

U. S. DEPARTMENT OF THE INTERIOR
U. S. GEOLOGICAL SURVEY

**GEOCHEMICAL STUDIES OF ANTHROPOGENIC AND NATURAL
ORGANIC COMPOUNDS AT THE SONOMA BAYLANDS WETLAND
DEMONSTRATION PROJECT SITE AND ADJACENT
MARSHLANDS, SONOMA COUNTY, CALIFORNIA**

by

**Wilfred E. Pereira, Frances D. Hostettler, Robert J. Rosenbauer,
Keith A. Kvenvolden, and Fred Murphy**

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U. S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS AND ABBREVIATIONS

<i>Multiply</i>	<i>By</i>	<i>To obtain</i>
feet	3.048×10^{-4}	kilometers
centimeter (cm)	3.94×10^{-1}	inch
gram (gm)	3.53×10^{-2}	ounce, avoirdupois
microgram (μg)	3.53×10^{-8}	ounce, avoirdupois
micrometer (μm)	3.94×10^{-5}	inch
milligram (mg)	3.53×10^{-5}	ounce, avoirdupois
millimeter (mm)	3.94×10^{-2}	inch
nanogram (ng)	3.53×10^{-11}	ounce, avoirdupois
nanometer	3.94×10^{-8}	inch
acre	4,047	meter ²
yard ³ (yd ³)	0.7646	meter ³ (m ³)

Degree Celsius (⁰C) may be converted to degree Fahrenheit (⁰F) by using the following equation:

$$^{\circ}\text{F} = [9 \times ^{\circ}\text{C} / 5] + 32$$

Abbreviated water-quality units used in this report:

ng/g nanogram per gram

Other units used in this report:

⁰C/min degrees Celsius per minute

Other abbreviations and symbols used in this report:

PAHs polycyclic aromatic hydrocarbons

DDT 4,4'-dichlorodiphenyltrichloroethane

DDD 4,4'-dichlorodiphenyldichloroethane

DDE 4,4'-dichlorodiphenyldichloroethene

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ABSTRACT

A geochemical study was conducted to establish baseline data of selected organic contaminants in fill-materials at the Sonoma Baylands Wetland Demonstration Project (SBWDP) site, in soils of the adjacent marshlands, and in benthic sediments of the adjacent marshland tidal channels. The study also includes sediments of the Petaluma Tidal Marsh Restoration Project (PTMRP) site which were deposited by natural sedimentation processes when the site was exposed to tidal action. Sediments were analyzed for atomic C, H, and N. Organic contaminants were identified by gas-chromatography/mass spectrometry, and included aliphatic hydrocarbons, biomarker hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), chlorinated pesticides DDT and its degradates DDD and DDE, chlordanes and dieldrin. C/N ratios in fill-material at the SBWDP site and in benthic sediments from the adjacent tidal channels indicated mixed inputs of organic matter from terrigenous and marine sources. C/N ratios in soils of the adjacent marshlands were characteristic of terrigenous inputs of organic matter. C/N ratios of fill sediments at the SBWDP site may be a sensitive indicator of wetland development and restoration.

Aliphatic hydrocarbons in sediments from the Pilot and Main sites, and benthic sediments from the tidal channels, ranged from C₁₃-C₃₇, with varying levels of an unresolved complex mixture of aliphatic hydrocarbons (UCM), indicating different

degrees of petrogenic contamination that has undergone biodegradation. In contrast, the smaller UCMs in soils of the adjacent reference marshlands and the PTMRP site indicated lower levels of biodegraded petrogenic contamination. Biomarker ratios also indicated varying levels of petrogenic contamination. The hopene diploptene is a specific marker or indicator compound of agricultural soil underlying the fill-material at the SBWDP site. Concentrations of aliphatic hydrocarbons in sediments varied from: 2310-5450 ng/g at the Pilot site; 1946-4273 ng/g at the Main site ; 1698-2721 ng/g at the PTMRP site; and 3755-13,683 ng/g in benthic sediments from the tidal channels. Concentrations of aliphatic hydrocarbons in soils of the adjacent reference marshlands ranged from 1556-5552 ng/g.

Methylphenanthrene/phenanthrene (MP/P) ratios in all sediments in this study generally were less than one, indicating that these polycyclic aromatic hydrocarbons (PAHs) are derived from combustion processes rather than from recent petroleum spills. Concentrations of total PAHs in sediments ranged from: 990-1350 at the Pilot site; to 56-786 at the Main site; to 257-419 ng/g at the PTMRP site; and to 722-4498 ng/g in benthic sediments of the tidal channels. Concentrations of total PAHs in soils from the adjacent reference marshlands ranged from 161-3140 ng/g.

Low concentrations of DDT and its degradates were present at all sites in the study area. However, one sediment sample from the adjacent reference marshland in close proximity to an agricultural pump and drain system contained high concentrations of DDTs. Concentrations of total DDTs in sediments ranged from: 1.0-7.7 ng/g at the Pilot site; from 1.1-21 ng/g at the Main site; from 0.4-0.9 ng/g at the PTMRP site; and from 0.2-11 ng/g in benthic sediments of the tidal channels. Concentrations of total DDTs in soils of the adjacent reference marshlands ranged from 1.1-249 ng/g.

A significant correlation was observed between total organic carbon (TOC) and total alkanes in benthic sediments of marshland tidal channels suggesting partitioning of the alkanes into the organic carbon of sediments. However, a lack of correlation between total PAHs and TOC suggested that the combustion derived PAHs may be bound or

occluded in soot particles, and as such, they may be less available for biological uptake than PAHs derived from petroleum spills.

Concentrations of total PAHs and total DDTs at most sites generally were below the Effects Range-Low (ER-L) concentrations of total PAHs and DDTs. Thus, the potential for toxic effects to biota exposed to these sediments is low. In some cases, the concentrations of PAHs and DDTs slightly exceeded the ER-L values, potentially making these sediments low to moderately toxic to biota. The baseline contaminant data at the SBWDP site indicates that the fill-materials used to raise the site do not pose any foreseeable problems, and probably are suitable for use in wetland restoration.

INTRODUCTION

During its early history, wetlands covered 221 million of the 2.3 billion acres of the United States. Since the 1780's, 22 states have lost 50 percent or more, and 10 states have lost 70 percent or more of their wetlands (Adler, 1995). An estimated forty percent of threatened or endangered species rely on wetlands for their habitat. In addition to being an important component of the hydrologic cycle, wetlands serve other important functions such as maintaining and enhancing biodiversity, acting as a buffer zone between land and water bodies, controlling floods, and improving water quality by decontaminating water and sediments. The natural process of phytoremediation in wetlands is rapidly gaining wide acceptance for the treatment of wastewater and other industrial effluents (Watanabe, 1997).

Prior to 1850, the San Francisco Bay region supported 1400 square kilometers of freshwater wetlands and 800 kilometers of salt marshes (Figure 1). In 1994, only 125 square kilometers of undiked marshes remain of the original 2200 square kilometers, representing a 95 percent loss of wetland habitat (Dingler, 1994). Anthropogenic activities such as hydraulic mining in the late 1800's, and urban, industrial, and agricultural encroachment and reclamation in the 1900's are mainly responsible for loss of most of these wetlands. The remaining 125 square kilometers of wetland potentially are at

risk from urbanization, erosion, and rise in sea levels. Loss of tidal wetlands in the San Francisco Bay region has resulted in loss of habitat to many species of fish and wild life.

San Francisco Bay estuary is the largest estuary on the Pacific coast of the United States and covers an area of approximately $1.24 \times 10^9 \text{ m}^2$. The bay drains a catchment area of about 153,000 km^2 (Conomos and others, 1985). The bay is located at the mouth of the Sacramento and San Joaquin Rivers and drains about 40 percent of the State of California. San Francisco Bay estuary is impacted by urban, municipal, industrial, and agricultural activities. There are about 50 municipal sewage treatment plants, more than 20 State Superfund sites, over 300 industrial facilities, and 6 large oil refineries that refine about 5 % of the Nation's petroleum (Nichols and others, 1986). These facilities are all potential point sources of pollutants to San Francisco Bay. In addition, agricultural activities in the Central Valley of California, where about 10 percent of the Nation's pesticides are applied, have resulted in nonpoint source contamination of the estuary by synthetic organic agrochemicals (Pereira and others, 1994). Many organochlorine pesticides, PCBs, and PAHs have been identified in sediments and biota in San Francisco Bay (Spies and others, 1985; Phillips and Spies, 1988; Long and others, 1988; Hostettler and others, 1989; Boehm and others, 1991; Domagalski and Kuivila, 1993; Pereira and others, 1994; SFEI, 1997).

In order to protect remaining wetlands, the government often requires the creation of new wetlands to compensate for those lost. The Sonoma Baylands Wetland Demonstration Project was authorized by Congress under the Water Resources Development Act of 1992. The U. S. Army Corps of Engineers is currently investigating the feasibility of using dredged spoils on subsided former diked tidelands to restore historic habitat losses. If this project is successful, it will provide a beneficial use of dredged material, expand the feeding and nesting areas for waterfowl along the Pacific flyway, and provide habitat for many endangered species such as the salt marsh mouse and the California clapper rail. Tidal mudflats in San Francisco Bay are colonized by benthic invertebrates that provide a food source for estuarine fish, shorebirds, waterfowl

and juvenile Dungeness crabs (Nichols and others, 1988). This habitat is used by striped bass, Pacific herring, salmon, steel head trout, American shad, pelicans, cormorants, herons, 35 species of waterfowl, and 39 species of shorebirds. Thus, preservation of existing wetlands is vital to the survival of the Bay and its ecology.

One of the key resource management issues facing State and Federal agencies is the suitability of dredged materials for wetland restoration. Of concern is the potential for sediment-bound contaminants to be remobilized and made available to indigenous biota in San Francisco Bay following dredging and disposal operations. Because dredged material containing trace levels of organic contaminants from the Oakland Harbor and the Petaluma River navigation channel is being evaluated by the Corps of Engineers as a resource to restore this site to historic tideland status, it is important to monitor levels of organic contaminants as the wetland develops at this site, and to compare the organic geochemistry of the sediments with those of the adjacent established wetland.

An initial evaluation of the suitability of these sediments for wetland creation was conducted by the U.S. Army Corps of Engineers prior to use at the Sonoma Baylands Wetland Demonstration Project site (Lee, and others, 1991; U.S. Army Corps of Engineers, 1994). An earlier investigation (Pereira and others, 1997) reported baseline concentrations of organic contaminants in peninsula berms and agricultural soils at the Sonoma Baylands Wetland Demonstration Project site and adjacent seasonal wetlands. This report provides baseline data of organic contaminants in sediment at this site prior to tidal action, and it is intended to yield information that will improve the planning and construction of future wetland restoration projects using dredged material.

Purpose and Scope

The purpose of this study is to report base-line organic contaminant data for fill-material at the SBWDP site prior to exposure to tidal action, natural sediments at the PTMRP site, and benthic sediments of marshland tidal channels that are in hydraulic

connection with the SBWDP site. This data is compared with contaminant data for the surrounding natural marshland soils.

Study Area

The Sonoma Baylands Wetland Demonstration Project:

The Sonoma Baylands Wetland Demonstration Project Site is a 348 acre parcel of diked former tidelands located on the northwestern shoreline of San Pablo Bay near the mouth of the Petaluma River that was used in the past for oat-hay farming (Figure 2). The wetland restoration site is located 11 miles south of the city of Petaluma and 4 miles east of the city of Novato. It consists of a 39 acre western Pilot unit, and a 309 acre eastern Main unit that are divided by an interior levee (Figure 3). Within each unit there are a series of low interior “berms” or peninsulas the function of which are to provide tidal deflection and facilitate sediment deposition by breaking up long lengths of wave-fetches once the site is opened to tidal action. The site is bounded on the north by the Northwestern Pacific Railroad (NWPRR), on the west by a diked wetland parcel, on the east by hayfields, and on the south by a tidal marsh that is mostly within the San Pablo Bay Wildlife Refuge. In 1994, the western Pilot unit was filled with about 264,000 cubic yards of maintenance-dredged material from the Petaluma River across-the-flats navigation channel. After a period of settling and compaction of sediment, the Pilot unit was exposed to tidal action in January 1995 by breaching an existing bay-front levee. The eastern main unit also was filled with about 2.5 million yards of Oakland Harbor Deepening Project sediment in 1995, and exposed to tidal action in October 1996 after a period of settling and compaction of sediment. The purpose of the fill-material at both sites is to partially restore the ground elevation to historic tidal marsh elevation and accelerate the restoration of vegetated tidal wetlands.

The Petaluma Tidal Marsh Restoration Project:

The Petaluma Tidal Marsh Restoration Project (PMR) is a 46 acre parcel of diked historic tidal marsh and 9 acres of tidal marsh located on the east side of the Petaluma River just north of the Highway 37 bridge near black point in Sonoma County, California. (Figure 4). The 46 acre parcel was used in the past for oat-hay farming. This restoration site was tidal marsh until 30-35 years ago when it was reclaimed for agricultural production. This site underwent passive restoration in 1994, when the existing levee was breached and the site was exposed to tidal influence. Because sedimentation rates in the Petaluma River are high, approximately two feet of new sediment have already been deposited naturally at the site. It is anticipated that initially, most of the site will be converted to lower intertidal mudflat, providing foraging habitat for shorebirds at low tide and diving and dabbling ducks at high tide. The site will also provide nursery habitat for estuarine fish. It is estimated that elevations suitable for the establishment of tidal salt marsh will be attained in about 5 years.

METHODS

Sample Collection

Sampling sites for the sediment cores were located using a Global Positioning Satellite system, ± 100 m, WGS '84 (Table 1). Sediment cores were collected at four sampling locations (SWPA, SWPB, SWPC, SWPD) in the Pilot site and from one reference location (AWRC-1) in the adjacent marshland in February 1995 (Figure 3). One reference core (AWRC-2) was collected from the adjacent marshland in July 1995. Four cores (SWM-3, SWM-8, SWMM, SWM-14) were collected from the Main site (Figure 3), one core from the Petaluma Marsh Restoration Project site (PMR-1) (Figure 4), and one reference core (AWRC-3) (Fig. 3) in the adjacent marshland in November, 1995. Sediment cores were collected with a slide-hammer coring device provided with a pre-cleaned cellulose acetate butyrate (CAB) liner. Cores were transported to the laboratory, sectioned, and the sediments were air-dried in clean aluminum pans. Samples were ground

in a mortar with a pestle until they passed a #32 mesh screen, mixed thoroughly, and stored in a refrigerator until analysis.

Sample Preparation and Analysis

About 10-20g of dry sediment was weighed into the lined extraction vessel of the MES-1000 microwave extraction system (CEM Corporation, North Carolina). Deuterium labeled internal standards (d8-naphthalene, d10-acenaphthene, d10-phenanthrene, d12-chrysene, d12-perylene, d8-4,4'-DDT, d8-4,4'-DDD, and d8-4,4'-DDE) were added to the sediment followed by twenty to forty milliliters of hexane:acetone (1:1). The labeled internal standards were used to correct for analyte losses that may occur during sample extraction and analysis. The sample was extracted by microwave assisted extraction (Temp., 115°C; Press. 80 psi; Time, 15 min.). The sample was cooled and centrifuged. The supernatant was decanted and filtered through a bed of anhydrous Na₂SO₄ placed over a plug of glass wool into the concentrator vessel of a Zymark Turbovap 500 concentrator. The sediment in the extraction vessel was treated with two successive 10 mL portions of hexane:acetone (1:1), mixed, centrifuged, and the rinsings transferred to the concentrator vessel. The solution was concentrated to a volume of 1 ml. The solvent was exchanged with three successive 3 ml portions of hexane, and once with cyclohexane. The extract was treated with activated copper powder to remove sulfur. The extract was then chromatographed on a column of 5 gm and 2.5 gm activated silica gel (Davison, Nos. 923 and 62, respectively) and 2.5 gm deactivated (5 percent water) alumina. The column was eluted with hexane (alkane fraction), 30 percent benzene or dichloromethane in hexane, and benzene or dichloromethane (aromatic fractions). The hexane fraction was analyzed for petroleum biomarkers by GC-MS by monitoring m/z 191 for triterpanes and hopanes, and m/z 217 for stearanes according to methods reported previously (Hostettler and others, 1994). The combined hexane-benzene and benzene fractions were analyzed by gas chromatography-ion trap mass spectrometry for PAHs and chlorinated pesticides.

Samples were analyzed on a Finnigan Mat Magnum gas chromatograph ion-trap mass spectrometer equipped with a SPI injector, or a Finnigan Mat GCQ ion-trap mass spectrometer in the full scan or single ion monitoring modes. The gas chromatograph was maintained at 60⁰C for 5 min. and programmed at 6⁰C/min. to 300⁰C. The SPI injector was at 60⁰C initially, and it was then programmed at 100⁰C/min immediately following the injection to 300⁰C. The capillary column (30m long, 0.25 mm i.d., containing a 0.25 micrometer bonded phase of DB-5 MS) was interfaced directly to the ion source of the mass spectrometer. Four point calibration curves were constructed and were linear over the calibration range investigated. Laboratory and glassware blanks were processed with the samples. A mid-level analytical standard solution of analytes was analyzed daily with each set of samples. A Standard Reference Marine Sediment (HR-4, NRC Canada) was analyzed in triplicate for PAHs. Results of analyses of marine sediment NRC HS-4 are shown in Table 2. Duplicate sediment samples from the site as well as from the adjacent marshland were also analyzed. Results of the duplicate analyses for n-alkane hydrocarbons and aromatic compounds are shown in Tables 3 and 4 respectively.

