Continental Shelf Research 29 (2009) 1821–1835

Contents lists available at ScienceDirect

Continental Shelf Research

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

Impacts of stormwater runoff in the Southern California Bight: Relationships among plume constituents

Kristen M. Reifel[a,*], Scott C. Johnson[b], Paul M. DiGiacomo[c], Michael J. Mengel[d], Nikolay P. Nezlin[e], Jonathan A. Warrick[f], Burton H. Jones[a]

[a] Marine Environmental Biology, Department of Biological Sciences, University of Southern California, 3616 Trousdale Parkway, Los Angeles, CA 90089, USA
[b] Aquatic Bioassay and Consulting Laboratories, 29 North Olive Street, Ventura, CA 93001, USA
[c] NOAA-NESDIS Center for Satellite Applications and Research (STAR), 5200 Auth Road, Camp Springs, MD 20746, USA
[d] Orange County Sanitation District, 10844 Ellis Avenue, Fountain Valley, CA 92728, USA
[e] Southern California Coastal Water Research Project, 3535 Harbor Blvd, #110, Costa Mesa, CA 92626, USA
[f] USGS Coastal and Marine Geology Program, 400 Natural Bridges Drive, Santa Cruz, CA 95060, USA

ARTICLE INFO

Article history:
Received 18 September 2008
Received in revised form
22 June 2009
Accepted 26 June 2009
Available online 2 July 2009

Keywords:
Colored dissolved organic matter
Fecal indicator bacteria
Beam attenuation
Water quality
Remote sensing
Southern California Bight
32°00′N–34°30′N
120°00′W–117°00′W

ABSTRACT

The effects from two winter rain storms on the coastal ocean of the Southern California Bight were examined as part of the Bight '03 program during February 2004 and February–March 2005. The impacts of stormwater from fecal indicator bacteria, water column toxicity, and nutrients were evaluated for five major river discharges: the Santa Clara River, Ballona Creek, the San Pedro Shelf (including the Los Angeles, San Gabriel, and Santa Ana Rivers), the San Diego River, and the Tijuana River. Exceedances of bacterial standards were observed in most of the systems. However, the areas of impact were generally spatially limited, and contaminant concentrations decreased below California Ocean Plan standards typically within 2–3 days. The largest bacterial concentrations occurred in the Tijuana River system where exceedances of fecal indicator bacteria were noted well away from the river mouth. Maximum nitrate concentrations (~40 μM) occurred in the San Pedro Shelf region near the mouth of the Los Angeles River. Based on the results of general linear models, individual sources of stormwater differ in both nutrient concentrations and the concentration and composition of fecal indicator bacteria. While nutrients appeared to decrease in plume waters due to simple mixing and dilution, the concentration of fecal indicator bacteria in plumes depends on more than loading and dilution rates. The relationships between contaminants (nutrients and fecal indicator bacteria) and plume indicators (salinity and total suspended solids) were not strong indicating the presence of other potentially important sources and/or sinks of both nutrients and fecal indicator bacteria. California Ocean Plan standards were often exceeded in waters containing greater than 10% stormwater (<28–30 salinity range). The median concentration dropped below the standard in the 32–33 salinity range (1–4% stormwater) for total coliforms and *Enterococcus* spp. and in the 28–30 salinity range (10–16% stormwater) for fecal coliforms. Nutrients showed a similar pattern with the highest median concentrations in water with greater than 10% stormwater. Relationships between colored dissolved organic matter (CDOM) and salinity and between total suspended solids and beam attenuation indicate that readily measurable, optically active variables can be used as proxies to provide at least a qualitative, if not quantitative, evaluation of the distribution of the dissolved, as well as the particulate, components of stormwater plumes. In this context, both CDOM absorption and the beam attenuation coefficient can be derived from satellite ocean color measurements of inherent optical properties suggesting that remote sensing of ocean color should be useful in mapping the spatial areas and durations of impacts from these contaminants.

1. Introduction

The monitoring and improvement of water quality is a major issue for local, state, and federal agencies and organizations. Coastal waters provide numerous beneficial uses including recreation, commercial and sport fisheries, marine habitat, commerce and transportation, and aesthetic enjoyment. In southern California, approximately $9 billion of the local economies of coastal communities comes from ocean-dependent activities (Bay et al., 2003). A broad range of chemical and biological contaminants is discharged into coastal waters of the Southern California Bight (SCB) including pesticides, fertilizers, trace metals, synthetic

* Corresponding author. Tel.: +1 213 821 1431; fax: +1 213 740 8123.
E-mail address: kreifel@usc.edu (K.M. Reifel).

0278-4343/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.csr.2009.06.011

organic compounds, suspended sediments, inorganic nutrients, and human pathogens (National Research Council, 1990). Reductions in water quality due to these discharges can adversely affect the beneficial uses of the receiving waters and can affect the local coastal economies.

Flood events due to rain storms contribute more than 95% of the total runoff volume annually to the coastal zone (Schiff et al., 2000). Surface runoff, which receives no treatment prior to discharge into ocean waters, is one of the largest sources of contaminants to the SCB (Schiff et al., 2000). Many studies of stormwater runoff conducted in southern California have focused on public health issues such as human pathogens and contaminants (Schiff et al., 2002). Beach closures due to high levels of fecal indicator bacteria (FIBs) and other indicators of human pathogens have been common during and immediately following rain events (Geesey, 1993). Public health officials currently advise the public to avoid any contact with stormwater runoff for at least 72 h following a significant storm event (CDPH, 2006). Evidence of high levels of toxicity associated with urban runoff, especially stormwater runoff, has also been noted in several southern California regions (Bay et al., 2003; Gersberg et al., 2004). Even the high levels of sediment themselves can cause environmental damage through several mechanisms such as smothering of benthic organisms, reduction of visual clarity, irritation of fish gills, and reduction of light available for photosynthesis (Davies-Colley and Smith, 2001). Proper management of these parameters is important for restoring and maintaining healthy beaches, marinas, bays, and coastal areas.

Both *in situ* and satellite remote sensing studies of stormwater plumes in the SCB have shown that plumes created from pulses of stormwater runoff can affect large areas, can penetrate up to 10 m into the water column, and can persist for days to weeks (Washburn et al., 2003; Nezlin et al., 2005). Although the spatial and temporal extents of stormwater plumes have begun to be examined, the extent of impact from human pathogens, nutrients, and toxicants is not well known (e.g. Nezlin et al., 2008). Runoff plumes have the potential, however, to disperse these constituents over large distances (Warrick et al., 2007), especially small particles and dissolved materials that remain in the surface waters.

The California Ocean Plan (COP) and Assembly Bill 411 define the current standards required by the state of California for beach monitoring (State Water Resources Control Board, 2005). Beach posting is recommended, and in some cases required, when single FIB samples exceed these standards. The accepted monitoring protocols involve collection of water samples that are evaluated for FIBs using assays that require 24–48 h to complete, thus limiting the number of samples that can be practically analyzed. It is impossible to adequately and routinely sample plumes by collecting water samples from a few locations limited by sampling capabilities and resources. Remotely sensed ocean color could be used as a way to track stormwater plumes over large spatial scales with high temporal frequency (e.g. Nezlin and DiGiacomo, 2005; Nezlin et al., 2005, 2007b, 2008). Knowledge of the distribution and fate of contaminants within the plumes is still limited and is a focus of this study.

Based on data collected by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate-resolution Imaging Spectroradiometer (MODIS), remote sensing studies of stormwater plumes have used reflectance from the near-surface layer, typically measured as normalized water-leaving radiance in the range 551–555 nm (nLw551 for MODIS and nLw555 for SeaWiFS), as a tracer of plumes in the southern California coastal area. Remote sensing reflectance at these wavelengths is primarily a function of light backscattering from small particles, and is therefore related to turbidity. By analyzing SeaWiFS imagery, Nezlin and DiGiacomo (2005) concluded that measurements of nLw555 greater than $1.3\,\mathrm{mW\,cm^{-2}\,\mu m^{-1}\,sr^{-1}}$ distinguished stormwater plumes from ambient water on the San Pedro shelf. As turbidity is associated with sediment particles, the majority of which quickly sink from surface waters (Hill et al., 2000; Warrick et al., 2004), turbidity can only be used as a short-term, non-conservative tracer to follow the particulate components of stormwater plumes. The actual freshwater plume could be much more extensive than the sediment plume (Geyer et al., 2000). Colored or chromophoric dissolved organic matter (CDOM), defined as the light-absorbing fraction of dissolved organic matter, is a more conservative tracer. CDOM is not subject to sedimentation. Decreases in its concentration occur through the process of photodegradation, which takes weeks to months to occur (Vodacek et al., 1997; Opsahl and Benner, 1998). Rivers constitute a major source of CDOM in the coastal ocean (Siegel et al., 2002; Del Castillo, 2005). CDOM concentration is therefore useful in tracking freshwater plumes and can be used to assess the impact of river-borne components such as nutrients and pollutants in the coastal ocean (Coble et al., 2004). Like turbidity, CDOM can also be estimated from ocean color but is more likely to be associated with the dissolved constituents of plumes rather than the particulate fractions.

The "Bight" projects, organized by the Southern California Coastal Water Research Project (SCCWRP), coordinate regional monitoring efforts by local municipalities that have agreed to work cooperatively toward a regional assessment of coastal conditions. Bight '03, the most recent Bight project, focused on coastal ecology, water quality, and shoreline microbiology and involved 65 federal, state, and local agencies. Results from the water quality component of Bight '03 have been combined into a synthesis report available through SCCWRP (Nezlin et al., 2007a). Also, several studies utilizing data collected during this project have been published in the peer-reviewed literature including an analysis of the dispersal patterns and dynamics of stormwater plumes (Warrick et al., 2007) and the utility of satellite imagery to detect and classify stormwater runoff plumes relative to *in situ* observations of surface salinity and FIB concentrations (Nezlin et al., 2008). We analyzed data collected during the water quality component of the Bight '03 Project to address two aspects of the impact of plumes on the continental shelf of the SCB. First, we attempted to determine the magnitude and area of impact of contaminants (nutrients and FIBs) in the coastal zone based on ship-based sampling. Second, we evaluated the utility of variables that can be derived from remotely sensed measurements of ocean color (e.g. CDOM and beam attenuation) to estimate the distribution and impacts of runoff plumes in the coastal area. We examined the correlation between known contaminants and components that can be readily measured using ocean color data, to evaluate the extent to which remotely sensed ocean color can be used to infer the magnitude and spatial extent of plume impacts.

2. Methods

2.1. Field collections

Seven agencies participated in field collections during Bight '03: City of Oxnard/ABC Labs, City of Los Angeles, Los Angeles County Sanitation District, Weston Solutions (formerly MEC Analytical Systems, Inc.), Orange County Sanitation District, City of San Diego, and Universidad Autónoma de Baja California. Shipboard sampling for this study occurred on grids offshore of five regions (including eight major river systems) in the SCB (Fig. 1). Storm 1 took place on 25 February 2004, which is considered Day 0 in the following analyses. For the San Diego and Tijuana Rivers, an earlier storm that ended on 23 February was also sampled. Storm 2 occurred on 22 March 2005 (Day 0). A separate storm that ended on 12 February 2005 was sampled offshore of the San Diego and Tijuana Rivers. Stations were scheduled to be sampled on days 1, 3, and 5 after storm 1 and on days 1, 2, and 3 after storm 2. However, sampling was sometimes shifted forward or back a day depending on sampling conditions and vessel/crew availability. Not all sites were sampled on all days largely due to limitations from weather and sea state.

