TURBIDITY, TSS, AND TOXICITY: AN INVESTIGATION OF OPERATIONAL IMPACTS DUE TO DREDGING-INDUCED RESUSPENSION OF SEDIMENTS

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ABSTRACT

The Los Angeles Contaminated Sediments Task Force, a multi-agency entity established to plan for regional dredging and disposal of contaminated sediments in Los Angeles County, California, identified effects of resuspension as an existing data gap in their long-term management strategy. In the Los Angeles region, monitoring requirements for dredging projects routinely include light transmittance measurements in the vicinity of dredging and disposal operations, and have used a fixed percentage reduction as a trigger for mitigation measures. This study sought to investigate a number of questions relating to the validity of this approach and whether waters qualified as exhibiting increased turbidity were impacting the marine environment.

The first component of the study utilized large carbouys to mimic Greenbook/ITM suspended particulate phase testing on a scale which would allow sampling of the overlying and flocculent layers through time as particulates settled. Turbidity, total suspended solids (TSS), and toxicity samples were collected over a 48-hour period. Light transmittance was found to be a moderate predictor of TSS, but only for a range below 30 mg/L, a concentration below the threshold at which toxicity might be expected (80 mg/L, Anchor Environmental 2003). Results of bivalve embryo development tests indicated that overlying supernatant and centrifuged flocculent waters were generally not toxic, though uncentrifuged flocculent samples were found to be universally lethal.

The second component of the study utilized an ongoing dredging monitoring program to investigate whether contaminated sediment dredging plumes impacted the environment. An existing monitoring program was augmented to include toxicity testing and optical backscatter measurements to address similar questions to those addressed in the first phase, but in a field environment. Toxicity test results indicated that toxic effects were not observed at the spatial resolution normally incorporated into monitoring programs, but that in close proximity to operations, toxicity and water quality objective exceedances were observed.

Conclusions of this study include ramifications to the design of dredging and disposal operation monitoring programs in the Los Angeles region, a discussion of the limitations of various measurements of turbidity, and considerations regarding the applicability of using suspended particulate phase test data as an indicator of in situ water quality impacts.

INTRODUCTION

Participants of meetings of the Los Angeles Contaminated Sediments Task Force (CSTF) have recently identified a number of important gaps in knowledge related to the environmental assessment of sediment plumes during dredge operations in ports and harbors. Of particular interest to the CSTF are understanding: 1) the appropriateness of various *in-situ* plume turbidity measurement techniques; and 2) the ability of current standard suspended particulate phase (SPP) laboratory toxicity procedures to simulate potential impacts to local biota at the site of dredged material operations. Relationships between total suspended solids (TSS) and turbidity were examined to assess the appropriateness of current field plume measurements. The ability of SPP laboratory toxicity procedures to simulate potential impacts to local biota was assessed by examining relationships between toxicity, turbidity, and several chemicals of potential concern. Studies were performed in controlled laboratory conditions with samples collected at active dredging operations. Sediments that have been characterized as both suitable and unsuitable for ocean disposal were evaluated.

These studies were undertaken as part of a program to utilize ongoing Port of Long Beach (Port) projects by augmenting sediment characterization and dredging operations monitoring data with additional field and laboratory studies. Specifically, this study sought to capitalize on and expand the scope of data being collected from two concurrent projects at the Port: 1) the sediment characterization effort for the Back Channel and Inner Harbor

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Navigation Safety Improvements Project (AMEC 2004); and 2) the water quality monitoring program for the Pier T Wharf Extension Project (Figure 1).

The first study consisted of an evaluation of sediment elutriates prepared under controlled laboratory conditions. Sediment collection was conducted by AMEC Earth and Environmental, Inc. (AMEC) in February 2004 following U.S. Army Corps of Engineers (USACE) and U.S. Environmental Protection Agency (EPA) guidance outlined in the document titled *Evaluation of Dredged Material Proposed for Discharge in Waters of the U.S.* (Inland Testing Manual [ITM]) (EPA/USACE 1998).

Sediments collected from the Back Channel and Inner Harbor Navigation Safety Improvements Project site were artificially suspended in the laboratory using procedures comparable to ITM methods, but on a larger scale and for a longer duration than is generally employed. Under ITM guidance, supernatant is to be collected after 1 hour and, if necessary, centrifuged to remove suspended sediments thereby limiting exposure of test organisms to the dissolved contaminant fraction. The ITM protocol results can be interpreted as a model of how dissolved contaminants affect water quality in terms of biological impacts that may occur after the prescribed settling time. However, in practice, the protocol settling time is often extended in order to generate a sufficiently large elutriate sample with minimal centrifugation. This study took a time-series approach, and sampled at multiple times during the settling process and at multiple depths in the simulated water column. Furthermore, to study effects of suspended particulates on bivalve embryo larvae toxicity, both centrifuged and uncentrifuged subsamples were tested. TSS and turbidity measurements were also incorporated into the experimental design to provide data comparable to commonly used field metrics of water quality.

Part two of this study consisted of an evaluation of water quality of samples collected in dredge plumes at the site of the Pier T Redevelopment project. Water quality monitoring of dredging operations for the Pier T Redevelopment project was conducted under contract to the Port of Long Beach by MBC Applied Environmental Sciences, Inc. (MBC) for permit compliance purposes in accordance with Los Angeles Regional Water Quality Control Board (LARWQCB) Monitoring and Reporting Program No. 8115 (File No. 99-144). Samples consisted of turbid water samples collected according to the LARWQCB's monitoring program. Samples were collected over a range of suspended solid concentrations at operations which were dredging sediments both suitable and unsuitable for aquatic disposal. Chemical analysis and bivalve embryo development toxicity tests were performed on the samples concurrently and the resultant data evaluated in the context of sediment quality and field turbidity measurements.

LABORATORY ELUTRIATE STUDY

Laboratory Elutriate Study Background

The proposed Back Channel and Inner Harbor project will require dredging approximately 400,000 cubic yards (cy) of sediment (Figure 1). Sediment samples were collected in four separate areas (Areas A, B, C, and D) (Figure 1). Multiple cores were collected in each of the four areas, and were subsequently composited into two strata for each area: the top stratum was defined as the top 5 ft below the mud line and the bottom stratum was material sampled from 5 ft below the mud line to the project design depth or core refusal. The eight test composite samples were tested for chemical constituents, grain size, and solid-phase (SP) and SPP toxicity. Results were compared to a reference sample collected in the vicinity of Anchorage C-13 in the Outer Harbor. Detailed sample handling, testing methodologies, and results are described in AMEC 2004.

Sediment analyses revealed an assortment of ERL exceedances, with mercury concentrations exceeding the ERM in three of the samples. Elutriate analyses results universally exceeded the California Toxics Rule, Saltwater Maximum Concentration Criterion (EPA 2000) for copper (4.8 µg/L) and ranged from 6.62 to 10.7 µg/L in test sediments (7.03 µg/L in the reference elutriate). Generally, top sediments were more contaminated than bottom sediments and bottom sediments had higher clay content. Sediments were not toxic, with the exception of statistically significant amphipod toxicity in both Area D composites. As part of their permitting process the Port proposed that the sediments suitable for temporary unconfined aquatic disposal included the Area B (top and bottom) and a portion of Area A sediments (approximately the southern half of the bottom stratum). All other sediments were considered appropriate for upland disposal based on chemical constituents and/or toxicity.

