Turner JL. 1966. Distribution of threadfin shad, *Dorosoma petenense*; tule perch, *Hysterocarpus traski*; sculpin spp. and crayfish spp. in the Sacramento-San Joaquin Delta. In: Turner JL, Kelley DW, compilers. Ecological studies of the Sacramento-San Joaquin Estuary. Part II. California Department of Fish and Game. Fish Bulletin 136. p 160–8.

Zar JH. 1999. Biostatistical analysis. 4th edition. Upper Saddle River (NJ): Prentice Hall, Inc.

EXPOSURE OF DELTA SMELT TO DISSOLVED PESTICIDES IN 1998 AND 1999

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INTRODUCTION

Delta smelt is a threatened species in the San Francisco Bay Estuary. Pesticide toxicity is a possible cause for the need to list this fish (Bennett and Moyle 1996; Moyle and others 1996). Numerous pesticides are transported into the estuary from area rivers (MacCoy and others 1995). However, there are minimal data to document the presence, or absence, of pesticides within delta smelt habitat, especially during their vulnerable early life stages. This study, conducted by the U.S. Geological Survey (USGS), documents the occurrence of pesticides within delta smelt habitat; specifically, the length and variability of their potential exposure to multiple dissolved pesticides.

This article reviews delta smelt habitat and early life stages followed by an explanation of the study design for assessing pesticide exposure. Results show the co-occurrence of multiple pesticides and delta smelt in their native habitat; these results are presented within the context of possible toxic effects to delta smelt. Finally, the annual variability of pesticide distributions is discussed.

DELTA SMELT LIFE STAGES AND HABITATS

For the purpose of discussion in this article, two delta smelt life stages are of primary interest. The first is the larval stage when delta smelt are incapable of extensive swimming. The second is the juvenile stage when delta smelt are relatively motile.

Delta smelt typically spawn in shallow areas during early spring. Delta smelt are known to spawn throughout the Sacramento-San Joaquin Delta (Moyle and others 1992, 1996). While spawning locations vary from year to year and depend on environmental conditions, one primary location is the northwestern Delta, including Cache and Lindsey sloughs (Figure 1).

The movements of newly hatched larvae are controlled primaritly by tidal currents. This implies that exposure of delta smelt larvae to pesticides is greatly controlled by residence time. In the tidal currents the larvae can be expected to behave generally as particles; therefore, the residence time of a particle within a particular slug of water can be used as a model of exposure time. In this study, residence times were calculated from measured velocities in Cache and Lindsey sloughs and in the Sacramento River at Rio Vista using Lagrangian particle tracking. In the main channel of Lindsey Slough, residence times were five to ten times longer than in the main channel of the Sacramento River at Rio Vista (USGS unpublished data 1999). Residence times are likely to be even longer in the shallower channel edges and in the upstream sections of the sloughs. Many of the larvae likely reside in side sloughs, such as Cache and Lindsey sloughs (Moyle and others 1992, 1996), where residence time is longer than in the main river channels. Co-occurrence of pesticides and larvae in these habitats result in a long exposure time of developing larvae to pesticides.

As delta smelt mature and become better swimmers, the juveniles tend to move downstream and congregate in waters having a salinity of about 2 ppt (Moyle and others 1992, 1996). These 2-ppt waters typically lie in Suisun Bay or near the confluence of the Sacramento and San Joaquin rivers (Jassby and others 1995; Gartner and Burau 1999) (Figure 1).

Study Design

To document pesticide exposure to the two early life stages of delta smelt, sampling was done in two parts. Samples were taken during 1998 and 1999 from a variety of sites within the Suisun Bay and the Delta. All samples were analyzed for pesticides using the methods described in Crepeau and others (2000).