Vertical profiles of conductivity and temperature (Sea-Bird SBE 25 or SBE 9/11), beam attenuation (WET Labs C-Star transmissometer), and CDOM fluorescence (WET Labs WETStar) were collected at each station. The instrument and manufacturer are given in parentheses; note that several different instruments were used among the seven participating agencies. Beam attenuation was computed from transmissometer observations as the beam attenuation coefficient at 660 nm (hereafter referred to as beam-c). CDOM fluorescence was converted to quinine sulfate dehydrate (QSD) concentration (ppb) using linear calibrations provided by the manufacturer. Water samples for total suspended solids (TSS), macronutrients (NO_2, NO_3, PO_4, SiO_4), FIBs and toxicity were also collected using 5 l Niskin bottles attached to the CTD carousel or by stringing individual bottles on a line in lieu of using a rosette. These samples were collected at 1 m depth at all stations. Multiple depths were sampled at three stations for each river system. Sampling occurred on regularly spaced grids for each region (Fig. 1). The primary intent of the grids was to sample the nearshore discharge areas and assess water quality there, not necessarily to fully encompass and track plumes as they advected away from the river mouth regions. Some stations were positioned further offshore and were intended to provide "non-plume" profiles for comparative purposes. Profiles were obtained to within 2 m of the seabed or to a depth of 60 m for sites deeper than 60 m. Figures of the spatial distributions of nutrients and FIBs were created using IGODS (Ocean Software, 2009).

Samples for the measurement of macronutrients and TSS were analyzed at the University of Southern California. NO_2, NO_3, PO_4, and SiO_4 concentrations were measured on an Alpkem RFA 300 Series nutrient analyzer (Sakamoto et al., 1990; Gordon et al., 1993). The bulk concentration of TSS was determined using EPA method 160.2 (USEPA, 1983). Briefly, whole water samples were filtered through pre-weighed Whatman GF/F (0.7 μm) filters. The filters were then dried at 100 °C for 2 h and re-weighed. FIB concentrations were measured by six of the participating agencies according to each agency's standard procedures. Prior to sampling, all laboratories participated in an inter-calibration exercise to ensure comparability. The among-laboratory variability was not significantly different from variability within each laboratory (Griffith et al., 2006). Samples were collected in sterile 120 ml polystyrene bottles and transported to local laboratories on ice. The concentration of total coliforms and fecal coliforms were determined using standard methods for multiple-tube fermentation (APHA methods 9221B and 9221E.1) or membrane filtration (APHA methods 9222B and 9222E); (APHA, 1998d, c, b, a). *Enterococcus* spp. were enumerated using Enterolert^{TM} (IDEXX Westbrook, ME) defined substrate kits following the manufacturer's instructions, or using membrane filtration and EPA Method 1600 (Messer and Dufour, 1998). Toxicity was measured as percent fertilization in the sea urchin fertilization assay (USEPA, 1995). In this method, sea urchin sperm are exposed to the sample, and the ability of the sperm to fertilize the egg is evaluated. Significant toxicity was chosen to be those values where sea urchin fertilization success was less than 84% (Bay et al., 2003).

2.2. Correlation analyses

To examine the fate of various contaminants in relation to stormwater plumes, relationships of contaminants to salinity and

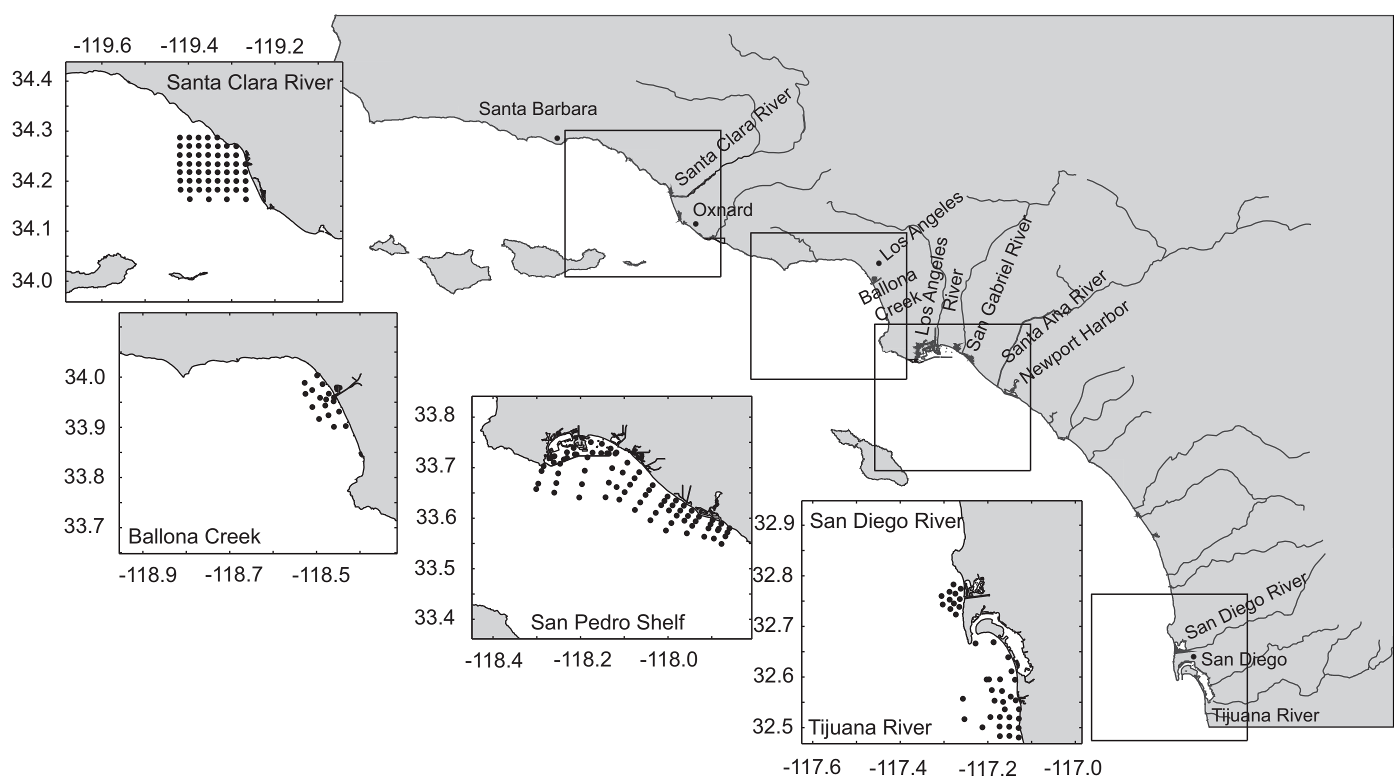

Fig. 1. Map of the Southern California Bight indicating the regions sampled during the Bight '03 study. Note that the San Pedro Shelf region was broken into the Los Angeles/San Gabriel Rivers, the Santa Ana River, and Newport Harbor for correlation analyses. Black dots indicate the locations of stations sampled during the field sampling effort.

TSS were explored. The contaminants measured include nitrate (NO_3^-), nitrite (NO_2^-), phosphate (PO_4^{3-}), silicate (SiO_4), FIBs (total coliforms, fecal coliforms, and *Enterococcus* spp.), and toxicity (measured as percent fertilization in the sea urchin assay). Stations were separated into regional groupings based on their proximity to major sources of inflow. For the three regions in the San Pedro Shelf area (Los Angeles/San Gabriel Rivers, Santa Ana River, and Newport Harbor), stations were grouped by examining nearshore salinity data. Note that these regions were not analyzed individually in the spatial analyses but were grouped as the San Pedro Shelf. General linear models (GLMs) were constructed for each contaminant for each storm. Salinity or TSS (continuous), region (categorical), and day after storm (categorical) were included in the models as independent variables. Only data from the top 5 m were included as the majority of stormwater is found within this depth (Washburn et al., 2003). Because the number of samples was very high (250–376), *P*-values were generally low and were not always useful in distinguishing model fit. We therefore focused on improvements to other parameters such as the coefficient of determination (R^2) when selecting the best models. The adjusted R^2 was considered to account for erroneous improvements in model fit due to the inclusion of additional independent variables. Statistical analyses were done using SYSTAT^{TM} v. 11.0 (SSI, 2004b).

Approximately 28%, 56%, and 59% of the total coliform, fecal coliform, and *Enterococcus* spp. data, respectively, were recorded as being below one of 3 detection limits (10 and 100 most probable number (MPN)/100 ml for total and fecal coliforms; 10 and 20 MPN/100 ml for *Enterococcus* spp.). An additional 7 total coliform values (approximately 1%) were reported as $>$80,000 MPN/100 ml. A small number of nitrite and nitrate samples were also recorded as being below a detection limit (0.1 and 0.05 μM, respectively). Data whose values are known only to be above or below a threshold value are referred to as censored data. Censored data cannot be analyzed using standard statistical methods. Instead, the data were analyzed using the methods of Helsel (2005) through the S-language software package NADA, an add-on package for the R environment for statistical computing (R Development Core Team, 2006). These methods can be used to analyze multiply-censored data sets (data sets with multiple detection limits) with up to 80% censored data. The program, however, only supports left-censored data. Therefore, the 7 total coliform data points reported as $>$80,000 MPN/100 ml were replaced with the value 80,000 MPN/100 ml. Though this will introduce some error, these values represent such a small proportion of the data set that this error is expected to be small. For data sets containing censored data, GLMs were constructed using the cenreg function in NADA. This function computes GLM parameters (e.g. slope and intercept) using maximum likelihood estimation (MLE). MLE assumes that data above and below the detection limit follow a particular distribution. Parameters are computed that best match a fitted distribution to the observed values above each detection limit and to the percentage of data below each limit (Helsel, 2005). The cenreg function also estimates the likelihood R^2 (similar to R^2 in linear regression), the log-likelihood statistic, and the associated *P*-value.

In addition to GLM analyses, contaminant data were examined by grouping the data into several salinity and TSS ranges and calculating summary statistics for each group. Box plots were created showing the median and spread of data within each group. For all uncensored data, box plots were created using SigmaPlot v. 9.01 (SSI, 2004a). For groups containing censored data, summary statistics were calculated using the censored regression on order statistics (ROS) method (Lee and Helsel, 2005). ROS is a probability plotting and regression procedure that models censored distributions using a linear regression model of observed concentrations vs. their normal quantiles. This method has been evaluated as one of the most reliable procedures for developing summary statistics of multiply-censored data (Shumway et al., 2002). Censored box plots were created using the NADA package for *R*.

We also explored the relationships between *in situ* tracers of plume water and variables that can be estimated using ocean color data from satellite imagery. The best *in situ* tracer of freshwater plumes is salinity. Because evaporation will have a minimal effect over the time spans of storm events, surface salinity acts as a conservative tracer of freshwater runoff. Salinity is not currently measured using satellite imagery. Other dissolved constituents with high concentrations in stormwater, such as CDOM, can be estimated using satellite ocean color. We therefore explored the *in situ* relationship between salinity and CDOM to determine whether salinity could ultimately be approximated from CDOM via satellite ocean color observations (Monahan and Pybus, 1978; D'Sa et al., 2002; Busse et al., 2006). A second commonly used tracer of stormwater plumes is turbidity. Turbidity can be measured *in situ* by measuring the concentration of TSS in bulk water samples or optically with a transmissometer that measures beam-c. Whereas salinity and CDOM represent the dissolved components of the plume, TSS, and beam-c represent the particulate components. Again, TSS cannot be measured directly from satellites, but beam-c can be estimated from ocean color data. GLMs were constructed with salinity or TSS, region, and day after storm as independent variables and CDOM or beam-c as the dependent variable. The number of samples was very high (276–1030); therefore, we again focused on adjusted R^2 values when selecting the best models.

3. Results

This section will be presented in three parts. The first part evaluates the spatial and temporal extent of contaminant impacts in the SCB, specifically FIBs, toxicity, and nutrients. In the second part, the use of remotely sensed ocean color is considered for the evaluation of plume impacts based on the ability to estimate water quality parameters of interest from satellite ocean color observations using *in situ*-satellite proxy relationships to infer spatial and temporal scales of stormwater impacts. The third part examines relationships between the contaminants and readily measured, commonly used *in situ* water quality parameters that are considered robust tracers of stormwater plumes (salinity, TSS). It addresses the question of the extent to which these parameters can be used as a proxy for contaminants of concern.

