

FINAL

**Legacy Pesticides in San Francisco  
Bay  
Conceptual Model/Impairment Assessment**

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**Prepared for**

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# Executive Summary

This report has been produced for the Clean Estuary Partnership (CEP). The CEP is a collaboration of the Bay Area Clean Water Agencies, Bay Area Stormwater Management Agencies Association, and the San Francisco Bay Regional Water Control Board and other participants. This cooperative partnership facilitates efforts to improve water quality in San Francisco Bay by providing financial and staff support for technical studies, discussion of management questions and strategies, and stakeholder outreach activities.

Several Conceptual Model/Impairment Assessment (CM/IA) reports have been commissioned by the CEP for pollutants that have been identified in the past as possible causes of impairment to beneficial uses in San Francisco Bay. These CM/IA reports have several objectives:

- Evaluate the current level of impairment of beneficial uses, including description of standards or screening indicators and relevant data.
- Develop a conceptual model that describes the current state of knowledge for the pollutant of concern, including sources, loads, and pathways into and out of the Bay and its water, sediment, and biota.
- Identify potential studies that might reduce uncertainties associated with the report's conclusions.

This CM/IA report examines legacy pesticides, that is, pesticides that are no longer used but that persist in San Francisco Bay. The pesticides of concern include DDTs, chlordanes, and dieldrin.

## Impairment Assessment

The impairment assessment reviews past information, which led the U.S. Environmental Protection Agency to determine that sport fishing in San Francisco Bay was impaired by legacy pesticides. The assessment then uses the most recent, available data on concentrations of legacy pesticides in fish tissues, water, sediments, and bird eggs to determine whether sport fishing or other beneficial uses of the Bay are currently impaired. The assessment compares the data to screening values and other criteria derived from regulatory standards and the scientific literature to determine whether the weight of evidence indicates:

- **No impairment:** The available data demonstrate no negative effect on beneficial uses of the Bay, and there is sufficient information to make the finding.
- **Impairment unlikely:** The data indicate that legacy pesticides cause no impairment to the Bay. However, there is some uncertainty, due to lack of sufficient information or disagreement about how to interpret the data.

- **Possible impairment:** There is some suggestion of impairment, but the uncertainties preclude making a definitive judgment.
- **Definite impairment:** The data clearly demonstrate a negative effect on the beneficial uses of the Bay.
- **Unable to determine impairment:** There is insufficient information to make any determination.

The assessment found some indications that beneficial uses of San Francisco Bay may be impaired by legacy pesticides. In particular, water and fish data indicate impairment of the use of the Bay for fishing and fish consumption (Table 1). The level of impairment is not high when compared to other organochlorine compounds, such as PCBs, and there is evidence of long-term declines in pesticide levels.

There is less evidence of impairment of other uses of the Bay—preservation of rare and endangered species, fish spawning, or wildlife and estuarine habitat. Chlordane concentrations in sediments may, in some locations, affect animals living in the sediments, and DDT concentrations in bird eggs may be close to limits that would indicate impairment.

Table 1. Impairment summary

	DDTs	Chlordanes	Dieldrin
<b>Fish</b>	Possible impairment of sport fishing	Impairment unlikely	Possible impairment of sport fishing
<b>Water</b>	Possible impairment of sport fishing	Impairment unlikely	Possible impairment of sport fishing
<b>Sediments</b>	Impairment unlikely	Possible impairment of fish and wildlife uses	Impairment unlikely
<b>Wildlife</b>	Impairment unlikely	Impairment unlikely	Impairment unlikely

## Conceptual Model

The conceptual model provides a framework for optimizing management decisions and actions for reducing contamination by legacy pesticides in San Francisco Bay. The conceptual model:

- Presents a simple **one-box model** of the Bay.
- Synthesizes information on the **sources** of DDTs, chlordanes, and dieldrin to the Bay.
- Estimates total **loads** to the Bay.
- Describes the chemical characteristics of the pesticides and the dominant **processes** that determine their fate within the Bay.
- Uses the one-box model to facilitate understanding responses within the Bay and estimating **recovery** rates.

The conceptual model also identifies areas of uncertainty, which limit the ability to quantify responses and rates.

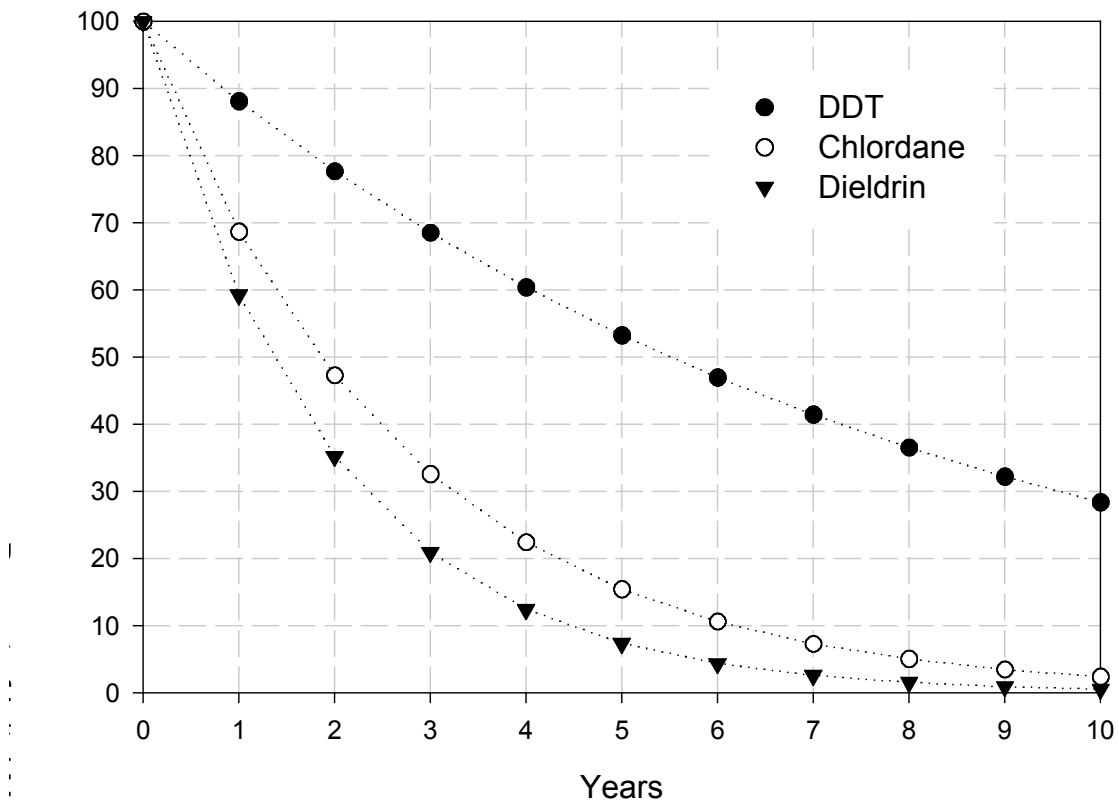
Legacy pesticides enter the water and active sediment of San Francisco Bay in runoff from the Central Valley and local watersheds, in municipal and industrial effluent, by deposition from the atmosphere, by erosion of historically contaminated sediment deposits, and through dredging and disposal of dredged material. Runoff from the Central Valley and the local watershed introduce the largest loads of legacy pesticides to the Bay (Table 2).

*Table 2. Estimated loads (best estimate and range) of legacy pesticides to San Francisco Bay (kg/year).*

<b>Pathway</b>	<b>DDTs</b>	<b>Chlordanes</b>	<b>Dieldrin</b>
Central Valley	15 (5 – 40)	2 (0.7 – 5)	5 (2 – 13)
Local watersheds	40 (9 – 190)	30 (7 – 160)	3 (0.7 – 15)
Municipal wastewater	0.2 (0.02 – 2)	0.1 (0.003 – 2)	0.06 (0.008 – 0.4)
Industrial wastewater	<0.2	<0.1	<0.06
Atmospheric deposition	1 (0.02 – 2)	0.9	1 (0.2 – 2)
Erosion of sediment deposits	9 (0.2 – 18)	2 (0 – 4)	0.2 (0 – 0.6)
Dredged material	-2 (-3 – -0.03)	-0.3 (-0.6 – 0)	-0.03 (-0.1 – 0)
<b>Total Best Estimate</b>	<b>60 (10 – 250)</b>	<b>30 (10 – 170)</b>	<b>10 (3 – 30)</b>

The fate of legacy pesticides in San Francisco Bay is controlled by several processes, including dissolved/solid partitioning (the attributes that control whether the pesticides are dissolved or associated with particles), bioaccumulation in the food web, sediment and hydrologic transport, degradation in the sediments or the water, and volatilization to the atmosphere. Some of these processes—including degradation, outflow through the Golden Gate, and volatilization—result in removal of pesticides from the Bay.

Information about the processes was used to estimate recovery times of the Bay under various scenarios. For example, under a scenario in which no new legacy pesticides entered the Bay, the model predicted that system would cleanse itself within one to three decades (Figure 1). Under scenarios of continued inputs to the Bay, recovery time would be considerably longer or not reached at all.



*Figure 1. Declines in legacy pesticides under conditions of no new inputs to San Francisco Bay*

## Information Gaps

There are many uncertainties and information gaps in this report's conclusions, for example:

- Uncertain understanding of the large runoff events from the Central Valley.
- Uncertain understanding of loads from small tributaries.
- Model uncertainties.
- Lack of established criteria for determining impairment.
- Uncertain understanding of trends in pesticide concentrations.
- Lack of understanding of sediment "hot spots."

Future projects will obtain additional data and conduct more analysis of the sources, fate, transport, and effects of legacy pesticides. In other documents or forums, the CEP will develop appropriate strategies for addressing legacy pesticides in the Bay and its watersheds. There may be control measures, remediation, and regulatory actions that can and should begin now, even with existing uncertainties. CEP partners are committed to identifying these actions. Future CEP data gathering and technical analysis should focus on determining the potential effectiveness and actual effects of actions to reduce or eliminate impairment and to restore beneficial uses of the Bay.

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# **1. Introduction**

This report has been produced for the Clean Estuary Partnership (CEP). The CEP is a collaboration of the Bay Area Clean Water Agencies, Bay Area Stormwater Management Agencies Association, and the San Francisco Bay Regional Water Quality Control Board. Other important participants include the San Francisco Estuary Institute, Clean Water Fund, San Francisco Bay Keeper, Port of Oakland, and the Western States Petroleum Association. This cooperative partnership facilitates efforts to improve water quality in San Francisco Bay by providing financial and staff support for technical studies, discussion of management questions and strategies, and stakeholder outreach activities.

Several Conceptual Model/Impairment Assessment (CM/IA) reports have been commissioned by the CEP for pollutants that have been identified in the past as possible causes of impairment to beneficial uses in San Francisco Bay. The general objectives of these CM/IA reports are:

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- Develop a conceptual model that describes the current state of knowledge for the pollutant of concern, including sources, loads, and pathways into and out of the Bay and its water, sediment, and biota.
- Identify potential studies that might reduce uncertainties associated with the report's conclusions.

Since the state of knowledge varies among pollutants, initial CM/IA reports may lack the resources to fully achieve all these objectives in each case. This CM/IA report should be viewed as a tool for planning and an important step in resolution of legacy pesticide-related issues and not as a conclusive statement on the conceptual model, beneficial use impairment, or next steps needed to resolve legacy pesticide-related issues.

This introduction presents the regulatory background for considering waters as impaired, the San Francisco Bay setting and its designated beneficial uses, and a brief description of legacy pesticides.

## **1.1 Regulatory Background**

The federal Clean Water Act (CWA) provides protection to the surface waters of the United States. Section 101(a)(2) of the act establishes a national goal of “water quality which provides for the protection and propagation of fish, shellfish, and wildlife, and recreation in and on the water, wherever attainable.” Section 303(d) requires states to compile lists of water bodies that do not meet water quality standards and to develop plans (known as total maximum daily loads or TMDLs) for achieving the standards. U.S. Environmental Protection Agency

(USEPA) regulations require that 303(d) lists be compiled every two years. In California, Section 13001 of the California Water Code identifies the California State Water Resources Control Board (SWRCB) and Regional Water Quality Control Boards (RWQCBs) as the principal agencies responsible for controlling water quality.

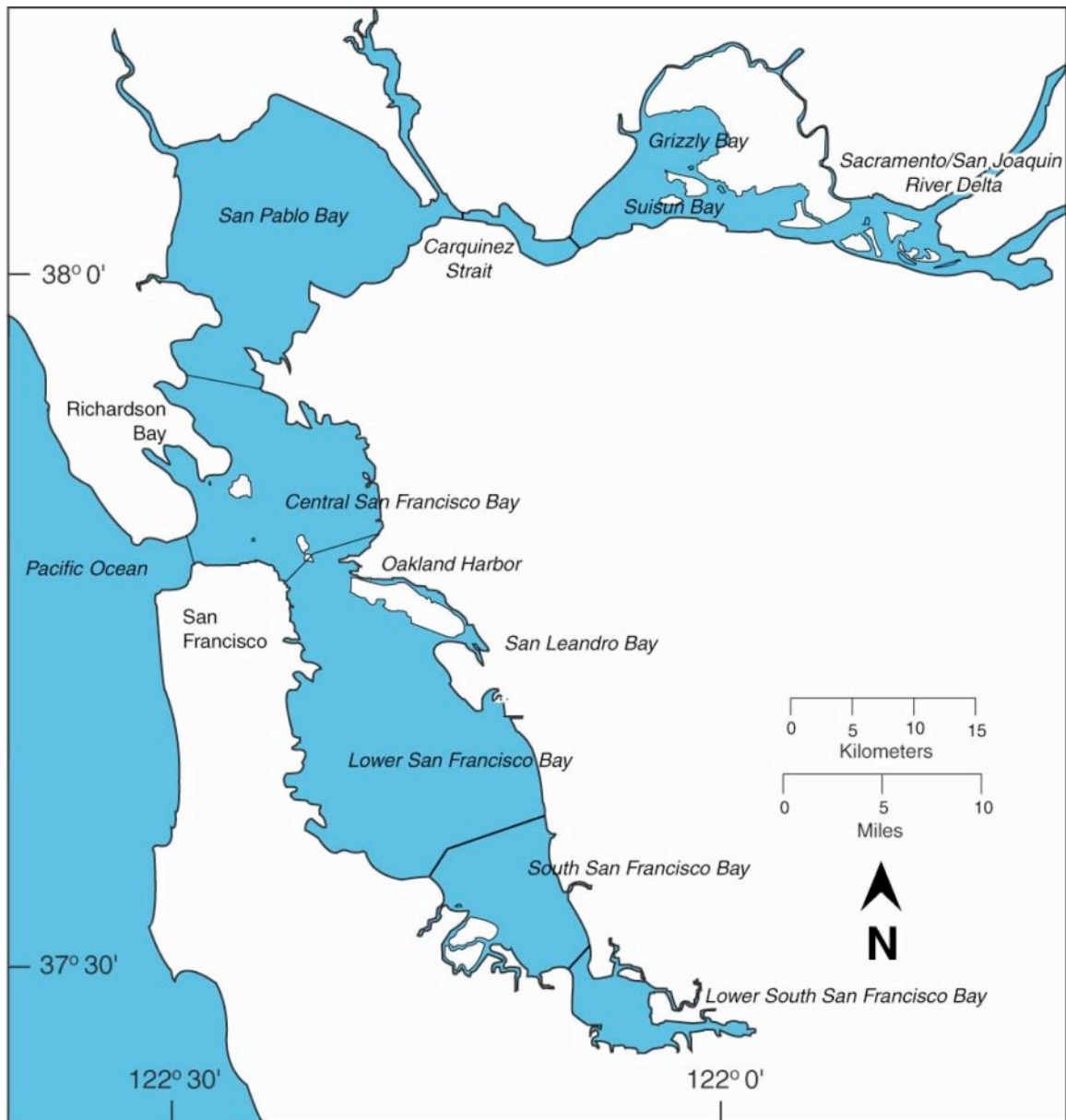
## **1.2 San Francisco Bay**

San Francisco Bay is located on the central coast of California. It is the largest estuary on the West Coast of the United States, draining a watershed of 60,000 square miles. Much of the Bay is shallow, and the average depth is only about 14 feet. At its deepest, however, the Bay is more than 300 feet deep.

The federal and state regulatory bodies divide San Francisco Bay into eight segments: Sacramento /San Joaquin River Delta, Suisun Bay, Carquinez Strait, San Pablo Bay (including Castro Cove), Richardson Bay, Central San Francisco Bay (including Oakland Harbor and San Leandro Bay), Lower San Francisco Bay, and South San Francisco Bay (Figure 1-1).

The Bay is a popular fishing location, visited by thousands of anglers every year. The Bay is also important habitat for wildlife, including birds and marine mammals. The Bay is a staging and wintering area for approximately one million migratory waterfowl and one million shorebirds and also provides breeding habitat for many bird species. The Bay also supports a significant resident breeding population of Pacific harbor seals (Grigg, 2003).

The Water Quality Control Plan for the region (SFRWQCB, 1995) lists the beneficial uses for the Bay (Table 1-1).



*Figure 1-1. San Francisco Bay*

*Table 1-1. Beneficial uses of San Francisco Bay\**

<b>Use</b>	<b>Abbreviation</b>	<b>Definition</b>
Ocean, commercial, and sport fishing	COMM	Uses of water for commercial or recreational collection of fish, shellfish, or other organisms in oceans, bays, and estuaries, including but not limited to, uses involving organisms intended for human consumption
Estuarine habitat	EST	Uses of water that support estuarine ecosystems, including, but not limited to, preservation or enhancement of estuarine habitats, vegetation, fish, shellfish, or wildlife (e.g., estuarine mammals, waterfowl, shorebirds), and the propagation, sustenance, and migration of estuarine organisms.
Industrial service supply	IND	Uses of water for industrial activities that do not depend primarily on water quality, including, but not limited to, mining, cooling water supply, hydraulic conveyance, gravel washing, fire protection, and oil well repressurization
Fish migration	MIGR	Uses of water that support habitats necessary for migration, acclimatization between fresh water and salt water, and protection of aquatic organisms that are temporary inhabitants of waters within the region.
Navigation	NAV	Uses of water for shipping, travel, or other transportation by private, military, or commercial vessels.
Industrial process supply	PRO	Uses of water for industrial activities that depend primarily upon water quality.
Preservation of rare and endangered species	RARE	Uses of waters that support habitats necessary for the survival and successful maintenance of plant or animal species established under state and/or federal law as rare, threatened, or endangered.
Water contact recreation	REC1	Uses of water for recreational activities involving body contact with water where ingestion of water is reasonably possible. These uses included, but are not limited to, swimming, wading, water-skiing, skin and scuba diving, surfing, whitewater activities, fishing, and uses of natural hot springs.
Noncontact water recreation	REC-2	Uses of water for recreational activities involving proximity to water, but not normally involving contact with water where ingestion is reasonably possible. These uses include, but are not limited to, picnicking, sunbathing, hiking, beachcombing, camping, boating, tide pool and marine life study, hunting, sightseeing, or aesthetic enjoyment in conjunction with the above activities.
Shellfish harvesting	SHELL	Uses of water that support habitats suitable for the collection of crustaceans and filter-feeding shellfish (e.g., clams, oysters, and mussels) for human consumption, commercial, or sport purposes.
Fish spawning	SPWN	Uses of water that support high quality aquatic habitats suitable for reproduction and early development of fish
Wildlife habitat	WILD	Uses of waters that support wildlife habitats, including, but not limited to, the preservation and enhancement of vegetation and prey species used by wildlife, such as waterfowl

*\* All beneficial uses do not apply to all Bay segments.*

## 1.3 Legacy Pesticides

The legacy pesticides of concern in San Francisco Bay include:

- **DDTs**—the o,p'- and p,p'-isomers of dichlorodiphenyltrichloroethane. (DDT) and their breakdown products: dichlorodiphenyldichloroethylene (DDE) and dichlorodiphenyldichloroethane (DDD).
- **Chlordanes**—primarily alpha-chlordane, gamma-chlordane, cis-nonachlor, trans-nonachlor, oxychlordane, heptachlor, and heptachlor epoxide.
- **Dieldrin**.

These pesticides are part of the “organochlorine” category of pesticides, which were used as insecticides for agriculture, pest control, and mosquito abatement (Table 1-2).

Table 1-2. Use of legacy pesticides

Pesticide	Start of Use	End of Use	Major uses
Chlordane	1948	1988	Originally used on agricultural crops, lawns, gardens, and as a fumigating agent. Most uses banned in 1978, and after 1983, only used for termite control.
DDT	1939	1972	Broad spectrum insecticide used on agricultural crops, for pest control, and for mosquito abatement.
Dieldrin	1948	1987	Originally used on agricultural crops. After 1974, only used for termite control.

DDT was used in home and agricultural applications and for mosquito abatement beginning in the 1940s. Its use was restricted in California in 1963 (Mischke *et al.*, 1985), and the U.S. banned it for all but emergency public health uses in 1972. Its presence as a manufacturing byproduct in other pesticides was restricted to 0.1% in 1988.

Beginning in the late 1940s, chlordane was used in home and agricultural applications to control termites and other insect populations. Chlordane use was restricted in California in 1975 and throughout the U.S. in 1978. Production and sales ended in 1988.

Beginning in 1950, dieldrin was used on termites and other soil-dwelling insects, as a wood preservative, in moth-proofing clothing and carpets, and on cotton, corn, and citrus crops. Dieldrin was restricted in 1974, and most uses were banned in 1985. Use for underground termite control continued until 1987.

DDTs, chlordanes, and dieldrin are neurotoxins and classified by USEPA as probable human carcinogens. They are persistent in the environment, lipophilic, and subject to biomagnification in aquatic food webs.

## 2. Impairment Assessment

The San Francisco Bay segments have a variety of established beneficial uses, but only a few could be threatened by legacy pesticides (Table 2-1). The current listing cites the beneficial use of sport fishing as impaired for all segments. Effects on rare and endangered species, fish spawning, and wildlife or estuarine communities are also possible.

Table 2-1. Beneficial uses of San Francisco Bay that could be impaired by legacy pesticides.

Use	Abbreviation	Impairment
Ocean, commercial, and sport fishing	COMM	Sport fishing the most likely impairment. Cited as USEPA reason for the current listing.
Preservation of rare and endangered species	RARE	Possible
Fish spawning	SPWN	Possible
Wildlife habitat	WILD	Possible
Estuarine habitat	EST	Possible

This section of the report, the impairment assessment, first reviews the basis for the current impairment listing. The object of this review is not to determine impairment but to provide the background for why legacy pesticides became a concern. The review also introduces some of the methodology and rationale for determining impairment.

The assessment then determines current impairment, using the most recent, available data. The assessment uses the data to determine whether there is a weight of evidence indicating:

- **No impairment:** The available data demonstrate no negative effect on beneficial uses of the Bay, and there is sufficient information to make the finding.
- **Impairment unlikely:** The data indicate that legacy pesticides cause no impairment to the Bay. However, there is some uncertainty, due to lack of sufficient information or disagreement about how to interpret the data.
- **Possible impairment:** There is some suggestion of impairment, but the uncertainties preclude making a definitive judgment.
- **Definite impairment:** The data clearly demonstrate a negative effect on the beneficial uses of the Bay.
- **Unable to determine impairment:** There is insufficient information to make any determination.

The assessment attempts to distinguish possible impairment for individual segments as well as impairment of the Bay as a whole.

## **2.1 Historic Basis for the Impairment Listing**

Legacy pesticides were not included on California's 303(d) list as a result of actions taken by SWRCB or the RWQCB. In fact, the State did not believe that there were sufficient data to warrant a listing. However, USEPA disagreed and added the pesticides to the 1998 list, where they have remained. USEPA found that the State, in having decided not to list the pesticides, had not adequately analyzed the potential human health risk from consumption of seafood (May 12, 1999, letter from A. Strauss to W. Petit and accompanying November 3, 1998 staff report).

Specifically, USEPA found that SWRCB had not adequately addressed available fish tissue data:

*“EPA is identifying dieldrin, chlordane, and DDT for inclusion on the 303(d) list based primarily on the fish consumption advisory of San Francisco Bay which mentions these pesticides.”*

The fish consumption advisory referred to by USEPA is an interim advisory that has been in place since 1994. The Office of Environmental Health Hazard Assessment (OEHHA) issued the advisory, which is directed at consumption of sport fish from San Francisco Bay:

- Adults should consume no more than two meals per month of sport fish from the Bay.
- Adults should not eat striped bass over 35 inches long.
- Pregnant women, nursing mothers, and children under the age of six should limit their consumption of sport fish to one meal per month.
- Pregnant women, nursing mothers, and children under six should not eat striped bass over 27 inches long or shark over 24 inches long.

The interim advisory does not apply to some sport fish, such as salmon, anchovies, herring, and smelt. Neither does it apply to the commercial fisheries (bait shrimp, herring, and Dungeness crabs). It is based on a 1994 study (SFRWQCB *et al.*, 1995), which indicated that the legacy pesticides (DDTs, chlordanes, and dieldrin), as well as PCBs, mercury, and dioxins, were present at levels of potential concern. The study measured contaminants in fish from 13 locations chosen to represent all areas of the Bay, including areas suspected of low or high contamination and locations known to be popular for sport fishing.

The advisory was based on a preliminary review of the data, with OEHHA stating that:

*“More specific advisories and recommendations will be issued when a thorough evaluation of the study data is completed by OEHHA in conjunction with other public agencies.”*

One issue that could not be resolved by a data review was whether the advisory could be issued for specific locations instead of for the entire Bay. Different species were caught at different locations, making comparisons among stations difficult. OEHHA has reviewed data from subsequent rounds of fish sampling in 1997 (Davis *et al.*, 2002) and 2000 (Greenfield *et al.*, 2003) and has left the interim advisory in place.

