation to increase modestly in the northern part of the state, and year-to-year variability is also projected to increase (Pierce and others 2018). By the end of the century under the Representative Concentration Pathway (RCP)[1] 8.5 (business as usual) scenario, winter precipitation is projected to increase by up to 20%, but spring and autumn precipitation may decrease by up to 20%. Daily extreme precipitation values are projected to increase 5-15% under the RCP 4.5 (medium emissions) scenario to 15-20% under the RCP 8.5 scenario, presenting challenges for storm drainage and flood control.

The increase in total precipitation and intensity of precipitation events could result in more intense and prolonged flooding events in the Yolo Bypass. This will likely also manifest in a greater aerial extent of the Yolo Bypass being flooded during a storm event. Both manifestations could increase the production of MeHg and enhance MeHg export from the Bypass.

It is not clear what impact precipitation increases and increased storm intensity will have on MeHg production and behavior in the Delta.

Snowpack and Runoff Impacts

With warming trends predicted, more precipitation will fall as rain rather than snow, reducing the snowpack, and shifting runoff earlier in the year (Bedsworth and others 2018; and references therein). These predicted trends will clearly affect operation of reservoirs and water delivery systems (e.g. Wang and others 2018; Schwarz and others 2018), but it is unclear how these snowpack and runoff changes will affect the production and transport of MeHg in the Yolo Bypass and Delta system.

Drought Impacts

Drought periods are anticipated to be more frequent and more intense with dryer seasonal conditions, even if precipitation increases (Bedsworth and others 2018; and references therein). Climate projections show that seasonal summer dryness in California may become prolonged due to earlier spring soil drying that lasts longer into the fall and winter rainy season (Bedsworth and others 2018; and references therein). Obviously, if droughts are more frequent, there will be more frequent periods of time when the Yolo Bypass has no flow going through it and will not be contributing MeHg export to the Delta. Drought impacts on agricultural vegetative growth in the Bypass are probably minimal as the majority of agricultural vegetation in the Bypass is irrigated, including a significant proportion of its largest land-use-pasture. Sources of water in the Yolo Bypass include groundwater pumping and surface water.

[1] A Representative Concentration Pathway (RCP) is a greenhouse gas concentration (not emissions) trajectory adopted by the International Panel on Climate Change. RCP 8.5 refers to the concentration of carbon that delivers global warming at an average of 8.5 watts per square meter across the planet. The RCP 8.5 pathway delivers a temperature increase of about 4.3˚C by 2100, relative to pre-industrial temperatures.

One of the major findings of this report is that submerged vegetation undergoing degradation is a major process contributing to internal MeHg production in the Yolo Bypass (see Chapter 3 and Technical Appendix E). Hence, any process which will affect biomass production will likely also impact MeHg production. Droughts are typically associated with low biomass production. In the Yolo Bypass however, if irrigation water is available, drought periods will likely not significantly reduce the biomass available for methylation. Hence, during extended drought periods, if irrigation water continues to be available, winter biomass could reach peak production levels in areas that floodwaters would normally remove since flooding events will not occur as frequently. Subsequent flood events, following an extended drought period, will thus likely experience enhanced internal MeHg production from the vegetation that has built up during the drought period. If enhanced removal of vegetation occurs during major flood events, then it may take several years for high biomass levels to rebuild in some locations. Hence, vegetation driven MeHg production in the Yolo Bypass could experience boom and bust cycles based on more frequent and intense periods of drought combined with more intense storm flooding events which wipe out the vegetation. In some extreme droughts, biomass levels could also be lower if irrigation water was no longer available or was reduced. It is also possible that in winter, rye grass and other grazing forbs that remains standing in the Yolo Bypass, could change during an extended drought. We currently have no information on the production and release of MeHg from grasses and other vegetation other than rye grass.