3.1. Spatial and temporal extents of impact

The two sets of contaminants for which either a receiving water standard or environmental impact threshold exists are FIBs and toxicity as measured by the sea urchin fertilization test. Tables 1 and 2 summarize the number of samples and exceedances of these thresholds that occurred for each of the five major river discharges that were studied during the Bight '03 study (Santa Clara River, Ballona Creek, San Pedro Shelf, San Diego River, and Tijuana River). Nutrient distributions were also examined, but regulatory standards do not currently exist for these runoff constituents.

3.1.1. Fecal indicator bacteria

Over 2000 water samples were analyzed for FIBs from all surveys and river systems combined. Elevated concentrations of FIBs were found offshore of every major river system following

Table 1
Summary of the number of single sample exceedances of FIBs for each day for the first (2004) and second (2005) storm events.

	Santa Clara River	Ballona Creek	San Pedro Shelf	San Diego River	Tijuana River	Total
Storm 1–2004						
Total Coliforms[a]						
Day 1	n.d.	2 (8)	4 (38)	0 (18)	7 (18)	13 (82)
Day 2	n.d.	0 (23)	4 (74)	n.d.	0 (16)	4 (113)
Day 3	0 (18)	n.d.	n.d.	0 (18)	1 (37)	1 (73)
Day 4	n.d.	0 (23)	0 (78)	0 (18)	2 (35)	2 (154)
Fecal Coliforms[b]						
Day 1	n.d.	2 (8)	1 (14)	0 (18)	8 (18)	11 (58)
Day 2	n.d.	0 (23)	1 (50)	n.d.	0 (16)	1 (89)
Day 3	0 (18)	n.d.	n.d.	0 (18)	3 (37)	3 (73)
Day 4	n.d.	0 (23)	0 (54)	0 (18)	1 (35)	1 (130)
Enterococcus spp.[c]						
Day 1	n.d.	2 (8)	10 (38)	0 (18)	14 (18)	26 (82)
Day 2	n.d.	3 (23)	6 (74)	n.d.	6 (16)	15 (113)
Day 3	0 (18)	n.d.	n.d.	0 (18)	4 (37)	7 (73)
Day 4	n.d.	0 (23)	2 (78)	1 (18)	2 (35)	2 (154)
TOTAL	0 (54)	9 (162)	28 (498)	1 (162)	48 (318)	86 (1194)
% of samples	0%	5.6%	5.6%	0.6%	15%	7.2%
Storm 2–2005						
Total Coliforms[a]						
Day 1	n.d.	3 (10)	0 (26)	n.d.	9 (18)	12 (54)
Day 2	0 (20)	0 (23)	1 (28)	n.d.	11 (18)	12 (89)
Day 3	0 (20)	0 (23)	0 (80)	n.d.	4 (18)	4 (141)
Day 4	0 (20)	n.d.	n.d.	n.d.	n.d.	0 (20)
Fecal Coliforms[b]						
Day 1	n.d.	3 (10)	n.d.	n.d.	14 (30)	17 (40)
Day 2	0 (20)	0 (23)	0 (28)	n.d.	16 (30)	16 (101)
Day 3	0 (20)	0 (23)	0 (54)	n.d.	1 (18)	1 (115)
Day 4	0 (20)	n.d.	n.d.	n.d.	n.d.	0 (20)
Enterococcus spp.[c]						
Day 1	n.d.	3 (10)	3 (26)	n.d.	17 (30)	23 (66)
Day 2	0 (20)	0 (23)	0 (28)	n.d.	23 (30)	23 (101)
Day 3	1 (20)	0 (23)	1 (80)	n.d.	7 (18)	9 (141)
Day 4	1 (20)	n.d.	n.d.	n.d.	n.d.	1 (20)
TOTAL	2 (180)	9 (168)	5 (350)	n.d.	102 (210)	118 (908)
% of samples	1.1%	5.4%	1.4%	n.d.	49%	13%

Numbers in parentheses indicate total number of stations sampled. n.d.—no data.

[a] Total coliform COP single sample standard = 10,000 MPN/100 ml.
[b] Fecal coliform COP single sample standard = 400 MPN/100 ml.
[c] *Enterococcus* spp. COP single sample standard = 104 MPN/100 ml.

Table 2
Summary of toxicity evaluations (as percent fertilization in the sea urchin assay) for each of the sampling regions for both storm events.

	Santa Clara River			Ballona Creek			San Pedro Shelf			San Diego			Tijuana River			Total		
	>84	84–50	<50	>84	84–50	<50	>84	84–50	<50	>84	84–50	<50	>84	84–50	<50	>84	84–50	<50
Storm 1–2004																		
Day 1	n.d.	n.d.	n.d.	8	0	0	37	1	0	15	2	1	5	13	0	65	16	1
Day 2	n.d.	n.d.	n.d.	22	1	0	72	2	1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	94	3	1
Day 3	18	0	0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	18	0	0	18	0	0	54	0	0
Day 4	n.d.	n.d.	n.d.	21	2	0	74	4	0	18	0	0	17	1	0	130	7	0
TOTAL	18	0	0	51	3	0	183	7	1	51	2	1	40	14	0	343	26	2
% of samples	100	0	0	94.5	5.5	0	96	3.5	0.5	94.4	3.6	2	74	26	0	92.5	7.0	0.5
Storm 2–2005																		
Day 1	n.d.	n.d.	n.d.	11	0	0	52	2	0	n.d.	n.d.	n.d.	18	0	0	81	2	0
Day 2	20	0	0	23	0	0	28	0	0	n.d.	n.d.	n.d.	18	0	0	89	0	0
Day 3	20	0	0	23	0	0	80	0	0	n.d.	n.d.	n.d.	18	0	0	141	0	0
Day 4	20	0	0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	20	0	0
TOTAL	60	0	0	57	0	0	160	2	0	n.d.	n.d.	n.d.	54	0	0	331	2	0
% of samples	100	0	0	100	0	0	99	1	0	n.d.	n.d.	n.d.	100	0	0	99.4	0.6	0

Significant toxicity was chosen to be those values where fertilization was less than 84% (Bay et al., 2003). n.d.—no data.

both storm events, although the COP standards were not always exceeded (Fig. 2). Nearly all of the FIB exceedances occurred in the top 10 m of the water column and in the very nearshore region of the discharge. In 2004, less than 10% of the samples exceeded the COP standards offshore each of the river systems (Table 1). Exceedances tended to be highest during the first day after the storm but were sometimes higher on day 2, especially in the near the Tijuana River during storm 2 (2005). The extent of FIB impact was greatly reduced or absent by the third or fourth day of sampling. Of the three FIBs, the *Enterococcus* spp. threshold was

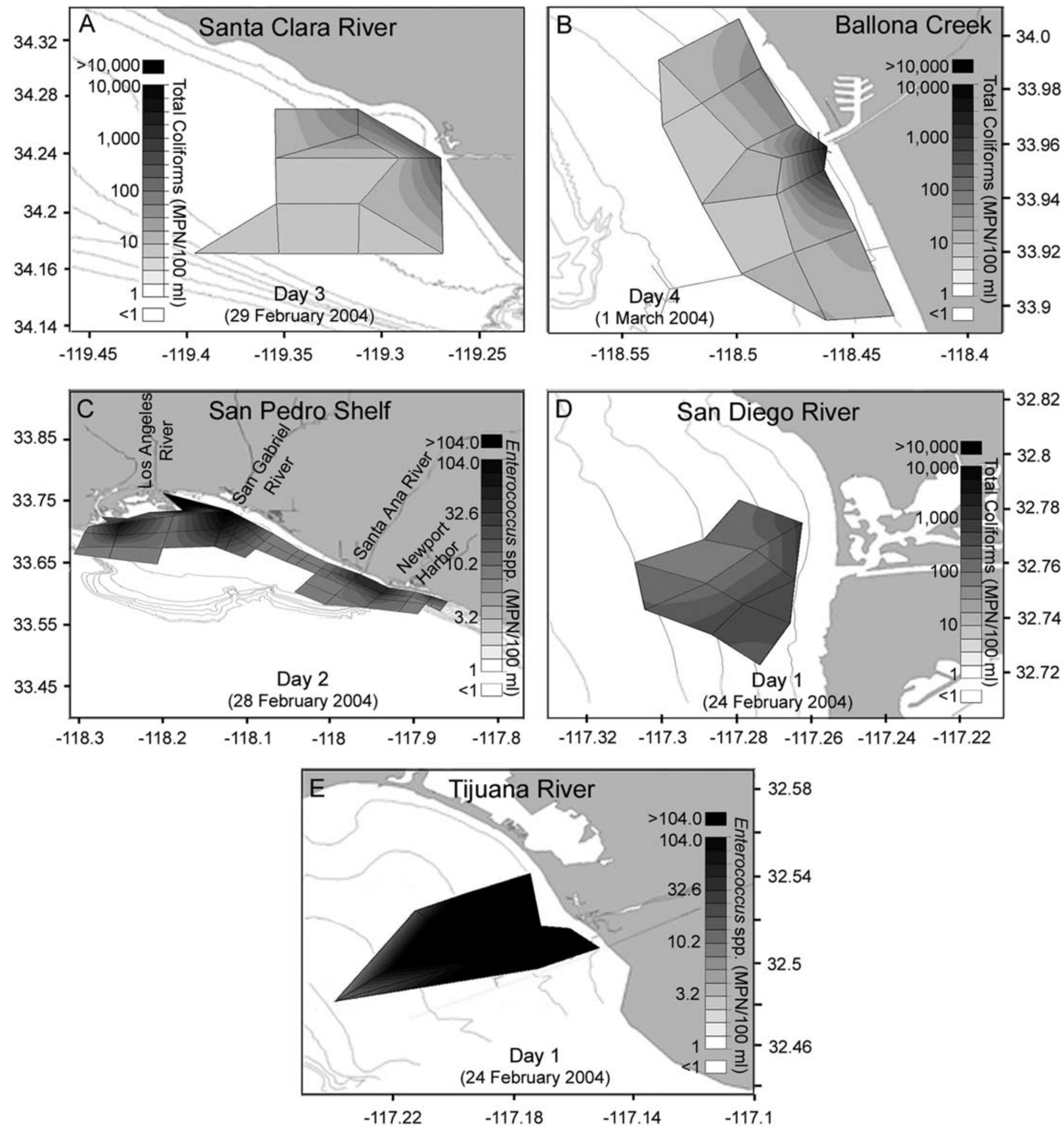

Fig. 2. Spatial distributions of FIBs for each of the five major regions following storm 1 (2004). Similar patterns were observed during storm 2 (2005). Dark areas (red or black) represent areas where a California Ocean Plan standard was exceeded. Note that the colorbars are plotted on log scales. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

most often exceeded. During 2005, the total number of exceedances across all river systems increased (from 7.2% in 2004 to 13% in 2005). However, this was the result of a large increase in exceedances of all FIBs offshore of the Tijuana River where the standards were exceeded in 49% of the samples. Exceedances offshore the Santa Clara River, Ballona Creek, and the San Pedro Shelf were similar or less than those in 2004.

The extent of impacts due to FIBs varied among regions. The San Pedro Shelf and the Tijuana River regions showed the largest areas of impact. During both storms, a large proportion of stations sampled offshore of the Tijuana River (up to 78%) exceeded the single sample standard on at least one day for each FIB group (Table 1; Fig. 2). This suggests that the sampling area may not have been large enough to encompass the entire affected area. Whereas exceedances in all other regions were confined near the major inflows, exceedances near the Tijuana River spanned a large area (Fig. 2). Coastal areas near the Santa Clara and San Diego Rivers appeared to be the least affected during both storms (Table 1). It is conceivable, however, that by the time of sampling, the plumes had advected away from the sampling areas, especially in the Santa Clara River region (Warrick et al., 2007).

