Coastal Water Quality Impact of Stormwater Runoff from an Urban Watershed in Southern California

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Field studies were conducted to assess the coastal water quality impact of stormwater runoff from the Santa Ana River, which drains a large urban watershed located in southern California. Stormwater runoff from the river leads to very poor surf zone water quality, with fecal indicator bacteria concentrations exceeding California ocean bathing water standards by up to 500%. However, cross-shore currents (e.g., rip cells) dilute contaminated surf zone water with cleaner water from offshore, such that surf zone contamination is generally confined to <5 km around the river outlet. Offshore of the surf zone, stormwater runoff ejected from the mouth of the river spreads out over a very large area, in some cases exceeding 100 km^2 on the basis of satellite observations. Fecal indicator bacteria concentrations in these large stormwater plumes generally do not exceed California ocean bathing water standards, even in cases where offshore samples test positive for human pathogenic viruses (human adenoviruses and enteroviruses) and fecal indicator viruses (F$^+$ coliphage). Multiple lines of evidence indicate that bacteria and viruses in the offshore stormwater plumes are either associated with relatively small particles (<53 μm) or not particle-associated. Collectively, these results demonstrate that stormwater runoff from the Santa Ana River negatively impacts coastal water quality, both in the surf zone and offshore. However, the extent of this impact, and its human health significance, is influenced by numerous factors, including prevailing ocean currents, within-plume processing of particles and pathogens, and the timing, magnitude, and nature of runoff discharged from river outlets over the course of a storm.

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Introduction

Oceans adjacent to large urban areas, or "urban oceans", are the final repositories of pollutants from a myriad of point and nonpoint sources of human waste (*1*). Pollutants are transported to the urban ocean by surface water runoff (*1*−*4*), discharge of treated sewage through submarine outfalls (*5*), wet and dry deposition of airborne pollutants (*6*), and submarine discharge of contaminated groundwater (*7*). Until recently, effluent from sewage treatment plants was often the primary source of urban coastal pollution, including nutrients, pathogens, pesticides, and heavy metals (*8*). However, pollutant loading from many sewage treatment plants has declined over the past several decades because of improvements in civil infrastructure (e.g., separation of the storm and sanitary sewer systems to prevent combined sewer overflows), pollutant source control, and disposal/treatment technology (*9*). As a result, surface water runoff, in many cases, has supplanted sewage treatment plants as the primary source of pollutant loading to the urban ocean (*3*, *10*).

The focus of this study is the coastal water quality impact of surface water runoff during storms, or "stormwater runoff", from an urban watershed in southern California. The study was motivated by several considerations. First, beneficial use designations for the coastal ocean in southern California apply year-round and, consequently, watershed managers are legally required to develop stormwater management plans for reducing wet-weather impairments of the coastal ocean (*11*). The impact of stormwater runoff on coastal water quality is of particular concern in arid regions such as southern California because, on an annual basis, a large percentage (>99.9% according to Reeves et al. (*2*) and >95% according to Schiff et al. (*10*)) of the surface water runoff and associated pollution flows into the ocean during a few storms in the winter. Second, while recreational use of the coastal ocean in southern California is lighter in the winter, compared to the summer, winter ocean recreation is still very common, particularly among surfers who surf the large waves that often accompany storm events (R. Wilson, personal communication). Third, to the extent that particles in stormwater runoff are associated with pathogens and other contaminants, their discharge to the ocean during storms may serve as a source of near-shore pollution that persists long after the storm season is over (*10*, *12*). Finally, in many urban watersheds in southern California and elsewhere, the flow of stormwater runoff is highly regulated by civil infrastructure (e.g., dams) designed to minimize flood potential and maximize water reclamation. As will be demonstrated later in this paper, the regulated nature of stormwater runoff implies that the ocean discharge of stormwater runoff from urban watersheds can occur days after the cessation of rain, when the potential for human exposure to pathogens by marine recreational contact is significant.

This paper describes how stormwater runoff from several major rivers in southern California, with particular focus on the Santa Ana River in Orange County, impacts coastal water quality, as measured by turbidity, particle size spectra, total organic carbon, fecal indicator bacteria, fecal indicator viruses, and human pathogenic viruses. The present study is unique in the combination of data resources utilized, including data and information from routine surf zone water quality and wave field monitoring programs, an automated in-situ ocean observing sensor, shipboard sampling cruises, and satellite sensors. Further, this is the first wet weather study to examine the linkage between water quality in the surf zone, where routine monitoring samples are collected

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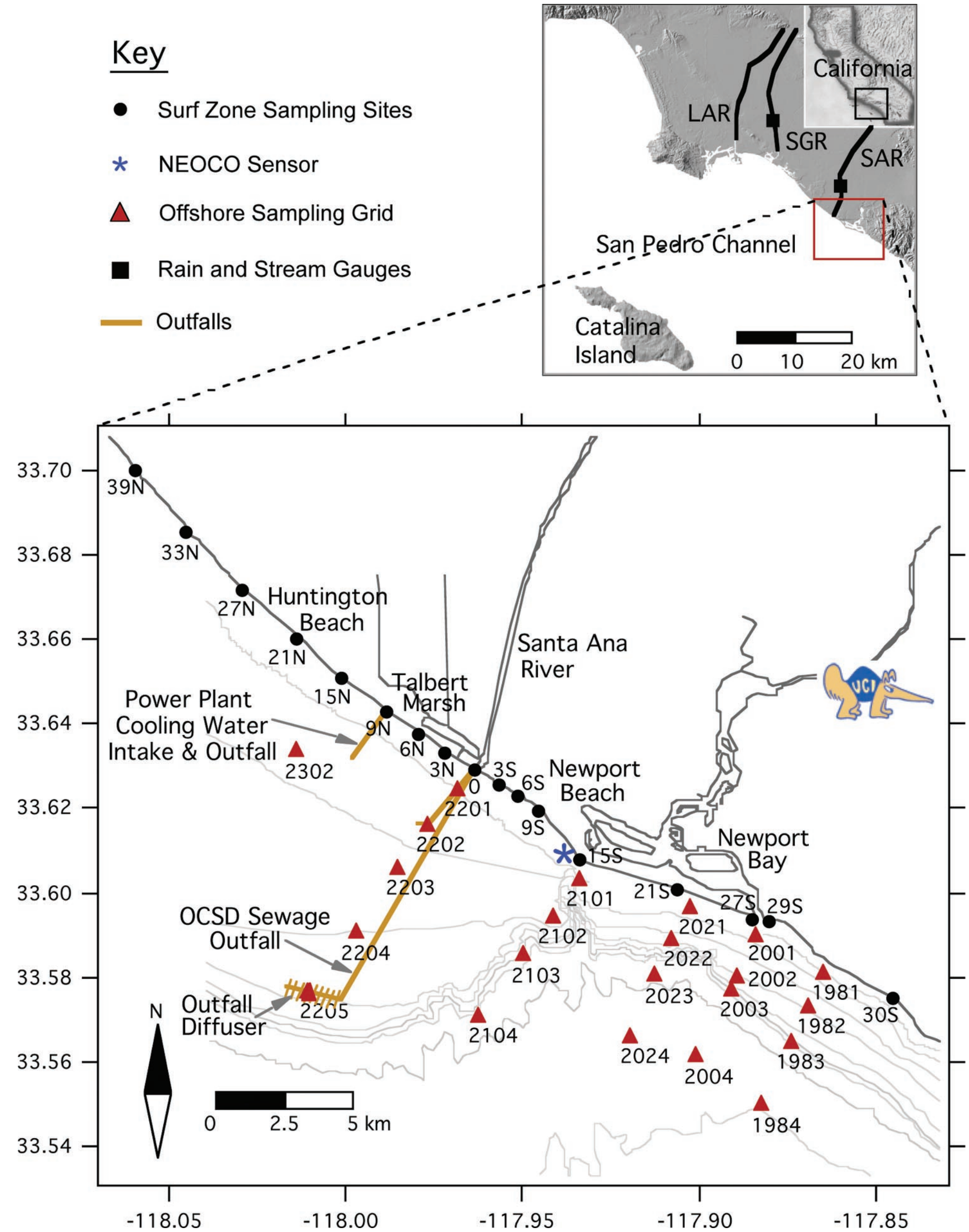

