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Contaminant Effects on California Bay–Delta Species and Human Health

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ABSTRACT

Many contaminants in the California Bay–Delta (Bay–Delta) exceed regulatory standards, affect aquatic species, and potentially affect human health. Recent studies provide multiple lines of evidence that contaminants affect species of concern in the Bay–Delta (e.g., the decline of several important fish species referred to as the "Pelagic Organism Decline" or POD). Contaminants occur as dynamic complex mixtures and exert effects at multiple levels of biological organization. Multiple chemicals impair processes at cellular and physiological levels (measured as growth, development, and behavior abnormalities), and when viability and reproductive output are affected, populations are affected. As an important example, the population decline of the endangered Delta Smelt (*Hypomesus transpacificus*) is significantly associated with multiple stressors, including insecticide use. New analyses presented in this paper show significant correlations between pyrethroid use and declining abundance of POD fish species. Water sampled from the Bay–Delta causes multiple deleterious effects in fish, and Delta Smelt collected from the Bay–Delta exhibit contaminant effects. Fish prey items are also affected by contaminants; this may have an indirect effect on their populations. Co-occurrence with thermal changes or disease can exacerbate contaminant effects. Contaminants also pose threats to human health via consumption of fish and shellfish, drinking water, and contact recreation, in particular, mercury, cyanobacteria toxins, disinfection byproducts, pathogens, pesticides, and pharmaceuticals and personal care products. The role of contaminants in the decline of Bay–Delta species is difficult to accurately assess in a complex, dynamic system. However, tools and approaches are available to evaluate contaminant effects on Bay–Delta species, and separate the effects of multiple stressors. Integrated monitoring and focused mechanistic studies are instrumental for addressing management needs. Effect and risk assessments should be conducted for different species across multiple life stages, with emphasis on early life stages of high-priority Bay–Delta species.

INTRODUCTION

The term contaminant refers broadly to a large number of substances from distributed and diverse sources that include urban and agricultural runoff, treated industrial and municipal wastewater, atmospheric deposition, and chemicals applied directly to surface waters for invasive plant and pest control.

The San Francisco Bay and Sacramento–San Joaquin Delta (Bay–Delta) has been identified as impaired for aquatic life by several specific contaminants on the Environmental Protection Agency 2010 List of Impaired Water Bodies (SWRCB 2010). The 2010 list of contaminants includes metals (copper, cadmium, mercury, and zinc), pesticides (chlordane, chlorpyrifos, DDE, DDT, diazinon, dieldrin, organophosphate insecticides, and toxaphene), and chlorinated compounds (dioxins, furans, and polychlorinated biphenyls [PCBs]). The Delta is also listed for sediment toxicity and unknown toxicity[1]. An unknown toxicity listing results from toxicity being detected in lab or field studies, but not yet being linked to a specific chemical. Since the 2010 list was adopted, additional contaminants of concern have been identified including additional pesticides, flame retardants, nutrients, naturally occurring toxins, micro-plastics (e.g., from synthetic clothing), and pharmaceuticals and personal care products (PPCPs). Essential elements (e.g., selenium) and nutrients, when outside the beneficial ranges, may negatively affect organism or community health. A legacy of contaminants in the Bay–Delta, such as persistent organic chemicals and mercury, can, in addition to affecting aquatic life, accumulate through the food web, leading to health risks for humans and wildlife.

Although many contaminants have been identified as impairing aquatic life, it is unknown how many other contaminants may exert toxic effects. Compared to other biotic and abiotic factors that cause aquatic ecosystem degradation worldwide, the role of contaminants is often under-estimated because of a lack of comprehensive, quantitative, and effect-based analyses (Stehle and Schulz 2015). Contaminants affect populations and communities at concentrations

detected in the Delta (Hasenbein et al. 2015c), but first exert their effects at the organism level by altering gene expression, physiological processes, and behavior. Historically, contaminant assessments focused predominantly on acute effects, but sublethal toxic effects can occur at exposure levels far below the concentrations that cause lethality. This does not imply that acute effects are no longer observed, but simply that there is greater awareness of the consequences of sublethal effects. Over the past decade, multiple lines of evidence demonstrate that contaminants, either singly or as mixtures, directly affect the health of Bay–Delta species (Table 1). These studies have provided much information about the risk of exposure to contaminants, and have also highlighted important knowledge gaps, including the significance of combined effects of chemical and other biotic and abiotic stressors.

Water quality standards are generally designed to be protective of 95% of aquatic life (i.e., of species for which we have toxicity data). Contaminant monitoring, coupled with toxicity testing that uses standard test species and methods, are also used as reliable indicators of "instream" threats to aquatic organisms (Grothe 1996; De Vlaming and Norberg–King 2000). In the past, contaminants were identified as impairing aquatic life primarily when chemical concentrations detected in Bay–Delta waters, sediment, or biota exceeded known water quality standards or caused toxicity. Although these tools are highly predictive of instream effects, they need to be paired with additional contaminant effect studies of resident or migratory species, whenever the abundance of these key species is linked to multiple stressors. It is noteworthy that when these standard regulatory tools were applied to the Bay–Delta and its tributaries, and the identified contaminants were examined in studies of resident species, effects were consistently confirmed.

The topic of Bay–Delta contaminants is broad, and by necessity a synthesis must focus on a subset of available information. In this paper we summarize new information which has become available since the State of Bay–Delta Science 2008 was published (Luoma et al. 2008). This synthesis emphasizes four topics:

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1   http://www.waterboards.ca.gov/water_issues/programs/ tmdl/2010state_ir_reports/table_of_contents.shtml#r5

1. The application of a weight-of-evidence approach to improve our ability to assess contaminant effects on Bay–Delta fish species that are experiencing significant population declines.

2. A synthesis of knowledge on known and emerging contaminants (not addressed in the weight-of-evidence examples).

3. An update on human health risks through fish consumption and drinking water from the Delta.

4. Recommendations on science priorities to address the current challenges in precisely defining the role of contaminants as one of many stressors.

APPLICATION OF A WEIGHT OF EVIDENCE APPROACH— CONTAMINANT EFFECTS ON DECLINING BAY–DELTA FISH SPECIES

One outstanding management challenge is that the role of contaminants in the decline of several Bay–Delta native and migratory species is not well understood. Even though the ecological effects of contaminants have been incorporated into Bay–Delta conceptual models, they have not been effectively quantified in terms of population declines. In recent years, a number of expert panels were convened to evaluate multiple stressors involved in the decline of Bay–Delta species. These expert panels identified contaminants as a stressor that warrants extensive investigation (Johnson et al. 2010; Mount et al. 2012; NRC 2013; IEP MAST 2015; Luoma et al. 2015), yet specific contaminants were not linked to the decline. Although several contaminants occur above their regulatory threshold concentration, we do not clearly understand the effect of these known contaminants on Bay–Delta species declines. Unknown contaminants could also be having an effect. Unequivocal identification of a specific contaminant as a cause of a species decline will continue to be a challenge, but recent research has generated multiple lines of evidence, which, when considered together, can be used to generate a weight of evidence that is more conclusive in identifying contaminants as an influential factor.

Quantifying the role of contaminants in observed Bay–Delta fish declines requires multiple approaches. For each species in decline, individual studies, or lines of evidence, can be synthesized to see if the weight of evidence supports that a contaminant is influencing species abundance. Some individual lines of evidence may determine that there is potential risk, but are clearly not definitive. For example, contaminants may be detected in the Bay–Delta at concentrations that exceed water quality standards, but these may not be adversely affecting the abundance of a particular species. Other lines of evidence may show species effects, but this is not enough to demonstrate that a contaminant is affecting the population as a whole. However, as we obtain multiple lines of evidence, it becomes more likely that effects are occurring, and that management action–or at least intensified studies– should be initiated. Potential lines of evidence include:

- major risk factors, such as:
  - declining species abundance not fully explained by other stressors
  - a statistical relationship between fish abundance and contaminant use
  - contaminants detected in fish habitats at levels of concern

- significant organism effects, such as:
  - effects detected in Bay–Delta waters or sediment on surrogate species
  - effects detected in Bay–Delta waters or sediment on the species of concern
  - effects detected in field-collected organisms
  - effects detected in laboratory and mesocosm studies conducted at contaminant levels detected in the Bay–Delta

- indirect effects of a contaminant, for example, on the food supply of a species known to be food limited

This synthesis focuses on the research conducted since 2005 that used field, mesocosm, and laboratory studies to evaluate the effects of contaminants on declining fish species including Delta Smelt (*Hypomesus transpacificus*), Longfin Smelt (*Spirinchus thaleichthys*), Threadfin Shad (*Dorosoma petenense*), juvenile Striped Bass (*Morone saxatilis*) and salmonids. We present available lines

Table 1 Sublethal effect-based assessments of contaminant impacts of contaminants present in the Bay-Delta