3.1.2. Nutrients

The distributions of nutrients offshore of the major regions after each storm tended to mirror FIB distributions. High concentrations were typically found near the river mouths, and nutrient concentrations tended to decrease and disperse over time (Fig. 3). Maximum nitrate concentrations (~40 μM) were found in the San Pedro Shelf region at the mouth of the Los Angeles River. Concentrations of 10–15 μM were also observed off the mouths of Ballona Creek and the Santa Clara River. In the San Diego region, concentrations were elevated but were less than 10 μM. The maximum near-surface nutrient concentrations were greater in 2004 than in 2005. Storm sampling in 2004 occurred one month earlier than in 2005. It is possible that many regions had been flushed out by earlier storm events prior to sampling in 2005 resulting in an overall decrease in nutrient loading from that storm. Another apparent difference between the two years is the higher concentrations of nutrients below 10 m in 2005. These higher concentrations may be due to upwelling occurring along the coast, which usually begins in mid to late March in this region.

3.1.3. Toxicity

Of the over 700 water samples that were analyzed for toxicity by the sea urchin fertilization assay from all surveys and river systems combined, very few exhibited toxicity (Table 2). Only 30 samples were considered toxic (<84% fertilization) and even fewer (2) exhibited highly toxic effects (<50% fertilization). All of these were located in the top 10 m of the water column. The greatest number of toxic samples was observed in the Tijuana River plume on the first day of sampling during the February 2004 event, when the fertilization rate for 13 out of 18 samples (72%) was less than 84%. In contrast, during February 2005 when high bacteria concentrations were observed in the Tijuana River plume, no toxicity values less than 84% fertilization were observed in the plume.

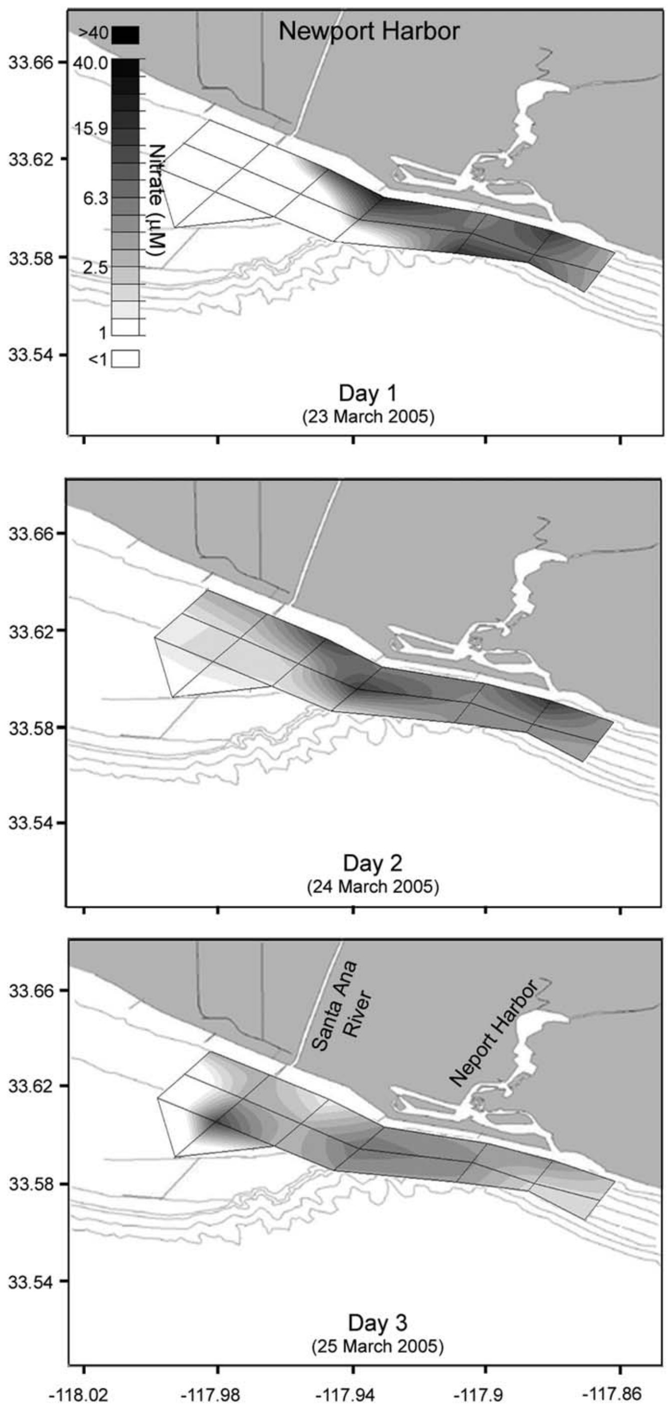

Fig. 3. Surface distributions of nitrate for the Newport Harbor area (including the Santa Ana River and Newport Harbor) for storm 2 (2005) showing the dispersion and dilution of nitrate over time after the storm. Note that the colorbars are plotted on log scales.

3.2. In situ relationships: CDOM vs. salinity and beam-c vs. TSS

CDOM concentration generally increased linearly with decreasing salinity, or increased freshwater content (Fig. 4). The opposite trend was observed in the beam-c vs. TSS relationship. Beam-c generally increased with increasing TSS concentration, with some scatter around the best-fit lines (Fig. 5). The addition of region as an independent variable greatly improved the CDOM/salinity models (increase in adjusted R^2 of ~0.1), and the addition of day after storm resulted in a slight further improvement (increase in adjusted R^2 of 0.01–0.04; Table 3). The addition of both region and day after storm improved the beam-c vs. TSS relationships (increase in adjusted R^2 of 0.04–0.06 and 0.03–0.05,

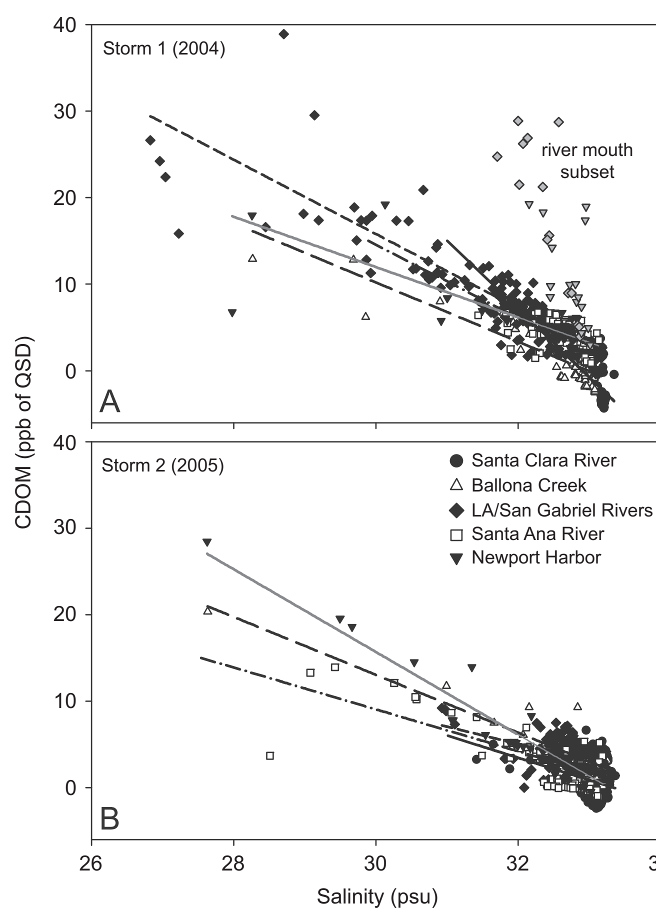

Fig. 4. Relationships between CDOM and salinity separated by region for the 2004 (A) and 2005 (B) storm events. Linear regressions are plotted for the Santa Clara River (solid line), Ballona Creek (long dashed line), Los Angeles/San Gabriel Rivers (short dashed line), Santa Ana River (dot-dashed line), and Newport Harbor (grey line). These lines are plotted for visual purposes and were not used for statistical analyses. CDOM data were not available for the San Diego and Tijuana Rivers. The river mouth subset in storm 1 (A, grey points) consists of three stations in the Los Angeles/San Gabriel Rivers region and three stations near Newport Harbor all located inside or just outside major river mouths (see Section 3.2).

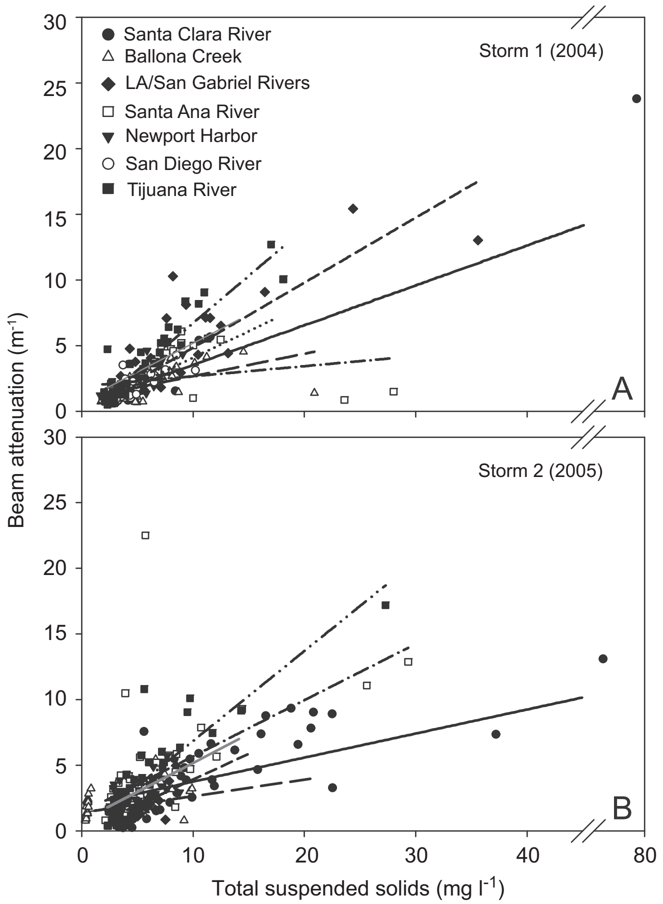

Fig. 5. Relationships between beam attenuation coefficient and total suspended solids separated by region for the 2004 (A) and 2005 (B) storm events. Linear regressions are plotted for the Santa Clara River (solid line) Ballona Creek (long dashed line), Los Angeles/San Gabriel Rivers (short dashed line), Santa Ana River (dot dashed line), Newport Harbor (grey line), San Diego River (dotted line), and Tijuana River (dot dot dashed line). These lines are plotted for visual purposes and were not used for statistical analyses. No data were available for the San Diego River for storm 2.

respectively; Table 3). The CDOM vs. salinity relationship was consistently strong (adjusted R^2 ~0.6 for both storms; Table 3). The relationship between beam-c and TSS, however, varied considerably between the two storm events (adjusted R^2 ranged from 0.4 to 0.7; Table 3).

In analyzing the CDOM vs. salinity relationship, a subset of the samples demonstrated increased CDOM fluorescence with little to no change in salinity (river mouth subset, Fig. 4). Samples within this subset were collected at three stations in the Los Angeles/San Gabriel River region and three stations near Newport Harbor during the 2004 storm event. Four of the six stations were only sampled in 2004. These stations were relatively shallow and were located either just inside or just outside major river mouths. At these stations, CDOM fluorescence was generally high at all depths even though low-salinity waters indicative of stormwater runoff were noted only in surface waters (the top 1 or 2 m). Twardowski and Donaghay (2001) mention that deviations from the typical inverse linear relationship between CDOM and salinity can arise even in coastal waters due to *in situ* CDOM production processes, including sediment resuspension and reworking of the products of primary production. Chen and Bada (1992) noticed that CDOM fluorescence decreased by about 20% after filtration in nearshore samples. In a more recent study, however, Belzile et al. (2006) observed little to no difference in CDOM fluorescence in filtered vs. unfiltered samples. The rapid formation of CDOM from dissolved organic matter precursors exuded by phytoplankton has been observed in several studies (reviewed in Twardowski and Donaghay 2001). Localized phytoplankton blooms tend to persist near the mouth of the Los Angeles River (Hardy, 1993; Gregorio and Pieper, 2000), and elevated concentrations of chlorophyll *a* were observed at stations within the Los Angeles Harbor. Although chlorophyll *a* concentrations were not high at stations near Newport Harbor at the time of sampling, we cannot rule out the production of CDOM from a past localized bloom in that area. Further research is needed to determine whether *in situ* production of CDOM occurs due to processes such as sediment resuspension or production of algal exudates in the Southern California Bight and whether these processes contribute to deviations in the CDOM/salinity relationship.

