Regional Studies in Marine Science 4 (2016) 34–46

SCCWRP #0890

Contents lists available at ScienceDirect

Regional Studies in Marine Science

journal homepage: www.elsevier.com/locate/rsma

Southern California Bight regional monitoring

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HIGHLIGHTS

- Expansive urbanization puts the SCB's coastal sediment quality at risk.
- Regional monitoring provides a holistic view of the SCB's sediment quality.
- Sediment quality in the SCB is largely in good condition.
- The habitats with the most impacted sediment quality are estuaries and marinas.
- Even the habitats with most impacted sediment quality are improving with time.

ARTICLE INFO

Article history:
Received 14 March 2015
Received in revised form
17 September 2015
Accepted 17 September 2015
Available online 1 October 2015

Keywords:
Regional monitoring
Southern California
Sediment quality
Sediment chemistry
Sediment toxicity
Infauna

ABSTRACT

The Southern California Bight (SCB) is a unique ecological and economic resource, home to some of the most productive coastal ecosystems, but also some of largest pollutant inputs in the United States. Historically, environmental monitoring of the coastal environment has been temporally intensive, but spatially focused on narrow areas closest to regulated discharges, providing a potentially biased perspective of overall coastal sediment quality. Beginning in 1994 and conducted approximately every five years thereafter, nearly 100 regulated, regulatory, non-governmental or academic organizations join forces to implement the SCB Regional Marine Monitoring Program (the Bight Program). The most recent Bight program sampled nearly 400 locations, from the head of tide in coastal estuaries to offshore basins 1000 m in depth, using a probabilistic survey design and measuring multiple indicators of sediment quality including chemistry, toxicity, and infauna. The three indicators were scored using regionally-developed assessment tools, and then combined for an integrated assessment of sediment quality. Results showed that the vast majority of SCB sediments do not have impacted sediment quality, but that not all habitats are in equally good condition. Most of the continental shelf is not impacted, despite the discharge of very large volumes (10^9 L/day) of treated wastewater discharges. In contrast, up to 50% of the area in estuaries and 45% of the area in marinas have impacted sediment quality. These generally quiescent waterbodies receive pollutant inputs from the region's extensively urbanized watersheds and high density of boating activities. Despite the relatively large extent of impacted sediment quality in embayments, sediment quality has been steadily improving in this habitat over the last decade based on surveys dating back to the 1998. The Bight Program has affected management actions in the region by focusing current efforts in habitats most impacted by poor sediment quality, and highlighting the improvements from previous management actions.

1. Introduction

The Southern California Bight (SCB) coastal environment is a unique ecological resource. Extending more than 600 km from Point Conception (USA) to Punta Banda (Mexico), the SCB is a dynamic region where the cold, southward-flowing California Current mixes with the warm, northward-flowing Davidson Countercurrent (Hickey, 1993). Highly productive reefs with the giant kelp *Macrocystis*, estuaries that provide fish nurseries and overwintering stops for birds along the Pacific Flyway, and over one dozen threatened or endangered marine mammals and birds can all be found in the SCB (Dailey et al., 1993). More than 350 fish and 5000 invertebrate species are endemic to the SCB, approximately 80% of which are at the range limits of their distribution (see Fig. 1).

The SCB is also a unique economic resource. Renowned for its beaches, the SCB hosts approximately 175 million beach visits annually, more than Florida, Hawaii, and New Jersey combined (Schiff et al., 2003). The five coastal counties in the SCB generated an estimated $22B/year in gross revenue and over 800,000 jobs

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http://dx.doi.org/10.1016/j.rsma.2015.09.003

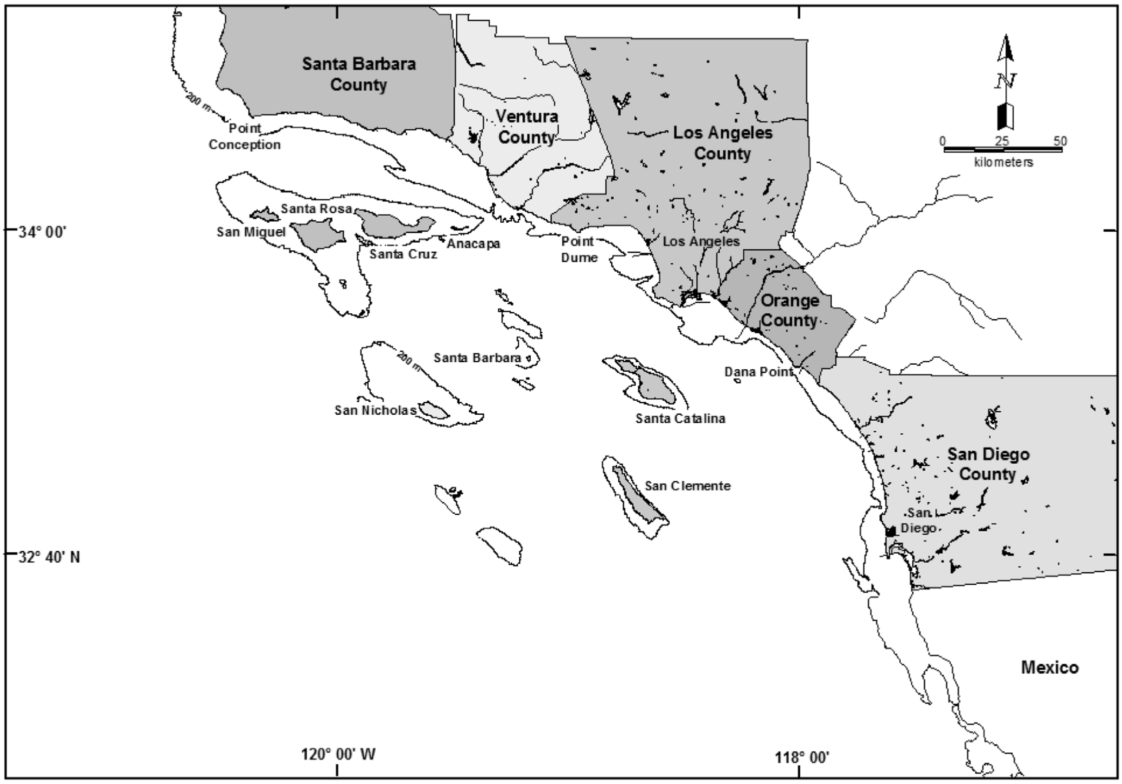

Fig. 1. Map of the Southern California Bight, which extends from Point Conception, California, to Punta Banda, Mexico, including the nine Channel Islands.

from ocean-related tourism and leisure activities in 2008 (Kildow et al., 2009).

The intersection of biodiversity and economics means that the SCB is a coastal ecosystem at risk from anthropogenic influences. More than 20 million people live within an hour's drive of the SCB coast. It is home to the two largest commercial ports (Los Angeles and Long Beach), the third largest naval facility (San Diego) in the US, and the world's largest manmade small-craft harbor (Marina del Rey). There are 17 wastewater treatment plants that discharge a cumulative 1.5B L/day of treated effluent to the ocean. While precipitation is relatively infrequent in the SCB (averaging 12 storms that total 30 cm per year), it is frequently intense with stormwater flows routinely increasing orders of magnitude in less than an hour (Schiff and Tiefenthaler, 2011). In total, there are 17 major watersheds that discharge largely untreated surface runoff from urban and agricultural land uses to the ocean.

Despite its enormous value and the potential risk, historical monitoring of the SCB did not provide a holistic view of impacts to the coastal environment. An estimated $32 M/yr was spent on routine monitoring of the SCB in 2003, with 75% allocated towards regulated discharges (Schiff et al., 2002). Combining monitoring data from individual programs presented enormous challenges, including differences in monitoring designs, sampling and laboratory methods, quality assurance and quality control (QA/QC), and data storage and management. Ultimately, even if all of these challenges could be overcome, most of the monitoring occurred near regulated discharges representing roughly 5% of the SCB area, potentially biasing the perspective of the SCB's overall condition.