Elemental Analyses

Atomic CHN determinations in sediments were made by MSI Analytical Laboratories, Santa Barbara, California.

RESULTS AND DISCUSSION

Pilot Site

C/N Ratios

It has been reported that C/N ratios of 12-14 in sediments are characteristic of terrigenous organic inputs (Prah1 and others, 1980), while C/N ratios in inputs from marine phytoplankton are ~ 6 (Müller, 1977). Atomic CHN analyses in pre-tidal sediments in the Pilot, and adjacent marshland reference site (AWRC-1) are shown in

Table 5. C/N ratios in sediments from the Pilot site ranged from 8.60-9.97 and are more characteristic of a mixed input from marine and terrigenous sources, while those in the reference core from the adjacent marshland were much greater and ranged from 10.75-12.75, and are more characteristic of terrigenous inputs of organic matter. The emergent vegetation and associated detritus in the adjacent marshland, which is a highly productive zone, are important sources of organic carbon and contribute to the higher C/N ratios. C/N ratios of fill-material at the Pilot site are about the same order of magnitude as C/N ratios reported for the suspended-silt fraction of Mississippi River sediments (Leenheer and others, 1995). As the Pilot site is restored to tidal action, and with the establishment of plant and animal communities, the C/N ratios should gradually increase to values characteristic of sediments in the adjacent marshland. Therefore, the C/N ratio in sediment may be a sensitive environmental indicator of wetland development and restoration.

Aliphatic Hydrocarbons

Distributions of aliphatic hydrocarbons in sediment cores from the Pilot and adjacent marshland reference (AWRC-1) sites are shown in Figure 5. Concentrations of the aliphatic hydrocarbons in sediments of the Pilot site ranged from 2310-6220 ng/g, and they generally were greater than those in surficial soil from the reference site in the adjacent marshland (Table 6). Hydrocarbon data in Table 6 indicates that the sediments at the Pilot site are stratified. In addition to n-alkanes from n-C₁₃ to n-C₃₇, chromatograms from the upper strata show varying degrees of an unresolved complex mixture (UCM) of compounds that is characteristic of a background contamination by weathered or biodegraded petroleum (Kennicutt and others, 1987). The UCMs in the surficial horizons of the fill material in the Pilot site are greater in magnitude than those at greater depth. Differences in UCMs with increasing depth suggest that either geochemical changes may be taking place in the hydrocarbon distributions in the deeper sediment horizons, or the deeper sediment horizons may be from a different source such as the underlying soil over which the fill material was placed. These geochemical changes may be abiotic or mediated by microorganisms. The n-alkanes in sediments of the Pilot site show a pronounced

odd/even predominance in the alkane range C_{23} - C_{33} , characteristic of inputs of higher plant waxes from terrigenous sources (Eglinton and Hamilton, 1967). Some alkane profiles show a bimodal distribution, with a marine algal contribution of alkanes maximizing around C_{15} to C_{17} , and a terrigenous input maximizing around C_{27} to C_{31} .

Biomarker tricyclic and pentacyclic triterpanes and steranes:

Various molecular biomarker compounds such as the tricyclic and pentacyclic triterpanes and steranes were examined in sediment cores collected from the Pilot and adjacent marshland reference (AWRC-1) sites. Hopanes and steranes evolve from biogenic molecules whose carbon skeletons have remained intact through processes of diagenesis and thermal maturation. As such, they serve as molecular tracers that are useful for correlation of oils with each other, and with their proposed source rocks, and for the assessment of thermal maturity (Mackenzie, 1984). Ratios of these geochemical correlation parameters are shown in Table 7. The biomarker ratios shown are standard source parameters (Tm/Ts and C_{30}/C_{29}) and maturity parameters (hopane $S/(S+R)$ and sterane $S/(S+R)$), and a diploptene index. The hopane maturity parameter in a mature oil has an equilibrium value of approximately 0.6, and the sterane parameter about 0.5. When the values decrease, it indicates mixing with input from less mature sources. Diploptene is a bacterial derived hopene that is a marker for very immature biogenic inputs in the sediments. Here, it is a constituent of the underlying agricultural field soil over which the fill material was emplaced. The ratio of diploptene to the $\alpha\beta$ C_{30} -hopane, a biomarker of highly mature input, especially of petrogenic origin, gives an indication of whether the core horizon is dominated by the fill material (index not measurable, diploptene levels too low) or the underlying field soil (index > 0). Values for the sterane parameter that are around 0.3 and a diploptene index greater than zero provide an indication of where the cores have penetrated the underlying field soil.

In general, the biomarker parameters show that the fill material from the Pilot site contains hydrocarbons of petrogenic origin. The source parameters are mostly within a narrow range, and the maturity parameters show high maturity, i.e., within the petroleum

window, at or close to the equilibrium value. These values are similar to what is found in bottom sediments throughout San Francisco Bay. The diploptene index and lower sterane ratios, which are also accompanied by substantially lower concentrations of the petrogenic biomarker hydrocarbons, indicate that cores SWPA, SWPB, SWPC, and SWPD all show fill material in the top horizon(s) and underlying field soil in the bottom horizon. The reference core from the adjacent marshland (AWRC-1) is stratified and shows anomalous biomarker values (i.e. 0.55 at a depth of 19-28 cm. The lower two horizons are contaminated with mature and highly degraded petroleum-like residues. Interestingly, these same two lower horizons of the core are contaminated with high levels of DDTs and PAHs respectively (see Table 7). These high levels of contamination in the lower two horizons of core AWRC-1 may be due to the proximity of this site to a nearby agricultural pump and drain, and probably reflect historic input of contaminants from the pump and drain system.

Polycyclic aromatic hydrocarbons:

Polycyclic aromatic hydrocarbons (PAHs) are cyclic higher homologs of benzene with the aromatic rings arranged in different configurations. PAHs are derived from natural or anthropogenic sources. Natural sources include: a) forest and prairie fires (Blumer and Youngblood, 1975); b) natural petroleum seeps; c) post-depositional transformations of biogenic precursors over relatively short periods of time (Wakeham and others, 1980). Anthropogenic sources include: a) combustion of fossil fuel (Hites and others, 1977), and long-range atmospheric transport of PAHs adsorbed onto soot or airborne particulate matter (Lunde and Bjorseth, 1977; La Flamme and others, 1978); b) urban runoff containing PAHs derived from abrasion of street asphalt and automobile tires, and vehicular emissions (Wakeham and others, 1980); c) spillage of petroleum and its refined products which contain complex assemblages of PAHs (Boehm and others, 1991).

Concentrations of PAHs in sediment cores from the Pilot and adjacent marshland reference (AWRC-1) sites are shown in Table 8. The PAHs ranged from 2-ring

naphthalene to 6-ring benzo[g,h,i]perylene. In general, concentrations of PAHs in the surficial horizons of the cores from the Pilot site were greater than those in the bottom horizons. Concentrations of fluoranthene and pyrene in the surficial sediments of the Pilot Site were greater than all the other individual PAHs that were analyzed. Biomarker data, shown previously, indicated that the bottom horizons of these sediment cores were mainly bottom-soil from the underlying former agricultural field. Therefore, cores collected from the Pilot site probably penetrated the bottom-soil from the underlying agricultural field during the coring operation. Thus, the bottom-soil from the underlying agricultural field probably contains lower level of PAHs than the fill material emplaced above it. Concentrations of PAHs in the sediments ranged from 83-1350 ng/g. These concentrations are well within the range of concentrations of total PAHs reported in sediments of San Francisco Bay (Long and others, 1988). For comparison, the average concentrations of total PAHs in Petaluma channel dredged material prior to emplacement at the site was reported to be 1810 ng/g (US Army Corps Of Engineers, 1994).

Concentrations of total PAHs in the surficial horizon of the reference core (AWRC-1) from the adjacent marshland were low (312 ng/g). However, the bottom horizon contained relatively higher levels of total PAHs (3410 ng/g), and obviously, is contaminated. These high levels of contamination in the bottom horizon of reference core AWRC-1 may be due to the proximity of this reference site to a nearby agricultural pump and drain (Figure 3), and probably reflects historic input of contaminants from the pump and drain system.

Combustion of organic materials such as fossil fuels, refuse etc., gives rise to PAHs by a step-wise free radical mechanism. Combustion derived PAHs are dominated by the unsubstituted species, whereas PAHs in petroleum are dominated by the alkylated homologs (LaFlamme and others,1978). In order to determine if the PAHs in sediments at the Sonoma site were derived from petrogenic or pyrogenic sources, ratios of methyl phenanthrenes to phenanthrene (MP/P) were examined. MP/P ratios are reported to be in the range of 0.5-1 in sediments dominated by PAHs arising from combustion processes,

and from 2-6 in sediments dominated by PAHs from undegraded petroleum (Prahl and Carpenter, 1983). The ratio of MP/P is reported to be 4.0 for used crankcase oil (Pruell and Quinn, 1988), close to 1.0 for street and urban dust samples (Takada and others, 1990; 1991), and about 0.5 for atmospheric fallout (Takada and others, 1991). Ratios of MP/P in fill material at the Pilot site ranged from 0.47-0.86, while those in the adjacent marshland reference site (AWRC-1) ranged from 0.38-0.57. Therefore, the MP/P ratios indicate that PAHs in the Pilot site and adjacent marshland are mainly derived from combustion processes and not from recent petrogenic inputs.

Potential for Toxicity:

The potential for toxic effects of PAHs in surficial sediments at the Pilot Site were evaluated using the Effects Range-Low (ER-L) and Effects Range-Medium (ER-M) criteria of Long and Morgan (1990) and Long and Markel (1992); this is shown in Figure 6a. The ER-L value is the chemical concentration above which adverse biological effects may be expected 10 percent of the time. The ER-M is the chemical concentration above which adverse chemical effects may be expected 50 percent of the time. Adverse biological effects include mortality, or sublethal effects such as reduced growth or reproductive success. ER-L values are the concentrations at which toxic effects may be first observed, whereas ER-M values are the concentrations often or always associated with toxic effects. Areas are assumed to have the highest potential for toxic effects where ambient chemical concentrations exceed the ER-M by large factors and where many chemical concentrations exceed ER-M values. The potential for toxic effects is moderate where ER-L values are exceeded, but ER-M values are not. The potential for toxic effects is assumed to be relatively low where ER-L values are not equaled or exceeded. Examination of Figure 6a indicates that concentrations of total PAHs in surficial sediments are well below the ER-L value of 4022ppb. Concentrations of total PAHs in surficial horizons of the adjacent marshlands are even lower than those in surficial sediments from the Pilot site. Even if the relatively high concentrations of PAHs in the bottom horizon of core AWRC-1 from the adjacent marshland are considered, these

concentrations are still below the ER-L value established for total PAHs. Thus, the potential for toxic effects from total PAHs sorbed to surficial sediments at the Pilot Site are relatively low.

Chlorinated pesticides:

Although several chlorinated pesticides such as the chlordanes, DCPA, DDT and Dieldrin were analyzed for in fill material at the Pilot Site, the only chlorinated pesticides that were detected were DDT and its degradates DDE and DDD. Under aerobic conditions, DDT is dehydrochlorinated to DDE by soil microorganisms (Matsumara and Benezet, 1978). Under anaerobic and reducing conditions, DDT is degraded by microorganisms (reductive dechlorination; Wedemeyer, 1967) and abiotically by iron porphyrins to DDD (Castro, 1964; Zoro and others, 1974; Baxter, 1990). Concentrations of DDT and its degradates in sediments from the Pilot Site and the adjacent marshland reference (AWRC-1) site are shown in Table 8. Concentrations of total DDTs at the Pilot site ranged from 1.0-7.7 ng/g (ppb), with the highest concentrations occurring in the surficial horizons. For comparison, average concentrations of total DDTs in Petaluma channel dredged material prior to emplacement at the SBWDP site was reported to be 8 ng/g (US Army Corps OF Engineers, 1994). In general, concentrations of DDD were slightly greater than DDE or DDT in sediments from the Pilot site, suggesting that this DDD is derived from anaerobic degradation of DDT. In contrast, the middle horizon (19-28 cm) from the reference marshland (AWRC-1) contained anomalously high levels of total DDT, with DDE being the major compound. These high levels of DDTs may be due to the proximity of the reference site (AWRC-1) to the agricultural pump and drain system, and probably reflects historic input of DDT from agricultural applications in the surrounding watershed. Thus, the sources of DDT and degradates in sediment from the Pilot site and the adjacent marshland are different. Ratios of DDE/DDT at the reference site in the adjacent marshland were greater than one indicating that the source of the DDE is from DDT treated soils subjected to long-term weathering (Hitch and Day, 1992).

Potential for toxicity:

The potential for toxic effects of DDTs sorbed to surficial sediments at the Pilot and reference (AWRC-1) sites are shown in Figure 6b. The ER-L for total DDTs is 3 ppb, while the ER-M is 350 ppb. Figure 6b shows that concentrations of total DDTs in surficial sediments at the Pilot Site are greater than the ER-L value, and therefore these sediments potentially may have very slight to moderate toxic effects on biota. However, the potential for toxicity also depends upon other site-specific factors such as grain size, organic carbon, etc. that determine the bioavailability and toxicity of sediment-associated contaminants. The concentrations of total DDTs in surficial horizons of the adjacent reference marshland (site AWRC-1) are near the ER-L of 3 ppb. However, if the high concentrations of total DDT in the middle horizon of site AWRC-1 (Table 8) are considered, then these high concentrations of total DDT tend to approach the ER-M value, and could potentially cause adverse biological effects to organisms that might be exposed to these high concentrations.

Main Site

C/N ratios:

Atomic CHN analyses in pre-tidal sediments in the Main site and the two reference sites (AWRC-2 and AWRC-3) in the adjacent marshland are shown in Table 9. C/N ratios in sediments from the Main site ranged from 8.12-11.08 and generally are characteristic of a mixture of marine and terrigenous inputs of organic matter. The high C/N ratio for sample SWM-M at a depth of 15-30 cm probably is due to admixture of the fill material from the Main site with soil from the adjacent marshland or the existing bayfront levee during site preparation. The reference sites AWRC-2 and AWRC-3 have C/N ratios closer to terrigenous values. As in the case of the Pilot site, C/N ratios in fill-sediments from the Main site should gradually increase during wetland development to values characteristic of the adjacent established marshlands.

Aliphatic hydrocarbons:

Distributions of aliphatic hydrocarbons in sediment cores from the Main and adjacent marshland reference sites (AWRC-2 and AWRC-3) are shown in Figure 7. Concentrations of the n-alkanes in sediments of the Main site ranged from 1893-9150 ng/g, whereas those in soils of the reference sites in the adjacent marshland ranged from 1556-5552 ng/g (Tables 10 and 11). As with the case of the Pilot site, sediments of the Main site show n-alkanes from n-C₁₃ to n-C₃₇, with a pronounced odd/even predominance in the alkane range n-C₂₃-C₃₃, indicating terrigenous inputs. All horizons of sediment from the different sampling locations in the Main site show varying degrees of a substantial UCM, characteristic of weathered degraded petroleum. However, one of these sites (SWM-M) only shows a small UCM in the surficial horizon, while the deeper horizons mainly show n-alkanes with little or no UCM, suggesting that the deeper horizons may not contain fill material. In addition, in sample SWM-M (30-50 cm), the amount of n-C₃₁ exceeds n-C₂₉, possibly indicating a different hydrocarbon source. This particular site probably is contaminated with soil from the existing bayfront levee which is in close proximity to this sampling location. In contrast, all sediment horizons at the reference sites in the adjacent marshland contain substantially less UCM than the fill material at the Main site, indicating lesser amounts of degraded petrogenic hydrocarbons.

Biomarker tricyclic and pentacyclic triterpanes:

Several geochemical biomarker correlation parameters for sediment from the Main site and the adjacent marshland reference (AWRC-2 and AWRC-3) sites are shown in Table 12. As in the case of the Pilot site, sediments from the Main site contain hydrocarbons of petrogenic origin as indicated by the narrow range of the source parameters, with the maturity parameters close to equilibrium values within the petroleum window. The diploptene index indicates that sediment samples from sites SWM-M (15-30 cm) and SWM-M (30-50 cm) are either mixed with soil from the existing bayfront levee which is in close proximity to this sampling site or contain bottom soil. Surprisingly however, the diploptene index was not measurable for all horizons at the reference sites AWRC-2 and AWRC-3. Therefore, the biogenic organic matter in the

adjacent marshland is different with respect to diploptene, than the soil underlying the fill material at the Main site.

Polycyclic aromatic hydrocarbons:

Concentrations of PAHs in sediment cores from the Main and adjacent marshland reference sites (AWRC-2 and AWRC-3) are shown in Tables 13 and 14. Concentrations of PAHs at reference site AWRC-1 in the adjacent marshland is shown for comparison in Table 14. The PAHs ranged from 2-ring naphthalene to 6-ring benzo[g,h,i]perylene. Total PAH concentrations in sediment of the Main site ranged from 56-786 ng/g, while those in soils from the adjacent marshland reference sites ranged from 161-3410 ng/g. For comparison, the mean concentration of total PAHs reported for Oakland sediments prior to emplacement at the SBWDP site was 726 ng/g for Oakland Outer Harbor sediments and 807 ng/g for Oakland Inner Harbor sediments (Lee and others, 1991). Higher concentrations of PAHs were present in core SWM-3 at a depth of 15-30 cm from the Main site (786 ng/g), and in core AWRC-3 at a depth of 30-50 cm from the adjacent marshland reference site (1080 ng/g). As in the case of the Pilot site, fluoranthene and pyrene were the major compounds.