Samples were collected at a fixed time interval from the Delta sites in conjunction with the 20-mm delta smelt surveys taken by the California Department of Fish and Game (DFG). These concurrent samplings allowed for direct comparison of pesticide concentrations and fish abundances. Samples were collected biweekly at five Delta sites in 1998 and ten Delta sites in 1999, from late April to late June, when larvae were expected to occur (Figure 1).

Samples were collected from Suisun Bay during periods of 2-ppt salinity when juveniles were expected to occur (June to August). Two sites where salinities of 2 ppt routinely occur were selected: Mallard Island and the Reserve Fleet (Gartner and Burau 1999) (Figure 1). Autosamplers were programmed to collect no more than one sample per day on the ebb tide as the 2-ppt waters passed their respective locations. Due to equipment difficulties, samples were not collected successfully from Suisun Bay in 1998. During the study period, salinities of 2 ppt occurred consistently at Mallard Island, but only intermittently at the Reserve Fleet in 1999 (USGS unpublished data 1999), so samples were collected only from Mallard Island.

Multiple Pesticides in Delta Smelt Habitat

In 1998 and 1999, the waters within the Delta and the confluence contained many different pesticides (Table 1). Of the 147 samples collected, all samples contained at least two pesticides, the median number of pesticides detected per sample was four and the maximum number of pesticides detected per sample was eight (Figure 2). Overall, the distributions of the number of pesticides detected in different samples were similar for 1998 and 1999 (USGS unpublished data 1998, 1999).

The complexity of the pesticide mixture in delta smelt habitat is illustrated further by examining the list of the individual pesticides (Table 1). Ten pesticides were detected in 1998 and 12 were detected in 1999. The frequency of detection and maximum concentration of each pesticide are shown in Table 1. Metolachlor was the most frequently detected pesticide, with detection in 98% of all samples. Other frequently detected pesticides included molinate, simazine, and thiobencarb with percent detections of 76%, 93%, and 70%, respectively. The pesticides EPTC, molinate, and thiobencarb had maximum concentrations of 7,700 ng/L, 2,500 ng/L, and 330 ng/L, respectively.