The Southern California Bight Regional Marine Monitoring (Bight) Program was born from the frustration of environmental managers' inability to answer simple, holistic questions about the SCB coastal environment (NRC, 1990). Initiated in 1994, the Bight Program has grown both in size and scope with each successive survey, which has been conducted about every five years (1998, 2003, 2008, 2013). Originated by 12 agencies and limited to examining only the SCB continental shelf, the Bight Program has grown to approximately 100 agencies sampling at sites ranging from the head of tide in estuaries to the deepest nearshore ocean basins, at 1000 m. Moreover, the number of indicators used in the Bight Program has grown. An initial focus on sediment monitoring has now grown to include physical oceanography, eutrophication, seafood contamination, overfishing, beach water quality, and plastic pollution.

The goal of this paper is to describe the sediment contamination element of the Bight Program by addressing three key questions:

(1) What is the extent and magnitude of sediment contamination impact in the SCB?
(2) How has the extent and magnitude of sediment contamination changed over the last decade?
(3) How has the regional monitoring for sediment contamination program affected management actions?

An additional goal was to discuss the keys to success and future challenges faced by the Bight Program in attempting to answer these three questions.

2. Methods

There are three essential study design elements that comprise the Bight Survey for this paper. The first study design element is a focus on sediment quality. Therefore, we focus this paper on sediment associated indicators and assessment tools including sediment chemistry, sediment toxicity, and benthic infauna. The second design element is a probability-based design that enables unbiased estimates of average condition (i.e., mean sediment concentration) or areal extent (i.e., % of area). The third design element is implementing the Bight Survey through an integrated network of collaborating agencies. Therefore, this paper addresses the requirements for communication, training, quality assurance, and consensus-building.

Table 1
Sediment sampling inventory from Southern California Bight Marine Monitoring Program (2008).

Habitat	Stratum (depth range)	Area (km^2)	Area (%)	Number of sediment stations per indicator			
				Infauna	Chemistry	Toxicity[a]	All three indicators
Estuaries	Estuaries	11.9	0.1	64	64	64	64
Enclosed bays	Marinas	17.5	0.1	44	44	44	44
	Ports	29.3	0.2	46	46	46	46
	Bays	70.0	0.4	38	38	38	38
Mainland continental shelf	Inner shelf (5–30 m)	1171	7.0	30	30	10	10
	Mid shelf (31–120 m)	2019	12.0	30	30	10	10
	Outer shelf (121–200 m)	605	3.6	30	30	10	10
Island continental shelf	Channel Islands shelf (5–200 m)	2193	13.1	30	0	0	0
Continental slope and basins	Upper slope (201–500 m)	3130	18.7	35	0	0	0
	Lower slope and basins (501–1000 m)	7535	44.9	35	0	0	0
Total		16,782	100	382	352	222	222

[a] Estuaries and enclosed bays tested with two species, remaining sites only one species. See text for details.

2.1. Sample frame and sampling methods

The probability-based monitoring design used in the Bight Program was adapted from the US EPA's Environmental Monitoring and Assessment Program (EMAP; Bergen, 1996; Stevens, 1997). Briefly, the sampling design randomly allocates sample sites across a hexagonal grid overlaid across the sample frame to prevent clumping of sites. The sample frame, which extends from Point Conception (north of Santa Barbara) to the US–Mexico International Border, nests five habitats (estuaries, bays, mainland continental shelf, island continental shelf, and slopes and basins), which are in turn separated into ten sampling strata based largely on a combination of biogeography (Thompson et al., 1993) and management units of concern (Table 1). The most recent complete data set was collected in 2008. This survey collected samples at a total of 382 sites, with all three indicators of sediment quality measured at a subset of 192 sites. These sites spanned all four embayment strata, plus all three continental shelf strata.

Sediment samples were collected using a 0.1 m^2 modified Van Veen grab sampler (Stubbs et al., 1987). Sediment samples for chemistry and toxicity were taken from the top 2 cm in coastal shelf, slope and basin strata, or the top 5 cm from embayment strata (Bight'08 Field and Logistics Committee, 2008). Whole Van Veen grabs, with penetration of at least 5 cm, were sieved through a 1-mm mesh screen for benthic infaunal analysis. Material retained on the screen was placed in a $MgSO_4$ or propylene phenoxytol relaxant solution for 30 min before preservation in 10% buffered formalin. After a minimum of 3 days in formalin, samples were then transferred to 70% ethanol.

2.2. Laboratory methods

The target chemical constituents for the Bight Program included grain size (sediment fines), total organic carbon (TOC), total nitrogen (TN), 11 metals (Al, As, Cd, Cr, Cu, Fe, Ni, Pb, Ag, Se, Zn), polychlorinated biphenyl (PCB) congeners, polycyclic aromatic hydrocarbons (PAH), chlorinated hydrocarbons (DDTs, PCBs, chlordanes), polybrominated diphenyl ether (PBDE) congeners, and pyrethroid pesticides (Table SI-1). Because six laboratories participated in the Bight'08 survey, a performance-based approach to quality assurance (QA) and comparability was instituted. Performance-based QA allows each lab to use its own instrumentation and techniques, but mandates strict adherence to sensitivity (detection limits), precision (duplicate samples to assess consistency within laboratory analysis), accuracy (certified reference materials and spiked samples), and comparability (split samples among laboratories). A list of these data quality objectives (DQOs) can be found in Table SI-2 or Bight'08 Coastal Ecology Committee (2008).

Two different tests were used for sediment toxicity analysis. The first was the amphipod, *Eohaustorius estuarius* (EE), 10-day survival test (US EPA, 1994; ASTM, 2010) to assess whole sediment toxicity at 222 stations, including both continental shelf and embayment strata. The second test was the mussel, *Mytilus galloprovincialis* (MG), embryo sediment–water interface test (US EPA, 1995; Anderson et al., 1996) conducted on a subset of 192 stations located exclusively in embayment strata.

Full details of testing methods can be found in Greenstein et al. (2013). Briefly, 20 amphipods were randomly added to each of 5 replicate 1 L beakers containing 5 cm of sediment and approximately 800 ml of 32 psu overlying water. The exposure period was 10 days at 15 °C under constant light with gentle aeration. At the end of the exposure period, sediment was passed through a 0.5 mm mesh sieve and the surviving animals were enumerated. An acceptable test needed to have mean survival in the control of 90% or greater, and control between replicate coefficient of variation 11.9% or less.

The MG test was conducted in 600 ml glass beakers with a sediment depth of 5 cm and approximately 300 ml of 32 psu overlying water. A polycarbonate tube with 25–30 μm mesh polyethylene screen was placed in the beaker such that the screen was just above the sediment surface. Approximately 250 fertilized MG eggs were added to the tube and given 48 h to develop. The exposure was conducted at 15 °C with a 16 h light: 8 h dark cycle. At the end of the exposure, the screen tubes were removed and the embryos rinsed into another container for preservation with formaldehyde. The embryos were examined microscopically and the number of normally and abnormally developed were recorded. The number of normally developed embryos was divided by the initial number added to determine the endpoint of percent normal-alive (PNA). An acceptable test needed to have a PNA in the control of 70% or greater.

Toxicity identification evaluations (TIE) were performed on selected stations that were found to be highly toxic to the amphipod test. The TIEs were performed on both whole sediment and pore water. The whole sediment TIEs were performed with the amphipod survival test using methods similar to those described above, except that the tests were performed in 250 ml beakers with 50 ml of sediment and 200 ml of overlying water with 10 animals per replicate. Pore water was extracted from the sediment by centrifugation at 3000 × g for 30 min. The amphipods were then exposed to the pore water TIE treatments in 20 ml glass vials with 10 ml of water for 10 days. Each vial contained 5 amphipods. Details of the treatments used and their expected effect on the toxicity of the samples can be found in Table SI-3.

Benthic infaunal organisms were sorted from the sample material and identified to the lowest possible taxonomic level, most often the species level. At a minimum, a random 10% aliquot of each sample was re-sorted by a second sorter. Samples sorted at less than 95% efficiency (i.e., >5% of the total number of target organisms were missed) were re-sorted as a corrective measure. A random 10% of all infaunal samples identified were re-identified and enumerated by an independent party without any knowledge of the original identities. Samples were expected to meet 90% concurrence with regard to taxonomic identity, taxonomic level (e.g., identified to genus vs. species levels), and number of individuals per taxon. If there were any systemic discrepancies by a given taxonomist, corrections to all samples associated with that taxonomist would be made via re-identification or re-enumeration, depending upon the nature of the discrepancy.