The USEPA decision to include the pesticides also cited a comment that had been received on the proposed 303(d) list:

*“Some additional information is in the record concerning contamination of San Francisco Bay fish by dieldrin, chlordane, and DDT. An EPA assessment of fish consumption risk found that dieldrin, chlordane, and DDT are responsible for a total of 9.9% of the total increased cancer risk due to consumption of Bay fish. This risk assessment found that the individual lifetime cancer risk associated with these three pesticides is in the range of  $2.0\text{--}3.9 \times 10^{-5}$ , about an order of magnitude higher than generally recognized ‘acceptable’ cancer risk of  $10^{-6}$ . This information provides support to the finding that dieldrin, chlordane, and DDT are contributing to the impairment of the fish consumption beneficial use. EPA has concluded that the fish consumption beneficial use of San Francisco Bay is being impaired, and that narrative standards which prohibit the discharge of toxic pollutants in amounts which adversely affect beneficial uses are not being met.”*

The risk assessment referred to by USEPA was prepared as part of the analysis of the implementation of the California Toxics Rule (CTR; USEPA, 1997 and presented in USEPA, 1999), and it relied on the same pilot study that OEHHA used to develop the interim fish consumption advisory (Table 2-2).

Table 2-2. Factors used in USEPA assessment of risk for recreational anglers consuming San Francisco Bay fish (from USEPA, 1999)

Factors	Source
Fish consumption rates	Median fish consumption rate of 21.4 g/day and 90 <sup>th</sup> percentile consumption rate of 107.1 g/day, based on Santa Monica Seafood Study (MBC Applied Environmental Services, 1994)
Fish contaminant concentrations	Bay Protection and Toxic Cleanup Program to measure concentrations of contaminants in fish (SFRWQCB <i>et al.</i> , 1995)
Species-weighted contaminant concentrations	National Marine Fisheries Services Marine Recreational Fishing Statistics Survey of the Pacific Coast for 1987, 1988, 1989, and 1993: <ul style="list-style-type: none"> <li>▪ White croaker 43%</li> <li>▪ Surf perch 35%</li> <li>▪ Striped bass 13.9%</li> <li>▪ Shark 8%</li> </ul>
Baseline risk levels	USEPA, 1989, assuming length of residences of 70 years and body weight of 70 kg

The results cited in the USEPA decision to add legacy pesticides to the 303(d) list reflected their calculated risks associated with the 90<sup>th</sup> percentile fish consumption rate of 107.1 g/day (Table 2-3).

Table 2-3. Baseline cancer risks for recreational anglers consuming San Francisco Bay fish cited in reason for listing (from USEPA, 1999)

Contaminant	Individual Excess Lifetime Cancer Risk	
	Average Consumption (21.4 g/day)	90 <sup>th</sup> Percentile Consumption (107.1 g/day)
4,4-DDT	$4.9 \times 10^{-6}$	$2.4 \times 10^{-5}$
Chlordane	$3.9 \times 10^{-6}$	$2.0 \times 10^{-5*}$
Dieldrin	$7.8 \times 10^{-6}$	$3.9 \times 10^{-5*}$

\* values cited in the USEPA decision to list San Francisco Bay as impaired by legacy pesticides

## 2.2 Current Conditions

The USEPA decision to list San Francisco Bay as impaired by legacy pesticides relied on fish tissue data collected in 1994. Since then, additional data have been collected. Because the 303(d) listing focuses on fish tissue data, this section of the report begins with a review of fish and shellfish data. The report then evaluates other relevant data: water quality, sediments, and wildlife health. For each of these data sets, the assessment presents:

- The relevant **regulatory standards**, if there are any, focusing on the best local standards, but including a discussion of alternatives and national or historic standards when needed for context.
- **Available data**, interpreted relative to the standards.
- A discussion of whether the data are **indicative of impairment**.

## 2.2.1 Fish and Shellfish

### **Fish and Shellfish Standards**

There are no state or federal standards for contaminant levels in fish and shellfish caught in the sport fishery. The U.S. Food and Drug Administration (FDA) does have standards, called “action levels,” for DDTs, chlordanes, and dieldrin (Table 2-4). These action levels are designed to regulate commercial rather than recreational fisheries—they are administrative guidelines that define the levels at which FDA may take action to remove a food item from the marketplace. In San Francisco Bay, the greater concern is for the sport fishery.

Table 2-4. FDA action levels for legacy pesticides

Contaminant	FDA Action Level (ppm)
DDTs	5.0
Chlordanes	0.3
Dieldrin	0.3

FDA and USEPA believe that FDA action levels are insufficient to protect recreational and subsistence anglers from contaminants in fish and shellfish. Therefore, USEPA has issued guidance for states to use in developing their own screening values for recreational fish and shellfish (USEPA, 2000a, b). These screening values are not meant to be regulatory standards, but rather indicators that more intensive site-specific monitoring and/or evaluation of human health risk should be conducted.

Volume 1 of that guidance presents an equation for calculating screening values for carcinogens:

$$\text{Screening value} = [(\text{Risk level}/\text{Cancer slope factor}) \times \text{Body weight}] / \text{Consumption rate}$$

where

**Screening value** = Screening value for a carcinogen (µg/g; ppm)

**Risk level** = Maximum acceptable risk level (unitless)

**Cancer slope factor** = Oral cancer slope factor (mg/kg-d)<sup>-1</sup>

**Body weight** = Mean body weight of general population of concern (kg)

**Consumption rate** = Mean daily consumption rate of the species of interest by the general population of concern over a 70-year lifetime (kg/d)

Each factor in the equation is open to some interpretation:

**Risk level:** USEPA (2000a) uses an acceptable risk level of 10<sup>-5</sup>, that is, a level of risk not to exceed one excess case of cancer per 100,000 people over a 70-year lifetime. However, states can use other levels—values

ranging from  $10^{-4}$  to  $10^{-7}$  are typical (one additional cancer in 10,000 to 10,000,000 people); the risk assessment cited in the listing decision used  $10^{-6}$ . USEPA regards choice of an acceptable risk level as a management rather than a scientific issue (USEPA, 2000a). This report uses  $10^{-5}$  and also discusses the implications of using  $10^{-6}$ , a more protective level.

**Cancer slope factor:** Two sets of cancer slope factors are currently used in California: those adopted by the California Toxics Rule (CTR) and currently used by OEHHA and those cited by USEPA for nationally recommended water quality criteria and available from the Integrated Risk Information System (IRIS) at [www.epa.gov/iris/subst/index.html](http://www.epa.gov/iris/subst/index.html). Cancer slopes for DDT and dieldrin are identical in the two datasets. USEPA recommends a lower slope factor for chlordane. Although the CTR values have the weight of regulatory standards, the IRIS values are the more recent and scientifically defensible. Therefore, the IRIS values are used for this assessment.

**Body weight:** USEPA uses 70 kg (154 pounds) as representative of all adults, with adult males weighing 78 kg (172 pounds) and adult females weighing 65 kg (143 pounds).

**Consumption rate:** Of all the factors used in calculating screening values, fish consumption rates may be the most controversial. USEPA's decision to include legacy pesticides on the 303(d) list was largely based on a risk assessment that assumed consumption of 107.1 grams of fish per day (about 14 meals per month). That 107.1 g/day consumption rate was the 90<sup>th</sup> percentile consumption rate measured in the Santa Monica Seafood Study (MBC Applied Environmental Services, 1994), a widely cited study of seafood consumption rates. The median consumption rate calculated by the study was 21.4 grams of fish per day (about three meals per month).

The Santa Monica Seafood Study is not the only source of data on fish consumption rates for sport fish. In its guidance for assessing data for use in fish advisories (USEPA, 2000a), USEPA recommends using 17.5 g/day, a value taken from a 1994 and 1996 U.S. Department of Agriculture study of food intake. In another application, the development of water quality criteria, USEPA used 6.5 g/day, based on data from a 1973-1974 study of per capita consumption of freshwater and estuarine fish and shellfish.

Fortunately, there is local information for San Francisco Bay. The San Francisco Seafood Consumption Study (SFEI, 2000) surveyed more than 1,000 recreational anglers from party boats, private boats, and popular shore-based sites to determine catch and consumption rates. Of those interviewed, 87% reported that they had eaten Bay fish at some time, and

13% said that they had not. Of those who had consumed fish from the Bay, 47% reported having eaten it within the past four weeks.

Table 2-5 presents consumption rates calculated for several groups:

- **Recent consumers**, that is, anglers who had consumed fish caught in San Francisco Bay during the four weeks prior to being interviewed.
- **Recent consumers, adjusted for “avidity,”** a measure of how frequently anglers go fishing. Statistically, anglers who fish often would be more likely to be over-sampled by the survey, and infrequent anglers would be under-represented. The avidity adjustment corrects for the over- and under-sampling.
- **All anglers, based on a “four-week recall,”** that is, the angler’s memory of fish consumption over the previous four weeks (adjusted for avidity).
- **All anglers, based on a twelve-month recall** (these data could not be adjusted for avidity).

*Table 2-5. Fish consumption rates in g/day, calculated by the San Francisco Seafood Consumption Study (SFEI, 2000)*

Subset of anglers	Median (50 <sup>th</sup> percentile)	95 <sup>th</sup> percentile
Recent consumers (not adjusted for avidity)	16.0	108
Recent consumers (adjusted)	16.0*	80
All consumers, four-week recall (adjusted)	0.0	32.0*
All consumers, twelve-month recall (not adjusted)	2.5	44.2

\* values used in this impairment assessment

The Clean Estuary Partnership has suggested centering the impairment assessment on consumption rates of 16 and 32 grams of fish per day as representative of median and 95<sup>th</sup> percentile consumption rates (CEP Technical Committee Special Meeting, Review of CMIA Reports, April 2, 2004).

Besides the total amount of fish eaten, there is also discussion about the species that make up the diets of recreational anglers and their families and friends. The USEPA decision to list the pesticides cited a mix of several species: 43% white croaker, 35% surf perches, 13.9% striped bass, and 8% sharks. These relative values were based on the National Marine Fisheries Services (NMFS) Marine Recreational Fishing Statistics Survey of the Pacific Coast for 1987, 1988, 1990, and 1993. USEPA assumed that the species proportions were the same for fishing catches and consumption.

The most recent NMFS data for Northern California, from 2002 ([www.st.nmfs.gov](http://www.st.nmfs.gov)) indicate a different recreational fishery, with catches made up of 3% white croaker, 3% surf perches, 26% striped bass, and 5% sharks (statistics are by weight for northern California inland marine and estuarine waters). Further, catch rates do not necessarily dictate consumption rates. The San Francisco Seafood Study examined the species composition of the meals consumed by recreational anglers and their families and friends. Among the 87% of survey respondents who said they had consumed Bay fish, about three fourths said they ate striped bass, while fewer people ate other species. Only 16% ate white croaker, and 4% ate shiner surfperch.

One cautionary note—while local data on fish consumption are valuable, it is important to remember that the interim fish advisory could affect consumption rates. Sixty percent of San Francisco Seafood Study respondents who identified themselves as consumers said that they were aware of the advisory, although only 6% understood the recommendation to limit consumption to two meals per month. Consumers who ate more fish than recommended were more likely to demonstrate a poor understanding of the advisory than those who consumed less fish. How consumption rates would change in absence of the advisory is unknown.

The ranges of factors that could be used to calculate screening values are presented in Tables 2-6a through 2-6e. Those data can be used to calculate a wide range of screening values. Screening values based on a maximum risk level of  $10^{-5}$  are included in Table 2-6e. Values based on  $10^{-6}$  would be ten times lower than those presented in the table. It is important to remember that although selected values are used in this assessment, they are not standards, and the methodology for calculating the values was not prepared as guidance for determining impairment of waterbodies.

Table 2-6a. Maximum risk level used to calculate screening values

	Acceptable risk level
Many studies	$10^{-4}$ to $10^{-7}$

Table 2-6b. Cancer slope factors used to calculate screening values

	DDT	Chlordane	Dieldrin
CTR	0.34	1.3	16
IRIS	0.34	0.35	16

Table 2-6c. Body weight used to calculate screening values

	Body weight
All studies	70 kg

Table 2-6d. Sources of fish consumption data

Consumption rate (g/day)	Source
107.1	90 <sup>th</sup> percentile value from Santa Monica Seafood Study. Cited in USEPA listing decision
32	95 <sup>th</sup> percentile of all consumers based on 4-week recall (SFEI, 2000)
21.4	Median value from Santa Monica Seafood Study
17.5	Average value from U.S. Department of Agriculture studies and recommended for calculating screening values (USEPA, 2000b)
16	Median value for recent consumers in San Francisco Bay (SFEI, 2000)
6.5	USEPA data from 1973-1974 for per capita freshwater/estuarine finfish and shellfish
0	Median value for all consumers of San Francisco Bay fish, based on 4-week and 12-month re-call (SFEI, 2000)

Table 2-6e. Fish screening values(risk level of  $10^{-5}$ ; values used in this report are in bold)

	Consumption rate (g/day)	DDT ppb	Chlordane ppb	Dieldrin ppb
CTR cancer slope factors	107.1	19	5.0	0.4
	32	<b>65</b>	17	<b>1.4</b>
	21.4	96*	25*	2.0*
	17.5	120	31	2.5
	16	<b>130</b>	34	<b>2.7</b>
	6.5	320	83	6.7
IRIS cancer slope factors	107.1	No change	19	No change
	32		<b>62</b>	
	21.4		93	
	17.5		114	
	16		<b>120</b>	
	6.5		310	

\* Brodberg and Pollack (1999) used these values rounded to one significant figure (DDT = 100; chlordane = 30; dieldrin = 2); those values have also been used in RMP reports, e.g., Greenfield et al., 2003.

### **Fish and Shellfish Data**

The 1994 study that led to the interim health advisory for people consuming fish from San Francisco Bay was a pilot project conducted by the Bay Protection and Toxic Cleanup Program to measure concentrations of contaminants in fish (SFRWQCB *et al.*, 1995). As a follow-up to that program, the San Francisco Estuary Regional Monitoring Program (RMP) began to monitor contaminants in sport fish from the Bay. Sampling and analysis occur every three years. Analyses have been completed for 1997 and 2000 (Davis *et al.*, 1999, 2002; Greenfield *et al.*, 2003). Sampling was also conducted in 2003, but results are not yet available. Special studies augment the core sampling effort.

The RMP focuses on seven of the most popular sport fish species taken from the Bay and consumed by the anglers (SFEI, 2000) (Table 2-7):

Table 2-7. Fish monitored by the RMP and percent anglers that consume each species

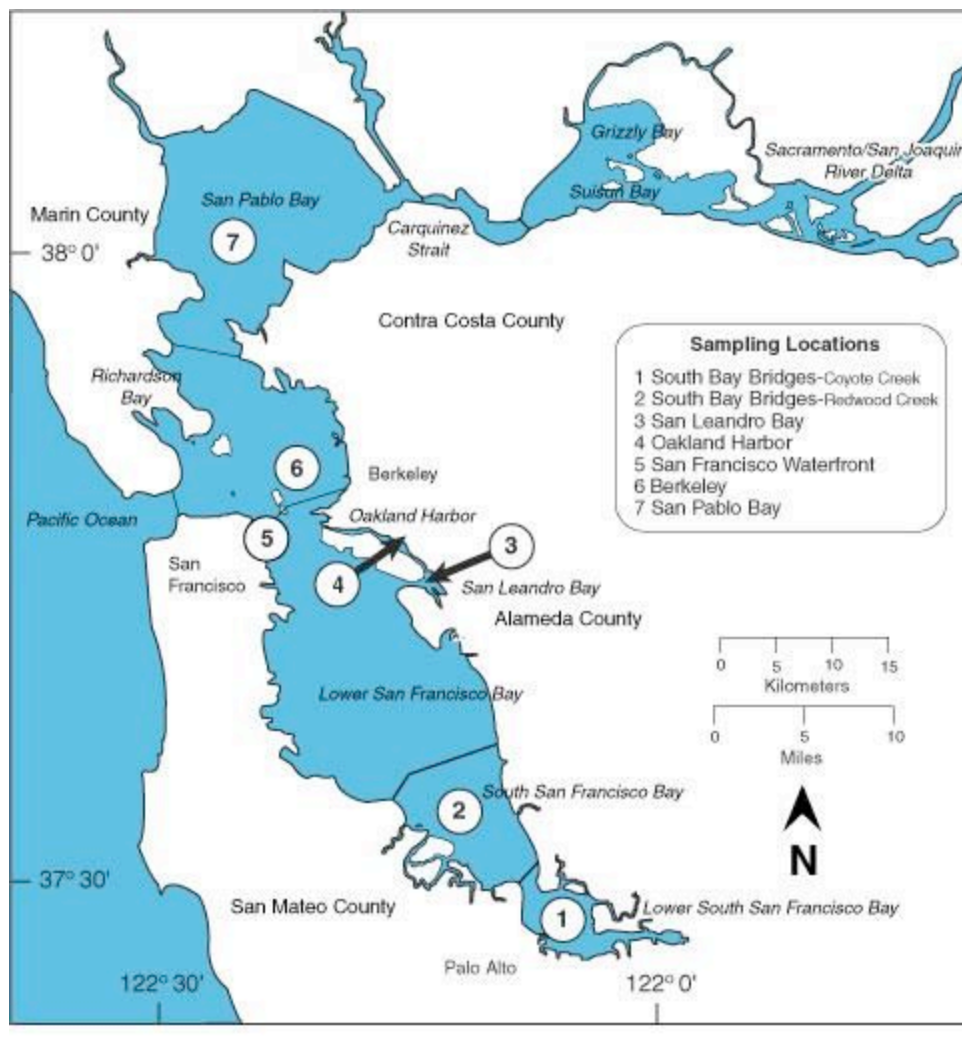
Common name	Scientific name	Percent anglers consuming
Jacksmelt	<i>Atherinopsis californiensis</i>	17
Shiner surfperch	<i>Cymatogaster aggregate</i>	4
White croaker	<i>Genyonemus lineatus</i>	16
Striped bass	<i>Morone saxatilis</i>	74
California halibut	<i>Parlichthys californicus</i>	24
Leopard shark	<i>Triakis semifasciata</i>	6
White sturgeon	<i>Acipenser transmontanus</i>	17

Sampling locations for 2000 (Figure 2-1) included popular fishing areas:

- San Pablo Bay
- Berkeley
- San Francisco Waterfront
- Oakland Harbor
- San Leandro Bay
- Two South Bay Bridges sites: Redwood Creek and Coyote Creek

The program has not sampled fish from the most northern segments of the Bay: Carquinez Strait, Suisun Bay, or the Sacramento/San Joaquin Delta.

Because of the popularity of crabbing and clamming in the region, the rock crab (*Cancer productus*) and Japanese littleneck clam (*Tapes japonica*) were subjects of a special study in 2000. Crabs were taken from three locations in the Central Bay. Clams were collected from two sites that had been identified as popular for clamming, the South Bay at Burlingame and Oakland Harbor at the Fruitvale Bridge.



*Figure 2-1. RMP fish sampling locations*

Fish fillets were prepared for analysis using methods that mimicked those used by many people who cook and consume each species—that is, jacksmelt and shiner surfperch had their heads, tails, and guts removed, leaving the muscle, skin, and bones. White croaker samples included muscle and skin, but no bones. Striped bass, halibut, leopard shark, and white sturgeon samples included only muscle. (A complete discussion of consumption methods by fish species and angler ethnicity, income, and education can be found in SFEI, 2000.) Samples were composited for analysis.

Eighty samples were analyzed in 2000. Results are presented in Figure 2-2. Contaminant concentrations of DDTs, chlordanes, and dieldrin were highest in shiner surfperch and white croaker, possibly due to lipid content—the fish with

the highest lipid content, the fattiest fish, had the highest concentrations of legacy pesticides (Greenfield *et al.*, 2003). Most of the dieldrin measurements fell below the detection limits, 2.0 ng/g, making evaluation of dieldrin difficult.

Using screening values that assumed a risk level of  $10^{-5}$  and consumption of 16 grams of fish per day, no samples from 2000 exceeded screening values for DDTs or chlordanes. Two samples exceeded the screening value for dieldrin: one white croaker and one shiner surfperch sample. Using the more protective values based on 32 grams of fish per day, almost half the white croaker samples exceeded the screening level for DDTs. No samples exceeded the screening values for chlordanes. The more protective screening value for dieldrin was lower than the detection limit, so all fish with detectable dieldrin exceeded the value (three shiner surfperch and four white croaker samples). No clams or crabs muscle samples exceeded screening values. Two crab hepatopancreas samples from the San Francisco waterfront exceeded the DDT level based on consumption of 32 grams of seafood per day. Were the more protective value of  $10^{-6}$  used, most samples would exceed screening values for both 16 and 32 grams of fish per day.

The 2000 fish data provided few insights into geographic patterns (Greenfield *et al.*, 2003). Figure 2-3 shows the 2000 DDT data by geographic region. Whereas concentrations of legacy pesticides might be expected to be highest in the South Bay, where there is less flushing than in other segments, the data show no such pattern. For white croaker, DDT concentrations were highest in fish from San Pablo Bay. Conversely, San Pablo Bay samples had the lowest DDT concentrations for shiner surfperch.

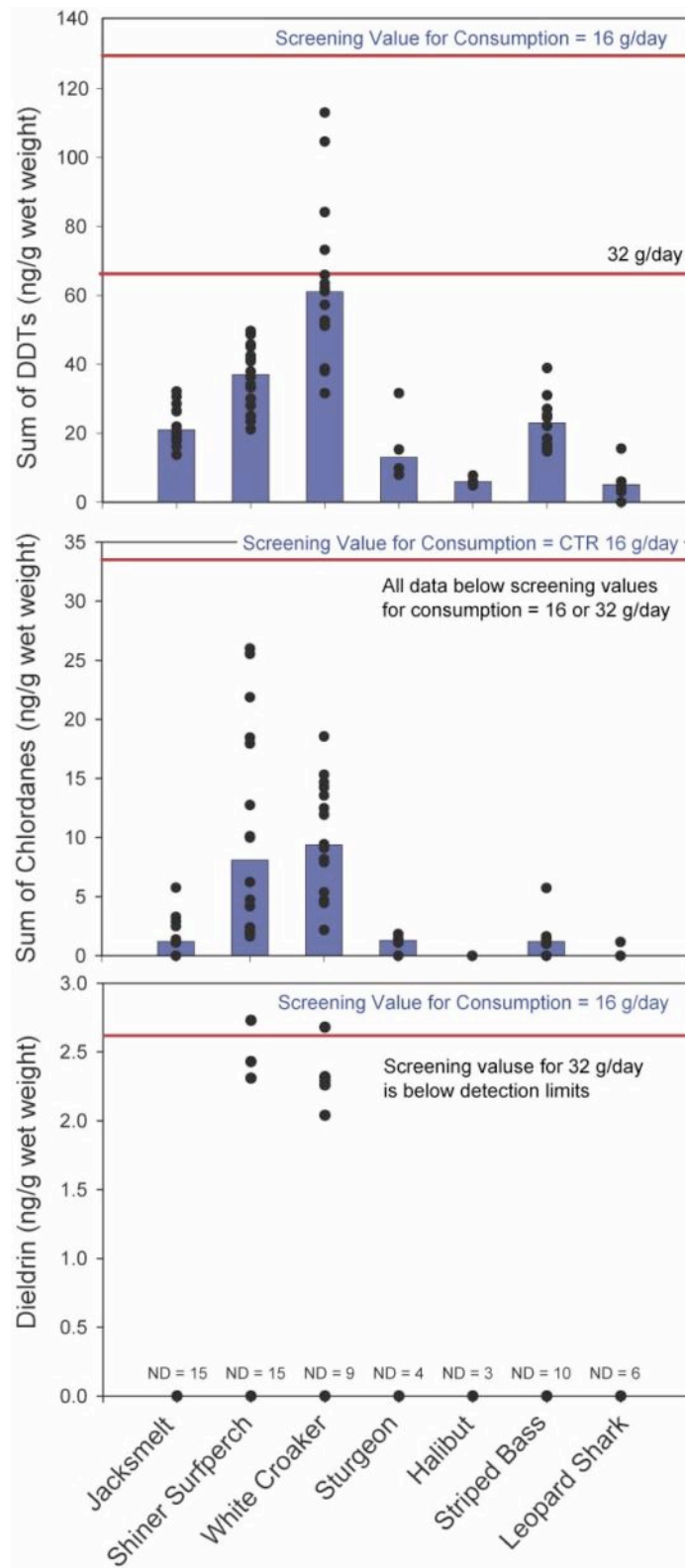


Figure 2-2. DDT, chlordane, and dieldrin concentrations in fish compared to screening levels

