Sediment quality in California bays and estuaries

Arthur M. Barnett, Steven M. Bay, Kerry J. Ritter, Shelly L. Moore and Stephen B. Weisberg

Abstract

Sediment quality in California bays and estuaries was evaluated using the multiple lines of evidence (MLOE) assessment framework proposed for use as part of the State Water Resources Control Board's new sediment quality objectives. Chemistry, toxicity, and benthic community data from 6 surveys conducted over 8 years were used to classify 381 sites into 6 condition categories: Unimpacted, Likely Unimpacted, Possibly Impacted, Likely Impacted, Clearly Impacted, and Inconclusive. Assessments were conducted at both a statewide level and for three regions: northern coastal embayments, southern coastal embayments, and San Francisco Bay. Approximately 83% of the 1295 km^2 of California marine embayments included in the analysis were classified as having some degree of impact related to sediment contamination. Most of the area was classified as Possibly Impacted and less than 1% of the area was classified as Clearly Impacted. Large variations in sediment condition were present among the three geographic regions. The North region had the best sediment conditions, with 58% of the area classified as Unimpacted and no sites classified as Clearly Impacted. Somewhat poorer sediment quality was observed in the South, with 43% of the area classified as Unimpacted and 2% classified as Clearly Impacted. A different distribution of sediment condition categories was present in San Francisco Bay; no sites were classified as Unimpacted and the proportion of area classified as Possibly Impacted (77%) was more than three times greater than that measured in the other regions. The large percentage of Possibly Impacted area within SFB suggests that sediment contaminants are more widespread and less concentrated in this region, possibly due to contaminant dilution and redistribution as a result of greater rainfall, high runoff inputs from urban and agricultural sources, and tidal mixing. The results of this study's integrated analysis using the SQO assessment framework produced a more comprehensive and robust assessment of statewide sediment quality than has been achieved previously. Moreover, this study's assessment of sediment conditions on both statewide and regional scales can be used as a benchmark for future studies.

Introduction

Sediment quality influences the overall condition of a water body. Sediments act as a reservoir for contaminants that can be transferred to the water column and are also a primary source of contaminant exposure for sediment-dwelling organisms. Sediment quality assessment has been an important feature of many California monitoring programs. It was a major focus in the Bay Protection and Toxic Cleanup Program (BPTCP; Anderson *et al*. 1997), the California Environmental Mapping and Assessment Program (EMAP; USEPA 2005), the San Francisco Regional Monitoring Program (SFEI 2003), and the Southern California Bight Regional Monitoring Program (SCCWRP 2003, 2007).

Sediment is a complex matrix of components. Consequently, evaluating sediment quality based on a single type of data (line of evidence) can be problematic. For example, bulk measures of chemical concentration fail to differentiate between the fraction of a contaminant that is tightly bound to sediment and that which is biologically available. Multiple modes of contaminant exposure, including uptake of chemicals from interstitial water, sediment ingestion, and bioaccumulation through the food web further complicate interpretation of sediment chemistry data. For these reasons, sediment quality assessment often involves simultaneously evaluating MLOEs that measure both contaminant exposure and effects on organisms: an approach commonly known as the sediment quality triad (Long and Chapman 1985). Sediment chemistry, toxicity, and benthic community condition are the lines of evidence (LOEs) often used. Most of the ambient sediment quality monitoring programs in this country rely on more than one line of evidence (USEPA 1998, Crane *et al*. 2000, MacDonald and Ingersoll 2002, USEPA 2004).

Such programs include the two largest nationwide estuarine monitoring programs: the United States Environmental Protection Agency (USEPA) EMAP and the National Oceanic and Atmospheric Administration (NOAA) National Status and Trends Program, as well as California's BPTCP (Anderson *et al*. 1997, Fairey *et al*. 1998, Phillips *et al*. 1998, Anderson *et al*. 2001, Hunt *et al*. 2001).

Comprehensive sediment quality information is needed for California's 305(b) and 303(d) programs to establish priorities for water quality management at the State and Regional Boards. However, previous statewide assessments of sediment condition in California have been limited in terms of data integration and interpretation. Results from a 1999 EMAP survey were used to describe the statewide extent of sediment contamination, toxicity, and benthic community characteristics, but these separate LOEs were not integrated to assess overall sediment condition (USEPA 2005). Recent 305(b) reports of California sediment quality have included data from multiple studies, but again the condition assessment was limited by a lack of integration of LOEs and the use of varying data interpretation approaches among studies (SWRCB 2006, USEPA 2004).

The State Water Resources Control Board (SWRCB) is in the process of adopting sediment quality objectives (SQOs) that use an assessment framework based on an MLOE approach to evaluate sediment quality in embayments (SWRCB 2008). These SQOs will become the regulatory standard against which ambient sediment quality is measured, influence management and regulatory decisions, and serve as the basis for evaluating water body impairment (e.g., 303(d) listings) with regard to sediment quality. This report represents the first application of the proposed assessment framework on a statewide basis to evaluate sediment quality in California's marine and estuarine embayments.