Ratios of methylphenanthrenes/phenanthrene (MP/P) in sediment from the Main site ranged from 0.59 to 0.82, while those from the adjacent wetland reference sites ranged from 0.47 to 1.05. As in the case of the Pilot site, MP/P ratios in sediment from the Main and adjacent marshland reference sites indicate that the PAHs are derived from combustion processes and not from recent petroleum inputs.

Potential for toxicity :

The potential for toxicity from PAHs in surficial horizons from the Main site was also evaluated using the ER-L criteria of Long and Morgan (1990) and Long and Markel (1992). Figure 8a shows that the ER-L values of PAHs in all sediments from the Main and reference sites are well below the ER-L value of 4022 ppb, indicating that the potential for toxic effects from total PAHs sorbed to sediment at the Main site are very low.

Chlorinated pesticides:

As in the case of the Pilot site, the only chlorinated pesticides detected in sediment from the Main site were DDT and its degradates, DDE and DDD. Concentrations of DDT and its degradates in sediments from the Main and adjacent wetland reference sites (AWRC-2 and AWRC-3) are shown in Tables 13 and 14. Concentrations of DDT and its degradates DDE and DDD in sediment from the adjacent marshland reference site (AWRC-1), are shown for comparison in Table 14. Concentrations of total DDT in sediment from the Main site ranged from 1.1 to 21 ng/g, while those in sediment from the adjacent marshland reference sites ranged from 1.1 to 249 ng/g.

For comparison, the mean concentration of total DDTs in Oakland Harbor sediments prior to emplacement at the SBWDP site was reported to be < 3 ng/g (Lee and others, 1991). In general, as in the case of the Pilot site, concentrations of DDD were slightly greater than DDE or DDT at the Main site, suggesting that this DDD is derived from anaerobic degradation of DDT. In contrast, concentrations of DDE were greater than DDT or DDD in sediments from the adjacent marshland reference sites indicating that DDT is aerobically degraded to DDE, or the adjacent marshland reference sites have been contaminated by runoff from weathered agricultural soils containing DDE. The high concentration of total DDT (21 ng/g) in sediment core SWM-M (15-30 cm) may be due to contamination with soil from the existing bayfront levee which is in close proximity to this sampling location.

Potential for toxicity

The potential for toxic effects of DDTs sorbed to surficial sediment at the Main and adjacent wetland reference sites is shown in Figure 8b. Concentrations of DDT are below the ER-L value of 3ppb for total DDT, indicating that the potential for toxic effects from DDTs sorbed to sediment at the Main site are relatively low. Even if the concentration of 21 ppb in core SWM-M (15-30 cm) is considered, this value is well below the ER-M value of 350 ppb for total DDT.

Petaluma Tidal Marsh Restoration Project

C/N ratios:

C/N ratios in different horizons from the core collected from the Petaluma Marsh Restoration site are shown in Table 15. C/N ratios ranged from 11.34 to 11.37, and they are more characteristic of terrigenous inputs of organic matter rather than inputs from marine sources. These findings are in agreement with the fact that these naturally and newly deposited sediments contain mainly riverine terrestrial inputs of organic matter.

Aliphatic hydrocarbons:

Distributions of aliphatic hydrocarbons in the sediment core from the Petaluma tidal Marsh Restoration Project are shown in Figure 7. Concentrations of these compounds are shown in Table 16. Concentrations of aliphatic hydrocarbons ranged from 1698 to 2721 ng/g. The n-alkanes ranged from n-C₁₃ to n-C₃₇, with a pronounced odd/even predominance in the alkane range n-C₂₃-C₃₃, characteristic of terrigenous inputs of higher plant waxes. While the upper two horizons contained a small UCM (low biodegraded petrogenic contamination), the bottom horizon showed little or no UCM suggesting little or no biodegraded petrogenic contamination..

Biomarker tricyclic and pentacyclic triterpanes:

Several geochemical biomarker correlation parameters for sediment from the Petaluma Tidal Marsh Restoration Project site are shown in Table 17. This site which was filled by natural sedimentation, shows a low but increasing diploptene index down core, suggesting higher native soil contributions downcore.

Polycyclic aromatic hydrocarbons:

Concentrations of PAHs in the different horizons of the sediment core from the Petaluma Tidal Marsh Restoration Project are shown in Table 18 . The PAHs ranged from 2-ring naphthalene to 6-ring benzo[g,h,i]perylene. Concentrations in this core ranged from 257 to 419 ng/g, with fluoranthene and pyrene as the major compounds.

Ratios of methylphenanthrene/phenanthrene (MP/P) were in the range of 0.90-1.1, indicating that these compounds were mainly derived from combustion sources, and not from recent petrogenic inputs.

Potential for toxicity:

The potential for toxicity from PAHs adsorbed to sediment at the Petaluma Tidal Marsh Restoration Project was also evaluated using the ER-L criteria. Figure 9a shows that concentrations of PAHs in these sediments are well below the ER-L value of 4022 ppb for total PAHs, indicating that the potential for toxic effects of PAHs sorbed to sediments at the Petaluma Tidal Marsh Restoration Project are relatively low.

Chlorinated pesticides:

The only chlorinated pesticides that were detected are low concentrations of DDT and its degradates, DDE and DDD. Concentrations of DDT and degradates in the sediment core from the Petaluma Tidal Marsh Restoration Project site are shown in Table 18. Concentrations of total DDTs ranged from 0.4 to 0.9 ng/g. Data in Table 18 indicates that the bottom horizon of sediment contained some DDT with lower concentrations of DDE and DDD. In going upcore, DDT is not measurable in the upper two horizons, while the amounts of DDD and DDE increase in the upper two horizons. This data suggests that DDT may be undergoing degradation to DDE and DDD after it is deposited at this site.

Potential for Toxicity :

The potential for toxic effects of DDTs sorbed to surficial sediments at the Petaluma Tidal Marsh Restoration Project site is shown in Figure 9b. Figure 9b shows that concentrations of DDTs are well below the ER-L value of 3.0 ppb for DDTs, indicating that the potential for toxic effects to organisms exposed to sediment from the Petaluma Tidal Marsh Restoration Project is very low.

Adjacent Marshland Tidal Marsh Channels

Benthic sediments from seven locations in several tidal marsh channels in the marshlands adjacent to the Sonoma Wetland Demonstration Project site were collected in April 1997, after the SBWDP was opened to tidal action, and analyzed for organic contaminants and organic carbon and nitrogen. These sites and sampling locations are shown in Figure 10 and Table 19. These sites were selected in order to maximize information concerning potential inputs and deposition of contaminants in the fill-material at the Sonoma Wetland Demonstration Project site via tidal action. Sites CH-1 to CH-4 in Figure 10 are adjacent to the Pilot site and sites CH-5 to CH-7 are adjacent to the Main site.

Atomic C/N Ratios:

Atomic CHN analyses of benthic sediments from tidal marsh channels in the marshlands adjacent to the SBWDP site are shown in Table 20. C/N ratios ranged from 7.73 to 9.86, indicating a mixture of terrestrial and marine inputs of organic matter (Prahl and others, 1980; Müller, 1977). Organic carbon and nitrogen values were the greatest at site CH-4 and CH-5, possibly indicating an area of accumulation of organic matter and associated contaminants, resulting from tidal action in the channels.

Aliphatic Hydrocarbons:

Concentrations of aliphatic hydrocarbons in benthic sediments of tidal marsh channels in the marshlands adjacent to the SBWDP site ranged from 3755 to 13,683 ng/g (Table 21). The distributions of aliphatic hydrocarbons in these sediments are fairly similar and they are shown in Figure 11. The aliphatic hydrocarbon distributions are bimodal, although the two modes vary with respect to each other, indicating different levels of specific inputs. The first mode is dominated by C₁₆ and C₁₇, indicative of recent marine algal input (Peters and Moldowan, 1993). The second mode is dominated by C₂₇-C₃₁ with a strong odd carbon predominance; this pattern is indicative of input from terrigenous vascular plants (Eglinton and Hamilton, 1967). Therefore, these hydrocarbon

distributions in the channel sediments show a possible mixture of sources. The first (algal) mode and the second (terrigenous plants) mode are indicative of recent biogenic inputs, and are comparable to what is seen in the sediments from the agricultural sites (peninsulas and adjacent agricultural farmland; Pereira and others, 1997). The terrigenous input is common to all the sediments, including the fill material, although the distribution of the three major alkanes in the tidal marsh channels is closer to the Oakland estuary fill material pattern at the Main site than to that of the immediately adjacent agricultural land. In addition, all of the chromatograms show varying levels of an Unresolved Complex Mix (UCM), indicative of different levels of weathered petrogenic contamination (Kennicutt and others, 1987; Gough and Rowland, 1990), with the UCM in tidal marsh channels CH-1 to CH-3 being the most abundant and that in CH-6 being the least abundant. By comparison, a UCM is particularly prominent in the fill material from both the Pilot and Main sites, but not in the underlying soils at the SBWDP site or in the neighbouring agricultural farmlands. These sites (CH-1-CH-3) that show increased levels of weathered petrogenic contamination, also are the most proximal to the agricultural pump and drain system (Figure 10), giving further evidence that this is the contamination.

Biomarker distributions:

The biomarker parameters (ratios) in bottom sediments from the tidal marsh channels in the marshlands adjacent to the Sonoma Wetland Demonstration Project site are shown in Table 22. In these channel bottom sediments, the biomarker parameters indicate a contribution from mature petrogenic material as well as lower maturity material. The hopane S/(S+R) ratios, except at site CH-6, are close to the equilibrium value of 0.6 indicating contribution of mature petrogenic material. Deviation of the sterane S/(S+R) ratios from the equilibrium value of 0.5 in all the channel sediments is indicative of contributions from lower maturity material. This is especially evident in sediment from CH-6 where the hopane S/(S+R) ratio is 0.52 and the sterane S/(S+R) ratio is only 0.28. Therefore, sediment at site CH-6 has very low levels of petrogenic contamination. The biomarker chromatograms in all the channel bottom sediments show essentially no

diploptene, and therefore little or no contribution from the type of biogenic input that is so prominent in the agricultural farm land (Pereira and others, 1997).

Polycyclic aromatic hydrocarbons :

Concentrations of polycyclic aromatic hydrocarbons in sediment from 7 tidal marsh channels in the adjacent marshland near the Sonoma Wetland Demonstration Project site are shown in Table 23. Concentrations of total PAHs ranged from 722-4498 ng/g. These concentrations are well within the range of concentrations of PAHs in sediments of San Francisco Bay (Long and others, 1988). The most abundant PAHs were fluoranthene and pyrene. The greatest concentrations of total PAHs were found at sites CH-1 to CH-3, which are in close proximity to the agricultural pump and drain (Figure 10). The aliphatic hydrocarbon data (shown earlier) also indicated that these latter 3 sites had the greatest UCMs, presumably resulting from weathered petrogenic contamination. The ratios of methylphenanthrene/phenanthrene (MP/P) in sediment from the 7 sites ranged from 0.30 to 0.77, indicating that these phenanthrene compounds probably are derived from incomplete combustion of fossil fuels such as petroleum and coal and not from a recent petroleum spill.

Potential for Toxicity:

The potential for toxic effects of PAHs in sediments of the tidal marsh channels in the adjacent marshlands near the Sonoma Wetland Demonstration Project site were also evaluated using the Effects Range-Low (ER-L) and the Effects Range-Medium (ER-M) criteria and are shown in Figure 12a. Examination of the data in Figure 12 indicates that only sediment from sites CH-1 and CH-3 exceed the ER-L value of 4022 ppb for total PAHs, whereas the sediment from all the other channel sites are well below this value. Therefore the potential for toxic effects from total PAHs sorbed to channel sediments are low to moderate at sites CH-1 and CH-3, and low at all the other channel sites.

Chlorinated Pesticides :

Concentrations of chlorinated pesticides in bottom sediments of 7 tidal marsh channels in the marshland adjacent to the SBWDP site are shown in Table 24.

Concentrations of total DDT ranged between 0.2 to 11 ng/g. The greatest concentrations of total DDT were present at sites CH-5 and CH-7, and they are well within the range of the concentrations of DDT in sediments of San Francisco Bay (Long and others, 1988). Concentrations of dieldrin ranged from 0.8 to 25 ng/g. The greatest concentration of dieldrin was at site CH-2.

Potential for toxicity:

The potential for toxic effects of DDT's sorbed to sediments of 7 tidal marsh channels in the marshlands adjacent to the SBWDP site is shown in Figure 12b. Concentrations of total DDT at sites CH-2, CH-3, and CH-6 are below the ER-L value of 3 ppb for total DDT. Therefore, the potential for toxic effects to organisms exposed to these sediments is relatively low. The concentrations of total DDT at all other sites range from 3.5 to 11 ppb. The potential for toxic effects of sediment at the latter 4 sites may be considered to be only moderate. However, these concentrations are well below the ER-M value of 350 ppb for total DDT.

Potential inputs of contaminants to the Sonoma Wetland Demonstration Project site:

The relationship between contaminant concentrations and organic carbon in benthic sediments of the tidal marsh channels was examined in order to better understand possible sources, distributions and potential inputs of these compounds. Figure 13 indicates that there is a significant correlation between TOC and total alkanes ($R=0.81$). This correlation suggests that lipophilic compounds such as the alkanes probably partition into the organic carbon coatings of sediment particles and are transported in this manner in the estuary. On the other hand, the total PAHs did not show any significant correlation with total organic carbon (Figure 14; $R=0.3$). Lack of a correlation between TOC and the PAHs in these sediments suggests that the PAHs probably are bound or occluded in soot particles that are generated during combustion of organic materials including fossil fuels, and as such they are less available to partition into the organic carbon of sediment (Readman and others, 1984). These bound combustion PAHs also may be less available for biological uptake than PAHs derived from petroleum spills

(Farrington and others, 1983; Gustafsson and others, 1997a; 1997b).

Further evidence that the PAHs in the tidal marsh channel sediments are mainly combustion derived with possible minor contributions from petroleum spills was observed for the MP/P ratios reported earlier, where MP/P ratios ranged from 0.30 to 0.77, characteristic of predominantly combustion sources. MP/P ratios for petroleum range from 2-6 in sediments dominated by petroleum derived PAHs (Prahl and Carpenter, 1983). Furthermore, it is reported that oil derived PAHs generally are introduced into the aquatic environment as emulsions that present a large surface area to degrading microorganisms. Thus, oil-derived PAHs undergo preferential biodegradation to combustion derived PAHs (Jones and others, 1986; Readman and others, 1984).

A significant correlation also was found between total DDT and total alkanes (Figure 15; $R=0.84$). However, the correlation between total DDT and TOC was not as robust (Figure 16; $R=0.6$). The correlation between total DDT and total alkanes suggests a commonality of inputs, i.e. terrestrial inputs predominantly from the Sacramento and San Joaquin Rivers. The less significant correlation between total DDT and total organic carbon probably indicates multiple inputs of organic carbon both terrestrial and marine.

CONCLUSIONS

The results of this geochemical study of contaminants in sediments of the SBWDP and PTMRP sites, as well as in benthic sediments of marshland tidal channels clearly demonstrate that these sites are contaminated with low levels of PAHs and chlorinated pesticides. However, the potential for toxic effects of these sediments to estuarine biota is low or moderate at best. In addition, the combustion-derived PAHs probably are bound or occluded to a soot particulate phase, thus making these contaminants less bioavailable than petroleum derived PAHs. The dredged spoils that were used to elevate the SBWDP site to historic tidal marsh elevation and the sediments that are naturally deposited at the PTMRP site appear to be no more contaminated than the surrounding natural marshlands.

Baseline contaminant data at wetland restoration sites are important in determining the feasibility of using dredged spoils for wetland creation in San Francisco Bay. The information gained from this study will be useful in the planning and construction of future wetland restoration projects using dredged material.

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Table 1. Sampling locations of sediment cores at the Sonoma Baylands.

Site	Description	Latitude	Longitude
Pilot Site			
1. SWPA	South of peninsula 1	38° 06.975' N	122° 29.438' W
2. SWPB	End of peninsula 1	38° 07.070' N	122° 29.409' W
3. SWPC	End of peninsula 2	38° 07.102' N	122° 29.355' W
4. SWPD	North of peninsula 2	38° 07.166' N	122° 29.303' W
Main Site			
1. SWM-3	End of peninsula 3	38° 07.169' N	122° 29.203' W
2. SWM-8	Middle of peninsula 8	38° 07.284' N	122° 28.876' W
3. SWMM	Middle	38° 07.010' N	122° 28.635' W
4. SWM-14	End of peninsula 14	38° 07.588' N	122° 28.406' W
Petaluma Marsh Restoration Project			
1. PMR-1	Petaluma Marsh	38° 07.120' N	122° 30.193' W
Adjacent Marshland			
1. AWRC-1	Near Ag. pump house	38° 06.892' N	122° 29.549' W
2. AWRC-2	Near Dingler site	38° 06.935' N	122° 28.955' W
3. AWRC-3	Near curve in Levee	38° 07.000' N	122° 28.657' W

Table 2. Results of analyses of standard reference marine sediment HS-4, NRC Canada ($\mu\text{g/g}$).