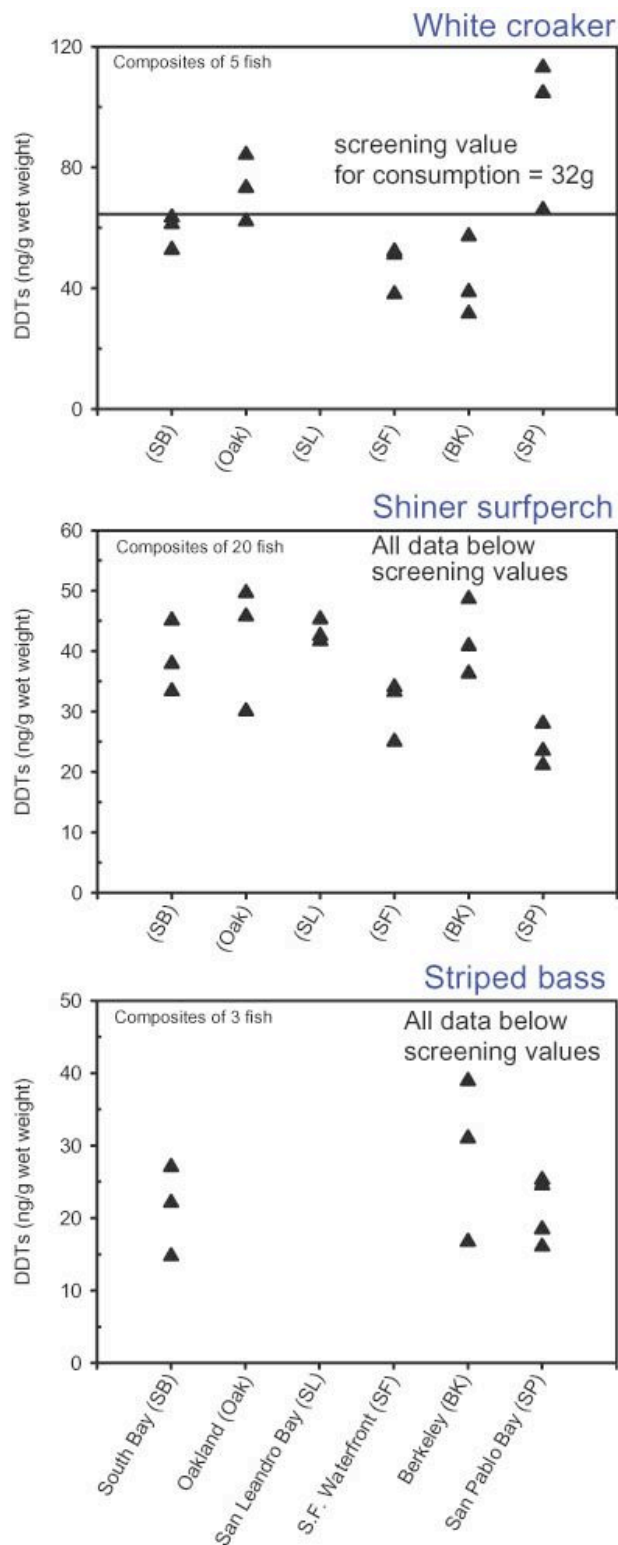
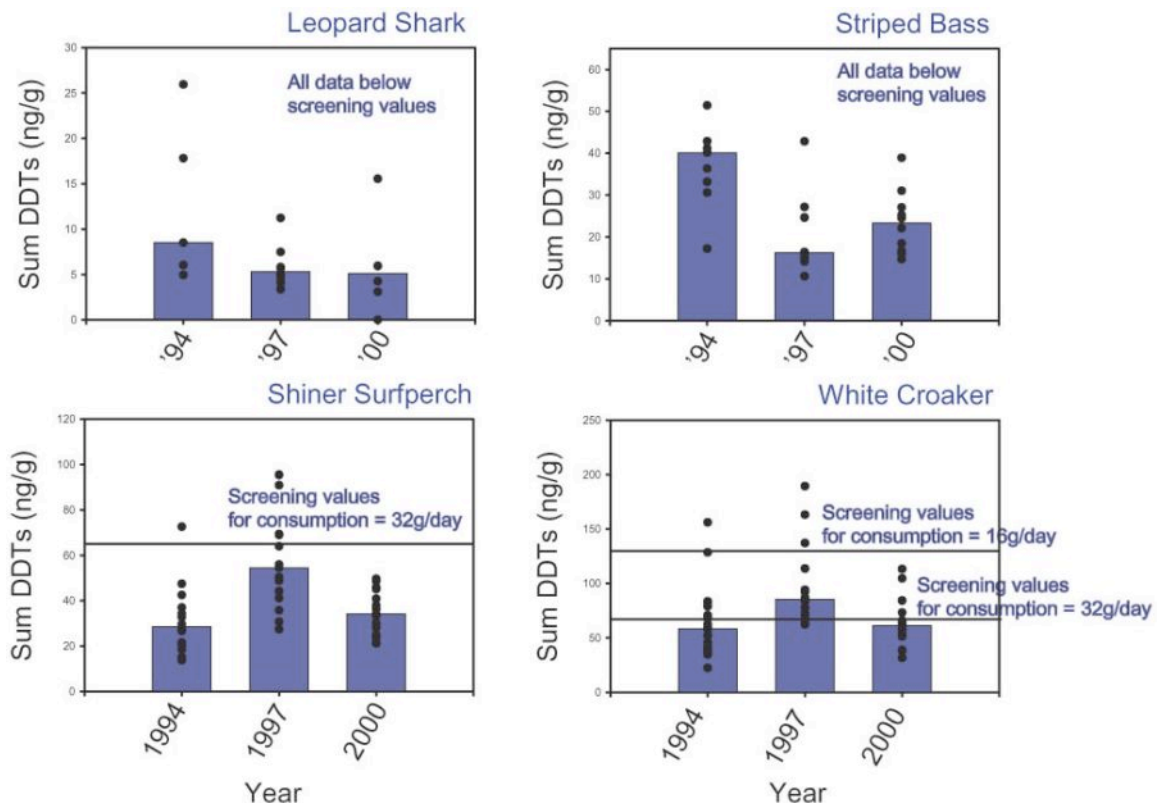


Figure 2-3. Geographic patterns in pesticide concentrations in fish tissues

There were also no consistent spatial patterns for chlordanes, although concentrations of chlordanes in jacksmelt and shiner surfperch were higher in fish from South Bay, San Leandro Bay, and Oakland Harbor than in those from other areas (data not shown). For dieldrin (data also not shown), the highest white croaker concentrations occurred in fish from Oakland Harbor and the South Bay bridges. The highest shiner surfperch concentrations occurred in fish from San Leandro Bay.

Comparison of data from 1994, 1997, and 2000 shows no clear pattern of declines in pesticide concentrations (Figures 2-4, 2-5). For DDTs, concentrations in striped bass and leopard shark did show some decline over the time period. However, concentrations in shiner surfperch and white croaker were highest in 1997. Concentrations of chlordanes in striped bass, white croaker, and leopard shark also declined from 1994-2000, while in shiner surfperch, concentrations were highest in 1997. There are insufficient RMP data to examine temporal trends in dieldrin concentrations.



*Figure 2-4. Temporal patterns of DDT concentrations in fish tissue*

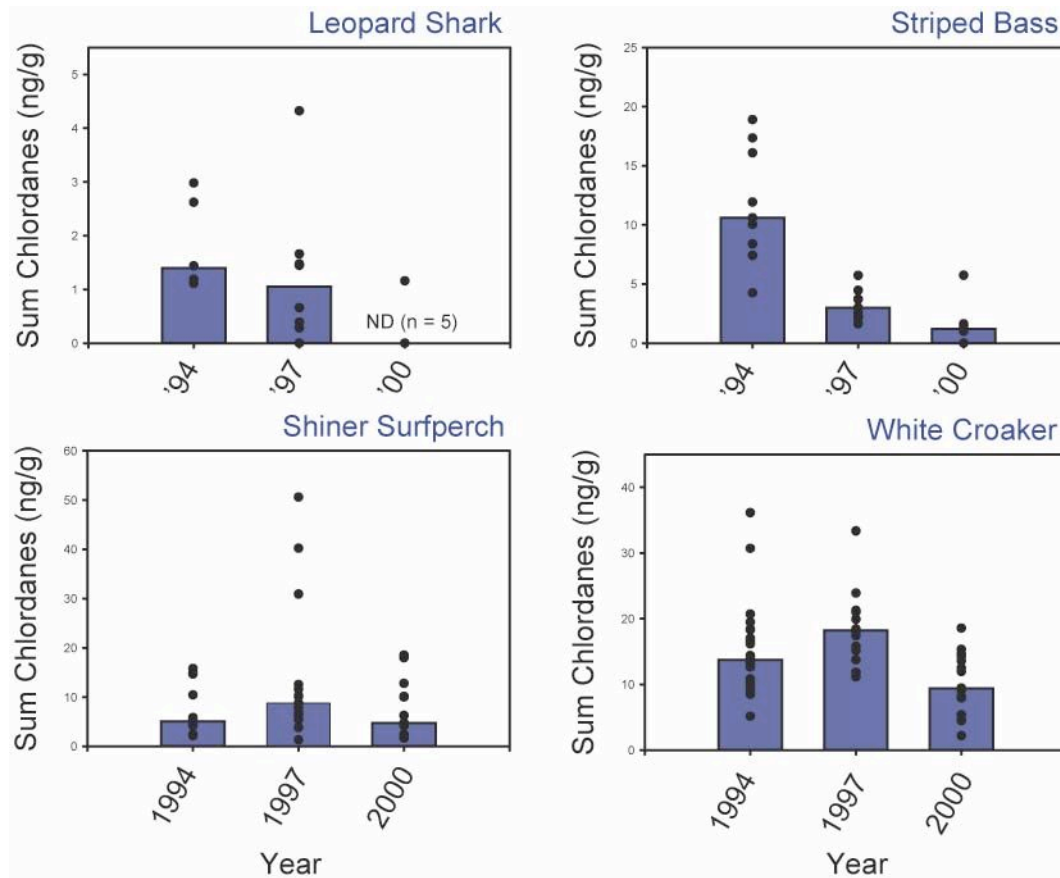


Figure 2-5. Temporal patterns of chlordane concentrations in fish tissue

Longer-term data for legacy pesticides in Bay fish are available from several sources, dating back to 1965. Over this longer time period, the compiled information tells a story of declines in legacy pesticide concentrations in Bay fish and shellfish. Concentrations of DDTs in shiner surfperch analyzed in 1965 had a median concentration of 1100 ng/g, approximately 40 times higher than the median concentration measured in 2000 (Greenfield *et al.*, 2003). Likewise, long-term data show significant declines in DDTs and, to a lesser extent, chlordanes in white sturgeon (Figure 2-6). Shellfish data have shown similar declines.

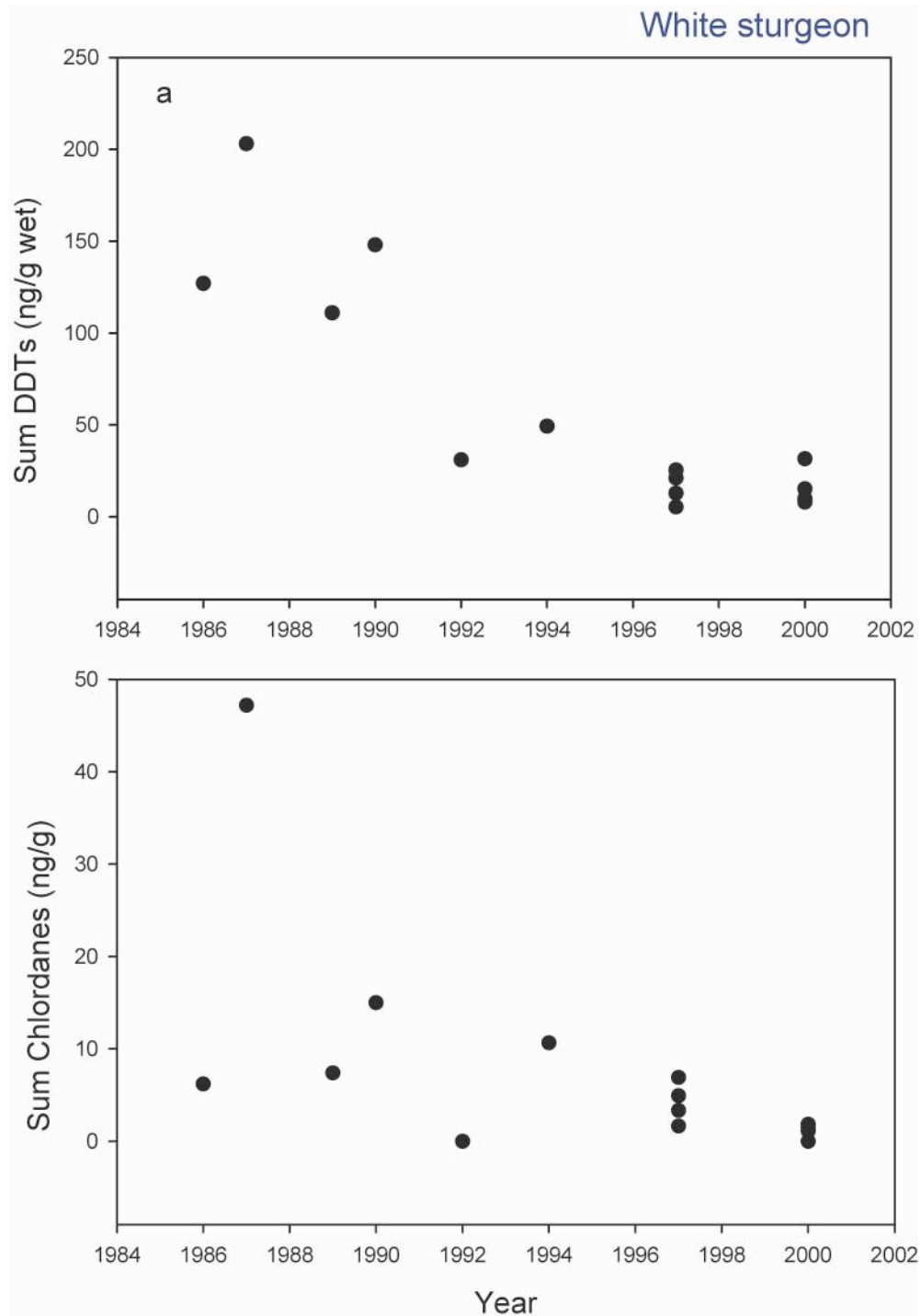


Figure 2-6. Long-term trends in pesticide concentrations in white sturgeon

### **Fish and Shellfish Data as Indicators of Impairment**

The fish and shellfish data indicate **possible impairment** of recreational fishing by DDTs and dieldrin and **impairment unlikely** by chlordane. However, the uncertainties preclude making a definitive judgment. Data from the 2003 program should be incorporated into the assessment as soon as they are available.

Additionally, there are varied areas of uncertainty and potential issues for additional research:

- **There are no regulatory standards for impairment.** The screening values calculated for this report have no regulatory standing. For screening values based on a consumption rate of 32 g/day, there are indications of possible impairment by DDTs and dieldrin. For screening values based on a consumption rate of 16 g/day, only dieldrin would appear to impair the fishery. Use of a different risk levels has an even greater effect on interpretation. Adoption of regulatory standards would allow a more definitive statement of impairment.
- **For dieldrin, the analytical detection limits are too high.** Concentrations of dieldrin in most samples analyzed by the RMP were below detection limits. Further, the screening value based on a fish consumption rate of 32 grams per day, was also below the detection limit. This analytical constraint makes data interpretation impossible.
- **Fish tissue data come from only six locations, making segment-specific impairment impossible to determine.** Ideally, impairment would be established separately for each segment of San Francisco Bay. The RMP data do not allow for a segment-by-segment review. There are no data at all from the Carquinez Strait, Suisun Bay, or the Sacramento/San Joaquin Delta. Water quality data, presented in Section 2.2.2, may provide a surrogate measurement for geographic patterns in fish concentrations, and additional fish collection, particularly from areas known to be contaminated and known as fishing spots, would be useful.
- **Indication of impairment comes from white croaker and shiner surfperch, which are eaten by relatively few anglers.** SFEI (2000) found that only 16% of anglers consumed white perch, and 4% ate shiner surfperch. (The USEPA studies that led to the 303(d) listing of the compounds assumed that the recreational fish diet was 43% white croaker and 35% surfperch.) Further investigation of consumption rates by species would be useful.
- **“Hot spots” have not been characterized.** Presence of hot spots may have a bearing on the effects of human consumption of contaminated fish. The location of hot spots in urban areas may have a disproportionate effect on subsistence anglers, who depend upon fishing for food.

## **2.2.2 Water Quality**

### ***Water Quality Standards***

There are two major types of water quality criteria: those designed to protect aquatic life and those aimed at protecting human health. Failing to meet the water quality criteria for the protection of aquatic life could indicate impairment of beneficial uses such as wildlife or estuarine habitat. Failure to meet water quality criteria for the protection of human health (salt and fresh water; organisms only,

meaning those criteria that are designed to protect human consumption of fish and shellfish) can be an indication of impairment of commercial or recreational fishing. Regulatory water quality standards to protect aquatic life and human health are listed in the California Toxics Rule (CTR; USEPA, 2000c) (Table 2-8).

Table 2-8. California Toxics Rule water quality criteria in µg/l

Parameter	Aquatic Life				Human Health	
	Fresh Water		Salt Water		Fresh Water	Salt & Fresh Water
	1-hour	4-day	1-hour	4-day	Water & Organisms	Organisms Only
p,p'-DDD	-	-	-	-	0.00083	0.00084
p,p'-DDE	-	-	-	-	0.00059	0.00059
p,p'-DDT	1.1	0.001	0.13	0.001	0.00059	0.00059
Chlordane	2.4	0.0043	0.09	0.004	0.00057	0.00059
Dieldrin	0.24	0.056	0.71	0.0019	0.00014	0.00014

Recently, USEPA published an updated compilation of nationally recommended water quality criteria (USEPA, 2002c). The recommendations include decreases in the criteria to protect human health for DDTs and dieldrin and an increase for chlordane (Table 2-9). These recommended criteria have not yet been adopted by California. However, since they are the most up-to-date and scientifically defensible numbers available, they are used in this impairment assessment.

Table 2-9. Current California Toxics Rule vs. USEPA nationally recommended water quality criteria for the protection of human health in salt and fresh waters (organisms only, data in µg/l)

Parameter	Human Health Salt & Freshwater Organisms Only	
	Current	Proposed
p,p'-DDD	0.00084	0.00031
p,p'-DDE	0.00059	0.00022
p,p'-DDT	0.00059	0.00022
Chlordane	0.00059	0.00081
Dieldrin	0.00014	0.000054

### Water Quality Data

The best available data set for assessing water quality is the RMP, which has monitored water quality and compared results to standards since 1993. Through 2001, monitoring was conducted at 21 sites located throughout the Estuary (Leatherbarrow *et al.*, 2003). The program has focused on several regions: rivers (that is, the Sacramento and San Joaquin rivers), Northern Estuary, Central Bay, South Bay, and the Estuary interface at the Standish Dam and the Guadalupe River (Figure 2-7).



*Figure 2-7. 2001 RMP water quality stations*

In 2002, the RMP implemented a new monitoring design, designed to provide greater spatial coverage and include both shallow areas and deep channels. This new design resulted in sampling 33 stations, 28 of which were randomly selected and located within the five major hydrographic regions of the Estuary: Suisun Bay, San Pablo Bay, Central Bay, South Bay, and Lower South Bay. Additional stations were in the Sacramento/San Joaquin River Delta, upstream from the Lower South Bay in San Jose and Sunnyvale, and outside the Golden Gate. The new design includes sampling only during the dry season, so as to remove variability caused by flushing during major rainstorms.

The concentrations of legacy pesticides in water monitored by the RMP have consistently been much lower than the criteria for the protection of aquatic life. Concentrations have at times exceeded the criteria for protection of human health, so this assessment of pesticides focuses on those standards.

Region-wide, from 1993-2001, the RMP has measured exceedances of CTR water quality standards in 5-20% of DDTs, chlordanes, and dieldrin samples (Figure 2-8). Adoption of the recommended national water quality criteria would increase the Bay-wide exceedances of DDTs and dieldrin samples considerably. For example, under the USEPA nationally recommended criteria, 45% of the dieldrin samples have been in exceedance.

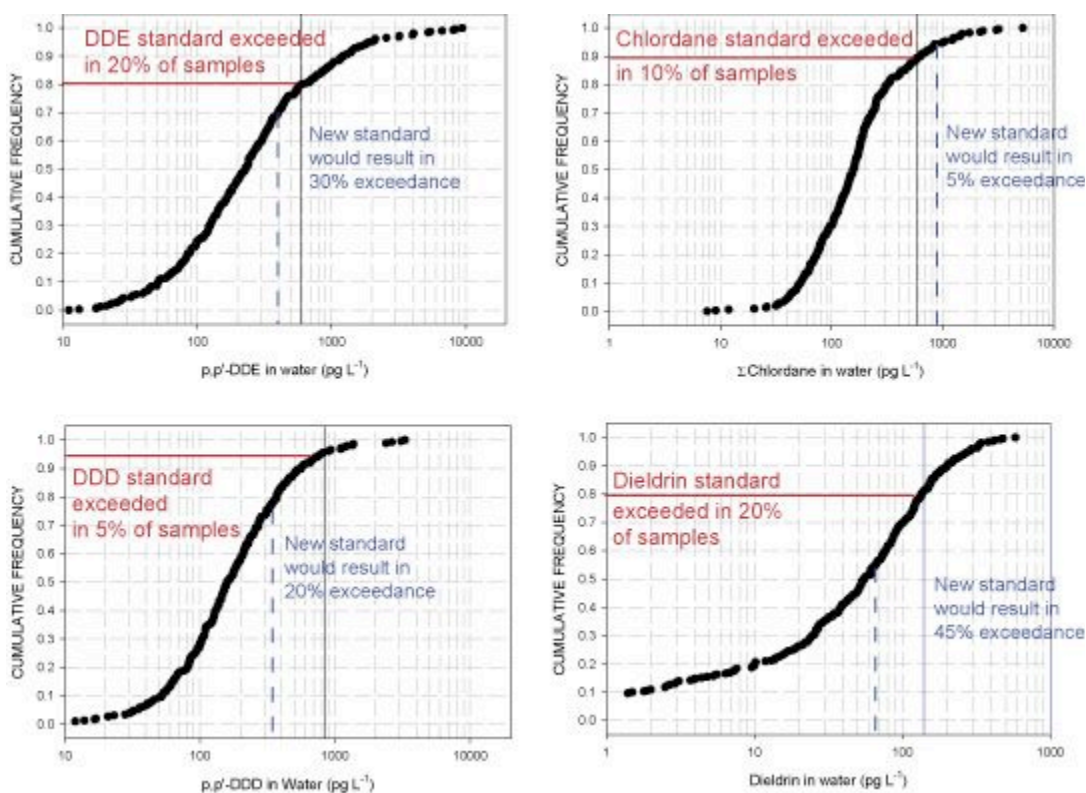


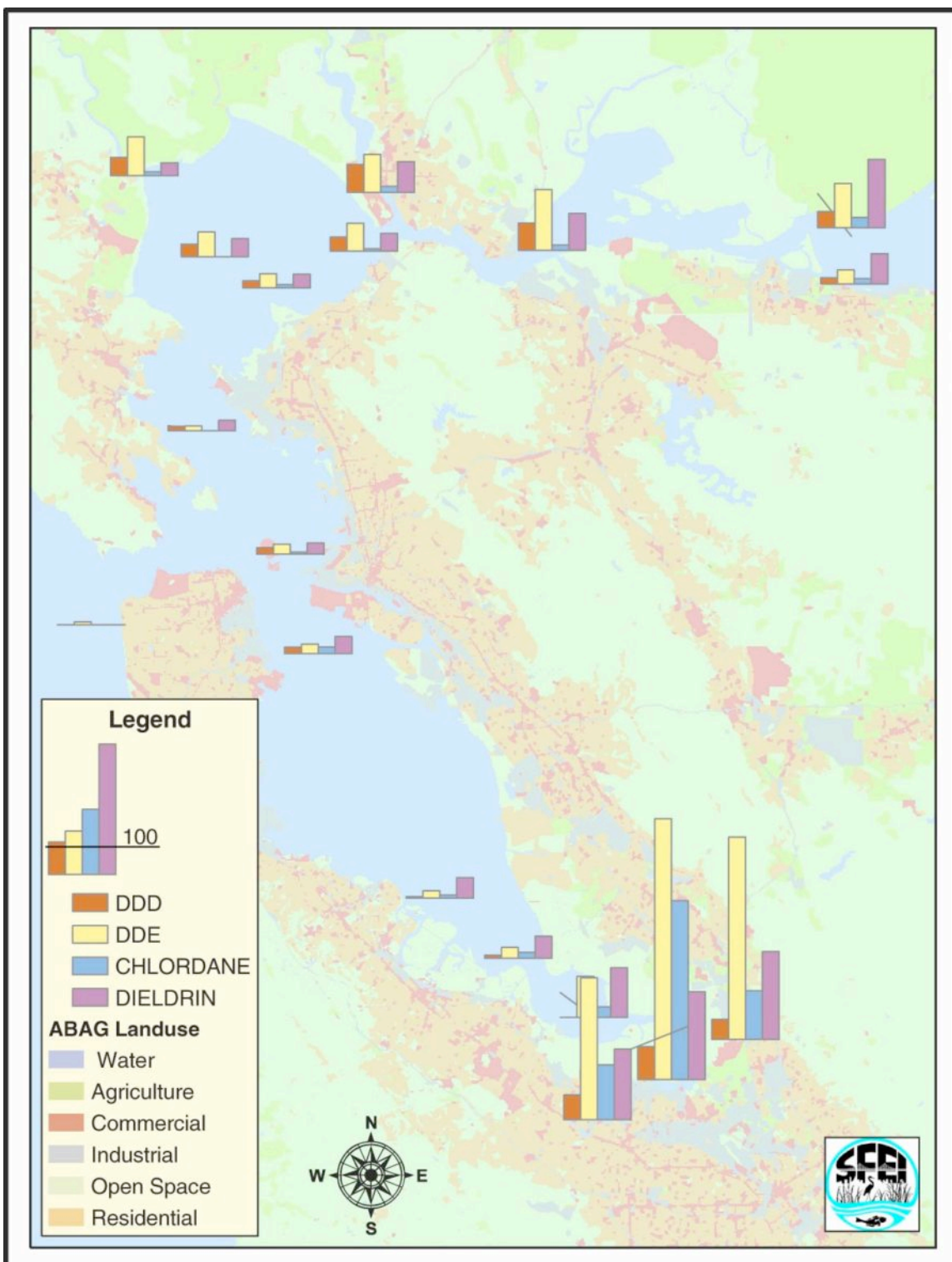
Figure 2-8. Concentrations of legacy pesticides in RMP water samples collected from 1993-2001.