Two levels of assessment were conducted (Figure 1). The first level evaluated statewide conditions. The purpose of this level was to determine the percentages of the State's embayments with various levels of impact from sediment contamination. At the second level, spatial assessments were conducted independently for three regions within the state in order to investigate patterns related to differences in size of embayments, land use, and hydrological characteristics. The northern region (North) included multiple small coastal embayments north of Point Conception to the Oregon border. The North embayments were characterized by low population density, where agricultural use is important and freshwater inputs are relatively high. The southern region (South) included multiple small coastal embayments south of Point Conception to the US-Mexico border. These southern embayments had low freshwater inputs and were often surrounded by high population density and extensive commercial/industrial use. The third assessment region was the San Francisco Bay and its contiguous marine embayment areas (SFB). The hydrology of the SFB is different from the North and South in that runoff into SFB is nearly continuous, tidal mixing is strong, and agricultural and industrial uses are relatively high.

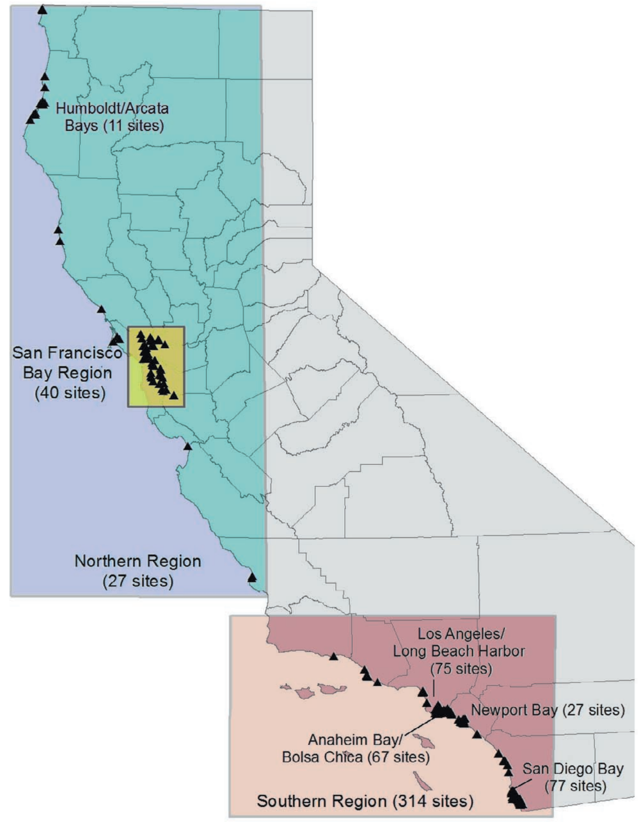

Figure 1. Distribution of sampling sites for the statewide assessment. The shaded boxes indicate the three regional assessment areas.

METHODS

The California SQO framework for assessing the direct effects of sediment contamination was applied to data from multiple random stratified surveys conducted throughout the state to evaluate the sediment quality of marine embayments at statewide and regional levels. The study design was not intended to provide a statistically robust assessment of individual water bodies, except for the San Francisco

Bay. The analysis consisted of three parts: 1) determining sediment condition at each sampling station (site) using MLOE response classifications or attributes of the assessment framework; 2) establishing a single statewide data set with known spatial attributes based on the integrated data for all stations within each survey; and 3) analyzing the integrated data set using spatial statistics to determine the percentage of area corresponding to each sediment condition category. Spatial analyses were conducted for the state as a whole and regionally for northern California (North), the San Francisco Bay (SFB), and southern California (South).

Data

The statewide and regional estimates of sediment condition were based on data collected from six stratified random surveys with probability-based designs, conducted over eight years. Probability-based designs were selected because the area represented by each site was known, allowing sampling results to be expressed as the percent area affected. In addition, each survey met the following criteria: i) samples were collected within 10 years of the current analysis; ii) site locations were subtidal areas within bays and estuaries; iii) corresponding data for sediment chemistry, toxicity, and benthic macrofauna were available; and iv) sampling and analysis methods were comparable to those specified in the proposed SQO assessment framework. These surveys followed the USEPA's Generalized Random Tessellation Stratified (GRTS) design with the intent of balancing samples spatially while allowing for intensification in certain areas of interest (http://www.epa.gov/nheerl/arm/designpages/design&analysis.htm). Sample collection for each survey was conducted in the summer and used comparable methods; however, the surveys encompassed different years and geographic regions. Two Western Environmental Monitoring and Assessment Program (WEMAP) surveys examined embayments along the entire California coast in 1999 and 2005, while one survey was limited to San Francisco Bay (2000). Three surveys included only southern California embayments: two examined multiple embayments along the entire southern coast (1998, 2003), while the third was an intensive study of Huntington Harbor and Anaheim Bay (2001).

Determination of Sediment Condition

Three lines of evidence, consisting of sediment chemistry, toxicity, and benthic macrofaunal community condition (benthos), were evaluated at each site. The indices and thresholds described in the draft water quality control plan for California bays and estuaries (SWRCB 2008) were then used to classify each LOE into one of four response-level categories: 1) no difference from background conditions, 2) a small response that might not be statistically distinguishable from background conditions, 3) a response that is clearly distinguishable from background, and 4) a large response indicative of extreme conditions. The LOE responses were then integrated using the assessment framework (Bay and Weisberg 2008) to determine the level of impact with respect to sediment contamination for each site.