Compound	WP-1	WP-2	WP-3	Mean ($\mu\text{g/g}$)	Relative standard deviation, percent	NRC ($\mu\text{g/g}$)
naphthalene	0.10	0.15	0.13	0.13	19.2	0.15*
acenaphthylene	0.02	0.02	0.02	0.02	0.0	0.15*
acenaphthene	0.02	0.02	0.02	0.02	0.0	0.15*
9[H]fluorene	0.05	0.05	0.05	0.05	0.0	0.15*
phenanthrene	0.53	0.53	0.52	0.53	1.1	0.68
anthracene	0.10	0.10	0.10	0.10	0.0	0.14
fluoranthene	1.42	1.35	1.47	1.41	0.0	1.25
pyrene	1.06	1.09	1.13	1.09	3.2	0.94
benz[a]anthracene	0.49	0.49	0.49	0.49	0.0	0.53
chrysene	0.69	0.68	0.63	0.67	4.5	0.65
benzo[b]fluoranthene	1.05	0.96	0.81	0.94	12.8	0.70
benzo[k]fluoranthene	0.42	0.45	0.47	0.45	5.6	0.36
benz[a]pyrene	0.52	0.48	0.41	0.47	11.9	0.65
indeno[1,2,3-cd]pyrene	0.52	0.47	0.45	0.48	7.5	0.51
dibenz[a,h]anthracene	0.07	0.08	0.09	0.08	12.5	0.12
benzo[g,h,i]perylene	0.46	0.41	0.39	0.42	8.6	0.58

Upper limit- *Amount present is not greater than 0.15 $\mu\text{g/g}$

Table 3. Duplicate analyses of aliphatic hydrocarbons in sediment core horizons from the Pilot site and the adjacent marshland.

Core Depth (cm)	SWPC 27-42	SWPC 27-42	AWRC-1 0-6	AWRC-1 0-6
Compound	Concentration (ng/g)			
n-C ₁₃	14	14	15	17
n-C ₁₄	17	19	27	33
n-C ₁₅	29	33	53	66
n-C ₁₆	26	28	46	59
n-C ₁₇	30	29	60	75
Pristane	19	16	54	71
n-C ₁₈	21	19	32	42
Phytane	13	13	22	27
n-C ₁₉	27	23	37	42
n-C ₂₀	24	24	30	37
n-C ₂₁	52	50	71	85
n-C ₂₂	47	44	49	59
n-C ₂₃	110	100	130	140
n-C ₂₄	54	49	61	71
n-C ₂₅	310	280	270	290
n-C ₂₆	68	61	78	81
n-C ₂₇	490	460	380	400
n-C ₂₈	110	110	100	100
n-C ₂₉	1560	1500	750	780
n-C ₃₀	150	140	120	130
n-C ₃₁	1900	1850	500	490
n-C ₃₂	120	120	75	73
n-C ₃₃	830	820	230	210
n-C ₃₄	56	56	47	48
n-C ₃₅	230	220	76	70
n-C ₃₆	21	8.0	21	21
TOTAL	6330	6090	3330	3520

Table 4. Duplicate analyses of polycyclic aromatic hydrocarbons and chlorinated pesticides in sediment cores from the Pilot site and adjacent marshland.

Core Depth (cm)	SWPC 27-42	SWPC 27-42	AWRC-1 0-6	AWRC-1 0-6
Compound	Concentration (ng/g)			
naphthalene	38	32	11	10
2-methylnaphthalene	26	24	6.7	8.2
1-methylnaphthalene	9.3	13	4	4.3
acenaphthylene	0.6	0.5	1.0	1.2
acenaphthene	0.4	0.5	1.1	1
9[H]fluorene	1.6	1.4	2.8	2.8
phenanthrene	13	12	20	20
anthracene	0.4	0.5	2.7	2.7
2-methylphenanthrene	5.0	5.3	6.9	5.9
1-methylphenanthrene	2.2	2.3	3.5	3.2
fluoranthene	11	10	40	42
pyrene	4.3	3.9	47	48
benz[a]anthracene	1.1	1.1	13	12
chrysene	4.9	4.9	18	18
benzo[b]fluoranthene	3.8	3.8	33	37
benzo[k]fluoranthene	1.2	1.0	8.4	7.5
benz[a]pyrene	0.7	0.4	23	24
perylene	1.4	1.0	26	25
indeno[1,2,3-cd]pyrene	0.7	0.2	5.1	5.0
dibenz[a,h]anthracene	0.2	0.3	4.9	3.7
benzo[g,h,i]perylene	0.5	0.5	32	31
Total PAH	126	119	310	313
p,p'-DDE	0.4	0.4	0.9	1.0
p,p'-DDD	0.2	0.2	0.9	0.8
p,p'-DDT	1.0	0.9	1.2	2.0
Total DDT	1.6	1.5	3.0	3.8

Table 5. Atomic CHN analyses in sediment cores from the Pilot site and the adjacent marshland.

Core depth (cm)	Weight percent			C/N ratio
	C	H	N	
Pilot Site				
A (0-15)	1.34	1.11	0.15	9.20
A (0-15)	1.41	1.16	0.15	9.34
A (21-36)	1.52	1.12	0.16	9.24
B (0-15)	1.27	1.39	0.15	8.60
B (15-62)	1.35	1.42	0.15	8.80
B (15-62)	1.26	1.12	0.14	9.12
B (62-82)	1.78	1.17	0.19	9.38
C (0-15)	1.30	1.17	0.14	9.23
C (0-15)	1.27	1.12	0.14	9.17
C (27-42)	1.67	1.47	0.18	9.28
D (0-15)	1.43	1.18	0.16	8.74
D (0-15)	1.43	1.20	0.17	8.65
D (24-40)	2.10	1.19	0.22	9.63
Adjacent marshland				
AWRC-1 (0-6)	2.70	1.32	0.25	10.75
AWRC-1 (19-28)	6.24	1.76	0.52	12.05
AWRC-1 (19-28)	6.92	1.89	0.54	12.75
AWRC-1 46-52)	1.59	1.22	0.15	10.95

Table 6. Concentrations of aliphatic hydrocarbons in sediment cores from the Pilot site and adjacent marshlands (ng/g).

Core	Concentration (ng/g)											
	SWPA 0-15	SWPA 21-36	SWPB 0-15	SWPB 15-62	SWPB 62-82	SWPC 0-15	SWPC 27-42	SWPD 0-15	SWPD 24-40	AWRC-1 0-6	AWRC-1 19-28	AWRC-1 46-52
n-C ₁₃	13	8.0	10	9.0	15	7.0	14	10	13	16	10	11
n-C ₁₄	23	27	18	11	26	13	18	15	20	30	10	13
n-C ₁₅	40	29	38	22	44	26	31	33	36	60	17	22
n-C ₁₆	34	25	40	20	41	28	27	37	35	53	16	21
n-C ₁₇	49	28	45	28	40	43	30	35	40	68	27	29
Pristane	37	10	35	30	29	29	18	59	57	63	36	16
n-C ₁₈	30	18	32	30	25	27	20	34	25	37	19	21
Phytane	47	21	46	46	15	42	13	55	21	25	10	21
n-C ₁₉	28	17	24	35	27	20	25	43	27	40	33	30
n-C ₂₀	27	18	44	40	27	32	24	46	33	34	35	22
n-C ₂₁	78	34	75	120	60	59	51	100	77	78	100	55
n-C ₂₂	66	30	45	48	48	35	45	56	52	54	96	40
n-C ₂₃	160	90	140	150	130	110	110	160	160	140	270	98
n-C ₂₄	70	47	84	66	61	62	51	56	78	66	150	45
n-C ₂₅	240	230	210	250	300	160	290	240	300	280	610	180
n-C ₂₆	79	67	71	78	75	47	64	75	85	80	220	50
n-C ₂₇	400	410	370	470	410	270	480	420	390	390	1100	260
n-C ₂₈	120	100	94	130	100	55	110	93	91	100	210	56
n-C ₂₉	1140	1280	1050	980	1190	500	1540	860	800	760	1670	490
n-C ₃₀	310	130	320	280	130	160	150	210	120	120	150	120
n-C ₃₁	940	1250	820	620	1180	290	1880	540	550	490	530	220
n-C ₃₂	230	110	180	150	120	57	120	96	54	74	42	44
n-C ₃₃	600	610	520	300	610	130	820	250	230	220	120	100
n-C ₃₄	280	41	230	110	100	44	56	85	27	48	38	31
n-C ₃₅	270	220	270	110	310	46	220	88	66	73	29	28
n-C ₃₆	140	10	110	38	77	15	15	58	5.0	21	4.0	6.0
TOTAL	5450	4860	4920	4170	5190	2310	6220	3750	3390	3420	5550	2030

Table 7. Biomarker correlation parameters in sediments from the Pilot site and adjacent marshlands.

Core depth (cm)	Hopanes (m/z 191)	Steranes (m/z 217)	Dominant Source			
	T_m/T_s	C_{30}/C_{29}	$\alpha\beta C_{31}-S/(S+R)$			
			Diploptene/ $\alpha\beta C_{30}$			
			$\alpha\alpha\alpha C_{29}-S/(S+R)$			
Pilot Site						
SWPA (0-15)	1.3	1.3	0.59	*	0.42	fill
SWPA (21-36)	2.2	1.3	0.51	0.51	0.29	bottom sed.
SWPB (0-15)	1.3	1.5	0.59	*	0.42	Fill
SWPB (15-62)	1.4	1.4	0.60	*	0.43	Fill
SWPB (62-82)	1.1	1.2	0.52	0.28	0.35	bottom sed.
SWPC (0-15)	1.3	1.4	0.60	0.10	0.43	Fill
SWPC (27-42)	2.8	1.4	0.50	0.64	0.30	fill + bottom sed.
SWPD (0-15)	1.3	1.4	0.6	0.10	0.40	Fill
SWPD (24-42)	1.5	1.5	0.56	0.42	0.39	fill+bottom sed.
Reference Site						
AWRC-1 (0-6)	1.4	1.5	0.58	0.21	0.43	Stratified
AWRC-1 (19-28)	1.2	1.3	0.60	0.66	0.55	Stratified; very mature; contaminated
AWRC-1 (46-52)	1.7	1.4	0.56	0.13	0.42	Relatively higher levels; contaminated

* not measurable (diploptene level too low)

Table 8. Concentrations of polycyclic aromatic hydrocarbons and chlorinated pesticides in sediment cores from the Pilot site and adjacent marshlands (ng/g).

Core Depth (cm)	SWPA 0-15	SWPA 21-36	SWPB 0-15	SWPB 15-62	SWPB 62-82	SWPC 0-15	SWPC 27-42	SWPD 0-15	SWPD 24-40	AWRC-1 0-6	AWRC-1 19-28
Compound	Concentration (ng/g)										
naphthalene	46	43	42	30	17	22	35	16	9.2	10.4	4.7
2-methylnaphthalene	30	30	27	24	12	17	25	11	6.8	7.5	3.4
1-methylnaphthalene	16	15	14	12	5.9	8.8	11	5.6	4.0	4.1	2.1
acenaphthylene	2.8	0.8	2.7	2.2	0.4	2.3	0.6	2.9	0.6	1.1	1.0
acenaphthene	2.5	0.5	2.4	2.1	0.3	1.9	0.5	2.7	0.5	1.0	0.5
9[H]fluorene	7.0	1.5	6.3	5.6	1.2	4.6	1.5	7.3	1.4	2.8	1.6
phenanthrene	45	9.5	49	41	9.1	39	12	54	12	20	16
anthracene	11	0.6	13	11	0.5	9.6	0.5	14	1.5	2.7	2.2
2-methylphenanthrene	12	5.0	14	12	4.9	10	5.2	14	5.3	6.4	5.4
1-methylphenanthrene	7.1	2.0	10	8.4	2.1	7.4	2.3	10	2.6	3.3	3.1
fluoranthene	150	6.5	180	140	8.0	150	11	200	33	41	54
pyrene	230	5.7	290	210	4.5	240	4.1	310	43	47	66
benz[a]anthracene	42	2.2	57	57	1.1	51	1.1	69	10	13	19
chrysene	45	4.8	59	56	4.8	55	4.9	65	13	18	34
benzo[b]fluoranthene	89	5.2	110	120	4.5	110	3.8	140	23	35	57
benzo[k]fluoranthene	24	1.1	23	38	1.2	26	1.1	37	7.5	7.9	8.0
benz[a]pyrene	63	1.6	93	94	1.1	97	0.6	120	20	24	42
perylene	100	3.7	120	130	0.3	120	1.2	150	30	26	20
indeno[1,2,3-cd]pyrene	11	1.2	9.7	18	0.6	14	0.4	15	4.2	4.9	9.3
dibenz[a,h]anthracene	9.1	0.8	7.4	11	2.6	11	0.3	20	3.6	4.3	8
benzo[g,h,i]perylene	49	2.3	50	110	0.9	94	0.5	88	24	32	55
Total PAH	990	143	1180	1130	83	1090	123	1350	255	312	412
p,p'-DDE	3.1	0.2	2.0	2.1	0.4	2.0	0.4	2.8	0.7	1.0	220
p,p'-DDD	3.7	0.2	3.4	2.1	0.3	2.5	0.3	3.2	0.7	0.8	27
p,p'-DDT	0.9	0.6	nd	0.6	1.7	0.2	0.9	1.2	0.6	1.6	2.0
Total DDT	7.7	1.0	5.4	4.8	2.4	4.7	1.6	7.2	2.0	3.4	249

Table 9. Atomic CHN analyses in sediment cores from the Main site and two reference sites in the adjacent marshlands.

Core depth (cm)	C	Weight percent H	N	C/N ratio
Main site				
SWM-3 (0-15)	0.97	1.32	0.12	8.29
SWM-3 (15-30)	0.94	0.92	0.11	8.25
SWM-3 (15-30)*	0.94	0.97	0.11	8.24
SWM-3 (30-50)	0.96	1.08	0.11	8.61
SWM-M (0-15)	1.38	1.42	0.13	10.26
SWM-M (15-30)	3.73	1.60	0.34	11.08
SWM-M (30-50)	2.94	1.55	0.30	9.93
SWM-8 (0-15)	0.79	1.07	0.09	8.51
SWM-8 (15-30)	1.23	1.56	0.15	8.12
SWM-8 (30-50)	1.33	1.38	0.16	8.46
SWM-14 (0-15)	1.16	1.24	0.14	8.16
SWM-14 (15-30)	1.23	1.56	0.15	8.12
SWM-14 (30-50)	1.33	1.38	0.16	8.46
Reference site				
AWRC-3 (0-15)	2.62	1.65	0.25	10.51
AWRC-3 (0-15)*	2.36	1.73	0.20	11.62
AWRC-3 (15-45)	2.35	1.63	0.16	14.90
AWRC-3 (45-75)	1.41	1.42	0.12	11.67
AWRC-2 (0-6)	0.93	1.01	0.12	8.05
AWRC-2 (6-23)	2.43	1.29	0.23	10.6
AWRC-2 (23-38)	1.44	1.64	0.16	8.99

* Duplicate analyses

Table 10. Concentrations of aliphatic hydrocarbons in sediment cores from the Main site (ng/g).

Core	Concentration (ng/g)											
	SWM-3	SWM-3	SWM-3	SWM-M	SWM-M	SWM-M	SWM-8	SWM-8	SWM-8	SWM-14	SWM-14	SWM-14
Depth (cm)	0-15	15-30	30-50	0-15	15-30	30-50	0-15	15-30	30-50	0-15	15-30	30-50
n-C ₁₃	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
n-C ₁₄	2	1	1	2	4	3	2	4	2	4	2	3
n-C ₁₅	8	4	6	16	20	8	13	36	12	12	9	17
n-C ₁₆	12	10	13	20	27	14	17	41	22	19	19	23
n-C ₁₇	39	26	41	58	39	19	34	91	52	45	103	69
Pristane	32	20	23	25	12	5	23	58	44	28	29	38
n-C ₁₈	18	14	17	23	33	16	17	48	40	24	33	38
Phytane	53	33	39	41	9	4	35	115	72	48	57	64
n-C ₁₉	49	24	31	34	30	19	26	80	50	40	44	49
n-C ₂₀	26	16	21	24	26	16	18	67	30	24	27	35
n-C ₂₁	121	67	87	90	69	54	56	263	144	94	205	144
n-C ₂₂	36	20	22	34	53	34	20	62	27	29	86	41
n-C ₂₃	72	48	54	90	146	120	42	127	58	68	105	111
n-C ₂₄	36	23	28	50	72	68	23	102	33	45	49	53
n-C ₂₅	163	137	168	271	513	311	137	316	182	182	183	256
n-C ₂₆	92	50	56	89	112	106	43	125	65	77	118	138
n-C ₂₇	290	188	230	430	858	432	203	495	275	279	328	424
n-C ₂₈	192	67	143	219	187	178	143	313	235	149	198	258
n-C ₂₉	728	490	544	1427	3968	1697	528	980	687	625	812	1127
n-C ₃₀	181	114	129	149	207	207	85	294	231	158	193	242
n-C ₃₁	258	175	215	572	1788	1280	174	341	214	234	309	523
n-C ₃₂	59	39	45	62	82	100	34	173	113	67	71	120
n-C ₃₃	224	163	132	323	691	529	157	370	147	186	215	370
n-C ₃₄	110	84	88	94	40	29	57	242	174	101	162	184
n-C ₃₅	109	57	86	103	113	110	48	249	154	99	108	165
n-C ₃₆	42	21	21	27	52	4	14	89	50	37	35	53
TOTAL	2951	1893	2241	4273	9150	5361	1946	5081	3115	2670	3501	4544

Table 11. Concentrations of aliphatic hydrocarbons in sediment cores from the adjacent marshland reference sites (ng/g).