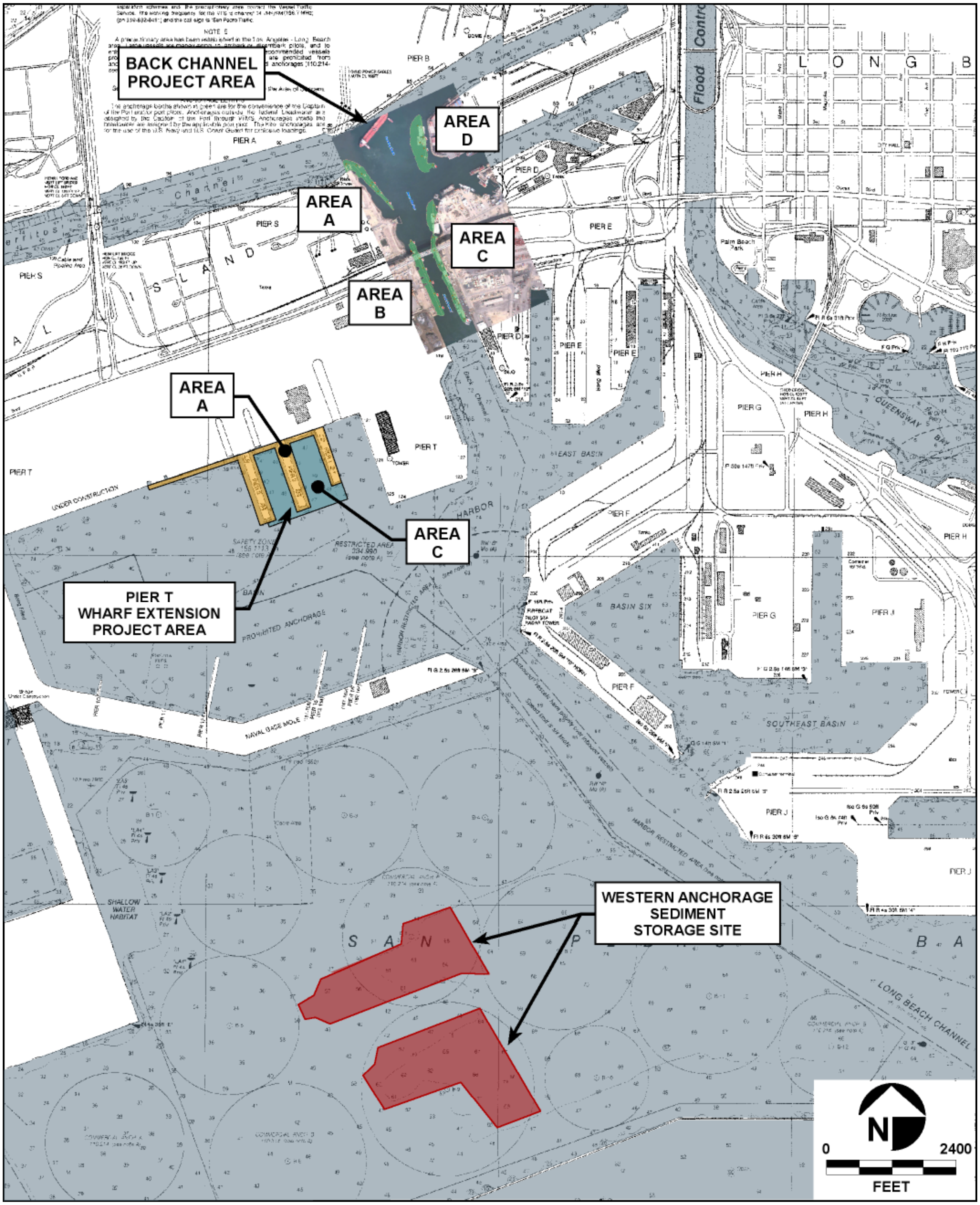

Figure 1. Locations of Port of Long Beach projects utilized for laboratory and field aspects of this study.

Laboratory Study Materials and Methods

Sediment Sample Selection

The project proposal identified grain size distribution and potential contaminant load as determinants by which three of the eight available sediment samples would be selected for the mesocosm experiments. Based on the preliminary results of the sediment characterization study, the three samples designated for additional toxicity, turbidity, and TSS analysis were A-Top, C-Top, and D-Top. Sediments from the top strata were selected due to their likelihood of exhibiting greater contamination; C-Top and D-Top were selected as those among the most contaminated. The A-Top sample was selected to represent sediments with elevated contaminant levels, but with a higher sand content Sample Preparation and Sampling

Sediment elutriates for the three primary sites (A-Top, C-Top, and D-Top) were prepared on 20 November 2003 by AMEC personnel. Elutriates were prepared by vigorously mixing a 1:4 ratio of sediment to seawater (10 gallons sediment and 40 gallons seawater) in a 55-gallon high-density polypropylene plastic carboy for a period of 30 minutes (Figure 2a). Mixing was performed using a 0.25-horsepower motor with a stainless steel propeller. Immediately upon completion of mixing, 1.5-liters (L) of elutriate was siphoned from two inches below the surface into a 2-L plastic beaker (Figure 2b). This was considered the time zero sample. As the suspended sediment settled, separate 1.5-L aliquots were siphoned from 2 inches below both the water surface and below the elutriate/flocculent layer boundary at five time periods (0.5, 1, 6, 24, 48 hours following mixing). The material below the water surface was termed the overlying water (OW) while the sample just below the elutriate/flocculent boundary was termed flocculent layer (Floc). A portion of the flocculent layer sample from each time period was also centrifuged at 3500 revolutions per minute (2100 g) for 15 minutes. The resulting supernatant was identified as C-Floc.

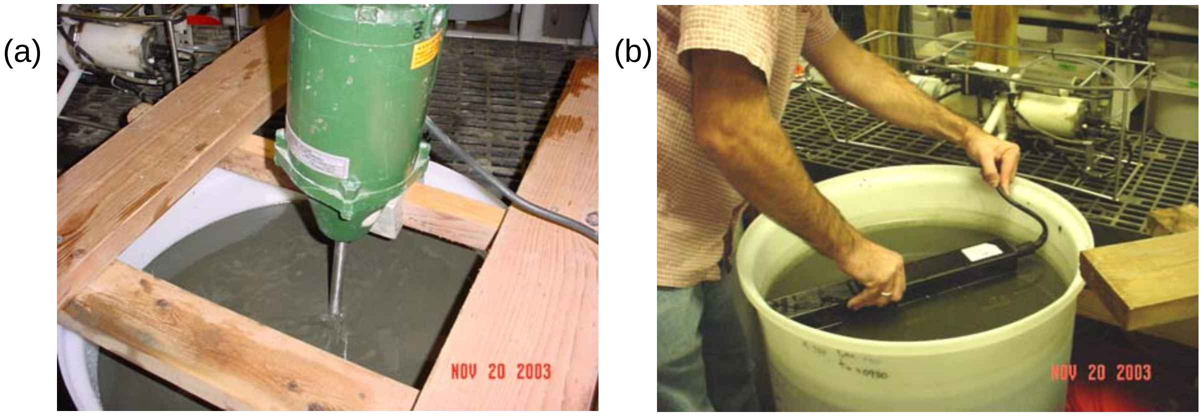

Figure 2. (a) Laboratory sediment elutriate preparation, and (b)transmissivity measurement in overlying water.