Lines of Evidence

An average of two sediment chemistry indices was used to determine the magnitude of chemical exposure at each site: the California Logistic Regression Model (CA LRM) and the Chemical Score Indicator (CSI). The CA LRM was developed using a logistic regression modeling approach that estimates the probability of acute toxicity in sediments based on the chemical concentration (USEPA 2005) calibrated using California data (Bay *et al*. 2007a). The CSI was developed using California data and is based on the association of chemical concentration with benthic community disturbance (Ritter *et al*. 2007). Calculation of the CSI differed from Ritter *et al*. (2007) by not including data for cadmium in order to maintain consistency with the SWRCB draft policy. The response-level categories used to define chemical exposure were:

- Minimal Exposure - Sediment-associated contamination may be present, but exposure is unlikely to result in effects.
- Low Exposure - Small increase in contaminant exposure that 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 amphipod (*Eohaustorius estuarius*) 10-day survival test was used to determine the magnitude of sediment toxicity at each site (USEPA 1994). Thresholds based on percentage survival and statistical significance were used to classify the toxicity response level into one of the following categories (Bay *et al*. 2007b):

- Nontoxic - Response not substantially different from that in uncontaminated control sediments.
- Low Toxicity - A low magnitude response that differs from control survival, but is within the variability typical for that test and thus may not be a reproducible effect.
- 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.

A combination of up to four benthic community condition indices was used to determine the magnitude of disturbance to the benthos at each site (Ranasinghe *et al*. 2007): the Benthic Response Index (BRI), Index of Benthic Biotic Integrity (IBI), Relative Benthic Index (RBI), River Invertebrate Prediction and Classification System (RIVPACS). Not all indices were used in each region, due to the lack of calibration for some habitats. All four indices were used for most stations in the South (except that RIVPACS data were not available for the Huntington Harbor and Anaheim Bay survey) and portions of SFB. The RBI and IBI were used to evaluate the remainder of the SFB sites. The RBI was used to evaluate all of the North sites.

Thresholds specific to regional assemblages were applied to the results in order to classify each index result according to the level of disturbance. The median of index results was used to determine overall benthos response level. The four response-level categories used to define benthic condition assessments were:

- Reference - A community composition equivalent to a “least affected” or “unaffected” site.
- Low Disturbance - A community that shows some indication of stress, but could be within measurement error of unaffected condition.
- Moderate Disturbance - Confident that the community shows evidence of physical, chemical, natural, or anthropogenic stress.
- High Disturbance - Changes in the benthos are substantial enough to limit community function.

Integration of LOE Response Levels

The individual LOEs were integrated in a two-step process to determine the sediment condition at each site. First, the response level categories for each LOE were compared to address two key elements of a risk assessment paradigm: 1) Is there biological degradation at the site? and 2) Is chemical exposure at the site high enough to potentially result in an adverse biological response? The benthos and toxicity LOEs were integrated to determine the severity of effects (e.g., Unaffected, Low, Moderate, High). The chemistry and toxicity LOEs were integrated to determine the potential for chemically mediated biological effects (e.g., Minimal, Low, Moderate, High).

The final LOE integration step combined the severity of effect and potential for chemically mediated effects classifications to assign a site into one of six condition categories (Table 1):

- Unimpacted - Confident that contamination is not causing significantly adverse impacts to aquatic life in the sediment.
- Likely Unimpacted - Contamination is not expected to cause adverse impacts to aquatic life in the sediment, but some disagreement among LOEs reduces certainty that the site is unimpacted.
- Possibly Impacted - Contamination at the site may be causing adverse impacts to aquatic life in the sediment, but the level of impact is either small or is uncertain because of disagreement among LOEs.
- Likely Impacted - Evidence of contaminant related impacts to aquatic life in the sediment is persuasive, in spite of some disagreement among LOEs.
- Clearly Impacted - Sediment contamination at the site is causing clear and severe adverse impacts to aquatic life in the sediment.
- Inconclusive - Disagreement among LOEs suggests that either data are suspect or additional information is needed for classification.

Table 1. Relationship of intermediate LOE classifications to final MLOE site condition categories. Arrows indicate the sequence of classification.

Potential for Chemically Mediated Effects	Condition Category	Severity of Biological Effects
High Potential	Clearly Impacted	High Effect
High Potential	Clearly Impacted	Moderate Effect
High Potential	Likely Impacted	Low Effect
Moderate Potential	Likely Impacted	High Effect
Moderate Potential	Likely Impacted	Moderate Effect
Low Potential	Possibly Impacted	High Effect
Low Potential	Possibly Impacted	Moderate Effect
Moderate Potential	Possibly Impacted	Low Effect
Minimal Potential	Likely Unimpacted	Moderate Effect
Minimal Potential	Likely Unimpacted	Low Effect
Low Potential	Likely Unimpacted	Low Effect
Moderate Potential	Likely Unimpacted	Unaffected
Minimal Potential	Unimpacted	Unaffected
Low Potential	Unimpacted	Unaffected
High Potential	Inconclusive	Unaffected
Minimal Potential	Inconclusive	High Effect
Moderate Potential	Inconclusive [1]	Low Effect

[1] Inconclusive category results when High toxicity, Minimal chemical exposure, and a Reference benthic community are present.

