SAN FRANCISCO ESTUARY & WATERSHED SCIENCE
Sponsored by the Delta Science Program and the UC Davis John Muir Institute of the Environment

Title:

Contaminant Effects on California Bay–Delta Species and Human Health

Journal Issue:

San Francisco Estuary and Watershed Science, 14(4)

Author:

Fong, Stephanie, State and Federal Contractors Water Agency
Louie, Stephen, Water Branch, California Department of Fish and Wildlife
Werner, Inge, Swiss Centre for Applied Ecotoxicology
Davis, Jay, San Francisco Estuary Institute
Connon, Richard E., School of Veterinary Medicine, University of California, Davis

Publication Date:

2016

Permalink:

http://escholarship.org/uc/item/52m780xj

Acknowledgements:

We thank the Delta Science Program of the Delta Stewardship Council for inviting us to write this review, and their staff for providing helpful guidance in the process. We also appreciate the valuable perspectives provided by numerous contributors and rev

Local Identifier:

jmie_sfews_33448

Abstract:

doi: https://doi.org/10.15447/sfews.2016v14iss4art5

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.

Supporting material:

Appendix A: Potential Contribution of Pyrethroid Insecticides to the Pelagic Organism Decline

Copyright Information:

DECEMBER 2016

SAN FRANCISCO
ESTUARY & WATERSHED SCIENCE
Sponsored by the Delta Science Program and the UC Davis John Muir Institute of the Environment

SPECIAL ISSUE: THE STATE OF BAY–DELTA SCIENCE 2016, PART 3

Contaminant Effects on California Bay–Delta Species and Human Health

Stephanie Fong,[1] Stephen Louie,[2] Inge Werner,[3] Jay Davis,[4] and Richard E. Connon*[5]

Volume 14, Issue 4 | Article 5
doi: *http://dx.doi.org/10.15447/sfews.2016v14iss4art5*

- * Corresponding Author: *reconnon@ucdavis.edu*
1. State and Federal Contractors Water Agency
   Sacramento, CA 95814 USA
2. Water Branch, California Department of Fish and Wildlife
   Sacramento, CA 95811 USA
3. Swiss Centre for Applied Ecotoxicology
   Eawag–EPFL, 8600 Dübendorf, Switzerland
4. San Francisco Estuary Institute
   Richmond, CA 94804 USA
5. School of Veterinary Medicine, University of California, Davis
   Davis, CA 95616 USA

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:

---

[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-

---

[2] *http://www.waterboards.ca.gov/centralvalley/water_issues/tmdl/central_valley_projects/central_valley_pesticides/pyrethroid_tmdl_bpa/index.shtml*

http://dx.doi.org/10.15447/sfews.2016v14iss4art5

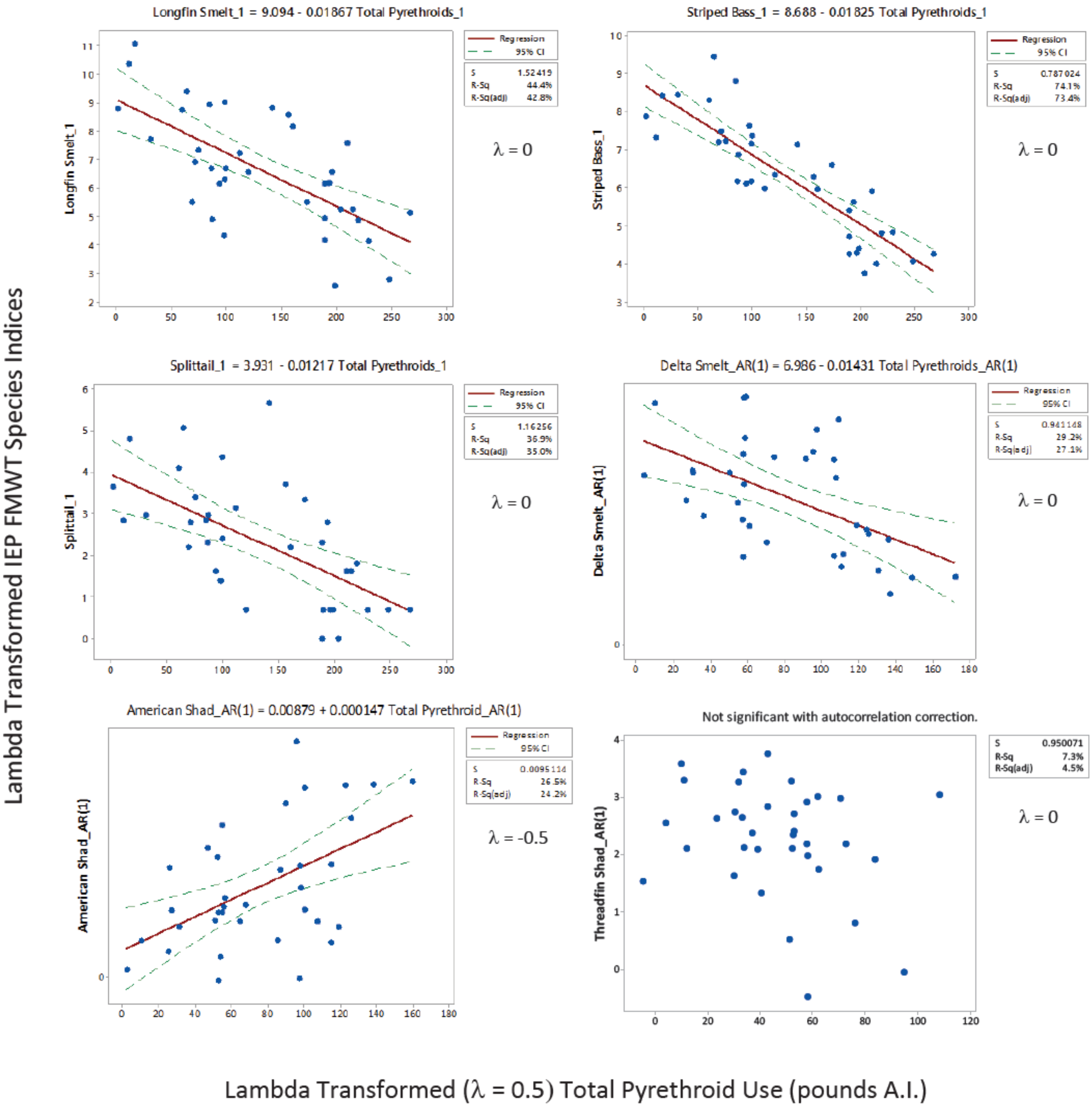

Figure 1 Ordinary least squares regression fitted line plots and 95% confidence intervals of IEP FMWT species abundance indices (autocorrelation corrected) as a function of annual pyrethroid pesticide use in the counties of the Delta from 1978–2014

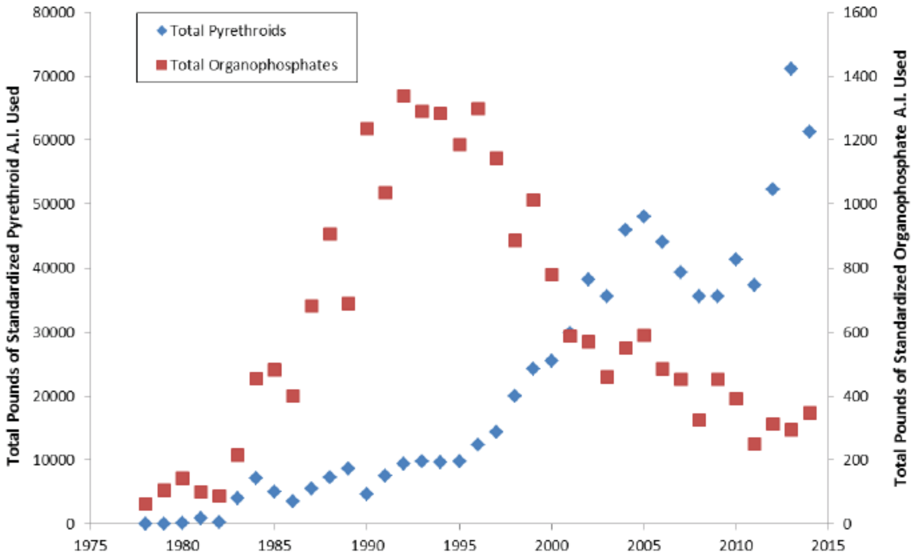

Figure 2 Plot displaying the total pounds of A.I. for pyrethroid use and organophosphate use in the counties of the Delta during 1978-2014 from the California DPR PUR database. The pounds of A.I. were standardized to the toxicity strength of the pesticides using conversion factors (see Appendix A, Table 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 pounds of pyrethroid pesticide use ($\lambda = 0.5$)					
		Pearson's *r*		Spearman's rho		Kendall's tau-a	
Transformed IEP FMWT abundance indices	**Lambda transformation**	**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 $4.8\ \mu g\ L^{-1}$. Dissolved copper concentrations up to 4.64 and $4.93\ \mu g\ L^{-1}$ 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 $58.9\ \mu g\ L^{-1}$ 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 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

---

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

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 ($0.5\,\text{ng L}^{-1}$) 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 ($11.3\,\mu\text{g–g}^{-1}$ 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 $1\,\mu\text{g g}^{-1}$ 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