Total Suspended Solids Analyses

TSS subsamples were delivered by courier to by Calscience Environmental Laboratories (Calscience) for analysis. Samples were transported to Calscience either on the day of generation or one day following. Analyses were undertaken using EPA Method 160.2.

Laboratory Turbidity Measurements

Transmissivity was measured using two approaches. In order to measure light transmittance as it would be measured in a field-monitoring program, a CTD equipped with a Wetlabs C-star transmissometer was employed. C-star transmissometers measure percent transmittance of a 660-nanometer (nm) ray of light across a 25-centimeter (cm) field. During the experiment, the transmissometer was carefully deployed at the surface of each of the mesocosm vessels for each time interval (Figure 2b). The transmissometer was not lowered any further into the water column to avoid possible resuspension of the flocculent layer into the supernatant layer.

A second light transmissivity measurement was undertaken on the flocculent layer. A bench-scale portable Hach spectrophotometer set to 660 nm wavelength (the same wavelength as the CTD) was employed to measure light transmissivity in the 25-mL aliquots. Samples were collected from all experimental samples, including the elutriate layer. Spectrophotometer transmissivity was measured immediately following collection of the samples.

After the above mixing experiments were completed, the mesocosms were remixed twice (once for the 0.5-, 1-, and 6-hr sample times and once for the 24- and 48-hr sampling times) and the CTD transmissometer re-deployed to measure the transmissivity of the flocculent layer.

Upon review of the data from the light transmissivity and TSS analyses results, it was noted that the TSS concentration threshold at which light transmissivity dropped to zero (approximately 30 mg/L) was substantially lower than the estimated threshold of potential toxicity to bivalve embryos (80 mg/L, Anchor 2003). In an attempt to obtain data more applicable to the study objectives, an optical backscatter (OBS) meter was added to the CTD to test the hypothesis that OBS data would better predict the TSS load, particularly above the 80 mg/L threshold concentration.

Bioassay Protocol - Bivalve Embryo Development using the Blue Mussel (Mytilus galloprovincialis)

The bivalve embryo development assay was performed in accordance with "Conducting Static Acute Toxicity Tests Starting with Embryos of Four Species of Saltwater Bivalve Molluscs," ASTM Designation E 724-89 (ASTM 1989) as it pertains to the blue mussel *Mytilus galloprovincialis.* Mussel brood stock was purchased from Carlsbad Aquafarms in Carlsbad, California. Shipments of mussels were received on the day of, or one to two days prior to, testing. Toxicity tests were performed on 19, 20, and 24 November 2003 for the laboratory elutriate studies and between 6 January and 1 April 2004 for the field plume studies. Samples were tested at 50 and 100 percent concentrations. Dilution water and laboratory controls consisted of sand-filtered seawater obtained from Scripps Institute of Oceanography in La Jolla, California. A concurrent reference toxicant test using copper chloride was conducted with each batch of tests.

Statistical analyses were performed using the Comprehensive Environmental Toxicity Information System (CETIS), version 1.0, CETIS's predecessor: ToxCalc Scientific Software, Version 5.0, and GraphPad Prism Version 4.02 statistical software. Relationships between toxicity, ammonia, sulfides, TSS, transmittance, and absorbance were evaluated using Spearman Rank correlations for the laboratory elutriate study. This nonparametric method was applied to untransformed data because there were few data points available for analysis (N=6), and much of the data were not normally distributed. Normal distribution of the data was evaluated using the D'Agostino and Pearson omnibus normality test.

Prior to statistical analysis, embryo development data expressed as percent normal were normalized to concurrent controls due to tests occurring on more than one day for both lab elutriate and field plume studies. Due to this calculation, several normalized values exceeded 100 percent. Thus, the ability to perform arcsine square-root transformation of the data was not available. A variety of other data transforms failed to normalize the distribution of toxicity data, therefore it was left untransformed for correlation analysis.

Laboratory Elutriate Study Results

Total Suspended Solids

As expected, TSS concentrations in the overlying water decreased with time as sediments settled within the water column. The maximum value of 220 mg/L (after 0.5 hours of settling) was observed in Sample A-Bottom, a sample best described as loamy (i.e., having approximately equal parts sand, silt, and clay).

Transmissivity Results

Light transmittance results were compared to TSS concentrations in order to mimic common field monitoring techniques in a controlled laboratory setting. The CTD transmissometer data collected in the overlying water showed that light transmission was reduced to near-zero at a TSS concentration of approximately 30 mg/L (Figure 5). The relationship, while statistically significant, is not very predictive ($p=0.004$, $r^2=0.425$, $N=25$). Light transmission in the upper flocculent layer was similarly near-zero (light transmittance data did not fall below 3 to 4 percent in even the most turbid samples, indicating that a slight zero-offset is appropriate). An analysis of the laboratory spectrophotometer data indicated a good linear relationship between light transmittance and TSS (r^2 of 0.92 for the relationship, $p<0.001$, $N=25$). However, the relationship exceeded its range of application at approximately 272 mg/L TSS, well below the minimum TSS value observed in the flocculent layer (7,100 mg/L for C-Top at 0.5 hrs).

Sediment Elutriate Toxicity

Due to the nature of the elutriate sampling, the bivalve tests were performed over a three-day period to ensure samples were tested within a 36-hour holding time. Samples collected during elutriate settling times 0 through 6 hours were tested as one batch on 20 November 2003. Samples collected during elutriate settling times of 24 and 48 hrs were tested on 21 and 24 November 2003, respectively.

All water quality results were within the ranges specified in the test protocol indicating adequate test conditions and the absence of undue stress to test organisms. Average normal development among the negative controls was 92 percent. Due to test initiations occurring over a period of three days, all results were normalized to their respective controls for comparison purposes. As a result, some of the data points have greater than 100 percent normal values indicating that the mean number of normal embryos for that sample was greater than the respective concurrent control. Average normal development among all sites, time periods, and concentrations ranged from 0 to 127 percent.

Zero percent normal development was observed exclusively and throughout all flocculent samples, and was due to the fact that no larvae, normal or abnormal, could be recovered from these samples. The flocculent samples had high levels of suspended particulates that, upon settling, appeared to bury developing embryos. The concentration of suspended particulates in the flocculent layer was much greater than the highest levels measured historically during water quality monitoring programs for regional dredging activities.

Excluding the flocculent samples (i.e., including overlying water and centrifuged flocculent samples), average normal development of bivalve embryos among sites, time periods, and concentrations ranged from 92 to 127 percent (Figures 3 and 4). Dunnett's test and Bonferroni *t*-test revealed a statistically significant reduction in normality relative to concurrent controls in five samples, all of which were associated with the centrifuged flocculent fraction (Appendix B).

Bivalve embryo development results were similar in overlying water and centrifuged flocculent fractions across sites and settling times (Figures 3 and 4). Three of the 15 paired data sets did exhibit a statistically significant differences in normal development between overlying water and centrifuged flocculent (*t*-test, $p < 0.05$), however, the greatest difference was only six percent for Site D Top after a settling time of six hours. The EC_{50} value was determined to be >100 percent for all samples tested using the linear interpolation method of point estimation.