FIGURE 1. Map showing location of field site and sampling sites in the surf zone and offshore. Also shown are the locations of the NEOCO sensor on the end of the Newport Pier and the rain and stream gauges located on the Santa Ana River and the San Gabriel River. Abbreviations are Los Angeles River (LAR), San Gabriel River (SGR), Santa Ana River (SAR), Orange County Sanitary District (OCSD), and University of California, Irvine (UCI).

and most human exposure occurs, and water quality offshore of the surf zone. The work described in this study was carried out in parallel with a watershed-focused study that examined the spatial variability of fecal indicators, and the relationship between suspended particle size and fecal indicators, in storm runoff from the Santa Ana River watershed (*13*). Background information is available elsewhere on coastal water quality impairment at our Orange County field site (*2*, *14*−*18*) and the transport and mixing dynamics of sediment plumes as they flow into the coastal ocean from river outlets in southern California (*4*, *19*, *20*).

Materials and Methods

Rainfall and River Discharge. Weather information and Next Generation Radar (NEXRAD) images for planning the field studies and interpreting rainfall patterns were obtained on-line from the National Weather Service (http://www.nwsla.noaa.gov/). Precipitation and stream discharge data were obtained at two sites, one located where the Santa Ana River crosses 5th Street in the City of Santa Ana and another located where the San Gabriel River crosses Spring Street in the City of Long Beach (black squares in inset, Figure 1). These data were obtained, respectively, from the U.S. Army Corps of Engineers and the Los Angeles County Department of Public Works. Both of these gauge sites are located relatively close (within 11 km) to the rivers' respective ocean outlets, and hence streamflow measured at these sites will likely make its way to the ocean.

Surf Zone Measurements: NEOCO Data. Time series of water temperature, conductivity, chlorophyll, and water depth were obtained from an instrument package deployed at the end of the Newport Pier, where the local water depth is between 6.5 and 9 m (blue star in Figure 1). This instrument package is part of a recently deployed network of coastal sensors in southern California called the Network for Environmental Observations of the Coastal Ocean (NEOCO). The NEOCO sensor package contains an SBE-16plus CTD (Sea-Bird Electronics, Inc., Bellevue, WA) and a Seapoint Chlorophyll Fluorometer (Seapoint Sensors, Inc.). These instruments are mounted on a pier piling at a depth of approximately 1 m (below mean lower low water) and are programmed to acquire data at a sampling frequency of 0.25 min^{-1}.

Surf Zone Measurements: Fecal Indicator Bacteria and Breaking Waves. The concentration of fecal indicator bacteria in the surf zone was measured at 17 stations (black circles along shoreline in Figure 1) by personnel at the Orange County Sanitation District (OCSD). The stations are designated by OCSD according to their distance (in thousands of feet) north or south of the Santa Ana River outlet (e.g., station 15N is located approximately 15 000 ft, approximately 5 km, north of the Santa Ana River outlet). Water samples were collected 5 days per week (not on Friday and Sunday) from 5:30 to 10:00 local time at ankle depth on an incoming wave, placed on ice in the dark, and returned to the OCSD (Fountain Valley, CA) where they were analyzed within 6 h of collection for total coliform (TC), fecal coliform (FC), and enterococci bacteria (ENT) using standard methods 9221B and 9221E and EPA method 1600, respectively. Results are reported in units of colony forming units per 100 mL of sample (CFU/100 mL). Wave conditions, including both the direction and height of breaking waves, were recorded by lifeguards at the Newport Beach pier (near surf zone station 15S, Figure 1) twice per day, once at 7:00 and again at 14:00 local time.

Offshore Measurements: Satellite Ocean Color Imagery. The satellite images used in this study were collected by NASA's Moderate-Resolution Imaging Spectroradiometer (MODIS) instruments. These instruments operate onboard two near-polar sun-synchronous satellite platforms orbiting at 705 km altitude: Terra (since February 24, 2000) and Aqua (since June 24, 2002). Terra passes across the equator from north to south at ~10:30 local time, while Aqua passes the equator south to north at ~13:30 local time. As such, all the images were acquired within 2 h before or after local noon or between 18:00 and 22:00 UTC. The MODIS sensors collect data in 36 spectral bands, from 400 to 14 000 nm. We utilized bands 1 (250-m spatial resolution, 620−670 nm), 3, and 4 (500-m resolution, 459−479 and 545−565 nm, respectively) to produce "true color" (i.e., RGB) images, with band 1 used for the red channel, band 4 for the green channel, and band 3 for the blue channel. Using a MATLAB program, the 500-m green (band 4) and blue (band 3) monochrome channels were "sharpened" to 250-m resolution using fine details from the higher resolution red channel (band 1). Then, the contrast of each of these monochrome channels was increased to emphasize maximum details in the coastal ocean region of interest. Finally, all three monochrome channels (i.e., red, green, and blue) were combined to form a single true color image. In all, 16 satellite images from February 23 to March 5 were acquired and processed for this study; four of them were selected as most illustrative, on the basis of their quality and observed features. The timing of these satellite acquisitions relative to the storms and sampling periods is indicated at the top of Figure 2.

Offshore Measurements: Sampling Cruises. The offshore monitoring grid (red triangles in Figure 1) was sampled during three separate cruises on February 23, February 28, and March 1, 2004, coinciding with a sequence of storm events in late February 2004. Table 1 provides a summary of activities performed during each cruise. A short description of the offshore sampling and analysis protocols is presented here; details can be found in the Supporting Information for this paper. All offshore water samples were analyzed for salinity and fecal indicator bacteria, specifically, total coliform (TC), *Escherichia coli* (EC, a subset of FC), and enterococci bacteria (ENT), using the defined substrate tests known commercially as Colilert-18 and Enterolert (IDEXX, Westbrook, ME) implemented in a 97-well quantitray format; results are reported in units of most probable number of bacteria per 100 mL of sample (MPN/100 mL). A subset of the offshore water samples was analyzed for total organic carbon (TOC) by U.S. EPA Method 415.1, fecal indicator viruses (F^+ coliphage) by a two-step enrichment method (U.S. EPA Method 1601), and human pathogenic viruses (human adenovirus and human enterovirus) by real-time quantitative polymerase chain reaction (Q-PCR), nested PCR, and reverse-transcriptase (RT)-PCR using published protocols (*21*−*25*). Details on the PCR protocols used here can be found in the Supporting Information for this paper.