---

[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

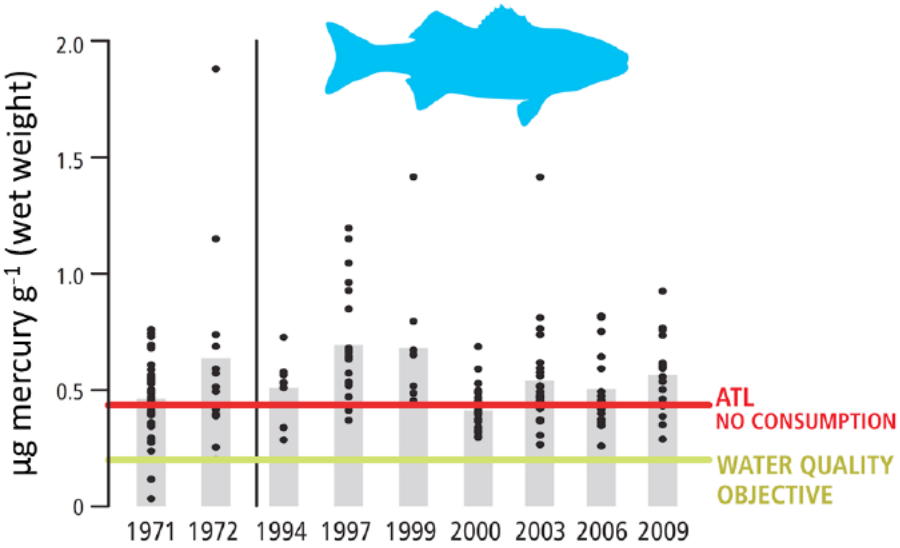

Figure 3 Mercury concentrations (µg g^{-1} wet weight) in striped bass from the Bay-Delta, 1971-2009. Bars indicate average concentrations. Points represent individual fish. Source: RMP (1994-2009) and California State Department of Public Health (1971-1972). "Advisory Tissue Level (ATL) No Consumption" 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.

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

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, 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

---

[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

---

[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.

ACKNOWLEDGMENTS

We thank the Delta Science Program of the Delta Stewardship Council for inviting us to write this review, and their staff for providing helpful guidance in the process. We also appreciate the valuable perspectives provided by numerous contributors and reviewers that made this review possible.

REFERENCES

Ackerman JT, Eagles–Smith CA, Heinz GH, De La Cruz SE, Takekawa JY, Miles AK, et al. 2014. Mercury in birds of San Francisco Bay–Delta, California—trophic pathways, bioaccumulation, and ecotoxicological risk to avian reproduction: U.S. Geological Survey Open-File Report 2014–1251. 202 p. doi: *http://dx.doi.org/10.3133/ofr20141251*

Acuña S, Baxa D, Teh S. 2012a. Sublethal dietary effects of microcystin producing *Microcystis* on threadfin shad, *Dorosoma petenense*. Toxicon 60:1191–202. doi: *http://dx.doi.org/10.1016/j.toxicon.2012.08.004*

Acuña S, Deng D–F, Lehman P, Teh S. 2012b. Sublethal dietary effects of *Microcystis* on Sacramento Splittail, *Pogonichthys macrolepidotus*. Aquat Toxicol 110–111:1-8. doi: *http://dx.doi.org/10.1016/j.aquatox.2011.12.004*

Amweg EL, Weston DP, Ureda NM. 2005. Use and toxicity of pyrethroid pesticides in the Central Valley, California, USA. Environ Toxicol Chem 24:966–72. doi: *http://onlinelibrary.wiley.com/doi/10.1897/04-146R1.1/abstract*

Archibald Consulting. 2012. California State Water Project watershed sanitary survey, 2011 update. [Internet]. [accessed 2015 October 24]. Palencia Consulting Engineers, Starr Consulting. Available from: *http://www.water.ca.gov/waterquality/drinkingwater/docs/Printerscopycombin.pdf*

Baginska B. 2015. Total maximum daily load selenium in north San Francisco Bay: staff report for Proposed Basin Plan Amendment. [Internet]. [accessed 2015 October 24]. Oakland (CA): San Francisco Bay Regional Water Quality Control Board. Available from: *http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/seleniumtmdl.shtml*

Bailey HC, Alexander C, DiGiorgio C, Miller MA, Doroshov SI, Hinton DE. 1994. The effect of agricultural discharge on striped bass (*Morone saxatilis*) in California's Sacramento–San Joaquin drainage. Ecotoxicology 3:123–142. doi: *http://link.springer.com/article/10.1007/BF00143410*

Baldwin DH, Spromberg JA, Collier TK, Scholz NL. 2009. A fish of many scales: extrapolating sublethal pesticide exposures to the productivity of wild salmon populations. Ecol Appl 19:2004–2015. doi: *http://onlinelibrary.wiley.com/doi/10.1890/08-1891.1/abstract;jsessionid=4F35FB27B9F04E403DB5B79472BA9D41.f02t04*

Baxter R, Breuer R, Brown L, Conrad L, Feyrer F, Fong S, et al. 2010. Interagency Ecological Program 2010 Pelagic Organism Decline workplan and synthesis of results. [Internet]. [accessed 2015 October 24]. Available from: *http://www.water.ca.gov/iep/docs/FinalPOD2010Workplan12610.pdf*

Beggel S, Werner I, Connon RE, Geist JP. 2010. Sublethal toxicity of commercial insecticide formulations and their active ingredients to larval fathead minnow (*Pimephales promelas*). Sci Tot Environ 408:3169–75. doi: *http://www.ncbi.nlm.nih.gov/pubmed/20434756*

Beggel S, Werner I, Connon RE, Geist JP. 2012. Impacts of the phenylpyrazole insecticide fipronil on larval fish: time-series gene transcription responses in fathead minnow (*Pimephales promelas*) following short-term exposure. Sci Tot Environ 426:160–165. doi: *http://www.ncbi.nlm.nih.gov/pubmed/22542256*

Biales AD, Denton DL, Riordan D, Breuer R, Batt AL, Crane DB, et al. 2015. Complex watersheds, collaborative teams: Assessing pollutant presence and effects in the San Francisco Delta. Integr Environ Assess Manag 11:674–88. doi: *http://onlinelibrary.wiley.com/doi/10.1002/ieam.1633/abstract*

Bispo A, Jourdain MJ, Jauzein M. 1999. Toxicity and genotoxicity of industrial soils polluted by polycyclic aromatic hydrocarbons (PAHs). Org Geochem 30:947–952. doi: *http://dx.doi.org/10.1016/S0146-6380(99)00078-9*

Blanchard J, Grosell M. 2006. Copper toxicity across salinities from freshwater to seawater in the euryhaline fish *Fundulus heteroclitus*: is copper an ionoregulatory toxicant in high salinities? Aquat Toxicol 80:131–9. doi: *http://www.sciencedirect.com/science/article/pii/S0166445X06003225*

Blaser S, Parker A, Wilkerson F. 2011. Diuron and imazapyr herbicides impact estuarine phytoplankton carbon assimilation: evidence from an experimental study. [Internet]. [accessed 2015 October 24]. IEP Newsletter 24:3–11. Available from: *http://www.water.ca.gov/iep/newsletters/2011/IEPNewsletterFinalSummer2011.pdf*

Bortone SA, Davis WP. 1994. Fish intersexuality as indicator of environmental stress. Bioscience 165–172 p. doi: *https://www.jstor.org/stable/1312253?seq=1#page_scan_tab_contents*

Brander SM, Connon RE, He G, Hobbs JA, Smalling KL, Teh SJ, et al. 2013. From 'omics to otoliths: responses of an estuarine fish to endocrine disrupting compounds across biological scales. PLOS One 8:e74251. doi: *http://www.ncbi.nlm.nih.gov/pubmed/24086325*

Brander SM, Gabler MK, Fowler NL, Connon RE, Schlenk D. 2016a. Pyrethroid pesticides as endocrine disruptors: molecular mechanisms in vertebrates with a focus on fishes. Environ Sci Technol 50:8977–92. doi: *http://pubs.acs.org/doi/abs/10.1021/acs.est.6b02253*

Brander SM, Jeffries KM, Cole BJ, DeCourten BM, White JW, Hasenbein S, et al. 2016b. Transcriptomic changes underlie altered egg protein production and reduced fecundity in an estuarine model fish exposed to bifenthrin. Aquat Toxicol 174:247–60. doi: *http://www.ncbi.nlm.nih.gov/pubmed/26975043*

Brooks ML, Fleishman E, Brown LR, Lehman PW, Werner I, Scholz N, et al. 2012. Life histories, salinity zones, and sublethal contributions of contaminants to pelagic fish declines illustrated with a case study of San Francisco Estuary, California, USA. Estuaries Coasts 35:603-621. doi: *http://link.springer.com/article/10.1007/s12237-011-9459-6*

Brown LR, Baxter R, Castillo G, Conrad L, Culberson S, Erickson G, Feyrer F, Fong S, Gehrts K, Grimaldo L, et al. 2014. Synthesis of studies in the fall low-salinity zone of the San Francisco Estuary, September–December 2011. U.S. Geological Survey Scientific Investigations Report 2014–5041. doi: *https://pubs.er.usgs.gov/publication/sir20145041*

Brown LR, Kimmerer W, Conrad JL, Lesmeister S, Mueller–Solger A. 2016. Food webs of the Delta, Suisun Bay, and Suisun Marsh: an update on current understanding and possibilities for management. San Franc Estuary Watershed Sci 14(3). doi: *http://dx.doi.org/10.15447/sfews.2016v14iss3art4*

Brozinski JM, Lahti M, Meierjohann A, Oikari A, Kronberg L. 2013. The anti-inflammatory drugs diclofenac, naproxen and ibuprofen are found in the bile of wild fish caught downstream of a wastewater treatment plant. Environ Sci Technol. 47:342–8. doi: *http://pubs.acs.org/doi/abs/10.1021/es303013j*

Callinan–Hoffmann K, Deanovic LA, Stillway M, Teh SJ. 2012. The toxicity and interactions among common aquatic contaminants in binary mixtures. [Internet]. [accessed 2015 October 24]. Sacramento (CA): State Water Resources Control Board. 63 p. Available from: *http://www.waterboards.ca.gov/centralvalley/water_issues/swamp/sacramento_sanjoaquin_river_delta/mixtures_rpt.pdf*