DELTA SPECIFIC SUBLETHAL EFFECTS STUDIES FROM 2005 TO PRESENT	General Stress	Immune System	Osmoregulation	Nervous system	Muscular system	Endocrine system (reproductive)	Tissue effects / Histopathology	Necrosis / Apoptosis	Low Nutritional Status	Growth	Development	Deformities	Behavior	Reproductive Output
Pyrethroid insecticides	Ch[1-3] Sb[4] Sp[5] Ds[6]	Ch[1-3] Sb[4] Ds[6,7] Is[8]	Ds[6,7] Rt[9]	Ds[7] Fm[10,11]	Ds[7] Fm[10,11]	Fm[11] Is[8,12-15] Rt[16] Jm[17]	Sp[5]	Sp[5] Ds[6,7]		Sb[4] Sp[5] Ds[6,7] Cd[18,19] Ha[18,20]	Ds[6,7] Rt[16]	Sp[5]	Sb[4] Ds[7] Fm[10,11] Cd[18,19] Ce[21] Ha[20]	Is[8,12,14]
Organophosphate insecticides	Ch[1-3] Sp[5]	Ch[1-3]		Ch[22] Rt[23]			Sp[5]	Sp[5]		Sp[5] Cd[18,19] Ch[22]		Sp[5]	Cd[18,19] Ha[20] Ch[22] Rt[24]	
Phenylpyrazole insecticides				Fm[11,25]	Fm[11,25]	Fm[11,25]						Fm[11]	Fm[11,25]	
Pharmaceuticals and Personal Care Products	Is[26]	Is[26]	Is[26]	Fm[27]	Fm[27]						Is[26]		Fm[27]	
Metals and Metalloids	Sb[4] Lmb[28]	Sb[4] Ds[29] Lmb[28]		Ds[29]	Ds[29]		Sp[30] Lmb[28]	Ds[29]	Sp[30]	Sb[4] Ds[29] Ha[20] Sp[30]	Ds[29]	Sp[30,31]	Sb[4] Ds[29] Ha[20]	
Persistent Organic Pollutants	Sb[32,33]						Sb[34]			Sb[34]	Sb[34]			
Ammonia and Ammonium	Ds[35]	Ds[36]		Ds[36]				Ds[35]			Ds[35,36]		Ds[35]	Pf[37]
Microcystin	Jm[38]						Jm[38] Ts[39] Sp[40]	Jm[38] Ts[39] Sp[40]	Ts[39] Sp[40]	Ts[39] Sp[40]			Eg[41]	
Delta Water Samples (Laboratory)	Sb[33] Ts[39]	Ds[36]		Fm[42]	Ds[36,43]	Sb[33] Fm[42,44] Rt[45,46]	Fm[42]	DS[43]		Fm[42,44] Ds[43] Ha[47-49]	Ds[36] Fm[42,44] Ds[43]		Fm[44]	
Delta Water Samples (In-situ, field collected fish)	Fm[42] Sb[50]			Sb[50]		Is[12] Fm[42,44] Sb[50] Rt[17]	Fm[42] Ds[51] Sp[52] Is[12]	Sb[50]	Sb[50] Sp[52]	Ds[51] Sp[52]	Is[12]	Sb[50]		

Key: *Fish species:* Ch = Chinook Salmon; Sb = Striped Bass; Sp = Sacramento Splittail; Ds = Delta Smelt; Is = Inland Silversides; Rt = Rainbow Trout; Fm = Fathead Minnow; Jm = Japanese Medaka; Lmb = Largemouth Bass; Ts = Threadfin Shad; *Invertebrate species:* Ha = *Hyalella azteca*; Cd = *Chironomous dilutus*; Ce = *Ceriodaphia dubia.* Pf = *Pseudodiaptomus forbesi*; Eg = *Eudiaptomus gracilis.*

Sources: [1]Eder et al. 2008; [2]Eder et al. 2007; [3]Eder et al. 2009; [4]Geist et al. 2007; [5]Teh et al. 2005; [6]Jeffries et al. 2015b; [7]Connon et al. 2009; [8]Brander et al. 2016; [9]Riar et al. 2013; [10]Beggel et al. 2011; [11]Beggel et al. 2010; [12]Beggel et al. 2012; [13]Brander et al. 2013; [14]Brander et al. 2012a; [15]DeGroot and Brander 2014; [16]Forsgren et al. 2013,[17]Schlenk et al. 2012; [18]Hasenbein et al. 2015a; [19]Hasenbein et al. 2015b; [20]Callinan-Hoffmann et al. 2012; [21]Brander et al. 2012b; [22]Baldwin et al. 2009; [23]Maryoung et al. 2014; [24]Maryoung et al. 2015; [25]Beggel et al. 2012; [26]Jeffries et al. 2015a; [27]Fritsch et al. 2013; [28]Gehringer et al. 2012; [29]Connon et al. 2011a; [30]Deng et al. 2007; [31]Rigby et al. 2010; [32]Durieux et al. 2012; [33]Spearow et al. 2011; [34]Ostrach et al. 2008; [35]Connon et al. 2011b; [36]Hasenbein et al. 2014; [37]Teh et al. 2011 [38]Deng et al. 2010; [39]Acuña et al. 2012a; [40]Acuña et al. 2012b; [41]Ger et al. 2011; [42]Deanovic et al. 2014, unreferenced, see "Notes"; [43]Connon et al. 2011, unreferenced, see "Notes"; [44]Biales et al. 2015; [45]de Vlaming et al. 2006; [46]Lavado et al. 2009; [47]Werner et al. 2010a; [48]Werner et al. 2008; [49]Werner et al. 2010b; [50]Ostrach and Groff 2009; [51]Hammock et al. 2015; [52]Greenfield et al. 2008. Citations in red indicate evaluations conducted at concentrations detected in the Bay-Delta, or on Bay-Delta water samples.

See reference information for sources listed beginning on page 30.

of evidence, which, when taken together, provide a weight of evidence that contaminants, in combination with other stressors, have negatively affected Delta Smelt. There is also evidence of contaminant effects on salmon. Less is known about the precise role of contaminants on other Bay–Delta fish declines, but a synthesis of recent studies suggests the potential for contaminant effects, and identifies critical gaps in our knowledge (Table 1).

Evidence of Declining Species Abundance Not Fully Explained by Other Stressors

A step-decline in abundance of Delta Smelt, Longfin Smelt, Threadfin Shad, and Striped Bass (young-of-year) was observed in the early 2000s (Thomson et al. 2010). Declining numbers of estuary-dependent fish species such as Chinook Salmon (*Oncorhynchus tshawytscha*), Steelhead Trout (*O. mykiss*), and Green Sturgeon (*Apicenser medirostris*), as well as invertebrates—in particular calanoid copepods and mysids—and desirable primary producers have also been documented (Winder and Jassby 2011). Contaminants have been concomitantly detected at concentrations that can elicit acute and chronic effects (e.g., reduced growth, reduced reproduction) in related species. Studies of sublethal effects on Bay–Delta species began more recently. Although these investigations noted decreases in growth rates and fecundity, many did not fully assess the role of contaminants. The general conclusion of the recent investigations is that multiple stressors were involved (FLaSH; Brown et al. 2014).

Monitoring the abundance and distribution of aquatic species (e.g., algae, macroinvertebrates, fish) can identify changes in populations, but analyses of multiple stressors are required in order to understand why species abundance and composition fluctuates. Such analyses must include contaminants and their effects on organisms and the ecosystem if their role is to be defined.

Example of Correlations Between Declining Fish Abundance and Increasing Insecticide Use

Several investigations have conceptualized but not quantified the role of contaminants in Bay–Delta fish declines (Brooks et al. 2012; Scholz et al. 2012).

A new analysis, presented here as a representative example of changing pesticide use, indicates that pyrethroid insecticide use in the Delta is strongly correlated with fish abundances (Figure 1).

Why Pyrethroids as an Example? Although pyrethroids are classified as neurotoxicants, they have a number of additional effects that can be detrimental to fish, including endocrine disruption and growth and development alteration (Table 1). Pyrethroids are the fourth most-used group of insecticides worldwide (Hénault–Ethier 2015; Brander et al. 2016a), and their use has increased steadily since 1979, while the use of organophosphate insecticides (OPs) (e.g., diazinon chlorpyrifos) has declined since their peak in the early 1990s (Figure 2). Concentrations of pyrethroids were predicted to increase markedly in waters tributary to the Bay–Delta starting in 2000 (Jorgenson et al. 2013). The California Department of Pesticide Regulation's (CDPR) Surface Water Protection Program has ranked pyrethroids as high priority for monitoring because they have high potentials to cause surface water toxicity from urban and agricultural uses (Luo et al. 2014). The Central Valley Regional Water Quality Control Board (CVRWQCB)[2] is currently establishing a control program for pyrethroid insecticides to protect Bay–Delta watershed aquatic life. The hydrophobic nature and strong binding affinity of pyrethroids to particulate matter were thought to reduce or prevent their runoff into surface waters; however, studies have shown that runoff from areas treated with pyrethroids was more toxic to fish than runoff from areas treated with OPs (Werner et al. 2002; Jiang et al. 2016).

Associations between pyrethroid use (agricultural and professional urban application) in the six counties of the Delta (*http://www.cdpr.ca.gov/docs/ pur/purmain.htm*) and fish abundance indices for the Pelagic Organism Decline (POD) species from Interagency Ecological Program (IEP) Fall Midwater Trawl (FMWT; 1978 to 2014) suggest that pyrethroids may be a contributor to fish population declines in the Delta (Table 2). The use of six pyrethroids in the Delta region (permethrin, esfenvalerate/fenvalerate, bifenthrin, cyfluthrin, cypermethrin, and lambda-