Coincident with the collection of the offshore water samples, temperature, particle size spectra, and light transmissivity were measured using an LISST-100 (laser in situ scattering and transmissometry) analyzer (Sequoia Scientific, Inc., Bellevue, WA). The LISST-100 estimates the particle volume per unit fluid volume (ΔV) resident in 32 logarithmically spaced particle diameter bins ranging in size from d_p = 2.5 to 500 μm. At least 10 replicates of the particle size spectra were collected at each offshore station. Following the recommendation of Mikkelsen (*26*), ΔV was taken as the median of all replicate measurements. The LISST-100 data are presented in this paper in one of three ways: (1) particle size spectra represented by plots of $\Delta V/\Delta \log d_p$ against log d_p, (2) the number of particles per unit fluid volume or total number concentration (TNC), and (3) the number-averaged particle size, $\bar{d}$. The last two parameters were computed from the particle size spectra as follows (*26*, *27*):

$$\mathrm{TNC} = \sum_{i=1}^{32} \frac{6\Delta V_i}{\pi {d_{p,i}}^3} \tag{1a}$$

$$\bar{d} = \sqrt[3]{\frac{6}{\pi}\frac{\sum_{i=1}^{32} \Delta V_i}{\mathrm{TNC}}} \tag{1b}$$

Results and Discussion

Rainfall and River Discharge. Over the period of study (February 18 through March 3, 2004), four rain events were recorded by the rain gauge on the Santa Ana River in the City of Santa Ana (black curve, top panel, top axis, Figure 2). The first event accumulated 16.0 mm of rain in the afternoon of February 21 (RE_1 in Figure 2), the second event accumulated 23.4 mm of rain in the afternoon of February 22 (RE_2), the third event accumulated 51.3 mm of rain in the evening of February 25 (RE_3), and the fourth event accumulated 6.8 mm of rain in the evening of March 1 (RE_4). The rain gauge located on the San Gabriel River in the City of Long Beach did not record RE_2 but recorded a fifth rain event on February 18 (red curve, top panel, top axis, Figure 2). The difference in rainfall recorded at the Santa Ana River and the San Gabriel River sites is a consequence of the spatial variability of rainfall near the coast (see Figures S1 and S2, Supporting Information, for NEXRAD maps acquired during RE_1 and RE_2). Records of stream discharge (in units of m^3/s) at the Santa Ana River and the San Gabriel River sites are also quite different (black and red curves, top panel, bottom axis, Figure 2). While rainfall and stream discharge are coupled at the San Gabriel River site (i.e., stream discharge increases shortly after locally recorded rain events, compare set of red curves in top panel, Figure 2), rainfall and stream discharge are frequently uncoupled at the Santa Ana River site. For example, the Santa Ana River discharge events DE_3 and DE_4 do not obviously correlate with records of local rainfall. Instead, these two discharge events can be traced to stormwater runoff generated from inland regions of the Santa Ana River watershed

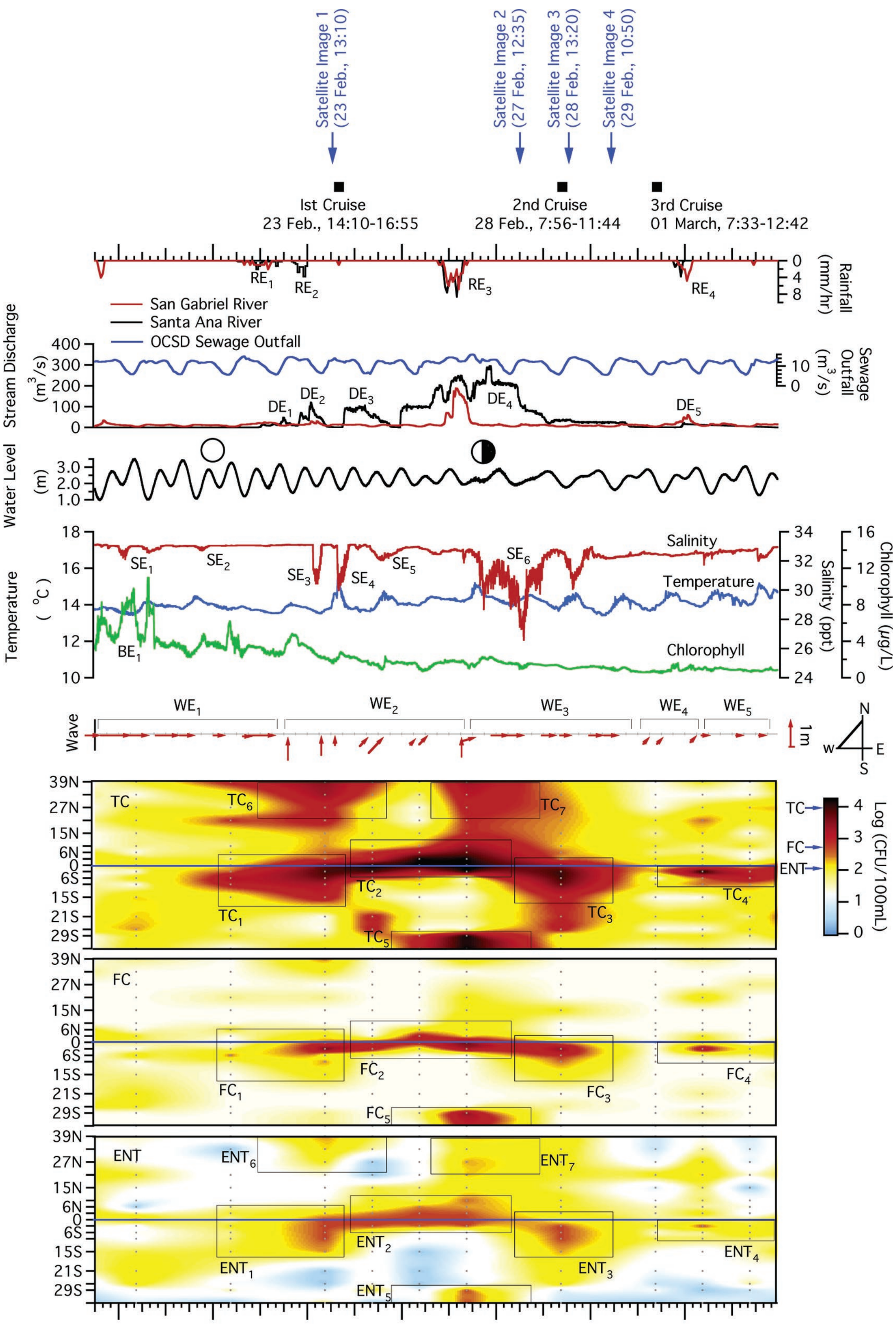

FIGURE 2. Time series measurements of rainfall, stream discharge at the Santa Ana River and San Gabriel River, and discharge of treated sewage from the OCSD outfall (top panel); water level, salinity, temperature, and chlorophyll measured at the NEOCO sensor (second and third panels); the direction and height of breaking waves at the Newport Beach Pier (fourth panel); and the concentration of fecal indicator bacteria in the surf zone (color contour plots, fifth through seventh panels). Shown at the top of the figure is the timing of the satellite images (blue lettering) and the offshore sampling cruises (black squares).

that was released from inland dams after the cessation of rain (*13*). For comparison, we have also included in the plot hourly volume discharge records (unit of m^3/s, blue curve, top panel, Figure 2) of treated sewage discharged from the Orange County Sanitation District (OCSD) sewage outfall (courtesy of OCSD).