Additionally, there are sufficient water-column data to compare geographic regions: during 1993-2001 concentrations of the legacy pesticides in the water column were highest in the southern reaches of the Bay (Figure 2-9), while concentrations in Central San Francisco Bay usually met standards.

As designed, sampling in 2002 provided additional information about spatial patterns (Figures 2-10a – 2-10c). Overall, no 2002 water column samples contained concentrations of legacy pesticides that exceeded the CTR standards; however, there were exceedances of the proposed criteria for p,p'-DDD, p,p'-

DDE, and dieldrin. Concentrations of DDTs were highest in Lower South Bay and San Pablo Bay. The proposed national criterion for p,p'-DDD was exceeded only in the samples from Sunnyvale and San Jose. The criterion for p,p'-DDE was exceeded in samples from those sites, in one of six samples from the Lower South Bay, and in one of four samples from San Pablo Bay. The proposed dieldrin criterion was exceeded at Sunnyvale and San Jose, in the Sacramento and San Joaquin rivers, in two of six samples from Lower South Bay, and in one of four samples from Suisun Bay.

Analysis of the data by year showed some apparent decreases in pesticide concentrations from 1993 through 2001 (Figures 2-11a – 2-11c). However, those years also included a transition from predominantly wet years (1995-1998) to dry years (1999-2001), and any apparent trends may be related to weather conditions rather than to changes in inputs of the legacy pesticides to the Bay (Leatherbarrow *et al.*, 2003). Preliminary data from the Guadalupe River suggest that loading of pesticides is greatest during severe storm events (SFEI, unpublished data).



*Figure 2-9. Geographic patterns in pesticide concentrations in water, 1993-2001*

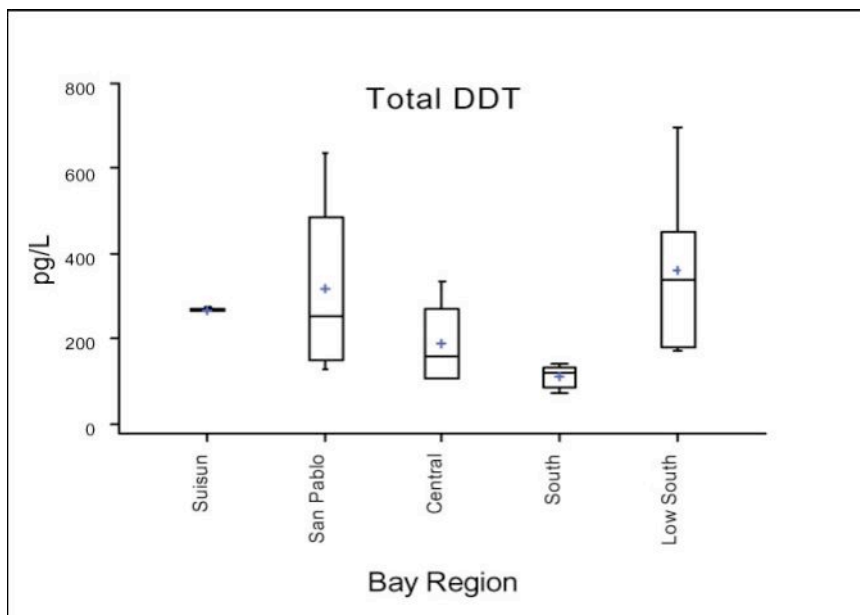
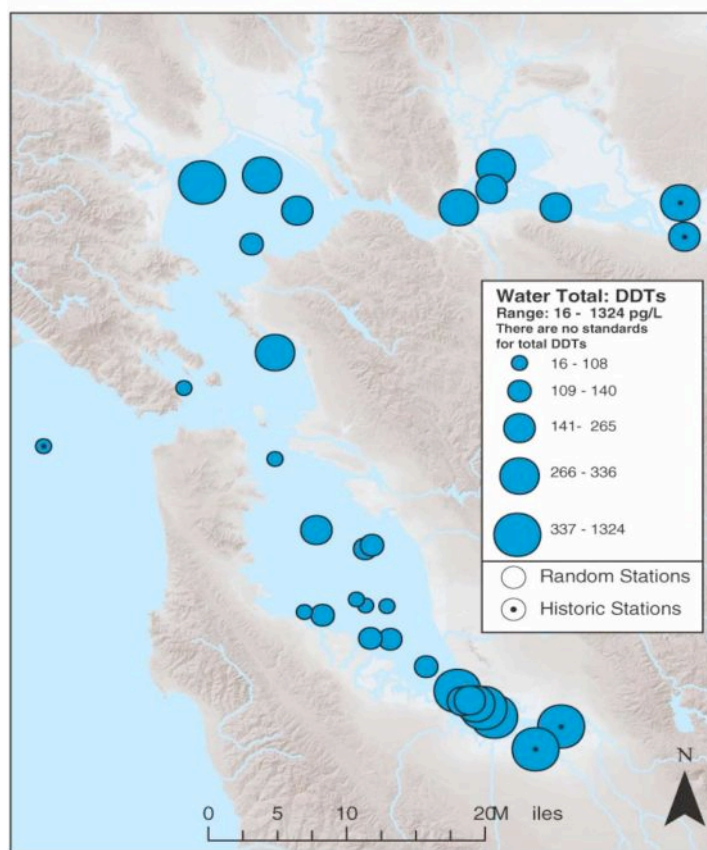


Figure 2-10a. Geographic patterns in DDTs concentrations in water, 2002

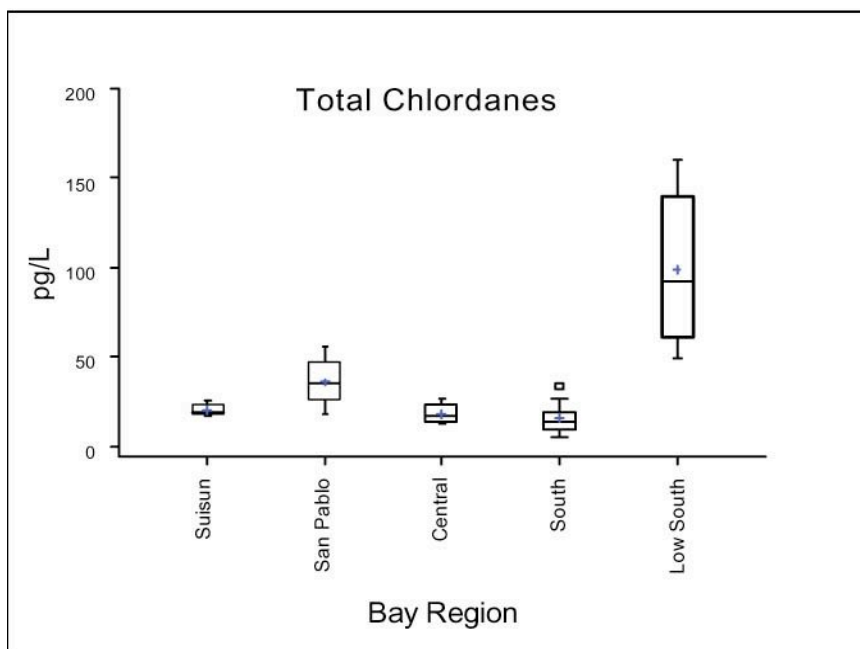
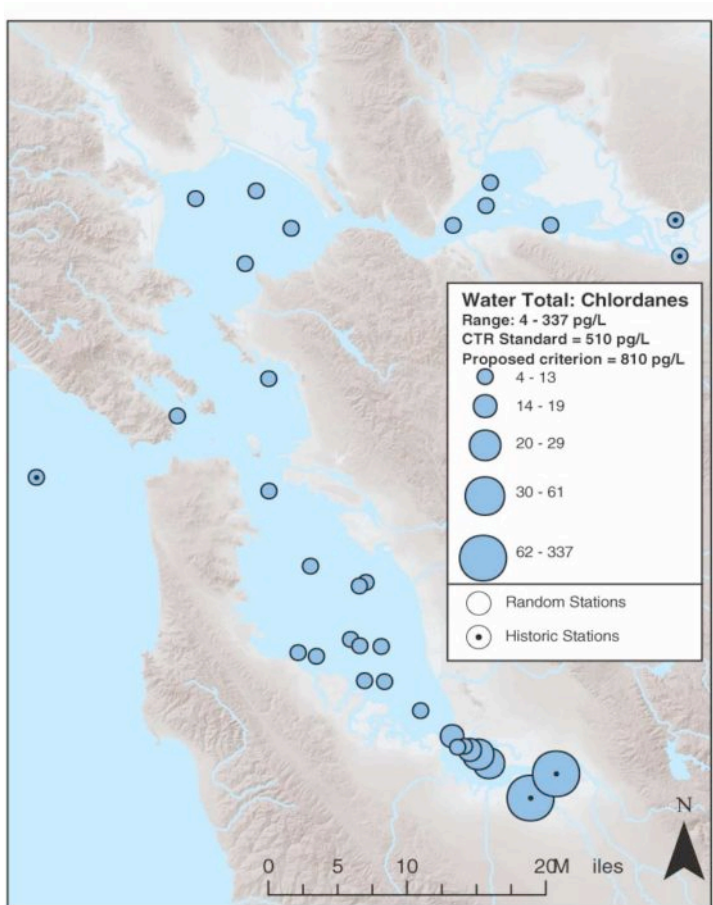


Figure 2-10b. Geographic patterns in chlordanes concentrations in water, 2002

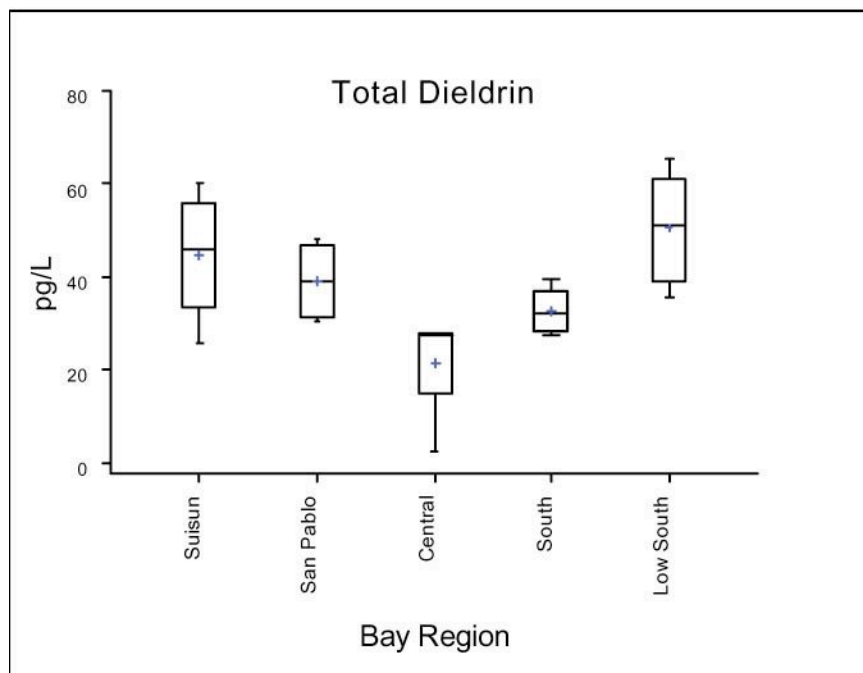
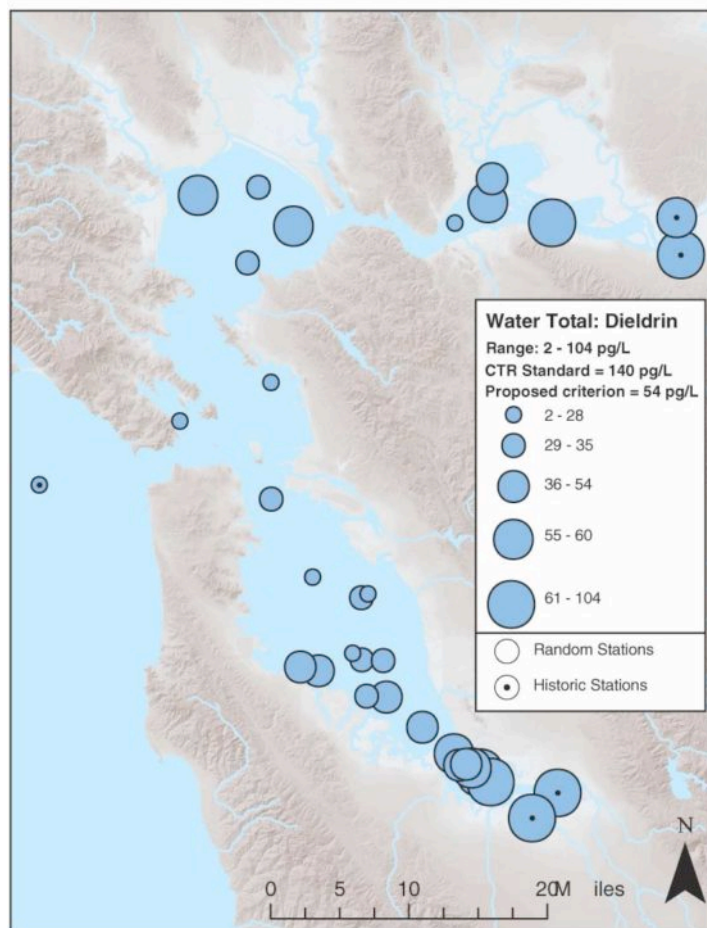
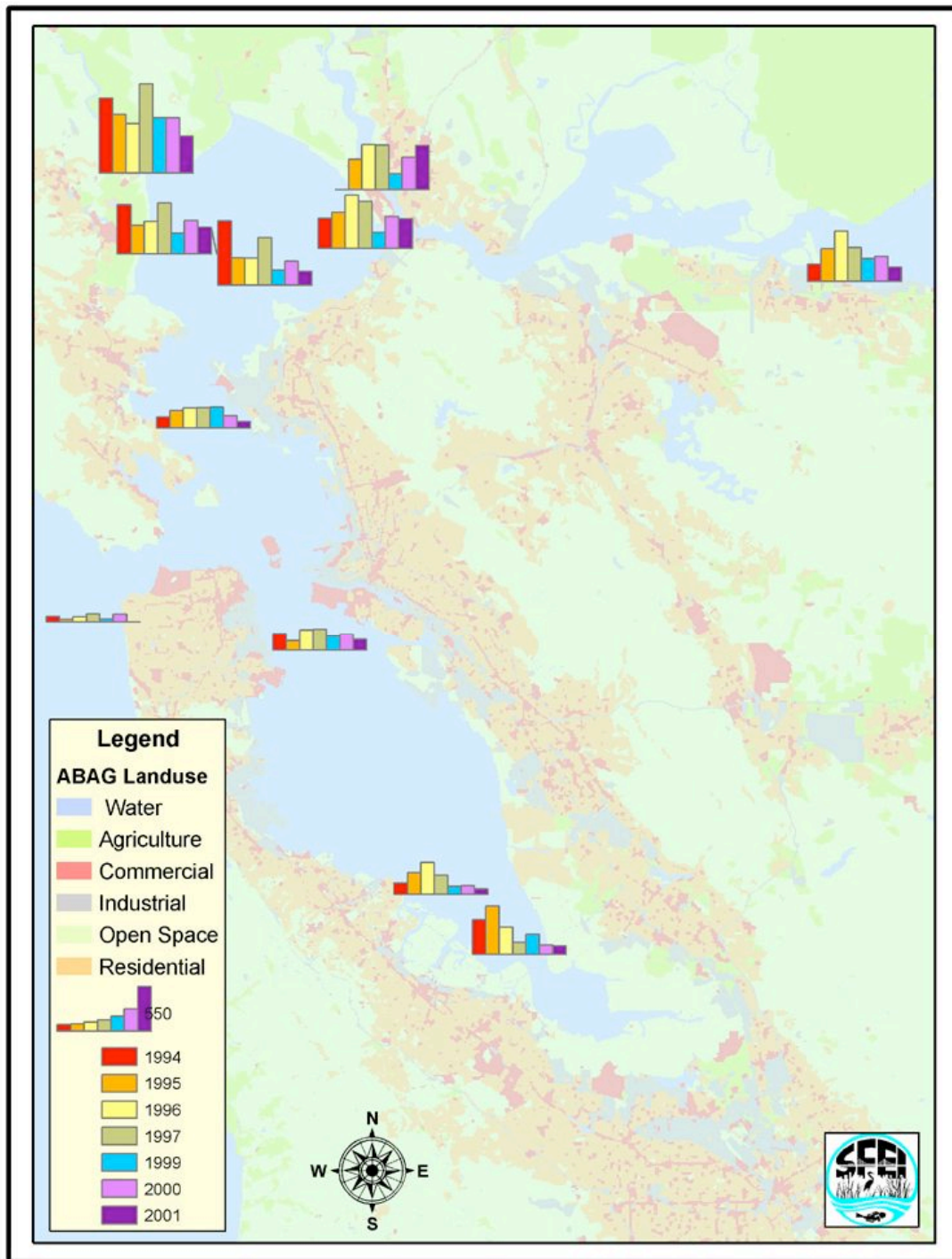
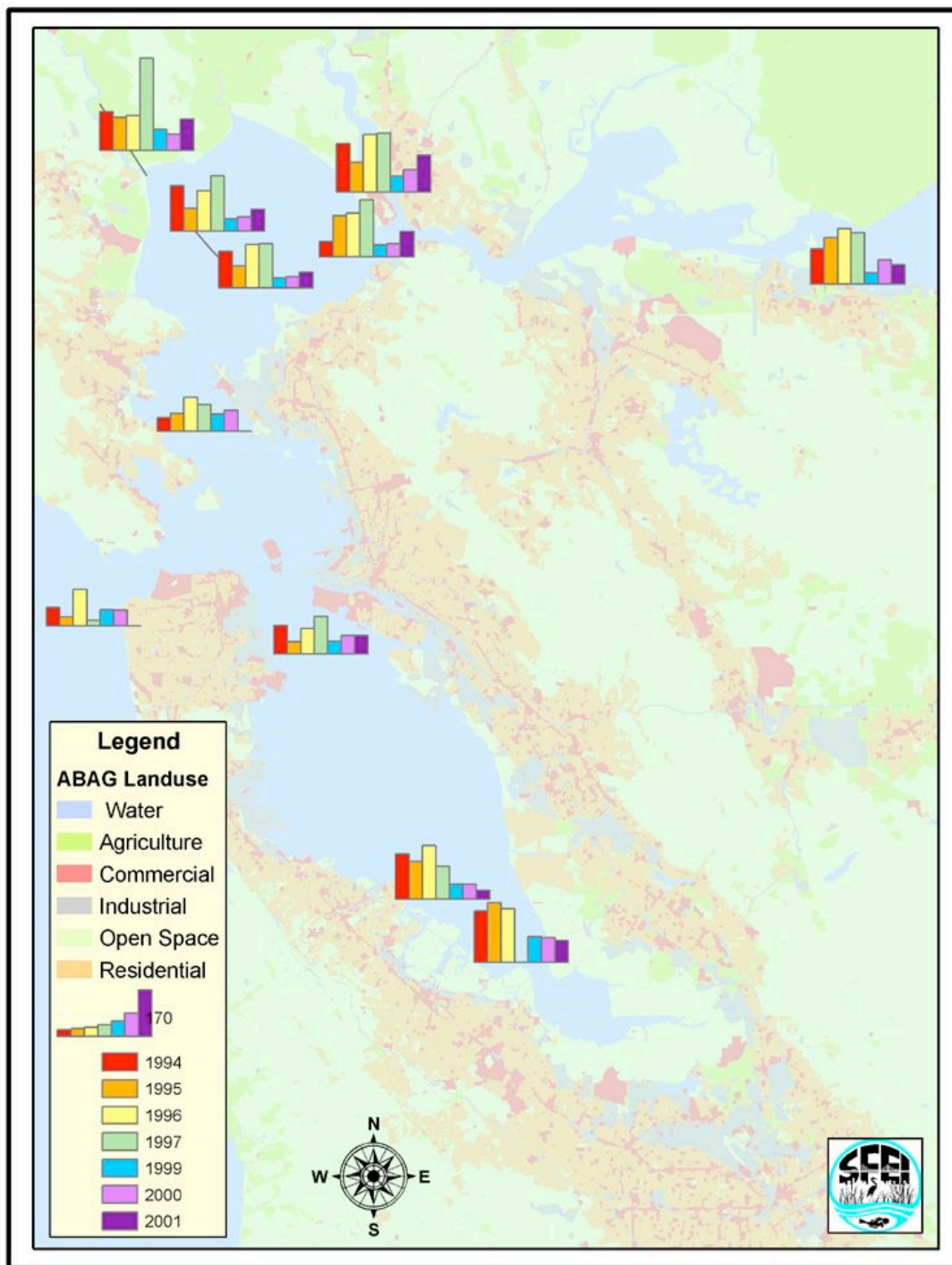


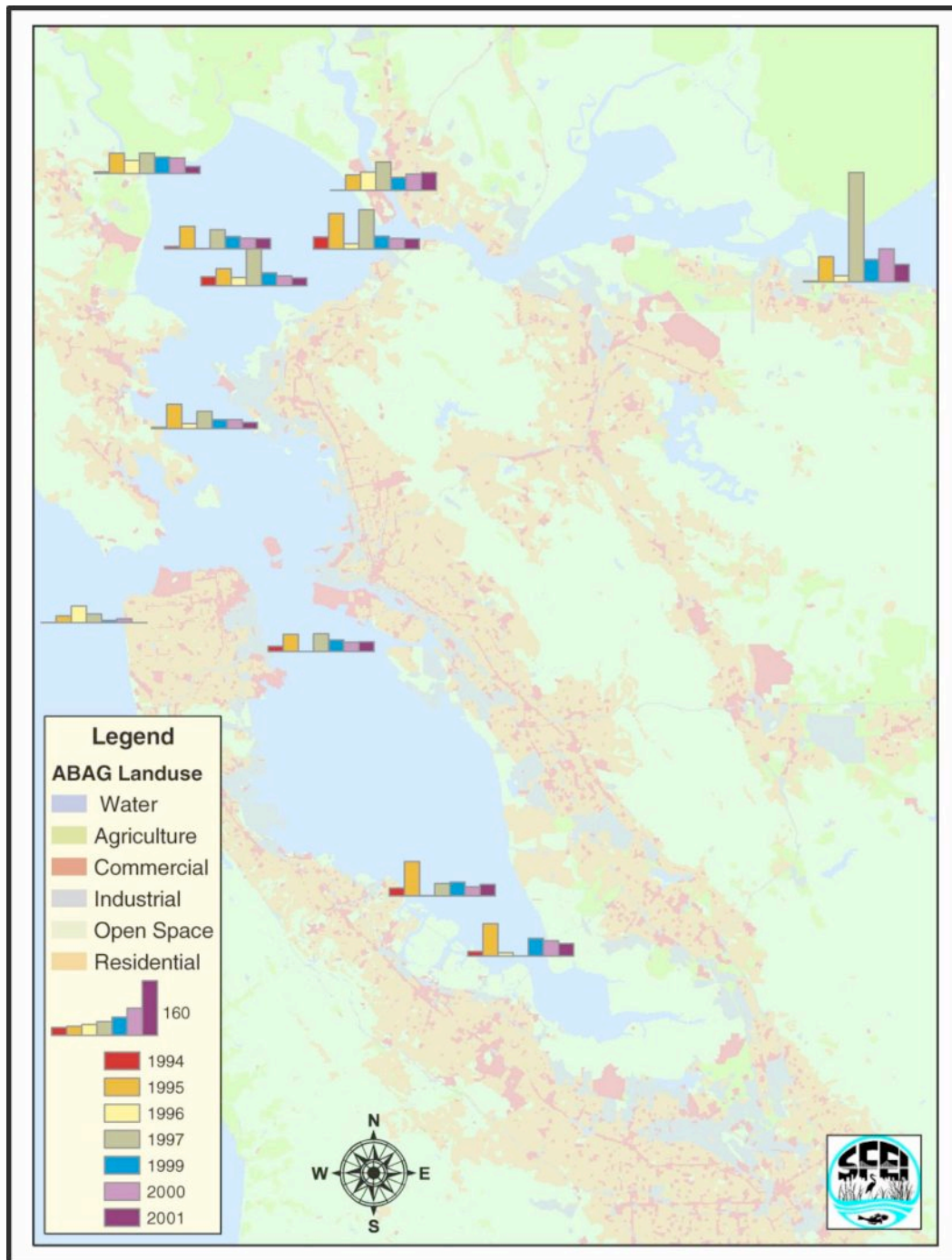
Figure 2-10c. Geographic patterns in dieldrin concentrations in water, 2002



*Figure 2-11a. Temporal patterns in DDT concentrations in water*



*Figure 2-11b. Temporal patterns in chlordane concentrations in water*



*Figure 2-11c. Temporal patterns in dieldrin concentrations in water*

### **Water Quality Data as Indicators of Impairment**

The water quality data indicate **no impairment** of the beneficial uses of San Francisco Bay related to the environmental status of marine and estuarine organisms and communities, such as preservation of rare and endangered species, fish spawning, or wildlife habitat. The data bolster the fish tissue data by indicating **possible impairment** of recreational fishing by DDTs and dieldrin but **impairment unlikely** by chlordane. The indications of possible impairment are present only in some segments of the Bay: the Sacramento/San Joaquin River Delta, San Pablo Bay, and Lower South Bay for DDTs and Suisun and Lower South bays for dieldrin.