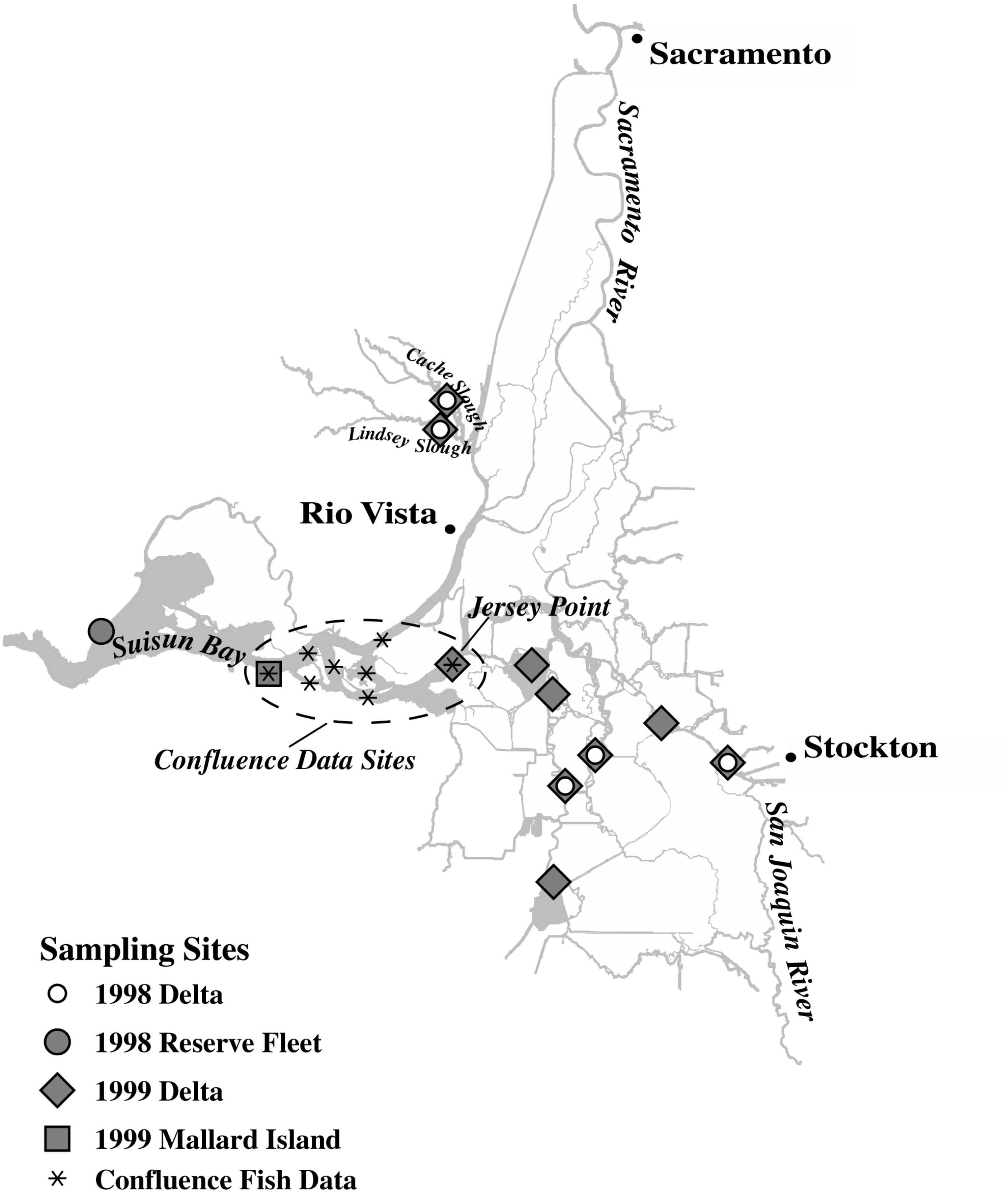

Figure 1 Map of sampling locations

Table 1 List of pesticides detected

Pesticide	Samples Detected[a] (%) 1998	Samples Detected[a] (%) 1999	Maximum Concentration (ng/L) 1998	Maximum Concentration (ng/L) 1999
Alachlor	0	2	---[b]	56
Atrazine	10	7	43	24
Carbaryl	0	5	---[b]	210
Carbofuran	50	29	30	82
Diazinon	18	0	46	---[b]
EPTC	45	29	1500	7700
Metolachlor	100	96	210	210
Molinate	25	76	2500	440
Pebulate	13	1	140	84
Simazine	93	41	68	64
Sulfotep	0	24	---[b]	120
Thiobencarb	13	70	330	150
Trifluralin	20	14	8	65

[a] Percent values given are the percent of samples in which each pesticide was detected in each year. In 1998 *n* = 40, in 1999 *n* = 107

[b] Dashes indicate the constituent was not detected.

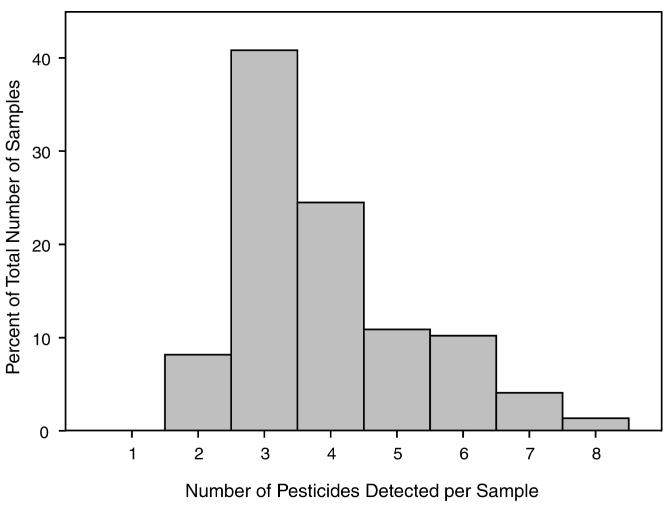

Figure 2 Number pesticides detected per sample. This graph shows a plot of the relative number of samples containing different numbers of pesticides in 1998 and 1999.