TABLE 1. Summary of Analyses Performed during the Sampling Cruises

sampling parameters	methods	number of offshore sites sampled: February 23, 2004	February 28, 2004	March 1, 2004
conductivity[a]	Thermo Orion162A or CTD (SBE-32)	20	21	21
temperature[b]	thermocouple w/ LISST-100 or CTD (SBE-32)	20	21	21
total coliform, *Escherichia coli*, enterococcus[c]	Colillert and Enterolert (IDEXX)	20 (+2 sets of fractionated samples)	21 (+6 sets of fractionated samples)	21
total organic carbon[d]	EPA 415.1	17 (+2 sets of fractionated samples)		
human adenoviruses & enteroviruses[5]	nested PCR RT-PCR	2	6	
fecal indicator viruses (F+coliphage)[e]	two-step enrichment	2	6	
particle size spectra	LISST-100 (light diffraction)	20	16	21
transmissivity	LISST-100	20	16	21

[a] Measured using a Thermo Orion 162A conductivity meter on February 23 and a CTD instrument (SBE-32) on February 28 and March 1. [b] Measured using a thermocouple bundled with an LISST-100 on February 23 and a CTD instrument (SBE-32) on February 28 and March 1. [c] Samples collected by UCI and analyzed by OCSD on February 23 and collected and analyzed by OCSD on February 28 and March 1. Fractionated samples collected and analyzed by UCI on February 23 and 28. [d] Collected by UCI and analyzed by Del Mar Analytical (Irvine, CA). [e] Carried out on the fractionated samples and measured using a real-time PCR for enterovirus and a nested PCR for adenovirus.

Surf Zone Measurements: NEOCO Data. Water level, salinity, temperature, and chlorophyll measurements at the NEOCO sensor, located on the end of the Newport Pier at the offshore edge of the surf zone, are presented in Figure 2 (second and third panels). The largest rain event (RE_3) and the largest discharge of stormwater runoff from the Santa Ana River (DE_4) occurred during a neap tide when the daily tide range was small (see quarter moon and water level measurements in the second panel, Figure 2). The other rainfall and stream discharge events occurred during periods of time when the daily tide range was larger, either during the transition from spring to neap tide (RE_1, RE_2, DE_1, DE_2, DE_3) or during the transition from neap to spring tide (RE_4, DE_5).

Salinity recorded at the NEOCO sensor is characterized by a series of low salinity events, relative to ambient ocean water salinity of 32.5−33.0 ppt (salinity events SE_1−SE_6, Figure 2). These low salinity events may be caused, at least in part, by stormwater discharged from the Santa Ana River (e.g., SE_6 appears to be related to DE_4). However, correlating discharge and the low salinity events is complicated by the fact that once river water is discharged to the ocean, its offshore transport is controlled by a complex set of near-shore currents (*28*). These near-shore currents, and their impact on the spatial distribution of stormwater runoff plumes, are explored in the next several sections. Temperature and chlorophyll records at the NEOCO sensor appear to be relatively unaffected by rainfall or discharge from the Santa Ana River. Surf zone temperature exhibits a diurnal pattern consistent with solar heating (i.e., temperatures are higher during the day and lower at night). Chlorophyll measurements indicate a bloom event occurred early in the study period (bloom event 1, BE_1), but this bloom event mostly dissipated prior to the rain and discharge events that occurred later. While the chlorophyll fluorometer was being maintained during this period, we cannot rule out the possibility that the downward trend in the chlorophyll signal is related to instrument fouling.

Surf Zone Measurements: Wave Data and Along-Shore Currents. Wave conditions, including the direction and height of breaking waves, were recorded twice per day by lifeguards stationed at the Newport Pier (surf zone station 15S, Figure 1). These wave data, which are plotted in the fourth panel of Figure 2, can be divided into five events, depending on whether waves approach the beach from the west (WE_1, WE_3, and WE_5) or from the south to southwest (WE_2 and WE_4). Because this particular stretch of shoreline strikes northwest−southeast (see Figure 1), waves approaching the beach from the west are likely to yield a down-coast surf zone current (i.e., directed to the southeast). Likewise, waves approaching the beach from the south are likely to yield an up-coast surf zone current (i.e., directed to the northwest) (*28*, *29*).

This expectation is consistent with the salinity signal measured at the NEOCO sensor, which is located approximately 5 km down-coast of the Santa Ana River ocean outlet. The onset of low salinity event SE_6 at the NEOCO sensor coincides very closely in time with the change in wave conditions from WE_2 to WE_3 and a likely change in the direction of the surf zone current from up-coast to down-coast (Figure 2). Discharge from the Santa Ana River was particularly high during this period (discharge event DE_4 overlaps wave events WE_2 and WE_3). Hence, the onset of SE_6 was probably triggered by a change in the direction of wave-driven surf zone currents from up-coast during WE_2 to down-coast during WE_3 and a consequent down-coast transport of stormwater runoff entrained in the surf zone from the Santa Ana River during DE_4.

Employing the same logic, low salinity events SE_3−SE_5, which occurred during a period when waves were out of the south to southwest, may have originated from stormwater discharged by river outlets or embayment located down-coast of the NEOCO sensor (e.g., the Newport Bay outlet). Low salinity events SE_1 and SE_2, which occurred during a period when waves were out of the west, may have originated from stormwater discharged by outlets located up-coast of the NEOCO sensor, although no significant discharge from the Santa Ana River was recorded during this period of time.

Some of these low salinity events may have originated from the cross-shore transport of lower salinity water from offshore, perhaps from surface runoff plumes or submarine wastewater fields associated with local sewage outfalls (*16*), or from the submarine discharge of low salinity groundwater (*7*). While the power-plant cooling water intake and outfall appear to affect local circulation patterns offshore of Huntington Beach (*30*), the power-plant effluent consists of pure ocean water and therefore is very unlikely to be a source of the low salinity events documented in Figure 2. It is theoretically possible that the OCSD sewage outfall is a source of SE_1 and SE_2, although there is nothing unusual about the sewage discharge rates observed during these two periods of time (compare SE_1 and SE_2 with the blue curve, top panel, Figure 2).

Surf Zone Measurements: Fecal Indicator Bacteria. The concentrations of the three fecal indicator bacteria groups (TC, FC, and ENT) in the surf zone are presented as a set of color contour plots in Figure 2 (bottom three panels). Fecal indicator bacteria concentrations were log-transformed to visualize the temporal and spatial variability associated with these measurements. For comparison, the California single-sample standards for the three fecal indicator bacteria (10^4 for TC, $10^{2.602}$ for FC, and $10^{2.017}$ for ENT, all CFU or MPN/100 mL) are indicated by a set of arrows on the scale bar in the figure. The concentration of fecal indicator bacteria was frequently elevated around the ocean outlet of the Santa Ana River (near surf zone station 0), particularly during and after rain events when stormwater was discharging from the river. For example, during stormwater discharge events (DE_3 and DE_4), water quality around the Santa Ana River outlet was very poor (see water quality events TC_2, FC_2, and ENT_2 in Figure 2). During this period of time, fecal indicator bacteria concentrations around the Santa Ana River outlet frequently exceeded one or more state standards, in some cases by as much as 300−500% (depending on the fecal indicator group).

The spatial distribution of fecal indicator bacteria in the surf zone around the Santa Ana River outlet appears to be controlled by local wave conditions, in a manner consistent with the earlier discussion of wave-driven surf zone currents. When waves approach the beach from the west and down-coast currents are likely to prevail, the concentration of fecal indicator bacteria in the surf zone is higher on the down-coast side of the ocean outlet (compare WE_1 with TC_1, FC_1, ENT_1 and WE_3 with TC_3, FC_3, ENT_3). Likewise, when waves approach the beach from the south and up-coast currents are likely to prevail, the concentration of fecal indicator bacteria in the surf zone is higher on the up-coast side of the ocean outlet (compare WE_2 with TC_2, FC_2, ENT_2). The exception is a short period of time when relatively small waves (wave height $<$ 0.5 m) approach the beach from the southwest and the concentration of fecal indicator bacteria is higher on the down-coast side of the river (compare WE_4 with TC_4, FC_4, ENT_4). This exception can be rationalized by noting that waves out of the southwest break with their crests parallel to the beach, and hence the direction of long-shore transport in the surf zone is likely to be unpredictable under these conditions. The apparent time delay between change in wave direction (e.g., from WE_1 to WE_2) and change in the spatial distribution of fecal indicator bacteria around the Santa Ana River outlet (e.g., from TC_1 to TC_2) is, at least in part, a sampling artifact. Wave height and direction were recorded twice per day while fecal indicator bacteria concentrations in the surf zone were sampled at most once per day (the gray dots in the color contour plots indicate the timing of surf samples at each station).