Carey CC, Ibelings BW, Hoffmann EP, Hamilton DP, Brookes JD. 2012. Eco-physiological adaptations that favour freshwater cyanobacteria in a changing climate. Water Res 46:1394–1407. doi: *http://dx.doi.org/10.1016/j.watres.2011.12.016*

Carvalho RN, Arukwe A, Ait-Aissa S, Bado-Nilles A, Balzamo S, Baun A, et al. 2014. Mixtures of chemical pollutants at European legislation safety concentrations: how safe are they? Toxicol Sci 141:218–33. doi: *http://toxsci.oxfordjournals.org/content/early/2014/06/23/toxsci.kfu118.short*

Cedergreen N. 2014. Quantifying synergy: a systematic review of mixture toxicity studies within environmental toxicology. PLoS ONE 9:e96580. doi: *http://dx.doi.org/10.1371%2Fjournal.pone.0096580*

Chen L, Meseck SL, Roy SB, Grieb TM, Baginska B. 2012. Modeling fate, transport, and biological uptake of selenium in North San Francisco Bay. Estuaries Coasts 35:1551–1570. doi: *http://dx.doi.org/10.1007/s12237-012-9530-y*

Cole BJ, Brander SM, Jeffries KM, Hasenbein S, He G, Denison MS, et al. 2016. Changes in *Menidia beryllina* gene expression and in vitro hormone-receptor activation after exposure to estuarine waters near treated wastewater outfalls. Arch Environ Contam Toxicol 71(2):210–233. doi: *http://dx.doi.org/10.1007/s00244-016-0282-8*

Connon RE, Beggel S, D'Abronzo LS, Geist JP, Pfeiff J, Loguinov AV, et al. 2011a. Linking molecular biomarkers with higher level condition indicators to identify effects of copper exposures on the endangered delta smelt (*Hypomesus transpacificus*). Environ Toxicol Chem 30:290–300. doi: *http://dx.doi.org/10.1002/etc.400*

Connon RE, Deanovic LA, Fritsch EB, D'Abronzo LS, Werner I. 2011b. Sublethal responses to ammonia exposure in the endangered Delta Smelt; *Hypomesus transpacificus* (Fam. Osmeridae). Aquat Toxicol 105(3–4):369–77. doi: *http://dx.doi.org/10.1016/j.aquatox.2011.07.002*

Connon RE, Geist J, Pfeiff J, Loguinov AV, D'Abronzo LS, Wintz H, et al. 2009. Linking mechanistic and behavioral responses to sublethal esfenvalerate exposure in the endangered Delta Smelt; *Hypomesus transpacificus* (Fam. Osmeridae). BMC Genomics 10:608. doi: *http://dx.doi.org/10.1186/1471-2164-10-608*

Connon RE, Hasenbein M, Fritsch EB, Javidmehr A, Deanovic LA, Werner I. 2012. Refinement and application of novel molecular and biochemical biomarkers to determine sublethal contaminant exposure and effects in archived Delta Smelt samples. [Internet]. [accessed 2015 October 24]. Available from: *http://www.dfg.ca.gov/erp/biomarkers_planning.asp*

[CVRWQCB] Central Valley Regional Water Quality Control Board. 2013. Amendment to the water quality control plan for the Sacramento River and San Joaquin River basins to establish a drinking water policy for surface waters of the Sacramento–San Joaquin Delta and upstream tributaries. [Internet]. [accessed 2015 October 24]. Available from: *http://www.waterboards.ca.gov/centralvalley/water_issues/drinking_water_policy/final_stfrpt.pdf*

Davis JA, Greenfield BK, Ichikawa G, Stephenson M. 2008. Mercury in sport fish from the Sacramento–San Joaquin Delta region, California, USA. Sci Total Environ 391:66–75. Available from: *http://islandora.mlml.calstate.edu/islandora/object/ir%3A1076*

Davis JA, Looker RE, Yee D, Marvin-Di Pasquale M, Grenier JL, Austin CM, et al. 2012. Reducing methylmercury accumulation in the food webs of San Francisco Bay and its local watersheds. Environ Res 119:3–26. doi: *http://dx.doi.org/10.1016/j.envres.2012.10.002*

Davis JA, May MD, Ichikawa G, Crane D. 2000. Contaminant concentrations in fish from the Sacramento–San Joaquin Delta and Lower San Joaquin River, 1998. [Internet]. [accessed 2015 October 24]. Richmond (CA): San Francisco Estuary Institute. Available from: *http://www.waterboards.ca.gov/water_issues/programs/tmdl/records/region_5/2003/ref1219.pdf*

Davis JA, Ross JRM, Bezalel SN, Hunt JA, Ichikawa G, Bonnema A, et al. 2013. Contaminants in fish from california rivers and streams, 2011. A report of the surface water ambient monitoring program (SWAMP). [Internet]. [accessed 2015 October 24]. Sacramento (CA): State Water Resources Control Board. Available from: *http://www.waterboards.ca.gov/water_issues/programs/swamp/docs/rivers_study/rs_rptonly.pdf* de Vlaming V, Norberg–King TJ. 2000. A review of single species toxicity tests: are the tests reliable predictors of aquatic ecosystem community responses? [Internet]. [accessed 2015 October 24]. Washington, D.C.: U.S. Environmental Protection Agency. Available from: *https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=63192*

DeGroot BC, Brander SM. 2014. The role of P450 metabolism in the estrogenic activity of bifenthrin in fish. Aquat Toxicol 156:17–20. doi: *http://dx.doi.org/10.1016/j.aquatox.2014.07.007*

Deng DF, Hung SS, Teh SJ. 2007. Selenium depuration: residual effects of dietary selenium on Sacramento Splittail (*Pogonichthys macrolepidotus*). Sci Tot Environ 377:224–32. doi: *http://dx.doi.org/10.1016/j.scitotenv.2007.02.025*

Durieux ED, Connon RE, Werner I, D'Abronzo LS, Fitzgerald PS, Spearow JL, et al. 2012. Cytochrome P4501A mRNA and protein induction in striped bass (*Morone saxatilis*). Fish Physiol Biochem 38:1107–16. doi: *http://dx.doi.org/10.1007/s10695-011-9597-6*

[CDWR] California Department of Water Resources. 2010. The Municipal Water Quality Investigations Program: summary and findings of data collected from the Sacramento–San Joaquin Delta region, October 2007 – September 2009. [Internet]. [accessed 2015 October 24]. Available from: *http://www.water.ca.gov/waterquality/drinkingwater/docs/discrete_reports/the_municipal_water_quality_investigations_program_summary_and_findings_of_data_collected_from_the_sacramento-san_joaquin_delta_region,_october_2007-september_2009.pdf*

Eder KJ, Clifford MA, Hedrick RP, Kohler HR, Werner I. 2008. Expression of immune-regulatory genes in juvenile Chinook salmon following exposure to pesticides and infectious hematopoietic necrosis virus (IHNV). Fish Shellfish Immunol 25:508–16. doi: *http://www.ncbi.nlm.nih.gov/pubmed/18691654*

Ensminger MP, Budd R, Kelley KC, Goh KS. 2013. Pesticide occurrence and aquatic benchmark exceedances in urban surface waters and sediments in three urban areas of California, USA, 2008–2011. Environ Monit Assess 185:3697–710. doi: *http://link.springer.com/article/10.1007/s10661-012-2821-8*

Escher BI, Allinson M, Altenburger R, Bain PA, Balaguer P, Busch W, et al. 2014. Benchmarking organic micropollutants in wastewater, recycled water and drinking water with in vitro bioassays. Environ Sci Technol 48:1940–56. doi: *http://pubs.acs.org/doi/abs/10.1021/es403899t*

Escher BI, Bramaz N, Quayle P, Rutishauser S, Vermeirssen EL. 2008. Monitoring of the ecotoxicological hazard potential by polar organic micropollutants in sewage treatment plants and surface waters using a mode-of-action based test battery. J Environ Monit 10:622–31. doi: *http://pubs.rsc.org/en/content/articlehtml/2008/em/b800951a*

Feist BE, Buhle ER, Arnold P, Davis JW, Scholz NL. 2011. Landscape ecotoxicology of Coho Salmon spawner mortality in urban streams. PLoS ONE. 6:e23424. doi: *http://dx.doi.org/10.1371/journal.pone.0023424*

Fent K, Weston AA, Caminada D. 2006. Ecotoxicology of human pharmaceuticals. Aquat Toxicol 76:122–159. doi: *http://dx.doi.org/10.1016/j.aquatox.2005.09.009*

Feyrer F, Herbold B, Matern SA, Moyle PB. 2003. Dietary shifts in a stressed fish assemblage: consequences of a bivalve invasion in the San Francisco Estuary. Environ Biol Fish 67:277–288. doi: *http://dx.doi.org/10.1023/A:1025839132274*

Fleeger JW, Carman KR, Nisbet RM. 2003. Indirect effects of contaminants in aquatic ecosystems. S ci Tot Environ 317:207–233. doi: *http://dx.doi.org/10.1016/S0048-9697(03)00141-4*

Forsgren KL, Riar N, Schlenk D. 2013. The effects of the pyrethroid insecticide, bifenthrin, on steroid hormone levels and gonadal development of steelhead (*Oncorhynchus mykiss*) under hypersaline conditions. Gen Comp Endocrinol 186:101–7. doi: *http://www.ncbi.nlm.nih.gov/pubmed/23518481*