EXPOSURE OF DELTA SMELT TO MULTIPLE PESTICIDES

Multiple pesticides occurred within delta smelt habitat; however, the question of interest was, "Are delta smelt exposed to these pesticides?" To answer this question, fish densities from the 20-mm survey for delta smelt, which catches both larval and juvenile delta smelt, were compared with pesticide concentrations from this study.

In 1998, few delta smelt were caught by DFG at the sites with concurrent pesticide sampling by the USGS. In 1998, high spring outflows centered the delta smelt population downstream in Suisun Bay (Sweetnam 1999). Because delta smelt were not present at the pesticide sampling sites in 1998, no estimate could be made of their exposure to pesticides.

In 1999, the 20-mm survey found that delta smelt were present at the pesticide sampling sites. Comparison of the delta smelt densities and pesticide concentrations show that delta smelt were exposed to pesticides in 1999 (Figure 3). Examination of the data for the San Joaquin River at Jersey Point (Figure 1) revealed that fish abundances and pesticide concentrations were very similar to those observed at the confluence. Therefore, the data from Jersey Point were excluded from the Delta data (Figure 3A) and grouped with the confluence data (Figure 3B) for purposes of interpretation. In Figure 3A, the fish densities at each of the remaining nine Delta sites were averaged for each sampling date. The total pesticide concentration at each site for each sampling date was calculated as the sum of individual pesticide concentrations. The total pesticide concentrations were averaged across the nine Delta sites for each sampling date to give the pesticide data in Figure 3A. The highest densities of delta smelt were present at the Delta sites from May 10 through June 7 (Figure 3A). During this time, fish co-occurred with the pesticides with the highest concentrations detected on May 10. Extremely high concentrations of EPTC (7,700 ng/L and 4,300 ng/L) detected at two sites within the Delta strongly influenced the high total pesticide concentration on May 10. Even without EPTC, however, pesticide concentrations were elevated throughout the period that delta smelt were present in the Delta.

As the juvenile delta smelt migrated toward and congregated in the confluence, they were exposed to elevated concentrations of dissolved pesticides for an additional one to two months (Figure 3B). Fish densities in Figure 3B were an average of the densities at the nine DFG sites within the confluence area (Figure 1) and pesticide concentrations are total pesticide concentrations from Jersey Point and Mallard Island. The timing of the peak fish abundance at the confluence sites lagged the Delta sites by two weeks, with the largest number of delta smelt being found on June 21. As in the Delta, the highest densities of delta smelt co-occurred with the highest concentrations of dissolved pesticides. The rise and fall of pesticide concentrations was comprised primarily of the rice pesticides molinate and thiobencarb (USGS unpublished data 1999).