Sea Level Rise

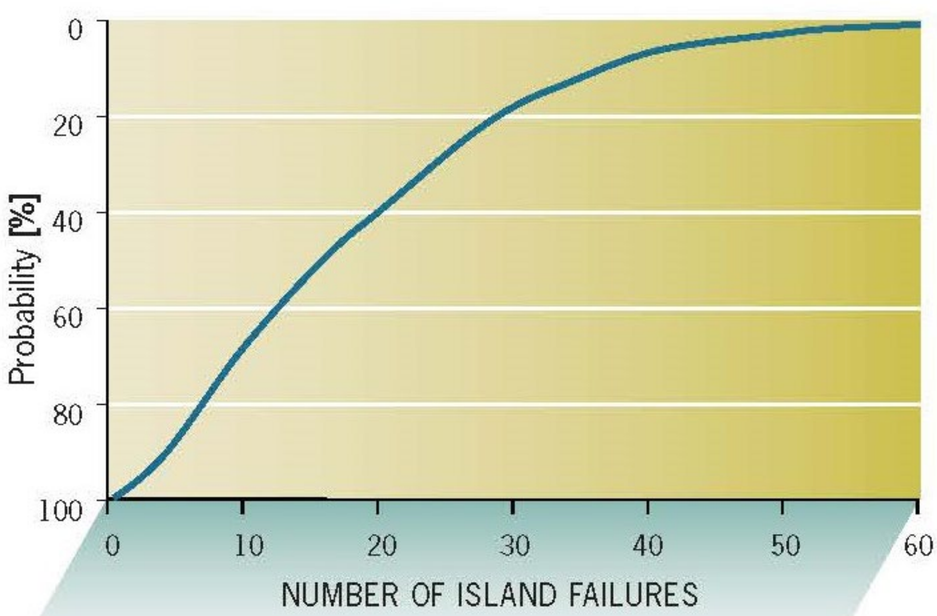
Over the last 100 years, there have been 158 island failures resulting in Delta island flooding (Department of Water Resources, 2009) (Figure 6-1). The pressure on Delta levees will increase with rising sea levels on the water side and falling land surface elevations (subsidence) on the land side of the levee. Predictions combining sea level rise and Delta island subsidence indicate that Delta levees may no longer meet the federal levee height standard (PL84-99) in the time frame of 2060-2080 (Brooks and others 2018). This will result in an increased risk of Delta levees being breached and previously dry pasture and farmland becoming submerged, creating newly flooded aquatic habitat, possibly permanently (Dettinger and others 2016). Even without climate change, the calculated probability of at least 10 island failures is estimated to be between 60 and 80% (Figure 6-2).

A rapid inundation of newly flooded land could have significant impacts on MeHg levels in overlying water. It is well known that creation of hydroelectric reservoirs by enlargement of riverine lakes and flooding of adjacent forested land leads to a marked rise in rates of MeHg production by microorganisms in sediments and is manifest in significant MeHg increases in finfish residing in the newly impounded waters (Jackson 1988; Kelly and others 1997; Willacker and others 2016). Moreover, this increase in MeHg production and increase in fish mercury levels can persist for many years to decades (Hall and others 2005; Bodaly and others 2007). It is reasonable to assume that a similar phenomenon will result in the Delta if levees are breached and pasture and farmland is rapidly inundated. This expansion of flooded land and enhanced potential for mercury methylation will be further exacerbated as much of the newly flooded land is highly peat rich, which would be a carbon source for promoting and enhancing microbial activity (Department of Water Resources,1995). The impact of a slow sea level rise to expanding the areas of inundation in the Delta will likely be minimal as levees keep water flow highly channelized. However, while sea level rise is a slow process, it will ultimately result in inundating some low-lying areas increasing the surface area for production of MeHg, in areas where no flooding had previously reached.

Figure 6-1 Photo of Jones Tract Levee Failure (June 4, 2004)

Source: DWR

Figure 6-2 Probability of exceeding a number of simultaneous islands flooding due to high water conditions over a 25-year period (2005-2030)



Source: Adapted from Delta Risk Management Strategy (DRMS) Report URS/JBA 2008c, Figure 13-11.