2.3. Data analysis

The sediment chemistry data from Bight '08 were analyzed to determine descriptive statistics of sediment contamination and to assess the extent and magnitude of sediment contamination. Descriptive statistics focused on two types of analyses: (1) distributions and central tendencies of parameter values including the area-weighted mean and confidence interval for each of the strata of interest and the SCB as a whole; and (2) geographical distributions including thematic maps of sediment concentrations by parameter.

Assessment of extent and magnitude focused on three types of analyses: (1) estimating the proportion of contaminant mass for each constituent relative to the amount of area occupied for individual strata; (2) comparison of sediment concentrations to sediment quality thresholds; and (3) comparison of sediment contamination extent to results from previous surveys. The threshold of choice was the newly promulgated sediment quality objectives by the State of California (SWRCB, 2012).

The area-weighted mean for each stratum was calculated using a ratio estimator approach following Thompson (1992):

$$m = \frac{\sum_{i=1}^{n}(p_i * w_i)}{\sum_{i=1}^{n} w_i}$$

m = Area-weighted mean concentration for population j
p_i = Parameter value (e.g., concentration) at station i
w_i = Area weight for station i
n = Number of stations in population j.

The ratio estimator was used in lieu of a stratified mean because an unknown portion of each stratum can never be sampled (e.g., hard bottom). As a result, the estimated area, a random variable, is used in the denominator rather than the unknown true area. The standard error of the mean is calculated using the following equation:

$$\text{Standard Error} = \sqrt{\frac{\sum_{i=1}^{n}((p_i - m) * w_i)^2}{\left(\sum_{i=1}^{n} w_i\right)^2}}.$$

The 95% confidence intervals about the mean were calculated as 1.96 times the standard error. Use of the ratio estimator for the standard error approximates joint inclusion probabilities among samples and assumes a negligible spatial covariance, an assumption that appears to be valid based upon examination of the data. The assumption is conservative, in that its violation would lead to overestimation of the confidence intervals (Stevens and Kincaid, 1997).

California recently promulgated sediment quality objectives (SQO) for bays and estuaries of the state (SWRCB, 2012, Bay and Weisberg, 2012). These objectives require three lines of evidence for evaluation; benthic infauna, sediment toxicity, and sediment chemistry. For each line of evidence, an assessment of condition is made, then the three lines of evidence are combined for a final site assessment. California's SQOs, first for the individual lines of evidence and then for the integrated multiple lines of evidence, were used as thresholds for estimating areal extent.

Sediment chemistry: Concentrations for constituents were combined into a single index scaled from one to four. The four thresholds increase in chemical exposure that may lead to biological effects as follows:

- **Minimal exposure**: Sediment-associated contamination may be present, but exposure is unlikely to result in effects.
- **Low exposure**: Small increase in contaminant exposure; may be associated with increased effects, but magnitude or frequency of occurrence of biological impacts is low.
- **Moderate exposure**: Clear evidence of sediment contaminant exposure at concentrations that are likely to result in biological effects.
- **High exposure**: Contaminant exposure is highly likely to result in substantial biological effects.

The subset of analytes specific to the SQO framework are listed in Table SI-2. The threshold for determining if a site is too contaminated lies between low and moderate exposure.

Sediment toxicity: The two sediment toxicity tests were individually scored on a scale of one to four, then combined into a single score. The four thresholds increase in toxicological response as follows:

- **Nontoxic**: Response not substantially different from that expected in sediments that are uncontaminated and have optimum characteristics for the test species (e.g. control sediments).
- **Low toxicity**: A response of relatively low magnitude; the response may not be greater than test variability.
- **Moderate toxicity**: High confidence that a statistically significant toxic effect is present.
- **High toxicity**: High confidence that a toxic effect is present and the magnitude of response includes the strongest effects observed for the test method.

The threshold between toxic and non-toxic samples was between the low toxicity and moderate toxicity thresholds.

Benthic infauna: Macrobenthic community condition was assessed for samples collected from the continental shelf (10–200 m depth) and enclosed bay and estuary (i.e., estuaries, bays, ports, and marinas) habitats using the SQO benthic line of evidence (Ranasinghe et al., 2009) assessment tools. This assessment tool was developed to infer condition from community composition and classify a sample into one of four condition classes based upon community composition and difference from a reference community profile (Teixeira et al., 2010). The four thresholds increase in the disturbance of community condition as follows:

- **Reference**: Expected conditions for the habitat
- **Low disturbance**: Some indication of stress, but differences were within expected variability of reference profile
- **Moderate disturbance**: Clear evidence of exposure to stress; distinct differences from reference profile
- **High disturbance**: Evidence of exposure to high magnitude of stress; very different community from reference profile.

The threshold for disturbed benthic community condition lies between low and moderate disturbance.

Integrated assessment: The three indicators, with their categorical scores, were ultimately combined into a single score for each site (Bay and Weisberg, 2012). The five categories of sediment condition, with thresholds of increasing in level of impact, were as follows:

- **Likely unimpacted**
- **Possibly unimpacted**
- **Possibly impacted**
- **Likely impacted**
- **Clearly impacted**.

The "bright line" threshold for an impacted site lies between Possibly unimpacted and Possibly impacted.

The largest assumption using the SQO guidelines in this paper was its application to the continental shelf because the assessment guidelines were calibrated and validated for embayments. However, no other California-specific SQO assessment framework currently exists for the continental shelf. There three steps were taken to ensure comparability between scoring in embayment and continental shelf habitats: (1) the same chemical constituents in both shelf and embayment habitats were used for scoring exposure; (2) the same toxicity test was used for scoring toxicity on the shelf as in the embayments (*E. estuaries* 10-day test), and; (3) one of the four infaunal assessment tools used in embayments was also used for scoring benthic community condition on the shelf (the Benthic response Index or BRI). The BRI was chosen specifically because it was calibrated and validated to work in shelf habitats as well as embayments (Smith et al., 2001), whereas the other three infaunal assessment tools for the SQO framework were only calibrated and validated in embayments.

2.4. Governance

The Bight Program governance is structured around the Planning Committee. The Planning Committee is the focal point for deriving the monitoring questions, sanctioning the study design, and approval of all reports emanating from the Bight Program. As such, Planning Committee members are expected to represent their agency's needs and requirements, and are authorized to commit their agency's in-kind resources to the Bight Program. The Planning Committee is supported by a network of Technical Committees associated with primary indicators and activities including field sampling, chemistry, toxicity, infauna, and information management. Technical Committees are the focal point for data generation and quality assurance. As such, Technical Committee members are expected to represent their agency's laboratory and field programs, and are charged with creating field and laboratory manuals and standard operating procedures, and conducting training and interlaboratory calibrations. In addition, the Technical Committees are responsible for reviewing and approving data sets, and for writing drafts of their respective Technical Reports for Planning Committee approval. Finally, there is an Executive Advisory Committee, which provides advice and guidance to the various Planning Committees that oversee each element of the Bight Program. The Executive Advisory Committee is responsible for ensuring appropriate interpretation of, and guiding management reactions to, Bight findings. In addition, the Executive Advisory Committee is responsible for identifying linkages between the various Bight Planning Committees so interdisciplinary approaches to management can be taken. As such, Executive Advisory Committee members are expected to be high-level managers that oversee multiple programs within their agencies, and to create documents that synthesize Bight technical reports and findings into easy-to-read, easy-to-understand documents for the larger management community.

3. Results

3.1. Sediment chemistry

The Bight Program observed at least four distinct patterns in the geographic distribution and magnitude of sediment concentration, illustrating that not all sediment constituents come from the same source and that constituents may differ in their ultimate fate within the SCB. The first pattern, which represents the natural backdrop for all constituents, is a clear enrichment in fine-grained sediments (<64 μm) along the depth gradient from the shelf, through slope and basin strata (Table 2). Mean fine sediment content increased from 22% at the shallowest depth zone (inner Shelf) to a maximum of 90% for the lower slope & basin zone, with concomitant increases in both TOC and TN. Not surprisingly, average trace metal concentrations also increased along this depth gradient in proportion to the increase with sediment fines. A similar trend of increasing concentration with depth was observed for a subset of the trace organic constituents, including total PAH.