Compound	Concentration (ng/g)									
	Core Depth (cm)	AWRC-1 0-6	AWRC-1 19-28	AWRC-1 46-52	AWRC-2 0-6	AWRC-2 6-22.5	AWRC-2 22.5-38	AWRC-3 0-15	AWRC-3 15-45	AWRC-3 45-75
n-C ₁₃	16	10	11	<1	<1	<1	<1	<1	<1	<1
n-C ₁₄	30	10	13	2	2	1	2	1	1	1
n-C ₁₅	60	17	22	11	7	3	14	8	3	3
n-C ₁₆	53	16	21	18	13	6	17	9	6	6
n-C ₁₇	68	27	29	44	24	9	41	16	18	18
Pristane	63	36	16	14	11	4	13	6	4	4
n-C ₁₈	37	19	21	17	16	6	24	10	5	5
Phytane	25	10	21	17	12	6	14	9	14	14
n-C ₁₉	40	33	30	22	18	9	21	15	19	19
n-C ₂₀	34	35	22	21	19	11	20	14	17	17
n-C ₂₁	78	100	55	77	73	39	85	56	63	63
n-C ₂₂	54	96	40	35	31	19	28	20	24	24
n-C ₂₃	140	270	98	114	72	32	88	69	90	90
n-C ₂₄	66	150	45	60	36	22	52	40	52	52
n-C ₂₅	280	610	180	307	114	93	276	211	209	209
n-C ₂₆	80	220	50	124	68	31	117	87	72	72
n-C ₂₇	390	1100	260	495	311	171	585	413	394	394
n-C ₂₈	100	210	56	178	191	99	278	189	216	216
n-C ₂₉	760	1670	490	980	758	513	2262	998	1166	1166
n-C ₃₀	120	150	120	133	118	78	215	139	93	93
n-C ₃₁	490	530	220	406	360	168	654	266	294	294
n-C ₃₂	74	42	44	41	66	30	57	33	37	37
n-C ₃₃	220	120	100	217	194	125	277	148	198	198
n-C ₃₄	48	38	31	61	64	39	72	51	62	62
n-C ₃₅	73	29	28	60	57	35	71	44	53	53
n-C ₃₆	21	4	6	15	17	6	21	12	8	8
TOTAL	3420	5552	2029	3469	2650	1556	5304	2865	3121	3121

Table 12. Biomarker correlation parameters in sediments from the Main and adjacent marshland reference sites.

Core depth (cm)	Hopanes (m/z 191)		$\alpha\beta C_{31}^-$ S/(S+R)	Diploptene/ $\alpha\beta C_{30}$	Steranes (m/z 217)		Dominant Source
	Tm/Ts	C ₃₀ /C ₂₉			$\alpha\alpha\alpha C_{29}^-$ S/(S+R)		
Main sites							
SWM-3 (0-15)	1.3	1.3	0.58	*	0.41	Fill	
SWM-3 (15-30)	1.3	1.4	0.57	*	0.39	Fill	
SWM-3 (30-50)	1.2	1.3	0.58	*	0.43	Fill	
SWM-M (0-15)	1.3	1.4	0.57	*	0.39	Fill	
SWM-M (15-30)	1.6	1.5	0.56	0.54	0.46	fill +bottom sed.	
SWM-M (30-50)	3.1	1.3	0.57	0.86	0.31	Bottom sed.	
SWM-8 (0-15)	1.4	1.4	0.57	*	0.40	Fill	
SWM-8 (15-30)	1.2	1.4	0.57	*	0.40	Fill	
SWM-8 (30-50)	1.2	1.3	0.56	*	0.39	Fill	
SWM-14 (0-15)	1.2	1.4	0.57	*	0.41	Fill	
SWM-14 (15-30)	1.2	1.4	0.57	*	0.44	Fill	
SWM-14 (30-50)	1.2	1.4	0.57	*	0.44	Fill	
Reference Sites							
AWRC-2 (0-6)	1.3	1.4	0.58	*	0.48	Biogenic	
AWRC-2 (6-23)	1.2	1.5	0.58	*	0.50	Biogenic	
AWRC-2 (23-38)	1.4	1.5	0.59	*	0.47	Biogenic	
AWRC-3 (0-15)	1.2	1.4	0.58	*	0.54	Biogenic	
AWRC-3 (15-30)	1.4	1.4	0.60	*	0.46	Biogenic	
AWRC-3 (30-50)	1.8	1.4	0.58	*	0.41	Biogenic	

*not measurable (diploptene levels too low)

Table 13. Concentrations of polycyclic aromatic hydrocarbons and chlorinated pesticides in sediment cores from the Main site (ng/g).

Compound	Core		Concentration (ng/g)												
	Depth (cm)		SWM-3	SWM-3	SWM-3	SWM-M	SWM-M	SWM-M	SWM-M	SWM-8	SWM-8	SWM-8	SWM-8	SWM-14	SWM-14
naphthalene			24	31	12	21	9.4	5.5	6.5	13	14	14	14	9.3	18
2-methylnaphthalene			1.9	<0.1	2.8	1.4	1.7	1.9	3.9	4.0	5.4	5.0	5.3	4.9	
1-methylnaphthalene			<0.1	<0.1	1.5	0.5	0.6	0.6	1.7	1.1	2.6	1.6	1.9	2.1	
acenaphthylene			19	23	6.6	3.7	0.7	0.1	7.7	4.1	6.0	9.0	3.1	4.6	
acenaphthene			3.6	0.9	3.0	2.1	<0.1	0.1	2.4	2.3	2.1	3.0	4.5	4.1	
9[H]fluorene			8.0	7.6	7.8	7.1	0.8	0.3	6.4	8.0	7.9	7.4	7.7	11	
phenanthrene			21	22	15	14	6.7	3.7	26	15	15	20	15	15	
anthracene			7.3	7.6	4.8	4.5	0.7	0.2	7.8	6.1	6.5	6.8	6.2	7.0	
2-methylphenanthrene			7.2	8.0	5.9	4.8	2.9	1.7	8.4	5.2	5.8	6.6	5.1	4.6	
1-methylphenanthrene			5.2	5.4	4.1	3.0	1.6	0.7	6.4	3.3	3.4	4.7	3.3	3.0	
fluoranthene			200	360	85	64	18	5.3	280	71	88	210	98	74	
pyrene			79	89	64	56	19	4.8	80	66	73	85	78	71	
benz[a]anthracene			17	17	14	12	9.5	6.8	13	16	16	16	17	17	
chrysene			19	20	15	11	9.3	7.6	20	16	18	20	18	18	
benzo[b]fluoranthene			29	29	24	23	9.1	3.3	25	30	33	33	32	32	
benzo[k]fluoranthene			10	12	10	8.1	2.1	0.6	9.4	11	11	14	12	12	
benzo[a]pyrene			23	23	18	16	4.9	1.0	19	22	23	27	22	23	
perylene			30	32	20	26	9.0	5.7	21	29	27	23	21	22	
indeno[1,2,3-cd]pyrene			0.8	3.5	20	19	9.2	3.0	3.1	1.6	11	12	12	2.0	
dibenz[a,h]anthracene			3.7	5.5	2.8	2.1	<0.1	0.5	1.6	2.2	2.1	3.4	1.8	1.6	
benzo[g,h,i]perylene			34	58	21	19	7.6	3.0	0.5	3.3	11	26	4.3	12	
Total PAH			543	786	357	318	123	56	550	330	382	550	378	359	
p,p'-DDE			0.7	0.5	0.5	0.8	3.6	0.6	0.5	1.5	1.6	0.6	0.8	0.8	
p,p'-DDD			1.2	0.7	0.6	1.0	6.3	0.7	0.5	2.3	2.7	0.8	0.9	0.9	
p,p'-DDT			<0.1	<0.1	<0.1	1.0	11	3.1	1.8	0.3	<0.1	<0.1	<0.1	<0.1	
Total DDT			1.9	1.2	1.1	2.8	21	4.4	2.8	4.1	4.3	1.4	1.7	1.7	

Table 14. Concentrations of polycyclic aromatic hydrocarbons and chlorinated pesticides in sediment cores from the adjacent reference marshlands.

Compound	Concentration (mg/g)									
	Core Depth (cm)	AWRC-1 0-6	AWRC-1 19-28	AWRC-1 46-52	AWRC-2 0-6	AWRC-2 6-23	AWRC-2 23-38	AWRC-3 0-15	AWRC-3 15-45	AWRC-3 30-50
naphthalene		10.0	4.7	8.6	4.8	4.2	5.4	7.7	12	18
2-methylnaphthalene		8.0	3.4	5.9	<0.1	<0.1	<0.1	3.2	2.1	1.1
1-methylnaphthalene		4.1	2.1	3.3	<0.1	<0.1	<0.1	0.9	0.6	0.6
acenaphthylene		1.1	1.0	7.4	2.7	3.6	4.1	1.3	2.6	5.8
acenaphthene		1.0	0.5	2.3	<0.1	<0.1	<0.1	<0.1	0.7	1.0
9[H]fluorene		2.8	1.6	4.3	2.0	<0.1	1.1	1.6	1.7	3.9
phenanthrene		20	16	90	7.7	6.2	9.9	6.3	13	23
anthracene		2.7	2.2	16	1.8	1.1	1.6	1.1	2.6	5.6
2-methylphenanthrene		6.4	5.4	16	4.0	3.8	3.8	3.0	3.6	4.2
1-methylphenanthrene		3.3	3.1	12	2.3	2.2	2.3	1.7	2.5	3.0
fluoranthene		41	54	630	41	51	110	24	120	180
pyrene		47	66	1030	36	43	62	27	65	290
benz[a]anthracene		13	19	170	9.6	9.4	9.6	9.6	13	37
chrysene		18	34	200	9.3	9.1	13	9.3	18	42
benzo[b]fluoranthene		35	57	350	17	15	25	14	32	110
benzo[k]fluoranthene		7.9	8.0	97	4.9	4.3	6.8	3.5	11	24
benz[a]pyrene		24	42	310	9.8	8.6	15	8.5	25	91
perylene		26	20	110	13	9.5	9.9	9.9	14	36
indeno[1,2,3-cd]pyrene		4.9	9.3	50	18	19	30	8.5	32	90
dibenz[a,h]anthracene		4.3	8.0	19	2.2	2.1	4.2	1.2	2.9	6.1
benzo[g,h,i]perylene		32	55	280	20	21	49	19	64	105
Total PAH		312	412	3410	206	213	364	161	433	1080
p,p'-DDE		1.0	220	0.3	0.6	1.7	0.5	3.4	2.3	0.2
p,p'-DDD		0.8	27	<0.1	0.4	0.8	0.2	0.5	0.5	<0.1
p,p'-DDT		1.6	2.0	<0.1	0.1	2.1	0.5	0.5	0.1	0.1
Total DDT		3.4	249	0.3	1.1	4.6	1.2	4.4	2.9	0.3

Table 15. Atomic CHN analyses of a sediment core from the Petaluma Marsh Restoration Project.

Core depth (cm)	C	Weight percent H	N	C/N ratio
Petaluma Marsh				
PMR-1 (0-15)	1.27	1.36	0.11	11.34
PMR-1 (15-30)	1.38	1.40	0.12	11.87
PMR-1 (30-56)	1.20	1.33	0.10	11.75

Table 16.
Concentrations of aliphatic hydrocarbons in a sediment core
from the Petaluma Marsh Restoration Project (ng/g).

Core Depth (cm)	PMR-1 0-15	PMR-1 15-30	PMR-1 30-55.5
Compound	Concentration (ng/g)		
n-C ₁₃	<1	<1	<1
n-C ₁₄	2	1	1
n-C ₁₅	7	5	3
n-C ₁₆	11	9	6
n-C ₁₇	29	21	12
Pristane	13	5	4
n-C ₁₈	13	11	9
Phytane	21	14	6
n-C ₁₉	25	19	12
n-C ₂₀	25	16	13
n-C ₂₁	61	49	28
n-C ₂₂	15	10	22
n-C ₂₃	80	74	54
n-C ₂₄	35	30	26
n-C ₂₅	174	171	123
n-C ₂₆	61	43	39
n-C ₂₇	327	292	212
n-C ₂₈	138	81	72
n-C ₂₉	888	840	632
n-C ₃₀	87	82	38
n-C ₃₁	369	406	225
n-C ₃₂	52	40	21
n-C ₃₃	155	164	102
n-C ₃₄	63	47	11
n-C ₃₅	58	51	25
n-C ₃₆	12	6	2
TOTAL	2721	2487	1698

Table 17. Biomarker correlation parameters in a sediment core from the Petaluma Tidal Marsh Restoration Project.

Core depth (cm)		Hopanes (m/z 191)	Steranes (m/z 217)	Dominant Source		
	Tm/Ts	C_{30}/C_{29}	$\alpha\beta C_{31}\text{-}S/(S+R)$	$Diploptene/\alpha\beta C_{30}$	$\alpha\alpha C_{29}\text{-}S/(S+R)$	
PMR-1 (0-15)	1.4	1.3	0.55	0.05	0.49	Petrogenic contamination Biogenic
PMR-1 (15-30)	1.3	1.5	0.58	0.06	0.41	
PMR-1 (30-50)	2.2	1.4	0.53	0.13	0.40	

Table 18. Concentrations of polycyclic aromatic hydrocarbons and chlorinated pesticides in a sediment core from the Petaluma Tidal Marsh Restoration Project.

Core Depth (cm)	PMR-1 0-15	PMR-1 15-30	PMR-1 30-56
Compound	Concentration (ng/g)		
naphthalene	6.9	9.7	9.9
2-methylnaphthalene	3.8	2.5	<0.1
1-methylnaphthalene	1.8	1.0	<0.1
acenaphthylene	4.8	7.8	3.3
acenaphthene	<0.1	<0.1	<0.1
9[H]fluorene	2.9	2.7	0.9
phenanthrene	9.5	14	8.2
anthracene	2.4	2.3	1.6
2-methylphenanthrene	4.1	6.2	4.6
1-methylphenanthrene	2.5	3.8	3.1
fluoranthene	61	153	82
pyrene	49	64	49
benz[a]anthracene	9.8	13	10
chrysene	12	15	11
benzo[b]fluoranthene	20	24	16
benzo[k]fluoranthene	5.4	7.6	5.8
benz[a]pyrene	14	16	11
perylene	19	16	8.9
indeno[1,2,3-cd]pyrene	0.4	23	14
dibenz[a,h]anthracene	1.7	2.0	1.5
benzo[g,h,i]perylene	29	35	16
Total PAH	260	419	257
p,p'-DDE	0.5	0.2	0.1
p,p'-DDD	0.4	0.3	0.1
p,p'-DDT	<0.1	<0.1	0.2
Total DDT	0.9	0.5	0.4

Table 19. Sampling locations of sediment of tidal marsh channels in the marshlands adjacent to the Sonoma Wetland Demonstration Project site.

Site	Description	Latitude	Longitude
CH1	Near Pilot Site	38 ⁰ 6.930' N	122 ⁰ 29.451' W
CH2	"	38 ⁰ 6.936' N	122 ⁰ 29.432' W
CH3	"	38 ⁰ 6.945' N	122 ⁰ 29.484' W
CH4	"	38 ⁰ 6.918' N	122 ⁰ 29.393' W
CH5	Near Main Site	38 ⁰ 6.982' N	122 ⁰ 28.672' W
CH6	"	38 ⁰ 7.048' N	122 ⁰ 28.430' W
CH7	"	38 ⁰ 7.143' N	122 ⁰ 28.415' W

Table 20. Atomic CHN analyses of sediment of tidal marsh channels in the marshlands adjacent to the Sonoma Wetland Demonstration Project site.

Site	C	H	N	C/N Ratio
CH-1	1.19	1.35	0.15	7.90
CH-2	1.72	1.52	0.17	9.86
CH-3	1.16	1.44	0.14	8.46
CH-4	2.06	1.55	0.23	9.01
CH-5	2.01	1.75	0.23	8.56
CH-6	1.04	1.41	0.12	8.79
CH-7	1.33	1.60	0.17	7.73

Table 21. Concentrations of aliphatic hydrocarbons in sediments of tidal marsh channels in the adjacent marshlands near the Sonoma Wetland Demonstration Project (ng/g).

Compound	CH-1	CH-2	CH-3	CH-4	CH-5A*	CH-5B*	CH-6	CH-7
n-C ₁₃	<1	<1	<1	0.5	<1	<1	<1	<1
n-C ₁₄	<1	<1	10	10	11	10	<1	<1
n-C ₁₅	33	67	102	90	132	124	26	51
n-C ₁₆	211	355	418	355	465	473	73	278
n-C ₁₇	266	412	463	1060	571	571	101	370
Pristane	91	143	140	137	178	175	33	119
n-C ₁₈	120	194	228	181	231	232	25	175
Phytane	28	58	56	72	70	68	2	55
n-C ₁₉	40	76	87	81	99	100	10	78
n-C ₂₀	25	32	47	50	45	47	24	48
n-C ₂₁	66	124	105	158	160	156	50	131
n-C ₂₂	27	39	53	72	56	56	32	60
n-C ₂₃	96	151	220	357	257	249	113	191
n-C ₂₄	34	60	58	105	91	94	41	78
n-C ₂₅	142	238	264	576	527	562	227	335
n-C ₂₆	47	63	66	166	156	150	57	104
n-C ₂₇	378	629	629	1214	1389	1388	570	905
n-C ₂₈	56	98	103	175	246	322	102	140
n-C ₂₉	754	1316	1157	2194	3724	3752	1204	1778
n-C ₃₀	203	128	212	145	428	383	148	174
n-C ₃₁	371	543	601	1452	2966	2981	657	1507
n-C ₃₂	162	208	217	272	327	405	219	216
n-C ₃₃	242	243	280	459	693	732	302	507
n-C ₃₄	173	196	204	209	218	242	153	221
n-C ₃₅	190	176	200	274	293	287	206	289
n-C ₃₆	<1	132	<1	<1	130	124	<1	141
Total Alkanes	3755	5681	5923	9863	13464	13683	4375	7951

* Duplicate analyses

Table 22. Biomarker correlation parameters of sediments from tidal marsh channels in the marshlands adjacent to the Sonoma Baylands Wetland Demonstration Project.