Stormwater runoff discharged from the Santa Ana River appears to severely impact water quality in the surf zone over a fairly limited stretch of the beach ($<$5 km either side of the river between surf zone stations 15N and 15S). This spatial confinement of stormwater plumes in the surf zone, which is particularly evident for FC and ENT, could be the result of physical transport processes (e.g., dilution by rip cell mediated exchange of water between the surf zone and offshore) or nonconservative processes (e.g., the removal of fecal indicator bacteria from the surf zone by die-off or sedimentation) (*28*, *29*). An analysis of historical fecal indicator bacteria measurements at Huntington Beach concluded that the length of surf zone impacted by point sources of fecal indicator bacteria, such as the Santa Ana River, is influenced more by rip cell dilution and less by nonconservative processes such as die-off (*31*). The decay length scale reported here of 5 km is very close to the length scale predicted by rip cell dilution alone (2−4 km, assuming a rip cell spacing of 0.5 km) (*31*). Hence, die-off probably plays a secondary role, compared to dilution, in limiting the distance over which water quality is impaired in the surf zone by stormwater runoff from the Santa Ana River.

Fecal indicator bacteria events also occur in the surf zone at the northern (events TC_6, TC_7, ENT_6, ENT_7) and southern (events TC_5, FC_5, and ENT_5) edges of our study area. Possible sources of these fecal indicator bacteria events include stormwater discharged from the Huntington Harbor and Newport Bay Harbor located at the extreme northern (5 km up-coast of station 39N) and southern (stations 27S and 29S) ends of the study site and, possibly, from river outlets located outside of the study area (e.g., the Los Angeles River and San Gabriel River, see inset in Figure 1). Boehm and co-workers (*32*, *33*) suggested that the OCSD sewage outfall might be a source of fecal indicator bacteria in the surf zone at Huntington Beach, particularly during dry weather summer periods. However, compared to the Santa Ana River, the sewage outfall probably had a negligible impact on surf zone water quality at Huntington Beach and Newport Beach during the storm events sampled in this study. This conclusion is based on the following evidence. First, during our study period, sewage effluent discharged by OCSD was chlorinated and the fecal indicator bacteria concentrations in the final effluent (mean of 6000, 400, and 100 MPN/100 mL for TC, EC, and ENT, $n = 17$, C. McGee, personal communication) were significantly below the concentration of fecal indicator bacteria measured in stormwater runoff from the Santa Ana River (mean 17000, 5000, and 8000 MPN/100 mL for TC, EC, and ENT, $n = 30$, Surbeck et al. (*13*)). Second, the peak discharge rate from the OCSD outfall (ca. 13 m^3/s) is much smaller than the peak discharge rate of stormwater runoff from the Santa Ana River (ca. 300 m^3/s) (compare blue and black curves, second panel, Figure 2). Third, the sewage effluent is discharged 6 km offshore of the surf zone through a 1-km-long diffuser located at the end of OCSD's submarine outfall at a water depth of approximately 60 m (hatched region of the outfall pipe in Figure 1). By contrast, stormwater runoff from the Santa Ana River is discharged into the ocean directly at the surf line.

Offshore Measurements: Satellite Ocean Color Imagery. The spatio-temporal distributions of offshore stormwater runoff plumes sampled during this study are revealed by MODIS true color satellite imagery of a 100-km stretch of the coastline centered around our field site (Figure 3). The monitoring grid sampled during the offshore cruises is depicted on the satellite images by yellow dots. The timing of the satellite passes, relative to rain events, discharge events,

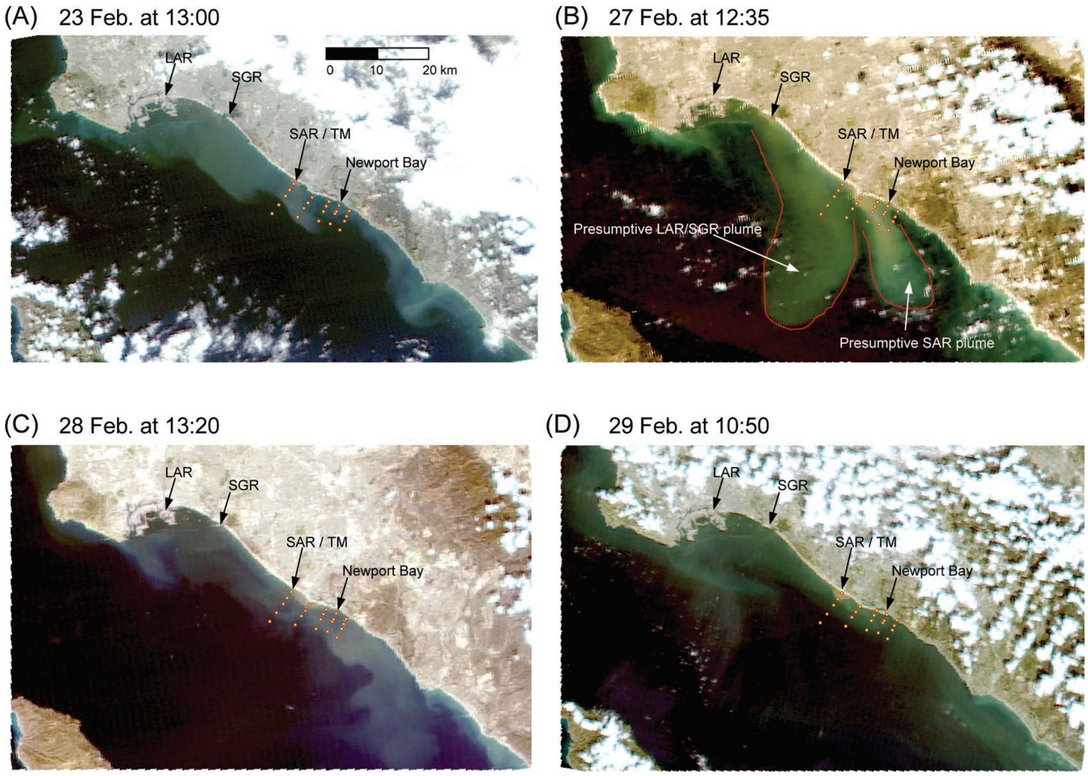

FIGURE 3. MODIS Terra and Aqua true color satellite imagery of stormwater runoff plumes along the San Pedro Channel, California, with nominal spatial resolution of 250 m. Yellow dots indicate location of field sampling stations offshore of Huntington and Newport Beach; black arrows denote the Los Angeles River (LAR) outlet, San Gabriel River (SGR) outlet, Santa Ana River/Talbert Marsh (SAR/TM) outlet, and Newport Bay outlet. (A) MODIS-Aqua, February 23, 2004, at 21:00 UTC (13:00 local time), (B) MODIS-Aqua, February 27, 2004, at 20:35 UTC (12:35 local time), (C) MODIS-Aqua, February 28, 2004, at 21:20 UTC (13:20 local time), (D) MODIS-Terra, February 29, 2004, at 18:50 UTC (10:50 local time).

wave events, surf zone water quality events, and offshore sampling cruises, is indicated at the top of Figure 2.