The second pattern of sediment concentrations is relative to offshore discharges from POTWs. The best example is the spatial distribution of total DDT, where maximum concentrations were greatest at Palos Verdes and Los Angeles Harbor, then declined moving northward through Santa Monica Bay and the Santa Barbara Channel in the net current direction (Hickey, 1993) (Fig. 2). Sediment concentrations to the south stayed uniformly low. This pattern is consistent with the large inputs of total DDT from the Montrose Chemical Corporation between 1950 and 1972 via the Los Angeles County Sanitation District's ocean outfall at Palos Verdes and the Dominguez Channel that discharges to inner Los Angeles Harbor (Lee et al., 2002). These are now US EPA Superfund sites, and planned clean-up of this contaminated sediment continues to this day.

The third spatial pattern of sediment concentration is relative to near-shore sources (Fig. 3). Although copper concentrations generally increased with depth offshore (the first pattern), the greatest concentrations of copper occurred in marinas (160 ± 45 μg/dry g) and ports (68 ± 12 μg/dry g), in close proximity to the SCB's bustling boating activity. This pattern is consistent with large inputs of copper from anti-fouling paints used on the bottom of recreational and commercial vessels (Maruya and Schiff, 2009). Copper, which acts as a biocide, may be added in large doses (up to 76%) to bottom paints specifically to retard the growth of algae and encrusting marine organisms (Schiff et al., 2004).

The fourth spatial pattern of sediment concentration relates to runoff from the region's developed watersheds. Good examples of this source include two constituents of emerging concern measured regionally for the first time in 2008, pyrethroid pesticides and PBDEs, both of which have been described in detail (Dodder et al., 2012; Lao et al., 2012). The greatest concentrations of both pyrethroids and PBDEs were observed in estuaries and marinas, with the highest concentrations of both constituents found at the mouths of the region's most urban estuaries. Pyrethroids are a current-use pesticide, unlike the legacy pesticide DDT that has been banned for more than four decades. An estimated 100 metric tons of pyrethroids pesticides (active ingredient) were reportedly used in the SCB's coastal counties the year prior to the Bight Survey (Lao et al., 2012). Meanwhile, PBDEs are a class of flame retardants in a number of products, including plastics, foams and textiles. The physical–chemical properties of PBDEs mimic PCBs, which was another class of industrial chemicals banned in 1976. Restrictions on use have been put in place for both PBDEs and pyrethroids.

Approximately 97% (standard error ±6%) of SCB sediments were found to have low to minimal exposure based on the SQO assessment framework (Fig. 4). Approximately 2% (±1%) of SCB sediments had moderate exposure to sediment chemistry. The remaining 0.2% (±0.07%) of SCB sediments had high exposure to sediment chemistry. The three most impacted strata were marinas, ports, and estuaries (74%, 47%, and 42% of area with unacceptable sediment chemistry, respectively). Least impacted were the continental shelf habitats, where only 2% of the area exhibited unacceptable condition based on sediment chemistry. Thus, because the continental shelf comprises the vast majority (97%) of the SCB, the SCB as a whole mimics the condition of this offshore stratum.

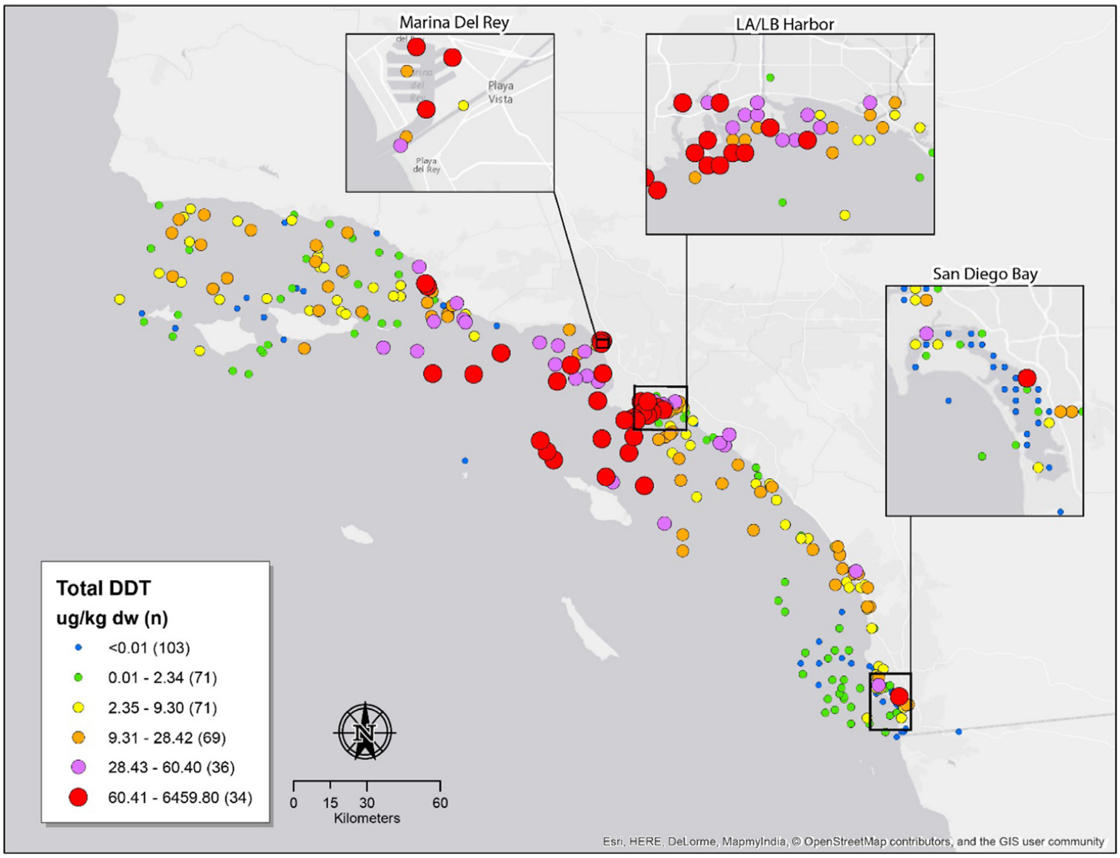

Fig. 2. Spatial distribution of total DDT sediment concentrations (µg/kg dry wt) during the Southern California Bight Regional Marine Monitoring Program (2008).

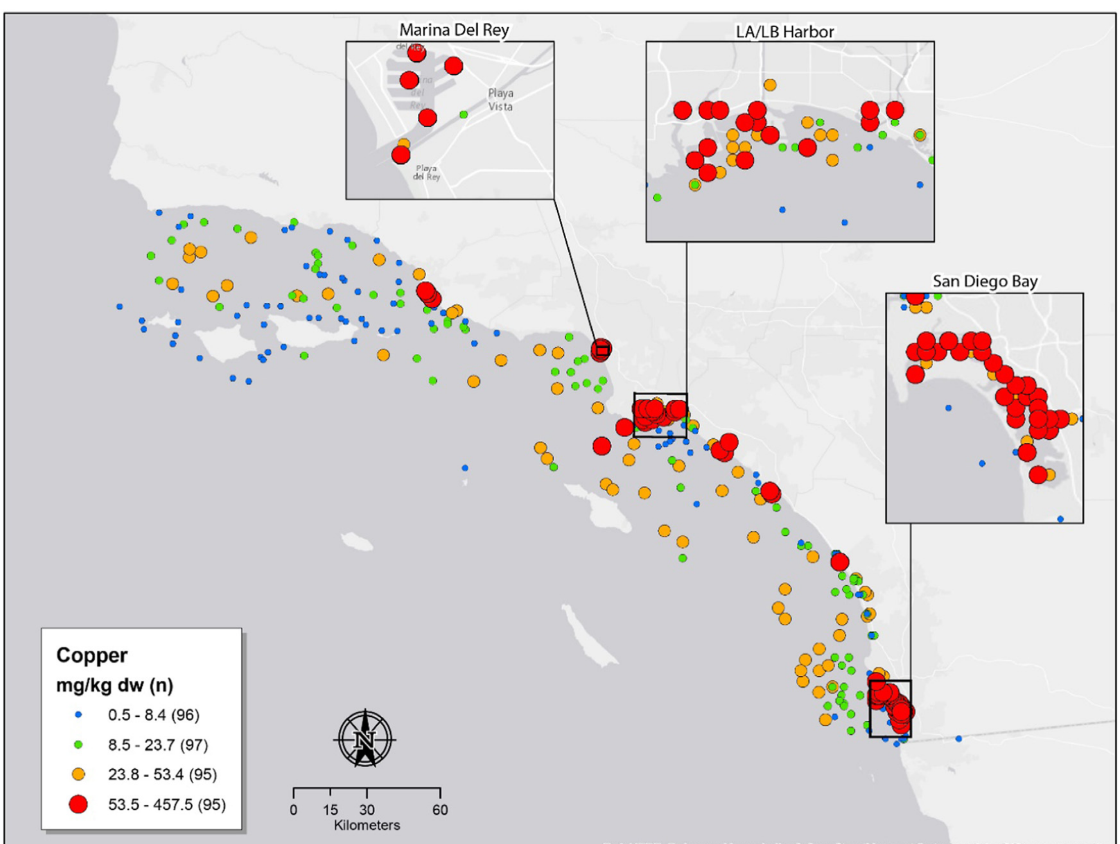

Fig. 3. Spatial distribution of copper concentrations (mg/kg dry wt) in sediment during the Southern California Bight Regional Marine Monitoring Program (2008).