Figure 6-3 Historic Island Flooding in the Delta and Suisun Marsh Since 1900

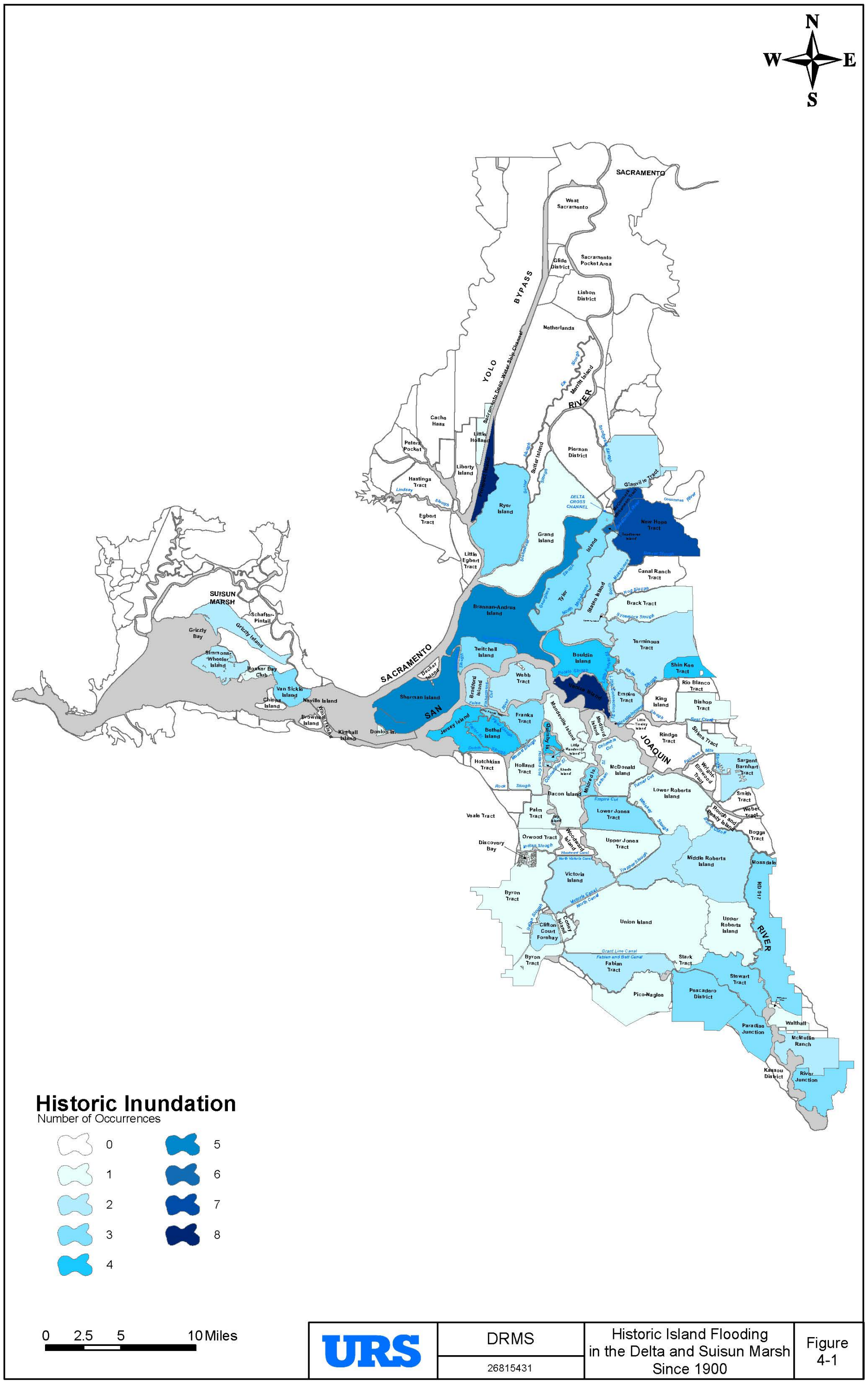
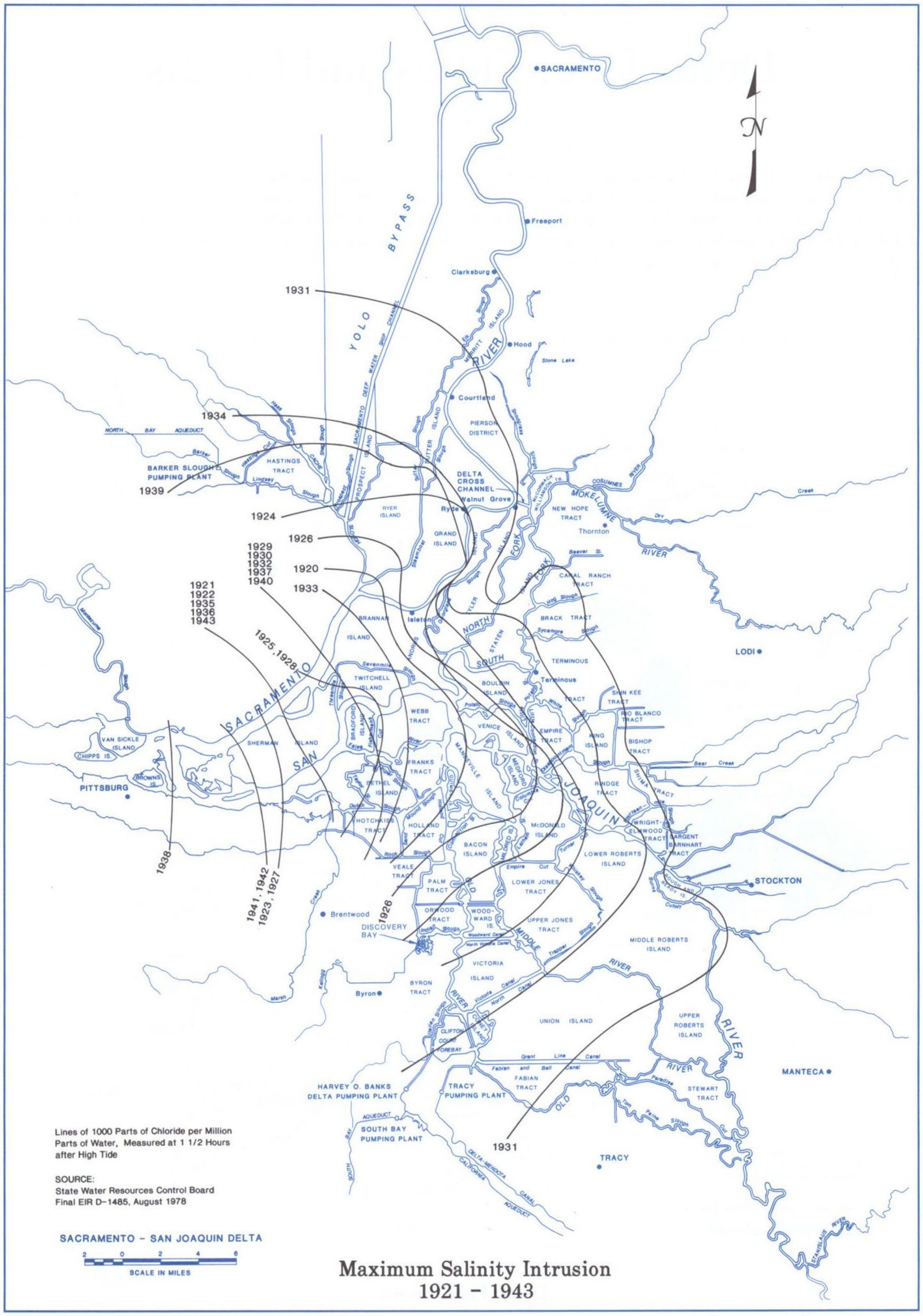