The flocculent samples exhibited a steady increase in TSS during the first 24 hours (Figure 4). After 48 hours of settling, however, there was a distinct decrease in TSS in all samples. Although not statistically significant, a trend between bivalve embryo development in centrifuged samples and TSS in original uncentrifuged samples is apparent for Sites C Top and D Top. The concentration of biologically available toxicants may be related to the TSS concentration. Centrifuging the sample likely released a certain fraction of particulate-bound contaminants into the water column that were previously not bioavailable.

PIER T REDEVELOPMENT PROJECT FIELD STUDY

Project Background of the Field Study

Water sample collection was targeted during dredging operations at two locations based on permitted disposal locations. Sediments at Pier T in the Port of Long Beach have been previously characterized to evaluate their suitability for aquatic or ocean disposal (MEC Analytical Systems 1999) using the Evaluation of Dredged Material Proposed for Ocean Disposal (Greenbook) (EPA/USACE 1991) protocols to conduct a Tier III analysis. For purposes of this study, the data for the upper 5 ft of Area A (collected from along the shoreline and pier margins) and Area C (collected from the vicinity of Navy Pier 1 [now demolished]) sediments (Figure 1)were of particular interest in order to compare sediment characteristics to water quality conditions during the dredging of the sediments. Based on chemical and toxicological sediment characteristics, the regulatory determination was that the Site A material was unsuitable for aquatic disposal, while Site C sediments were suitable for aquatic disposal .

Generally, Area A sediments were contaminated (i.e., exceeded the ERM) with metals (mercury and zinc), total PCBs, and total PAHs. Area A sediments were found to be toxic to amphipods and did not meet the Greenbook

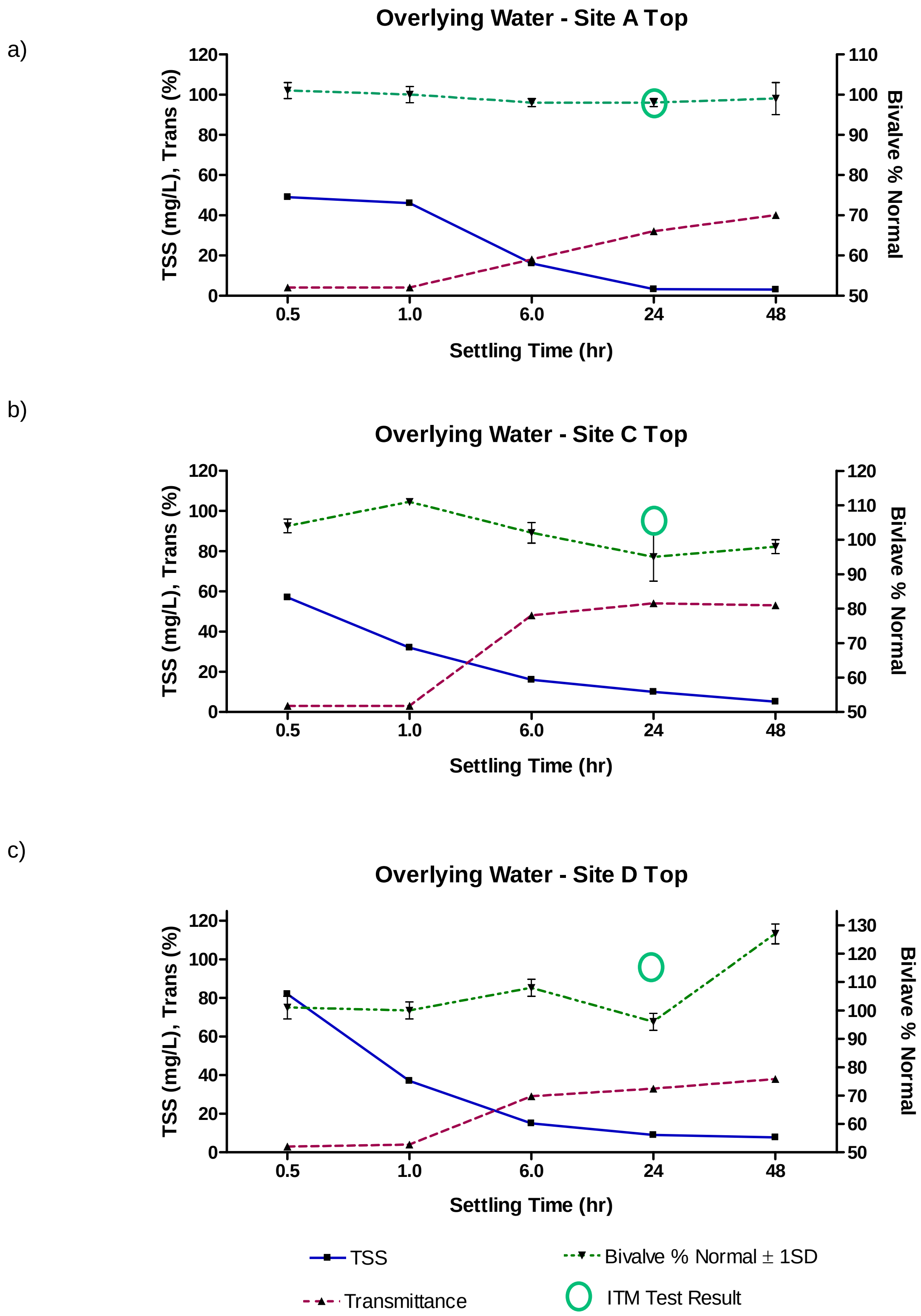

Figure 3. Relationship between bivalve normality, transmissivity, and TSS in the overlying water layer samples. Previously tested bivalve ITM in-harbor disposal evaluation toxicity results (AMEC 2004) are included for comparison.