There are uncertainties associated with the data:

- Using water column data as surrogates for fish tissue data is less compelling than actual fish tissue data.
- There has been only one year of sampling since the RMP redesign, so information on temporal and spatial patterns is not yet definitive. Even with additional years of sampling the limited scope of the program, 30 samples per year, may prove less robust than would be ideal.

## **2.2.3 Sediments**

### **Sediment Standards**

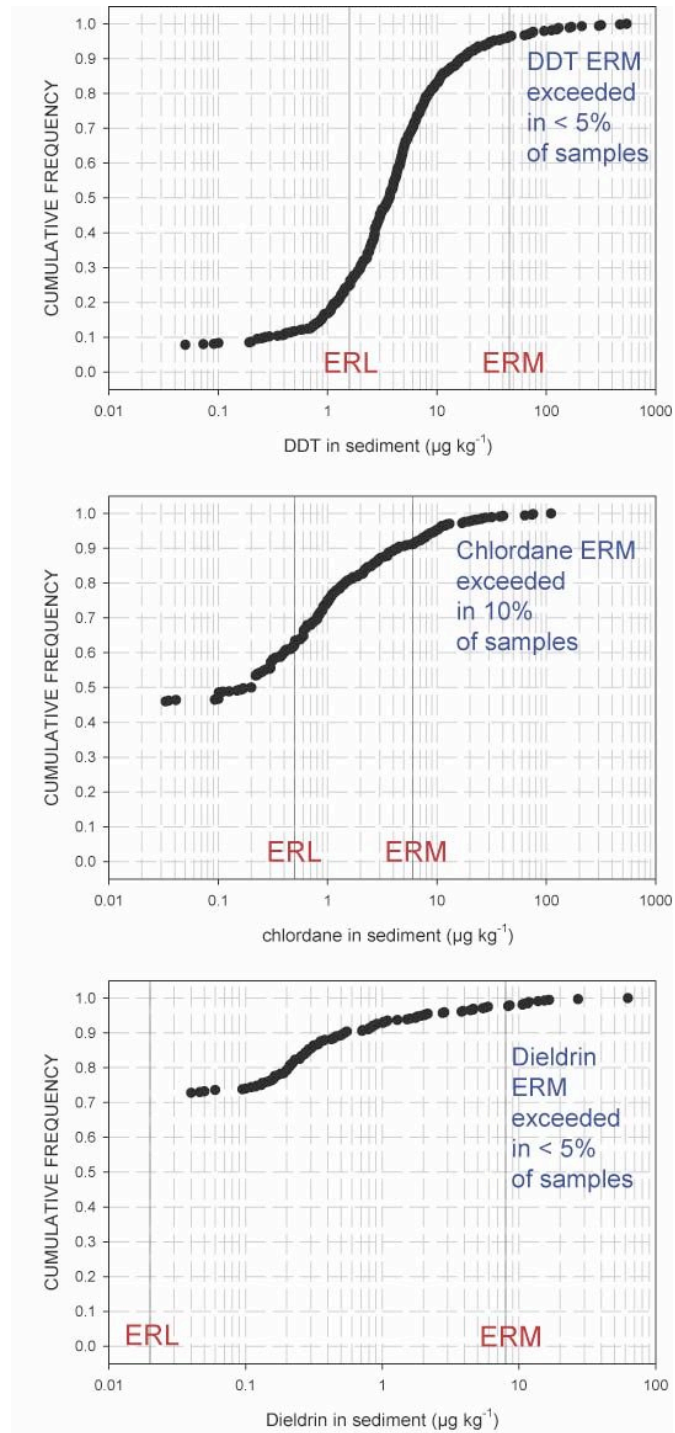
Concentrations of contaminants in sediments are monitored because they can provide information on impairments of resources and wildlife. California is in the process of developing sediment quality criteria, but there are currently no regulatory standards for sediment contaminant concentrations in San Francisco Bay. Sediment quality guidelines developed by the National Oceanic and Atmospheric Administration (NOAA) are sometimes used as screening tools (Table 2-10). The NOAA guidelines were derived from an extensive literature review (Long *et al.*, 1995). The “Effects Range-Low” (ERL) was set as the lower tenth percentile of concentrations of a pollutant in sediments determined to be toxic. The “Effects Range-Median” (ERM) was set as the median concentration of a pollutant in sediments determined to be toxic. Exceedances of ERMs may be indicative of a problem. ERLs are not thought to be useful thresholds of sediment toxicity but can provide insights when comparing data across regions or time (O’Connor, 2003).

Table 2-10. ERL and ERM values for legacy pesticides ( $\mu\text{g/kg}$ )

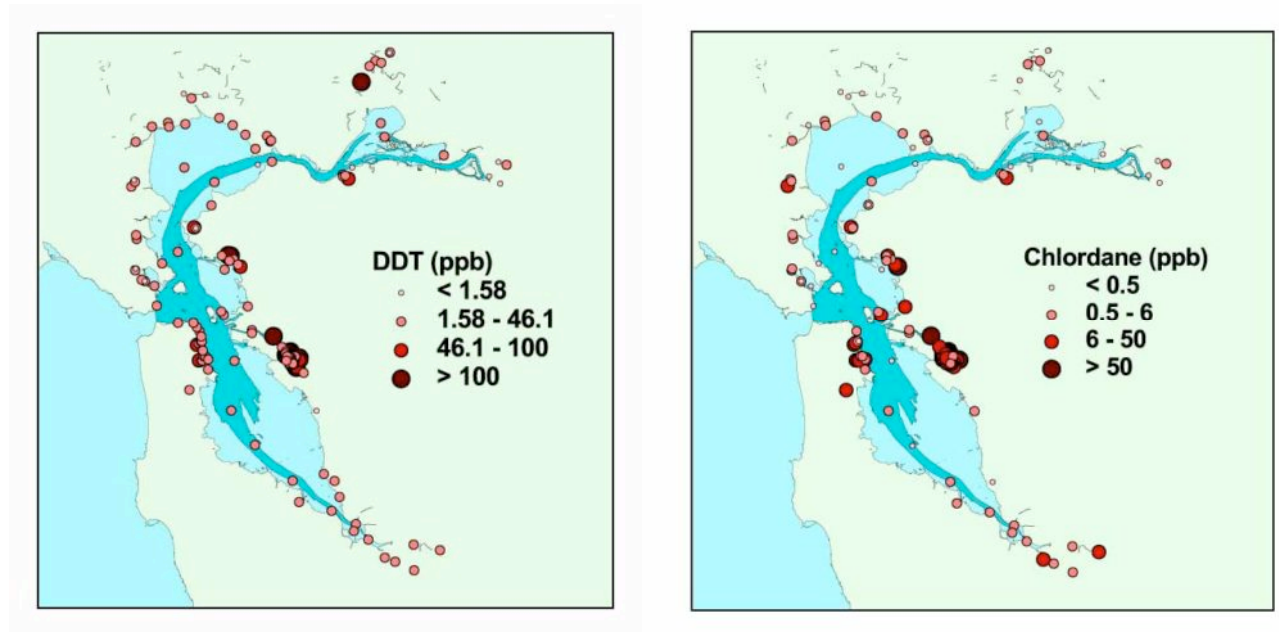
	<b>ERL</b>	<b>ERM</b>
DDTs	1.58	46.1
Chlordanes	0.5	6
Dieldrin	0.02	8

### **Sediment Data**

Sediment data from San Francisco Bay have been collected by the RMP (*e.g.*, SFEI, 2002) and the Bay Protection and Toxic Cleanup Program (Hunt *et al.*, 1998). Compilations of those data show that, Bay-wide, samples have exceeded ERM<sub>s</sub> in about 10% of chlordane analyses, but in less than 5% of DDT and dieldrin measurements (Figure 2-12). For DDTs and dieldrin, most measurements have fallen between the ERL and the ERM. The programs found higher concentrations of pesticides in the shallower areas at the urbanized edges of the Bay, such as Oakland Harbor (Figures 2-13, 2-14).



*Figure 2-12. Concentrations of legacy pesticides in sediments, 1991-2001. (Data collected by RMP, 1993-2001, Pilot RMP, 1991-1992, BPTCP, 1994-1997, and BADA LEMP, 1994-1997).*



*Figure 2-13. DDT and chlordane concentrations in Bay sediment, 1991-1999. Data are average concentrations at locations monitored by RMP 1993-1999, PRMP 1991-1992, BPTCP 1994-1997, and Daum et al., 2000 (The ERM for DDTs is 46.1 ppb and for chlordanes is 6 is ppb.)*

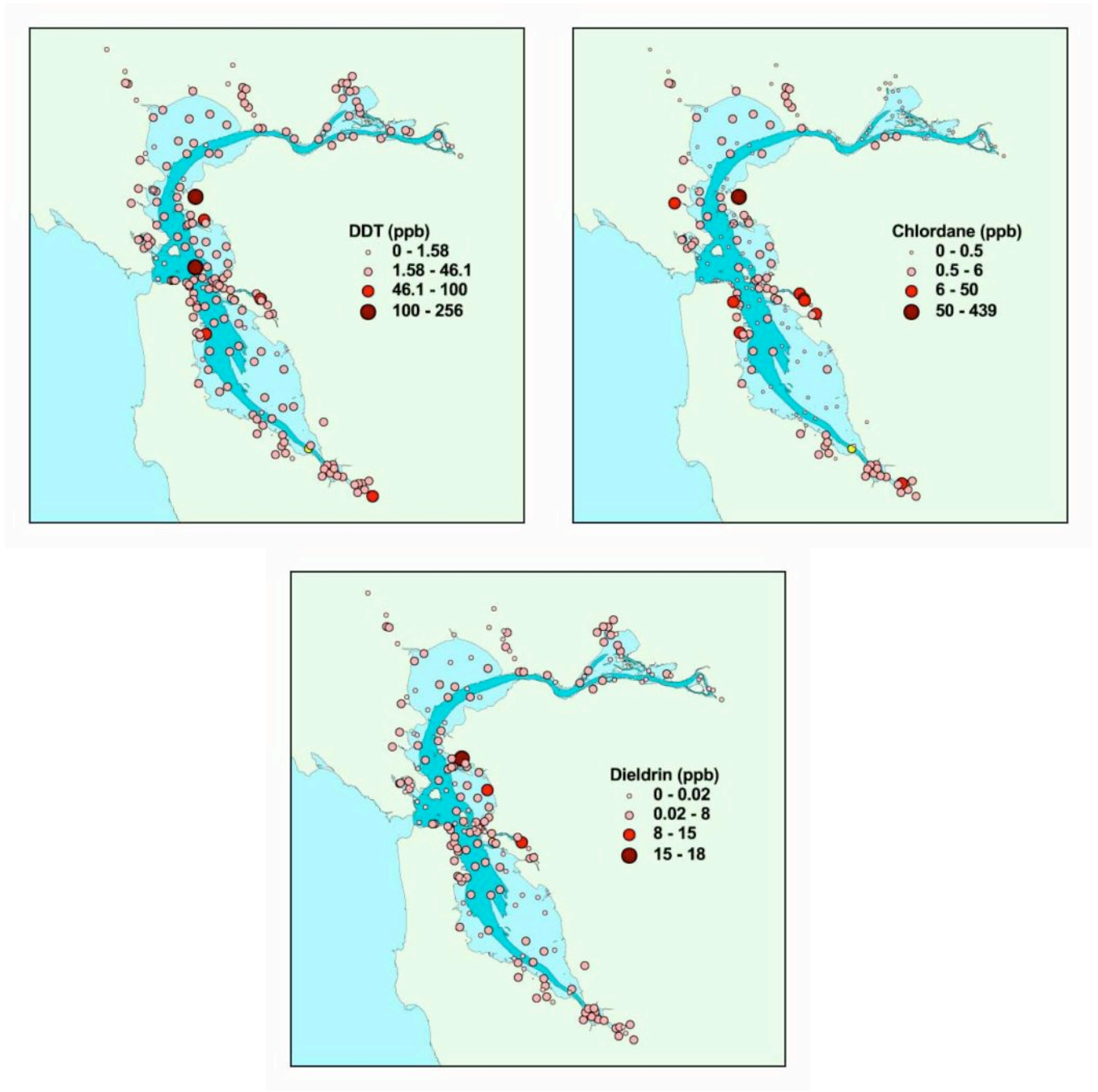


Figure 2-14. Preliminary DDT, chlordane, and dieldrin concentrations in Bay sediment, 2000-2001. Data are from NOAA and EMAP monitoring conducted in 2000 and 2001 (unpublished data).

One special study conducted as part of the Bay Protection and Toxic Cleanup Program specifically implicated chlordanes as key contaminants correlated with sediment toxicity in San Francisco Bay (Thompson *et al.*, 1999). Between 1991 and 1996, 14 sites were monitored for sediment contamination and toxicity, and

statistical analyses identified the suites of contaminants that were associated with toxicity at each site. Chlordane concentrations, along with silver and cadmium concentrations, were significantly correlated with amphipod survival in the North Bay. Chlordane concentrations decreased during the course of the study.

### ***Sediment Data as Indicators of Impairment***

The sediment data indicate **possible impairment** of ecological beneficial uses of the Bay by chlordanes but **no impairment** by DDTs or dieldrin. The spatial data suggest, however, that impairments are localized, in areas at the edge of the Bay, particularly Oakland Harbor, rather than generalized for the Bay or even for the major segments.

There are uncertainties associated with use of sediment data to indicate impairment:

- **There are no standards for impairment.** The sediment quality criteria under development for California will be useful in decisive determination of impairment.
- **Additional analyses are needed** to delineate spatial boundaries of impaired areas.

## **2.2.4 Wildlife Health**

### ***Wildlife Standards***

The principal wildlife health concerns relating to legacy pesticide contamination are for the reproduction of species at the top of the Bay food web, particularly fish-eating birds (such as terns and cormorants) and harbor seals. There are no standards of impairment for these indicator species. This section focuses on data from birds, comparing local data with available information on impaired reproduction and eggshell thinning.

### ***Wildlife Data***

Several studies of legacy pesticide accumulation and effects on birds have been conducted since the 1980s. Studies conducted in the 1980s found DDT concentrations that exceeded known thresholds for impaired reproduction and that were correlated with eggshell thinning. For example, in a 1982 study, Ohlendorf *et al.* (1988) found that 5 of 47 Black-crowned Night-Heron eggs from Bair Island in the South Bay exceeded 8 ppm DDE, a concentration associated with impaired reproduction in this species. Similar DDE concentrations were observed in other species from this location, including Caspian Terns, Forster's Terns, and Snowy Egrets. A follow-up study on samples from 1982 and 1983 also found Night-Heron eggs with DDE concentrations above 8 ppm; concentrations were correlated with eggshell thinning (Ohlendorf and Marois, 1990).

More recent studies, however, have found lower concentrations of legacy pesticides in birds. A study of Night-Herons and Snowy Egrets collected in 1989-1991 found concentrations that were below known effects thresholds (Hothem *et al.*, 1995). DDE concentrations in Clapper Rail eggs collected in 1992 were also low, an order of magnitude below effects thresholds (Schwarzbach *et al.*, 2001).

In 1999-2001, the Coastal Intensive Sites Network (CISNet) conducted a project in San Pablo Bay to evaluate the possible effects of pollutants on two bird species occupying different niches (Davis *et al.*, 2003). One species, the Double-crested Cormorant (*Phalacrocorax auritus*) was representative of the open waters of the Bay. It is a year-round resident and feeds on fish. Two composites of 10 freshly laid eggs and one composite of 10 eggs that had undergone normal incubation but failed to hatch were analyzed for chemical contaminants, including the legacy pesticides.

The study found elevated concentrations of DDE in the eggs, but the levels were below those associated with effects on reproductive success (Davis *et al.*, 2003, Figure 2-15). Concentrations ranged from approximately 1.5-3.0 ppm fresh weight. (Fresh weight is the wet weight of the egg contents, adjusted for moisture loss after laying.) Concentrations of DDE in fresh and the fail-to-hatch eggs did not differ. The lowest concentration of DDE that has been associated with reproductive impairment in cormorants is 5.0 ppm fresh weight, which resulted in reduced numbers of young produced per nest in Double-crested Cormorants from the Great Lakes (Weseloh *et al.*, 1983). Eggshell thinning, which was a major concern resulting in banning of DDT has a higher threshold in this species, 24 ppm fresh weight DDE (Gress *et al.*, 1973).

The eggs also had measurable, but lower, concentrations of dieldrin and chlordanes. Concentrations of the measured pesticides were higher than those measured in Song Sparrow eggs and fish from San Pablo Bay (Davis *et al.*, 2002).

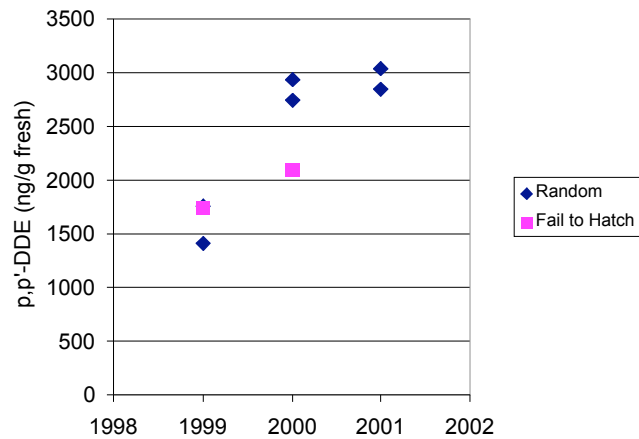


Figure 2-15. *p,p'*-DDE concentrations (ng/g fresh weight) in random and fail-to-hatch cormorant eggs from the Richmond Bridge. Each point represents a composite of 10 eggs.

### Wildlife Data as Indicators of Impairment

The limited available data on wildlife indicate **no impairment** of the Bay by legacy pesticides or **impairment unlikely**. There are no data implicating chlordanes or dieldrin as impairing beneficial uses of the Bay. Concentrations of DDT, although elevated, remain below levels that would indicate impairment. However, data are very limited.

## 2.3 Impairment Summary

In summary, there are indications that beneficial uses of San Francisco Bay may be impaired by legacy pesticides. In particular, water and fish data indicate impairment of the use of the Bay for fishing and fish consumption (COMM, Table 3-11), although not for all legacy pesticides and not for all segments of the Bay. The level of impairment is not high when compared to other organochlorine compounds, such as PCBs, and there is evidence of long-term declines in pesticide levels.

There is less evidence of impairment of other uses of the Bay—preservation of rare and endangered species, fish spawning, or wildlife and estuarine habitat (RARE, SPWN, WILD, or EST). Chlordane concentrations in sediments may, in some locations, affect animals living in the sediments, and DDT concentrations in bird eggs may be close to limits that would indicate impairment.

*Table 2-11. Impairment summary*

	<b>DDTs</b>	<b>Chlordanes</b>	<b>Dieldrin</b>
<b>Fish</b>	Possible impairment of COMM	Impairment unlikely	Possible impairment of COMM
<b>Water</b>	Possible impairment of COMM	Impairment unlikely	Possible impairment of COMM
<b>Sediments</b>	Impairment unlikely	Possible impairment of RARE, SPWN, WILD, or EST	Impairment unlikely
<b>Wildlife</b>	Impairment unlikely	Impairment unlikely	Impairment unlikely

## 3. Conceptual Model

The conceptual model presented in this section provides a framework for optimizing management decisions and actions for reducing contamination by legacy pesticides in San Francisco Bay. This conceptual model:

- Presents a simple **one-box model** of the Bay.
- Synthesizes information on the **sources** of DDTs, chlordanes, and dieldrin to the Bay.
- Estimates total **loads** to the Bay.
- Describes the chemical characteristics of the pesticides and the dominant **processes** that determine their fate within the Bay.
- Uses the one-box model to facilitate understanding responses within the Bay and estimating **recovery** rates.

The conceptual model also describes areas of uncertainty and assesses the extent to which they limit the ability to quantify responses and rates.

### 3.1 One-Box Model

A simple way to examine inputs and losses of contaminants to San Francisco Bay has been to use a mass-budget model, called a one-box model, because it considers the Bay to be one box, with inputs and losses (Figure 3-1). The boundaries of the box are a little unusual, as they include both the water column and the surface sediment, known as the “active layer.” Inputs to the box include atmospheric deposition, local runoff, municipal, industrial, and river discharge, and erosion or dredging of deeper sediments. The annual loadings of these inputs are presented in Section 3.3. Losses include volatilization to the atmosphere, discharge through the Golden Gate, and degradation within the Bay. These losses are quantified in Section 3.4. Output from the model is used in Section 3.5 to estimate recovery of the Bay.

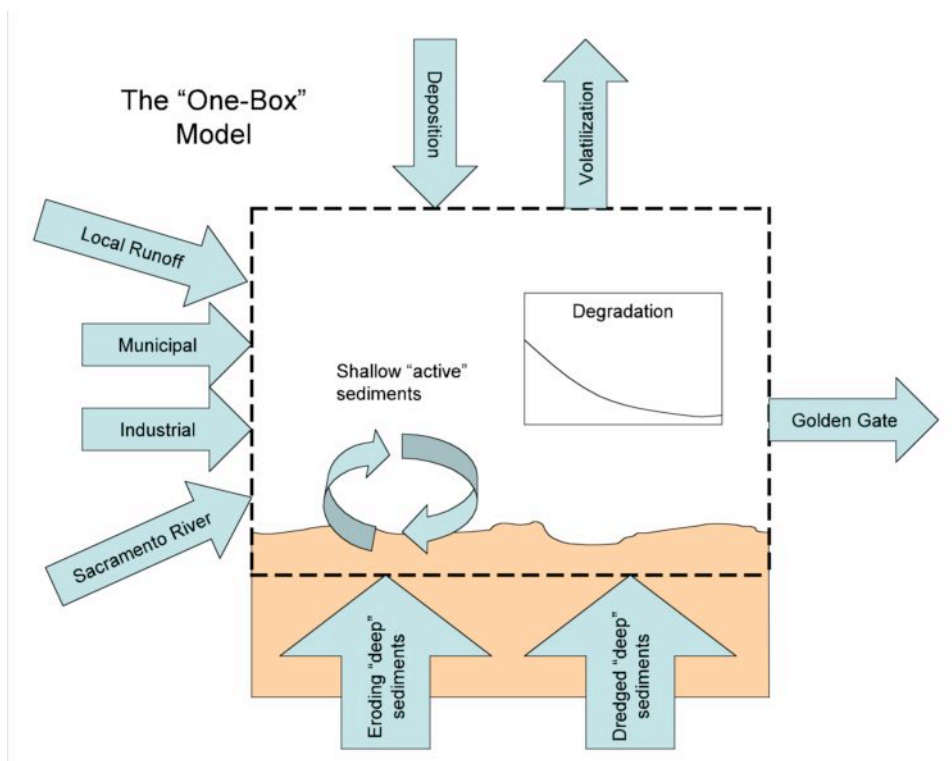


Figure 3-1. One-box model (figure courtesy of Dan Cloak)

### 3.2 Sources and Pathways

DDTs, chlordanes, and dieldrin enter San Francisco Bay from several sources (Davis *et al.*, 2001) (Figure 3-2):

- Agricultural and urban **watersheds** with histories of pesticide application.
- **Wastewater effluent**.
- **Atmospheric deposition**.
- Erosion of **historic deposits** within the Bay.
- Dredging and disposal of **dredged material**.

Some sources and loadings of legacy pesticides may be controllable, while others are not.

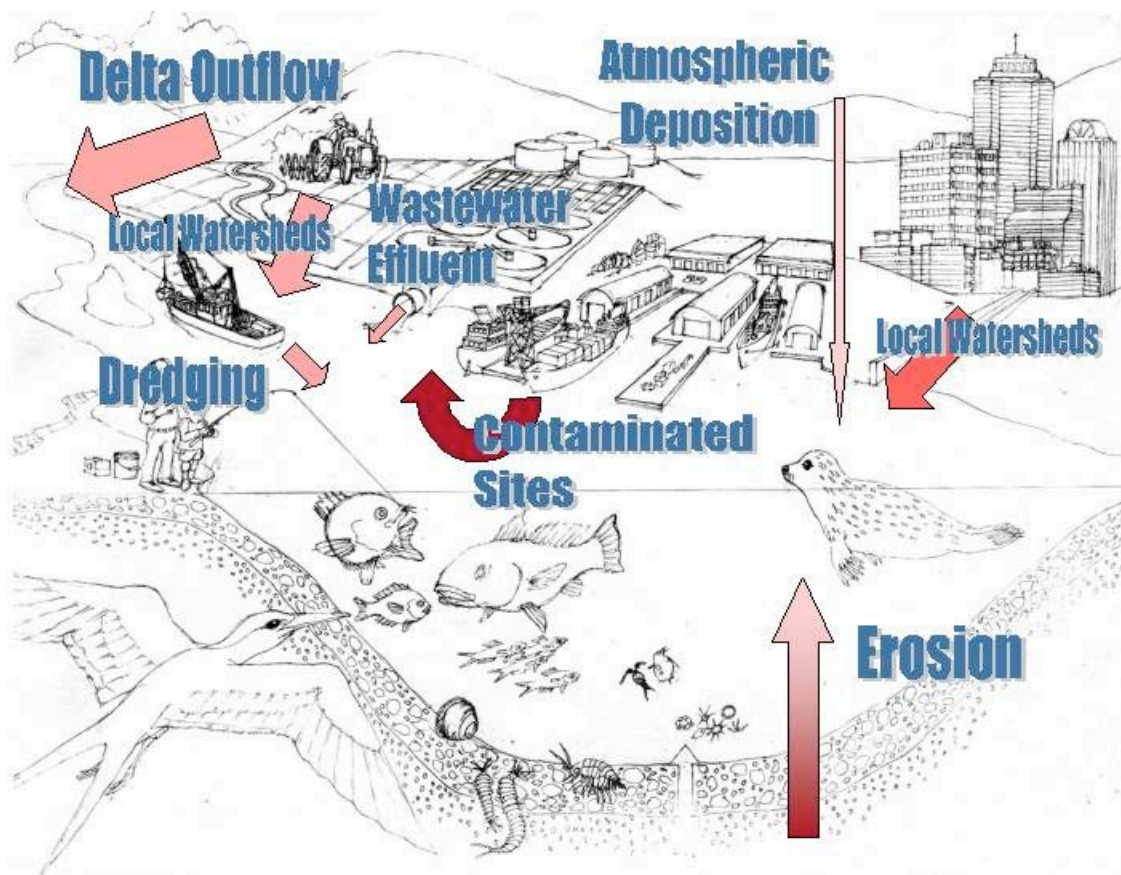


Figure 3-2. Sources of legacy pesticides to San Francisco Bay

### 3.2.1 Watersheds

Because of the widespread historic use of the legacy pesticides throughout the country and the enormity of the area that feeds the Bay, almost 60,000 square miles, runoff from the watersheds, particularly the Central Valley, is a major pathway for legacy pesticides to reach the Bay. Historic use left persistent residues of pesticides in soils and in the sediments of floodplains, banks, and beds of channels throughout California and the Bay Area (Mischke *et al.*, 1985; Law and Goerlitz, 1974; KLI, 2002; Salop *et al.*, 2002). Pesticide residues primarily associated with particles entrained in surface runoff and resuspended in channels are transported to the Bay during large storm events (Bergamaschi *et al.*, 2001; Leatherbarrow *et al.*, 2002; McKee *et al.*, 2004; Leatherbarrow *et al.*, 2004).