Figure Note: From Technical Memorandum: Delta Risk Management Strategy (DRMS) Phase 1. Topical Area: Levee Vulnerability Final, Figure 4-1, May 2008.

Figure 6-4 Historical Maximum Salinity Intrusions (Approximately 5 Percent Sea Water) Between 1921-1943 Prior to the Building of Shasta Dam



Sacramento–San Joaquin Delta Atlas — Department of Water Resources

Source: DWR, 1995.

Salinity in the Delta depends on the balance between salt water coming into the Delta from the ocean and freshwater from tributary rivers pushing the saline water toward San Francisco Bay. When freshwater flows are higher, the Delta is less saline. When freshwater flows are lower, salinity intrudes further into the Delta. Under sea level rise, more saline water will flow into the Delta if adequate freshwater releases from upstream reservoirs are not available to keep the salinity in San Francisco Bay. Historically prior to the completion of the Central Valley Project, historical maximum salinity intrusions extended into the southern end of the Yolo Bypass (Figure 6-4) (Department of Water Resources, 1995). How a more saline environment will affect MeHg production is currently unknown.

Wildfire Impacts

Wildfires are predicted to be larger and more frequent in the Western United States, driven by reduced fuel moisture due to warming-induced increases in evaporative demand, reduced snowpack, and reduced warm-season precipitation frequency (Williams and others 2019; and references therein). A recent assessment by Williams and others (2019) found that between 1972 and 2018, California experienced a five-fold increase in annual burned area, mainly due to more than an eight-fold increase in summer forest-fire extent, which was attributed to significantly increasing the atmospheric vapor pressure deficit driven by climate change.

Mercury sequestered in biomass and soils is released during a fire into the atmosphere where a significant portion can be deposited locally in fallout (Biswas and others 2007; Rothenberg and others 2010; Pompeani and others 2018). This locally deposited mercury can enter into waterways and provide additional mercury substrate for methylation in aquatic systems. The impact can be quite significant, Kelly and others (2006) observed a 5-fold increase in whole-body mercury accumulation for rainbow trout in a mountain lake impacted by a forest fire.

Operational Impacts

California's water supply is tightly woven up with climate change. The majority of climate models project that the number and potentially the intensity of atmospheric rivers making landfall in California will increase significantly in the 21st century if greenhouse-gas emissions continue to increase (Dettinger 2011; Warner and others 2015; Hagos and others 2016), potentially resulting in larger peak flows and flood risks in the warming future. However, future changes in precipitation are much less certain than warming and some other changes like sea level rise and declines in surface air humidity (Cayan and others 2008; Dettinger and others, 2016). Climate change warming projections predict that both droughts and floods will increase as the climate warms, with storms becoming more intense, and intervening periods drier, longer, and warmer. Riverine inflows into the Delta will be affected by both shifting precipitation and runoff patterns and management decision on how to operate upstream reservoirs. A greater fraction of runoff generated could pass through the Delta earlier in the year. Warming will likely affect riverine inflows to the Delta, as winter storms warm and become rainier (less snow), and snowpacks melt earlier. As a result, summer salinity in the upper San Francisco Bay and Delta is projected to increase (Knowles and Cayan, 2004; Cloern and others, 2011) if sufficient freshwater releases from upstream reservoirs are not available counteract the salinity intrusion. Decreases in surface air humidity would result in greater potential for evapotranspiration from soil and vegetation, intensifying hydrologic droughts (Dettinger and others, 2016).

Warming temperatures, shifting hydrology, and rising sea levels associated with climate change is anticipated to have significant impacts on reservoir operations, and the State's water systems (Wang and others, 2018). Extra runoff is predicted from early snow melting and a higher percentage of rain in the winter and early spring. This extra runoff will not be conserved in reservoirs, but rather released as flood water in the winter and early spring to become Delta outflow. By mid-century, Delta exports are expected to be reduced by a half million-acre feet and north of Delta carryover storage would diminish by 1.5 million-acre feet. Reservoir dead storage is expected to occur much more frequently. Delta exports would reduce to half of those found in historical droughts while carryover storage would diminish to one-fifth of those found in historical droughts.