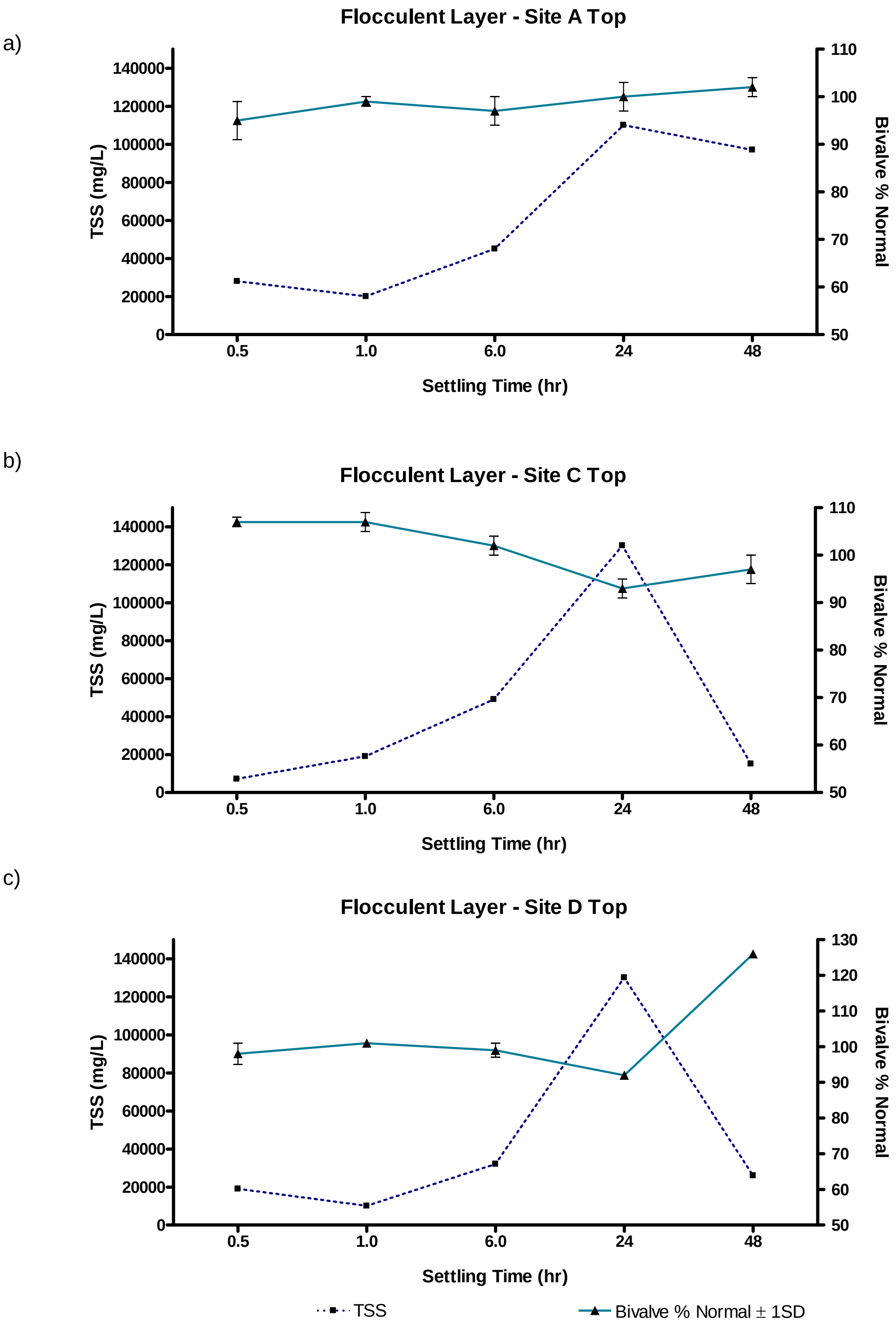

Figure 4. Relationship between bivalve normality and TSS in the centrifuged flocculent layer.

limiting permissible concentration (LPC) requirement for ocean disposal. Area C sediments were relatively uncontaminated, and although mysids exposed to Area C sediments exhibited reduced mean survival, the LPC criteria were met.

It is important to recognize that sediment samples were composites (18 and 12 cores were collected from Areas A and C, respectively), and that direct comparisons between sediment characteristics and the results of this study are not appropriate since the dredging activity took place at a single location rather than over a large area.

Field Study Materials and Methods

Water Sample Selection, Collection, and Analysis

Plume samples for chemical analysis and toxicity testing were collected using Van Dorn bottles attached to a Seabird CTD instrument. Station A was 100 ft (30.5 m) upcurrent of dredge operations; Station B was 100 ft (30.5 m) downcurrent of dredge operations; and Station C was 300 ft (91.5 m) downcurrent of dredge operations. Instrumentation was configured to provide real-time data to monitors on-board the sampling vessel. Samples were initially targeted to be collected from three levels of transmissivity (< 30 percent, 30 to 70 percent, and 70 to 100 percent) at two locations: one unsuitable for aquatic disposal (Area A); and one suitable for aquatic disposal (Area C).

Immediately following collection, samples from the two Van Dorn Bottles were homogenized in one container and distributed to labeled and pre-rinsed certified clean sample containers. Sample containers for toxicity tests consisted of opaque 4-L plastic cubitainers. Samples for toxicity testing were shipped via overnight delivery service to AMEC. Samples for TSS and chemical analysis were delivered by courier to Calscience for analysis either on the day of generation or one day following. Analytical methods for the different parameters measured follow: EPA 2540D (TSS); EPA 1640 (trace metals); EPA 625 (PAHs, chlorinated pesticides and PCB's); and SM 6400-NH_3 F (ammonia). Specific analytes, analytical methods, and results of analyses are summarized in the results section.

Based on historical data, sediments were selected from areas that were considered both suitable and unsuitable for ocean disposal. The first five samples collected from 07 January to 06 February 2004 were low in particulate matter despite transmissivity values ranging from 2 to 49 percent. These samples were not centrifuged prior to toxicity testing because limited visible particulate matter was observed. All five samples (3 suitable and 2 unsuitable) were non-toxic. Due to a lack of toxicity in the first five samples received from MBC and available TSS-light transmittance correlation data, remaining samples were collected from areas of the plume with higher turbidity (i.e., in closer proximity to the dredging operation than the 100-ft distance required for the monitoring program). This alteration in the original sampling protocol was undertaken to reflect a "worst-case" scenario. Stations 4, 5, and 6 were collected within 5 meters of the dredge bucket during a pause in operations. On these sampling events, an OBS meter was added to the CTD instrument to obtain backscatter turbidity data. Also, a D&A Instruments OBS-3 backscatter meter was added to the CTD instrument for the latter sampling events (5 March 2004 and later).

Toxicity Testing

Organism procurement, handling, and bioassay protocols were identical to that described above in Section 2.2.5. Since the toxicity tests were run on different dates, the results were control-normalized for all comparisons.

Statistical Analyses

Relationships between TSS, transmittance, turbidity, copper, zinc, and total PAHs were evaluated using Pearson correlations for the field plume study. TSS, transmittance, turbidity, Cu, Zn, and total PAHs were log transformed prior to analysis to normalize the distribution of the data. Bivalve normality data was evaluated using Spearman Rank correlations due to the non-normal distribution of the data. Due to values either below the detection limit or well below toxicological concern, ammonia and sulfide data were not included in these analyses.

Field Plume Study Results

TSS, Transmissivity, and Turbidity

Total suspended solids among 10 of the 11 samples monitored ranged from 11 to 259 mg/L; light transmittance from 0 to 49 percent. A TSS result of 749 mg/L for the 12 January 2004 sample (confirmed with MBC and the laboratory) was determined to be an outlier due to an inconsistency with the light transmittance value and was excluded from further analyses. Turbidity ranged from 22 to 82 nephelometric turbidity units (NTUs) for the six events monitored with the OBS instrument. The relationships between TSS and these two parameters are shown in Figure 5.

When the outlier TSS value was removed, the relationship between TSS and transmittance was statistically significant ($p=0.004$, $r^2 = 0.658$, $n=11$). However, due to the number of data points with zero transmittance above 30 mg/L TSS, this relationship is clearly not linear. Application of nonlinear exponential regression model obtained a much stronger relationship with an r^2 value of 0.911.

The relationship between TSS and OBS data was not statistically significant at a *p* value of 0.05 ($p=0.067$, $r^2 = 0.611$). However, this relationship may be characterized as relatively strong, especially considering the small number of sampling points (N=6). Correlation coefficients between TSS and both transmittance and OBS were similar.