Fritsch EB, Connon RE, Werner I, Davies RE, Beggel S, Feng W, Pessah IN. 2013. Triclosan impairs swimming behavior and alters expression of excitation-contraction coupling proteins in fathead minnow (*Pimephales promelas*). Environ Sci Technol 47:2008–17. doi: *http://www.ncbi.nlm.nih.gov/pubmed/23305567*

Gassel M, Brodberg R, Klasing SLC. 2011. Health advisory and safe eating guidelines for San Francisco Bay fish and shellfish. [Internet]. [accessed 2015 October 24]. Sacramento (CA): California Office of Environmental Health Hazard Assessment. Available from: *http://oehha.ca.gov/media/downloads/advisories/sfbayadvisory21may2011.pdf*

Gassel M, Brodberg RK, Klasing S, Roberts S. 2007. Draft safe eating guidelines for fish and shellfish from the San Joaquin River and South Delta (Contra Costa, San Joaquin, Stanislaus, Merced, Madera, and Fresno counties). [Internet]. [accessed 2015 October 24]. Sacramento (CA): California Office of Environmental Health Hazard Assessment. Available from: *http://oehha.ca.gov/fish/pdf/SJRSD030907part1.pdf*

Gehringer DB, Finkelstein ME, Coale KH, Stephenson M, Geller JB. 2012. Assessing mercury exposure and biomarkers in Largemouth Bass (*Micropterus salmoides*) from a contaminated river system in California. Arch Environ Contam Toxicol 64:484–493. doi: *http://dx.doi.org/10.1007/s00244-012-9838-4*

Geist J, Werner I, Eder KJ, Leutenegger CM. 2007. Comparisons of tissue-specific transcription of stress response genes with whole animal endpoints of adverse effect in striped bass (*Morone saxatilis*) following treatment with copper and esfenvalerate. Aquat Toxicol 85:28–39. doi: *http://www.ncbi.nlm.nih.gov/pubmed/17767966*

Grayson KL, Mitchell NJ, Monks JM, Keall SN, Wilson JN, Nelson NJ. 2014. Sex ratio bias and extinction risk in an isolated population of Tuatara (*Sphenodon punctatus*). PLoS ONE. 9: e94214. doi: *http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3979778/*

Grosell M, Nielsen C, Bianchini A. 2002. Sodium turnover rate determines sensitivity to acute copper and silver exposure in freshwater animals. Comp Biochem Physiol C Toxicol Pharmacol 133:287–303. doi: *https://www.ncbi.nlm.nih.gov/pubmed/12356534*

Grossman GD. 2016. Predation on fishes in the Sacramento–San Joaquin Delta: current knowledge and future directions. San Franc Estuary Watershed Sci 14(2). doi: *http://dx.doi.org/10.15447/sfews.2016v14iss2art8*

Grothe KLDDKR–J. 1996. Whole effluent toxicity testing: an evaluation of methods and prediction of receiving system impacts. Pensacola (FL): SETAC Press.

Guo YC, Krasner SW, Fitzsimmons S, Woodside G, Yamachika N. 2010. Source, fate and transport of endocrine disruptors, pharmaceuticals and personal care products in drinking water sources in California. [Internet]. [accessed 2015 October 24]. Fountain Valley (CA): Natural Water Research Institute. Available from: *http://www.nwri-usa.org/CECs.htm*

Hammock BG, Hobbs JA, Slater SB, Acuña S, Teh SJ. 2015. Contaminant and food limitation stress in an endangered estuarine fish. Sci Tot Environ 532:316–326. doi: *http://dx.doi.org/10.1016/j.scitotenv.2015.06.018*

Hasenbein M, Werner I, Deanovic LA, Geist J, Fritsch EB, Javidmehr A, et al. 2014. Transcriptomic profiling permits the identification of pollutant sources and effects in ambient water samples. Sci Tot Environ 468–469:688–98. doi: *http://dx.doi.org/10.1016/j.scitotenv.2013.08.081*

Hasenbein S, Connon RE, Lawler SP, Geist J. 2015a. A comparison of the sublethal and lethal toxicity of four pesticides in *Hyalella azteca* and *Chironomus dilutus*. Environ Sci Pollut Res Int 22(15):11327–39. doi: *http://dx.doi.org/10.1007/s11356-015-4374-1*

Hasenbein S, Lawler SP, Geist J, Connon RE. 2015b. The use of growth and behavioral endpoints to assess the effects of pesticide mixtures upon aquatic organisms. Ecotoxicology 24(4):746–59. doi: *http://dx.doi.org/10.1007/s10646-015-1420-1*

Hasenbein S, Lawler SP, Gesist J, Connon RE. 2015c. A long-term assessment of pesticide mixture effects on aquatic invertebrate communities. Environ Toxicol Chem 35:218–232. doi: *http://onlinelibrary.wiley.com/doi/10.1002/etc.3187/full*

Hénault-Ethier L. 2015. Health and environmental impacts of pyrethroid insecticides: what we know, what we don't know and what we should do about it. Executive summary and scientific literature review. **In:** Équiterre, Montreal, Canada. 68 p. doi: *http://www.equiterre.org/publication/revue-delitteraturesur-les-impacts-des-insecticides-pyrethrinoides-sur-la-sante-et-len*

Hennessy A. 2011. Zooplankton monitoring 2010. [Internet]. [accessed 2015 October 24]. IEP Newsletter 24:20–27. doi: *http://www.water.ca.gov/iep/newsletters/2011/IEPNewsletterFinalSping2011.pdf*

Holmes RW, Anderson BS, Phillips BM, Hunt JW, Crane DB, Mekebri A, et al. 2008. Statewide investigation of the role of pyrethroid pesticides in sediment toxicity in California's urban waterways. Environ Sci Technol 42:7003–9. doi: *http://www.ncbi.nlm.nih.gov/pubmed/18853823*

Hoogeweg CG, Denton DL, Breuer R, Williams WM, TenBrook P. 2012. Development of a Spatial-temporal co-occurrence index to evaluate relative pesticide risks to threatened and endangered species. Pesticide Regulation and the Endangered Species Act. 1111. American Chemical Society. p 303–323. doi: *http://dx.doi.org/10.1021/bk-2012-1111.ch022*

Ibelings BW, Havens KE. 2008. Cyanobacterial toxins: a qualitative meta-analysis of concentrations, dosage and effects in freshwater, estuarine and marine biota. Adv Exp Med Biol 619: 675-732. doi: *http://dx.doi.org/10.1007/978-0-387-75865-7_32*

[IEP MAST] Interagency Ecological Program, Management, Analysis, and Synthesis Team. 2015. An updated conceptual model of Delta Smelt biology: our evolving understanding of an estuarine fish. [Internet]. [accessed 2015 October 24]. IEP Technical Report 90. Sacramento (CA): IEP. Available from: *http://www.water.ca.gov/iep/docs/Delta_Smelt_MAST_Synthesis_Report_January%20 2015.pdf*

Jassby AD, Cloern JE, Müller-Solger A. 2003. Phytoplankton fuels Delta food web. Cal Agric 57:104-109. doi: *http://dx.doi.org/10.3733/ca.v057n04p104*

Jeffries KM, Brander SM, Britton MT, Fangue NA, Connon RE. 2015a. Chronic exposures to low and high concentrations of ibuprofen elicit different gene response patterns in a euryhaline fish. Environ Sci Pollut 22(22):17397-413. doi: *http://dx.doi.org/10.1007/s11356-015-4227-y*

Jeffries KM, Komoroske LM, Truong J, Werner I, Hasenbein M, Hasenbein S, et al. 2015b. The transcriptome-wide effects of exposure to a pyrethroid pesticide on the critically endangered Delta Smelt *Hypomesus transpacificus*. Endanger Species Res 28:43-60. doi: *http://dx.doi.org/10.3354/esr00679*

Jiang W, Luo Y, Conkle JL, Li J, Gan J. 2016. Pesticides on residential outdoor surfaces: environmental impacts and aquatic toxicity. Pest Manag Sci 72:1411-1420. doi: *http://dx.doi.org/10.1002/ps.4168*

Johnson ML, Werner I, Teh SJ, Loge F. 2010. Evaluation of chemical, toxicological, and histopathologic data to determine their role in the pelagic organism decline. [Internet]. [accessed 2015 October 24]. Final report to the California State Water Resources Control Board and Central Valley Regional Water Quality Control Board. University of California, Davis. Available from: *http://www.water.ca.gov/iep/docs/contaminant_synthesis_report.pdf*

Johnston EL, Roberts DA. 2009. Contaminants reduce the richness and evenness of marine communities: a review and meta-analysis. Environ Pollut 157:1745-52. doi: *http://dx.doi.org/10.1016/j.envpol.2009.02.017*

Jorgenson B, Fleishman E, Macneale KH, Schlenk D, Scholz NL, Spromberg JA, et al. 2013. Predicted transport of pyrethroid insecticides from an urban landscape to surface water. Env Toxicol Chem 32:2469-2477. doi: *http://dx.doi.org/10.1002/etc.2352*

Kuivila KM, Hladik ML. 2008. Understanding the occurrence and transport of current-use pesticide in the San Francisco Estuary Watershed. San Franc Estuary Watershed Sci 6(3). doi: *http://dx.doi.org/10.15447/sfews.2008v6iss3art2*

Kurobe T, Baxa DV, Mioni CE, Kudela RM, Smythe TR, Waller S, et al. 2013. Identification of harmful cyanobacteria in the Sacramento-San Joaquin Delta and Clear Lake, California by DNA barcoding. Springer Plus 2:491. doi: *http://dx.doi.org/10.1186/2193-1801-2-491*

Lee C-FT, Krasner SW, Sclimenti MJ, Prescott M, Guo YC. 2015. Nitrosamine precursors and wastewater indicators in discharges in the Sacramento-San Joaquin Delta. Chapter 7 In: Karanfil T, Mitch B, Westerhoff P, Xie Y, editors. Recent advances in disinfection by-products. American Chemical Society Symposium Series 1190. p. 119-133. doi: *http://dx.doi.org/10.1021/bk-2015-1190.ch007*