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2 *http://www.waterboards.ca.gov/centralvalley/water_issues/tmdl/central_valley_projects/central_valley_pesticides/pyrethroid_tmdl_bpa/index.shtml*
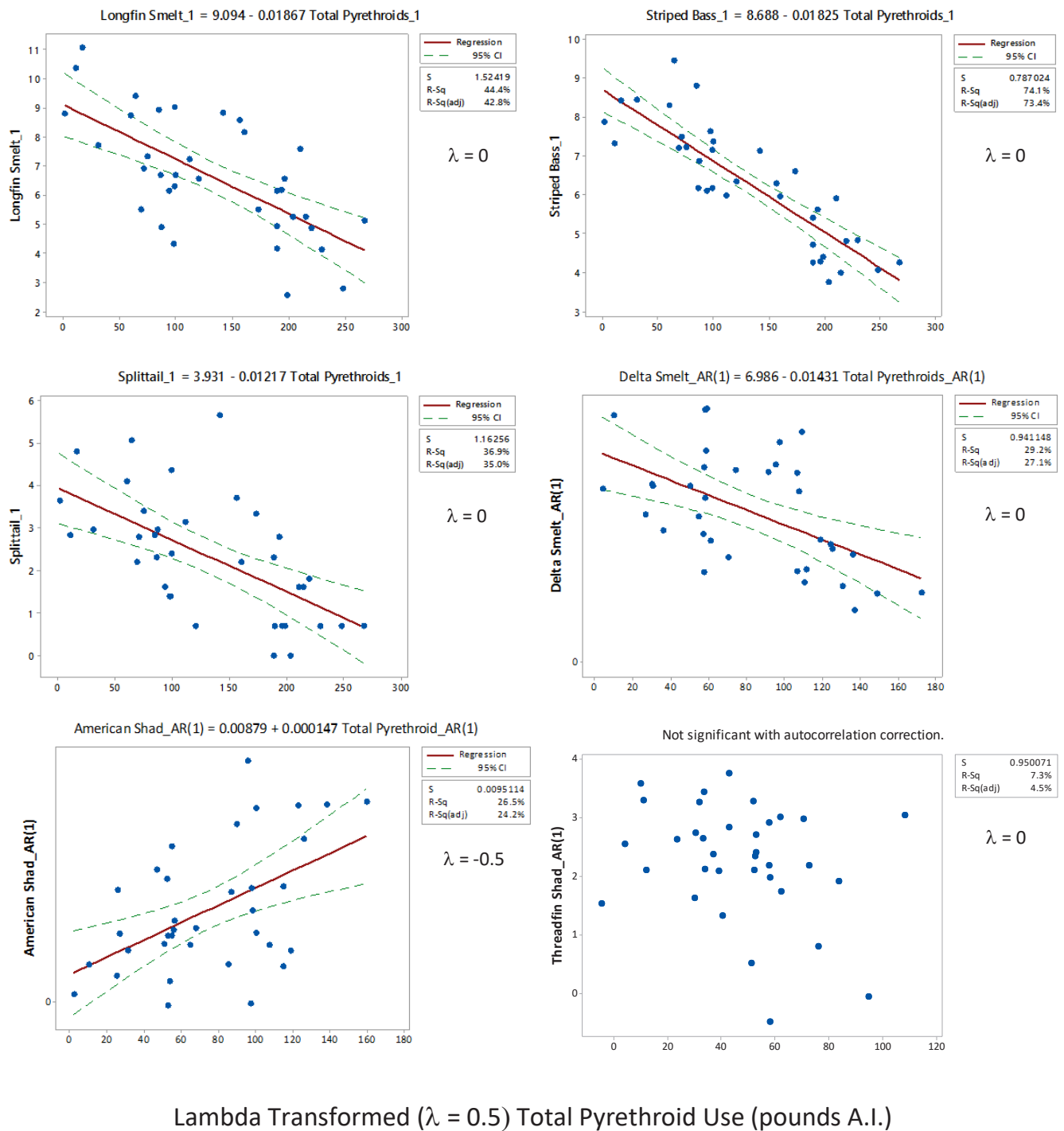
Figure 1   Ordinary least squares regression fitted line plots and 95% confidence intervals of IEP FMWT species abundance indices (autocorrelation corrected) as a function of annual pyrethroid pesticide use in the counties of the Delta from 1978–2014
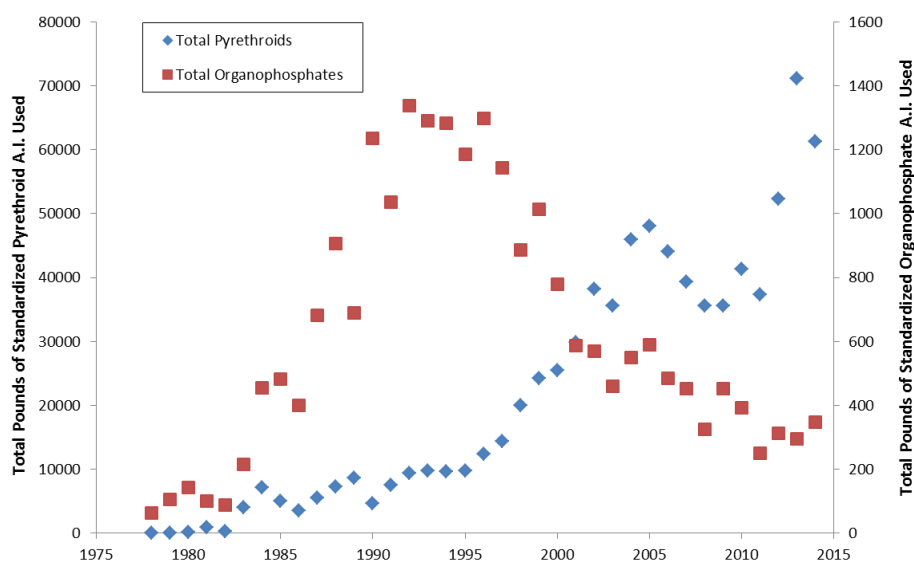
Figure 2 Plot displaying the total pounds of A.I. for pyrethroid use and organophosphate use in the counties of the Delta during 1978-2014 from the California DPR PUR database. The pounds of A.I. were standardized to the toxicity strength of the pesticides using conversion factors (see Appendix A, Table A–1).

cyhalothrin) explains 24% to 73% of the interannual variability in FMWT species abundance indices (Figure 1). See Appendix A for further details of the statistical analyses.

Understanding interactions between contaminant exposure and environmental factors, and their effect on populations, will likely require comprehensive analyses of disparate datasets. For example, Bailey et al. (1994) used flow-adjusted Striped Bass abundance indices and pesticide concentrations to correlate rice agricultural discharges to their decline. Conceptually, flow variability is also

hypothesized to be the most important decadal-scale driver in reducing the ecological resilience of the Bay–Delta which contributed to the POD (Baxter et al. 2010). More recently a synthesis report established quantitative relationships between Delta Smelt abundance indices and habitat location (X2; location at salinity of 2 PSU) and recruitment variables (IEP MAST 2015). Herein, models were developed to compare the relative influence of flow and pyrethroid use on species abundance (Table 3). The model that explained the greatest amount of variability in an abundance index was for Longfin

Table 2 Pearson's r, Spearman's rho, and Kendall's tau correlation coefficients measuring associations between IEP FMWT abundance indices and pyrethroid use in the Delta.

Transformed IEP FMWT abundance indices	Lambda transformation	Transformed pounds of pyrethroid pesticide use ($\lambda = 0.5$)					
		Pearson's r		Spearman's rho		Kendall's tau-a	
		Correlation coefficient	p-value	Correlation coefficient	p-value	Correlation coefficient	p-value
Longfin Smelt	0	−0.67	<0.0001	−0.65	<0.0001	−0.48	<0.0001
Delta Smelt	0	−0.67	<0.0001	−0.58	<0.001	−0.40	<0.001
Sacramento Splittail	0	−0.61	<0.0001	−0.64	<0.0001	−0.45	<0.001
American Shad	−0.5	0.62	<0.0001	0.51	<0.01	0.35	<0.01
Threadfin Shad	0	−0.48	<0.01	−0.39	<0.02	−0.23	<0.05
Striped Bass	0	−0.86	<0.0001	−0.89	<0.0001	−0.69	<0.0001

Table 3 Predictor variables and summary statistics for multiple linear regression models explaining IEP FMWT species abundance variability from 1978–2014.

Species	R^2-adj.	Predictor variables	Partial coefficients	95% CI	*p*-value
Longfin Smelt	0.79	Pyrethroid use	−1.097	(−1.422, −0.771)	<0.001
		Delta Inflow	−1.228	(−1.533, −0.902)	
Striped Bass	0.77	Pyrethroid use	−1.235	(−1.494, −0.977)	<0.001
		Delta Inflow	−0.336	(−0.622, −0.050)	
		Delta Exports	−0.322	(−0.602, −0.042)	
Delta Smelt	0.37	Pyrethroid use	−1.01	(−1.567, −0.452)	<0.001
		Delta Exports	0.422	(0.107, 0.737)	
American Shad	0.41	Pyrethroid use	0.00973	(0.00472, 0.01473)	<0.001
		Delta Exports	−0.00464	(−0.00778, −0.00150)	
Sacramento Splittail	0.54	Pyrethroid use	−0.744	(−1.089, −0.400)	<0.001
		Delta Inflow	−0.651	(−0.995, −0.307)	

Smelt ($R^2 - \text{adj} = 0.79$, $p < 0.001$, F-test), with average Delta inflow explaining slightly more variability than pyrethroid use. This is consistent with Baxter et al. (2010), where Longfin Smelt abundance trends were best explained by seasonal Delta outflow. For the other species, pyrethroid use was a more important determinant of abundance variability than flow. Overall, this analysis suggests that pyrethroid use may have played a comparable role to other stressors in the POD. The strong correlation observed suggests an urgent need for further analyses to assess whether this is a causal relationship, especially because research has highlighted deleterious effects at multiple levels of biological organization, in multiple species (Table 1).