Table 2
Area-weighted means and associated 95% confidence intervals (CIs) for sediment chemistry of the different habitat strata measured from the southern California Bight (2008). All units in dry weight.

Parameter	Shelf						Slope and basin			
	Inner (5–30 m)		Mid (30–120 m)		Outer (120–200 m)		Upper (200–500 m)		Lower (500–1000 m)	
	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
Fines (%)	22.2	6.6	46.8	6.9	60.0	6.5	81.3	5.5	90.4	3.0
TOC (%)	0.66	0.41	1.0	0.28	1.5	0.30	2.6	0.43	4.0	0.39
TN (%)	0.03	0.01	0.07	0.01	0.10	0.01	0.25	0.05	0.33	0.04
Aluminum (mg/kg)	5256	726	10 035	1512	11 473	2043	17 536	2231	20 760	1198
Antimony (mg/kg)	0.12	0.02	0.18	0.05	0.22	0.06	0.24	0.08	0.36	0.13
Arsenic (mg/kg)	4.3	1.2	6.1	2.2	6.1	1.3	8.8	1.2	7.3	1.1
Barium (mg/kg)	85	20	289	33	151	64	174	70	330	39
Beryllium (mg/kg)	0.12	0.02	0.30	0.09	0.19	0.08	0.29	0.13	0.39	0.11
Cadmium (mg/kg)	0.23	0.03	0.32	0.04	0.47	0.06	1.4	0.4	1.0	0.28
Chromium (mg/kg)	16	3.8	31	4.2	36	3.5	68	15	78	21
Copper (mg/kg)	4.4	0.83	10.7	1.7	12.3	2.6	22.8	3.5	34.5	3.3
Iron (mg/kg)	10 239	2233	20 724	4826	23 988	3196	33 427	2916	31 967	3378
Lead (mg/kg)	5.0	1.3	7.8	1.8	9.1	0.076	15	1.3	16	1.6
Mercury (mg/kg)	0.02	0.01	0.05	0.02	0.05	0.01	0.09	0.02	0.12	0.03
Nickel (mg/kg)	8.6	1.7	12	3.4	17	2.2	29	3.8	39	4.1
Selenium (mg/kg)	0.44	0.11	0.72	0.26	0.54	0.15	1.6	0.31	3.8	0.38
Silver (mg/kg)	0.12	0.06	0.24	0.12	0.25	0.14	0.29	0.16	1.9	0.29
Zinc (mg/kg)	25	6.8	46	7.9	52	4.9	79	8.8	96	4.3
Total DDT (μg/kg)	20	22	16	6.4	56	82	238	432	165	92
Total PCB (μg/kg)	10	2.1	13	3.3	19	8.2	36	31	11	3.5
Total PAH (μg/kg)	199	43	179	40	231	37	234	47	358	81
Total chlordanes (μg/kg)	0.48	0.13	0.61	0.18	0.62	0.28	2.6	3.3	2.1	0.84
Total pyrethroid pesticides (μg/kg)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Total PBDE (μg/kg)	0.22	0.15	2.2	0.83	2.0	2.0	4.3	5.1	4.9	2.8
Irgarol (μg/kg)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Parameter	Embayment area								Channel Islands (30–120 m)	
	Marinas		Estuaries		Ports		Bays			
	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
Fines (%)	78.1	7.8	60.6	3.1	69.9	5.5	61.3	5.0	28.1	6.0
TOC (%)	1.5	0.31	1.6	0.5	0.9	0.35	1.1	0.3	4.1	0.9
TN (%)	0.10	0.02	0.13	0.04	0.07	0.01	0.08	0.02	0.07	0.01
Aluminum (mg/kg)	20 831	2646	16 062	2168	17 835	1932	18 854	2168	5375	715
Antimony (mg/kg)	0.34	0.06	0.32	0.05	0.51	0.09	0.39	0.07	0.29	0.04
Arsenic (mg/kg)	9.7	1.2	6.1	1.5	9.8	1.3	8.0	1.4	3.0	0.28
Barium (mg/kg)	123	25	80	19	162	31	138	26	63	14
Beryllium (mg/kg)	0.53	0.12	0.24	0.08	0.44	0.12	0.36	0.18	0.01	0.00
Cadmium (mg/kg)	0.57	0.23	0.60	0.13	0.30	0.18	0.52	0.14	0.61	0.17
Chromium (mg/kg)	51	8.8	27	7.5	42	16	38	21	21	3.5
Copper (mg/kg)	160	45	34	10	68	12	48	7.3	5.4	0.85
Iron (mg/kg)	30 630	3568	22 363	4762	27 942	3456	26 822	3397	9693	1282
Lead (mg/kg)	51	29	20	8.2	27	9.0	28	9.4	3.2	0.49
Mercury (mg/kg)	0.51	0.19	0.05	0.008	0.23	0.13	0.18	0.10	0.02	0.003
Nickel (mg/kg)	23	4.1	16	3.4	22	5.6	17	3.8	10	1.4
Selenium (mg/kg)	0.60	0.21	0.45	0.14	0.37	0.10	1.63	0.86	0.37	0.12
Silver (mg/kg)	0.79	0.58	0.55	0.17	0.33	0.08	0.37	0.08	0.02	0.001
Zinc (mg/kg)	218	34	108	29	127	24	126	26	23	2.6
Total DDT (μg/kg)	45	19	33	34	49	20	22	11	4.6	1.6
Total PCB (μg/kg)	58	22	17	5.4	43	19	27	6.5	10.74	1.32
Total PAH (μg/kg)	1086	477	417	157	2549	1493	503	128	251	32
Total chlordanes (μg/kg)	4.8	3.4	3.2	1.8	1.1	0.15	1.6	0.63	0.29	0.09
Total pyrethroid pesticides (μg/kg)	20	18	22	26	0.23	0.18	2.8	3.3	NA	NA
Total PBDE (μg/kg)	52	41	57	38	31	38	19	4.5	NA	NA
Irgarol (μg/kg)	2.8	1.1	NA	NA	NA	NA	NA	NA	NA	NA

3.2. *Sediment toxicity*

Based on the SQO assessment framework, the overall extent of sediment toxicity in the SCB was quite low (Fig. 5). Seventy-seven percent of the shelf stratum was nontoxic and the remaining 23% indicated low (uncertain) toxicity. In contrast, 50% of the embayment strata had sediment in one of the toxic categories, the vast majority of which was in low (39%) as opposed to high toxicity (1.2%).

Within the embayment strata, the greatest degree of both extent and magnitude of sediment toxicity was in the Marina and Estuary strata (Fig. 5). High toxicity was observed in 7.8% of the Estuary and 4.6% of the Marina strata, while another 14% and 20% of the area was considered moderately toxic in each stratum, respectively. The Port and Bay strata had the least extent and magnitude of toxicity in embayments, with 6% and 9% of their area deemed moderately toxic, respectively. Neither the Port nor Bay strata observed high toxicity, although a majority of Bay stratum (51%) exhibited low toxicity.