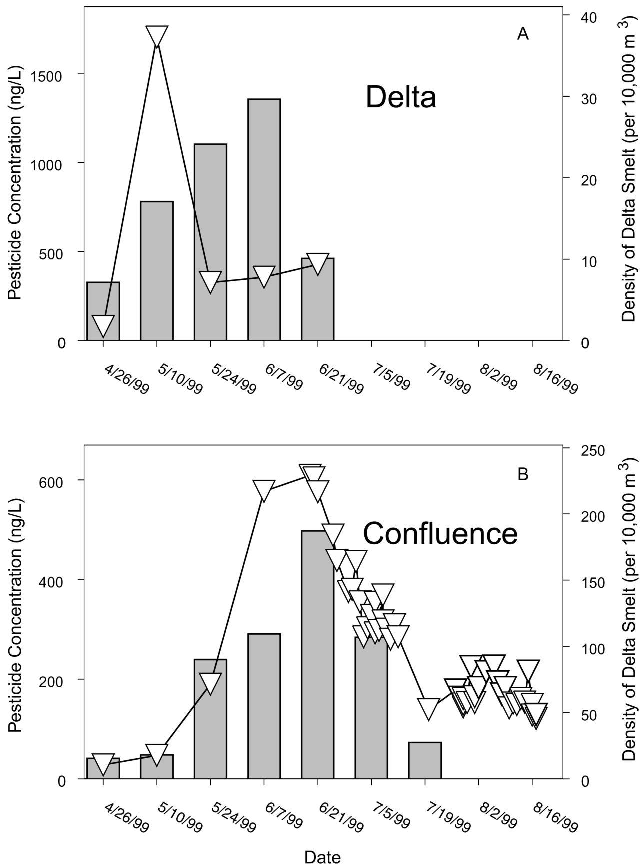

Figure 3 Co-occurrence of pesticides and delta smelt. These graphs contain both a line plot of pesticide concentrations and a bar plot of density of delta smelt in the Delta (A) and in the confluence (B). See text for calculation methods.

Previous studies (Bennett 1996) have suggested the timing of pesticide pulses is offset from fish abundance and exposure to pesticides is not important. Bennett (1996) found that the maximum densities of striped bass larvae and concentrations of molinate did not occur concurrently; however, he noted that his two data sets were not sampled concurrently and suggested future studies should be designed accordingly. Our study did conduct concurrent sampling and found that delta smelt were exposed to a complex mixture of dissolved pesticides in 1999.

The maximum concentrations for each pesticide (Table 1) were well below the LC50 values for most fish species (Tomlin 1997); therefore, it is unlikely that even the mixtures of pesticides observed in 1999 caused acute toxicity to delta smelt. However, chronic exposure to individual and multiple pesticides may hinder growth rate, reproduction, and swimming performance (Rand 1995). Indirect effects of pesticide exposure, such as alteration of delta smelt diet, also are possible (Rand 1995). Information on chronic pesticide exposure is needed to fully evaluate the environmental effects of pesticides on the delta smelt population.

ANNUAL VARIABILITY OF PESTICIDE DISTRIBUTION

Multiple pesticides were detected in delta smelt habitat in 1998 and 1999; however, there was considerable variability in the maximum concentration and distribution of the pesticides. The pesticides alachlor, carbaryl, and sulfotep were not detected in 1998 but were detected in 1999 (Table 1). Conversely, diazinon was detected in 1998 but not in 1999 (Table 1). Several other pesticides were detected both years, but at very different concentrations. The maximum concentrations of EPTC and trifluralin were five and eight times higher, respectively, in 1999 than in 1998. In contrast, the concentrations of molinate and thiobencarb were approximately five times and two times lower, respectively, in 1999 than 1998. The differences in concentrations of pesticides may be due to variations in the amount applied or in the timing of sampling relative to application. The two pesticides molinate and thiobencarb are applied to rice, and the observed differences in concentration have been explained previously by variations in the actual holding time of water on rice fields before release (Crepeau and Kuivila 2000).

The spatial distribution of pesticides also varied from year to year. In 1998, the concentrations of molinate and thiobencarb peaked at 2,500 ng/L and 330 ng/L, respectively, in Cache and Lindsey sloughs. However, these pesticides were not detected at any other Delta sites in 1998 (USGS unpublished data 1998). In 1999, however, the concentrations of molinate and thiobencarb in the central Delta sites were very similar to those in Cache and Lindsey sloughs (USGS unpublished data 1999). This difference in pesticide distribution between the two years can be explained by the effect of Delta hydrodynamics on pesticides originating from the Sacramento River watershed (Figure 4).