These analyses are only a cursory evaluation of multiple-factor effects on fish species abundances; mechanistic studies are needed to evaluate the biological significance of the correlation. Recovery efforts for Bay–Delta aquatic species need to include analyses of contaminant effects in conjunction with other pertinent factors. Additional data and analyses are needed to better understand the interactions between habitat and biology. For example, Baxter et al. (2010) hypothesized that salinity, landscape, temperature, turbidity, nutrients, and harvest, in addition to flow and contaminants, were long-term drivers of the POD. In addition, Thomson et al. (Thomson et al. 2010) (2010) indicated that

water clarity and Delta flow characteristics were drivers of Bay–Delta fish species abundances; however, the researchers did not evaluate possible contaminant effects. The ability to explain changes in fish abundance by pyrethroid use in the Delta may be altered by the inclusion of other important factors. For example, Bailey et al. (1994) showed that the discharge of rice agriculture pesticides, primarily carbamates, likely contributed greatly to earlier Striped Bass declines. However, carbamate insecticides have been replaced primarily with pyrethroids, and young-of-year Striped Bass abundances have not recovered. Monitoring, special studies, and models are needed to link the processes that occur from contaminant sources to a resulting species decline (e.g., pesticide runoff, bioenergetic costs of exposure to contaminants, decreases in food availability, or reductions in fecundity or fish survival).

It must be noted however, that pyrethroids are only one class of a multitude of pesticides detected in Bay–Delta waters, and are presented here as an example. Even though regulation of some pesticides has decreased their effect, replacement products can be similarly problematic. Effective attenuation measures are needed in order to reduce the entry of contaminants into California waterways, which will increase the probability of species recovery.

Evidence of Contaminants Detected in Fish Habitats at Levels of Concern

Monitoring entities and research studies have detected multiple contaminants occurring simultaneously in Delta water samples (Ensminger et al. 2013; Orlando et al. 2013, 2014). Multiple pesticides are continuously detected in the two primary tributaries to the Delta. For example, 27 pesticides or degradation products were detected in Sacramento River samples, and the average number of pesticides per sample was six. In San Joaquin River samples, 26 pesticides or degradation products were detected, and the average number detected per sample was 9. Water quality objectives do not exist for most of these compounds. However, these were targeted chemical analyses, and hundreds of compounds have been detected in individual Delta water samples using other non-targeted techniques (2016 in-person conversation with T. Young, J. Orlando and R. Connon, unreferenced, see "Notes").

Organisms are exposed to a dynamic mixture of contaminants (e.g., introduction of new chemicals, varied use patterns). Although pesticides generally have a seasonal pattern, PPCPs are continuously introduced into the environment (Deanovic et al. 2014, unreferenced, see "Notes"; Biales et al. 2015). This raises concern because exposure to chemical mixtures has shown adverse effects on aquatic organisms at concentrations at which no observable adverse effects occur for single constituents (Carvalho et al. 2014; Cedergreen 2014), and little is known about potential synergistic, antagonistic, or additive effects of exposure to contaminant mixtures.

Pyrethroids have been found in sediments of agricultural and urban waters upstream of the Delta at concentrations that are acutely toxic to numerous benthic and epibenthic macroinvertebrates (Amweg et al. 2005; Holmes et al. 2008; Weston et al. 2008; Weston et al. 2015b).

Copper is present throughout the Delta at concentrations known to cause adverse effects. The copper threshold established for enclosed bays and estuaries is 4.8 µg L^{-1}. Dissolved copper concentrations up to 4.64 and 4.93 µg L^{-1} were detected in freshwater water samples from Cache–Lindsey Slough and Rough and Ready Island, respectively, and elevated dissolved copper concentrations of 37.2 and 58.9 µg L^{-1} have also been detected at Suisun Bay and Carquinez Strait, respectively (Werner et al. 2010a). A recent study (Sommers et al. 2016) indicated that although the effect of copper on salmon olfaction is reduced in brackish and saline waters, copper can still cause avoidance behavior at environmentally relevant concentrations.

In a study conducted to evaluate the effects of pesticides, trace metals, and PPCPs present in Sacramento River samples, the most frequently detected substances were pharmaceuticals. PPCPs comprised 51% of the detected analytes: trace metals and pesticides comprised 28% and 21% of the analytes, respectively (Deanovic et al. 2014, unreferenced, see "Notes"). Other studies also found a high incidence of pharmaceuticals in Sacramento River water (Biales et al. 2015). Guo et al. (2010) completed a source, fate, and transport study that included 11 sampling sites in the Delta associated with the State Water Project (SWP). Forty-nine chemicals were detected, many at concentrations above those that elicit adverse effects.

Evidence of Effects on Surrogate Species Detected in Delta Waters or Sediment

Multiple studies have found sublethal, lethal, chronic, and acute toxicity of Bay–Delta waters to model test species of phytoplankton, invertebrates, and vertebrates (Jassby et al. 2003; Johnson et al. 2010; Blaser et al. 2011; Brooks et al. 2012; Scholz et al. 2012). Multiple-species studies that evaluated Bay–Delta ambient water samples, or conducted *in situ* exposures (referenced in Table 1), have repeatedly identified a broad set of mechanistic, systemic (immune, neurological, endocrine), histopathological (tissue damage), and whole-organism effects (e.g., growth, development, deformities). Endocrine-disruptive effects have been measured in samples from Sacramento River tributaries and in the Bay–Delta (Schlenk et al. 2012; Brander et al. 2013; Cole et al. 2016).

Although identification of chemical classes responsible for these effects is limited, because of the complexities resulting from mixtures of multiple chemicals, several studies (see Table 1) have highlighted pyrethroid pesticides as responsible

for toxicity, endocrine disruption, and neurological impairments in both fish and their prey (Brander et al. 2013, 2016b; Hasenbein et al. 2015c; Jeffries et al. 2015b; Weston et al. 2015a).

Evidence of Effects on Delta Species of Concern

Delta Smelt: Several recent studies on Delta Smelt support that contaminants are a significant stressor. Ambient water samples collected in the Delta contained sufficient bioavailable compounds that in laboratory exposures Delta Smelt exhibited decreases in growth and altered development compared to fish exposed to control water. Specific effects were detected in gene expression associated with their immune system and muscular system (Hasenbein et al. 2014). Apoptosis and necrosis were also observed (Connon et al. 2012). Delta Smelt collected from the estuary were observed to have tissue-level effects, demonstrated through histopathology, which was associated with decreased growth (Hammock et al. 2015). These lines of evidence support that contaminants are bioavailable in Bay–Delta waters at concentrations that are affecting Delta Smelt.

In addition to studies that rely on ambient water or field-collected fish, studies have examined the effect of specific contaminants on cultured smelt. Pyrethroids have been documented to cause general stress responses and effects on the immune, nervous, muscular and osmoregulatory systems (Jeffries et al. 2015b). Decreased growth, abnormal development, and altered behavior have been detected from exposure to pyrethroids at levels detected in the Delta (Connon et al. 2009; Jeffries et al. 2015b). However, pyrethroids are not the only contaminant thought to be negatively affecting Delta Smelt. Smelt exposed to copper in the lab at levels detected in the Delta exhibited effects on their immune, nervous, and muscular systems (Connon et al. 2011a). Growth and development, as well as behavior, were also negatively affected, the latter raising concern with about the effects on homing ability (Connon et al. 2011a). Ammonium induced effects similar to those observed after exposure to pyrethroids and metals (Connon et al. 2011b), affecting immune- and muscular-system functioning, as well as development and behavior (Connon et al. 2011b; Hasenbein et al. 2014). The weight of evidence supports the

hypothesis that multiple contaminants are having a direct effect on Delta Smelt by affecting multiple levels of biological organization.

Contaminants can cause indirect effects by causing trophic cascades that affect population dynamics, food webs, community structure, and the Bay–Delta ecosystem as a whole (Fleeger et al. 2003; Johnston and Roberts 2009). Indirect effects of contaminants can also result in changes in nutrient and oxygen dynamics, altering phytoplankton and zooplankton communities (Brown et al. 2016; Moyle et al. 2016). Delta Smelt are known to be food limited (Hammock et al. 2015), and trend data shows reductions in prey availability over time (Hennessy 2011). Ambient water samples (Werner et al. 2008; Werner et al. 2010b), mesocosm studies (Hasenbein et al. 2015c), and laboratory studies (Hasenbein et al. 2015a; Hasenbein et al. 2015b) suggest that smelt prey organisms exhibit effects when exposed to ambient Delta waters or control waters amended with Delta-relevant concentrations of contaminants. Not only do pesticides reduce prey abundance, but pyrethroids have been shown to transfer to fish through prey (Muggelberg et al. 2016).

Taken together, these lines of evidence support the hypothesis that Delta Smelt are exposed to toxic levels of multiple contaminants found in the Delta. Delta Smelt populations are in decline, and the decline is significantly associated with multiple stressors. Delta water samples caused deleterious effects in Delta Smelt, and Delta Smelt collected from the Delta exhibit contaminant effects. Laboratory studies show that multiple levels of biological organization are affected by multiple chemicals, and negative organism-level responses (measured as growth, development, and behavior abnormalities) have been observed. In addition to these direct effects, food availability for Delta Smelt may be reduced by contaminants, and this may indirectly affect the population. A huge data gap is that limited studies examine the relationships between contaminants and specific responses by Delta Smelt, particularly during the early embryo-to-larval life stages.

Other POD Species. Much less is known about the role of contaminants in the decline of the other POD species. Although Longfin Smelt, and Threadfin Shad

declines were significantly correlated with pyrethroid use, a large data gap exists since no contaminant exposure studies have been conducted on these species. The Striped Bass decline is also significantly correlated with pyrethroid use, but exposure studies with Striped Bass have focused on polycyclic aromatic hydrocarbons (PAHs) and polyhalogenated aromatic hydrocarbons (PHAHs), including PCBs and dioxins. Exposure and bioaccumulation of polybrominated diphenyl ethers (PBDEs), PCBs, and legacy pesticides can result in these contaminants being transferred maternally from females to eggs, which affects egg size, fecundity, brain and liver development, impaired growth, and survival (Ostrach et al. 2008). These compounds are widespread in the Bay–Delta, and studies have demonstrated their effect on fish health and development (Spearow et al. 2011; Durieux et al. 2012).