How these operational impacts will this effect MeHg behavior is currently unknown.

Major Climate Change Impacts on Methylmercury Biogeochemistry in the Yolo Bypass and Sacramento-San Joaquin Delta system

The previous section provided an overview of the generalized large-scale climate change impacts potentially affecting MeHg production in the Delta and the Yolo Bypass. In this section we relate work summarized in this report to site specific predictions for the Delta and Yolo Bypass based on a literature understanding of mercury and MeHg biogeochemistry.

Yolo Bypass

Another major finding of our vegetation senescence studies is that submerged vegetation undergoing degradation may be a significant contributor to internal MeHg production in the Yolo Bypass (see Chapter 3 and Technical Appendix E). Hence, any process which will affect vegetation biomass production will likely also impact MeHg production. Within the Yolo Bypass there are over 17,400 acres of vegetated pasture (area calculated from the Yolo Bypass D-MCM land use map), the largest land use in the Yolo Bypass. MeHg increases in both the water column and on the particles of vegetation. With increased volatility of rainfall, flooding and drought events, it is reasonable to assume that the Yolo Bypass will experience extended periods of drought. If water deliveries remain relatively "drought-proof," then we can expect to see the same level of biomass for irrigated pasture regardless of the water year type. However, biomass quantities for non-irrigated pasture may increase over successive, non-flood years. Seasonally non-irrigated pasture experiences seed germination with winter and spring rains. Since this vegetation is not irrigated, this vegetation dies during the heat of summer, forming a layer of dead grass material as well as thatch. The cycle repeats each season, resulting in a cumulative year over year build-up of dead vegetated material. Depending on the grazing pressure, this can form a dense build-up of biomass. The return frequency of large-scale inundation events then dictates when most of this vegetation will be removed. The longer the time-period between flood years, the potentially greater biomass from non-irrigated pasture, available for Hg methylation when flood waters return. Hence, vegetation driven MeHg production in the Bypass will experience boom and bust cycles based on more frequent and intense periods of drought combined with more intense storm flooding events which wipe out the vegetation.

Based on these vegetation dynamics, under projected climate change scenarios, our vegetation senescence experiments suggest that the Yolo Bypass will continue to be a net exporter of MeHg to the Delta. The combination of changes in temperature and precipitation, resulting in more precipitation falling as rain rather than snow, and occasional more intense storms, is projected to increase the frequency and magnitude of floods in the tributaries that feed the Delta, including the Yolo Bypass. With increased flood severity and frequency, overtopping of the Fremont weir and widespread flooding of the Yolo Bypass will potentially increase. When flooding occurs, large acreages of pastureland will continue to be flooded with the potential for more acreage to become submerged if the severity and duration of the floods increases. Large areas of submerged vegetation will thus continue to serve as MeHg sources contributing to MeHg export from the Yolo Bypass.

Sacramento-San Joaquin Delta system

Climate change amounts to an, "additional" stressor in the Sacramento-San Joaquin Delta system. The Delta's climate is characterized by high variability, and climate change is expected to accentuate this variability, resulting in both more extreme flood risks and greater drought risks. Thus, the Delta of the future will be very different than the Delta we know today. Effects on the Delta ecosystem include sea level rise, reduced snowpack, earlier snowmelt and larger storm-driven streamflow's, warmer and longer summers, warmer summer water temperatures, and water quality changes.

It is reasonable to assume that larger and more frequent storm driven stream flows will result in greater erosion of Hg contaminated sediments in the Sierras and Coastal mountain ranges, resulting in enhanced loads of Hg entering the Delta. If this does occur, then there will likely be a greater abundance of Hg available for methylation than in the current case. This is consistent with our current work, where it was observed that as tributary flow into the Yolo Bypass increased during a flood event, the delivery of Hg and MeHg increased as well (see Chapter 3 and Technical Appendix B). Moreover, it is highly likely that most of the delivery of Hg loads to the Delta will occur primarily in the more intense storms, which are predicted to be more frequent under climate change.