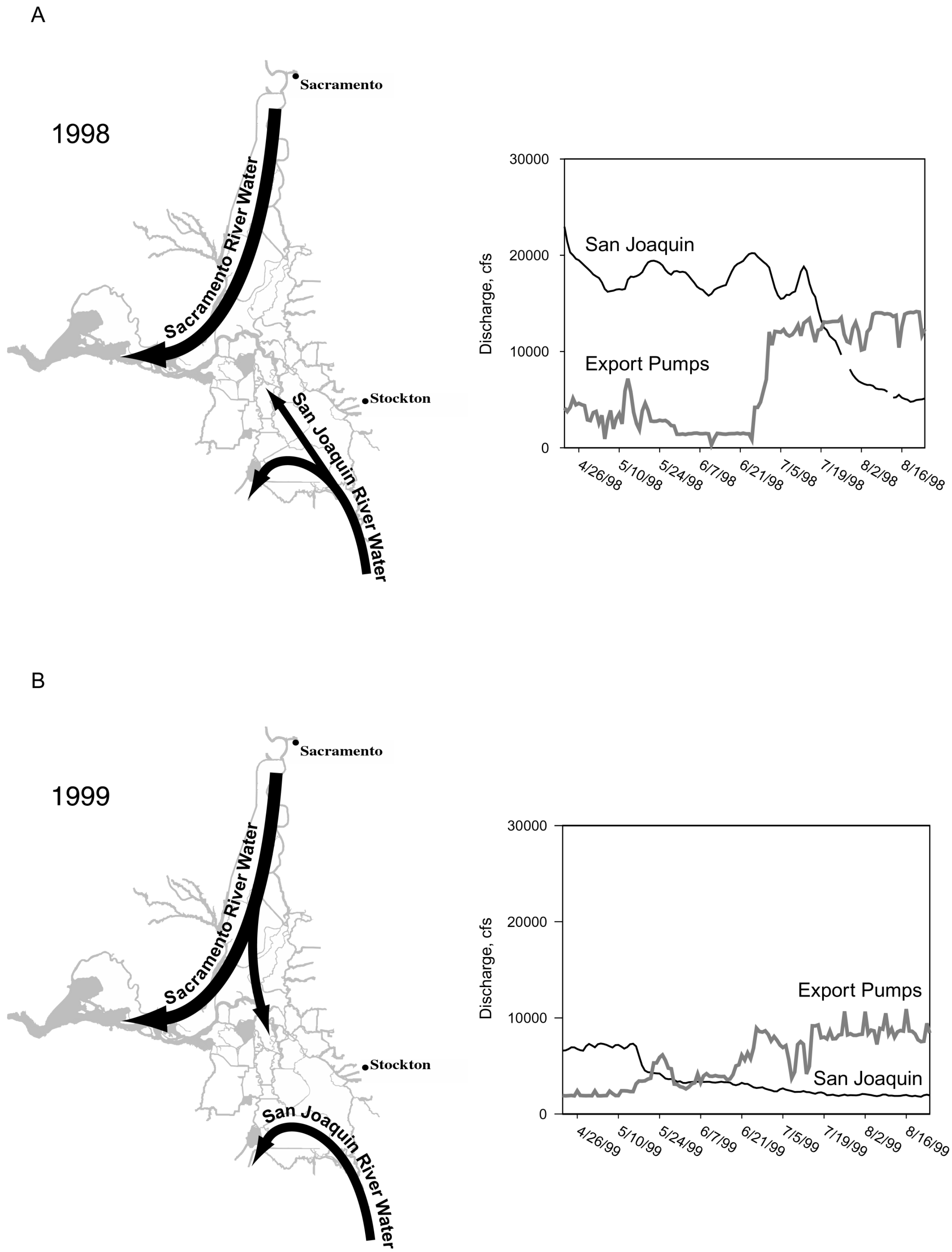

Figure 4 Transport of water and pesticides through the Delta in 1998 (A) and 1999 (B). This figure depicts the Sacramento and San Joaquin River discharges and water project exports.