Salmon abundance is declining, and several important stressors have been identified. Both pesticides and copper exposure can affect fish migration and orientation. The most commonly observed links with these behavioral disruptions include cholinesterase (ChE) inhibition, altered brain neurotransmitter levels, and sensory deprivation (Scott and Sloman 2004). Scholz et al. (2000) also concluded that exposures to low concentrations of diazinon likely increased the straying of the adult hatchery Chinook salmon over the control group. Furthermore, juvenile salmonids exposed to pesticides during development may fail to imprint to their natal waters, which can lead to increased adult straying (NMFS 2009). Chlorpyrifos exposure directly affects the nervous system (Baldwin et al. 2009) and the olfactory system (Maryoung et al. 2015). There is evidence that behavioral effects of pesticides affect salmon populations in other ecosystems. For example, cypermethrin prevented male Atlantic salmon from detecting and responding to the reproduction-priming pheromone prostaglandin, which is released by ovulating females (Moore and Waring 2001). Copper concentrations of $2\,\mu g\,L^{-1}$ significantly affect the olfactory system in juvenile salmonids (see video[3], Sandahl et al. 2007; Grossman 2016), increasing predation risk and impairing osmotic homeostasis (Grosell et al. 2002). This is of concern because

3   See page 2 at this link: *http://pubs.acs.org/doi/suppl/10.1021/es062287r* (accessed 2016 October 24).

dissolved copper concentrations detected in water samples from Cache–Lindsey Slough and Rough and Ready Island were above threshold. Also, copper causes cholinesterase (ChE) inhibition, so its effects may be additive when present with OPs. In addition to behavioral effects, OPs have been shown to affect the immune system in Chinook Salmon, increasing their susceptibility to disease (Eder et al. 2008). Histopathological abnormalities and reduced growth have been reported for both invertebrate and fish species (Baldwin et al. 2009; Hasenbein et al. 2015b). Impaired gonadal or thyroid hormone levels in salmon have also been observed (Scott and Sloman 2004). Perhaps the most important point provided by existing studies is that the behavioral effects of contaminants on salmon should be investigated further. Contaminants could be the proximate cause of salmon mortality that is currently attributed to disease and predation (Grossman 2016).

In summary, this section illustrates how using a weight-of-evidence approach can facilitate a better understanding of the potential for contaminants to be influencing factors in the declining abundance of Bay–Delta fish species. Multiple studies support the potential importance of contaminants affecting Delta Smelt. Salmon studies are sufficient to prompt more study on behavioral effects. The paucity of research on the other POD species illustrates that this approach can identify critical data gaps.

Evidence that Contaminant Exposure Leads to Population Effects

Numerous contaminants detected throughout the Bay–Delta can affect the overall health of individuals, leading to behavior and reproductive impairment that translate to alterations in population dynamics. Global decreases in aquatic biodiversity have been associated with increases in pesticide contamination; for example, macroinvertebrate family richness is reduced by ~30% even when pesticide concentrations were within regulatory thresholds (Stehle and Schulz 2015). Models predict that a 6% reduction in length and 16% in mass would result in a >50% reduction in spawner abundance over 20 years in Chinook salmon (Baldwin et al. 2009). Population growth rates of Delta species are affected by exposure to contaminants (Brooks et al. 2012). Recent research

conducted in the Delta determined that contaminants sourced via water treatment plants disrupt endocrine system function in Inland Silversides (*Menidia beryllina*), resulting in alterations to gonado-somatic indices (GSI), testicular necrosis, and biased sex ratios (Brander et al. 2013). Adult Inland Silversides exposed to low, Delta-relevant concentrations (0.5 ng L^{-1}) of the pyrethroid bifenthrin had a significant reduction in reproductive output and biased sex ratios (fertilized eggs per female; Brander et al. 2013, 2016b). Risks associated with exposure to endocrine-disrupting compounds (EDCs), have been extensively reviewed (Bortone and Davis 1994; Tyler et al. 1998; Brander et al. 2013, 2016a). Risk of extinction in isolated populations has recently been associated with biased sex ratios (Grayson et al. 2014). Studies have demonstrated that exposures to neurotoxic insecticides (Baldwin et al. 2009) affect populations of multiple species and their community structures (Hasenbein et al. 2015c; Orlinskiy et al. 2015). More globally, Feist et al. (2011) describe how urban runoff contaminants in the U.S. Pacific Northwest caused up to 90% mortality of pre-spawning Coho Salmon (*Oncorhynchus kisutch*), thus, severely affecting population numbers through reductions in recruitment.

A SYNTHESIS OF SPECIFIC BAY–DELTA CONTAMINANTS

Metals and Metalloids

Contaminants that biomagnify pose major risks to aquatic species at higher trophic levels in the Bay–Delta; including fish, birds, and mammals. Two bioaccumulative contaminants, selenium and mercury, were among the high-priority water quality issues described by Luoma et al. (2008).

Linares–Casenave et al. (2015) reported high selenium concentrations in tissues of older, reproductively mature female White Sturgeon in the Bay–Delta. This is concerning because selenium-enriched yolk in sturgeon eggs can cause developmental defects as well as mortality of embryos and yolk-sac larvae, affecting recruitment. Similarly, kidney lesions, reduced growth and deformities have been observed in Sacramento Splittail fed a selenium-based diet (Deng et al. 2007). White Sturgeon and Splittail populations are exposed to high levels of selenium

through their diet, notably from *Corbula amurensis*, the invasive overbite clam (Feyrer et al. 2003; Stewart et al. 2013). In recent years, the average selenium concentrations in White Sturgeon from the bay have been below the threshold (11.3 µg–g^{-1} dry weight in muscle) established to prevent effects on Sturgeon reproduction as part of the North Bay Total Maximum Daily Load (TMDL; Baginska 2015). Extensive research has been conducted to support development of the TMDL and revised criteria for the Bay, including an ecosystem-scale selenium model, a model of transport, fate, and uptake into the food web, and additional monitoring and review (Chen et al. 2012; Presser and Luoma 2013). Long-term trend monitoring by the Regional Monitoring Program for Water Quality in San Francisco Bay (Bay RMP) and the USGS also continues (SFEI 2013; Stewart et al. 2013). The Bay RMP is performing pilot studies to evaluate non-lethal methods of monitoring selenium in sturgeon muscle that would increase the number of samples available to track long-term trends. A more precise understanding of the concentrations that elicit deleterious effects would be valuable.

Mercury, in the highly toxic form of methylmercury, can pose major risks to both aquatic and terrestrial species at higher trophic levels in the Bay–Delta, including fish, birds, and mammals. Methylmercury exposure is a significant concern for special-status bird species, including the federally endangered Ridgway's Rail (*Rallus obsoletus*) and California Least Tern (*Sternula antillarum browni*). Forster's Tern (*Sterna fosteri*) is the species at greatest risk: Ackerman et al. (2014) found that 79% of eggs from this species were above a high-risk threshold of 1 µg g^{-1} fresh wet weight. The control plans for mercury in both the Bay and the Delta (SFBRWQCB 2006; Wood et al. 2010) include a concentration target for prey fish to protect piscivorous birds. Average concentrations of methylmercury in species of concern are also commonly in the range known to affect biochemical processes, damage cells and tissue, and reduce reproduction in fish; particularly in peripheral areas of the Delta (Sandheinrich and Wiener 2011). For example, Gehringer et al. (2012) presented histopathological evidence of immunosuppression in juvenile largemouth bass from methylmercury contaminated areas in the Delta.

Copper exposure was shown to elicit general stress responses, affect the immune, nervous and muscular systems, and impair growth, development, and behavior in Bay–Delta fishes (Geist et al. 2007; Connon et al. 2011a; Gehringer et al. 2012) and invertebrates (Callinan–Hoffmann et al. 2012). Copper toxicity and accumulation in fishes differs between species, between freshwater and saltwater environments, as well as among the specific organs that are affected (Blanchard and Grosell 2006). While increased salinity is generally considered as protective against loss of olfactory function from dissolved copper, the presence of sub-lethal levels of dissolved copper altered the behavior of juvenile Chinook Salmon by inducing an avoidance response in both freshwater and seawater (Sommers et al. 2016). Further, species-specific evaluations are needed at higher salinity sites in order to determine potential effects on species of concern.

Persistent Organic Pollutants

PAHs and PHAHs including PCBs and dioxins are widespread in the Bay–Delta. Numerous studies have demonstrated their effect on fish health and development (Spearow et al. 2011; Durieux et al. 2012). Two contaminants of concern have received significant attention in the last few years: polybrominated diphenyl ethers (PBDEs) and perfluorooctane sulfonate (PFOS), however, effect-based assessments are lacking for Bay–Delta species.

PBDE flame retardants have been detected in Bay fish and wildlife since the 1990s. High detections spurred voluntary reductions and a California ban that took effect in 2006, which resulted in reduced concentrations in bivalves, fish, and bird eggs (Sutton et al. 2015). On the other hand, concern has increased regarding PFOS. PFOS is widely used as a stain repellant for textiles, furniture, and carpets; as a surfactant in fire-fighting foams and metal finishing processes; as an ingredient in the production of fluoropolymers; and as an insecticide. PFOS has been detected globally, including in San Francisco Bay birds and seals (2016 in-person conversation between M. Sedlak and J. Davis, unreferenced, see "Notes"). Bird eggs collected in the southern portion of the bay in 2006 and 2009 contained levels of PFOS above a threshold ($1\,\mu g\;g^{-1}$ wet weight) that affects offspring

survival in birds. Fortunately, more recent results (2012) are 70% lower than prior levels and well below the threshold. However, PFOS concentrations in seals do not show similar declines. PBDEs and PFOS have not been monitored in the Delta.