Toxicity identification evaluations were successfully conducted on sediment and pore water samples from two of the most toxic stations. One was in the Ballona Creek Estuary, and the other in

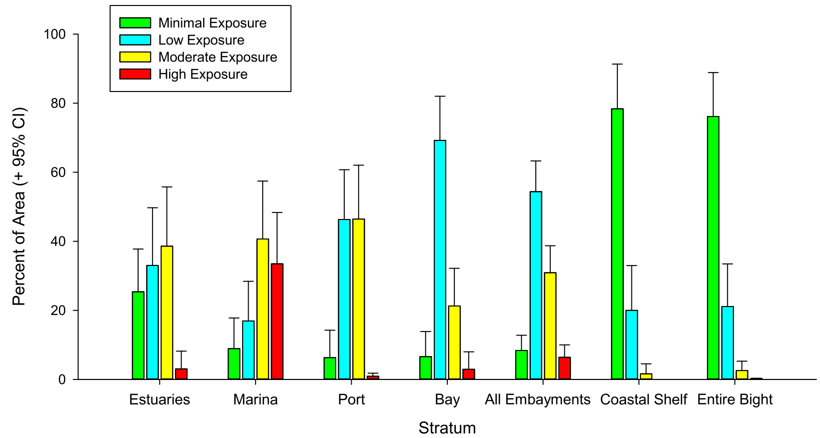

Fig. 4. Areal extent (±95% confidence interval) of sediment contaminant exposure by stratum. See text for categorical definitions.

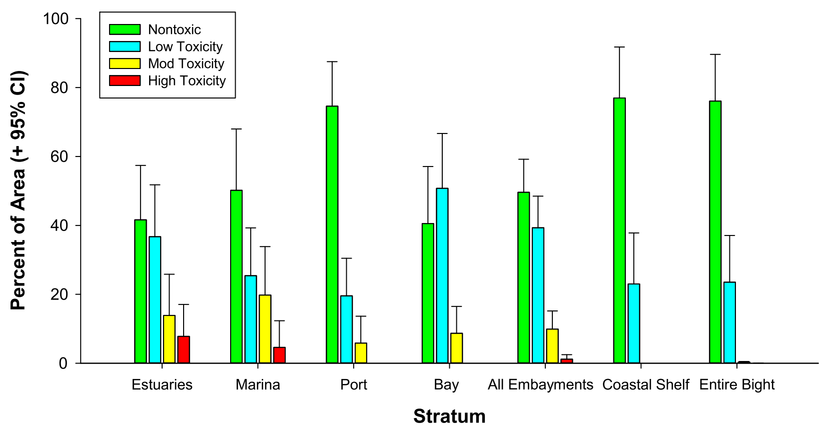

Fig. 5. Areal extent (±95% confidence interval) of sediment toxicity by stratum. See text for categorical definitions.

Mugu Lagoon. For the Ballona Creek sample, addition of coconut carbon greatly reduced toxicity in the sediment, while addition of piperonyl butoxide and reduction in test temperature increased toxicity in the pore water (Fig. 6, Figure SI-1). This combination is diagnostic of pyrethroid pesticide-induced toxicity. The Mugu Lagoon sediment TIE had a similar pattern for coconut carbon and PBO additions, but also had reduced toxicity associated with the dilution treatment (Fig. 6). In addition, none of the treatments were effective for the pore water. Due to the presence of elevated ammonia in the sediments, it was likely that a combination of ammonia and pyrethroid pesticides were responsible for the observed toxicity at Mugu Lagoon.

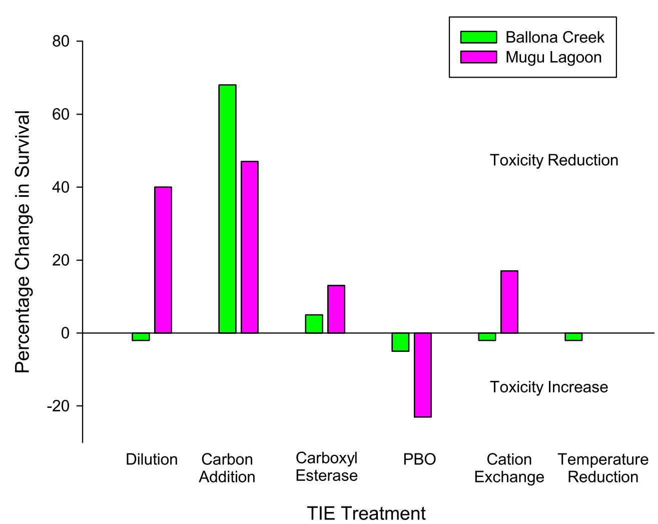

Fig. 6. Sediment toxicity identification evaluations (TIE) results at selected stations from the Bight Program.

3.3. Benthic infauna

Non-metric multidimensional scaling (nMDS) ordination of the benthic samples shows a clear biogeographic separation of the samples by embayment, continental shelf, and continental slope strata (Fig. 7). The community structure differences among the strata (Table SI-6) were likely related to differences in salinity variability, temperature, and depth/pressure (e.g., Kinne, 1964; Gray and Elliott, 2009). Samples from the embayments were characterized by the estuarine/coastal endemic taxa: aorid amphipods (*Amphideutopus oculatus*), bivalves (e.g., *Theora lubrica*), and a mix of capitellid (*Mediomastus* sp.), spionid (e.g., *Pseudopolydora paucibranchiata*) and lumbrinerid (*Scoletoma* spp.) polychaetes. The invasive mussel *Musculista senhousia* was also found in relatively high numbers and in a large percentage of embayment samples. Much like the embayments, samples from the continental shelf were typically composed of a mix of polychaetes, most commonly capitellids (*Mediomastus* sp.), spionids (e.g., *Spiophanes bombyx*, *S. duplex*, *Paraprionospio alata*), and maldanids (Euclymeninae spp.). In contrast, continental shelf samples were also dominated by amphiurid ophiuroids (*Amphiodia urtica* and *Amphiodia* sp.), as opposed to the crustaceans and bivalves found in the embayment strata. The samples from the continental slope were distinct from the embayment or continental shelf strata, with benthic communities characterized primarily by maldanid (*Maldane sarsi*), spi-

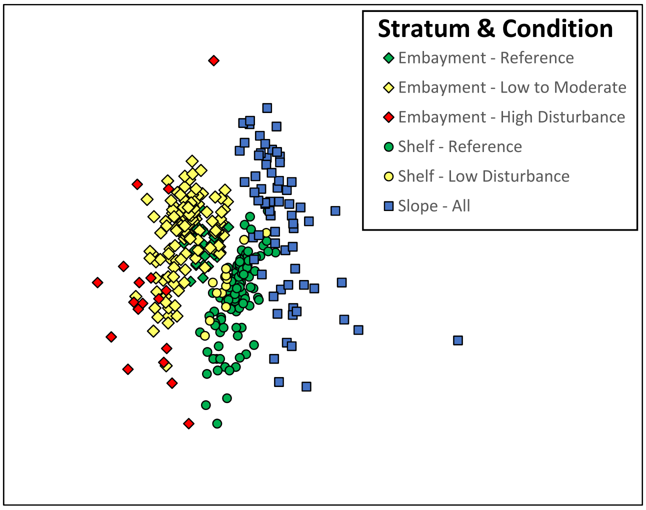

Fig. 7. Non-metric multidimensional scaling (nMDS) ordination of samples collected across three major strata of the Southern California Bight in 2008. Note the separation of samples first by stratum and secondly by the condition of the sample.

onid (*Prionospio* (*Prionospio*) *ehlersi*, *Paraprionospio alta*), and phyllodocid (*Nephtys cornuta*) polychaetes, followed by ampeliscid amphipods (*Ampelisca unsocalae*).

Closer inspection of nMDS analysis reveals a secondary separation of samples within stratum (Fig. 7, Table SI-6). This separation was attributed to condition class, which is assumed to be from sediment quality rather than natural gradients. The greatest separation occurred in the embayment stratum. Highly disturbed embayment samples were characterized by spionid (*Polydora nuchalis*) and capitellid (*Capitella capitata* Cmplx) polychaetes, aorid amphipods (*Grandidierella japonica*), and gastropods (*Acteocina inculta*); all taxa thought to indicative of excessive sediment organic matter. In contrast, the reference condition embayment samples were characterized by different capitellid (*Mediomastus* sp.) and spionid (e.g., *P. paucibranchiata*, *Spiophanes duplex*) polychaetes, as well as aorid (*A. oculatus*) and ampeliscid (*Ampelisca cristata cristata*) amphipods. Moderate and low disturbance samples comprised a mélange of characteristic organisms from the two infaunal community condition end members. Samples were still populated with *P. nuchalis* and *G. japonica*, but with increasing dominance of *P. paucibranchiata*, *Mediomastus* sp., syllid (*Exogone lourei*) and sabellid (*Fabricinuda limnicola*) polychaetes.