Table 3
Results of general linear models of CDOM vs. salinity and beam-c vs. TSS with region and day after storm included as additional independent variables.

Independent variable(s)					**Independent variable *P*-value**		
	n	**Slope**	**y-Intercept**	**Adjusted R^2**	**Salinity/TSS**	**Region**	**Day**
CDOM vs. Salinity							
Storm 1–2004							
Salinity	816	−4.576	152.622	0.567	<0.0005	n/a	n/a
Salinity+region	816	−4.021	133.941	0.660	<0.0005	<0.0005	n/a
Salinity+region+day	816	−3.984	132.082	0.664	<0.0005	<0.0005	0.004
Storm 2–2005							
Salinity	1030	−3.416	114.763	0.470	<0.0005	n/a	n/a
Salinity+region	1030	−3.198	107.596	0.569	<0.0005	<0.0005	n/a
Salinity+region+day	1030	−3.169	106.633	0.608	<0.0005	<0.0005	<0.0005
Beam-c vs. TSS							
Storm 1–2004							
TSS	323	0.335	0.609	0.635	<0.0005	n/a	n/a
TSS+region	323	0.339	0.552	0.675	<0.0005	<0.0005	n/a
TSS+region+day	323	0.329	0.545	0.702	<0.0005	<0.0005	<0.0005
Storm 2–2005							
TSS	276	0.258	1.453	0.386	<0.0005	n/a	n/a
TSS+region	276	0.263	1.460	0.451	<0.0005	<0.0005	n/a
TSS+region+day	276	0.237	1.590	0.499	<0.0005	<0.0005	<0.0005

n/a—not applicable.

3.3. In situ contaminant relationships with salinity and TSS

Relationships of nutrients and salinity were variable but were generally negative, i.e. increasing nutrient concentrations with decreasing salinity (Table 4). The addition of region as an independent variable again greatly improved most relationships. The addition of day after storm also improved the models, but in many cases only slightly. Even when both region and day after storm were included; however, the models only explained up to half of the variation in the nutrient data (adjusted R^2 or likelihood $R^2 = 0.26$–0.55; Table 4). Although the data were variable, nutrient concentrations did appear to decrease as the fraction of stormwater decreased (Fig. 6A–D). The largest decrease in all nutrients occurred in the 32–33 psu (1–4% stormwater) salinity range where median nutrient concentrations were 2–3 times lower than in the next lower salinity range (30–32 psu; 4–10% stormwater). Not surprisingly, the relationships between nutrients and TSS, an index of turbidity, were not as strong as the nutrient vs. salinity relationships. GLMs that included region and day after storm as independent variables again explained only up to half of the variation (adjusted R^2 or likelihood $R^2 = 0.19$–0.52; Table 4). When grouped into TSS ranges, higher nutrient concentrations tended to occur at very high concentrations of TSS ($>30\,\mathrm{mg\,l^{-1}}$; Fig. 6E–H).

Relationships between salinity and FIBs were generally negative (Table 4). Unlike the nutrient relationships, the addition of day after storm as well as region improved the models. When both variables were included, the models explained less than half of the variation in the FIB data (likelihood $R^2 = 0.35$–0.48; Table 4). The median FIB concentration dropped below COP standards in the 32–33 psu salinity range (1–4% stormwater) for total coliforms and *Enterococcus* spp. and in the 28–30 psu salinity range (10–16% stormwater) for fecal coliforms (Fig. 7A–D). When salinity values indicated that greater than 10% stormwater was present (<28 and 28–30 psu ranges), the median FIB concentrations often exceeded COP standards. FIBs were generally at very low concentrations, often below the maximum detection limit, in water where the salinity was greater than 32–33 psu. Median FIB concentrations in the greater than 33 psu salinity range were 7–16 times lower than those in the next lower salinity range (32–33 psu).

The relationships between FIBs and TSS were quite weak (Table 4). Similar to the FIBs vs. salinity relationships, the strongest models included both region and day after storm as independent variables. These models, however, explained only a small amount of the variation in the FIB data (likelihood $R^2 = 0.28$–0.40; Table 4). Similar to what was observed with nutrient concentrations, FIBs were characteristically higher in waters with higher TSS loadings ($>30\,\mathrm{mg\,l^{-1}}$; Fig. 7 E–H). This result is somewhat surprising as we generally find that human pathogenic bacteria are associated with smallest size fractions, not with larger particulate size fractions (i.e. $<1\,\mu\mathrm{m}$, J. Fuhrman, personal communication; Ahn et al., 2005). At lower TSS concentrations, FIBs were generally below COP standards, and for fecal coliforms and *Enterococcus* spp., were often below detection limits.

Toxicity showed no patterns with salinity or with TSS (Figs. 6 and 7). The median percent fertilization was around 100% for all salinity and TSS ranges and never fell below 84%.

4. Discussion

The *in situ* measurement of contaminants requires significant effort to both acquire and analyze (especially in a timely manner) samples, limiting the ability to make frequent offshore measurements for FIBs, water column toxicity, and nutrients. The results presented above indicate that impacts from contaminants such as nutrients and FIBs after storm events are generally brief and tend to occur near the major sources of stormwater in the SCB. However, important exceptions to this, such as stormwater from the Tijuana River, do occur.

4.1. How problematic is stormwater?

Relationships of nutrient concentrations with salinity and TSS varied among regions but not between the days sampled. Individual sources of stormwater, therefore, probably differ in nutrient composition, but nutrients seem to decrease in plume waters due to simple mixing and dilution. The conservative mixing of nutrients associated with stormwater runoff has also been observed in past studies (Warrick et al., 2005). The lack of a strong linear relationship indicates that other sources of nutrients, such as upwelling, were likely present in the coastal ocean creating variability in ambient nutrient concentrations. Unlike nutrients, relationships of FIBs with salinity and TSS depended on both region and the number of days after the storm. This indicates that the composition and concentration of FIBs in stormwater runoff varies among regions, and that their concentration within stormwater plumes is dependent on more than just loading and dilution rates. FIBs cannot survive for long periods of time in the surface ocean, and mortality is increased by exposure to ultraviolet radiation (Fujioka et al., 1981; Sinton et al., 2002; Anderson et al., 2005). Therefore, they are likely lost from plume waters faster than they would be through simple mixing with ambient coastal water. Some studies have found relationships between salinity and various contaminants such as nutrients or toxicity (Bay et al., 2003; Ragan, 2003). Others, however, have found no consistent relationship between FIBs and plume tracers (Ahn et al., 2005). Concentrations of contaminants seem to be highly variable, especially when the proportion of stormwater is ~1–4% (see Figs. 6 and 7). We can, however, determine when and where contaminants are likely to exceed COP standards through quick and easy measurements such as salinity and TSS concentration by using the median values as a guideline.

In past studies of the SCB, high concentrations of FIBs and/or toxicity were found in stormwater itself, near sewage outfalls and stormdrains/river outlets, and at sites very nearshore (e.g. beaches and surfzone areas; Geesey, 1993; Bay et al., 2003; Gersberg et al., 2004). The few studies that have attempted to examine FIBs in offshore waters have found that they tend to occur in low concentrations but can exceed California standards offshore of major rivers after storm events (ZoBell, 1941; Ahn et al., 2005). During the Bight ‘03 project, exceedances of COP standards generally occurred near areas of stormwater discharge during the first day or two after the storm event, similar to what was found in these past studies. However, several major exceptions are worth noting.

Waters offshore of the Tijuana River consistently exceeded COP standards for multiple FIBs, and in 2005 the area of exceedance was even larger than what could be mapped based on the fixed sampling grid. Gersberg et al. (2004) also found marked increases in toxicity in the Tijuana River during storm events. The Tijuana River, with a discharge rate of 5–$10\,\mathrm{m^3\,s^{-1}}$, does not have a large flow volume compared to the Los Angeles or San Gabriel River systems whose storm discharge rates often exceed $1000\,\mathrm{m^3\,s^{-1}}$ (see Warrick et al., 2007). This implies that FIBs in the Tijuana River are highly concentrated and are not always rapidly diluted or advected from the region in the three to four days following the storm.

Contrary to prior studies, very few samples collected during the Bight ‘03 survey showed high levels of toxicity, and toxicity

Table 4
Results of general linear models of contaminants vs. salinity and contaminants vs. TSS with region and day after storm included as additional independent variables.