Generally speaking, in this collection of true color imagery the stormwater runoff plumes appear to be characterized by a band of turbid water turquoise to brown in appearance that is observed along the entire imaged region, although both cross-shelf and along-shore gradients in the color signature are evident. Following the rain events on February 21−22 (total of 39.4 mm, see RE_1 and RE_2 in Figure 2), a MODIS Aqua imagery from February 23 demonstrates the cross-shelf extent of the runoff plume to be variable, ranging from under 1 km in some places to more than 10 km offshore of the Los Angeles River and San Gabriel River (Figure 3A). At our study site, which is centrally located within this broad region, a distinct and apparently heavily particulate-laden runoff plume was observed in the vicinity of the Santa Ana River outlet and nearby station 2201 (see Figure 1 for numerical designation of offshore sampling sites). The Santa Ana River plume extended offshore past station 2203, with an apparent turn down-coast (i.e., southeast), continuing past stations 2104 and 2024. During this time, breaking waves were out of the south and the transport direction of fecal indicator bacteria in the surf zone was directed up-coast, opposite the apparent transport direction of stormwater plumes offshore of the surf zone (compare timing of satellite image 1 with WE_2 and fecal indicator bacteria events TC_2, FC_2, and ENT_2, Figure 2). It also appears that a portion of the Los Angeles River and the San Gabriel River stormwater plumes may have advected south and comingled with the Santa Ana River stormwater plume. Further south, offshore particulate loadings off the Newport Bay outlet (station 2001) do not appear to be as large as those off the Santa Ana River outlet.

A MODIS image on February 27 revealed two distinct plumes of considerable size and offshore extent (Figure 3B). This satellite acquisition preceded by 1 day the sampling cruise on February 28 (described in the next section), followed the large precipitation event on February 25−26 (total of 51.3 mm, see RE_3 in Figure 2), and followed the large discharge event from the Santa Ana River (DE_4, in Figure 2). The plume to the northwest in this image appears to be associated with the Los Angeles River or the San Gabriel River outlets, with an approximate areal extent of 450 km^2. The plume to the southeast appears to be distinct from the former plume and likely originated from the Santa Ana River outlet, with an approximate areal extent of 100 km^2 (the presumptive Los Angeles River, San Gabriel River, and Santa Ana River plumes are delineated by red lines in Figure 3B). The February 27 Santa Ana River stormwater plume is considerably larger in size than the one observed on February 23 (compare Figure 3A and 3B), consistent with the very large volume of water discharged from the Santa Ana River just prior to this satellite acquisition (approximately 4×10^7 m^3, see DE_4 in Figure 2). Further, the Los Angeles River, San Gabriel River, and Santa Ana River runoff plumes on February 27 differed from those on February 23 in that they penetrated farther offshore (30 km compared to 10 km) and thus potentially transported more sediments into the deep waters of the San Pedro Channel.

The jetlike appearance of the presumptive Los Angeles River, San Gabriel River, and Santa Ana River stormwater runoff plumes in Figure 3B has been observed elsewhere in the Southern California Bight, for example, off the Santa Clara River discharge (*4*, *29*), and is potentially the result of inertia-driven flow. At the time of this second satellite acquisition, breaking waves out of the west, and along-shore transport in the surf zone and offshore of the surf zone, appear to be directed down-coast (compare timing of satellite image 2 with WE_3 and fecal indicator events TC_3, FC_3, and ENT_3).

Subsequent MODIS true color imagery on February 28 (Figure 3C) and February 29 (Figure 3D) indicates that both

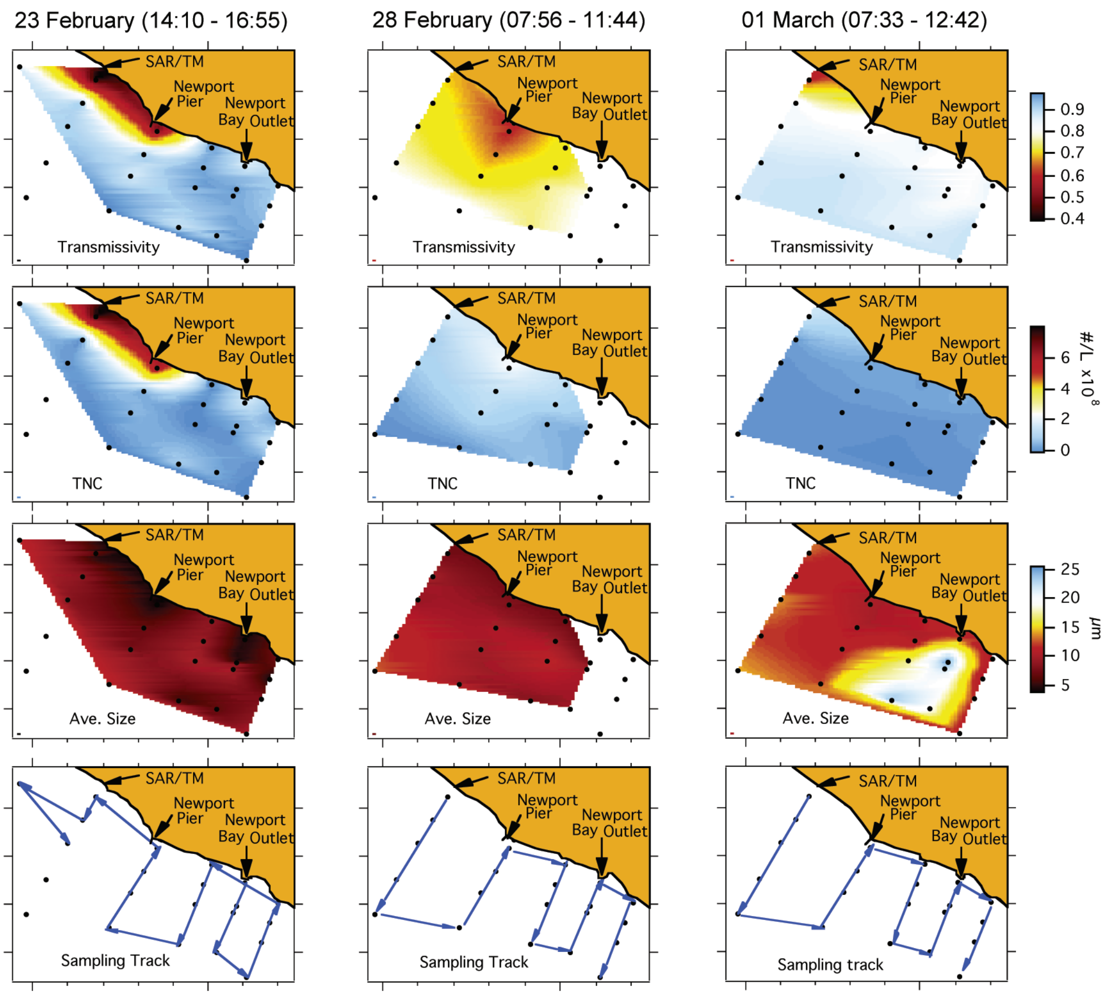

FIGURE 4. Particle measurements collected during the three sampling cruises. The bottom row of panels indicates the sampling track. TNC is an abbreviation for total particle number concentration. TNC and number-averaged particle size were calculated from measured particle size spectra using eq 1a, b.

the Los Angeles River/San Gabriel River and the Santa Ana River runoff plumes had significantly decreased in size, consistent with reduced flow out of the respective rivers (compare stream discharge curves with timing of satellite images 2 and 3, Figure 2). However, particulate matter appeared to remain high in the general vicinity of the Santa Ana River outlet. Whereas this zone of elevated particulate matter extended south to at least station 2021 on February 27–28, by February 29 it had receded somewhat and was fairly localized around station 2201. Unfortunately, no satellite imagery was available the following day (March 1) to complement the third sampling cruise, given persistent regional cloud cover that day.