The SQO assessment framework indicated that the SCB benthic infaunal communities are generally healthy (Fig. 8). Approximately 80.9% of the SCB was in reference condition, with 18.7% assessed as low disturbance, 0.3% as moderately disturbed, and 0.1% highly disturbed. There were distinctly different amounts of disturbed habitat between the shelf strata offshore and the strata within embayments (ports, marinas, estuaries and bays). There was no amount of moderate or highly disturbed habitat observed on the shelf, while more than 58% of estuarine area and 40% of marina area were moderately or highly disturbed.

3.4. Multi-indicator assessment

Combining all three lines of evidence together – sediment chemistry, sediment toxicity, and benthic infauna – the status of sediment quality in the SCB is quite good (Fig. 9). Approximately 99% of the area in the SCB was either unimpacted or likely unimpacted. However, not all habitats in the SCB contained sediments in equally good condition. The vast majority of impacted sediment quality was located in embayment habitats (up to 25% of embayment area), while the sediment quality located offshore on the continental shelf habitat was judged to be 100% in good condition. Even within embayments, not all strata had similar sediment quality. Estuaries (51% of area) and Marinas (54% of area) had the greatest extent of impacted sediments of any embayment strata.

While the embayment stratum had the greatest extent of impacted sediment quality in 2008, sediment quality has been improving over the last decade (Fig. 10). In 1998, 55% of the embayment area was considered impacted. By 2003, the areal extent of impacted sediment quality in embayments was 43%. Impacted sediment quality finally dropped to 27% of embayment area in 2008. Overall, the areal extent of impacted embayment sediment was cut in half over the 10-year survey period.

Not only was there a reduction in the overall extent of sediment impact based on multiple indicators, but the magnitude of impact was also substantially reduced (Fig. 10). In 1998, 22% of the embayment area was considered either likely or clearly impacted. By 2003, the areal extent of this high magnitude impact in embayments was 7%. A similar extent of likely or clearly impacted sediment quality was observed in 2008. The areal extent of clearly or likely impacted sediment quality in the offshore continental shelf was much less than in embayments, but even this small area of impacted sediment quality has been decreasing over time. Approximately 5% of the continental shelf had impacted sediment quality in 1998, but that extent decreased to less than 1% in 2008.

4. Discussion

At regional scales, and by all measures, sediment quality in the SCB is largely in good condition. Based on results from the

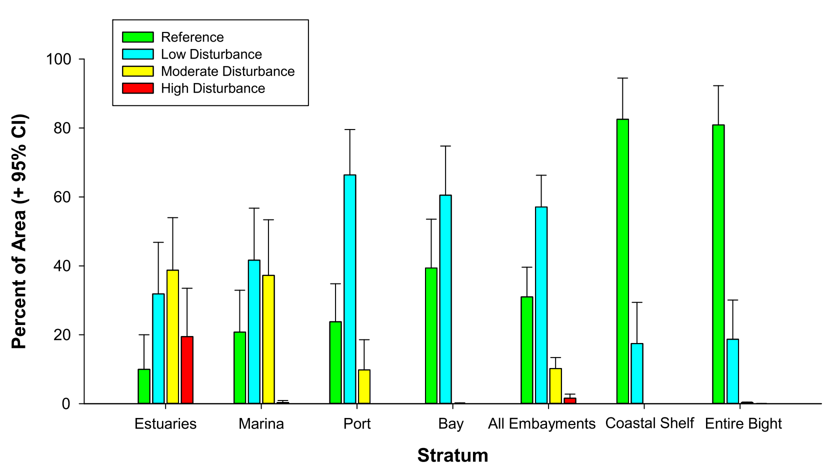

Fig. 8. Areal extent (±95% confidence interval) of infaunal community condition by stratum. See text for categorical definitions.

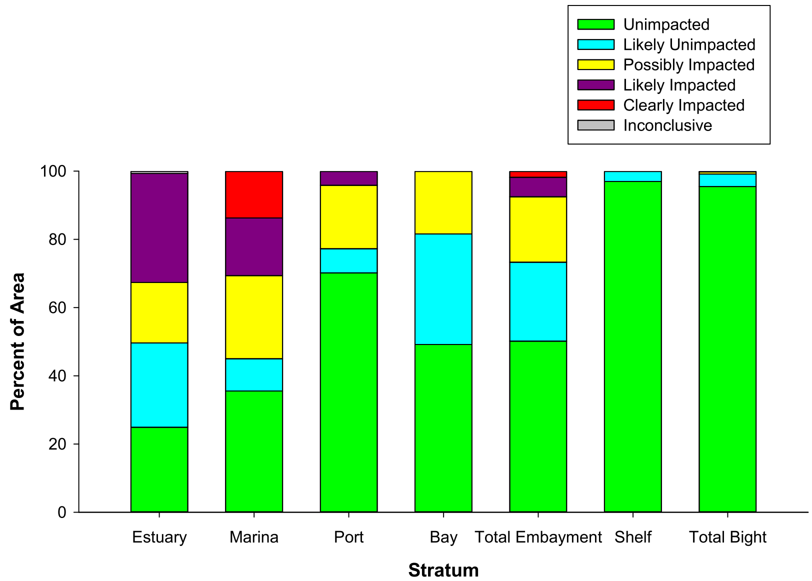

Fig. 9. Areal extent of sediment quality by stratum based on multiple lines of evidence from the Southern California Bight Regional Marine Monitoring Program (2008). See text for definition of impact categories.

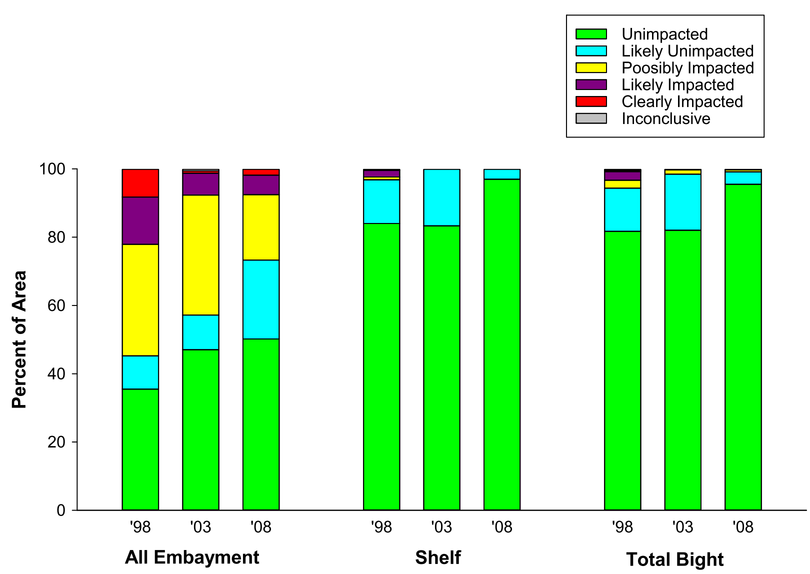

Fig. 10. Trends in areal extent of sediment quality by stratum based on multiple lines of evidence from the Southern California Bight Regional Marine Monitoring Program (1998, 2003, and 2008). See text for definition of impact categories.

Bight regional monitoring program in 2008, sediment quality is especially good in the offshore regions of the continental shelf. For environmental managers, this is particularly informative because the largest treated municipal wastewater outfalls discharge in this habitat. Increasing regulations since the early 1970s have led to increased treatment and source control, significantly decreasing pollutant loading from these sources (Schiff et al., 2001). There had been indications of locally improving sediment quality (Stein and Cadien, 2009), but the extent beyond these local sources due to pollutant fate and transport was not routinely known. For some legacy pollutants such as DDT, the Bight Program revealed that sediment chemistry was much more widespread than scientists previously thought, extending for over 100 km (Schiff, 2000). However, the Bight Program also revealed that sediment chemistry was not resulting in widespread toxicity or impacts to benthic infauna (Ranasinghe et al., 2010).