It is further reasonable to speculate that climate impacts on the behavior, fate and transport of dissolved organic carbon (DOC) and particles, especially particulate organic carbon, will play a major role in how Hg biogeochemistry responds to climate change impacts in the Delta. This prediction is based on several factors and observations. First, it is well known that dissolved and particulate organic carbon plays a major role in the transport of Hg in aquatic systems (Mierle and Ingram, 1991; Driscoll and others, 1995; Mason and Sullivan, 1998; Schuster and others, 2011; Chiasson-Gould and others, 2014). Second, it is also well known that availability of labile organic matter for microorganism's productivity is one key parameter that strongly influences MeHg production (Lambertsson and Nilsson 2006; Graham and others, 2012; Marvin-DiPasquale and others, 2014). In the Yolo Bypass, Marvin-DiPasquale and others (2014) observed that MeHg production in agricultural and non-agricultural wetlands was not limited by sulfate bioavailability, but rather by the availability of labile organic carbon for microbial respiration. And third, several studies have predicted or observed that when tributary runoff increases (as is predicted for the Delta under climate change) there are often increases in organic carbon concentrations or loading and commensurate increases in Hg concentrations or loading (Shanley and others, 2008; Sebestyen and others, 2009; Dittman and others, 2010; Schuster and others, 2011; Schelker and others, 2011). Hence, if more Hg and organic matter is delivered to the Delta under a changing climate, one could reasonably predict that microbial production of MeHg will also increase. While the prediction that MeHg production is likely to increase under a changing climate in the Delta, the significance and magnitude of the enhancement is currently not known and will likely involve high uncertainty.

Data Gaps and Next Steps

How MeHg production, fate, and transport will change from climate change stressors has not been evaluated for the Yolo Bypass and the Delta Region. While general predictions (increase, decrease, remain the same) can be made based on our current understanding of MeHg biogeochemistry, such assessments have high uncertainty and do not provide magnitude or significance predictions. Modelling efforts and laboratory and field-based investigations (to fill critical data gaps for the modelling efforts) are warranted to test various scenarios regarding climate change impacts on MeHg production, behavior and transport in the Yolo Bypass and Delta. The hydrodynamic and Hg biogeochemistry models described in this report (the Yolo Bypass Dynamic Mercury Cycling Model [D-MCM] and the Delta Simulation Model 2 [DSM2] with mercury module) along with DWR's CalSim model[2] can be used to perform various climate change scenario investigations. Preliminary scenario testing with the above models can be used to identify major climate change drivers affecting MeHg production, behavior, fate, and transport, and to identify gaps in our knowledge that can be filled with laboratory or field-based investigations.

Specific questions to investigate regarding climate change driven alterations in MeHg production, behavior and transport in the Yolo Bypass and Delta include:

- How does the timing and magnitude of changes in tributary run-off influence MeHg production, behavior and transport?
- How does sea level rise (combined with subsidence) influence MeHg production, behavior and transport? What affect will salinity intrusion have on mercury methylation processes?
- How will changes in operations of the water delivery systems (to meet demands) influence MeHg production, behavior and transport?
- How will extended drought conditions influence MeHg production, behavior and transport? Of particular interest is whether MeHg production during a flood event in the Yolo bypass will increase, decrease or remain the same due to climate driven changes in vegetation biomass in pasture lands?
- How will atmospheric input of mercury change from climate impacts?
- Will levees be built-up in response to sea level rise or be allowed to breach and flood?
- How will conversion of primarily freshwater tidal wetlands to more saline tidal wetlands affect MeHg production as a result of sea level rise?
- Will larger and more frequent floods act to deliver fresh new Hg to the Delta from erosion in the Sierras?

[2] CalSim is a water resources planning model, jointly developed by the California Department of Water Resources (DWR) and the Mid-Pacific Region of the U.S. Bureau of Reclamation, to simulate operations of the State Water Project (SWP) and the Central Valley Project (CVP) and much of the water resources infrastructure in the Central Valley of California and the Sacramento-San Joaquin Delta region.

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