Two central concepts were incorporated in the determination of the impact categories: i) both exposure and effect must be present in order to classify a site as impacted and ii) a greater magnitude of effect or exposure results in a more severe impact assessment category.

Determination of Percent Area for Each Site Condition Category

The six surveys used in this study varied in terms of level of stratification, sampling frame, and sampling density. Consequently, the area weights (proportional to the number of sites within a stratum) of individual sample points varied greatly between surveys. In order to conduct a statewide assessment that was spatially representative, the survey designs were combined to produce a common sampling frame and level of stratification. Three strata (regions) were established: North, SFB, and South. Within each region, the polygons representing survey-specific sampling frames and different sample densities were compared for each survey and a single set of polygons were drawn that included all of the combined area sampled. New area weights were calculated for the sites within each region by dividing the area of each final polygon by the number of sites within the area (Barnett *et al*. 2008).

Two years of survey data were combined for the North, consisting of samples analyzed as part of 1999 and 2005 surveys conducted by the WEMAP. No stratification was used for the data from the 2005 survey. As a result, we used the polygons from the 1999 survey and recalculated area weights based on the number of samples from both surveys falling within these polygons. For SFB, there was only one survey, WEMAP 2000, therefore no adjustment of polygons or area weights were needed. Data from five surveys were integrated for the South stratum. Polygons that overlapped among surveys were split into subpolygons that reflected disjoint areas. New area weights were calculated by dividing the area of each subpolygon by the number of samples that fell into that subpolygon, regardless of survey.

Estimates of the percent area representing various sediment condition classifications were calculated using the new area weights. The proportion of each region representing each MLOE condition category was calculated as the sum of the area weights of the samples that fell into that category divided by the sum of the area weights for all samples within the region. This proportion was then converted to a percentage. The area (km^2) represented by this percentage was calculated by multiplying the proportion by the total area of the region. Confidence intervals for these estimates were computed using the local variance estimator option in the EPA analysis tools (Stevens and Olsen 2003, http://www.epa.gov/nheerl/arm/designpages/design&analysis.htm).

Statewide estimates of condition were calculated in the same manner used for the regional estimates. The area weights of sites having the same MLOE sediment condition classification in all regions were summed and then divided by the sum of the area weights in all regions. This calculation was repeated for each MLOE site condition category. The statewide area corresponding to each MLOE condition category was calculated by multiplying the proportion by the total area of the three regions.

Results

Statewide Assessment of Sediment Quality

Approximately 83% of the 1295 km^2 of California marine embayments included in the analysis was classified as having some degree of impact related to sediment contamination. Most of the area was classified as Possibly Impacted, the most uncertain of the classifications representing impacts, and less than 1% of the area was classified as Clearly Impacted, the most severe impact category (Figure 2). The statewide analysis results were dominated by the conditions present in SFB, which represented nearly 80% of the embayment area.

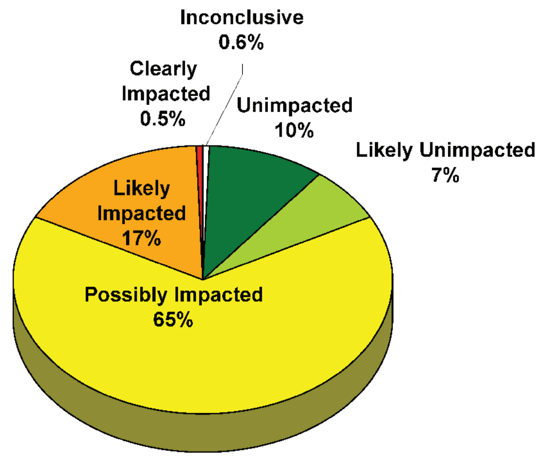

Figure 2. Percent area of California embayments for each sediment condition category as classified by the MLOE assessment framework. Further details on confidence limits and areas represented by each condition classification can be found in Barnett *et al.* (2008).

Regional Assessment of Sediment Quality

Large variations in sediment condition were present among the three geographic regions. The North region had the best sediment condition, with 58% of the area classified as Unimpacted and no sites in the Clearly Impacted category (Figure 3). Somewhat poorer sediment quality was observed in the South, with 43% of the area classified as Unimpacted and 2% classified as Clearly Impacted. A different distribution of sediment condition categories was present in SFB; no stations were classified as Unimpacted and the proportion of area assigned to the Possibly Impacted category (77%) was more than three times greater than that measured in the other regions. The uncertainty in condition

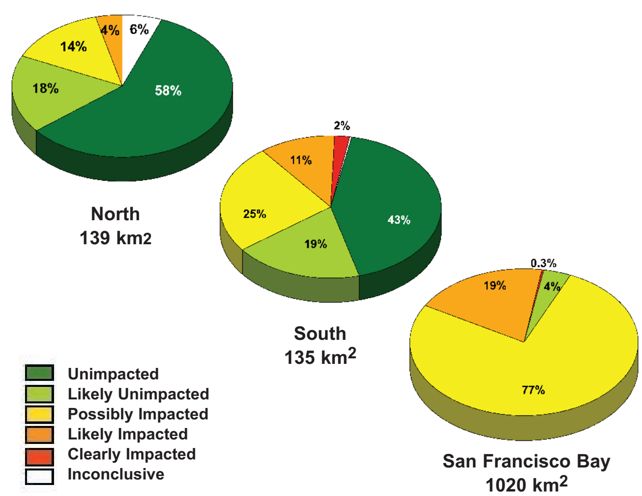

Figure 3. Percent area of sediment quality classification for regional MLOE assessments. Further details on confidence limits and areas represented by each condition classification can be found in Barnett et al. (2008).

estimates varied among regions as a function of sample size. The estimates were most precise for the South, with 95th percentile confidence intervals of about 10%; confidence intervals for SFB and the North were usually two to three times greater for those categories representing most of the area (e.g., Likely Unimpacted, Possibly Impacted, Likely Impacted).