Lehman PW, Marr K, Boyer GL, Acuna S, Teh SJ. 2013. Long-term trends and causal factors associated with *Microcystis* abundance and toxicity in San Francisco Estuary and implications for climate change impacts. Hydrobiologia 718:141-158. doi: *http://dx.doi.org/10.1007/s10750-013-1612-8*

Linares-Casenave J, Linville R, Van Eenennaam JP, Muguet JB, Doroshov SI. 2015. Selenium tissue burden compartmentalization in resident White Sturgeon (*Acipenser transmontanus*) of the San Francisco Bay Delta estuary. Environ Toxicol Chem 34:152-60. doi: *http://dx.doi.org/10.1002/etc.2775*

Luo Y, Ensminger M, Budd R, Deng X, DaSilva A. 2014. Methodology for prioritizing pesticides for surface water monitoring in agricultural and urban areas II: refined priority list. Sacramento (CA): Department of Pesticide Regulation. Available from: *http://www.cdpr.ca.gov/docs/emon/pubs/ehapreps/analysis_memos/prioritization_report_2.pdf*

Luoma SN, Anderson SA, Bergamaschi B, Holm L, Ruhl C, Schoellhamer DH, et al. 2008. Chapter 3: water quality. In: Healey MC, Dettinger MD, Norgaard RB, editors. The State of Bay–Delta Science 2008. Sacramento (CA): CALFED Science Program. p. 55-72. Available from: *http://www.science.calwater.ca.gov/pdf/publications/sbds/sbds_final_update_122408.pdf*

Luoma SN, Dahm CN, Healey M, Moore JN. 2015. Challenges Facing the Sacramento–San Joaquin Delta: Complex, Chaotic, or Simply Cantankerous? San Franc Estuary Watershed Sci 13(3). doi: *http://dx.doi.org/10.15447/sfews.2015v13iss3art7*

Markiewicz D, Stillway M, Teh S. 2012. Toxicity in California Waters: Central Valley Region. In. Central Vally Regionat Water Quality Control Board: Surface Water Ambient Monitoring Program. 38 p. Available from: *http://www.waterboards.ca.gov/water_issues/programs/swamp/docs/reglrpts/rb5_toxicity_2012.pdf*

Maryoung LA, Blunt B, Tierney KB, Schlenk D. 2015. Sublethal toxicity of chlorpyrifos to salmonid olfaction after hypersaline acclimation. Aquat Toxicol 161:94-101. doi: *http://dx.doi.org/10.1016/j.aquatox.2015.01.026*

Melwani AR, Bezalel SN, Hunt JL, Grenier JL, Ichikawa G, Heim WA, et al. 2009. Spatial trends and impairment assessment of mercury in sport fish in the Sacramento–San Joaquin Delta watershed. Environ Poll 157:3137-3149. doi: *http://dx.doi.org/10.1016/j.envpol.2009.05.013*

Miller MA, Kudela RM, Mekebri A, Crane D, Oates SC, Tinker MT, et al. 2010. Evidence for a novel marine harmful algal bloom: cyanotoxin (microcystin) transfer from land to sea otters. PLoS One 5. doi: *http://dx.doi.org/10.1371/journal.pone.0012576*

Moore A, Waring CP. 2001. The effects of a synthetic pyrethroid pesticide on some aspects of reproduction in Atlantic salmon (*Salmo salar L.*). Aquat Toxicol 52:1-12. doi: *http://dx.doi.org/10.1016/S0166-445X(00)00133-8*

Moschet C, Wittmer I, Simovic J, Junghans M, Piazzoli A, Singer H, et al. 2014. How a complete pesticide screening changes the assessment of surface water quality. Env Sci Technol 48:5423-5432. doi: *http://dx.doi.org/10.1021/es500371t*

Mount J, Bennet W, Durand J, Fleenor W, Hanak E, Lund JR, et al. 2012. Aquatic ecosystem stressors in the Sacramento–San Joaquin Delta. San Francisco (CA): Public Policy Institute of California. 22 p. Available from: *http://www.ppic.org/content/pubs/report/R_612JMR.pdf*

Moyle PB, Brown LR, Durand JR, Hobbs JA. 2016. Delta Smelt: life history and decline of a once-abundant species in the San Francisco Estuary. San Franc Estuary Watershed Sci 14(2). doi: *http://dx.doi.org/10.15447/sfews.2016v14iss2art6*

Muggelberg LL, Huff Hartz KE, Nutile SA, Harwood AD, Heim JR, Derby AP, et al. 2016. Do pyrethroid-resistant *Hyalella azteca* have greater bioaccumulation potential compared to non-resistant populations? Implications for bioaccumulation in fish. Environ Pollut doi: *http://dx.doi.org/10.1016/j.envpol.2016.09.073*

[NMFS] National Marine Fisheries Service. 2009. NMFS endangered species act section 7 consultation: EPA registration of pesticides containing carbaryl, carbofuran, and methomyl. Biological opinion. Silver Spring (MD): U.S. Department of Commerce. 609 p. doi: *http://www.nmfs.noaa.gov/pr/pdfs/carbamate.pdf*

[NRC] National Research Council of the Academy of Sciences. 2013. Assessing risks to endangered and threatened species from pesticides. Washington, D.C.: NRC. doi: *http://dx.doi.org/10.17226/18344*

Orlando JL, McWayne M, Sanders C, Hladik ML. 2014. Dissolved pesticide concentrations entering the Sacramento–San Joaquin Delta from the Sacramento and San Joaquin rivers, California, 2012–13. U.S. Geological Survey Data Series 28. doi: *http://dx.doi.org/10.3133/ds876*

Orlando JL, Smalling KL, Reilly TJ, Fishman NS, Boehlke A, Meyer MT, et al. 2013. Occurrence of fungicides and other pesticides in surface water, groundwater, and sediment from three targeted-use areas in the United States, 2009. U.S. Geological Survey Data Series. 797:73. doi: *http://dx.doi.org/10.3133/ds2013797*

Orlinskiy P, Munze R, Beketov M, Gunold R, Paschke A, Knillmann S, et al. 2015. Forested headwaters mitigate pesticide effects on macroinvertebrate communities in streams: Mechanisms and quantification. Sci Total Environ 524-525:115-23. doi: *http://dx.doi.org/10.1016/j.scitotenv.2015.03.143*

Oros D, Werner I. 2005. Pyrethroid insecticides: an analysis of use patterns, distributions, potential toxicity and fate in the Sacramento-San Joaquin Delta and Central Valley. [Internet]. [accessed 2015 October 24]. White paper for the Interagency Ecological Program. SFEI Contribution 415. Oakland (CA): San Francisco Estuary Institute. Available from: *http://www.water.ca.gov/iep/docs/pod/Pyrethroids_White_Paper_Final.pdf*

Ostrach DJ, Low-Marchelli JM, Eder KJ, Whiteman SJ, Zinkl JG. 2008. Maternal transfer of xenobiotics and effects on larval striped bass in the San Francisco Estuary. Proc Natl Acad Sci 105:19354-9. doi: *http://dx.doi.org/10.1073/pnas.0802616105*

Paerl HW, Fulton RS, 3rd, Moisander PH, Dyble J. 2001. Harmful freshwater algal blooms, with an emphasis on cyanobacteria. Sci World J 1:76-113. doi: *http://dx.doi.org/10.1100/tsw.2001.16*

Presser TS, Luoma SN. 2013. Ecosystem-scale selenium model for the San Francisco Bay–Delta Regional Ecosystem Restoration Implementation Plan. San Franc Estuary Watershed Sci 11(1). doi: *http://dx.doi.org/10.15447/sfews.2013v11iss1art2*

Riar N, Crago J, Jiang W, Maryoung LA, Gan J, Schlenk D. 2013. Effects of salinity acclimation on the endocrine disruption and acute toxicity of bifenthrin in freshwater and euryhaline strains of *Oncorhynchus mykiss*. Env Toxicol Chem 32:2779-2785. doi: *http://dx.doi.org/10.1002/etc.2370*

Sandahl JF, Baldwin DH, Jenkins JJ, Scholz NL. 2007. A sensory system at the interface between urban stormwater runoff and salmon survival. Environ Sci Technol 41: 2998-3004. doi: *http://www.ncbi.nlm.nih.gov/pubmed/17533870*

Sandheinrich MB, Wiener JG. 2011. Methylmercury in freshwater fish: recent advances in assessing toxicity of environmentally relevant exposures. Boca Raton (FL): CRC Press. doi: *http://dx.doi.org/10.1201/b10598-6*

Schlenk D, Lavado R, Loyo-Rosales JE, Jones W, Maryoung L, Riar N, et al. 2012. Reconstitution studies of pesticides and surfactants exploring the cause of estrogenic activity observed in surface waters of the San Francisco Bay Delta. Environ Sci Technol 46:9106-11. doi: *http://dx.doi.org/10.1021/es3016759*

Scholz NL, Fleishman E, Brown L, Werner I, Johnson ML, Brooks ML, et al. 2012. A perspective on modern pesticides, pelagic fish declines, and unknown ecological resilience in highly managed ecosystems. BioScience 62:428-434. doi: *http://dx.doi.org/10.1525/bio.2012.62.4.13*

Scholz NL, Truelove NK, French BL, Berejikian BA, Quinn TP, Casillas E, et al. 2000. Diazinon disrupts antipredator and homing behaviors in chinook salmon (*Oncorhynchus tshawytscha*). Can J Fish Aquat Sci 57:1911-1918. doi: *http://dx.doi.org/10.1139/cjfas-57-9-1911*