Although there was a statistically significant relationship between transmissivity and TSS, 4 of 11 samples with TSS values ranging from 66 to 259 mg/L had zero percent transmittance readings. The field derived data confirmed conclusions of the mesocosm study: light transmittance using an instrument path length of 25 cm does not appear to be a viable method for predicting TSS above approximately 30 mg/L. OBS is preferable over the range of TSS observed within dredge plumes. Due to the small samples size for OBS/TSS comparisons, further investigation is warranted.

Field plume TSS values were within or exceeded the range observed in the laboratory study overlying water samples (Table 1). The concentration of suspended particulates in the flocculent layer of laboratory elutriates was much greater than that observed in the field even when samples were collected as close as possible to the dredge head during dredge operations. Field plume TSS values were approximately 3.5 percent of the minimum laboratory flocculent layer values measured.

Chemical Constituent Summary

Total copper and zinc concentrations were greater than current EPA acute criterion maximum concentrations (CMCs) under the California Toxics Rule (EPA 2000) in several samples. Total concentrations of copper ranged from 0.8 to 67 μg/L and zinc from 6.5 to 135 μg/L. CMC values for these two trace metals are 4.8 and 90 μg/L, respectively. CMC values have been derived for the dissolved fraction of chemicals as opposed to total concentrations. Since the data are total concentrations, they may be considered as worst-case estimates.

Detectable concentrations of various PAHs were recorded in all samples; total values ranged from 0.16 to 28.1 μg/L. Current Federal or State of California approved water quality criteria have not been established for total PAHs (EPA 1999, 2000). Arochlor 1254 and several PCB congeners were detected in the Station 4 sample; the total PCBs concentration was 0.18 μg/L. The chlorinated pesticide 4,4'-DDE was detected in the Station 4 elutriate sample at a concentration of 0.117 μg/L and in the Station 5 sample at a concentration of 0.047 μg/L. Alpha-BHC was detected in the Station 6 sample at a concentration of 116 μg/L. CMC values for total PCBs; 4,4'-DDE; and alpha-BHC have not been established, but a chronic criterion maximum concentration has been established for total PCBs (0.03 μg/L).

Field Plume Toxicity

Mean normal development in the negative controls ranged from 88 to 98 percent among the 11 tests conducted. Since tests were performed on different dates over a period of approximately 3 months, all results were normalized to their respective controls for comparison purposes. As a result, some of the data points exceed 100 percent indicating that the mean number of normal embryos for that sample was greater than their respective concurrent control. Average normal development among all sites, time periods, and concentrations ranged from 55 to 106 percent. All water quality data were within the ranges specified in the test protocol indicating adequate conditions and the absence of undue stress to test organisms.

Toxicity in the undiluted samples from four of the eleven stations (4, 6, A, and B; all sampled in the latter half of the study) were statistically different from the control. Stations A and B exhibited differences of only four and five percent from the control, respectively, and were therefore not necessarily representative of a toxic response, but rather a reflection of low test variability. Survival in untreated samples from Stations 4 and 6 (52 percent and 67.6 percent, respectively) were significantly increased (*t*-test, $p<0.05$) by centrifugation to 80 percent and 88.2 percent, respectively. Dissolved constituents, therefore, do not appear to be responsible for most of the observed toxicity in these samples.

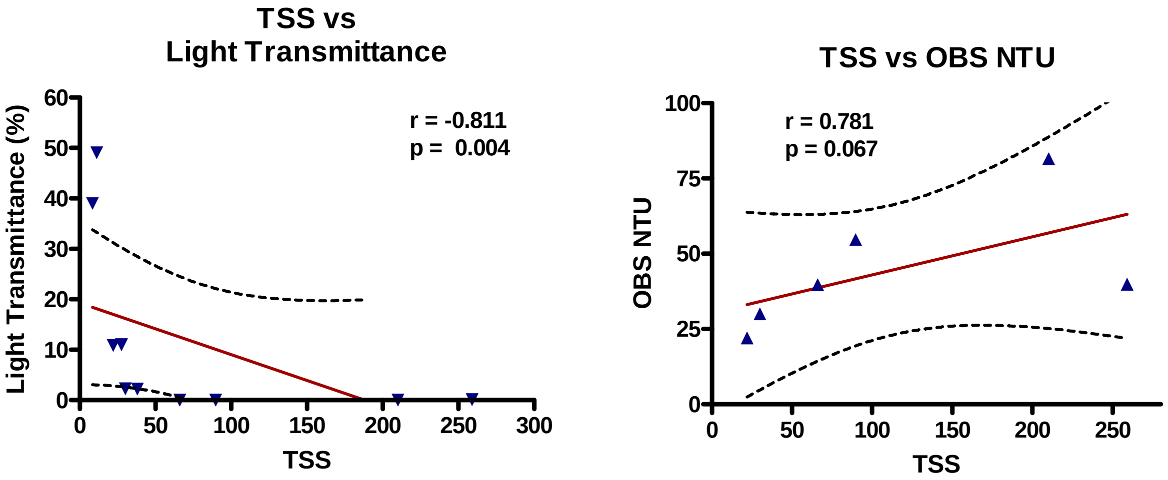

Figure 5. Pearson correlation relationships between a) TSS and light transmittance (percent) and b) TSS and OBS.

Table 1. Comparative median and ranges of TSS data for laboratory prepared elutriates and field plumes.

Settling Time (hr)	Overlying Water	Flocculent Layer	Field Plumes
0	NT	NT	38 (8.4-749)
0.5	82 (49-220)	19,000 (7,100-48,000)	NA
1	46 (32-96)	19,000 (10,000-51,000)	NA
6	17 (15-20)	45,000 (17,000-140,000)	NA
24	11 (3.2-16)	110,000 (76,000-130,000)	NA
48	10 (3-19)	78,000 (15,000-140,000)	NA

NT – not tested.

NA – not applicable.

Relationships between Toxicity and TSS, Transmittance, Turbidity, and Selected Chemical Constituents

Relationships between toxicity and TSS, transmittance, and turbidity were assessed using Spearman Rank analysis and indicated no statistically significant relationships. Relationships between toxicity and selected chemical parameters that exceeded EPA CMC values, including copper and zinc, are shown in Figures 6a and 6b. Relationships to total PAHs are displayed in Figure 6c. Although toxicity was not significantly correlated with these measurements, there does appear to be a trend for both copper and total PAHs (both of which were between