Relationships Among LOEs

The regional differences in sediment quality identified by the MLOE assessment were evaluated by analysis of the underlying lines of evidence (Chemistry, Toxicity, and Benthic Community). The percentage of area classified as having Moderate or High effects (i.e., affected) for each LOE were calculated for each region (Table 2). Sediment chemistry showed the lowest level of response in the North (1%) and greater impacts in the South and SFB. The North also had a low percentage of area with elevated toxicity (Table 2); however, a moderately high percentage of the area was classified as having affected benthos. This combination of results suggests that the benthos in the North might be affected by physical disturbance or noncontaminant stressors or that our indices are less well calibrated in this region.

The greater proportion of area with Possibly Impacted or Likely Impacted designations in SFB (Figure 3) was reflective of large percentages of this region's total area having either affected benthos or toxicity (Table 2). With lower percentages of areas of the South in the affected categories for benthos and toxicity (relative to SFB) and a higher percentage affected for chemistry, the MLOE assessment framework seemed consistent in classifying most of the South as Unimpacted or Likely Unimpacted, although to a lesser degree than in the North (Figure 3).

Table 2. Percent of area affected for each LOE. Area 'Affected' = sum of percent area classified as moderate and high response categories.

Region	Percent Area Affected Per LOE		
	Benthos	Toxicity	Chemistry
North	27	17	1
SFB	34	85	20
South	23	28	40

Thus, the patterns of individual LOE responses found in each region were consistent with the regional percentage area results.

There appeared to be a different relationship between chemistry and toxicity for the South and SFB. San Francisco Bay had higher incidences of affected benthos and toxicity than the South, yet the extent of chemical contamination was lower in general (Table 2). The difference in this relationship is evident when the magnitude of toxicity (percent mortality) in a sample is compared to the magnitude of contamination between the regions (Figure 4). San Francisco Bay sediments tend to produce a greater toxic response than southern California sediments at similar levels of contamination (as represented by the CA LRM P_{max} value).

Sediment Condition in Individual Embayments

Eight embayments contained 84% of the data and had sufficient numbers of sites to examine spatial patterns of condition within them (Figure 5). Patterns of sediment condition could not be described for many of the small embayments because only one or two sites were located within them.

Two major spatial patterns of site condition were evident among the selected embayments. First, there was a greater proportion of Likely Impacted and Clearly Impacted sites in inner harbor and marina areas (e.g., Los Angeles and Huntington Harbors). Sediment conditions were better at the deeper loca-

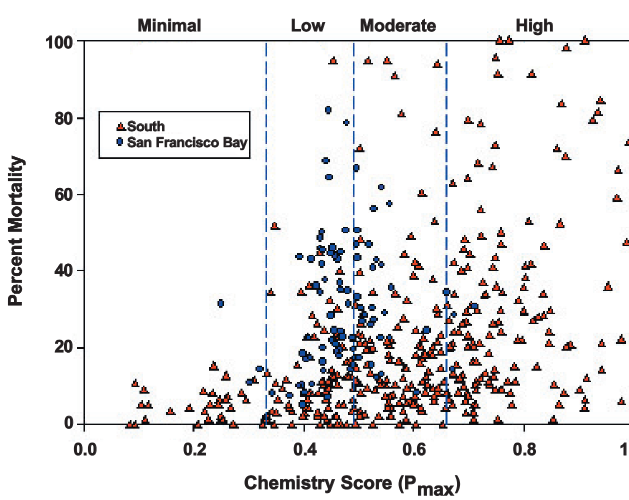

Figure 4. Relationship between chemistry and toxicity in the South and SFB regions. The chemistry score is the CA LRM maximum probability of toxicity; dashed lines indicate the probability thresholds for the four response-level categories of chemical exposure.