Ammonia and Ammonium

Toxicity to aquatic organisms is primarily attributable to the un-ionized form, ammonia. Ammonium is increasingly converted into ammonia as pH rises. Ammonium can enhance cell membrane permeability increasing its toxicity to species, and their susceptibility to the synergistic effects of multi-contaminant exposures (Connon et al. 2011b; Hasenbein et al. 2014). Freshwater mussels, for example, are highly sensitive to increased ammonia concentrations (USEPA 2013) and total ammonia nitrogen concentrations detected in the Sacramento River, downstream of Hood, are at levels potentially toxic to *Pseudodiaptomus forbesi* (Teh et al. 2011).

Pesticides

Multiple insecticides, fungicides, herbicides, and antibacterials are commonly detected throughout the Bay–Delta. The CDPR reports that 13,084 pesticide formulations are registered in the state, including 1,040 registered active ingredients, and >60% of those pesticide products are applied in the Central Valley (Pesticide Use Report; *http://www.cdpr.ca.gov*). OPs, pyrethroids and phenylpyrazoles (e.g., fipronil) are of greatest concern with regard to fish and zooplankton health. However, there is also concern over the use of herbicides, and their potential effect on the food web. In 2014, over 12,000 L of herbicide (formulation Fluridone) were applied to over 2,600 acres to control water hyacinth in the Delta, but this does not include the herbicides applied for other aquatic weeds such as *Egeria densa*, spongeplant (*Limnobium laevigatum*), and curly leaf pondweed (*Potamogeton crispus*).

Organophosphate insecticide registrants agreed to phase out urban sales in 2001. Many researchers have called attention to the decreased use of OPs (Oros and Werner 2005; Kuivila and Hladik 2008; Johnson et al. 2010) with a move toward increased use of pyrethroids, phenypyrazoles, and neonicotinoids (e.g.,

imidacloprid), yet studies continue to detect OPs in Bay–Delta waters (Ensminger et al. 2013; Weston et al. 2015a).

Pyrethroid insecticide exposure has negative effects on hormonal and neurological development or reproductive output. At low concentrations (ng L^{-1}) they act as EDCs through blocking, mimicking, or synergizing endogenous hormones (Brander et al. 2016a). Pyrethroid metabolites are reported to have even greater estrogenic activity than parent compounds (DeGroot and Brander 2014) as well as a significant occurrence (>20%) of deformities in offspring of exposed adults (2016 in-person conversation with B. Decourten, see "Notes"). Pyrethroids such as bifenthrin and permethrin are present in the Bay–Delta at concentrations that alter numerous metabolic processes, which result in protein degradation (Werner and Moran 2008; Vandenberg et al., 2012). They also alter osmoregulation capacity (Riar et al. 2013; Jeffries et al. 2015b), nervous- and muscular-system functions (Connon et al. 2009), and behavior (Beggel et al. 2010), as well as result in reduced growth and development (Geist et al. 2007; Forsgren et al. 2013; Riar et al. 2013). Larval deformities and histopathological abnormalities have also been reported for Sacramento Splittail exposed to pyrethroids (Teh et al. 2005).

Fipronil and its degradation products have been detected in urban creeks and tributaries to the Bay–Delta. It is a broad-spectrum insecticide used on pets and for structural pest control. Its occurrence in the Bay–Delta poses new challenges because degradation products have been shown to be more toxic than their parent compounds (Weston and Lydy 2014). Delta-relevant studies on Fipronil are limited to acute toxicity evaluations on invertebrates. However, effects to nervous and muscular systems, decreased swimming performance, and potential endocrine disrupting properties have been demonstrated with Fathead Minnow that require further investigation (Beggel et al. 2010, 2012). Fipronil concentrations in bay sediment have raised concern for potential effects on benthic invertebrates (SFEI 2013).

Pharmaceuticals and Personal Care Products

Pharmaceuticals and personal care products (PPCPs), such as pain and blood pressure medications,

antidepressants, antibiotics, antibacterials, and micro-plastics are used in large quantities and can enter waterways from indoor drains (e.g., excretion, improper disposal, bathing) through wastewater treatment plants. Over the past 2 decades, the U.S. Food and Drug Administration (FDA) center for Drug Evaluation and Research listed 2,817 drugs (medications containing an active substance; excluding personal care products), with 45 new drugs approved in 2015 alone.[4] A large number of PPCPs have been detected in the Bay–Delta (SFEI 2013; Deanovic et al. 2014, unreferenced, see "Notes"; Biales et al. 2015), but their relative contributions to the contaminant load in the Bay–Delta have not been comprehensively assessed. PPCPs are not regulated in surface and drinking water, and the risks to aquatic life are largely unknown.

Ibuprofen is one of the most commonly detected pharmaceuticals in wastewater effluent worldwide (Fent et al. 2006). Exposure to ibuprofen was shown to affect the expression of genes involved in oxidative stress, aerobic respiration, immune function, and osmoregulation, as well as skeletal development in Inland Silversides (Jeffries et al. 2015a). Although concentrations of pharmaceuticals detected in water samples are relatively low compared to those that elicit responses in fish, the concentration detected in water samples may be misleading because un-metabolized ibuprofen levels in wild fish plasma and bile for example, can be 100 to 1000 times higher, respectively, than those found in surrounding water samples (Brozinski et al. 2013).

Triclosan is an antibacterial widely used in consumer products (e.g., toothpaste, hand soaps), and is also found in wastewater effluent. Triclosan has been shown to negatively affect swimming behavior in fish by disrupting the excitation–contraction processes of skeletal muscle (Fritsch et al. 2013). Triclosan can readily accumulate in fish muscle and brain, thus posing a risk to Bay–Delta fishes.

Cyanotoxins

Naturally occurring cyanobacteria (blue–green algae) are common in ecosystems worldwide, and can produce toxins that negatively affect the ecosystem

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4 *http://www.fda.gov/Drugs/DevelopmentApprovalProcess/ DrugInnovation/ucm474696.htm*

much like chemical contaminants. At least 46 species of cyanobacteria have been shown to produce toxins that pose health risks to humans and wildlife (Carey et al. 2012; Lehman et al. 2013). Common cyanobacteria genera can produce a suite of toxins, such as hepatotoxins (microcystins), cytotoxins (cylindrospermopsin), neurotoxins (anatoxin-*a*, antillatoxin, saxitoxins), and dermatoxins (lyngbyatoxins). Research in the Bay–Delta has primarily focused on *Microcystis* spp. blooms, which were first recorded in 1999, and occur annually (Kurobe et al. 2013; Lehman et al. 2013). *Microcystis* can thrive in highly altered and nutrient-rich habitats. They can produce microcystin, which may promote liver cancer in humans and wildlife (Ibelings and Havens 2008). Studies conducted on Threadfin Shad and Sacramento Splittail demonstrated that consumption of *Microcystis* adversely affected their nutritional status, and resulted in severe liver and gonadal lesions (Acuña et al. 2012a, 2012b). Cyanobacterial blooms can further affect wildlife by lowering dissolved oxygen concentrations, and can also cause taste and odor problems in drinking water (Paerl et al. 2001). In a synthesis of Delta data from 2004 to 2008, Lehman et al. (2013) found that dry years resulted in higher microcystin concentrations in the water and mesoplankton tissues. Miller et al. (2010) concluded that microcystin-contaminated freshwater that entered Monterey Bay was bioaccumulated by bivalves, resulting in the death of 21 southern sea otters. This raises concern for risks to sturgeon and other species that consume bivalves, including humans.

UPDATE ON HUMAN HEALTH CONCERNS

Contaminant Exposure through Fish Consumption

Contamination of sport fish by two legacy contaminants, mercury and PCBs, is a high priority management issue in the Bay–Delta. Concentrations of mercury (in its highly toxic form, methylmercury) and PCBs are high enough that the California Office of Environmental Health Hazard Assessment has issued advisories that cover the entire estuary. These advisories have been updated and expanded in recent years (Gassel et al. 2007, 2011). Methylmercury is a major driver of advisories in the Bay–Delta, and though PCBs are also a major driver for Bay

advisories, they are lesser studied in the Delta. Risks to human health and the resulting consumption advisories are an important part of the bay mercury (SFBRWQCB 2006) and Delta methylmercury (Wood et al. 2010) control plans as well as the bay PCBs TMDL (SFBRWQCB, 2008).

Spatial patterns in sport fish methylmercury in the Delta have been fairly well-characterized, but very few data are available on inter-annual variation and long-term trends. Existing time-series at specific Delta locations are far from ideal, because of inconsistencies in sampling location, sample sizes, size ranges, and species, but the data do suggest consistent spatial patterns over time, with relatively high concentrations at the sites around the periphery of the Delta, and lower concentrations in the Central Delta (Davis et al. 2000, 2008, 2013; Melwani et al. 2009). Time-series based on repeated, directly comparable measurements are needed to rigorously characterize long-term trends that would serve as a performance measure to evaluate the effectiveness of the methylmercury TMDL.

Striped Bass is an important indicator species for methylmercury contamination throughout the Bay–Delta because of their high trophic position, consequentially high bioaccumulation, and popularity for consumption. Striped Bass from the Bay–Delta have the highest average mercury concentration in US estuaries (Davis et al. 2012). A historical dataset exists for Striped Bass in the bay, allowing trends over 39 years from 1971 to 2009 (Figure 3) to be evaluated. Concentrations measured in recent years are not significantly different from those measured in the early 1970s.