#### **Central Valley**

The intense agricultural activity in the Central Valley left pesticide residues in the soils, stream sediments, water and biota (Mischke *et al.*, 1985; Gilliom and Clifton, 1990; Pereira *et al.*, 1996; Kratzer, 1999; Brown, 1997). Urban use of pesticides was also common and occurred more recently than agricultural use, as

agricultural restrictions to the pesticides preceded their overall bans. In particular, total urban use of chlordanes may have exceeded agricultural use (Nowell *et al.*, 1999). Consequently, while the contemporary occurrence and distribution of DDTs and dieldrin in the Central Valley are typically associated with historic agricultural applications, the presence of chlordanes is more likely related to historic use for termite and ant control in residential and commercial applications.

In 1985, concentrations of DDTs and dieldrin in sediments from the San Joaquin River watershed were among the highest in the nation (Gilliom and Clifton, 1990). The stations with the highest concentrations were located in westside tributaries that primarily carried agricultural surface runoff and overflow from the Delta-Mendota Canal. Pereira *et al.* (1996) observed a similar pattern, with high concentrations of DDTs and dieldrin in water, suspended sediments, sediments, and biota of a westside tributary, Orestimba Creek, which is bordered by apple orchards, field crops, and row crops. In contrast, maximum chlordane concentrations in suspended sediments were measured in samples from Dry Creek, which receives urban runoff from Modesto.

### **Local Watersheds**

Inputs of legacy pesticides from the other watersheds that feed San Francisco Bay besides the Central Valley also reflect historic and current land use. Much of the area directly adjacent to the Bay was used for agriculture before the post-World War II period of rapid population growth and urbanization. Two studies conducted in the 1970s and 1980s found that DDT residues were ubiquitous and persistent in agricultural soils and tributary sediments throughout the Bay Area (Law and Goerlitz, 1974; Mischke *et al.*, 1985). More recent monitoring conducted in 2001 found that concentrations of DDTs in sediments from urbanized regions of the watersheds were greater than those from non-urbanized, non-agricultural open space, with concentrations ranging as high as 4,010 µg/kg (KLI, 2002).

The urban influence on chlordane and dieldrin distribution in the local watersheds has also been evident. Law and Goerlitz (1974) detected chlordanes in 92% of sediment samples from tributaries to the Bay, with no spatial differences between the northern and southern regions. After that study, pesticide use declined—statistics from the California Department of Pesticide Regulation (CDPR) indicate a particularly rapid decline in chlordane use from 1989-1990 (Table 3-1).

*Table 3-1. Chlordane use in the Bay Area, 1989-1990 (data from CDPR, 2003)*

	<b>Amount applied (kg)</b>	<b>Counties applying chlordane</b>
1989	240	Alameda, Contra Costa, San Mateo, Santa Clara
1990	78	Santa Clara

Recent measurements (KLI, 2002) found concentrations of chlordanes in sediments as high as 11,300 µg/kg in urban, industrial locations, with much lower concentrations in sediments from open space. In the same study, dieldrin concentrations were as high as 70 µg/kg, with no dieldrin detected in samples from the non-urban open space locations (KLI, 2002).

Legacy pesticide contamination is widely distributed in the Bay watersheds, and complete elimination of watershed loadings is not feasible. Contaminated soils and sediments from the watersheds will continue to wash into the Bay and constitute a continuing input that will delay recovery. However, as the pesticides degrade, loads from the watersheds are expected to decline.

### **3.2.2 Wastewater Effluent**

Municipal wastewater treatment plants receive inputs of legacy pesticides from various sources, including water supply, stormwater runoff, human and food waste, landfill leachate, and hazardous waste disposal (EIP, 1997). In a study of sampling and analysis methodologies, there was great variation in concentrations of pesticides in samples collected in 1999 and 2000 from four Bay Area municipal wastewater treatment plants (Table 3-2) (Yee *et al.*, 2001). (The purpose of the study was not monitoring, so calculation of means for comparison with water quality standards is not possible.)

*Table 3-2. Range of concentrations of legacy pesticides in municipal wastewater.*

<b>Pesticide</b>	<b>Concentration range (pg/liter)</b>
DDTs	4 to 1,900
Chlordanes	Less than ~1-3 to 1,800
Dieldrin	Less than ~1-3 to 450 pg/l

Legacy pesticide contamination of the human food supply due to the global distribution of these chemicals and their accumulation in the human food web, especially meats and dairy products, will cause a continued level of loading from municipal wastewater that would be very difficult to control. Small quantities of pesticides may also occur in industrial discharges.

### **3.2.3 Atmospheric Deposition**

Much of the input of legacy pesticides from the atmosphere to San Francisco Bay is an indirect result of deposition onto the land surface in the watershed, and those inputs are considered to be part of the runoff inputs from the watershed. There is some local re-deposition of pesticides that are volatilized, evaporated, or eroded from surface soils, water, and sediment. There is also some direct atmospheric deposition resulting from long-range transport in air masses. This input is not controllable and will contribute to continued loading of legacy pesticides to the Bay via direct and indirect atmospheric deposition.

### **3.2.4 Erosion of Sediment Deposits**

While deposition of sediments can be a sink for legacy pesticides in some areas of the Bay, as of 1990, Suisun, San Pablo, and South bays were areas of net erosion (Capiella *et al.*, 1999; Jaffe *et al.*, 1998; Foxgrover *et al.*, 2003). Considering that Suisun and San Pablo bays are in close proximity to inputs from the Central Valley, continued erosion will potentially uncover more contaminated layers of historically deposited pesticides.

Remobilization of sediments from highly contaminated areas, or “hot spots,” may contribute potentially significant inputs to the Bay. One known location of former pesticide use is the United Heckathorn site on Richmond Harbor (Pereira *et al.*, 1994; Anderson *et al.*, 2000). The United Heckathorn facility received technical grade pesticides, primarily DDT, from chemical manufacturers and prepared and packaged them for final sale. Despite on-land soil and subtidal sediment cleanup, one part of the site, the Lauritzen Channel, remains contaminated with DDTs and dieldrin.

### **3.2.5 Dredging and Dredged Material Disposal**

Sediment is dredged from Bay channels and ports and disposed of in and outside of the Bay. In the recent mercury TMDL report, Johnson and Looker (2003) estimated that there is greater out-of-Bay disposal of dredged sediment than in-Bay disposal, resulting in an overall net loss of sediment from the Bay. However, on a more localized regional or Bay-segment level, dredged material disposal may contribute to net addition of pesticide mass. For example, dredged material disposed of at Alcatraz Island may increase the mass of sediment and associated pesticides in the Central Bay.

## **3.3 Loads**

Estimated loads of legacy pesticides to the water column and active sediment layer of San Francisco Bay are approximately 60 kg/year DDTs, 30 kg/year chlordanes, and 10 kg/year dieldrin (Table 3-3). The estimates have some large uncertainties. The amount of pesticides available for transport from the watershed is the largest factor. Limited information of historic pesticide use and loading, as well as considerable variability in the hydrologic and geomorphic processes in the watersheds, preclude making a definitive estimate of the pesticide mass being stored within the watershed.

Table 3-3. Estimated loads (best estimate and range) of legacy pesticides to San Francisco Bay (kg/year).

Pathway	DDTs	Chlordanes	Dieldrin
Central Valley	15 (5 – 40)	2 (0.7 – 5)	5 (2 – 13)
Local watersheds	40 (9 – 190)	30 (7 – 160)	3 (0.7 – 15)
Municipal wastewater	0.2 (0.02 – 2)	0.1 (0.003 – 2)	0.06 (0.008 – 0.4)
Industrial wastewater	<0.2	<0.1	<0.06
Atmospheric deposition	1 (0.02 – 2)	0.9	1 (0.2 – 2)
Erosion of sediment deposits	9 (0.2 – 18)	2 (0 – 4)	0.2 (0 – 0.6)
Dredged material	-2 (-3 – -0.03)	-0.3 (-0.6 – 0)	-0.03 (-0.1 – 0)
<b>Total Best Estimate</b>	<b>60 (10 – 250)</b>	<b>30 (10 – 170)</b>	<b>10 (3 – 30)</b>

This section of the report describes the calculations, assumptions, and uncertainties associated with the values presented in Table 3-3.

### 3.3.1 Loads from Watersheds

#### Central Valley

Pesticide loads from the Sacramento and San Joaquin rivers that drain the Central Valley were estimated from preliminary contaminant data collected as part of a RMP special study conducted in 2002 and 2003 at Mallard Island, a site located approximately five kilometers downstream from the confluence of the two rivers (Leatherbarrow *et al.*, 2004). Since 1994, the United States Geological Survey (USGS) has been collecting continuous turbidity data on 15-minute intervals at the Mallard Island site. This continuous turbidity data set, used in conjunction with regressions between suspended sediment and pesticide concentrations, allowed for extrapolation of continuous records of suspended sediment, DDT, and chlordane (methods described in McKee *et al.*, 2002; McKee and Foe, 2002). Best estimate loads in Table 2-4 were derived from the median and ranges of annual loads estimated from 1995-2003 using two methods:

- Regression between turbidity (and suspended sediment concentrations) and pesticides.
- Flow-weighted mean concentrations of pesticides (SFEI, unpublished data).

Variability in Delta outflow and sediment transport led to a range of contaminant load estimates that spanned an order of magnitude. The maximum pesticide load, in 1995, occurred because of above-average outflow from the Delta (52,000 Mm<sup>3</sup>) that was approximately six times greater than flow in 2001 (8,600 Mm<sup>3</sup>).

Several sources of uncertainty in the calculations were described in detail by McKee *et al.* (2002) and McKee and Foe (2002): averaging of suspended sediment concentration data on a daily time step to estimate daily loads, error in the Delta outflow calculation, cross-sectional variability of suspended sediment concentrations, tidal influence, and regression errors between turbidity, suspended sediment concentrations, and pesticide concentrations. Estimates of error associated with pesticide loading estimates for individual years were  $\pm 38\%$  for DDTs,  $\pm 39\%$  for chlordanes, and  $\pm 44\%$  for dieldrin.

Another source of uncertainty is that data used for estimating loads from the Central Valley were collected during two years of below-average Delta outflow (based on a 30-year average from 1971 to 2000). Calculating loads for years prior to 2002 relies on the assumption that the relationships between turbidity, suspended sediment, and pesticides remained constant over the entire range of Delta outflows. In reality, these relationships may vary at higher flows that carry sediment and freshwater from varying sources in the Central Valley. Monitoring pesticide concentrations downstream of the large rivers during periods of above-average Delta outflow would help characterize the pesticide concentrations and transport processes observed over the full range of variability in sediment transport and freshwater runoff from the Central Valley.

### **Local Watersheds**

Estimating pesticide loads from the combined Bay Area watersheds is inherently difficult, due to limited available data and insufficient techniques for extrapolating from existing data and accounting for different land uses, hydrology, and other watershed characteristics. Bay Area stormwater management agencies used pesticide concentrations in bed sediments from stormwater conveyance systems and the SIMPLE model to derive preliminary estimates of DDT and chlordane loads (KLI, 2002; Salop *et al.*, 2002). Best estimates (and ranges) were 9.2 (0.9-20) kg DDT and 22 (19-102) kg chlordane, with 98% of the total attributed to urban sources. There are considerable uncertainties associated with the estimates derived from the SIMPLE model (Davis *et al.*, 2000; KLI, 2002). For example, the study focused on urban sources of the pesticides—no data exist to facilitate estimating loads from agricultural sources.

Pesticide loads from local watersheds were also estimated using preliminary data collected by McKee *et al.* (2004) in the lower Guadalupe River watershed in 2003 and extrapolated to all watersheds based on the overall sediment and water budgets in the Bay. The Guadalupe River watershed represents an area that was historically agricultural and converted to predominantly urban land uses during the period that the pesticides were used. Similar to Central Valley load estimates, estimated loads for local watersheds were derived using two types of data:

- Linear regression between suspended sediment concentrations and pesticides.
- Flow-weighted mean concentrations of pesticides.

Linear relationships between total pesticide concentrations in water and suspended sediment concentrations in 22 Guadalupe River samples provided an estimate of pesticide concentrations associated with suspended particulate material entering the Bay from a local watershed. Slopes of the regressions resulted in approximate suspended sediment-normalized concentrations of DDTs, chlordanes, and dieldrin, 46, 41, and 3.7  $\mu\text{g/kg}$ , respectively (McKee *et al.*, 2004).

The best available estimates of sediment transport to the Bay range from approximately 0.56 to 1.0 million metric tons (McKee *et al.*, 2003). Applying the suspended sediment concentration-normalized pesticide concentrations from Guadalupe River to the range of annual sediment loads from the combined local watershed area resulted in annual pesticide loads from the local watersheds of 26-46 kg DDTs, 23-41 kg chlordanes, and 2.0-3.5 kg dieldrin.

In the Guadalupe River water samples, flow-weighted mean concentrations of total DDTs, total chlordanes, and dieldrin were 48 ng/L, 40 ng/L, and 3.7 ng/L, respectively. Annual freshwater flow from local watersheds ranges from approximately 180  $\text{Mm}^3$  in dry years to 3,930  $\text{Mm}^3$  in wet years (McKee *et al.*, 2003). Using an average annual flow of 920  $\text{Mm}^3$ , annual pesticide loads were estimated to be approximately 44 kg DDTs, 37 kg chlordanes, and 3.4 kg dieldrin. These loads were consistent with the suspended sediment concentration-derived loads discussed above, while the range of local watershed pesticide loads presented in Table 3-3 reflects the variability expected between dry and wet years. Best estimates of loads were derived from the two methods of estimation.

Using the same methods, estimated chlordane loads were of similar magnitude to estimates calculated by the SIMPLE model (KLI, 2002); however, DDT loads were approximately an order of magnitude higher than SIMPLE model estimates. Lower DDT loads estimated by the SIMPLE model may be due to an underestimate of sediment loads by the model (McKee *et al.*, 2003) and the fact that non-urban sites were not well characterized in the studies by KLI (2002) and Salop *et al.* (2002). This discrepancy may not have greatly affected chlordane loads, since chlordane was primarily associated with urban land uses.

Using Guadalupe River data to estimate loads relies on the assumption that runoff from local watersheds has pesticide concentrations that are similar to those found in the Guadalupe River samples. In fact, there is great variability in pesticide concentrations (KLI, 2002; Salop *et al.*, 2002). The extent of variability remains an important unknown and introduces significant uncertainties when extrapolating from Guadalupe River data to other watersheds or applying the SIMPLE model on a regional scale. The lack of available data from other local watersheds and lack of more sophisticated modeling preclude estimating pesticide loads from the local watersheds with known accuracy or precision.

### **3.3.2 Loads from Wastewater Effluent**

Estimates of pesticide loads from municipal wastewater were based on concentration ranges in Yee *et al.* (2001) and an estimated combined effluent discharge of 600 million gallons per day (MGD) (D. Yee, SFEI, personal communication). Contaminant data from industrial dischargers were not readily available. However, the magnitude of industrial discharge is much lower than municipal discharge (Hetzl, 2004; Johnson and Looker, 2003), and the loads from industrial discharges were simply assumed to be less than loads from municipal discharges.

### **3.3.3 Loads from Atmospheric Deposition**

There are no local data on atmospheric deposition of pesticides to San Francisco Bay. However, ranges of wet- and dry-depositional fluxes of legacy pesticides have been estimated for other water bodies, including the Great Lakes (Chan *et al.*, 1994) and Galveston Bay in Texas (Park *et al.*, 2001). Chan *et al.* (1994) estimated that wet depositional fluxes in the Great Lakes ranged from 0.02-1.3 g/km<sup>2</sup>/yr for DDE and 0.2-1.9 g/km<sup>2</sup>/yr for dieldrin. The magnitudes of these fluxes were consistent with total (wet+dry) fluxes estimated by Park *et al.* (2001) for Galveston Bay: 1.9 g/km<sup>2</sup>/yr for DDTs, 0.75 g/km<sup>2</sup>/yr for chlordanes, and 0.79 g/km<sup>2</sup>/yr for cyclodienes, including dieldrin. If the magnitudes of atmospheric flux were similar in San Francisco Bay, resulting atmospheric loads would be approximately 0.02-2 kg/yr of DDTs, 0.9 kg/yr of chlordanes, and 0.2-2 kg/yr of dieldrin over the surface water area of the Bay ( $1.1 \times 10^9$  m<sup>2</sup>).

### **3.3.4 Loads from Historic Sediment Deposits**

Pesticide loads introduced from erosion of buried sediment were estimated using methods and assumptions outlined by Johnson and Looker (2003) in the mercury TMDL report for San Francisco Bay. These estimates were based on bathymetric studies of regions in Suisun Bay (Capiella *et al.*, 1999) and San Pablo Bay (Jaffe *et al.*, 1998) that were undergoing erosion as of 1990. Loading estimates from bed sediment were calculated using the following assumptions:

- There is an annual net loss of 1,100 Mkg of sediment from Suisun and San Pablo Bays.
- Eroded sediment is 50% water and 50% sediment by weight and comprises 740 kg of dry sediment per cubic meter of wet volume.
- Eroding material has approximately the same concentrations of pesticides as surface sediment monitored by the RMP.
- Eroded material remains within the Bay.

These assumptions do not account for varying pesticide concentrations with sediment depth, nor do they consider transport of eroding sediment out of the

Bay. USGS is currently developing a sediment-transport model that may be used to refine the assumptions.

Similar to Suisun and San Pablo bays, the South Bay underwent net erosion during 1956-1983 (Foxgrover *et al.*, 2003). Over this time period, approximately 70 Mm<sup>3</sup> (962 Mkg) of sediment eroded (an annual average of approximately 2.6 Mm<sup>3</sup>). The total estimate of sediment erosion in the Bay is approximately 2,100 Mkg of sediment.

Pesticide loads from erosion of buried sediment were estimated using the estimate of sediment erosion and a range of surface sediment pesticide concentrations measured at ambient water RMP stations from 1991 to 1999 (excluding stations in sloughs and tributaries). The best estimate and range of loads were based on average concentrations  $\pm$  one standard deviation. Average concentrations used to estimate loads of total DDTs, total chlordanes, and dieldrin were 4.1  $\mu$ g/kg, 0.71  $\mu$ g/kg, and 0.08  $\mu$ g/kg, respectively.

Load estimates in Table 3-3 do not account for erosion and lateral mixing of especially highly contaminated sediment from areas such as the Lauritzen Channel near the Richmond shoreline. These areas also influence the extent to which bed sediment contributes to future loading; however, data for estimating pesticide loading from such areas are not readily available. This is a large uncertainty, since these areas may continue to erode.

### **3.3.5 Loads from Dredged Material**

Pesticide loads to the Bay from dredged material disposal were estimated based on methods and assumptions used in the mercury TMDL report for San Francisco Bay (Johnson and Looker, 2003). The following assumptions were used:

- An annual average of 2.3 Myd<sup>3</sup> of sediment were disposed in the Bay out of 3 Myd<sup>3</sup> dredged.
- Dredged sediment is 50% water and 50% sediment by weight and comprises 570 kg of dry sediment per cubic meter of wet volume.
- Dredged material has approximately the same concentrations of legacy pesticides as surface sediment monitored by the RMP.
- Dredged material that is disposed of in the Bay remains within the Bay.

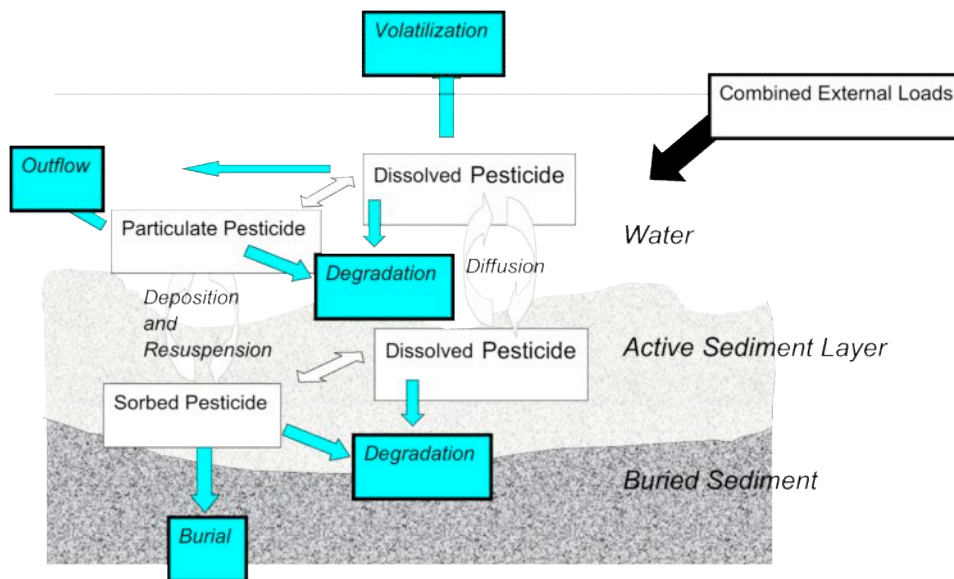
Net loads of pesticides from dredged material disposal were estimated from average concentrations ( $\pm$  one standard deviation), (Table 3-3). The dynamics associated with remobilizing or exposing contaminated sediments through dredging, the resulting magnitudes of pesticide loading to the Bay, and overall effects on water quality are unknown.

### 3.4 Processes

The fate of legacy pesticides in the water, sediments, and biota of San Francisco Bay is dependent upon the physical, chemical, and biological traits of the pesticides and of the San Francisco Bay environment (Figure 3-3). Processes include:

- Dissolved/solid partitioning.
- Bioaccumulation.
- Sediment transport and hydrodynamics.
- Sediment storage, mixing, and remobilization.
- Degradation in sediments.
- Degradation in water
- Volatilization.

Small differences in solubility and bioaccumulation rates of the individual pesticides affect their persistence in Bay sediment and biota and the extent to which they bioconcentrate. Sediment transport and hydrodynamics of the system affect the geographical distribution of the pesticides and the residence times of pesticides in the water column. Sediment storage, mixing, and remobilization are also major factors determining long-term fate. Degradation rates, although slow, also are important over the long-term and vary among the individual compounds.



*Figure 3-3. Fate of legacy pesticides in San Francisco Bay*

### 3.4.1 Dissolved/Solid Partitioning

The chemical properties of the legacy pesticides greatly affect their fates in San Francisco Bay. All organochlorine pesticides have low solubility in water, and they are found associated with particles and sediments (Table 3-4). Solubility of prominent DDT compounds (p,p'-DDE and p,p'-DDD) and chlordanes (alpha- and gamma-chlordane and cis- and trans-nonachlor) are particularly low. Association with particles (measured as  $K_{OC}$ , the soil organic carbon partition coefficient) is greatest for DDTs and least for dieldrin.

Most of the pesticide load entering the Bay in surface runoff is associated with suspended particles. Short transit times between the sources within the watersheds and the receiving waters in the Bay do not necessarily allow sufficient time for equilibrium conditions to be reached. Therefore, association with particles can be greater than predicted by equilibrium models (Bergamaschi *et al.*, 2001; Domagalski and Kuivila, 1993).