Offshore Measurements: In-Situ Turbidity and Number-Averaged Particle Size. In-situ turbidity measurements collected during the three offshore cruises are presented as a series of color contour plots in Figure 4. During the February 23 cruise, a region of high turbidity, as evidenced by low transmissivity and high TNC, is evident offshore of, and to the south of, the Santa Ana River outlet (left-hand column of panels, Figure 4). The number-averaged particle size is depressed in this same region, as well as in the region offshore of the Newport Bay outlet. During subsequent cruises, the ocean became progressively less turbid closer to shore (although not necessarily offshore), as evidenced by increasing transmissivity and decreasing TNC, and the number-averaged particle size progressively increased (second and third columns, Figure 4). These results suggest that, offshore of the surf zone, particle size was steadily increasing and particle concentrations were steadily decreasing following the rain and stream discharge events that ended on, or before, the evening of February 27. The above turbidity patterns are generally consistent with the plume signatures and gradients observed in the true color satellite imagery (Figure 3), although some differences exist which could result from the offset timing (up to several hours) between the acquisition of the satellite images and the field measurements. As a technical aside, the number-averaged particle size ($\bar{d}$, see eq 1b) and the median particle size (d_{50}) follow similar trends (i.e., they both rise and fall together), although the magnitude of d_{50} was approximately 16-fold larger (Figure S3, Supporting Information). For the results presented here, $\bar{d}$ was chosen because it emphasizes changes in the small end of particle size spectra.

Offshore Measurements: Fecal Indicator Bacteria. Water quality test results from the three offshore cruises are presented as a set of color contour plots in Figure 5. During the February 23 cruise, the concentration of fecal indicator bacteria exceeded the California single-sample standards for TC, ENT, and EC in several samples collected just offshore, and to the south, of the Santa Ana River and Newport Bay outlets (left-hand column of panels in Figure 5). Nevertheless, the highest concentrations measured offshore of the surf zone are generally lower, in many cases by several orders of magnitude, compared to the highest concentrations measured in the surf zone (compare concentration scales for EC, FC, and ENT in Figures 2 and 5). The difference in offshore and surf zone fecal indicator bacteria concentrations is even

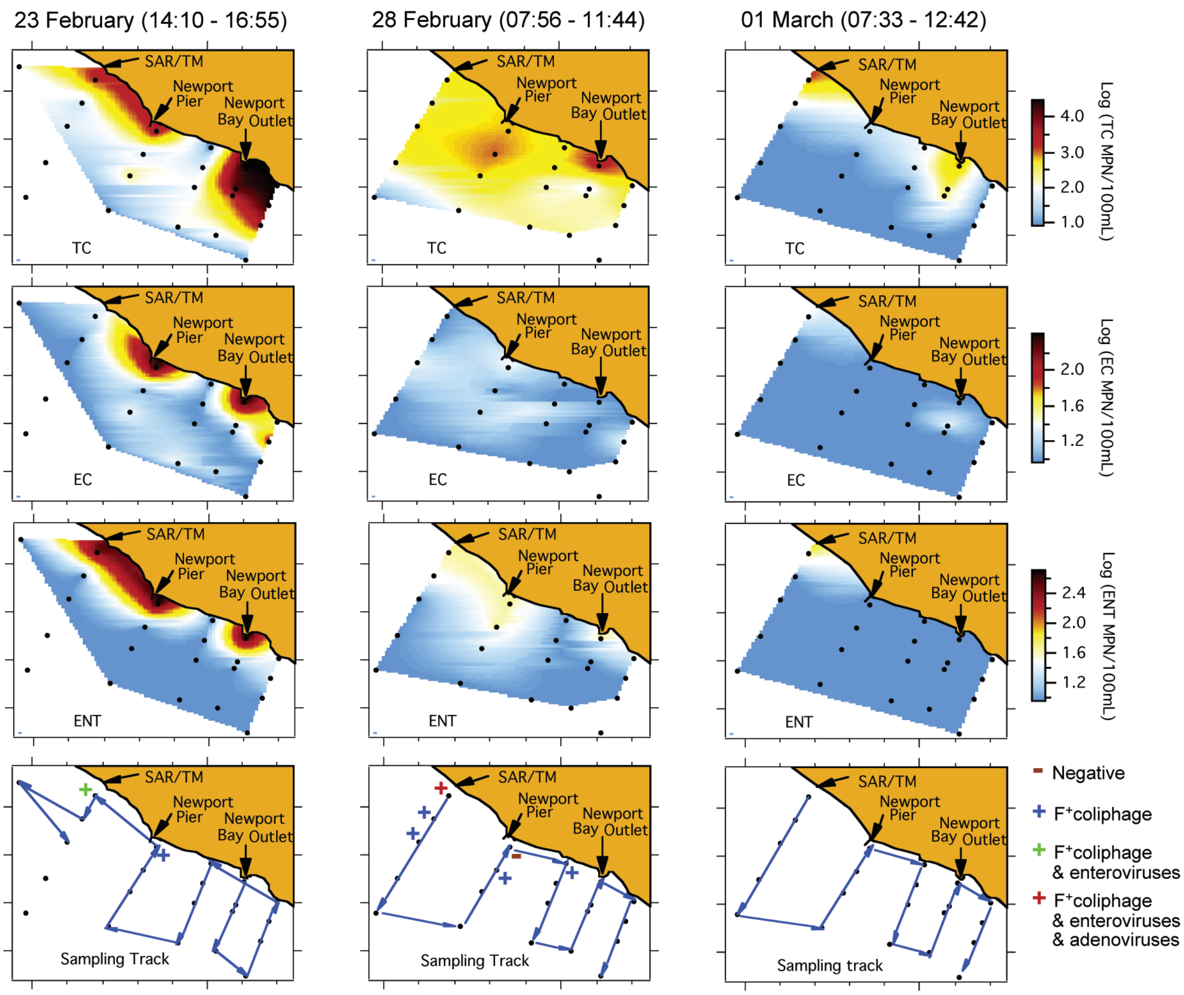

FIGURE 5. Fecal indicator bacteria concentrations measured during the three sampling cruises. The bottom row of panels indicates the sampling track (blue arrows) and the detection of F$^+$ coliphage and human viruses. SAR/TM is an abbreviation for the outlet of the Santa Ana River and Talbert Marsh.

more pronounced during the later cruise dates. For example, none of the samples collected during the February 28 and March 1 cruises exceeded state standards for fecal indicator bacteria, yet several of the samples collected from the surf zone during the same time period exceeded single-sample standards for one or more fecal indicator bacteria groups (compare concentrations measured during the second cruise date with TC_3, FC_3, and ENT_3 and concentrations measured during the third cruise date with TC_4, FC_4, and ENT_4, Figures 2 and 5).