Site	Hopanes (m/z191)			Steranes (m/z217)	
	T _m /T _s	C ₃₀ /C ₂₉	αβC ₃₁ - S/(S+R)	Dipl./ αβC ₃₀	ααC ₂₉ - S/(S+R)
CH-1	1.9	1.7	0.59	*	0.37
CH-2	1.8	1.7	0.59	*	0.36
CH-3	1.9	1.6	0.57	*	0.35
CH-4	1.4	1.7	0.59	0.02	0.41
CH-5A [†]	1.3	1.6	0.58	0.04	0.43
CH-5B [†]	1.3	1.6	0.58	*	0.43
CH-6	1.7	1.5	0.52	0.04	0.28
CH-7	1.2	1.6	0.59	0.03	0.40

[†] duplicate analyses

* not measurable (Diploptene level too low)

Table 23.**Concentrations of polycyclic aromatic hydrocarbons and chlorinated pesticides in sediments of tidal marsh channels in the marshlands adjacent to the Sonoma Wetland Demonstration Project (ng/g).**

Compound	CH-1	CH-2	CH-3	CH-4	CH-5A*	CH-5B*	CH-6	CH-7
naphthalene		51	144	36	130	55	23	34
2-methylnaphthalene	21	32	28	31	19	20	25	50
1-methylnaphthalene	19	29	24	25	15	15	24	48
acenaphthylene	15	11	16	5.0	3.4	3.4	3.1	3.2
acenaphthene	12	7.0	11	7.4	5.7	5.9	3.0	5.3
fluorene	24	17	26	12	13	13	7.3	8.1
phenanthrene	165	142	133	129	45	51	46	39
anthracene	36	41	38	18	9.7	12	13	10
2-methylphenanthrene	22	21	23	26	8.6	10	10	9.4
1-methylphenanthrene	19	24	22	18	6.6	9.3	11	8.1
fluoranthene	374	261	543	221	66	75	91	71
pyrene	827	421	1051	214	78	95	87	82
benz[a]anthracene	302	228	271	62	35	37	45	27
chrysene	185	177	216	98	82	69	65	46
benzo[b]fluoranthene	594	372	496	197	132	122	68	91
benzo[k]fluoranthene	169	115	179	61	26	41	18	27
benz[a]pyrene	439	275	379	154	107	102	50	69
perylene	309	246	283	138	86	81	51	77
indeno[1,2,3-cd]pyrene	284	228	275	140	82	63	34	94
dibenz[a,h]anthracene	51	38	38	19	20	13	7.5	12
benzo[g,h,i]perylene	304	280	302	161	84	68	40	127
Total PAHs	4479	3016	4498	1772	1054	961	722	938
gamma chlordane	<0.5	<0.5	<0.5	0.1	0.1	0.1	<0.5	0.1
alphachlordane	<0.5	<0.5	<0.5	0.1	<0.5	<0.5	<0.5	<0.5
trans nonachlor	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
dieldrin	8.2	25	1.3	2.6	1.5	2.4	0.8	1.5
p,p'-DDE	0.6	1.7	0.2	2.1	5.7	6.6	0.4	3.6
p,p'-DDD	0.8	<0.5	<0.5	2.0	3.5	3.2	0.2	3.3
p,p'-DDT	2.1	<0.5	<0.5	2.2	0.9	2.7	1.1	1.6
Total DDT	3.5	1.7	0.2	6.3	10	12	1.7	8.5

*Duplicate analyses

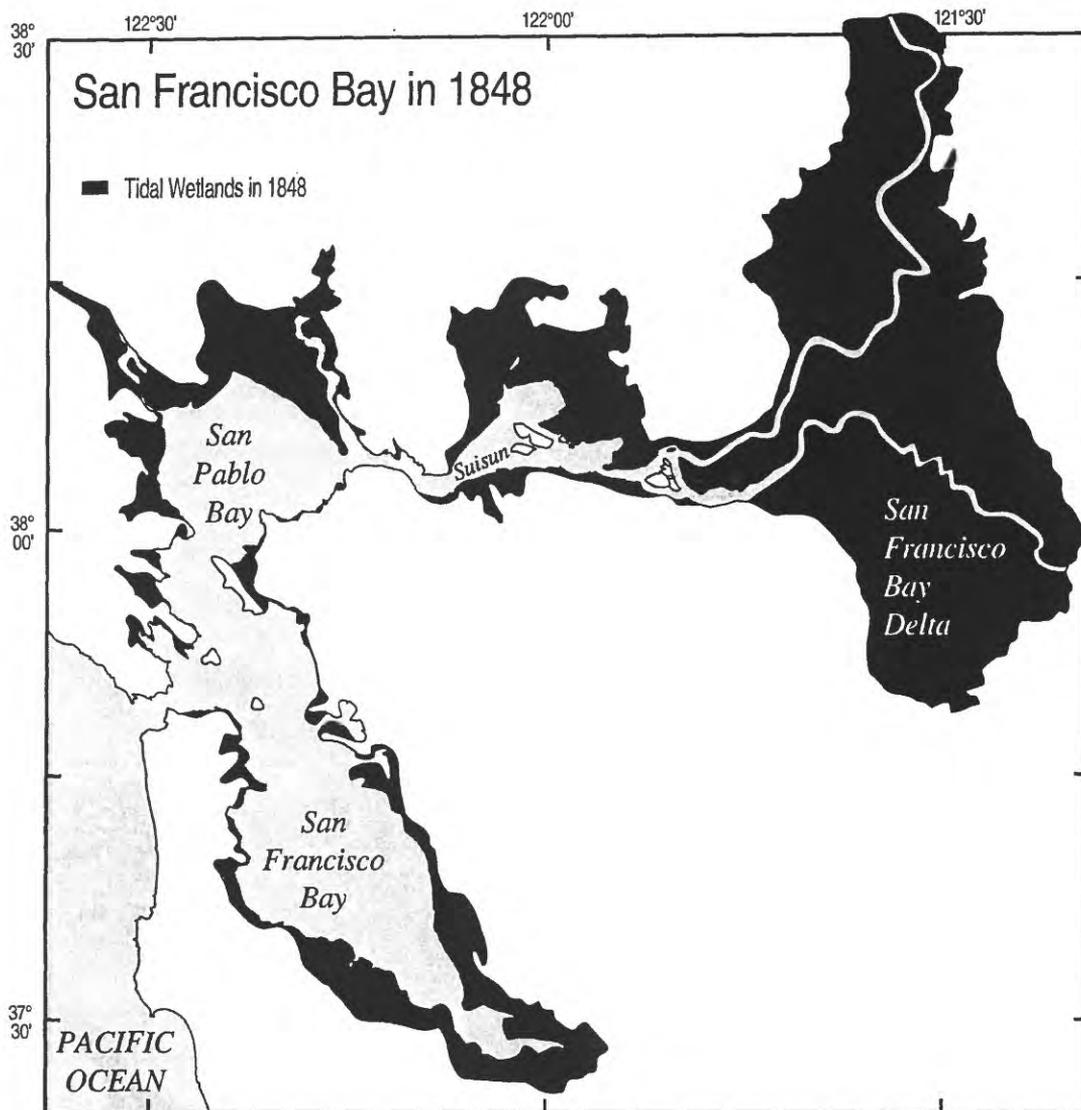


Fig. 1. Tidal wetlands in 1848 in San Francisco Bay.

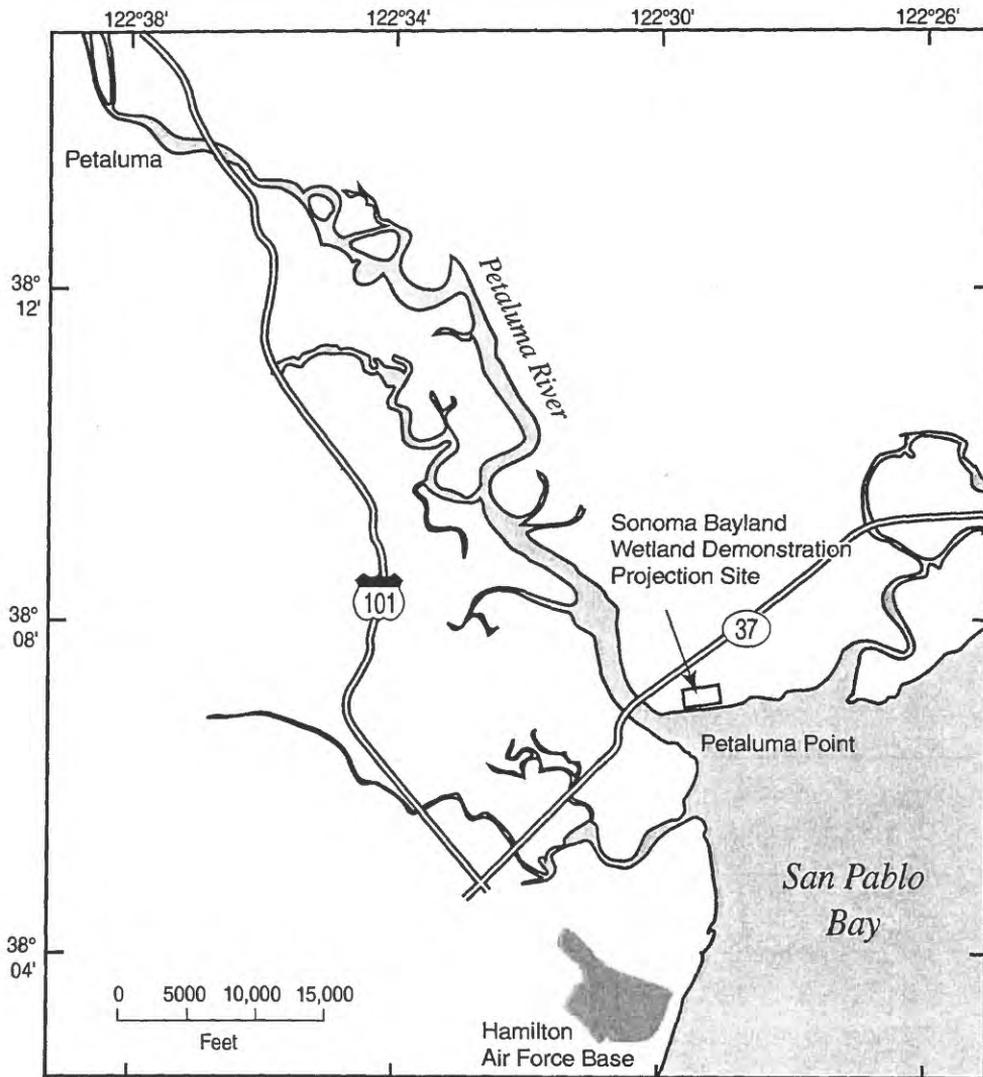


Fig. 2. Map showing location of the Sonoma Baylands Demonstration Project site.

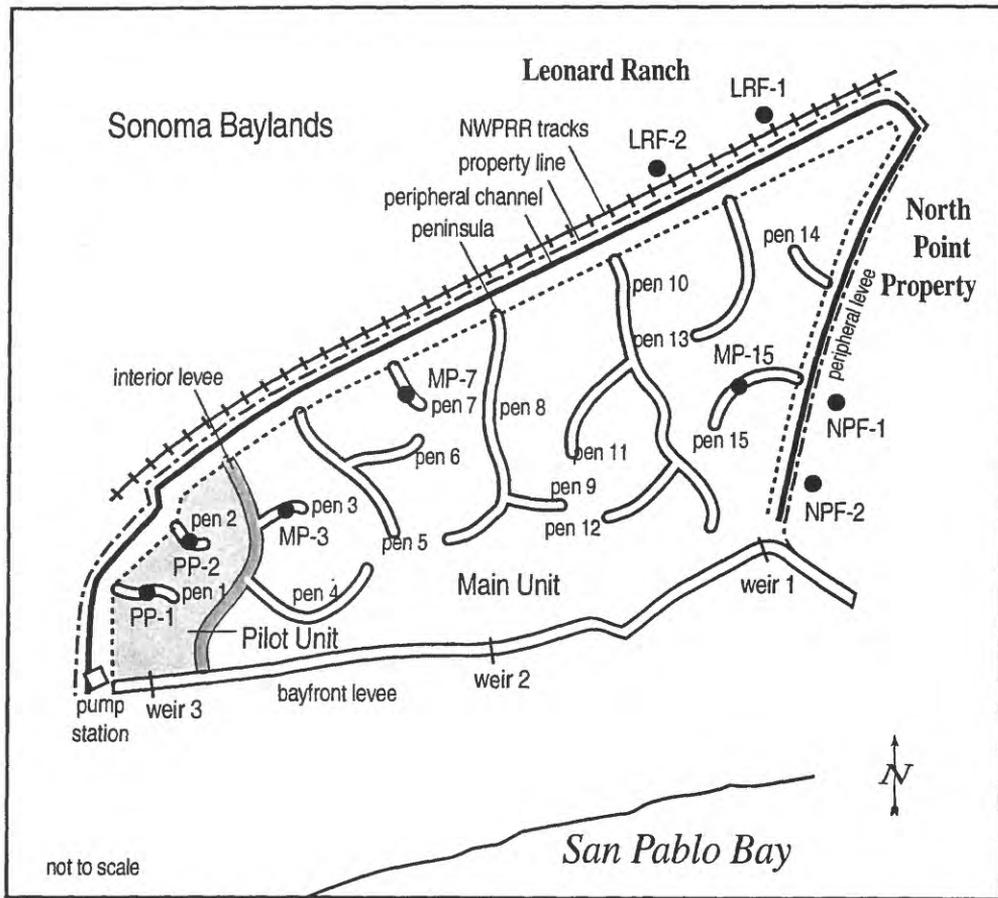


Fig. 3. The Sonoma Baylands Wetland Demonstration Project.

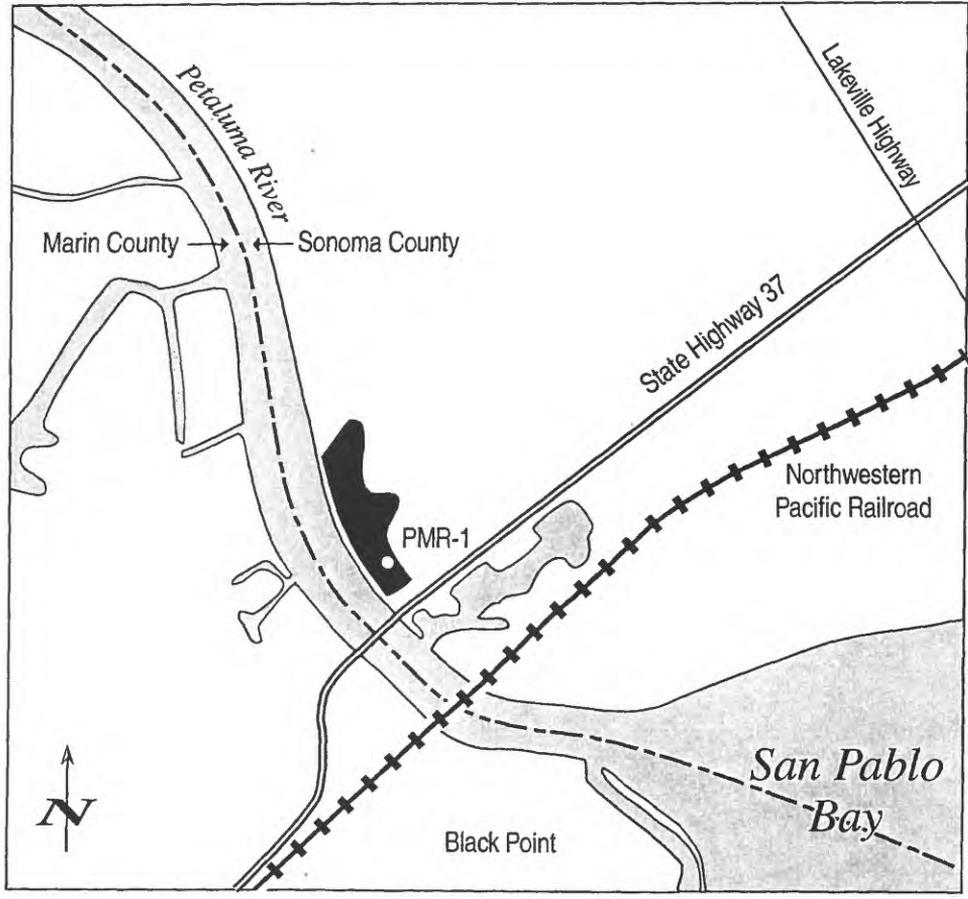


Fig. 4. The Petaluma Tidal Marsh Restoration Project.