Scott GR, Sloman KA. 2004. The effects of environmental pollutants on complex fish behaviour: integrating behavioural and physiological indicators of toxicity. Aquat Toxicol 68:369-92. doi: *http://dx.doi.org/10.1016/j.aquatox.2004.03.016*

[SFBRWQCB] San Francisco Bay Regional Water Quality Control Board. 2006. Mercury in San Francisco Bay: proposed basin plan amendment and staff report for revised total maximum daily load (TMDL) and proposed mercury water quality objectives. Oakland (CA): SFBRWQCB. Available from: *http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/sfbaymercury/sr080906.pdf*

[SFBRWQCB] San Francisco Bay Regional Water Quality Control Board. 2008. Total maximum daily load for PCBs in San Francisco Bay: final staff report for Proposed Basin Plan Amendment. [Internet]. [accessed 2015 October 24]. Oakland (CA): SFBRWQCB. Available from: *http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/sfbaypcbs/Staff_Report.pdf*

[SFEI] San Francisco Estuary Institute. 2013. The pulse of the bay: contaminants of emerging concern. [Internet]. [accessed 2015 October 24]. SFEI Contribution #701. Richmond (CA): SFEI. Available from: *http://www.sfei.org/sites/default/files/biblio_files/Pulse_2013_CECs.pdf*

Sommers F, Mudrock E, Labenia J, Baldwin D. 2016. Effects of salinity on olfactory toxicity and behavioral responses of juvenile salmonids from copper. Aquat Toxicol 175:260-8. doi: *http://dx.doi.org/10.1016/j.aquatox.2016.04.001*

Spearow JL, Kota RS, Ostrach DJ. 2011. Environmental contaminant effects on juvenile striped bass in the San Francisco Estuary, California, USA. Environ Toxicol Chem 30:393-402. doi: *http://dx.doi.org/10.1002/etc.386*

Stehle S, Schulz R. 2015. Agricultural insecticides threaten surface waters at the global scale. Proc Natl Acad Sci 112:5750-5755. doi: *http://dx.doi.org/10.1073/pnas.1500232112*

Stewart AR, Luoma SN, Elrick KA, Carter JL, van der Wegen M. 2013. Influence of estuarine processes on spatiotemporal variation in bioavailable selenium. Mar Ecol Prog Ser 492:41-56. doi: *http://www.int-res.com/abstracts/meps/v492/p41-56/*

Sutton R, Sedlak MD, Yee D, Davis JA, Crane D, Grace R, et al. 2015. Declines in polybrominated diphenyl ether contamination of San Francisco Bay following production phase-outs and bans. Env Sci Technol 49:777-784. doi: *http://dx.doi.org/10.1021/es503727b*

[SWRCB] State Water Resources Control Board. 2010. Transmittal of the 2010 Integrated Report [Clean Water Act Section 303(d) and Section 305(b)]. Letter to Alexis Strauss, USEPA, and four CDs of supporting materials, including the staff report, fact sheets, and responsiveness summary, dated October 11, 2010. [Internet]. [accessed 2015 October 24]. Available from: *https://www3.epa.gov/region9/water/tmdl/california.html*

Teh SJ, Flores I, Kawaguchi M, Lesmeister S, Teh C. 2011. Full life-cycle bioassay approach to assess chronic exposure of *Pseudodiaptomus forbesi* to ammonia/ammonium. [Internet]. [accessed 2015 October 24]. Sacramento (CA): State Water Resources Control Board. Available from: *http://www.waterboards.ca.gov/centralvalley/water_issues/delta_water_quality/ambient_ammonia_concentrations/tehetal_ammonium_exposure2011.pdf*

Teh SJ, Deng D, Werner I, Teh F, Hung SS. 2005. Sublethal toxicity of orchard stormwater runoff in Sacramento splittail (*Pogonichthys macrolepidotus*) larvae. Mar Environ Res 59:203-16. doi: *http://dx.doi.org/10.1016/j.marenvres.2003.12.005*

Thomson JR, Kimmerer WJ, Brown LR, Newman KB, Nally RM, Bennett WA, et al. 2010. Bayesian change point analysis of abundance trends for pelagic fishes in the upper San Francisco Estuary. Ecol Appl 20:1431-1448. doi: *http://dx.doi.org/10.1890/09-0998.1*

Trowbridge PR, Davis JA, Mumley T, Taberski K, Feger N, Valiela L, et al. 2016. The Regional Monitoring Program for Water Quality in San Francisco Bay, California, USA: Science in support of managing water quality. Regional Stud Mar Sci 4:21-33. doi: *http://dx.doi.org/10.1016/j.rsma.2015.10.002*

Tyler CR, Jobling S, Sumpter JP. 1998. Endocrine disruption in wildlife: a critical review of the evidence. Critical Rev Toxicol 28:319-361. doi: *http://dx.doi.org/10.1080/10408449891344236*

[USEPA] U.S. Environmental Protection Agency. 2013. Aquatic life ambient water quality criteria for ammonia—freshwater. [Internet]. [accessed 2015 October 24]. Washington, D.C.: USEPA, Office of Water, Office of Science and Technology. Available from: *https://www.epa.gov/sites/production/files/2015-08/documents/aquatic-life-ambient-water-quality-criteria-for-ammonia-freshwater-2013.pdf*

Vandenberg LN, Colborn T, Hayes TB, Heindel JJ, Jacobs DR, Jr., Lee D-H, et al. 2012. Hormones and endocrine-disrupting chemicals: low-dose effects and nonmonotonic dose responses. Endocrine Rev 33:378-455. doi: *http://dx.doi.org/10.1210/er.2011-1050*

Wei-Hsiang C, Haunschild K, Lund JR, Fleenor WE. 2010. Current and long-term effects of delta water quality on drinking water treatment costs from disinfection byproduct formation. San Franc Estuary Watershed Sci 8(3). doi: *http://dx.doi.org/10.15447/sfews.2010v8iss3art4*

Werner I, Deanovic LA, Hinton DE, Henderson JD, de Oliveira GH, Wilson BW, et al. 2002. Toxicity of stormwater runoff after dormant spray application of diazinon and esfenvalerate (Asana®) in a French prune orchard, Glenn County, California, USA. Bull Environ Contam Toxicol 68:29-36. doi: *http://dx.doi.org/10.1007/s00128-001-0215-7*

Werner I, Deanovic LA, Markiewicz D, Khamphanh M, Reece CK, Stillway M, et al. 2010a. Monitoring acute and chronic water column toxicity in the Northern Sacramento-San Joaquin Estuary, California, USA, using the euryhaline amphipod, *Hyalella azteca*: 2006 to 2007. Environ Toxicol Chem 29:2190-9. doi: *http://dx.doi.org/10.1002/etc.281*

Werner I, Deanovic LA, Markiewicz D, Stillway M, Offer N, Connon RE, et al. 2008. Pelagic Organism Decline (POD): acute and chronic invertebrate and fish toxicity testing in the Sacramento-San Joaquin Delta 2006-2007. [Internet]. [accessed 2015 October 24]. Sacramento (CA): California Department of Water Resources. Available from: *http://www.water.ca.gov/iep/docs/pod/Werner_Tox_Final_Report_w-Appendix.pdf*

Werner I, Markiewicz D, Deanovic LA, Connon RE, Beggel S, Teh SJ, et al. 2010b. Pelagic Organism Decline (POD): acute and chronic invertebrate and fish toxicity testing in the Sacramento-San Joaquin Delta 2008-2010. Sacramento (CA): California Department of Water Resources. doi: *http://www.water.ca.gov/iep/docs/pod/Werner_et_al_2008-2010_Final_Report_w-Appendices.pdf*

Werner I, Moran K. 2008. Effects of pyrethroid insecticides on aquatic organisms. Chapter 14. In: Gan J, Frank Spurlock F, Hendley P, Weston DP, editors. Synthetic pyrethroids. American Chemical Society Symposium Series 991. p 310-334. doi: *http://dx.doi.org/10.1021/bk-2008-0991.ch014*

Weston DP, Chen D, Lydy MJ. 2015a. Stormwater-related transport of the insecticides bifenthrin, fipronil, imidacloprid, and chlorpyrifos into a tidal wetland, San Francisco Bay, California. Sci Tot Environ 527–528:18-25. doi: *http://dx.doi.org/10.1016/j.scitotenv.2015.04.095*

Weston DP, Lydy MJ. 2014. Toxicity of the Insecticide Fipronil and Its Degradates to Benthic Macroinvertebrates of Urban Streams. Env Sci Technol 48:1290-1297. doi: *http://dx.doi.org/10.1021/es4045874*

Weston DP, Schlenk D, Riar N, Lydy MJ, Brooks ML. 2015b. Effects of pyrethroid insecticides in urban runoff on Chinook Salmon, Steelhead Trout, and their invertebrate prey. Environ Toxicol Chem 34:649-57. doi: *http://dx.doi.org/10.1002/etc.2850*

Weston DP, You J, Amweg EL, Lydy MJ. 2008. Sediment toxicity in agricultural areas of California and the role of hydrophobic pesticides. In: Gan J, Spurlock F, Hendley P, Weston D, editors. Synthetic oyrethroids: occurrence and behavior in aquatic environments. Washington, D.C.: American Chemical Society. doi: *http://dx.doi.org/10.1021/bk-2008-0991.ch002*

Winder M, Jassby AD. 2011. Shifts in zooplankton community structure: implications for food web processes in the upper San Francisco Estuary. Estuaries Coasts 34: 675-690. doi: *http://dx.doi.org/10.1007/s12237-010-9342-x*