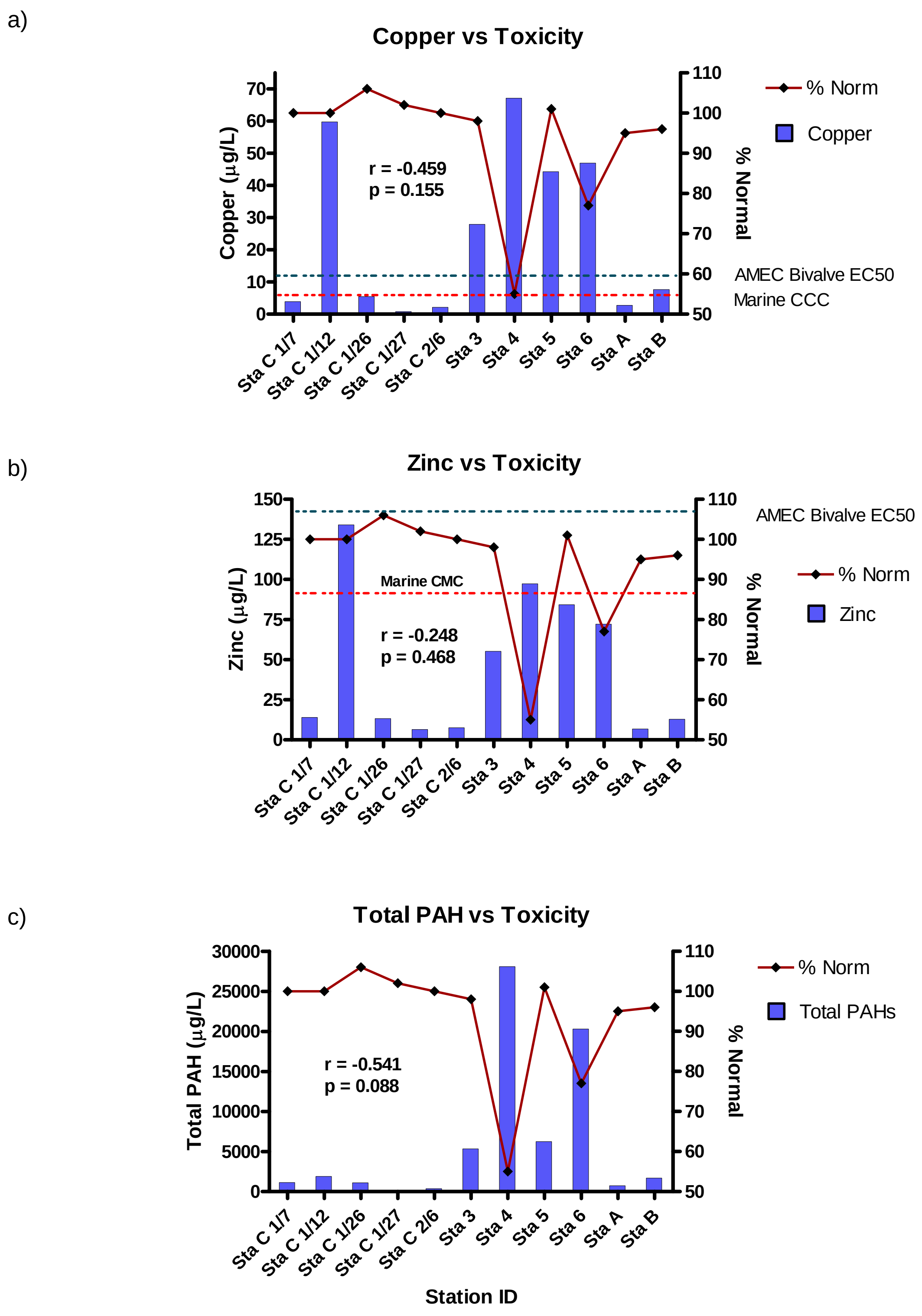

Figure 6. Toxicity relationships to copper, zinc, and total PAHs in field plume samples. Analyses performed using Spearman rank correlation.

respective ERL and ERM values in sediments). Spearman Rank correlations on untransformed data obtained *p* values of 0.04 and <0.001 for copper and PAHs, respectively.

Summary of Pearson Correlations Among Selected Analytical Parameters

Pearson correlation coefficients for selected analytical parameters indicated TSS, light transmissivity, and OBS all correlated with copper, zinc, and PAH concentrations. An increase in sample size and addition of samples from different locations may, however, further substantiate or alter these conclusions.

DISCUSSION

Implications for Suspended Particulate Phase Testing

Although the laboratory and field components of this study were not paired for direct comparison, this study does suggest that SPP elutriates prepared in the laboratory after 1 hour of settling approximate TSS levels expected in the vicinity of dredge operations (Table 1). The methodology, therefore, appears to be applicable to evaluations conducted at the site of a dredge operation in addition to that for which they were originally promulgated as a regulatory tool (i.e., for the site of disposal, EPA 1991).

Of the species routinely used for SPP testing (mysid shrimp, fish, and bivalve larvae), the bivalve embryo development test is often the most sensitive assay. It has previously been shown that settling of suspended particulates may cause adverse effects on recovery and development of this organism (Bailey et al. 2002). In this study, suspended particulates above approximately 80 mg/L appeared to be related to toxicity, though this was not universally the case: exposure to the Station 3 sample, which had a TSS concentration of 259 mg/L, did not result in a reduction in normal development of bivalve larvae.

TSS values observed in overlying water samples after 1 hour of settling were below or only slightly greater than the 80 mg/L threshold above which impacts may occur (Anchor Environmental 2003). It is important to note, however, that suspended particulate characteristics, such as size and charge, may be more important with regard to toxicity than a weight measurement such as TSS. Moreover, the close relationships between specific contaminants and toxicity (given the limited data available) suggest, unsurprisingly, that the type and magnitude of contaminant loading also impacts toxicity. SPP test toxicity observed in field samples, if at a level of concern, should always be investigated in the context of whether toxicity is due to mortal physical effects (i.e., particulates), or to toxic effects of dissolved contaminants.

Implications for Monitoring Program Turbidometers

These studies were undertaken to assess the usefulness of light transmissivity measurements in predicting environmental impacts due to dredging operations. Monitoring programs in the Los Angeles region often establish thresholds of significance on the basis of a reduction in light transmissivity. For example, a light transmittance reduction of 30 percent is currently used as a trigger value for conducting additional monitoring tasks during contaminated sediment dredging activities, such as analysis of chemical analytes in grab samples or increased frequency of monitoring. The comparisons between TSS and other study parameters were particularly interesting in the context of their relation to light transmittance. In terms of establishing meaningful dredging operation monitoring programs, using light transmittance as a measure of turbidity impacts lacks utility: Figure 5 illustrates that light transmissivity falls to zero well below the TSS threshold for a potential toxic response (i.e., >80 mg/L TSS, Anchor Environmental 2003). Interestingly, when the data set was limited to TSS values lower than 30 mg/L (i.e., data with corresponding light transmissivity values above zero), there was also no predictive relationship between TSS and transmissivity (r^2 of 0.003, ANOVA *p* value of 0.83, n =15 [laboratory study data only]). The lack of statistical significance is even more compelling when one considers that these data were collected in a controlled laboratory setting, outside the influence of *in situ* factors that add variability and further cloud the relationship between light transmissivity and corresponding TSS values.

Factors which contribute to the shortcomings of transmissometers include the dimensions of the instrument and the nature of the measurement. The CTD transmissometer used in this study has a relatively long laser path length (25 cm), and probably contributes to a low threshold for reduction in transmittance to zero. Transmissometers with 10-cm path lengths are readily available, but may not substantially improve the application of this technique for field monitoring programs. The 10-fold reduction in path length for the spectrophotometer method to approximately 2.5 cm yielded a much better predictive relationship (r^2=0.919, ANOVA p<0.001, n=25) with a much higher threshold

(272 mg/L). However, the bench spectrophotometer is not appropriate for deployment in the field; permit conditions often require turbidity data to be processed in the field at 1-meter depth intervals, presenting logistical constraints for the use of bench-top instruments in the field (though flow-through systems are an additional option).