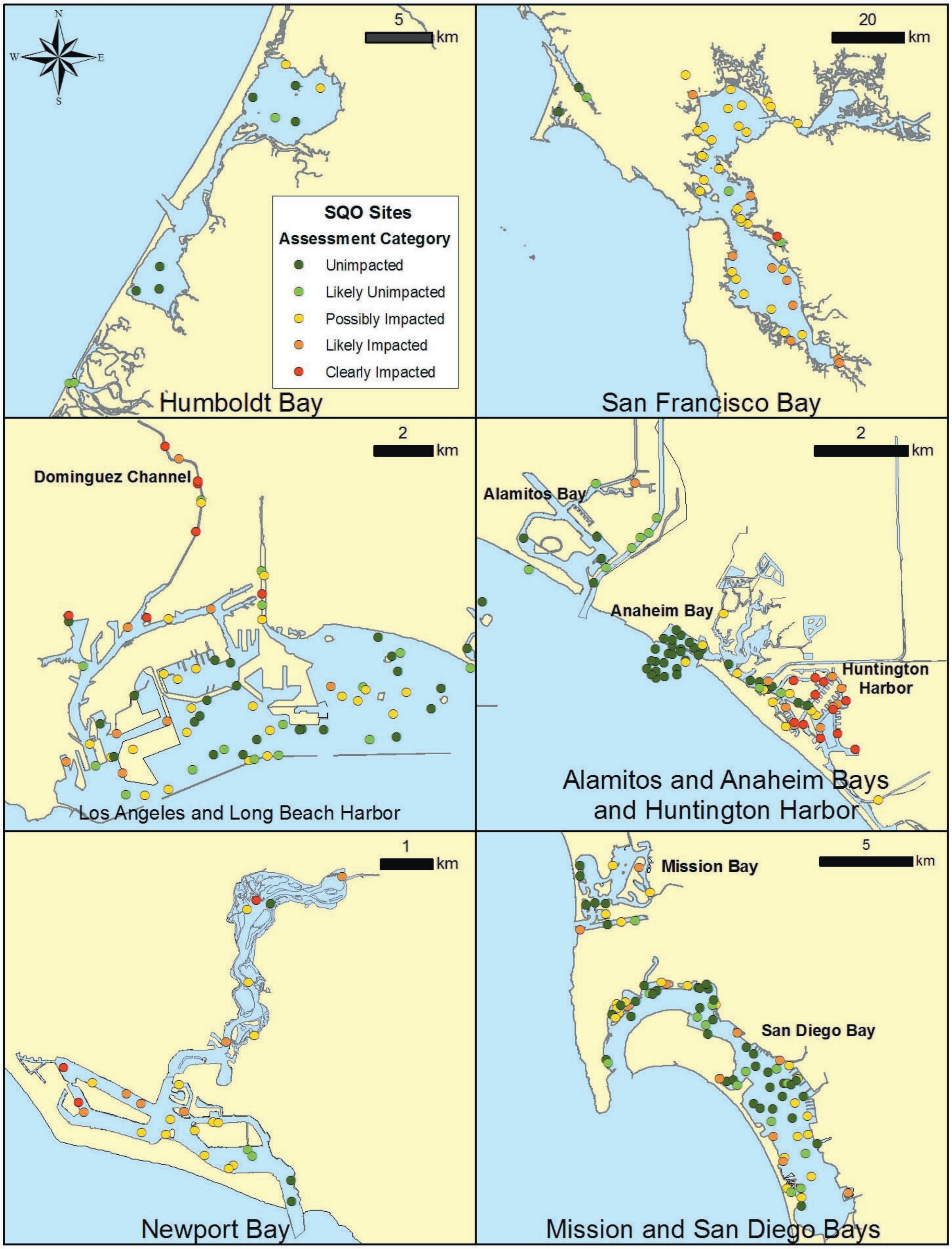

Figure 5. Sediment quality in selected California embayments.

tions in Los Angeles and Long Beach Harbors, San Diego Bay, and outer Anaheim Bay), presumably due to increased distance from sources and better circulation. Second, the more impacted sites tended to be located near the perimeters of the embayments where ports or commercial areas are situated (e.g., San Francisco and San Diego Bays).

Sites having Likely Impacted and Possibly Impacted sediment quality were most prevalent in Newport Bay and San Francisco Bay (Figure 5).

Newport Bay had 71% of sites (20 of 28) and San Francisco Bay had 92% of sites (37 of 40) classified as either Likely Impacted or Possibly Impacted.

Discussion

Sediment quality was found to be highly variable among California's marine and estuarine embayments. The SFB region had seven and one-half times the area of either the North or the South regions. As a result, the statewide assessment of condition in California embayments was dominated by the condition of SFB. A more representative view of the status of California's bays and estuaries was obtained from the regional analyses (Figure 3), which found northern embayments to be the least impacted, and southern embayments to be less impacted than SFB. However, in contrast to the North and South, most of the SFB region was assessed as Possibly Impacted.

This study used an integrated analysis based on a novel MLOE assessment framework, resulting in a more spatially and temporally comprehensive and standardized analysis than previous studies of sediment quality in California bays and estuaries. Nevertheless, the results of this study are consistent with prior analyses. An assessment of coastal condition in 1999 (that included the WEMAP 1999 data used in the present study) found low levels of metal and organic contamination in embayments in the North and South regions (USEPA 2005). The 1999 survey also measured a similar extent of sediment toxicity to *E. estuarius* (19 - 24% of the area) as the present assessment.

The high prevalence in the South relative to the other regions, of sediment with Possibly, Likely, or Clearly Impacted conditions is consistent with previous studies by BPTCP. The BPTCP surveys also found a high frequency of sediment toxicity to amphipods, benthic community degradation, and elevated contaminant concentrations in multiple Southern embayments, including San Diego Bay, Newport Bay, Huntington Harbor, and Los Angeles Harbor (Fairey *et al*. 1998, Phillips *et al*. 1998, Anderson *et al*. 2001). The BPTCP surveys had different objectives, however, and focused on identifying the most highly impacted sites.