Table 3-4. Chemical properties of legacy pesticides, summarized by Nowell *et al.* (1999).  
 $K_{OC}$ =soil organic carbon partition coefficient;  $K_{OW}$ =octanol-water partition coefficient;  
 $BCF$ =bioconcentration factor

Compound	Solubility mg L <sup>-1</sup> (@T° C)	Log $K_{OC}$	log $K_{OW}$	log BCF	Soil Half-lives (days)
o,p'-DDD	0.1 (25)	5.36	5.06 - 6.22	4.73	730 - 5,690
p,p'-DDD	0.05 (25)	5.38	5.06 - 6.22	4.73	730 - 5,690
o,p'-DDE	0.0013 (nr)	5.58	5.69 - 6.96	4.73 - 5.26	730 - 5,690
p,p'-DDE	0.065 (24)	5.95	5.69 - 6.96	4.73 - 5.26	730 - 5,690
o,p'-DDT	-	5.63	5.98 - 6.00	4.73	2,390
p,p'-DDT	0.0077 (20)	5.63	5.98 - 6.00	4.73	110 - 5,480
Chlordane	0.06 (25)	4.78	6	4.15	365
Nonachlor	0.06 (nr)	4.86	5.66	4.34	15
Heptachlor	0.056 (25-29)	4.38	4.4 - 5.5	3.0 - 4.32	250
Heptachlor epoxide	0.275-0.35 (25)	3.89	3.65	2.93 - 4.16	4.7 - 79
Oxychlordane	0.7 (25)	2.48	2.6	1.28	-
Dieldrin	0.14 (25)	4.08	3.69 - 6.2	3.67	1,000

Monitoring data show the extent to which organochlorine pesticides partition between suspended particulate matter and the dissolved phase in the water column in San Francisco Bay (Figure 3-4). According to RMP data, DDTs are predominantly associated with particles throughout the Bay. For chlordanes, compounds are predominantly associated with particles in samples from Coyote Creek, Guadalupe River, and Petaluma River. Dieldrin, which is the most soluble of the legacy pesticides, predominantly occurs in the dissolved phase at every station in the Estuary. (One caveat to these relationships is that the RMP

operationally defines the dissolved fraction as the portion of the sample that passes through a 1- $\mu$ m pore size filter. Since pesticides are sorbed onto small particles such as colloids, which pass through the filters, the fraction associated with the particulate fraction is underestimated.)

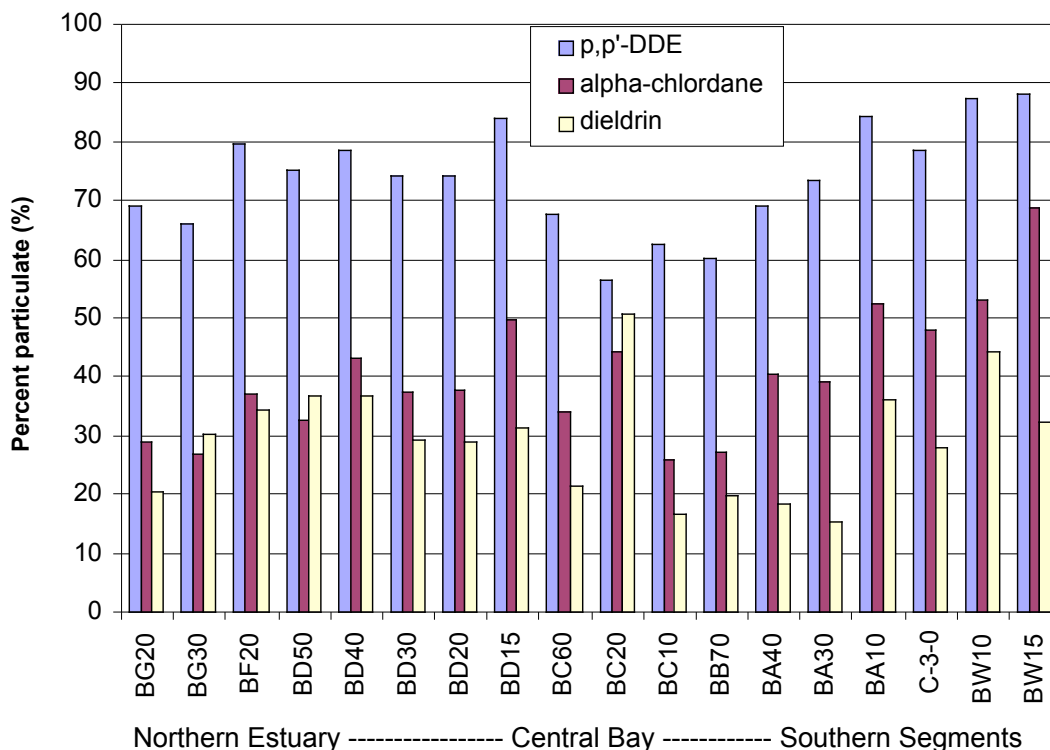
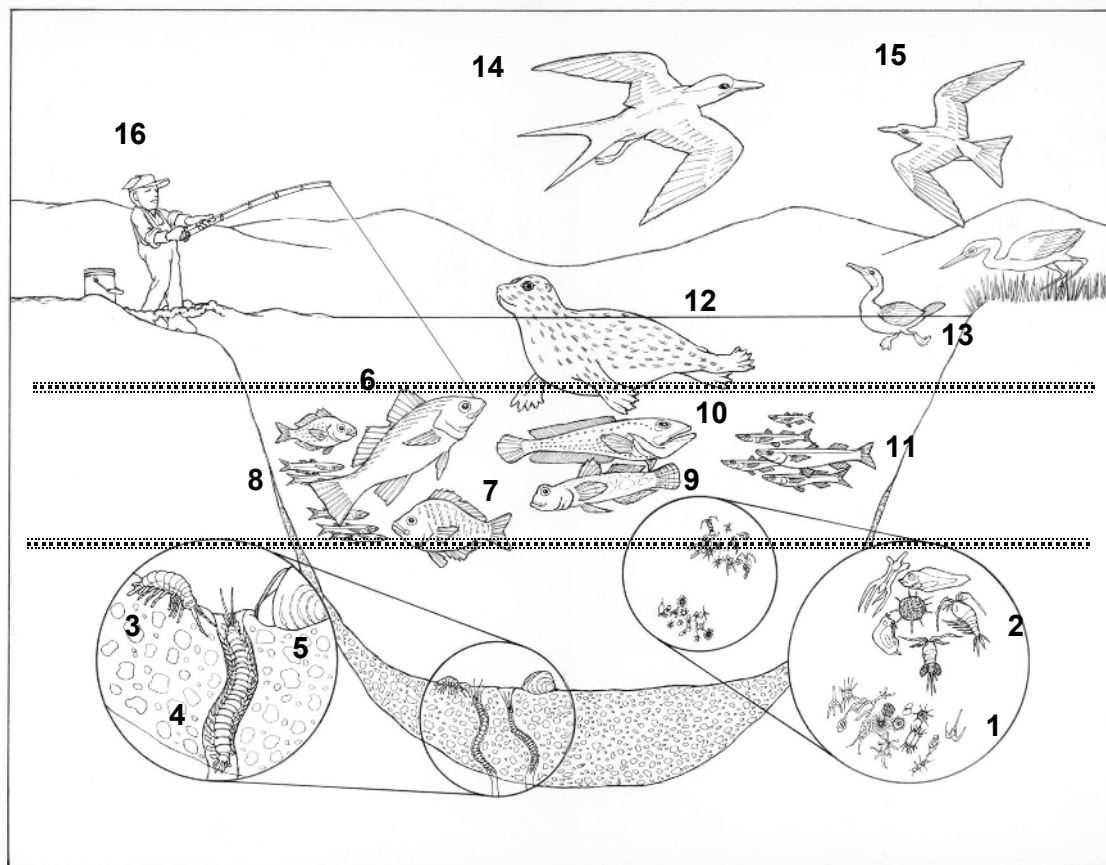


Figure 3-4. Percent contribution of particulate pesticide concentrations in water samples. Mean average values are presented for individual RMP monitoring stations from 1993 to 2001.

### 3.4.2 Bioaccumulation

All organochlorine pesticides are lipophilic and partition into the fats of living animals. The pesticides biomagnify, reaching higher concentrations with each step in the food chain (Figure 3-5). DDTs, particularly p,p'-DDE, bioaccumulate to a greater extent than chlordanes and dieldrin (measured as  $K_{OW}$ , the octanol-water partition factor, and BCF, bioconcentration factor, Table 3-4). Their tendency to bioaccumulate is the greatest concern for possible impairment of the beneficial uses of San Francisco Bay by the legacy pesticides.



*Figure 3-5. San Francisco Bay food web: (1) phytoplankton are consumed by (2) zooplankton and small invertebrates such as (3) amphipods, (4) worms, and (5) clams; (6-11) fish consume zooplankton and invertebrates; (12-16) fish are consumed by humans and wildlife species.*

Food-web models are tools for linking legacy pesticide concentrations in sediment and water with concentrations in important indicator species (sport fish, birds, and seals). A food-web model for PCB movement into Bay sport fish has been developed, and the predictions of the model have been found to be in reasonable agreement with the observed concentrations (Gobas and Wilcockson, 2003). Given the strong chemical similarities between the legacy pesticides and PCBs, the general lessons learned from the PCB modeling also apply to legacy pesticides. An important finding of the study was that the structure of the food web is an important influence on concentrations found in sport fish—concentrations of PCBs in jacksmelt were higher in large fish that had consumed clams and polychaete worms than in smaller fish that had fed on phytoplankton and zooplankton. The lipid content of indicator species is another important factor. RMP fish sampling has shown that species with higher lipid content accumulate higher legacy pesticide concentrations (Greenfield *et al.*, 2003). Seasonal variation in legacy pesticide concentrations in white croaker was also associated with the seasonal variation in lipid content, which reflects the reproductive cycle in this species.

### **3.4.3 Sediment Transport and Hydrodynamics**

Sediment transport and hydrodynamics are important factors in determining the distribution of legacy pesticides throughout San Francisco Bay. Transport and distribution of pesticides associated with suspended sediments are influenced by highly variable processes, including freshwater runoff, salinity, tidal flow, and wind.

Surface runoff from the Central Valley via the Sacramento and San Joaquin rivers comprises the largest portion of freshwater flow and sediment transport to the Bay (McKee *et al.*, 2003; Kron, 1979). Consequently, the northern segments of the Bay are well-flushed, especially during large storm events. In contrast, southern segments of the Bay receive little freshwater flow, resulting in longer residence times for water, sediment, and associated pesticides.

Once legacy pesticides reach the Bay, they can be remobilized and redistributed through tidal action and wind-driven waves. These processes account for most of the variability in suspended sediment concentrations observed in the Bay (Schoellhamer *et al.*, 2003). The strongest tidal events occur during the spring tides associated with new and full moons, while the strongest winds occur during the spring and summer.

The highest concentrations of legacy pesticides in the system are found along the margins of the Bay, in areas in close proximity to urban landscapes. These areas, including Oakland Harbor, Richmond Harbor, San Leandro Bay, and the South Bay sloughs, are depositional environments, affected by runoff from urban watersheds. In areas where tidal and wind-driven mixing are insufficient to transport the deposited sediment out into the open areas of the Bay, pesticides will persist in the sediments and be available for local resuspension and possible uptake into the biota.

The residence time of the Bay and its subembayments is a key influence on the ecosystem. Leatherbarrow *et al.* (2003) estimated that outflow through the Golden Gate was a more important process of pesticide removal for dieldrin than for DDTs or chlordanes. Dieldrin is more soluble in water, making it more available for outflow. Consequently, hydrodynamics exert a greater influence on dieldrin than on the other pesticides.

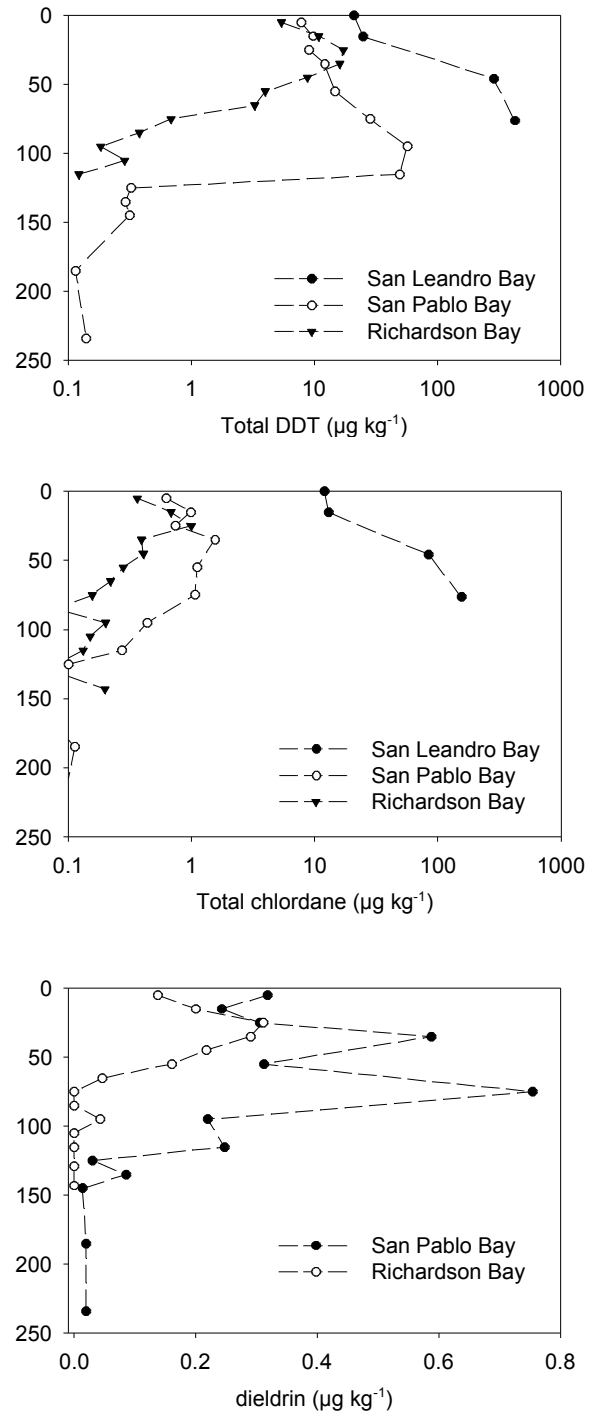
### **3.4.4 Sediment Storage, Mixing, and Remobilization**

Sediment storage, mixing, and remobilization are major determinants of the long-term fate of legacy pesticides in San Francisco Bay. Within depositional areas, pesticide residues are stored in the sediments. Data from cores taken from these depositional areas provide information on inputs, transport, and fate (*e.g.*, Venkatesan *et al.*, 1999, for San Pablo and Richardson bays; Daum *et al.*, 2000, for San Leandro Bay).

A core from San Pablo Bay had generally higher concentrations of DDTs and dieldrin relative to a core from Richardson Bay, while concentrations of chlordanes were more uniform between the cores (Figure 3-6). These findings reflect the inputs of DDTs and dieldrin from agricultural applications in the Central Valley to San Pablo Bay and the more urban application of chlordanes. Concentrations of DDTs and chlordanes were much higher in cores from shallow San Leandro Bay than in the cores from the deeper San Pablo and Richardson bays, illustrating the large contributions of pesticides from local watersheds and/or contaminated sites to the Bay margins.

In the San Pablo and Richardson bays cores, the subsurface maximum concentrations of DDTs were at least an order of magnitude greater than the subsurface maxima for chlordanes and dieldrin, while the difference was only a factor of two or three in the San Leandro Bay core. These patterns may indicate more recent use of chlordane and dieldrin in urban applications but are also confounded by varying loading and depositional processes in the sites. They also show that on a Bay-wide scale, there are greater stores of DDT than chlordane and dieldrin.

Organochlorine pesticides preferentially partition to sediments, including the active, surface layer as well as the buried deposits. The dynamics and depths of the active sediment layer are highly variable throughout the Estuary and not well-characterized (Fuller *et al.*, 1999; Davis, 2003). Recent modeling studies of contaminant fate have shown that the active sediment layer is one of the most influential, yet least understood, factors that affect the long-term fate of contaminants in the Bay (Davis, 2003; Greenfield and Davis, 2003; Leatherbarrow *et al.*, 2003). The depth of the active layer can vary from as little as three to more than 50 cm (Leahy *et al.*, 1976). Despite such great variability, a best estimate of 15 cm has been used in recent modeling of persistent organic contaminants in the Bay. Leatherbarrow *et al.* (2003) estimated that pesticide storage in an active sediment layer of 15 cm is approximately 350 kg total DDTs, 45 kg total chlordanes, and 13 kg dieldrin. These estimates are based on Bay-wide estimates of pesticide concentrations, which are highly variable. Therefore, the estimates have high degrees of uncertainty. Further characterization of the active sediment layer is necessary to improve the understanding of existing storage of legacy pesticides in Bay sediments.



*Figure 3-6. DDTs, chlordanes, and dieldrin in sediment cores from San Pablo, Richardson, and San Leandro bays (Note logarithmic scales for DDTs and chlordanes)*

Estimating the mass of legacy pesticides that are buried in the Bay but that could be exposed by erosion or dredging is confounded by the lack of data. The two cores from the Bay, one from Richardson Bay and one from San Pablo Bay (Venkatesan *et al.*, 1999), estimated inventories of total DDTs over the entire depths of the cores as 557 ng/cm<sup>2</sup> in the Richardson Bay core and 3,453 ng/cm<sup>2</sup> in the San Pablo Bay core. Extrapolating to the entire Bay (1.1 x 10<sup>9</sup> m<sup>2</sup>), results in a range of buried DDT mass of 6,000 to 38,000 kg. Non-DDT pesticide inventories ranged from 1,154 ng/cm<sup>2</sup> to 4,069 ng/cm<sup>2</sup> in Richardson and San Pablo bays, respectively. Dieldrin concentrations composed approximately 2-3% of total pesticides in the cores, while total chlordanes made up an average of 10% of total pesticides in the San Pablo Bay core and 18% in the Richardson Bay core. Using these percentages, the range of masses stored in buried deposits in the Bay are approximately 3,400-8,300 kg chlordanes and 380-2,500 kg dieldrin.

Spatial variability in contamination and depositional patterns introduces large uncertainties in estimating Bay-wide storages of pesticides in buried sediments from only two cores. The cores were collected offshore and provide only a rough estimate of pesticide storage in offshore or ambient Bay sediments. The lack of data from Bay margins precludes making an estimate of pesticide storage along the shorelines and in the sloughs.

Despite the uncertainties, existing data indicate that further erosion in the Bay could remobilize sediments that are more contaminated than those in the current active layer. Exposure of buried sediments along the Bay margins of particularly contaminated areas, such as Oakland Harbor or San Leandro Bay, could reintroduce sediments with high concentrations of pesticides. This possibility may be especially important with regard to sport fish, as the highest concentrations of chlordanes and dieldrin measured in the fish from the 2000 RMP collections were shiner surfperch and white croaker from Oakland Harbor and San Leandro Bay.

### **3.4.5 Degradation in Soils and Sediment**

The long-term persistence of DDTs, chlordanes, and dieldrin in watershed soils is well-documented (*e.g.*, Gilliom and Clifton, 1990; Mischke *et al.*, 1985; Spencer *et al.*, 1996; Stewart and Chisholm, 1971; Castro and Yoshida, 1971). Spencer *et al.* (1996) found that total DDT concentrations measured in the top 75 cm of agricultural soil samples collected in California in 1994 were approximately 10-28% of the concentrations measured in 1971. Assuming first order reaction rates, this corresponds to a half-life of approximately 7 to 13 years. At these rates, approximately 2-11% of total DDT applied in 1965 still remained in watershed soils in 2003.

The degradation of DDT to DDD and DDE poses an added complexity in understanding the total degradation rates. DDT readily undergoes reductive dechlorination under anaerobic conditions, and the flooding of soils promotes the degradation of DDT to DDD (Castro and Yoshida, 1971). In aerobic environments, DDT is dehydrochlorinated to DDE. Both DDD and DDE are much more recalcitrant in aerobic and anaerobic soils (Castro and Yoshida, 1971; Strompl and Thiele, 1997). As a result, in estuarine sediment, transformation rates of DDT compounds decrease in the order: DDT > DDD > DDE (Huang *et al.*, 2001).

Degradation rates have been shown to increase with increasing moisture in soil (Spencer *et al.*, 1995; Castro and Yoshida, 1971; Ghadiri *et al.*, 1995) and marine sediment (Kale *et al.*, 1999), suggesting that degradation rates are higher in the Bay than in watershed soils. However, degradation rates of organochlorine pesticides in marine and estuarine sediment have not been well-studied.

Leatherbarrow *et al.* (2003) compiled literature estimates of degradation rates in soil and sediment to derive applicable rates for a mass budget model of organochlorine pesticide fate in San Francisco Bay (Table 3-5).

Table 3-5. Best estimates of half-lives of legacy pesticides in soil and sediment

Pesticide	Half-life (years)
DDT	9
Chlordane	2.3
Dieldrin	2.8

There was considerable uncertainty associated with the degradation rate estimates, which typically spanned an order of magnitude. Estimated degradation rates for dieldrin spanned two orders of magnitude.

### 3.4.6 Degradation in Water

Degradation of legacy pesticides is faster in water than in soils or sediments. However, given that an estimated 97-99% of the mass of DDTs, chlordanes, and dieldrin in the Bay is associated with the actively mixed sediment layer, degradation in water is not thought to be a major removal process (Leatherbarrow *et al.*, 2003). In the water column, degradation occurs by direct and indirect photolysis and hydrolysis. Hydrolysis of legacy pesticides is not expected to be important (Mackay *et al.*, 1997).

While photolysis rates of DDT and DDD are not expected to be important (Callahan *et al.*, 1979), rates of DDE photolysis that would essentially remove all DDE from a water body within one day have been reported (Zepp and Cline, 1977). The persistence of p,p'-DDE and other DDT compounds in the water column and sediment of San Francisco Bay indicate that rates of degradation are

probably much slower than the reported values. Persistence of p,p'-DDE in other surface water bodies has been explained by its sorption to sediment (Zepp *et al.*, 1977), which can decrease photolysis rates in the water column (Miller and Zepp, 1979; Oliver *et al.*, 1979). Moreover, attenuation of sunlight in natural waters decreases photolysis rates of organic contaminants within the top few centimeters (Zepp and Cline, 1977).

### **3.4.7 Volatilization**

Volatilization of pesticides from the water column is expected to be an important pathway of pesticide removal from the Bay, based on the mass budget model (Leatherbarrow *et al.*, 2003). No data have been collected to directly study air-water exchange of legacy pesticides within the Bay; however, Henry's law constants compiled from the literature were used to estimate volatilization rates. (Henry's law states that the mass of a gas that dissolves in liquid is proportional to the pressure of the gas.) Varying Henry's law constants had only a minor effect on model output, indicating that uncertainty in this parameter is less important than others for estimating long-term fate of legacy pesticides in the Bay.

Of DDT compounds, p,p'-DDE has the highest volatility, increasing with soil moisture (Spencer *et al.*, 1996). Due to increased degradation and volatility of p,p'-DDE with increased moisture, agricultural areas that have been plowed and irrigated have shown greater long-term declines in total DDT concentrations than areas that have not been similarly managed (Spencer *et al.*, 1996). Since most of the total DDT residues measured in San Francisco Bay sport fish is in the form of p,p'-DDE, watershed management efforts that promote the degradation and volatilization of more volatile species, such as p,p'-DDE, could lead to faster reductions in the pesticide mass entering the Bay and more rapid declines in fish tissue concentrations.

## **3.5 Recovery of the Bay**

The recovery of San Francisco Bay from legacy pesticide contamination was evaluated using the one-box mass budget model, which considers inputs and losses to the water column and the sediment active layer, which interacts with the overlying water. The underlying mass of buried sediment is considered a long-term sink. The model accounted for five major pathways of addition to or removal of pesticides from the Bay: loading to the Bay, outflow to the Pacific Ocean, volatilization to the atmosphere, permanent burial to the sediment, and degradation (Figure 3-7). The loading term encompasses all inputs, including runoff from the Central Valley and the local watersheds, wastewater effluent, atmospheric deposition, and erosion or dredging of bottom sediments. The model also accounted for transfer of pesticides between water and the sediment active layer.

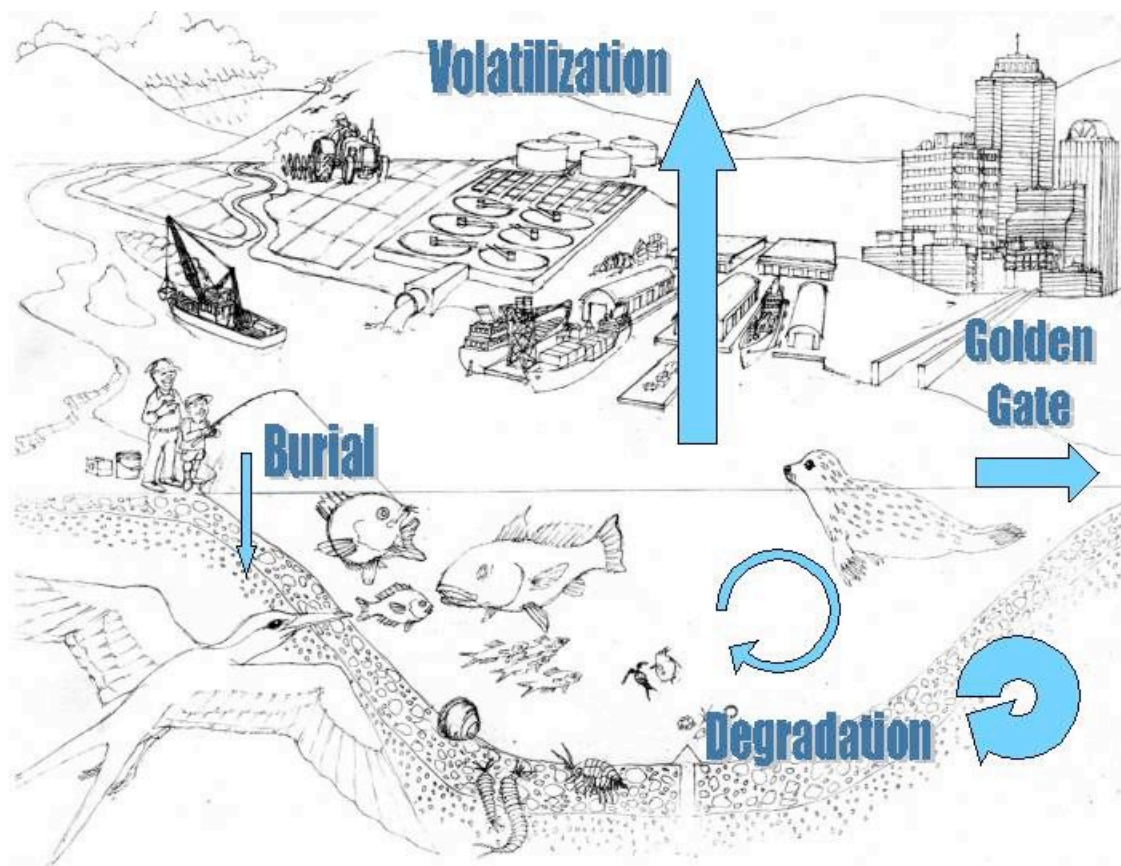


Figure 3-7. Loss pathways

Significant uncertainties were introduced to the model by using Bay-wide estimates of spatially variable parameters, such as concentrations in sediments and the depth of the active layer. Other uncertainties, such as those associated with loading and degradation, added to the overall uncertainty in model output. The cumulative effect of these uncertainties has not been defined. Consequently, the modeling exercise was only an initial attempt to integrate existing information. As improved information becomes available, more sophisticated modeling approaches can be used.