Dependent variable					Independent variable *P*-value[b]		
	n	Slope	y-Intercept	Adjusted R^2	Salinity/TSS	Region	Day
Contaminants vs. Salinity							
Storm 1–2004							
Nitrite	339	−0.460	13.355	0.211[a]	<0.0005	n/a	n/a
Nitrite+region	339	−0.356	10.391	0.423[a]	<0.0005	n/a	n/a
Nitrite+region+day	339	−0.352	10.159	0.484[a]	<0.0005	n/a	n/a
Nitrate	339	−2.663	90.201	0.281	<0.0005	n/a	n/a
Nitrate+region	339	−2.632	88.909	0.337	<0.0005	<0.0005	n/a
Nitrate+region+day	339	−2.733	91.989	0.338	<0.0005	<0.0005	0.383
Phosphate (PO_4)	339	−0.374	13.005	0.327	<0.0005	n/a	n/a
PO_4+region	339	−0.369	12.765	0.435	<0.0005	<0.0005	n/a
PO_4+region+day	339	−0.347	11.989	0.446	<0.0005	<0.0005	0.037
Silicate	339	−3.931	133.361	0.305	<0.0005	n/a	n/a
Silicate+region	339	−3.771	127.709	0.345	<0.0005	<0.0005	n/a
Silicate+region+day	339	−4.014	135.626	0.352	<0.0005	<0.0005	0.112
Total coliforms (TC)	335	−1.542	54.404	0.255[a]	<0.0005	n/a	n/a
TC+region	335	−1.708	59.793	0.316[a]	<0.0005	n/a	n/a
TC+region+day	335	−1.507	54.710	0.394[a]	<0.0005	n/a	n/a
Fecal coliforms (FC)	269	−0.980	33.762	0.092[a]	<0.0005	n/a	n/a
FC+region	269	−1.162	39.705	0.237[a]	<0.0005	n/a	n/a
FC+region+day	269	−0.744	28.244	0.355[a]	<0.0005	n/a	n/a
Enterococcus spp. (ent)	335	−1.260	42.321	0.195[a]	<0.0005	n/a	n/a
Ent+region	335	−1.370	46.124	0.252[a]	<0.0005	n/a	n/a
Ent+region+day	335	−1.071	38.513	0.346[a]	<0.0005	n/a	n/a
Storm 2–2005							
Nitrite	250	−0.038	1.632	0.003	0.176	n/a	n/a
Nitrate+region	250	−0.075	2.848	0.225	0.004	<0.0005	n/a
Nitrate+region+day	250	−0.102	3.719	0.265	<0.0005	<0.0005	0.001
Nitrate	250	−0.372	12.831	0.027[a]	0.002	n/a	n/a
Nitrate+region	250	−0.505	15.225	0.526[a]	<0.0005	n/a	n/a
Nitrate+region+day	250	−0.518	15.767	0.553[a]	<0.0005	n/a	n/a
Phosphate (PO_4)	250	−0.140	5.368	0.064	<0.0005	n/a	n/a
PO_4+region	250	−0.171	6.387	0.431	<0.0005	<0.0005	n/a
PO_4+region+day	250	−0.159	5.975	0.448	<0.0005	<0.0005	0.015
Silicate	250	−2.439	87.454	0.059	<0.0005	n/a	n/a
Silicate+region	250	−3.376	118.136	0.374	<0.0005	<0.0005	n/a
Silicate+region+day	250	−3.590	124.777	0.387	<0.0005	<0.0005	0.040
Total coliforms (TC)	252	−1.830	64.900	0.110[a]	<0.0005	n/a	n/a
TC+region	252	−1.824	64.513	0.301[a]	<0.0005	n/a	n/a
TC+region+day	252	−1.684	60.837	0.382[a]	<0.0005	n/a	n/a
Fecal coliforms (FC)	232	−1.070	37.520	0.040[a]	0.0002	n/a	n/a
FC+region	232	−1.316	44.842	0.370[a]	<0.0005	n/a	n/a
FC+region+day	232	−1.208	42.244	0.434[a]	<0.0005	n/a	n/a
Enterococcus spp. (ent)	276	−1.157	40.116	0.055[a]	<0.0005	n/a	n/a
Ent+region	276	−1.403	47.873	0.421[a]	<0.0005	n/a	n/a
Ent+region+day	276	−1.303	45.294	0.468[a]	<0.0005	n/a	n/a
Contaminants vs. TSS							
Storm 1–2004							
Nitrite	376	0.012	−1.713	0.006[a]	0.130	n/a	n/a
Nitrite+region	376	0.035	−1.385	0.383[a]	<0.0005	n/a	n/a
Nitrite+region+day	376	0.033	−1.328	0.425[a]	<0.0005	n/a	n/a
Nitrate	376	0.193	1.982	0.061	<0.0005	n/a	n/a
Nitrate+region	376	0.241	1.354	0.204	<0.0005	<0.0005	n/a
Nitrate+region+day	376	0.240	1.241	0.201	<0.0005	<0.0005	0.652
Phosphate (PO_4)	376	0.034	0.582	0.112	<0.0005	n/a	n/a
PO_4+region	376	0.039	0.450	0.306	<0.0005	<0.0005	n/a
PO_4+region+day	376	0.038	0.473	0.343	<0.0005	<0.0005	<0.0005
Silicate	376	0.248	3.589	0.049	<0.0005	n/a	n/a
Silicate+region	376	0.352	2.299	0.196	<0.0005	<0.0005	n/a
Silicate+region+day	376	0.358	2.252	0.188	<0.0005	<0.0005	0.636
Total coliforms (TC)	372	0.138	3.124	0.085[a]	<0.0005	n/a	n/a
TC+region	372	0.166	3.289	0.156[a]	<0.0005	n/a	n/a
TC+region+day	372	0.147	5.740	0.296[a]	<0.0005	n/a	n/a
Fecal coliforms (FC)	306	0.091	1.004	0.049[a]	<0.0005	n/a	n/a
FC+region	306	0.134	1.159	0.189[a]	<0.0005	n/a	n/a
FC+region+day	306	0.126	4.075	0.396[a]	<0.0005	n/a	n/a
Enterococcus spp. (ent)	372	0.108	0.303	0.050[a]	<0.0005	n/a	n/a
Ent+region	372	0.127	0.767	0.123[a]	<0.0005	n/a	n/a
Ent+region+day	372	0.108	3.550	0.275[a]	<0.0005	n/a	n/a
Storm 2–2005							
Nitrite	250	0.006	0.363	0.010	0.060	n/a	n/a

Table 4 (*continued*)

Dependent variable					Independent variable *P*-value[b]		
	n	Slope	y-Intercept	Adjusted R^2	Salinity/TSS	Region	Day
Nitrite+region	250	0.004	0.375	0.202	0.268	<0.0005	n/a
Nitrite+region+day	250	0.006	0.357	0.227	0.093	<0.0005	0.012
Nitrate	250	0.092	0.151	0.123[a]	<0.0005	n/a	n/a
Nitrate+region	250	0.044	−1.401	0.494[a]	<0.0005	n/a	n/a
Nitrate+region+day	250	0.041	−1.127	0.518[a]	<0.0005	n/a	n/a
Phosphate (PO_4)	250	0.029	0.620	0.208	<0.0005	n/a	n/a
PO_4+region	250	0.020	0.697	0.418	<0.0005	<0.0005	n/a
PO_4+region+day	250	0.018	0.683	0.436	<0.0005	<0.0005	0.014
Silicate	250	0.538	4.657	0.223	<0.0005	n/a	n/a
Silicate+region	250	0.369	5.885	0.345	<0.0005	<0.0005	n/a
Silicate+region+day	250	0.390	5.425	0.358	<0.0005	<0.0005	0.049
Total coliforms (TC)	252	0.134	4.532	0.062[a]	<0.0005	n/a	n/a
TC+region	252	0.144	4.530	0.241[a]	<0.0005	n/a	n/a
TC+region+day	252	0.118	5.895	0.317[a]	<0.0005	n/a	n/a
Fecal coliforms (FC)	208	0.111	1.596	0.053[a]	<0.0005	n/a	n/a
FC+region	208	0.113	1.585	0.269[a]	<0.0005	n/a	n/a
FC+region+day	208	0.087	3.443	0.351[a]	<0.0005	n/a	n/a
Enterococcus spp.	252	0.115	1.282	0.060[a]	<0.0005	n/a	n/a
Ent+region	252	0.121	1.724	0.306[a]	<0.0005	n/a	n/a
Ent+region+day	252	0.098	3.192	0.366[a]	<0.0005	n/a	n/a

n/a—not applicable.

[a] These are likelihood R^2 values estimated using the cenreg function in NADA.

[b] Note that cenreg calculates one *P*-value for the entire model and does not calculate *P*-values for each independent variable.

was not related to the variables used to track plume location (salinity and TSS). Bay et al. (2003) detected toxicity in samples collected in the Ballona Creek discharge plume when the proportion of stormwater exceeded 10%. Samples outside the Ballona Creek plume were not toxic. In their study, the authors did not use a fixed grid of samples but adapted their stations based on salinity levels always collecting samples both inside and outside the plume. The Bight '03 study was designed to monitor specific locations around major river discharges and not, in most cases, to adaptively track and sample plumes. This design likely missed much of the plumes as evidenced by the small proportion of sites located in low-salinity water. Runoff plumes can be advected through the area of a given sampling grid in as little as a day and are also often advected up or downcoast (Warrick et al., 2007; Nezlin et al., 2008). Because the plume is moving and the sampling grid is stationary, it is likely that even though the sampling was distributed over several days, the evolving discharge plume was not adequately sampled. Relationships between toxicity and variables indicative of plumes may have been detected under a different sampling scheme.

Differences between the results from Bight '03 and other past studies may also be due to differences in the time spans over which sampling took place. In a project of this type, it is difficult to obtain a good time series of observations that span the time from initial discharge to thorough dilution and/or dispersion in the coastal receiving waters. First, the exact timing of the storms is not known in advance, and it is difficult to guarantee the availability of the boat and crew during the event. Second, even if available, the sea state often prevents operations by the vessels typically used for this type of sampling (Nezlin et al., 2007b). And third, it is hard to maintain a sufficiently long time series to follow the evolution of these systems because of the commitments of the technical and scientific crews and vessels to other projects. During Bight '03, no sampling occurred during the initial portions of the runoff events, so the effects of the initial mixing of the stormwater into the coastal ocean were missed. Bay et al. (2003) were able to sample both during as well as immediately after storm events which may also explain the differences in their findings.

4.2. *Feasibility of using CDOM and beam-c to map plumes*

Beam-c and TSS represent two different ways to examine the particulate component of seawater. TSS is a measurement of the concentration, by weight, of particles whereas beam-c is an optical measurement related to both the size and concentration of particles. Because of the dependence of light attenuation on particle size, beam-c depends on the geometrical cross-section of particles per unit volume, not necessarily on TSS concentration alone (Davies-Colley and Smith, 2001). Therefore, changes in particle size and composition (i.e. inorganic vs. organic) can result in a change in beam-c without a corresponding change in TSS. We may expect the relationship between beam-c and TSS to change over space and time as the particle composition could be quite different just after a storm versus several days later due to the rapid sinking of large particles and flocs (Hill et al., 2000; Warrick et al., 2004). Particle composition might also vary among the various regions. Analysis of the Bight '03 data confirms that the relationship between beam-c and TSS varies between regions and over time after a storm event.

Salinity and CDOM both represent concentrations of dissolved constituents. River and runoff systems typically have elevated levels of CDOM that can correlate with salinity, such that CDOM concentration increases with decreasing salinity (Twardowski and Donaghay, 2001; D'Sa et al., 2002). In theory, salinity and CDOM could be used interchangeably as tracers of the dissolved portion of a runoff plume. CDOM has a characteristic absorption spectrum and can therefore also be detected using existing and future satellite-mounted ocean color sensors (e.g. Lee et al., 2002). In the SCB, the composition and concentration of CDOM likely varies among sources of stormwater runoff. It appears that over at least the first few days; however, CDOM concentration decreases in plume waters through simple mixing processes.

5. Conclusions

As part of the Bight '03 program, the effects of runoff from two storms, one in February 2004 and the other in February–March

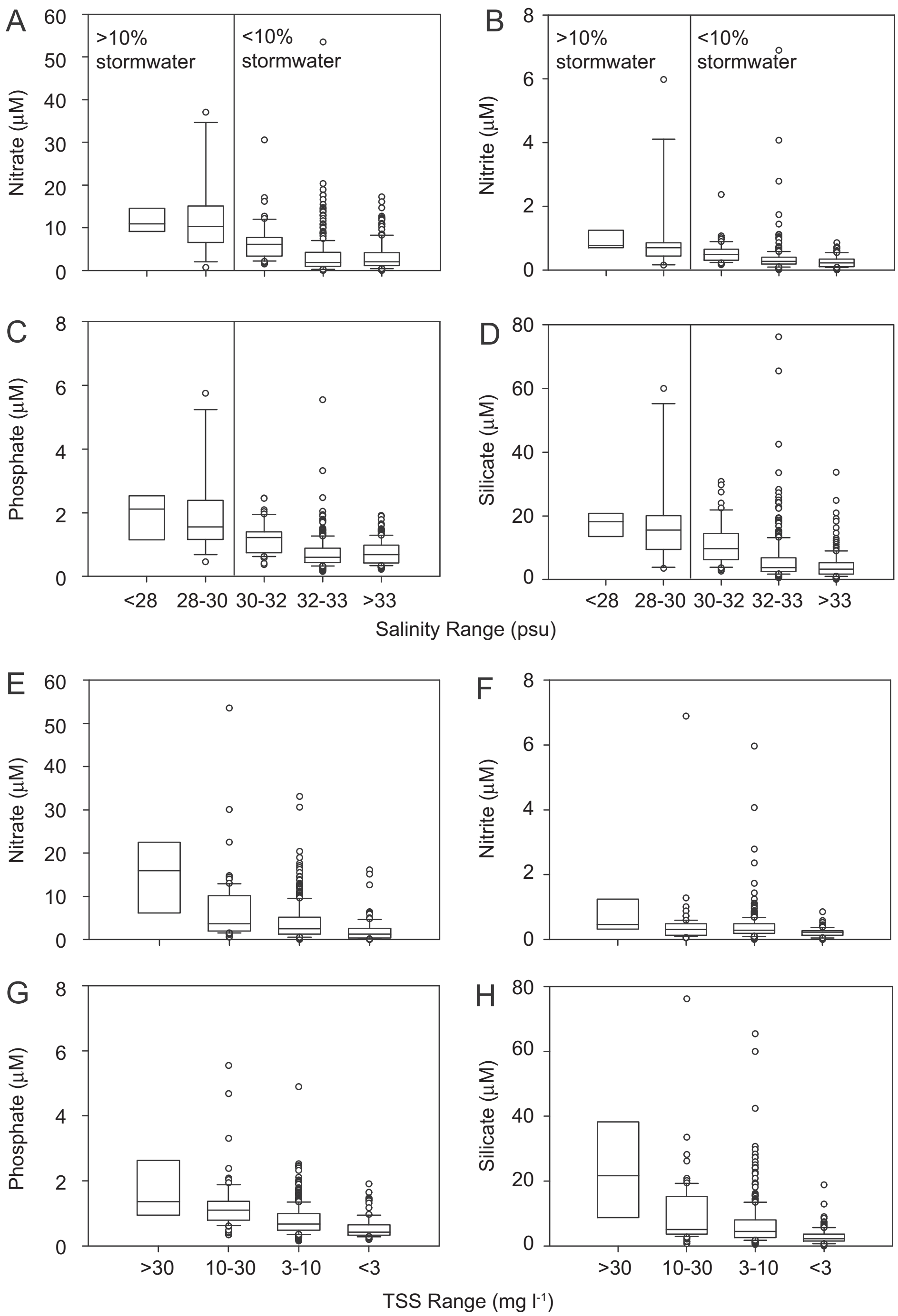

Fig. 6. Box plots showing the medians and quartiles of nutrient concentrations in five salinity ranges (A–D) and four ranges of total suspended solids (E–H). Vertical lines in plots A–D indicate the 10% stormwater salinity level. Whiskers on the box plots extend to the 10th and 90th percentiles. Points outside this range are shown as open circles.