In 1998, San Joaquin River flow was high relative to the export pumping by the State and federal water projects; therefore, flow from the San Joaquin River was sufficient to supply the pumps and the amount of Sacramento River water drawn into the central Delta was minimal until late July (Figure 4A). Conversely, during spring 1999, export pumping rates at times equaled or exceeded discharge from the San Joaquin River beginning in mid-May (Figure 4B). This resulted in Sacramento River water with its associated pesticide load being drawn into the central Delta in 1999. The observed variability in pesticide concentrations and distributions from year to year is evidence that caution is needed when extrapolating and estimating long-term exposure of delta smelt to pesticides without actually measuring both fish abundance and pesticide concentrations.

Summary and Conclusions

In 1998 and 1999, a complex mixture of pesticides was detected in delta smelt habitat. Furthermore, delta smelt were exposed to this complex mixture of pesticides in 1999 for extended periods during their larval and juvenile stages. The observed annual and spatial variability of pesticide concentrations suggest pesticide concentrations from one year cannot be realistically extrapolated into future years. Future studies of delta smelt exposure to pesticides should be designed accordingly. The environmental effects of pesticides on the delta smelt population cannot be evaluated fully until more data are available on the sublethal and indirect effects of chronic exposure of delta smelt larvae and juveniles to complex mixtures of pesticides.

References

Bennett WA. 1996. Framework for evaluating pesticide effects on fish populations. Interagency Ecological Program for the San Francisco Estuary. IEP Newsletter 8:2.

Bennett WA, Moyle PB. 1996. Where have all the fishes gone? Interactive factors producing fish declines in the Sacramento-San Joaquin Estuary. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem. San Francisco (CA): American Association for the Advancement of Science, Pacific Division.

Crepeau KL, Baker LM, Kuivila KM. 2000. Method of analysis and quality-assurance practices for determination of pesticides in water by solid-phase extraction and capillary-column gas chromatography/mass spectrometry at the U.S. Geological Survey California District Organic Chemistry Laboratory, 1996–1999. U.S. Geological Survey Open-File Report 00–229.

Crepeau KL, Kuivila KM. 2000. Rice pesticide concentrations in the Colusa Basin Drain and the Sacramento River, California, 1990–1993. J Environ Qual 29:926–35.

Gartner JW, Burau JR. 1999. Hydrodynamic measurements in Suisun Bay, California, 1992–93. U.S. Geological Survey Water-Resources Investigations Report 99–4049.

Jassby AD, Kimmerer WJ, Monismith SG, Armor C, Cloern JE, Powell TM, Schubel JR, Vendlinski TJ. 1995. Isohaline position as a habitat indicator for estuarine populations. Ecol App 5:272–89.

MacCoy D, Crepeau KL, Kuivila KM. 1995. Dissolved pesticide data for the San Joaquin River at Vernalis and the Sacramento River at Sacramento, California, 1991–94. U.S. Geological Survey Open-File Report 95–110.

Moyle PB, Herbold B, Stevens DE, Miller LW. 1992. Life history and status of delta smelt in the Sacramento-San Joaquin Estuary, California. Trans Am Fish Soc 121:67–77.

Moyle PB, Pine R, Brown LR, Hanson CH, Herbold B, Lentz KM, Meng L, Smith JJ, Sweetnam DA, Winternitz L. 1996. Recovery plan for the Sacramento-San Joaquin Delta native Fishes. U.S. Department of the Interior Fish and Wildlife Service, 15–46.

Rand GM. 1995. Fundamentals of aquatic toxicology: effects, environmental fate, and risk assessment. 2nd edition. London: Taylor and Frances.

Sweetnam DA. 1999. Delta smelt investigations. Interagency Ecological Program for the San Francisco Estuary. IEP Newsletter 12(2):25–8.

Tomlin CDS. 1997. The pesticide manual. 11th edition. Farnham (UK): British Crop Protection Council.