### 3.5.1 Current Inventory

Because DDTs, chlordanes, and dieldrin are sparingly soluble in water, most of the current mass of legacy pesticides in San Francisco Bay (excluding the buried sediment) resides in the active layer of the sediments rather than the water column (Leatherbarrow *et al.*, 2003; Davis *et al.*, 2003) (Table 3-6). Assuming a 15-cm active-sediment-layer depth, pesticide mass in sediments comprises 97-99% of the total mass of pesticides in the system, with an estimated 347 kg DDTs, 45 kg chlordanes, and 12 kg dieldrin.

Table 3-6. Concentration and mass of legacy pesticides in water and sediments

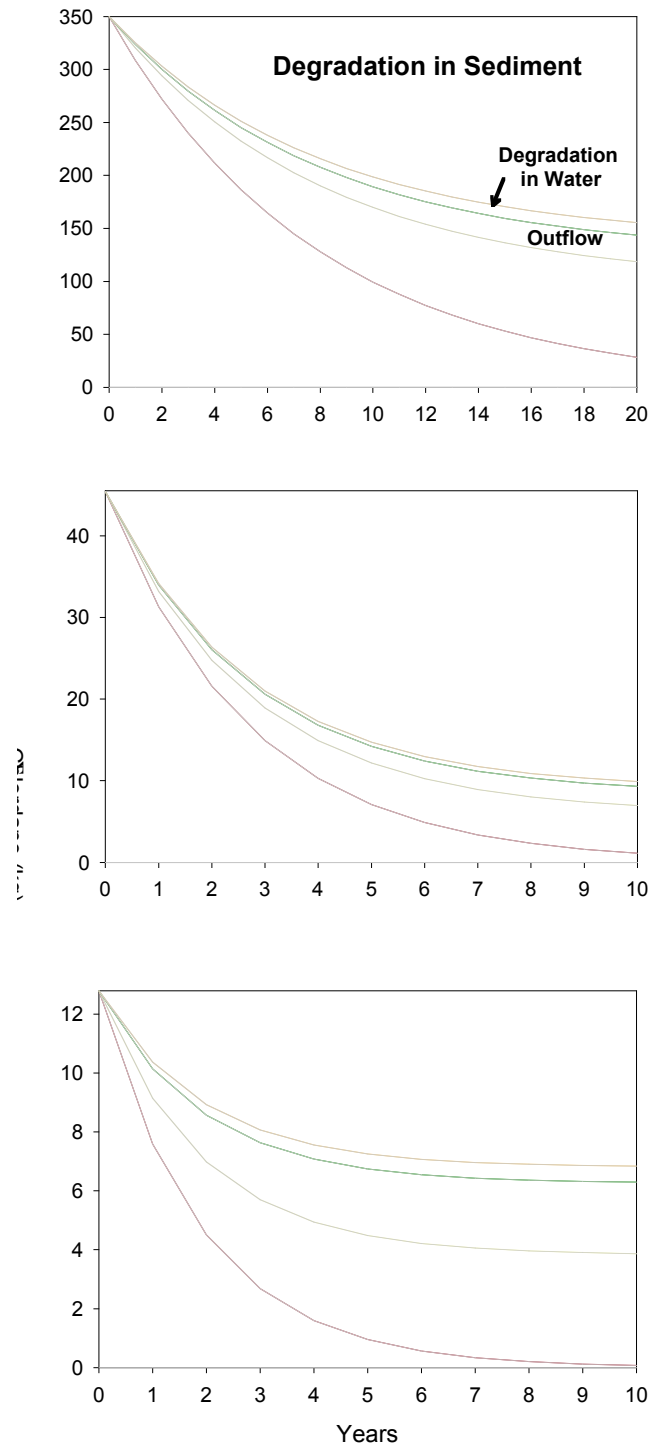
	Concentration		Mass		
	Water pg/l	Sediment µg/kg	Water kg	Sediment kg	Total kg
DDT	660	4.2	3.6	347	350
Chlordane	160	0.54	0.88	45	45
Dieldrin	77	0.15	0.42	12	13

### 3.5.2 Removal Pathways

The model compared the relative importance of the pathways of legacy pesticide removal from the Bay: outflow, degradation in water and sediment, volatilization, and burial (Figure 3-8). In all modeling scenarios, the rate of burial was assumed to be zero, based on bathymetric studies that have shown net erosion of sediments from the Bay in recent decades (*e.g.*, Foxgrover *et al.*, 2003).

The model results indicated that degradation in sediment is the major pathway of removal. Over a 10-year period with no loading, 72% of p,p'-DDE mass would be removed from the Bay, mostly through degradation in sediment. Similarly, the model predicted that 98% of the initial alpha-chlordane mass would be removed in 10 years, with most removed through degradation in sediment. Lower affinity of dieldrin for sediment would lead to removal processes in the water column having a greater effect than for other pesticides. All of the dieldrin mass was estimated to be removed within 10 years.

As previously noted, degradation rates of legacy pesticides in Bay sediments are important to estimates of long-term fate, but they are poorly characterized. For example, increasing the half-life of DDT over a plausible range of 2 to 16 years decreases the mass of DDT removed from the Bay in five years from 86% to 37%. However, even using the slowest reported degradation rates, degradation is the most important removal pathway for DDTs and chlordanes. Volatilization and outflow may be the more important removal pathways for the more soluble dieldrin.



*Figure 3-8. Removal pathways for legacy pesticides*

### 3.5.3 Removal Rates

The model was used to compare estimated recovery times of the Bay under various loading scenarios. Under a scenario with no new pesticide loading, the model estimated that DDT was the most persistent of the legacy pesticides, with a half-life of about five years (Figure 3-9). The half-life of chlordane was about two years, and the half-life of dieldrin was about one year, reflecting its higher degradation rate.

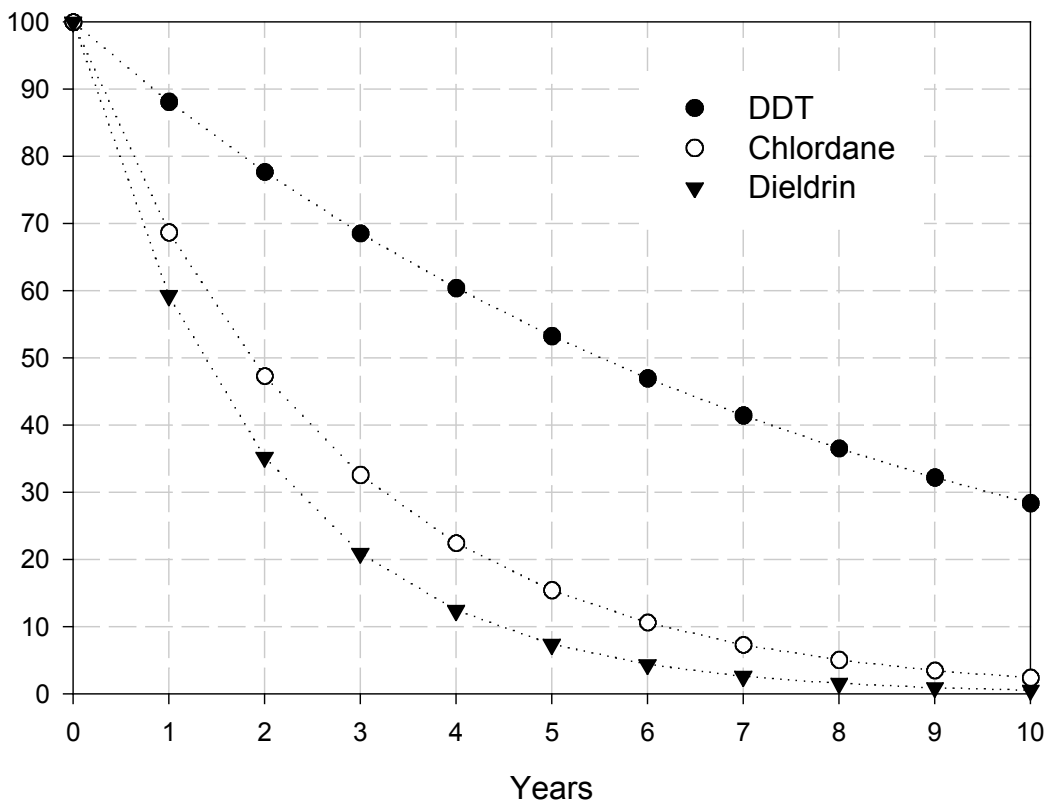


Figure 3-9. Half-lives of legacy pesticides under conditions of no new loading

The model estimated that, under conditions of no loading, San Francisco Bay would be cleared of legacy pesticides within one to three decades. In the absence of loading, 95% of the current mass DDTs, chlordanes, and dieldrin would be removed from the Bay within 25, 8, and 6 years, respectively.

Under scenarios of continued loading to the Bay, the model estimated that the Bay would eventually reach steady states of inputs and outputs (Figure 3-10). Annual loads of about 60 kg DDTs and 20 kg chlordanes and dieldrin would be sufficient to prevent any decrease in the current mass of pesticides in the Bay. These loads are of similar magnitude to the best estimates of current pesticide loads calculated for this report, 60 kg DDTs, 30 kg chlordanes, and 10 kg dieldrin. Although there are significant uncertainties in both the load estimates and the model outputs, the

results suggest a question as to whether pesticide mass (and concentrations) in the Bay will decline.

Actual trends in pesticide concentrations in the Bay were evaluated using bivalve data collected by the State Mussel Watch Program and the RMP (Figure 3-11). For all three pesticides, there have been obvious declines in concentrations over time, but these declines are less apparent since the early 1990s (Gunther *et al.*, 1999; Leatherbarrow *et al.*, 2003). Half-lives estimated from bivalve data were two to eight times longer than those measured by the model (under the scenario of no additional loading). The longer half-lives estimated from bivalve data provide evidence of continued pesticide loading to the Bay during the last two decades. Bivalve data also support model predictions that p,p'-DDE will be more persistent than other pesticides.

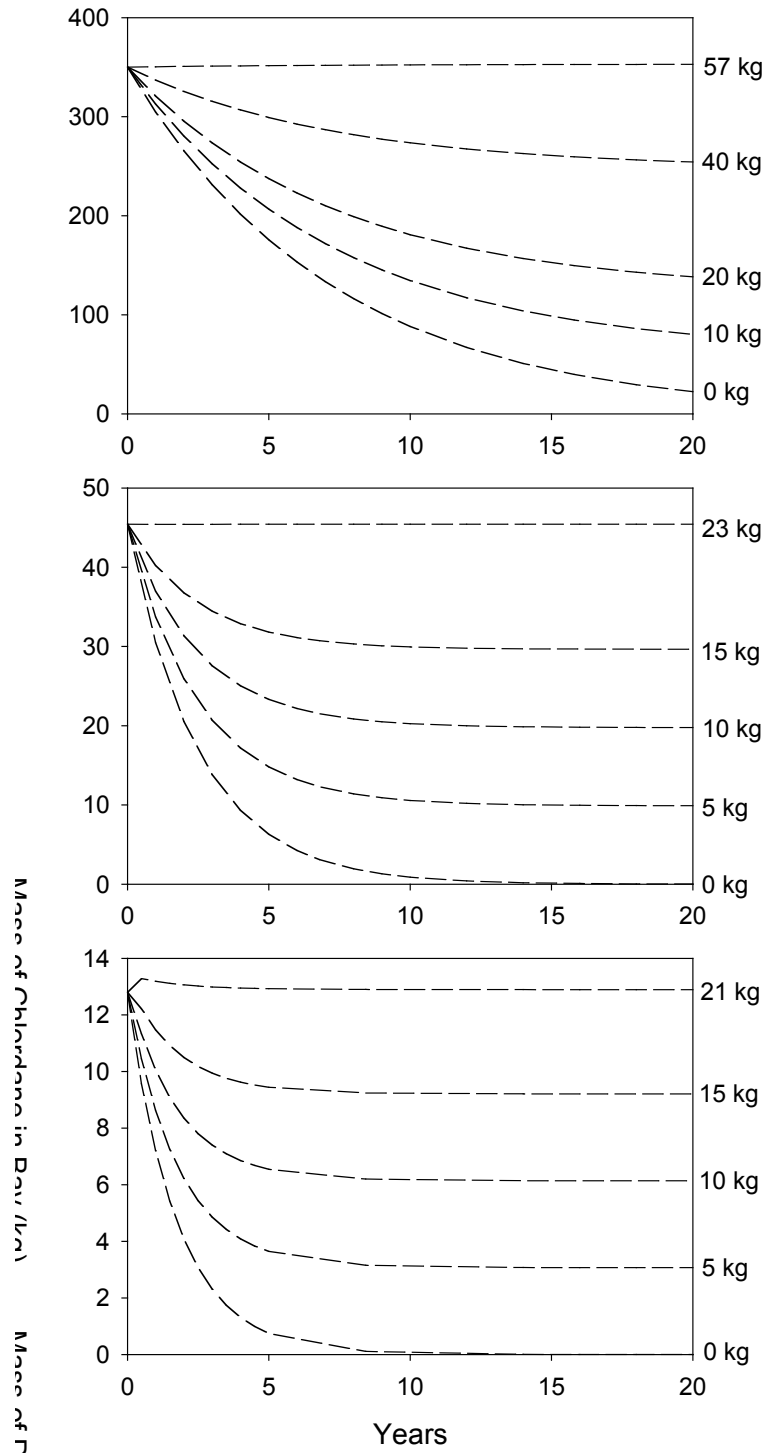


Figure 3-10. Model estimates of the change of legacy pesticide mass in San Francisco Bay with varying pesticide loading. (DDTs were modeled as *p,p'*-DDE. Chlordanes were modeled as *alpha*-chlordane.)

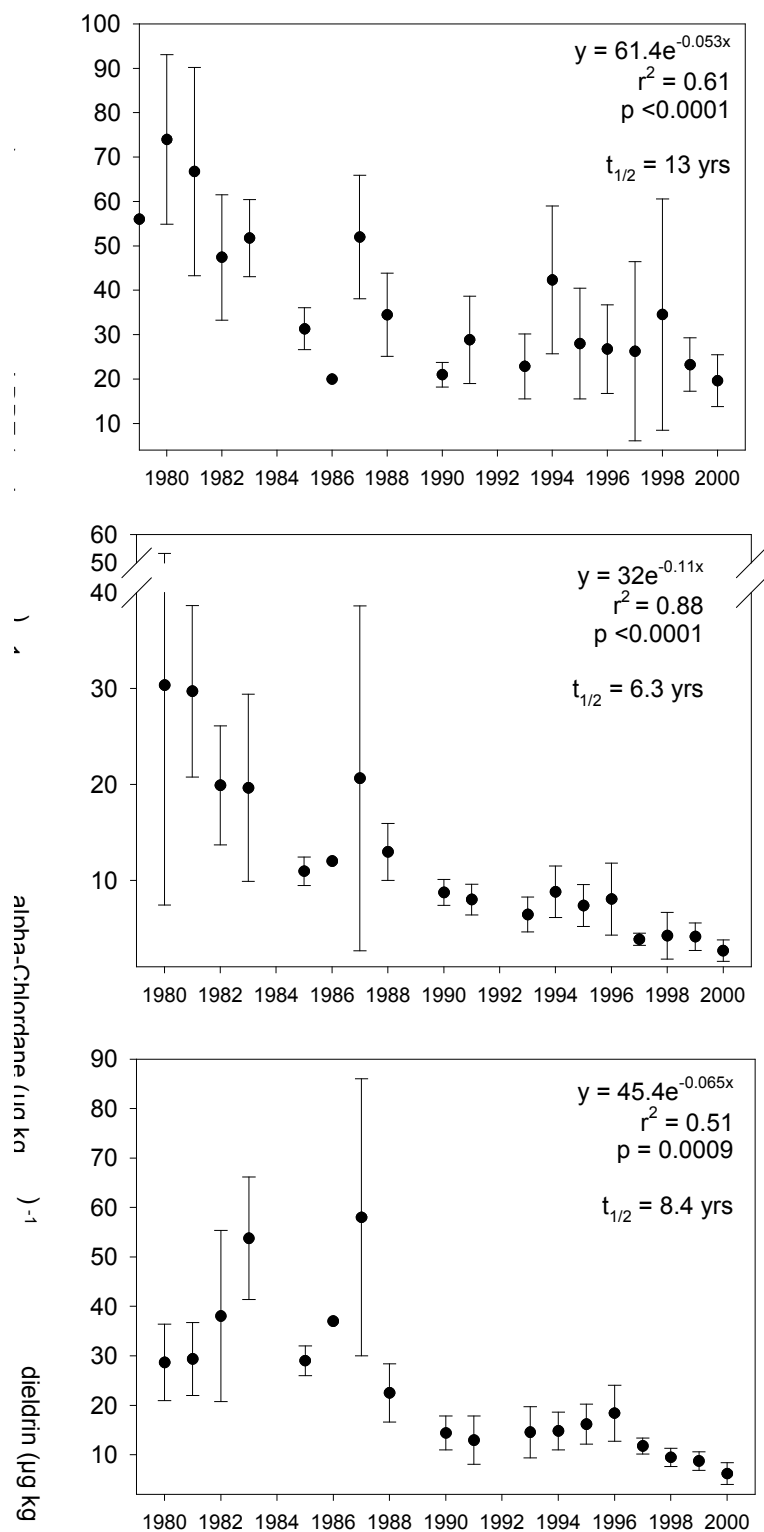


Figure 3-11. Pesticide concentrations in bivalves

## **4. Information Gaps**

This section summarizes the uncertainties in this report's conclusions and suggests some potential future projects to obtain additional data and conduct more analysis of the sources, fate, transport, and effects of legacy pesticides. In other documents or forums, the CEP will develop appropriate strategies for addressing legacy pesticides in the Bay and its watersheds. These strategies may include:

- Data collection or analysis.
- Implementation of corrective actions.
- Formulating and refining management questions and setting priorities for the above two activities.
- Determining an ongoing process for integrating all of the above.

There may be control measures, remediation, and regulatory actions that can and should begin now, even with existing uncertainties. CEP partners are committed to identifying these actions. Future CEP data gathering and technical analysis should focus on determining the potential effectiveness and actual effects of actions to reduce or eliminate impairment and to restore beneficial uses of the Bay.

Understanding the fate of the legacy pesticides and the level of impairment that they cause to San Francisco Bay is hampered by a variety of data gaps and uncertainties:

- Lack of established criteria for determining impairment.
- Uncertain understanding of trends in pesticide concentrations.
- Lack of understanding of sediment "hot spots."
- Uncertain understanding of the large runoff events from the Central Valley.
- Uncertain understanding of loads from small tributaries.
- Model uncertainties.

### **4.1 Impairment Criteria**

The beneficial use of the Bay that is most probably impaired by legacy pesticides is its value for sport fishing. Data from the water column and fish tissue provide some indications of this impairment. However, a good definition of impairment to sport fishing in San Francisco Bay depends upon calculation of screening values, and there are no standards for these values. There are also no established criteria for interpreting sediment or wildlife data. OEHHA, the San Francisco RWQCB, and USEPA should work together to establish criteria for determining impairment.

## **4.2 Trends in Pesticide Concentrations**

Monitoring data collected over a span of decades indicate that there have been large declines in concentrations of legacy pesticides in fish tissues. Trends over a shorter, more recent period are not as apparent. While pesticide loading to the Bay is probably declining, erosion of sediment may expose contaminated layers that had been buried. However, the best records of trends in sediments come from just two sediment cores taken by the USGS in the early 1990s. Additional information is needed to determine whether concentrations and loads of legacy pesticides in the Bay are continuing to decline, remaining somewhat stable, or even increasing. This is a primary data gap for which information is needed.

Possible actions include:

- **Continued monitoring of concentrations of pesticides in fish, bird eggs, water, and sediment** is necessary to determine trends and regularly inform managers about the status of impairment of the Bay.
- **Collection and analysis of sediment cores** from depositional areas would provide information on recent trends in pesticide concentrations. Cores collected from erosional areas would help determine the potential for future re-introduction of pesticides. Cores collected from near-shore environments and the individual segments of the Bay would provide information on geographic variation.

## **4.3 Near-Shore Locations and Hot Spots**

Monitoring has shown that areas of contamination exist in near-shore locations in the Bay and in localized areas within the watersheds. The location of such “hot spots” within urban areas may especially affect subsistence anglers, who depend upon fishing for food. For contaminated sites within the Bay, there is uncertainty as to whether processes such as erosion or dredging are contributing to overall loading of pesticides to the Bay. Many sites that are contaminated by legacy pesticides are also affected by other contaminants of concern, such as PCBs. As a result, management actions that successfully reduce PCB contamination will also reduce contamination by legacy pesticides.

Studies of water and sediment in close proximity to hot spots may provide information on the extent to which remobilization of near-shore sediments influences impairment of the Bay. These studies may assist managers in deciding whether to direct management resources to in-Bay remediation or to source reduction efforts in the watersheds.

## **4.4 Runoff from the Central Valley**

The Central Valley is a significant source of legacy pesticides to San Francisco Bay because of historic use of pesticides in its predominantly agricultural land and the large magnitude of sediment and freshwater flow from the Sacramento and San Joaquin rivers. An RMP special study of loading to the Bay from the rivers was conducted during years of relatively low to moderate Delta outflow and relatively low concentrations of suspended sediments. During larger storm events, different sources of pesticides within the watersheds might be activated. Characterization of the large runoff events would provide better information for understanding this large source of pesticides to the Bay.

It is difficult to predict the occurrence of wet vs. dry years, and it is especially difficult to predict the occurrence of the largest storm events. Therefore, successful characterization of large runoff events would require appropriate preparedness to conduct sampling whenever such an event occurred. Ideally, a monitoring plan would include sampling every year, which would provide a good understanding of interannual variability. A more efficient plan should provide for sampling on an opportunistic basis, focusing on large flood events. The number of years that such a study would last is difficult to predict.

## **4.5 Loadings from Small Tributaries**

Tributaries that drain the local watersheds are important pathways for legacy pesticides in terms of the magnitude of loads and also in determining practical management actions. Currently, there is uncertainty in estimates of loads from small tributaries. Data from the Guadalupe River have indicated that concentrations of legacy pesticides are correlated with sediment and discharge in a predominantly urban watershed. How these relationships differ in watersheds of varying land use and other characteristics and how they may change in response to management actions is not known. In particular, there are no recent data for pesticide concentrations in agricultural parts of the Bay Area. Also, as management actions are planned and implemented in local watersheds, it will be necessary to assess their effectiveness.

Possible actions include:

- **Characterization of watersheds with varying land use.** Concentrations of legacy pesticides and suspended sediments should be measured in the water column during runoff events for representative watersheds. This information would afford a better understanding of the range of variability in pesticide transport processes and their influence on concentrations and loading. The information would provide greater ability to extrapolate from existing data to the Bay as a whole.
- **Determination of the effectiveness of management actions.** Methods for evaluating the success of local management actions should be

established. This action may require a review of methods that other geographic areas have used to determine success in clean-up efforts. Assessment of success resulting from the PCB TMDL may also apply to legacy pesticides.

## **4.6 Modeling Uncertainties**

A mass budget modeling study of legacy pesticides in the Bay integrated existing information to provide an initial understanding of recovery rates of the Bay. However, the current one-box model lacks the spatial and temporal resolution necessary for accurate predictions of pesticide fate and transport in response to fluctuations in sediment transport and hydrodynamics in different parts of the Bay. There are several sources of uncertainty that may be reduced by further investigation:

- The model's annual time step neglects the effect of shorter-term variability in sediment transport and hydrodynamics.
- Better Bay-wide estimates of spatially variable parameters, such as pesticide concentrations in the sediments and the depth of the active layer, are essential for estimating the current reservoir of pesticide storage in the Bay and the time scales for recovery.
- Degradation rates in sediments are not well defined but are important factors for determining recovery.
- Linkage between concentrations and loads of legacy pesticides in the water and the sediments and those in the biota has not been established.

Possible actions include:

- **Development a five-box model of pesticide fate and transport.** A five-box model is currently being developed to predict the transport and fate of PCBs on a daily time step in five major regions of the Bay. If the modeling exercise is successful for PCBs, it could be applied to legacy pesticides as well and would provide greater temporal and spatial information.
- **Development a food-web model.** A food web model has been developed to link concentrations of PCBs in water and sediment samples with concentrations in important indicator organisms. The legacy pesticides share many chemical attributes with PCBs, and it is possible that this model could be adapted for use with pesticides.

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