Cyanobacteria

The magnitude, frequency, and distribution of cyanobacterial blooms are expected to increase in the Bay–Delta as a result of climate change (Carey et al. 2012) and excessive discharge of nutrients. Humans can be exposed to cyanotoxins from recreational contact as well as consumption of fish and shellfish, and drinking water; effects range from skin irritation to death. In the Bay–Delta, incidents of human health effects are poorly captured, but the World Health Organization has documented effects from all over
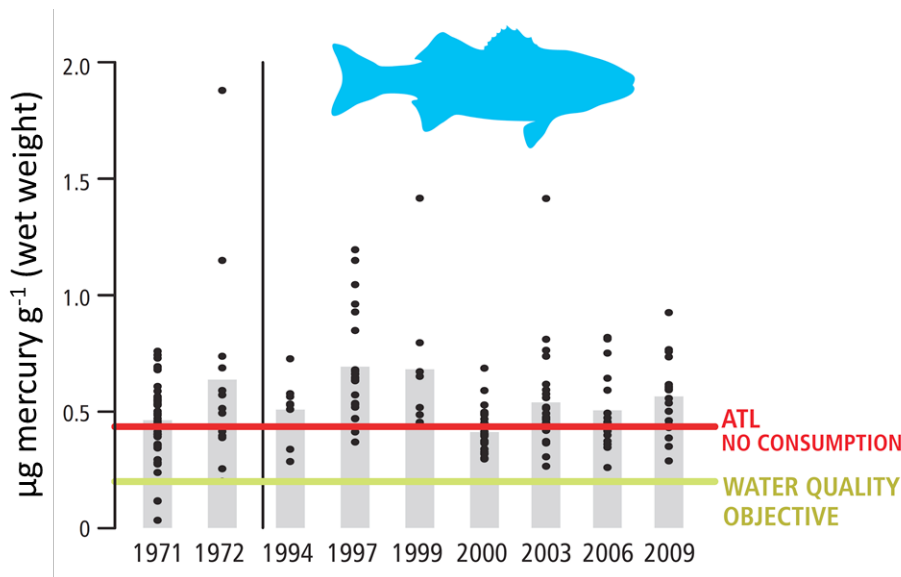
Figure 3 Mercury concentrations (µg g^{-1} wet weight) in striped bass from the Bay-Delta, 1971-2009. Bars indicate average concentrations. Points represent individual fish. Source: RMP (1994-2009) and California State Department of Public Health (1971-1972). "Advisory Tissue Level (ATL) No Consumption" is the Office of Environmental Health Hazard Assessment advisory tissue level of 0.44 µg g^{-1} calculated to protect women aged 18-45 years and children aged 1-17 years. Water quality objective for striped bass in the bay is 0.2 µg g^{-1}. To correct for variation in fish length, all plotted data have been calculated for a 60-cm fish using the residuals of a length vs. log(Hg) relationship.

Contaminants in Drinking Water

Contaminant effects on drinking water are very different from contaminant effects on the ecosystem because treated water complies with drinking water standards before its distribution. However, contaminants can affect the ability to meet standards, treatment requirements, aesthetic qualities of drinking water, water management programs, and drinking water provision costs. The Delta is an important source of drinking water for 25 million people in the San Francisco Bay area, Central Valley, and southern California. Priority drinking water quality issues described by Luoma et al. (2008) included salinity, bromide and natural organic matter, and remain important issues for Delta drinking water supplies. New drinking water regulations adopted or proposed by the USEPA and the SWRCB's Division of Drinking Water are driving additional monitoring and science needs for the Delta. Additional contaminants receiving attention include pathogens, cyanotoxins,

the world (*http://www.who.int/water_sanitation_health/bathing/srwe1-chap8.pdf?ua=1*).

PPCPs, and emerging disinfection by-products and their precursors.

Organic carbon reacts with drinking water treatment disinfectants to form carcinogenic byproducts, which are regulated at low levels to protect public health. Salinity affects the aesthetic qualities of drinking water and creates water-management challenges for blending, groundwater recharge, and water reuse. Bromide, a component of salinity, also contributes to the formation of carcinogenic disinfection byproducts during the water treatment process. Levels of these constituents in Delta water vary significantly because of hydrology and water project operations. Organic carbon concentrations increase during wet weather because of higher loading from stormwater, agricultural, forested land, or other runoff sources. An analysis of Delta water quality at Banks Pumping Plant in wet and dry years indicated that salinity and bromide concentrations were significantly higher in dry years, especially in the summer months (Archibald Consulting 2012) when seawater intrusion into the Delta is more pronounced (CDWR 2010). The recent severe drought (2012 to 2015) resulted in Delta water quality conditions that posed water

management and water-treatment challenges for drinking water agencies. Wei–Hsiang et al. (2010) evaluated the potential long-term changes in Delta water quality from sea level rise and levee failures of subsided western Delta islands, and found that under these long-term scenarios increases in salinity and bromide concentrations would significantly increase treatment costs for Delta water supplies.

Pathogens, such as *Cryptosporidium* spp. and *Giardia* spp., enter surface waters from animal and human sources, and can cause illness if consumed. Controlling the formation of disinfection by-products, from high concentrations of organic carbon and bromide in the source water, while implementing disinfection to inactivate pathogens, is an ongoing operational challenge for drinking water agencies that treat Delta water supplies. In recent years, the USEPA and SWRCB's Division of Drinking Water adopted more stringent drinking water regulations for disinfection by-products and pathogens, and the regulatory requirements are tied to concentrations of organic carbon and pathogens in the source water. Under these regulations, drinking water agencies are required to monitor their source water for *Cryptosporidium* to determine if more advanced treatment is needed to reduce pathogen levels in drinking water supplies.

In July 2013, the CVRWQCB adopted a new Drinking Water Policy for Surface Waters of the Sacramento–San Joaquin Delta and Upstream Tributaries (CVRWQCB 2013). The policy includes a narrative (i.e., non-numeric) water quality objective and monitoring requirements for *Cryptosporidium* and *Giardia*. The Delta Regional Monitoring Program (Delta RMP)[5] initiated a 2-year pathogen monitoring study in April 2015 to characterize ambient concentrations in the Delta concurrently with *Cryptosporidium* monitoring performed by drinking water agencies at their treatment plant intakes. The coordinated pathogen monitoring study is expected to characterize ambient background conditions and potential sources of pathogens in the Delta to fill an important data gap.

Cyanotoxin levels in the Delta are also a concern for drinking water, and cyanotoxins such as microcystin

and cylindrospermapsin in drinking water may require regulation. The USEPA has proposed to include cyanotoxins on the draft fourth Drinking Water Contaminant Candidate List (CCL 4) and as part of the Unregulated Contaminant Monitoring Rule. The purpose of these programs is to identify priority contaminants that need further study and regulation, and to require public water systems to monitor for suspected drinking water contaminants. In June 2015, to protect public health, the USEPA published non-regulatory Drinking Water Health Advisories for young children and adults that provide technical guidance on microcystin and cylindrospermopsin.

The California Department of Water Resources (CDWR) initiated microcystin monitoring in the SWP facilities in 2006. Between 2006 and 2012, dissolved microcystin was detected in 1% of samples, but in 2013, the CDWR changed laboratories and methods. The new method measures total microcystin, including the microcystin contained in cyanobacteria cells, resulting in more frequent detections at more locations and at higher concentrations. Consequently, microcystin has been frequently detected throughout the SWP at levels that exceed the health advisories. From July 2013 to August 2015, most samples from Clifton Court Forebay, in the south Delta, exceeded the microcystin health advisory that protects young children. Some drinking water treatment facilities can remove microcystin, but cyanotoxins are still a concern for drinking water supplies from the Delta.

Emerging water quality concerns for Delta drinking water supplies include PPCPs and additional disinfection byproducts of public health concern, such as nitrosamines, which may be human carcinogens. Guo et al. (2010) conducted a source, fate, and transport study of EDCs and PPCPs that included several sampling locations in the Delta. The six most frequently detected contaminants were carbamazepine, diuron, sulfamethoxazole, caffeine, primidone, and tris (2-chloroethyl) phosphate (TCEP), with the highest concentrations occurring at sites downstream of wastewater treatment plant discharges. The investigators concluded there is no evidence of human health risk from low levels of PPCPs detected; however, more toxicological studies are needed. Lee et al. (2015) conducted a monitoring study in the Delta to evaluate the presence and

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5   http://www.waterboards.ca.gov/centralvalley/water_issues/delta_water_quality/comprehensive_monitoring_program/index.shtml

source of N-nitrosodimethylamine (NDMA), other nitroamines, and their precursors. They found that wastewater treatment plants are an important source of NDMA precursors in the Delta, because they found higher levels of NDMA precursors downstream from the Sacramento Regional Wastewater Treatment Plant and the Stockton Regional Wastewater Control Facility. NDMA was not detected in river samples, likely because of dilution and photolysis.

In summary, contaminants continue to be detected in the Bay–Delta at concentrations that exceed regulatory standards, potentially causing detrimental effects. For example, mercury still occurs at levels that pose a risk to human health through consumption of contaminated fish, and Delta drinking water supplies are threatened by contaminant issues such as cyanotoxins, pharmaceuticals and personal care products, and new carcinogenic disinfection byproducts.

SCIENCE CHALLENGES, GAPS, AND RECOMMENDATIONS

Lacking the Right Monitoring Endpoints

Contaminant monitoring in the Bay–Delta, particularly in the Delta, falls short of answering priority questions to adequately inform water quality management. We cannot assume that reduced acute toxicity from one chemical or chemical class protects beneficial uses. Today's management questions are deeper and more far-reaching. Are contaminants delaying salmon from moving upstream when they need to? Are contaminants limiting productivity of nutritious fish food? And if so, is this constraining them to areas of greater risk for entrainment, predation, or other hazard? Are our control methods for aquatic vegetation and other invasive species affecting our primary productivity of the beneficial species? Managers need to consider multiple needs for multiple resources, and the cascading effects of contaminants. With more advanced monitoring, more integrative synthesis, and better input from multidisciplinary teams, resource managers will be better equipped with the information they need to make decisions.