Wood ML, Foe CG, Cooke J, Louie SJ. 2010. Sacramento–San Joaquin Delta estuary TMDL for methylmercury. Staff report. [Internet]. [accessed 2015 October 24]. Rancho Cordova (CA): Central Valley Regional Water Quality Control Board. Available from: *http://www.waterboards.ca.gov/centralvalley/water_issues/tmdl/central_valley_projects/delta_hg/april_2010_hg_tmdl_hearing/apr2010_tmdl_staffrpt_final.pdf*

TABLE 1 REFERENCES

Acuña S, Baxa D, Teh, S. 2012. Sublethal dietary effects of microcystin producing *Microcystis* on Threadfin Shad, *Dorosoma petenense*. Toxicon 60:1191-1202. doi: *http://dx.doi.org/10.1016/j.toxicon.2012.08.004*

Acuña S, Deng D-F, Lehman P, Teh S. 2012. Sublethal dietary effects of *Microcystis* on Sacramento Splittail, *Pogonichthys macrolepidotus*. Aquat Toxicol 110-111:1-8. doi: *http://dx.doi.org/10.1016/j.aquatox.2011.12.004*

Baldwin DH, Spromberg JA, Collier TK, Scholz NL. 2009. A fish of many scales: extrapolating sublethal pesticide exposures to the productivity of wild salmon populations. Ecol Appl 19:2004-2015. doi: *http://dx.doi.org/10.1890/08-1891.1*

Beggel S, Connon R, Werner I, Geist J. 2011. Changes in gene transcription and whole organism responses in larval fathead minnow (*Pimephales promelas*) following short-term exposure to the synthetic pyrethroid bifenthrin. Aquat Toxicol 105:180-188. doi: *http://dx.doi.org/10.1016/j.aquatox.2011.06.004*

Beggel S, Werner I, Connon RE, Geist JP. 2012. Impacts of the phenylpyrazole insecticide fipronil on larval fish: time-series gene transcription responses in fathead minnow (*Pimephales promelas*) following short-term exposure. Sci Tot Environ 426:160-165. doi: *http://dx.doi.org/10.1016/j.scitotenv.2012.04.005*

Beggel S, Werner I, Connon RE, Geist JP. 2010. Sublethal toxicity of commercial insecticide formulations and their active ingredients to larval fathead minnow (*Pimephales promelas*). Sci Tot Environ 408:3169-3175. doi: *http://dx.doi.org/10.1016/j.scitotenv.2010.04.004*

Biales AD, Denton DL, Riordan D, Breuer R, Batt AL. 2015. Complex watersheds, collaborative teams: Assessing pollutant presence and effects in the San Francisco Delta. Integr Environ Assess Manag 11:674-688. doi: *http://dx.doi.org/10.1002/ieam.1633*

Brander SM, Connon RE, Guochun H, Hobbs JA, Smalling KL, Teh SJ, White W, Werner I, Denison MS, Cherr GN. 2013. From 'omics to otoliths: responses of an estuarine fish to endocrine disrupting compounds across biological scales. PLoS One 8:e74251. doi: *http://dx.doi.org/10.1371/journal.pone.0074251*

Brander SM, Jeffries KM, Cole BJ, DeCourten BM, White JW, Hasenbein S, Fangue NA, Connon RE. 2016. Transcriptomic changes underlie altered egg protein production and reduced fecundity in an estuarine model fish exposed to bifenthrin. Aquat Toxicol 174:247-260. doi: *http://dx.doi.orgm*

Brander SM, He G, Smalling KL, Denison MS, Cherr GN. 2012. The in vivo estrogenic and in vitro anti-estrogenic activity of permethrin and bifenthrin. Env Toxicol Chem 31:2848-2855. doi: *http://dx.doi.org/10.1002/etc.2019*

Brander SM, Mosser CM, Geist J, Hladik ML, Werner I. 2012. Esfenvalerate toxicity to the cladoceran Ceriodaphnia dubia in the presence of green algae, *Pseudokirchneriella subcapitata*. Ecotoxicology 21:2409-2418. doi: *http://dx.doi.org/10.1007/s10646-012-0996-y*

Callinan–Hoffman K, Deanovic LA, Stillway M, Teh SJ. 2012. The toxicity and interactions among common aquatic contaminants in binary mixtures. [Internet]. [accessed 2015 October 24]. Sacramento (CA): Central Valley Regional Water Quality Resources Control Board. Available from: *http://www.waterboards.ca.gov/centralvalley/water_issues/swamp/sacramento_sanjoaquin_river_delta/mixtures_rpt.pdf*

Cole BJ, Brander SM, Jeffries KM, Hasenbein S, He G, Denison MS, Fangue NA, Connon RE. 2016. Changes in *Menidia beryllina* gene expression and *in vitro* hormone-receptor activation after exposure to estuarine waters near treated wastewater outfalls. Arch Environ Contam Toxicol 71(2):210-223. doi: *http://dx.doi.org/10.1007/s00244-016-0282-8*

Connon RE, Geist J, Pfeiff J, Loguinov AV, D'Abronzo LS, Wintz H, Vulpe CD, Werner I. 2009. Linking mechanistic and behavioral responses to sublethal esfenvalerate exposure in the endangered delta smelt; *Hypomesus transpacificus* (Fam. Osmeridae). BMC Genomics 10:608. doi: *http://dx.doi.org/10.1186/1471-2164-10-608*

Connon RE, Beggel S, D'Abronzo LS, Geist JP, Pfeiff J, Loguinov AV, Vulpe CD, Werner I. 2011a. Linking molecular biomarkers with higher level condition indicators to identify effects of copper exposures on the endangered delta smelt (*Hypomesus transpacificus*). Env Toxicol Chem 30:290-300. doi: *http://dx.doi.org/10.1002/etc.400*

Connon RE, Deanovic LA, Fritsch EB, D'Abronzo LS, Werner I. 2011b. Sublethal responses to ammonia exposure in the endangered Delta Smelt; *Hypomesus transpacificus* (Fam. Osmeridae). Aquat Toxicol 105:369-377. doi: *http://dx.doi.org/10.1016/j.aquatox.2011.07.002*

de Vlaming V, Biales A, Riordan D, Markiewicz, Holmes R, Otis P, Leutenegger C, Zander R, Lazorchak. 2006. Screening California surface waters for estrogenic endocrine disrupting chemicals (EEDC) with a juvenile Rainbow Trout liver vitellogenin mRNA procedure. [Internet]. [accessed 2015 October 24]. Sacramento (CA): State Water Resources Control Board. Available from: *http://www.waterboards.ca.gov/water_issues/programs/swamp/docs/reglrpts/rb5_swamp_eedcrpt.pdf*

DeGroot BC and Brander SM. 2014. The role of P450 metabolism in the estrogenic activity of bifenthrin in fish. Aquat Toxicol 156:17-20. doi: *http://dx.doi.org/10.1016/j.aquatox.2014.07.007*

Deng DF, Hung SS, Teh SJ. 2007. Selenium depuration: residual effects of dietary selenium on Sacramento splittail (*Pogonichthys macrolepidotus*). Sci Tot Environ 377:224-232. doi: *http://dx.doi.org/10.1016/j.scitotenv.2007.02.025*

Deng DF, Zheng K, Teh FC, Lehman PW, Teh SJ. 2010. Toxic threshold of dietary microcystin (-LR) for quart medaka. Toxicon 55(4):787-794. doi: *http://dx.doi.org/10.1016/j.toxicon.2009.11.012*

Durieux ED, Connon RE, Werner I, D'Abronozo LS, Fitzgerald PS, Spearow JL, Ostrach DJ. 2012. Cytochrome P4501A mRNA and protein induction in striped bass (*Morone saxatilis*). Fish Physiol Biochem 38:1107-1116. doi: *http://dx.doi.org/10.1007/s10695-011-9597-6*

Eder KJ, Clifford MA, Hedrick RP, Kohler HR, Werner I. 2008. Expression of immune-regulatory genes in juvenile Chinook salmon following exposure to pesticides and infectious hematopoietic necrosis virus (IHNV). Fish Shellfish Immunol 25:508-516. doi: *http://dx.doi.org/10.1016/j.fsi.2008.07.003*

Eder KJ, Kohler HR, Werner I. 2007. Pesticide and pathogen: heat shock protein expression and acetylcholinesterase inhibition in juvenile Chinook salmon in response to multiple stressors. Env Toxicol Chem 26:1233-1242. doi: *https://www.ncbi.nlm.nih.gov/pubmed/17571690*

Eder KJ, Leutenegger CM, Kohler HR, Werner I. 2009. Effects of neurotoxic insecticides on heat-shock proteins and cytokine transcription in Chinook Salmon (*Oncorhynchus tshawytscha*). Ecotoxicol Environ Saf 72:182-190. doi: *http://dx.doi.org/10.1016/j.ecoenv.2008.04.020*

Forsgren KL, Riar N, Schlenk D. 2013. The effects of the pyrethroid insecticide, bifenthrin, on steroid hormone levels and gonadal development of steelhead (*Oncorhynchus mykiss*) under hypersaline conditions. Gen Comparative Endocrinol 186:101-107. doi: *http://dx.doi.org/10.1016/j.ygcen.2013.02.047*

Fritsch EB, Connon RE, Werner I, Davies RE, Beggell S, Feng W Pessah IN. 2013. Triclosan impairs swimming behavior and alters expression of excitation-contraction coupling proteins in fathead minnow (*Pimephales promelas*). Env Sci Technol 47:2008-2017. doi: *http://dx.doi.org/10.1021/es303790b*

Gehringer DB, Finkelstein ME, Coale KH, Stephenson M, Geller JB. 2012. Assessing Mercury Exposure and Biomarkers in Largemouth Bass (*Micropterus salmoides*) from a Contaminated River System in California. Arch Environ Contamin Toxicol 64:484-493. doi: *http://dx.doi.org/10.1007/s00244-012-9838-4*