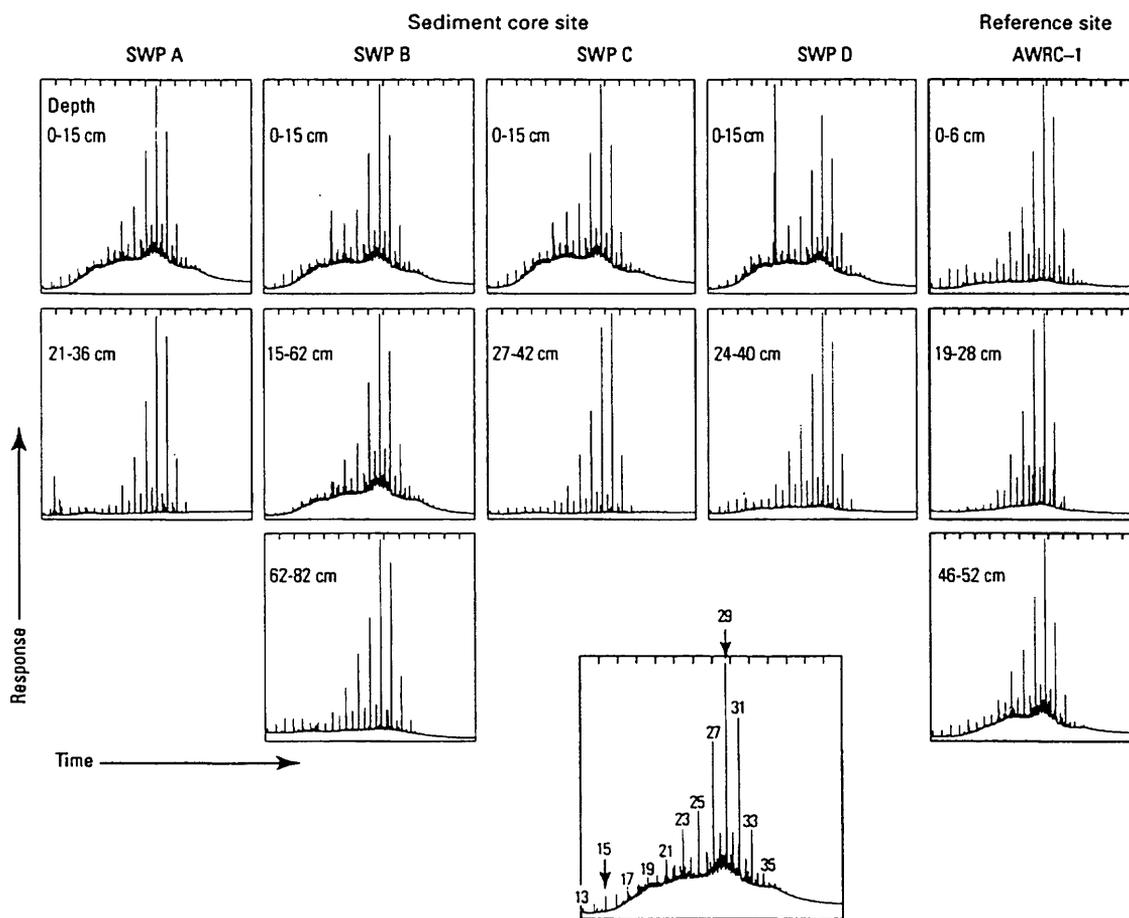


Fig. 5. Distributions of aliphatic hydrocarbons in sediment cores from the Pilot site and the adjacent marshland reference sites.

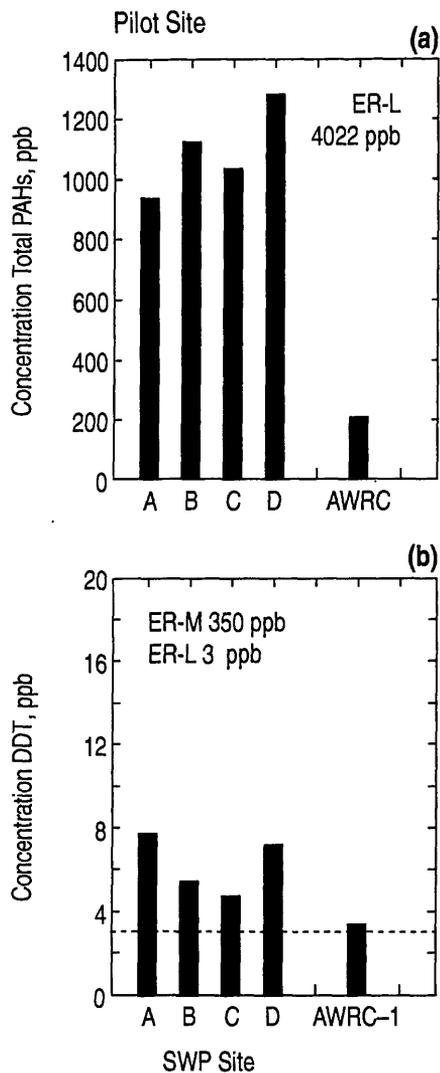


Fig. 6. (a) Concentrations of total PAHs in surficial sediments of the Pilot and adjacent marshland reference sites. ER-L (Effects Range-Low) and ER-M (Effects Range-Medium) concentrations for total PAHs. (b) Concentrations of total DDTs in surficial sediments of the Pilot and adjacent marshland reference sites. ER-L (Effects Range-Low) and ER-M (Effects Range-Medium) concentrations for total DDTs .

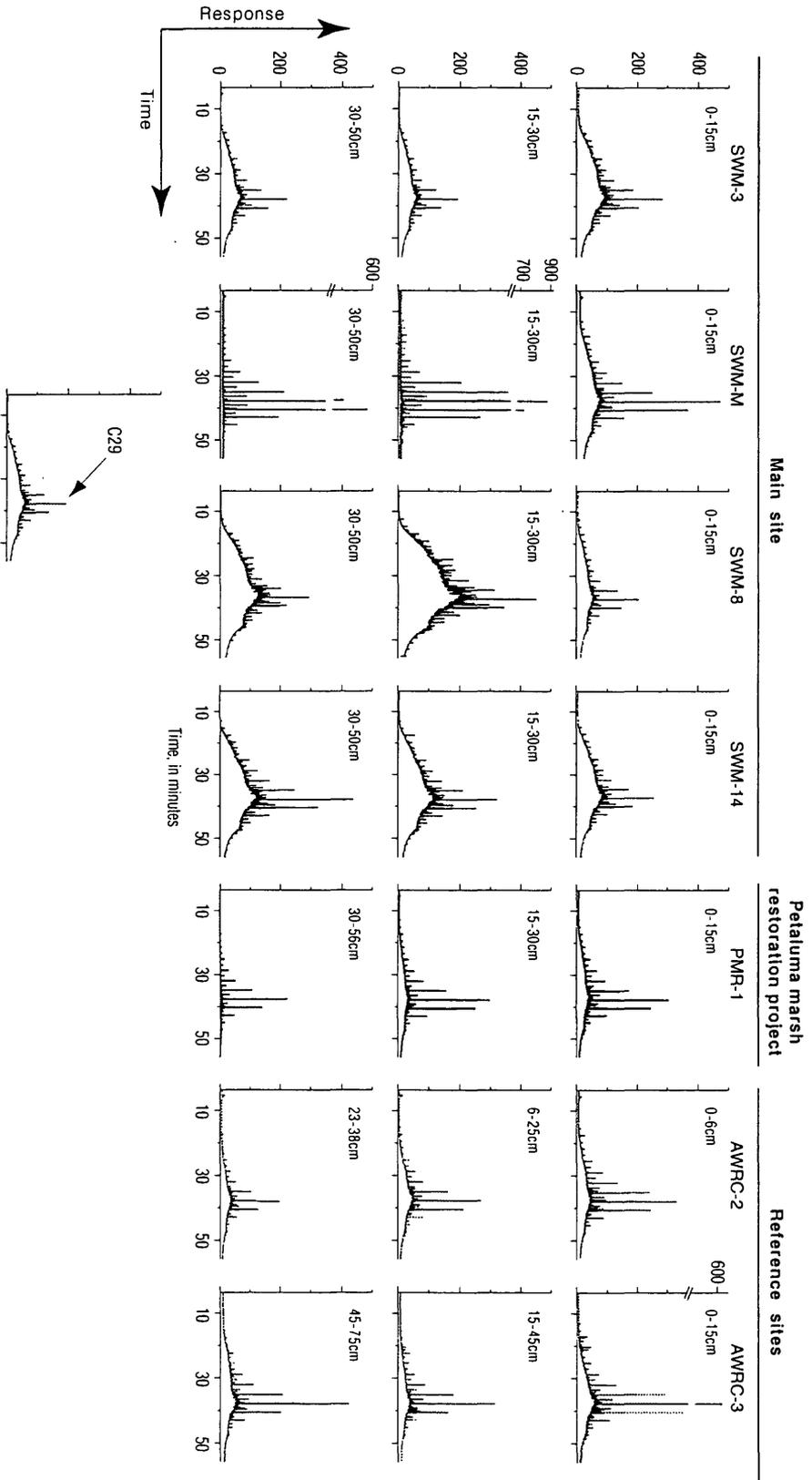


Fig. 7. Distributions of aliphatic hydrocarbons in sediment cores from the Main site, the Petaluma Tidal Marsh Restoration Project, and reference sites in the adjacent marshlands..

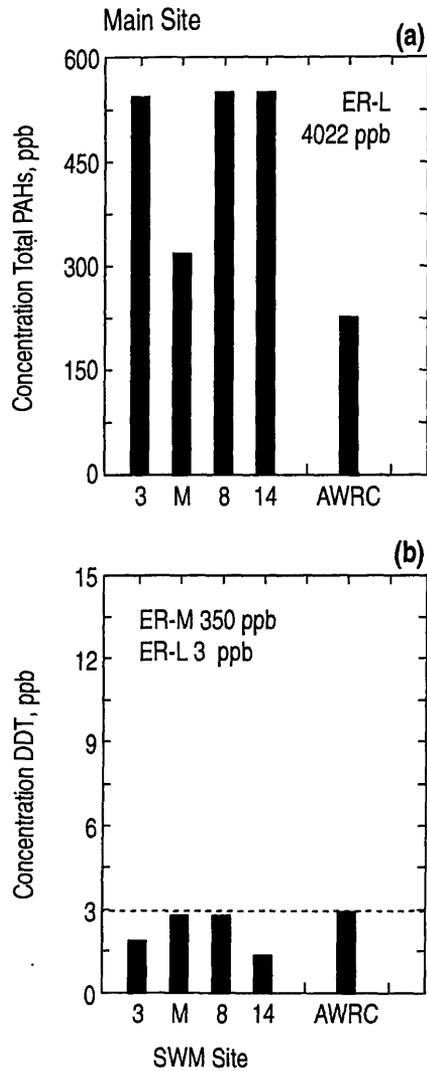


Fig. 8. (a) Concentrations of total PAHs in surficial sediments of the Main site and adjacent marshland reference sites. ER-L (Effects Range-Low) concentrations for total PAHs. (b) Concentrations of total DDTs in surficial sediments of the Main and adjacent marshland reference sites. ERL (Effects Range-Low) and (ER-M) Effects Range-Medium concentrations for total DDTs.

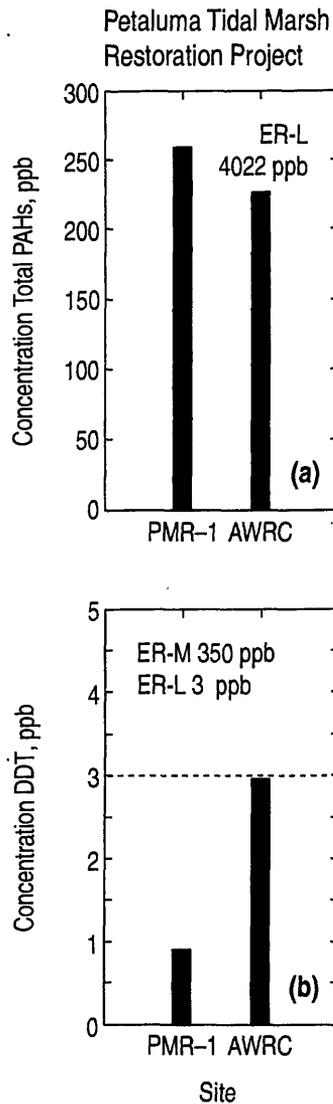


Fig. 9. (a) Concentrations of total PAHs in surficial sediments of the Petaluma tidal Marsh Restoration Project site. ER-L (Effects Range-Low) and ER-M (Effects Range-Medium) concentrations for total PAHs. (b) Concentrations of total DDTs in surficial sediments of the Petaluma Tidal Marsh Restoration Project site. ER-L (Effects Range-Low) and ER-M (Effects Range-Medium) concentrations for total DDTs.

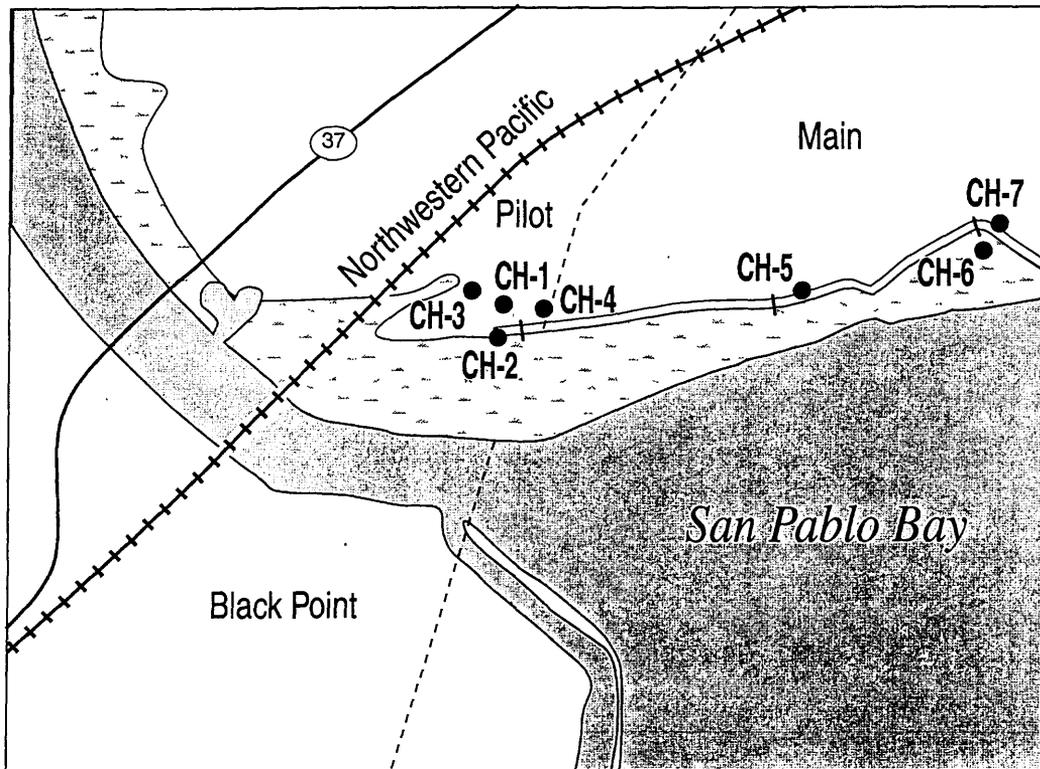


Fig. 10. Sampling locations of benthic sediments in tidal marsh channels in the marshlands adjacent to the SBWDP site.

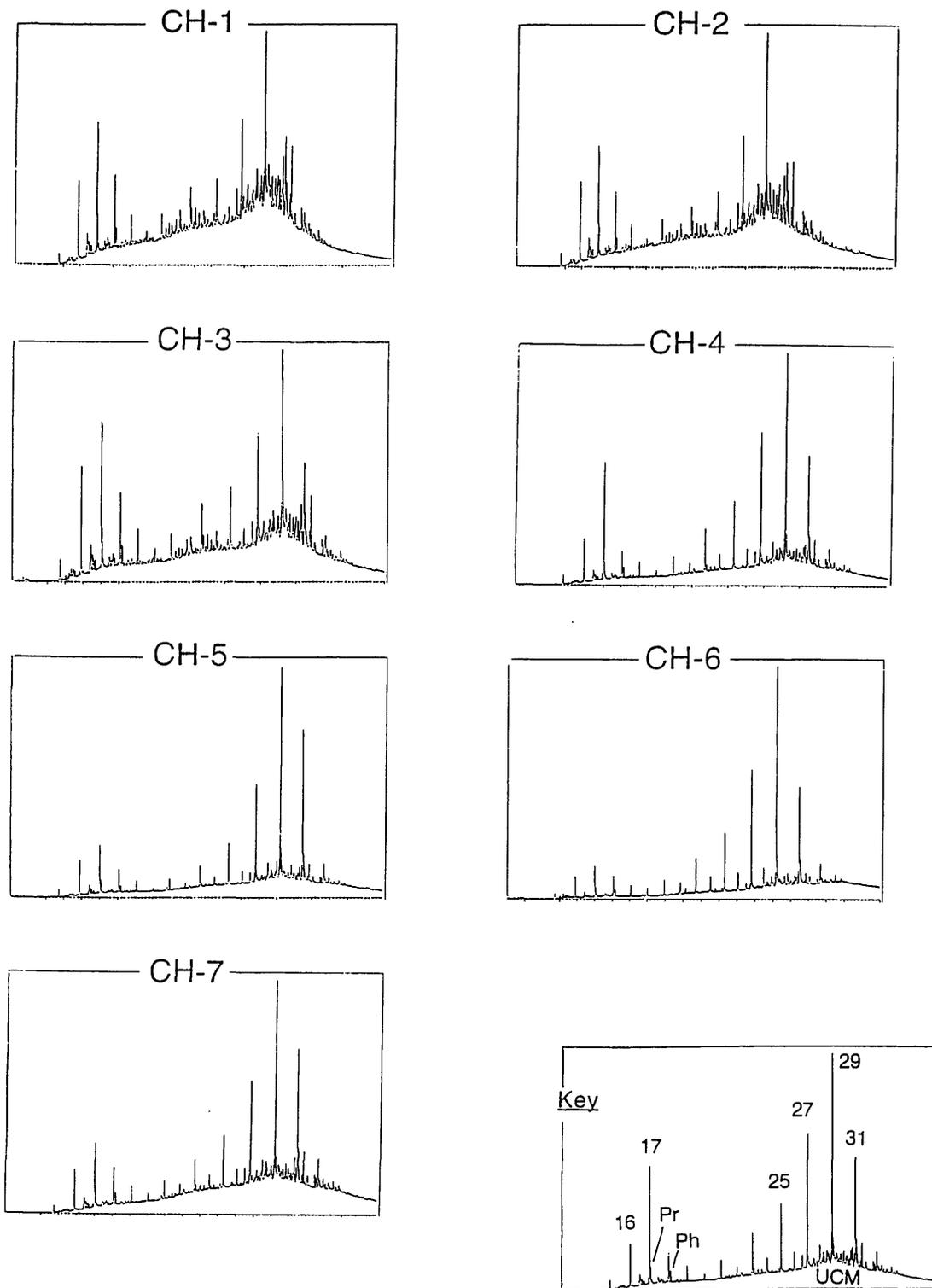


Fig. 11. Distributions of aliphatic hydrocarbons in benthic sediments of tidal marsh channels in the marshland adjacent to the SBWDP site.