Extensive water quality monitoring in the bay, has made it one of the most thoroughly-monitored estuaries in the world. The Bay RMP began monitoring in 1993, and has succeeded in its aims so well that funding has grown and been sustained. High quality monitoring data and special studies from the Bay RMP have guided dozens of important decisions about water quality management in the bay (Trowbridge et al. 2016). Monitoring has also provided an essential performance measure to evaluate the success of management decisions in meeting water quality goals. Collaborative governance by diverse interests allows the Bay RMP to optimize the use of funds, and to adapt to stay relevant as the ecosystem changes, new issues emerge, and knowledge advances.

A Delta RMP has been established and monitoring began in 2015. This program should be supported in becoming a long-term, robust, and comprehensive monitoring program that informs regulatory measures and management decisions.

More Spatial and Temporal Coverage

Better spatio-temporal coverage is critical to understand how water management changes can affect contaminant transport, fate, and effects. Monitoring for the Bay–Delta should include sites that are upstream and in back sloughs where more toxicity has been exhibited, rather than in larger channels (Werner et al. 2008; Werner et al. 2010b; Markiewicz et al. 2012). This will facilitate identification of toxicity and sources. Models like the Co-Occurrence Pesticide Species Tool (Hoogeweg et al. 2012) should be used to select monitoring stations where the greatest risk is posed by the likely co-occurrence of pesticides and sensitive species.

Fixed stations, like the CDWR monitoring station on the Sacramento River at Hood, should be installed in key areas to facilitate a combination of real-time physicochemical and flow-through biological monitoring. Such stations offer a more controllable test environment, thereby enhancing linkages between laboratory- and field-based study results. To better understand how instream chemical concentrations and abiotic stressors affect multiple species, methods from multiple disciplines spanning levels of biological hierarchy could be employed simultaneously (Biales et al. 2015).

Monitoring and assessment for Delta drinking water supplies should be expanded to include PPCPs and implemented at sufficient spatio-temporal scales to inform water management and drinking water treatment operations.

Time-series for mercury in Delta sport fish, based on repeated, directly comparable measurements, are needed for the rigorous characterization of long-term trends that would serve as a performance measure to evaluate the effectiveness of the Delta methylmercury TMDL.

Diversified Testing

Integrative toxicological studies using multiple species of diverse sensitivities, in conjunction with non-target chemical analyses, can be used to evaluate the ecological effects of contaminants, including unknown compounds. Simply monitoring for chemicals and comparing them to benchmarks of individual chemicals has proven inadequate to assess the ecological effects of contaminants (Bispo et al. 1999). Targeted chemical analyses have been shown to under-estimate mixture toxicity by a factor of two to ten compared to non-targeted analyses (Moschet et al. 2014). Employing non-targeted analyses could greatly advance the understanding of contaminant effects in the ecosystem by proactively assessing waters for new chemicals without limiting them to known compounds. Monitoring of contaminant presence should be paired with monitoring of effects on relevant species using sublethal effect endpoints. For example, the use of *Ceriodaphnia dubia* was appropriate in the past because they are sensitive to OPs and carbamates. However, *C. dubia* are relatively insensitive to several replacement insecticides; therefore, more appropriate species should be included to evaluate ecological effects. In a summary of toxicity tests from the Central Valley, researchers found that larval fish tests showed a higher frequency of toxicity than either invertebrates or algae, even though insecticides were determined to be the main cause of toxicity (Markiewicz et al. 2012). Had monitoring only included invertebrates, these sublethal effects on fish would have gone undetected.

To monitor surface waters, a comprehensive set of effect-based tools should be further developed that include important species, endpoints, and mechanisms of toxicity, and which consists of a combination of whole organism and *in vitro* tests. These effect-based assays are essential to address effects of low-level mixtures and unknown contaminants. In addition, biological assays can be tailored to comprehensively assess water quality by simultaneously evaluating contaminant effects on multiple modes of action (Escher et al. 2008, 2014). Environmental assessments should include techniques that are able to link physiological, biochemical, and molecular endpoints to organismal health condition. Although the association of sublethal effects and reproductive output has been demonstrated in non-native and surrogate species, analogous responses for threatened Bay–Delta species need to be confirmed. Sublethal effect concentration studies, particularly on early life stages of Bay–Delta species with contaminants of concern, should be performed.

More Synthesis, Analysis, and Use of Adaptive Management

Increased synthesis and analysis of monitoring data would allow for better trend analysis as well as improved assessment of ecosystem health. Past syntheses and analyses have been infrequent or incomplete because most Delta contaminant evaluations were special studies rather than systematic or comprehensive monitoring programs. Periodic events can go undetected by rigidly scheduled environmental monitoring (Brooks et al. 2012), thus monitoring needs to adapt to changing use patterns and be focused to identify risk to aquatic organisms. Regular analysis and synthesis are required to adaptively manage monitoring so management needs, and spatial and temporal variability, can be addressed.

Adaptive management has been successfully applied to contaminants. The successful reduction of PBDEs in the bay food web discussed above is an excellent example of adaptive management. In another example, a program was initiated in 1983 to address fish toxicity and drinking water taste and odor concerns associated with rice pesticides. By 2003, the Department of Food and Agriculture, Central Valley Regional Water Quality Control Board (CVRWQCB), the CDPR, County Agricultural Commissioners, and rice growers successfully worked together to identify management practices, water quality standards,

monitoring requirements and risk evaluations (e.g., use changes), and a communication and coordination mechanism to ensure that management practices would meet the performance goals and would not result in adverse effects on water quality.

Contaminants risks from past and present land use should be considered during planning and execution of habitat restoration efforts. With tens of thousands of acres of habitat restoration planned for the Delta and Suisun Marsh, those efforts could easily be confounded by contaminants. Many contaminants are sediment-bound, so sediment disturbance could cause resuspension and increased bioavailability. Additionally, repeated wetting and drying could increase risk over continual wetting (e.g., mercury methylation). Because wetlands are zones of deposition, sediment-bound contaminants will accumulate and may reduce the productivity and effectiveness of restoration efforts.

Robust planning, monitoring, analysis, reporting, and adjustments with cooperative participation and communication among regulators, industry, and other stakeholders can lead to reduced risk and improved water quality. Use of performance-based goals focused on contaminant effects alongside detection would better represent ecosystem health and function.

Integrate Efforts

Monitoring efforts of the Bay and Delta RMPs, the IEP's Environmental Monitoring Program (EMP), the CDWR's Municipal Water Quality Investigations (MWQIs), the SWRCB's Surface Water Ambient Monitoring Program (SWAMP), and the USGS's National Water Quality Assessment Program should be better integrated with each other and special studies. Their integration would not only make monitoring in the Delta more efficient, but it would facilitate multi-disciplinary evaluation of data across programs to allow for a better understanding of how water quality affects multiple levels of biological organization. Use of real-time monitoring data could provide in-depth information to interpret *in situ* testing results for multiple species at key sites, which would significantly enhance Bay–Delta monitoring efforts.

CHALLENGES

Managing Multiple Contaminants

A challenge is that the Water Quality Control Plan for the Sacramento and San Joaquin River Basins[6] calls for protection of water quality whether the toxicity is caused by a single substance or the interactive effect of multiple substances, yet control programs and regulatory tools have typically addressed single chemicals or classes of chemicals. The CVRWQCB Basin Plan addresses the need to consider cumulative effects, and the policy assumes potential additive toxicity when pollutants are known carcinogens, or manifest their toxic effects on the same organ systems or through similar mechanisms of action. However, the ability to evaluate such effects is limited by lack of sufficient data on mechanisms of action for many contaminants; therefore, chemical-specific criteria are often used, which are under-protective of aquatic populations. Chemical mixtures of compounds with unknown interactions, or those having no specific criteria, are not adequately addressed (Johnson et al. 2010; Brooks et al. 2012).

Consistent Resources

Resource managers need consistent financial support from state and federal entities to better address contaminants and water quality in the Bay–Delta. With all the gaps identified above, even with additional integration of existing programs, current contaminant monitoring programs and research are desperately underfunded.

CONCLUSION

Contaminant issues that were of concern in 2008 persist, and contaminants continue to be detected in ambient water samples at concentrations that cause detrimental effects. Enhanced monitoring in the Delta is a critical need. The limited, existing Delta contaminant monitoring is reactive—measuring what we know is of concern rather than proactively addressing new potential threats—while the use of pesticides, pharmaceuticals, and personal care products changes frequently, creating an ever-evolving cocktail of contaminants. Contaminants

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6 *http://www.waterboards.ca.gov/centralvalley/water_issues/basin_plans/*

thus do not occur as single compounds, but rather as mixtures that can interact additively, synergistically, and antagonistically with each other as well as with water quality parameters and food web processes, creating variable exposures and effects in time and space. The intertwined multiple-stressor effects of contaminants and their effects on Bay–Delta species requires a dedicated research program.

Contaminants likely played a significant role in the POD, but the specific role of contaminants in the health of the ecosystem will not be adequately understood until relationships are identified and tested through comprehensive studies that also relate the presence of contaminants to biological responses. Important Bay–Delta species are in decline, and their reduced abundance cannot be fully explained by other stressors. Direct effects on surrogate and important species range from decreased disease resistance and altered swimming behavior to lethality; and indirect effects are likely occurring through the food web. Multiple contaminants are detected in Bay–Delta waters, particularly in areas known to once support important species. Quantification of correlative relationships points to the need to include contaminant effects in ecosystem evaluations. The weight of evidence therefore suggests that numerous contaminants detected throughout the Bay–Delta have detrimentally affected the Bay–Delta ecosystem.

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