2005, were detailed. The overall impact of the plumes was, in most cases, not large. The areal impacts from bacterial contamination and from water column toxicity were generally constrained to small areas near the river mouths. The worst contamination occurred in the region off the Tijuana River where exceedances of the COP standards persisted for at least 2–3 days following the storm event and extended away from the river mouth. The effects from the rain events were confined primarily to the upper 5–10 m of the water column, and they tended to decrease below threshold levels of concern within 2–3 days. In addition, we found that the chance of exceeding the single COP standards was low in areas containing less than 4–10% (>30–32 psu) stormwater. Dramatic decreases in all FIBs (often to values below detection limits) and nutrients were observed in water with less than 1–4% (>32–33 psu) stormwater.

Detection of stormwater plumes off southern California using ocean color has generally relied on increases in nLw in the 531–551 nm range for MODIS (e.g. Nezlin et al., 2008) and 555 nm for SeaWiFS (e.g. Otero and Siegel, 2004; Nezlin and DiGiacomo, 2005; Nezlin et al., 2005). The increase in nLw at these wavelengths is likely due to increased concentrations of suspended sediments within plumes which increase backscattering.

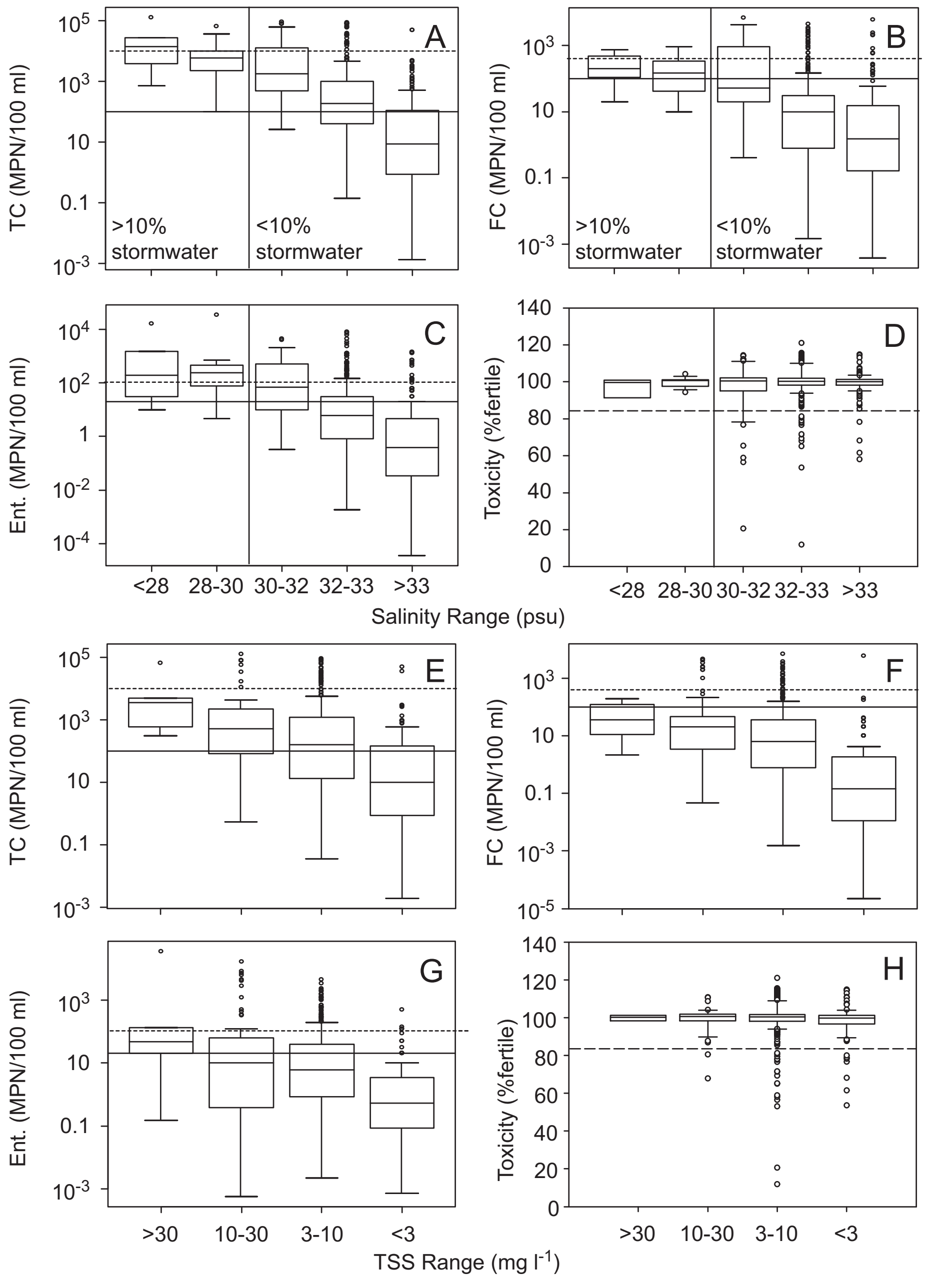

Fig. 7. Box plots showing the medians and quartiles of concentrations of fecal indicator bacteria and toxicity in five salinity ranges (A–D) and four ranges of total suspended solids (E–H). The solid horizontal lines indicate the maximum detection limit. Below this level, the distributions are estimated. The dashed lines indicate the single sample California Ocean Plan standards. The dashed line in the toxicity plots indicates 84% toxicity. Vertical lines in plots A–D indicate the 10% stormwater salinity level. Whiskers on the box plots extend to four times the interquartile range, except in plots in D and H where they extend to the 10th and 90th percentiles. Points outside these ranges are shown as open circles. TC—total coliforms, FC—fecal coliforms, Ent.—*Enterococcus* spp.

This signal is an indication of only the particulate portion of the plume. MODIS ocean color data analyzed as part of the Bight '03 project showed both an increase in nLw within the plume waters at longer wavelengths (primarily 531–551 nm) as well as a decrease in nLw at short wavelengths (primarily 412 nm), the latter potentially explained by light absorption by CDOM (Nezlin et al., 2008). In this manner, it should be possible to use satellite ocean color-derived estimates of CDOM absorption and increased backscatter (increased nLw) at long wavelengths as fairly conservative tracers of stormwater runoff plumes off southern California, representing the dissolved and particulate constituents of the plumes, respectively, as described above.

Analogs for CDOM and beam-c can be derived from the inherent optical properties of the water column, which in turn can be derived from the remote sensing reflectance obtained by satellite ocean color sensors. In this context, methods such as the Quasi-Analytical Algorithm (QAA) developed for deriving inherent optical properties (IOPs) from remotely sensed ocean color measurements (Lee et al., 2002, 2006) are available to do this in complex nearshore waters such as those off southern California, deriving potentially informative properties such as $a_{dg}(412)$ and $b_b(551)$. Strong correlations between CDOM and salinity, and beam-c and TSS indicate that satellite ocean color data can potentially be used to infer and perhaps accurately assess gradients in salinity and turbidity. The actual CDOM/salinity and beam-c/TSS relationships differ among regions and between storm events. Therefore, quantitative estimations of salinity or TSS via satellite ocean color measurements would require building empirical relationships specific to each region. Regardless, ocean color imagery can, and should, be built into regional monitoring programs to provide at a minimum qualitative information on the locations of plumes, locations of areas likely impacted by contaminants, and to guide ship-based monitoring efforts.

Acknowledgements

The authors wish to thank the members of the Bight '03 Steering Committee and all the organizations and individuals that participated in planning, collecting samples, processing, and analysis of the collected data. This study would not have been possible without the exceptional skill of the field sampling personnel from the following organizations: City of San Diego, Orange County Sanitation District, Los Angeles County Sanitation District, City of Los Angeles, Southern California Coastal Water Research Project, Aquatic Bioassay and Consulting Laboratories, Weston Solutions (formerly MEC Analytical Systems, Inc.), and Universidad Autónoma de Baja California. We would also like to thank Brandon Swan for help with statistical analyses. Comments from two anonymous reviewers and Alex Steele helped to improve this manuscript. This work was supported in part by a NASA Oceans & Ice Research Project Award (NRA-04-OES-02) and also through the NASA Earth Systems Science Fellowship Program (NNX06AF70H). The contents of this article are solely the opinions of the authors and do not constitute a statement of policy, decision, or position on behalf of the United States Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA) or the US Government.

References

Ahn, J.H., Grant, S.B., Surbeck, C.Q., DiGiacomo, P.M., Nezlin, N.P., Jiang, S., 2005. Coastal water quality impact of stormwater runoff from an urban watershed in southern California. Environmental Science & Technology 39 (16), 5940–5953.

Anderson, K.L., Whitlock, J.E., Harwood, V.J., 2005. Persistence and differential survival of fecal indicator bacteria in subtropical waters and sediments. Applied Environmental Microbiology 71 (6), 3041–3048.

APHA, 1998a. 9222D. Fecal coliform membrane filter procedure. In: Franson, M.A.H., Clesceri, L.S., Greenberg, A.E., Eaton, A.D. (Eds.), Standard Methods for the Examination of Water and Wastewater 20th edition American Public Health Association, American Water Works Association, Water Environment Federation, Washington, DC, pp. 63–65.

APHA, 1998b. 9221B. Standard total coliform fermentation technique. In: Franson, M.A.H., Clesceri, L.S., Greenberg, A.E., Eaton, A.D. (Eds.), Standard Methods for the Examination of Water and Wastewater 20th edition American Public Health Association, American Water Works Association, Water Environment Federation, Washington, DC, pp. 48–51.

APHA, 1998c. 9221E. Fecal coliform procedure. In: Franson, M.A.H., Clesceri, L.S., Greenberg, A.E., Eaton, A.D. (Eds.), Standard Methods for the Examination of Water and Wastewater 20th edition American Public Health Association, American Water Works Association, Water Environment Federation, Washington, DC, pp. 54–55.

APHA, 1998d. 9222B. Standard total coliform membrane filter procedure. In: Franson, M.A.H., Clesceri, L.S., Greenberg, A.E., Eaton, A.D. (Eds.), Standard Methods for the Examination of Water and Wastewater 20th edition American Public Health Association, American Water Works Association, Water Environment Federation, Washington, DC, pp. 57–62.