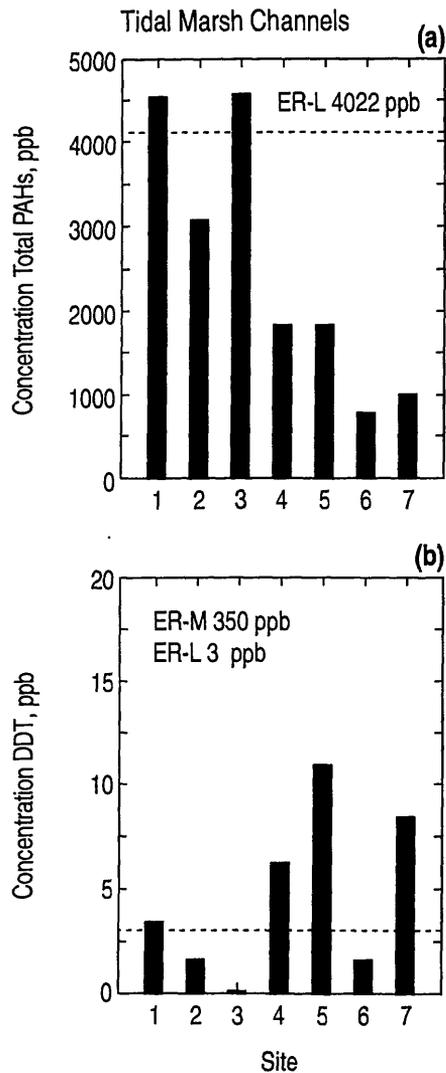


Fig. 12. (a) Concentrations of total PAHs in benthic sediments of tidal marsh channels in the marshlands adjacent to the SBWDP site. ER-L (Effects Range-Low) and ER-M (Effects Range-Medium) concentrations for total PAHs. (b) Concentrations of total DDTs in benthic sediments of tidal marsh channels in the marshlands adjacent to the SBWDP site. ER-L (Effects Range-Low) and ER-M (Effects Range-Medium) concentrations for total DDTs.

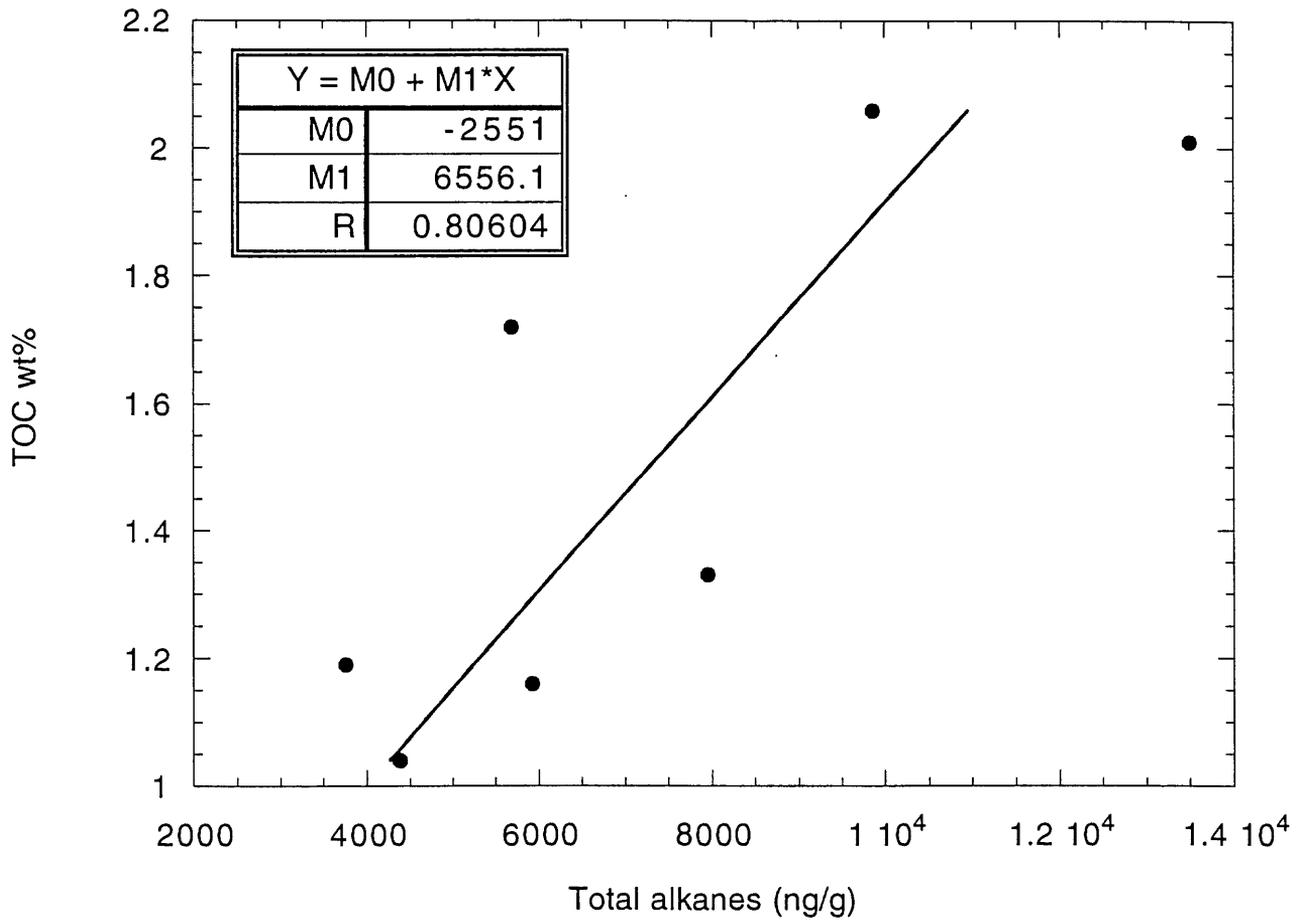


Fig. 13. Relation between total organic carbon (TOC) and total alkanes in benthic sediments of tidal marsh channels in the marshlands adjacent to the SBWDP site

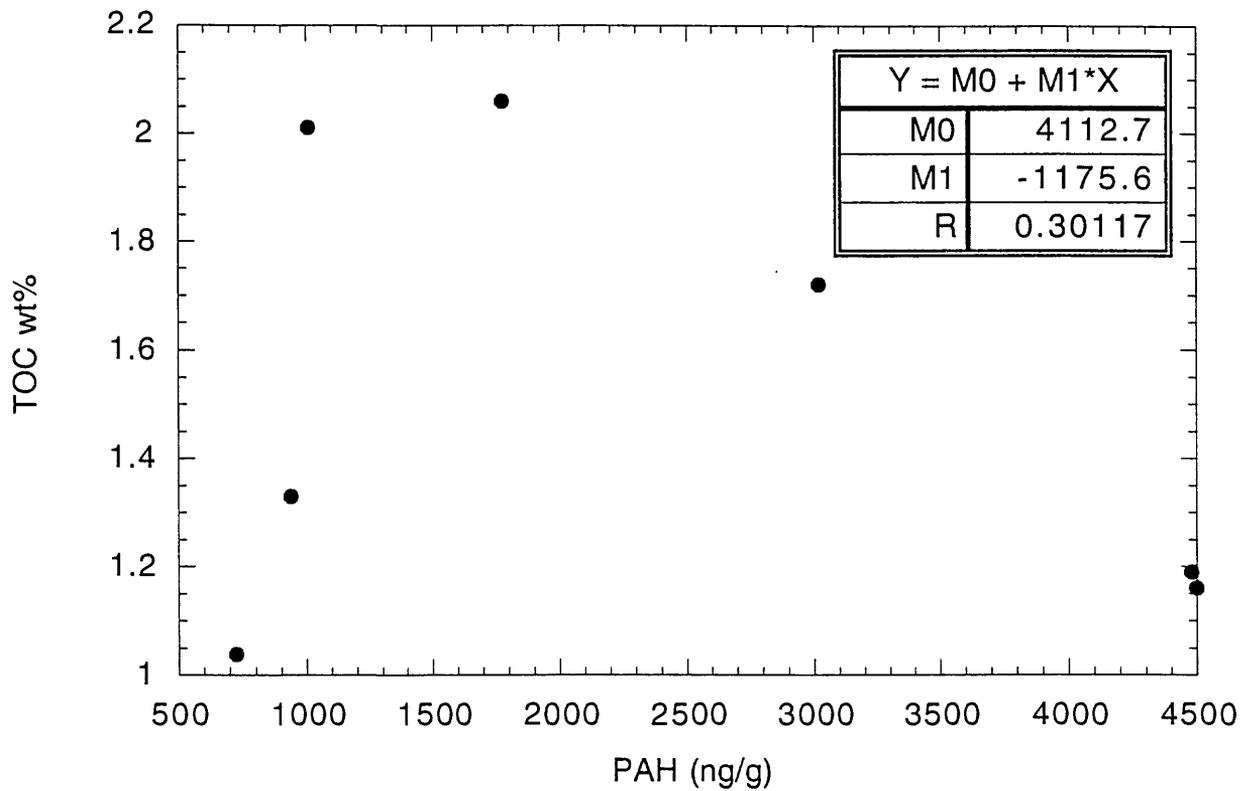


Fig. 14. Relation between total organic carbon (TOC) and total PAHs in benthic sediments of tidal marsh channels in the marshlands adjacent to the SBWDP site

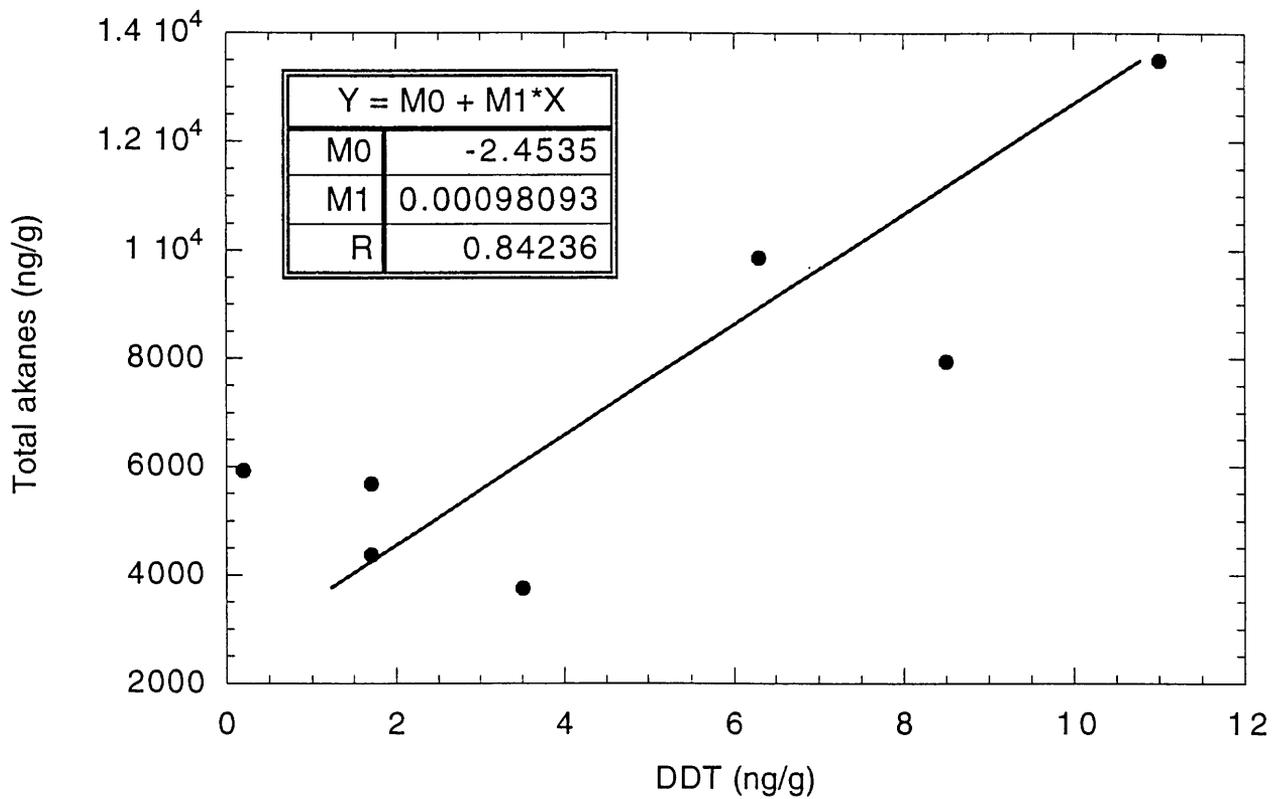


Fig. 15. Relation between total alkanes and total DDTs in benthic sediments of tidal marsh channels in the marshlands adjacent to the SBWDP site

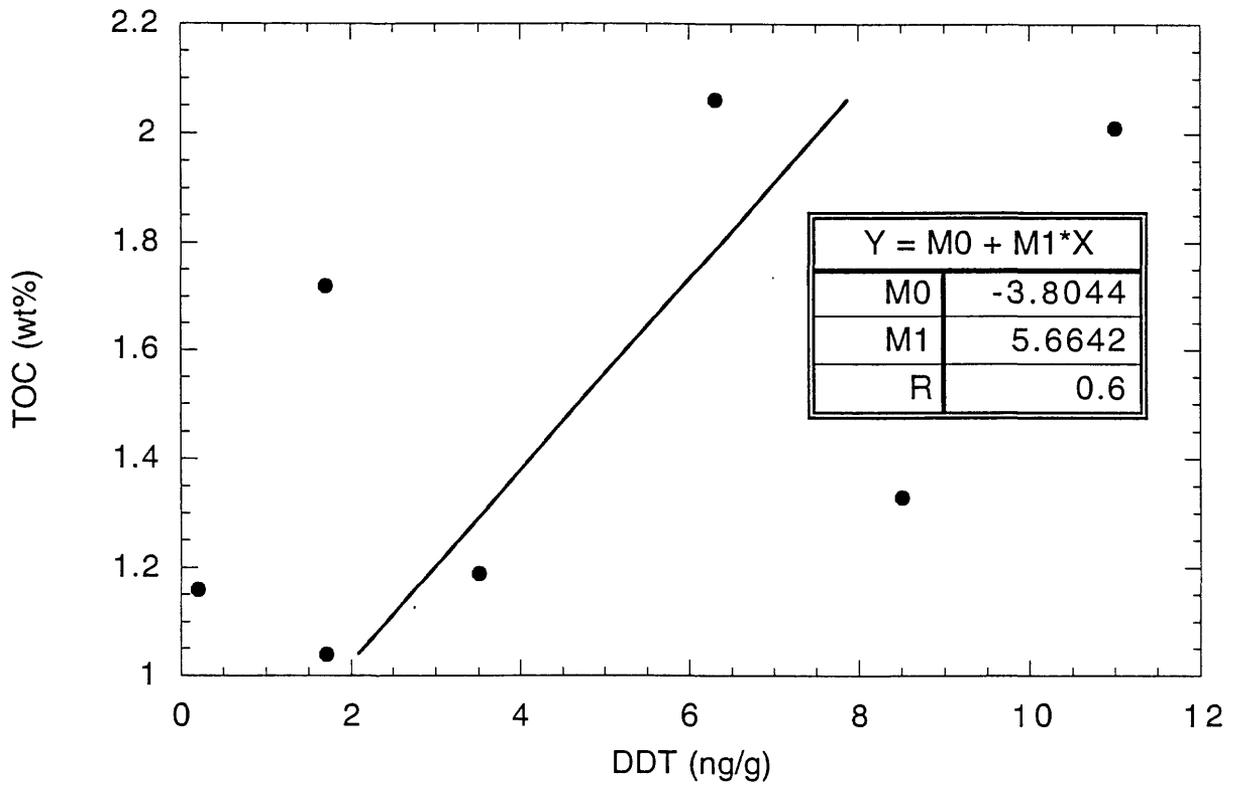


Fig. 16. Relation between total organic carbon (TOC) and total DDTs in benthic sediments of tidal marsh channels in the marshlands adjacent to the SBWDP site of tidal marsh channels in the marshlands