SFB had a greater percentage of area in the Likely Impacted and Possibly Impacted condition than in the South where a greater portion of the area was classified in the most extreme category of Clearly Impacted (Figure 3). Whereas southern California is an area of greater industrial, commercial, and population concentration, the pattern in SFB suggests that sediment contaminants are more widespread and less concentrated, possibly due to contaminant dilution and redistribution as a result of greater rainfall, runoff, and tidal mixing.

Sources of Uncertainty

This assessment utilized a new approach and there are several sources of uncertainty in the results. First, the indices used to classify benthic community condition varied among regions due to a lack of habitat-specific calibration data for some of the indices. Four indices were used in the South, whereas only one index (RBI) was available for the North. Four benthic indices were also used in central SFB, but only the RBI and IBI were available for use in interpreting data from San Pablo Bay and the south Bay. All available indices were used wherever possible, as analyses have shown that the use of multiple indices gives a more accurate assessment of benthic community condition (Ranasinghe *et al*. 2007). To test the effect of using various combinations of benthic indices on the classifications, the analyses were repeated using only the RBI to classify benthic community condition in each region (Barnett *et al*. 2008). While the percent of area classified as having affected benthos was increased when only the RBI was used, this change produced less than a five percentage point increase in the percent of area classified as impacted (i.e., Possibly, Likely, or Clearly Impacted).

The high abundance of nonindigenous species in SFB is another source of uncertainty in the benthic community evaluation. The effect of nonindigenous species on the assessments is expected to be small, since these species were included in the calibration of SFB benthic indices and prior analyses of southern California data indicate they do not confound the benthic index results. However, a detailed study to investigate the influence of nonindigenous species on the performance of the SFB benthic indices has not been conducted.

Additional uncertainty is related to limitations in the age and amount of data. The data used for the assessment spanned an eight-year interval and most were from samples collected more than six years ago. Thus, the conditions described in this report may not represent recent changes in sediment condition. A limited number of sites was available to characterize sediment quality in the North and SFB. In the present study, only 40 sites from a single survey were used in the SFB assessment, and only 27 sites were available to represent the North. Consequently, individual sites in the North and SFB had much greater area weights and a greater influence on the results than did individual sites in the South. This resulted in larger confidence intervals for the North and SFB area assessments. However, even with these large intervals, statistically significant differences were observed between regions for some sediment condition categories (Barnett *et al*. 2008).

A final source of uncertainty is related to the toxicity assessment. The results are based on only a single test of sediment toxicity: the 10-day amphipod survival test. While this is a widely used measure of sediment quality, the use of multiple tests is recommended for sediment quality assessment (Burton, Jr. *et al*. 1996, Greenstein *et al*. 2008); the SQO assessment framework is intended to be used with at least two tests. The impact of using a single test in this assessment is unknown, but a different proportion of the samples might have been identified as toxic if additional tests, especially those that measure sublethal effects, had been used.

There are several potential causes for the difference in toxicity response to contamination level between SFB and South. Variations in unmeasured contaminants, such as current use pesticides, may be responsible. Prior studies in the San Francisco Bay have shown a correlation between biological impacts and sediment contamination in general, but a specific chemical cause for the majority of the effects has yet to be identified (Thompson *et al*. 2007). It is also possible that regional differences in contaminant bioavailability or contamination patterns are affecting the relationship between chemistry and toxicity. Additional studies are needed before the reason for this apparent difference in toxicity response can be determined.

Literature Cited

Anderson, B.S., J.W. Hunt, B.M. Phillips, R. Fairey, C.A. Roberts, J.M. Oakden, H.M. Puckett, M. Stephenson, R.S. Tjeerdema, E.R. Long, C.J. Wilson and J.M. Lyons. 2001. Sediment quality in Los Angeles Harbor, USA: A triad assessment. *Environmental Toxicology and Chemistry* 20:359-370.

Anderson, B.S., J.W. Hunt, S. Tudor, J. Newman, R.S. Tjeerdema, R. Fairey, J.M. Oakden, C. Bretz, C.J. Wilson, F. LaCaro, G. Kapahi, M. Stephenson, H.M. Puckett, J.W. Anderson, E.R. Long, T. Fleming and J.K. Summers. 1997. Chemistry, toxicity and benthic community conditions in sediments of selected southern California bays and estuaries. California State Water Resources Control Board. Sacramento, CA.

Barnett, A.M., S.M. Bay, K.J. Ritter, S.L. Moore and S.B. Weisberg. 2008. Sediment quality in California bays and estuaries. Technical Report 522. Southern California Coastal Water Research Project. Costa Mesa, CA.

Bay, S., D. Greenstein and D. Young. 2007b. Evaluation of methods for measuring sediment toxicity in California bays and estuaries. Technical Report 503. Southern California Coastal Water Research Project. Costa Mesa, CA.

Bay, S.M., K.J. Ritter, D.E. Vidal-Dorsch and L.J. Field. 2007a. Comparison of national and regional sediment quality guidelines for predicting sediment toxicity in California. Technical Report 543. Southern California Coastal Water Research Project. Costa Mesa, CA.

Bay, S.M. and S.B. Weisberg. 2008. A framework for interpreting Sediment Quality Triad Data. pp. 175-185 *in*: S.B. Weisberg and K. Miller (eds.), Southern California Coastal Water Research Project Annual Report 2008. Costa Mesa, CA.