Bay, S., Jones, B.H., Schiff, K., Washburn, L., 2003. Water quality impacts of stormwater discharges to Santa Monica Bay. Marine Environmental Research 56 (1–2), 205–223.

Belzile, C., Roesler, C.S., Christensen, J.P., Shakhova, N., Semiletov, I., 2006. Fluorescence measured using the WETStar DOM fluorometer as a proxy for dissolved matter absorption. Estuarine, Coastal and Shelf Science 67 (3), 441–449.

Busse, L.B., Venrick, E.L., Antrobus, R., Miller, P.E., Vigilant, V., Silver, M.W., Mengelt, C., Mydlarz, L., Prezelin, B.B., 2006. Domoic acid in phytoplankton and fish in San Diego, CA, USA. Harmful Algae 5 (1), 91–101.

CDPH, 2006. Draft guidance for salt water beaches. California Department of Public Health, Division of Drinking Water and Environmental Management, Sacramento, CA.

Chen, R.F., Bada, J.L., 1992. The fluorescence of dissolved organic matter. Marine Chemistry 37 (3–4), 191–221.

Coble, P., Hu, C., Gould, R.W.J., Chang, G., Wood, M., 2004. Colored dissolved organic matter in the coastal ocean. Oceanography 17 (2), 50–59.

D'Sa, E.J., Hu, C., Muller-Karger, F.E., Carder, K.L., 2002. Estimation of colored dissolved organic matter and salinity fields in case 2 waters using SeaWiFS: examples from Florida Bay and Florida Shelf. Proceedings of the Indian Academy of Sciences 111 (3), 197–207.

Davies-Colley, R.J., Smith, D.G., 2001. Turbidity, suspended sediment, and water clarity: a review. Journal of the American Water Resources Association 37 (5), 1085–1101.

Del Castillo, C.E., 2005. Remote sensing of organic matter in coastal waters. In: Miller, R.L., Del Castillo, C.E., McKee, B.A. (Eds.), Remote Sensing of Coastal Aquatic Environments. Technologies, Techniques and Applications. Springer, Dordrecht, pp. 157–180.

Fujioka, R.S., Hashimoto, H.H., Siwak, E.B., Young, R.H.F., 1981. Effect of sunlight on survival of indicator bacteria in seawater. Applied Environmental Microbiology 41 (3), 690–696.

Geesey, G.G., 1993. Microbiology. In: Dailey, M.D., Reish, D.J., Anderson, J.W. (Eds.), Ecology of the Southern California Bight. University of California Press, Los Angeles, California, pp. 190–232.

Gersberg, R.M., Daft, D., Yorkey, D., 2004. Temporal pattern of toxicity in runoff from the Tijuana River watershed. Water Research 38 (3), 559–568.

Geyer, W.R., Hill, P., Milligan, T., Traykovski, P., 2000. The structure of the Eel River plume during floods. Continental Shelf Research 20 (16), 2067–2093.

Gordon, L.I., Jennings, J.C.J., Ross, A.A., Krest, J.M., 1993. A suggested protocol for continuous flow automated analysis of seawater nutrients (phosphate, nitrate, nitrite and silicic acid) in the WOCE Hydrographic Program and the Joint Global Ocean Fluxes Study. WHP Operations and Methods. WOCE Hydrographic Program Office, Methods Manual WHPO 91-1, Corvallis, Oregon.

Gregorio, D.E., Pieper, R.E., 2000. Investigations of red tides along the Southern California coast. Bulletin of the Southern California Academy of Sciences 99 (3), 147–160.

Griffith, J., Aumand, L., Lee, I., McGee, C., Othman, L., Ritter, K., Walker, K., Weisberg, S., 2006. Comparison and verification of bacterial water quality indicator measurement methods using ambient coastal water samples. Environmental Monitoring and Assessment 116 (1–3), 335–344.

Hardy, J.T., 1993. Phytoplankton. In: Dailey, M.D., Reish, D.J., Anderson, J.W. (Eds.), Ecology of the Southern California Bight. University of California Press, Los Angeles, California, pp. 233–265.

Helsel, D.R., 2005. Nondetects and Data Analysis. Wiley, New York, NY.

Hill, P.S., Milligan, T.G., Geyer, W.R., 2000. Controls on effective settling velocity of suspended sediment in the Eel River flood plume. Continental Shelf Research 20 (16), 2095–2111.

Lee, L., Helsel, D.R., 2005. Statistical analysis of water-quality data containing multiple detection limits: S-language software for regression on order statistics. Computers & Geosciences 31, 1241–1248.

Lee, Z., Carder, K.L., Arnone, R.A., 2002. Deriving inherent optical properties from water color: a multiband quasi-analytical algorithm for optically deep waters. Applied Optics 41 (27), 5755–5772.

Lee, Z., Carder, K.L., Arnone, R.A., 2006. The quasi-analytical algorithm. In: Lee, Z. (Ed.), Remote Sensing of Inherent Optical Properties: Fundamental Tests of Algorithms and Applications. IOCCG, Dartmouth, Canada, pp. 73–79.

Messer, J.W., Dufour, A.P., 1998. A rapid, specific membrane filtration procedure for enumeration of Enterococci in recreational water. Applied and Environmental Microbiology 64 (2), 678–680.

Monahan, E.C., Pybus, M.J., 1978. Colour, ultraviolet absorbance and salinity of the surface waters off the west coast of Ireland. Nature 274 (5673), 782–784.

National Research Council, 1990. Monitoring southern California Coastal waters. National Academy Press, Washington, DC.

Nezlin, N.P., DiGiacomo, P.M., 2005. Satellite ocean color observations of stormwater runoff plumes along the San Pedro Shelf (southern California) during 1997–2003. Continental Shelf Research 25, 1692–1711.

Nezlin, N.P., DiGiacomo, P.M., Stein, E.D., Ackerman, D., 2005. Stormwater runoff plumes observed by SeaWiFS radiometer in the southern California bight. Remote Sensing of Environment 98, 494–510.

Nezlin, N.P., DiGiacomo, P.M., Weisberg, S.B., Diehl, D.W., Warrick, J.A., Mengel, M.J., Jones, B.H., Reifel, K.M., Johnson, S.C., Ohlmann, J.C., Washburn, L., Terrill, E.J., 2007a. Southern California Bight 2003 regional monitoring program: V. Water quality. Southern California Coastal Water Research Project, Costa Mesa, CA.

Nezlin, N.P., Weisberg, S.B., Diehl, D.W., 2007b. Relative availability of satellite imagery and ship-based sampling for assessment of stormwater runoff plumes in coastal southern California. Estuarine, Coastal and Shelf Science 71 (1–2), 250–258.

Nezlin, N.P., DiGiacomo, P.M., Diehl, D.W., Jones, B.H., Johnson, S.C., Mengel, M.J., Reifel, K.M., Warrick, J.A., Wang, M., 2008. Stormwater plume detection by MODIS imagery in the southern California coastal ocean. Estuarine, Coastal and Shelf Science 80 (1), 141–152.

Ocean Software, 2009. Interactive Graphical Ocean Database System (IGODS).

Opsahl, S., Benner, R., 1998. Photochemical reactivity of dissolved lignin in river and ocean waters. Limnology & Oceanography 43 (6), 1297–1304.

Otero, M.P., Siegel, D.A., 2004. Spatial and temporal characteristics of sediment plumes and phytoplankton blooms in the Santa Barbara Channel. Deep-Sea Research Part II 51 (10–11), 1129–1149.

R Development Core Team, 2006. R: A Language and Environment for Statistical Computing, v. 2.4.1. R Foundation for Statistical Computing, Vienna, Austria.
Ragan, M.A., 2003. Response of inherent optical properties to stormwater runoff in Santa Monica Bay, California. Master of Science, University of Southern California, Los Angeles, CA.
Sakamoto, C.M., Friederich, G.E., Codispoti, L.A., 1990. MBARI procedures for automated nutrient analyses using a modified Alpkem series 300 rapid flow analyzer. MBARI Technical Report No. 90-2. Monterey Bay Aquarium Research Institute, Moss Landing, CA.
Schiff, K.C., Allen, M.J., Zeng, E.Y., Bay, S.M., 2000. Southern California. Marine Pollution Bulletin 41 (1–6), 76–93.
Schiff, K.C., Weisberg, S.B., Raco-Rands, V., 2002. Inventory of ocean monitoring in the southern California bight. Environmental Management 29 (6), 871–876.
Shumway, R.H., Azari, R.S., Kayhanian, M., 2002. Statistical approaches to estimating mean water quality concentrations with detection limits. Environmental Science & Technology 36 (15), 3345–3353.
Siegel, D.A., Maritorena, S., Nelson, N.B., Hansell, D.A., Lorenzi-Kayser, M., 2002. Global distribution and dynamics of colored dissolved and detrital organic materials. Journal of Geophysical Research 107 (C12), 3228, doi:10.1029/2001JC000965.
Sinton, L.W., Hall, C.H., Lynch, P.A., Davies-Colley, R.J., 2002. Sunlight inactivation of fecal indicator bacteria and bacteriophages from waste stabilization pond effluent in fresh and saline waters. Applied Environmental Microbiology 68 (3), 1122–1131.
SSI, 2004a. SigmaPlot, v. 9.01. Systat Software, Inc., Richmond, California.
SSI, 2004b. SYSTAT For Windows, v. 11. Systat Software, Inc., Richmond, California.
State Water Resources Control Board, 2005. California Ocean Plan. Sacramento, California.
Twardowski, M.J., Donaghay, P.L., 2001. Separating in situ and terrigenous sources of absorption by dissolved materials in coastal waters. Journal of Geophysical Research 106 (C2), 2545–2560.
USEPA, 1983. Method 160.2: residue, non-filterable (gravimetric, dried at 103–105 °C). In: Methods for Chemical Analysis of Water and Wastes, EPA 600/4-79/020. United States Environmental Protection Agency, Office of Research and Development, Cincinnati, Ohio, pp. 1602-1–1602-3.
USEPA, 1995. Purple urchin, *Strongylocentrotus purpuratus*, and sand dollar, *Dendraster excentricus*, fertilization test method. In: Chapman, G.A., Denton, D.L., Lazorchak, J.M. (Eds.), Short-Term Methods for Estimating The Chronic Toxicity of Effluents and Receiving Water to West Coast Marine and Estuarine Organisms, EPA600/R-95/136. United States Environmental Protection Agency, Office of Research and Development, Cincinnati, Ohio, pp. 389–465.
Vodacek, A., Blough, N.V., DeGrandpre, M.D., Peltzer, E.T., Nelson, R.K., 1997. Seasonal variation of CDOM and DOC in the Middle Atlantic Bight: Terrestrial inputs and photooxidation. Limnology & Oceanography 42 (4), 674–686.
Warrick, J.A., Mertes, L.A.K., Washburn, L., Siegel, D.A., 2004. A conceptual model for river water and sediment dispersal in the Santa Barbara Channel, California. Continental Shelf Research 24 (17), 2029–2043.
Warrick, J.A., Washburn, L., Brzezinski, M.A., Siegel, D.A., 2005. Nutrient contributions to the Santa Barbara Channel, California, from the ephemeral Santa Clara River. Estuarine, Coastal and Shelf Science 62 (4), 559–574.
Warrick, J.A., DiGiacomo, P.M., Weisberg, S.B., Nezlin, N.P., Mengel, M., Jones, B.H., Ohlmann, J.C., Washburn, L., Terrill, E.J., Farnsworth, K.L., 2007. River plume patterns and dynamics within the Southern California Bight. Continental Shelf Research 27 (19), 2427–2448.
Washburn, L., McClure, K.A., Jones, B.H., Bay, S.M., 2003. Spatial scales and evolution of stormwater plumes in Santa Monica Bay. Marine Environmental Research 56 (1–2), 103–125.
ZoBell, C.E., 1941. The occurrence of coliform bacteria in oceanic water. Journal of Bacteriology 42, 284.