Alternative techniques for turbidity measurement (e.g. Secchi disks, OBS) are available for incorporation into monitoring programs (USACE 2000), although each has shortcomings with regard to the applicability of the resulting data. Desirable turbidity data attributes include: 1) accurate and precise measurements in reference to some standard; 2) data that is easily obtained in the field to comply with monitoring requirements, such as sampling at 1-meter depth intervals; and 3) rapid data acquisition so that implementation of dredge operation best management practices can be undertaken as soon as possible.

Secchi disks are essentially black and white discs that are lowered into the water column to gauge water clarity (i.e., the depth of the water column through which the monitor can see the disc). The discs have a long history of use, and may be useful in limited circumstances, for example, when the goal is determining if a visual predator, such as a least tern, is impacted in terms of foraging potential by a turbidity plume. However, the method falls short on the first and third data requirements listed above. First, there is no true reference standard for the Secchi depth because of variability in the visual acuity of the monitor and meteorological conditions (e.g. cloud cover). Second, resulting data is a single linear value per location, integrating turbidity over some variable depth, as opposed to an instantaneous measurement at a defined depth.

Turbidometers also exist in the form of optical backscatter units that measure light reflected off suspended particles. These devices meet the above criteria, but have the additional advantage of producing data that is scaled from clear water to very turbid water, as opposed to transmissivity measurements, which minimize to a 0-value at approximately 30 mg/L TSS (Figure 5). Simply put, the nature of the transmissivity measurement is relative to two points: that at which light passes freely through water and that at which light is blocked by suspended particulates. Naturally the latter is of concern to monitoring programs because it is at this point at which the instrument’s applicability ceases, as discussed above. Turbidity, however, can also be assessed relative to how light is reflected off of suspended particulates, or backscatter. With this technique, turbidity is relative to a standard (formazin solution) and is defined in NTU. This measure, in practical terms, reaches its maximum in very particulate-laden waters and is relative only to the point at which there are no suspended particulates available to reflect light (i.e. clear water). A slurry of Yellow Sea silt is often cited as a standard of sorts for producing a maximally turbidsuspension; it yields a maximum NTU value of over 3,750 and corresponds to a TSS concentration of approximately 5,000 mg/L (D&A Instruments 1989). In this study, the last two mesocosms of the laboratory study were opportunistically used to test on a very rough scale whether an OBS meter might be practical for dredging operation monitoring programs.

The results are presented in Figure 7, and illustrate two benefits of incorporating backscatter units in monitoring programs. First, although only two suspensions were used for only two or three time periods, the relationships between NTUs and TSS concentration were similar for both the laboratory (Figure 7) and field studies, especially at TSS loads of less than 100 mg/L. This suggests that, for at least the loamy and sandy sediments tested, further evaluation may demonstrate a predictive relationship between OBS data and TSS concentrations. Second, as the figure suggests, the OBS data scale continues well past the 125 NTU upper range in the graph to a maximum of approximately 3750 NTUs (per manufacturer). Higher NTU values correspond to higher TSS values, and the method therefore might be more useful in defining monitoring thresholds than light transmittance techniques. One limitation of the method is that it is measured in NTUs, a reference standard that does not account for effects of grain size distribution on the transmittance. This is often cited as a limitation on the use of NTU-scaled data for monitoring programs and is not a unique problem. Light transmittance-TSS relationships may be similarly constrained in the range for which light transmittance data can be obtained. However, the effect of grain size distribution on the relationship between light transmittance and TSS cannot be determined above approximately 30 mg/L.

Implications for Monitoring Program Compliance Determinations

It is also relevant to consider the TSS concentration at which biological impacts might be expected in the context of monitoring programs and SPP testing regimes. A recent review of literature data (Anchor Environmental 2003) documented that the lowest TSS concentration at which one might expect to observe chronic-exposure sublethal effects was approximately 80 mg/L (i.e., with increased likelihood of effects at higher concentrations).

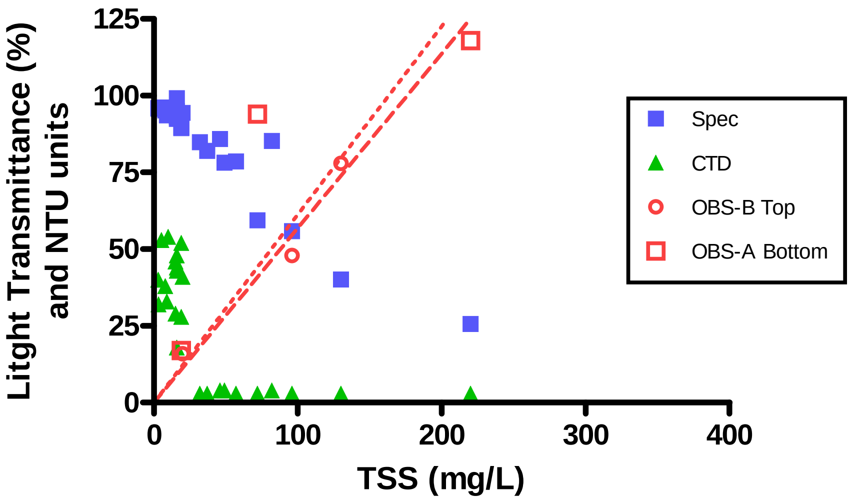

Figure 7. Laboratory elutriate OBS backscatter data in context of alternate techniques with lines of best fit for each mesocosm.

Approximately 30 percent of the Los Angeles regional dredging operation monitoring reports exceeded this threshold, indicating that the 30 mg/L threshold of the CTD transmissometers commonly used in the field is well below what that needed to discriminate between turbidity which might result in an impact and one which might not. For example, a CTD transmissometer reading corresponding to 40 mg/L would be identical (i.e. zero) to that corresponding to 100 mg/L, yet not distinguish between turbidity conditions which might impact biota and those which are probably not of high concern regarding potential impacts.

In the Los Angeles region, the advantage of the OBS technique is that backscatter measurement could be employed to measure turbidity for purposes of tracking the highest observed values in dredging or disposal scenarios; i.e., those most likely to impact beneficial uses. Disadvantages of both OBS and light transmittance approaches include the fact that the precise relationship between turbidity measurements and TSS is specific to the sediment grain size distribution and might require site- or project-specific studies. An additional hurdle to using this technique is that the NTU values are not intuitive and studies may be needed to be undertaken to identify appropriate monitoring thresholds for regulatory purposes. A recent report (MBC 2000) suggests the establishment of some threshold NTU value above which some percent or integral increase in NTUs might be considered a measure of compliance.

The State Water Resources Control Board (SWRCB) has established several maximum turbidity criteria on the basis of time-averaged values (75 NTU 30-day average, 100 NTU 7-day average, and the 225 NTU absolute maximum) in the California Ocean Plan (SWRCB 2001), although the values are “Effluent Limitations,” which may or may not be applicable to dredging operations. OBS data was collected as part of the monitoring program for the Pier 400 Phase II project in the Port of Los Angeles conducted primarily with the hydraulic dredge *Florida*. The monitoring program recorded 2,522 turbidity records during the period August 1997 through October 2000 and evaluated by the USACE (MEC 2003). Of these, 7 records (0.3 percent of the total) were greater than 225 NTUs, 56 records (2.2 percent of the total) greater than 100 NTU, and 75 records (3 percent) were greater than 75 NTU. If the data presented in Figure 7 is used as a preliminary tool to estimate the respective TSS concentrations, approximately 4.8 percent of the data was above the 80 mg/L TSS threshold.

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