The habitat that had the most impacted sediment quality was embayments, where up to half of the areal extent in estuaries and marinas were impacted. Although it does not rain frequently in temperate southern California, the flood control systems are extremely efficient at moving runoff to the coast during the region's intense bursts of precipitation. While the reduction in flooding is an engineering marvel, the accumulated pollutants in the region's highly developed watersheds during the dry period are also efficiently discharged (Schiff et al., 2001; Tiefenthaler et al., 2008). Exacerbating the problem, storm and sanitary sewer systems are separate in southern California, meaning that watershed discharges are not treated prior to entering the region's estuaries.

Even for the most impacted strata, including estuaries and marinas, management towards improved sediment quality is progressing. Regulatory enforcement such as municipal separate storm sewer system (MS4) regulations and total maximum daily loads (TMDLs), may be responsible for the improving trends for these strata. Unlike wastewater regulations that started reducing pollutant loads in the 1970's, MS4 permits have struggled to make significant reductions in pollutant loads from runoff that started in the 1990's (Lyon and Stein, 2009). Although successful non-point source pollutant control measures have been observed in embayments, these management successes are typically focused on local, short-term water column indicators such as bacteria (Dorsey, 2010). The challenge is that sediment quality is impacted by cumulative source mixing and the longevity of pollutants in the environment. The Bight Program represents the first in Southern California to demonstrate regional, long-term successes in sediment quality for non-point source control management measures.

There are many keys to success of the Bight Program, but six stand out among the rest. The first key to success is the ability to answer holistic questions. This was a result of the probability-based monitoring design, which does not intentionally target the worst or the best locations in the SCB. As a result, this design provides an unbiased estimate of environmental condition (Stevens, 1997). This stands in contrast to previous assessments that were based on sediment quality monitoring data compiled from site-specific programs. For example, the US EPA tried to create a regional assessment based on data compiled from the major sediment monitoring programs across the SCB (US EPA, 2001), which was focused near large treated wastewater outfalls at that time. While local outfall monitoring is an important component of managing discharges from this source, the regional assessment from these data concluded that bight-wide sediment quality was similar to that found near treated wastewater outfalls. The State of California also implemented a regional sediment monitoring program, but it was focused on identifying toxic hotspots (Anderson et al., 2001; Fairey et al., 1998). While not inappropriate from a sediment clean-up perspective, the State-led approach once again led to a biased perspective of the SCB's overall sediment quality.

A second key to success of the Bight Program is the development of assessment tools. In this paper, we describe the SQO, which quantitatively computes sediment quality status, including thresholds of concern, based on a multiple-lines-of-evidence approach (Bay and Weisberg, 2012). This assessment tool has proven particularly valuable because it distills complex information into easy-to-understand and easy-to-communicate messages for environmental decision-makers, many of whom are not trained environmental scientists. In this case, independent assessment tools were necessary for all three indicators of sediment quality: sediment chemistry, sediment toxicity and infauna. All three indicators have strengths and weaknesses, which is why a final framework is required to combine them. Sediment chemistry does not account for bioavailability, sediment toxicity does not differentiate between toxicants, and infauna can respond to non-pollutant stressors (i.e., physical disturbance or salinity changes). In fact, it was partly because some of the independent assessment tools were developed as part of the Bight program, which ultimately led to the State of California adopting the multiple line of evidence framework as sediment quality objectives (SWRCB, 2012).

A third key to success of the Bight Program is communication and consensus-building. The Bight Program was deliberately conceived to facilitate an integrated, collaborative approach to regional marine monitoring, as opposed to giving a single agency responsibility for conducting all of the sampling, analysis and interpretation. As a result, dozens of agencies participate in each five-year cycle, including members of regulated, regulatory, academic, and non-governmental organizations. By design, each participating agency is responsible for a small piece of the monitoring activities; then, these pieces are compiled into the whole. For a collaboration like this to succeed, an overarching philosophy of joint ownership prevails. The communication that must occur – starting with what monitoring questions to answer and ending with collective interpretation of results – leads to collegiality and trust. This communication and trust-building among the various sectors that traditionally are at odds is key to reaching consensus. Finally, because there is consensus among scientists, environmental decision makers are more apt to take action.

The fourth key to success of the Bight Program is the sampling trade-offs from routine monitoring for agencies to participate in the survey. Very little of the monitoring effort for the Bight Program is paid for with cash; nearly all are in-kind contributions. Although the Bight Program calls for nearly 400 sample sites, no single agency is responsible for more than 40 sites, and most are responsible for less than 30. Based on a review of previous site-specific monitoring programs, managers recognized that there was some inefficiencies in sampling design (NRC, 1990, Schiff et al., 2001). Therefore, regulators provided monitoring tradeoffs to the regulated agencies by reducing sampling at a subset of sites, reducing frequency, or reducing replication. In exchange, the monitoring agencies re-invest the monitoring reductions from their site-specific programs into new sites associated with the regional survey, gaining more effective and valuable information for addressing new management questions.

The fifth key to success in the Bight Program is the investment in methods standardization to enable comparability of data among the different participating agencies. Because many of the participating agencies have their own sampling teams and laboratories (or their own contractor), there is a need to ensure comparability so interagency variability does not contribute to excess variability and/or skew results. Methods standardization in the Bight Program is accomplished through extensive training and performance-based quality assurance, and verified through independent audits and laboratory intercalibrations. For example, field teams attend pre-survey checkout cruises and get tested on the measurement protocols they conduct at sea (i.e., fish taxonomic identifications). Chemistry laboratories not only split certified reference materials to ensure accuracy, but also split native samples from locations within the SCB to ensure precision among agencies in real matrix samples. The toxicology laboratories use the same approach with reference toxicants and native split samples, culminating in a pre-survey round-robin exercise. Invertebrate taxonomists, meanwhile, trade not just voucher specimens, but 10% of all samples randomized within and among participating laboratories to ensure accuracy of taxonomic identifications. Some of these protocols have become quite rigorous (Gossett et al., 2003, Bay et al., 2003, Ranasinghe et al., 2003). Ultimately, scientists within the SCB have formed trade associations or local scientific societies to continue these quality assurance exercises between surveys (see www.SCAMIT.org, www.SCAITe.org, or www.SoCalSETAC.org as examples).

The sixth key to success of the Bight Program is technology testing and development. Because the Bight Program makes a myriad of base measurements, scientists use this opportunity to test new technology alongside existing technology. Moreover, the bightwide application enables new technology evaluation across a wide range of natural and anthropogenic variability. Good examples identified in this paper included the measurement of pyrethroids and sediment TIEs, both of which are non-routine and collectively indicated that these current-use pesticides may be contributing to the sediment toxicity observed in embayments. Perhaps the most important attribute of the technology testing during the Bight Program, however, is that it is not a regulatory requirement. This provides managers the opportunity to evaluate a new technology's utility and cost-effectiveness before the technology gets codified in an NPDES permit requirement that likely will not change for some time.

Despite the Bight Program's successes, it faces at least two major challenges into the future. The first is the speed at which results become available. Managers would no doubt like to see a return on their monitoring investment in a more expeditious fashion. Although results have been delivered more rapidly with each monitoring survey cycle, the Bight Program is a large undertaking that, when considering its collaborative nature and its emphasis on communication and consensus-building, can take up to three years to complete. For example, although sampling for Bight'13 was completed in September 2013, not all of the results were available by early 2015 for inclusion in this manuscript.

The second challenge facing the Bight Program is striking the proper balance between maintaining a base regional monitoring component to track trends over time, and expanding the program to answer new monitoring questions. The Bight Program, which has grown in size and scope with each consecutive regional survey starting in 1994, arguably has become a victim of its own success. The Bight Program now addresses 12 strata when it started with three, and has added dozens of new indicators since its inception. As more researchers find out about the Bight Program, there is an inclination to add new special studies evaluating emerging technology or transitioning this technology to routine monitoring programs. Although all of these synergies are highly desired, there is a limit to how much effort can be re-allocated since the Bight Program is ultimately powered by monitoring tradeoffs. Participating managers are now faced with the difficult decisions that involve weighing the need for trends detection to assess changes from the past (i.e., resampling previous sites) against pressing needs to answer new and important questions that address future challenges and uncertainty.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.rsma.2015.09.003.

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