Geist J, Werner I, Eder KJ, Leutenegger CM. 2007. Comparisons of tissue-specific transcription of stress response genes with whole animal endpoints of adverse effect in striped bass (*Morone saxatilis*) following treatment with copper and esfenvalerate. Aquat Toxicol 85:28-39. doi: *http://dx.doi.org/10.1016/j.aquatox.2007.07.011*

Ger KA, Panosso R, Lürling M. 2011. Consequences of acclimation to *Microcystis* on the selective feeding behavior of the calanoid copepod *Eudiaptomus gracilis*. Limnol Oceanogr 56:2103-2114. doi: *http://dx.doi.org/10.4319/lo.2011.56.6.2103*

Greenfield BK, Teh SJ, Ross JR, Hunt J, Zhang G, Davis JA, Ichikawa G, Crane D, Hung SS, Deng D, Teh FC, Green PG. 2008. Contaminant Concentrations and Histopathological Effects in Sacramento Splittail (*Pogonichthys macrolepidotus*). Arch Environ Contam Toxicol 55:270-281. doi: *http://dx.doi.org/10.1007/s00244-007-9112-3*

Hammock BG, Hobbs JA, Slater SB, Acuña S, Teh SJ. 2015. Contaminant and food limitation stress in an endangered estuarine fish. Sci Tot Environ 532:316-326. doi: *http://dx.doi.org/10.1016/j.scitotenv.2015.06.018*

Hasenbein M, Werner I, Deanovic LA, Geist J, Fritsch EB, Javidmehr A, Foe C, Fangue NA, Connon RE. 2014. Transcriptomic profiling permits the identification of pollutant sources and effects in ambient water samples. Sci Tot Environ 468-469:688-698. doi: *http://dx.doi.org/10.1016/j.scitotenv.2013.08.081*

Hasenbein S, Connon RE, Lawler SP, Geist J. 2015. A comparison of the sublethal and lethal toxicity of four pesticides in *Hyalella azteca* and *Chironomus dilutus*. Environ Sci Pollut Res Int 22(15):11327–11339. doi: *http://dx.doi.org/10.1007/s11356-015-4374-1*

Hasenbein S, Lawler SP, Geist J, Connon RE. 2015. The use of growth and behavioral endpoints to assess the effects of pesticide mixtures upon aquatic organisms. Ecotoxicology 24:746-759. doi: *http://dx.doi.org/10.1007/s10646-015-1420-1*

Jeffries KM, Komoroske LM, Truong J, Werner I, Hasenbein M, Hasenbein S, Fangue NA, Connon RE. 2015. The transcriptome-wide effects of exposure to a pyrethroid pesticide on the Critically Endangered Delta Smelt *Hypomesus transpacificus*. Endanger Species Res 28:43-60. doi: *http://dx.doi.org/10.3354/esr00679*

Jeffries KM, Brander SM, Britton MT, Fangue NA, Connon RE. 2015. Chronic exposures to low and high concentrations of ibuprofen elicit different gene response patterns in a euryhaline fish. Environ Sci Pollut Res Int 22(22):17397–17413. doi: *http://dx.doi.org/10.1007/s11356-015-4227-y*

Lavado R, Loyo-Rosales JE, Floyd E, Kolodziej EP, Snyder SA, Sedlak DL, Schlenk D. 2009. Site-specific profiles of estrogenic activity in agricultural areas of California's inland waters. Env Sci Technol 43:9110-9116. doi: *http://dx.doi.org/10.1021/es902583q*

Maryoung LA, Blunt B, Tierney KB, Schlenk D. 2015. Sublethal toxicity of chlorpyrifos to salmonid olfaction after hypersaline acclimation. Aquat Toxicol 161:94-101. doi: *http://dx.doi.org/10.1016/j.aquatox.2015.01.026*

Maryoung LA, Lavado R, Schlenk D. 2014. Impacts of hypersaline acclimation on the acute toxicity of the organophosphate chlorpyrifos to salmonids. Aquat Toxicol 152:284-290. doi: *http://dx.doi.org/10.1016/j.aquatox.2014.04.017*

Ostrach D and Groff J. 2009. The Role of Contaminants, within the Context of Multiple Stressors, in the Collapse of the Striped Bass Population in the San Francisco Estuary and its Watershed Final Report. Department of Water Resources. Technical Report.

Ostrach DJ, Low-Marchelli JM, Eder KJ, Whiteman SJ, Zinkl JG. 2008. Maternal transfer of xenobiotics and effects on larval striped bass in the San Francisco Estuary. Proc Nat Acad Sci 105:19354-19359. doi: *http://dx.doi.org/10.1073/pnas.0802616105*

Riar N, Crago J, Jiang W, Maryoung LA, Gan J, Schlenk D. 2013. Effects of salinity acclimation on the endocrine disruption and acute toxicity of bifenthrin in freshwater and euryhaline strains of *Oncorhynchus mykiss*. Env Toxicol Chem 32:2779-2785. doi: *http://dx.doi.org/10.1002/etc.2370*

Rigby MC, Deng X, Grieb TM, Teh SJ, Hung SSO. 2010. Effect Threshold for Selenium Toxicity in Juvenile Splittail, *Pogonichthys macrolepidotus* A. Bull Environ Contam Toxicol 84:76-79. doi: *http://dx.doi.org/10.1007/s00128-009-9882-6*

Schlenk D, Lavado R, Loyo-Rosales JE, Jones W, Maryoung L, Riar N, Werner I, Sedlak D. Reconstitution studies of pesticides and surfactants exploring the cause of estrogenic activity observed in surface waters of the San Francisco Bay Delta. Env Sci Technol 46:9106-9111. doi: *http://dx.doi.org/10.1021/es3016759*

Sommers F, Mudrock E, Labenia J, Baldwin D. 2016. Effects of salinity on olfactory toxicity and behavioral responses of juvenile salmonids from copper. Aquat Toxicol 175:260–268. doi: *http://dx.doi.org/10.1016/j.aquatox.2016.04.001*

Spearow JL, Kota RS, Ostrach DJ. 2011. Environmental contaminant effects on juvenile striped bass in the San Francisco Estuary, California, USA. Env Toxicol Chem 30:393-402. doi: *http://dx.doi.org/10.1002/etc.386*

Teh SJ, Deng D, Werner I, Teh F, Hung SS. 2005. Sublethal toxicity of orchard stormwater runoff in Sacramento Splittail (*Pogonichthys macrolepidotus*) larvae. Mar Environ Res 59:203-216. doi: *http://dx.doi.org/10.1016/j.marenvres.2003.12.005*

Teh S, Flores I, Kawaguchi M, Lesmeister S, Teh C. 2011. Full Life-Cycle Bioassay Approach to Assess Chronic Exposure of *Pseudodiaptomus forbesi* to Ammonia/Ammonium. State Water Resources Control Board. Technical Report.

Werner I, Deanovic LA, Markiewicz D, Khamphanh M, Reece CK, Stillway M, Reece C. 2010. Monitoring acute and chronic water column toxicity in the Northern Sacramento-San Joaquin Estuary, California, USA, using the euryhaline amphipod, *Hyalella azteca*: 2006 to 2007. Env Toxicol Chem 29:2190-2199. doi: *http://dx.doi.org/10.1002/etc.281*

Werner I, Deanovic LA, Markiewicz D, Stillway M, Offer N, Connon RE, Brander SM. 2008. Pelagic organism decline (POD): acute and chronic invertebrate and fish toxicity testing in the Sacramento-San Joaquin Delta 2006-2007. Sacramento (CA): California Department of Water Resources. Available from: *http://www.water.ca.gov/iep/docs/pod/Werner_Tox_Final_Report_w-Appendix.pdf*

Werner I, Markiewicz D, Deanovic LA, Connon RE, Beggel S, Teh S, Stillway M, Reece C. 2010. Pelagic Organism Decline (POD): acute and chronic invertebrate and fish toxicity testing in the Sacramento-San Joaquin Delta 2008-2010 Final Report. California Department of Water Resources. Technical Report. Available from: *http://www.water.ca.gov/iep/docs/pod/Werner_et_al_2008-2010_Final_Report_w-Appendices.pdf*

NOTES

Connon RE, Hasenbein M, Holland E, Javidmehr A, Deanovic LA, Werner I. 2011. Genomic profiling in Delta Smelt (*Hypomesus transpacificus*): site-specific signatures [abstract]. [Internet]. [accessed 2014 October 24]. Presented at the Interagency Ecological Program (IEP) Annual Workshop; 2011 March 30, Folsom, CA. Available from: *http://www.water.ca.gov/iep/archive/2011/033011agenda.pdf*

Deanovic LA, Stillway M, Callinan–Hoffmann K, Jeffries KM, Connon RE, Teh SJ. 2014. A thorough toxicity assessment of the Sacramento River at Hood, CA, (testing the toxicity toolbox) [abstract]. [Internet]. [accessed 2014 October 24]. Presented at the Interagency Ecological Program (IEP) Annual Workshop; 2011 March 30, Folsom, CA. Available from: *http://www.water.ca.gov/iep/docs/2014_IEPWorkshopAgenda_FINAL_2_20_14.pdf*

Decourten B. 2016. In-person conversation between B. Decourten and S. Fong about larval deformities following parental exposure to pesticides. Presented at the Bay–Delta Science Conference, held 2016 November 17-19, Sacramento, CA.

Sedlak M. 2016. In-person communication between M. Sedlak and J. Davis regarding unpublished data on the detection of PFOS in San Francisco Bay birds and seals.

Young T, Orlando J. 2016. In-person conversation among T. Young, J. Orlando, and R. Connon about the latest information presented at the Bay–Delta Science Conference, held 2016 November 17-19 in Sacramento, CA, during the ”Contaminant Issues in the Bay-Delta” sessions.