Burton, Jr., G.A., C.G. Ingersoll, L.C. Burnett, M. Henry, M.L. Hinman, S.J. Klaine, P.F. Landrum, P. Ross and M. Tuchman. 1996. A comparison of sediment toxicity test methods at three Great Lake areas of concern. *International Association of Great Lakes Research* 22:495-511.

Crane, J.L., D.D. MacDonald, C.G. Ingersoll, D. Smorong, C.G. Lindskoog, C.G. Severn, T.A. Berger and L.J. Field. 2000. Development of a framework for evaluating numerical sediment quality targets and sediment contamination in the St. Louis River Area of Concern. US Environmental Protection Agency, Great Lakes National Program Office. Chicago, IL.

Fairey, R., C. Roberts, M. Jacobi, S. Lamerdin, R. Clark, J. Downing, E. Long, J. Hunt, B. Anderson, J. Newman, R. Tjeerdema, M. Stephenson and C. Wilson. 1998. Assessment of sediment toxicity and chemical concentrations in the San Diego Bay region, California, USA. *Environmental Toxicology and Chemistry* 17:1570-1581.

Greenstein, D., S. Bay, B. Anderson, G.T. Chandler, J.D. Farrar, C. Keppler, B. Phillips, A. Ringwood and D. Young. 2008. Comparison of methods for evaluating acute and chronic toxicity in marine sediments. *Environmental Toxicology and Chemistry* 27:933-944.

Hunt, J.W., B.S. Anderson, B.M. Phillips, R.S. Tjeerdema, K.M. Taberski, C.J. Wilson, H.M. Puckett, M. Stephenson, R. Fairey and J. Oakden. 2001. A large-scale categorization of sites in San Francisco Bay, USA, based on the sediment quality triad, toxicity identification evaluations, and gradient studies. *Environmental Toxicology and Chemistry* 20:1252-1265.

Long, E.R. and P.M. Chapman. 1985. A sediment quality triad - measures of sediment contamination, toxicity and infaunal community composition in Puget-Sound. *Marine Pollution Bulletin* 16:405-415.

MacDonald, D.D. and C.G. Ingersoll. 2002. A guidance manual to support the assessment of contaminated sediments in freshwater ecsystems. Volume I - An Ecosystem-Based Framework for Assessing and Managing Contaminated Sediments. US Environmental Protection Agency, Great Lakes National Program Office. Chicago, IL.

Phillips, B.M., B.S. Anderson, J.W. Hunt, J. Newman, R.S. Tjeerdema, C.J. Wilson, E.R. Long, M. Stephenson, H.M. Puckett, R. Fairey, J.M. Oakden, S. Dawson and H. Smythe. 1998. Sediment chemistry, toxicity and benthic community conditions in selected water bodies of the Santa Ana region. California State Water Resources Control Board. Sacramento, CA.

Ranasinghe, J.A., S.B. Weisberg, R.W. Smith, D.E. Montagne, B. Thompson, J.M. Oakden, D.D. Huff, D.B. Cadien, R.G. Velarde and K.J. Ritter. 2007. Evaluation of five indicators of benthic community condition in two California bay and estuary habitats. Technical Report 524. Southern California Coastal Water Research Project. Costa Mesa, CA.

Ritter, K.J., S.M. Bay, R.W. Smith, D.E. Vidal-Dorsch and L.J. Field. 2008. Development and evaluation of sediment quality guidelines based on benthic macrofauna responses. pp. 91-105 *in*: S.B. Weisberg and K. Miller (eds.), Southern California Coastal Water Research Project Annual Report 2008. Costa Mesa, CA.

San Francisco Estuary Institute (SFEI). 2003. The Pulse of the Estuary: Monitoring and Managing Contamination in the San Francisco Estuary. SFEI Contribution 74. SFEI. Oakland, CA.

Southern California Coastal Water Research Project (SCCWRP). 2003. Southern California Bight 1998 Regional Monitoring Program Executive Summary. SCCWRP. Westminster, CA.

SCCWRP. 2007. Southern California Bight 2003 Regional Monitoring Program Executive Summary. SCCWRP. Costa Mesa, CA.

State Water Resources Control Board (SWRCB). 2006. Water quality assessment of the condition of California coastal waters and wadeable streams. SWRCB. Sacramento, CA.

SWRCB. 2008. Water quality control plan for enclosed bays and estuaries. Sediment quality plan. Draft Staff Report. SWRCB. Sacramento, CA.

Stevens, Jr., D.L. and A.R. Olsen. 2003. Variance estimation for spatially balanced samples of environmental resources. *Environmetrics* 14:593-610.

United States Environmental Protection Agency (USEPA). 1994. Methods for assessing the toxicity of sediment-associated contaminants with estuarine and marine amphipods. EPA 600-R94-025. USEPA, Office of Research and Development. Washington, DC.

USEPA. 1998. Guidelines for ecological risk assessment. EPA/630/R-95/002F. USEPA. Washington, DC.

USEPA. 2004. National coastal condition report II. EPA-620/R-03/002. USEPA, Office of Water. Washington, DC.

USEPA. 2005. Condition of estuaries of California for 1999: A statistical summary. EPA/620/R-05/004. USEPA, Office of Research and Development. Washington, DC.

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