Offshore Measurements: F$^+$ Coliphage and Human Viruses. Offshore samples tested positive for F$^+$ coliphage ($n = 8$, see Table 1), with the exception of a single sample collected on the February 28 cruise from offshore of the Newport Pier (blue, green, and red plus symbols, bottom panels, Figure 5). Human adenoviruses and enteroviruses were detected by real time Q-PCR, nested PCR, and RT-PCR in a sample collected from station 2201 located directly offshore of the Santa Ana River outlet during the February 28 cruise (red plus, middle bottom panel, Figure 5). The concentration of human adenoviruses in this sample is estimated to be 9.5×10^3 genomes per liter of water, which is approximately equivalent to 10 plaque forming units per liter of water, according to a laboratory study comparing Q-PCR results with plaque assay (*35*). Human enteroviruses were also detected in a sample collected directly offshore of the Santa Ana River outlet (station 2201) on the February 23 cruise (green plus, bottom left panel, Figure 5). While relatively few samples were tested for human viruses ($n = 8$), these results demonstrate that human viruses are present in surface water offshore of the Santa Ana River outlet following storm events, even when the fecal indicator bacteria concentrations are below state standards (e.g., station 2201 during the February 28 cruise, Figure 5). These results are consistent with previous observations that human pathogenic viruses and fecal indicator viruses persist longer than fecal indicator bacteria in ocean water (*36*). Direct PCR measurement of pathogenic viruses in highly turbid water is challenging because of PCR inhibition (*35*).

Offshore Measurements: Relationship between Fecal Indicator Bacteria, Turbidity, and Number-Averaged Particle Size. Turbidity has been suggested as a possible proxy for water quality (*37, 38*). However, on the basis of our offshore data, turbidity per se appears to be an inconsistent proxy for the concentration of fecal indicator bacteria. For example, during the February 23 cruise, there is good coherence between turbidity and TC, EC, and ENT concentrations off the Santa Ana River outlet and Newport Pier (compare transmissivity and TNC with fecal indicator bacteria results, left-hand column of panels, Figures 4 and 5). However, turbidity is low off of the Newport Bay outlet where the bacteria concentrations are particularly high. In addition, there are no consistently robust relationships between shipboard measurements of fecal indicator bacteria and shipboard measurements of TOC, temperature, or salinity (see Figure S4, Supporting Information). The number-averaged particle size, on the other hand, comes close to matching the along-shore spatial pattern of fecal indicator

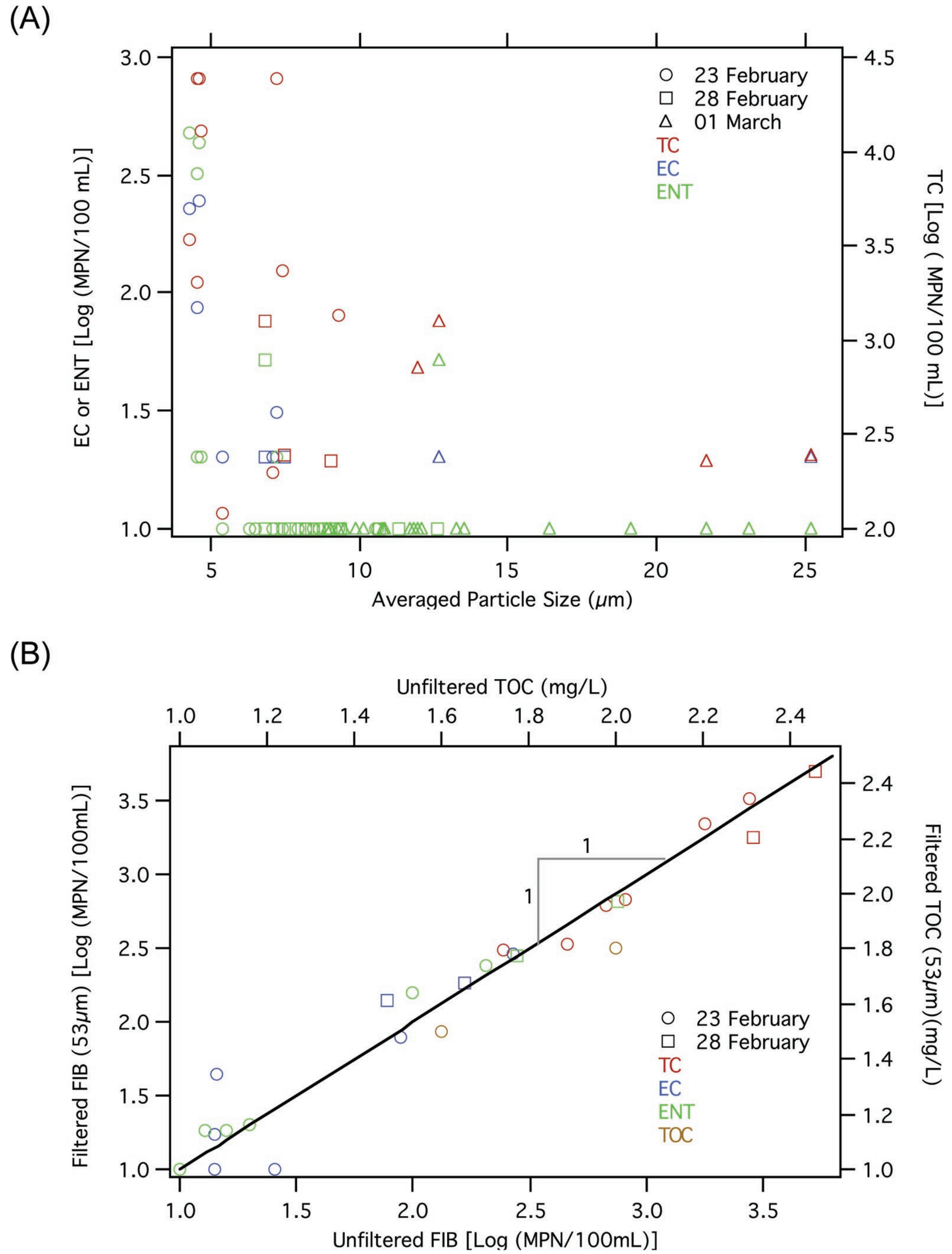

FIGURE 6. (A) Cross plots of log-transformed fecal indicator bacteria concentrations measured in samples collected during the three offshore cruises, against the corresponding number-averaged particle size. (B) Cross plots of log-transformed fecal indicator bacteria concentrations and TOC concentrations measured in samples collected during the three offshore cruises, before and after filtration through a 53-μm sieve. The one-to-one line corresponds to the case where the concentrations are the same before and after filtration.

bacteria measured during the February 23 cruise. Specifically, elevated fecal indicator bacteria concentration appears to correlate with depressed number-averaged particle size (compare fecal indicator bacteria and number-averaged particle size results for the February 23 cruise, left-hand column of panels, Figures 4 and 5). When all of the fecal indicator bacteria data collected during the three cruises are aggregated and plotted against number-averaged particle size, an inverse relationship between these two parameters emerges; specifically, samples with elevated fecal indicator bacteria concentrations also exhibit small number-averaged particle size (Figure 6A). Moreover, the concentration of fecal indicator bacteria in water samples collected during the first two cruises is the same, within error, before and after filtration through a 53-μm sieve (Figure 6B), implying that fecal indicator bacteria are either adsorbed to particles smaller than 53 μm or are not particle-associated. TOC also appears to pass through the 53-μm sieve (Figure 6B) as do human viruses and fecal indicator viruses (data not shown). The co-occurrence of small particles and indicators of fecal pollution (fecal indicator bacteria, fecal indicator viruses, and human pathogenic viruses) does not necessarily imply that the latter are adsorbed to the former. The inverse relationship evident in Figure 6A, for example, may reflect a temporal evolution of stormwater plumes as they age, from a predominance of small particles and high concentrations of fecal indicators initially, to larger particles and lower concentrations of fecal indicators later.

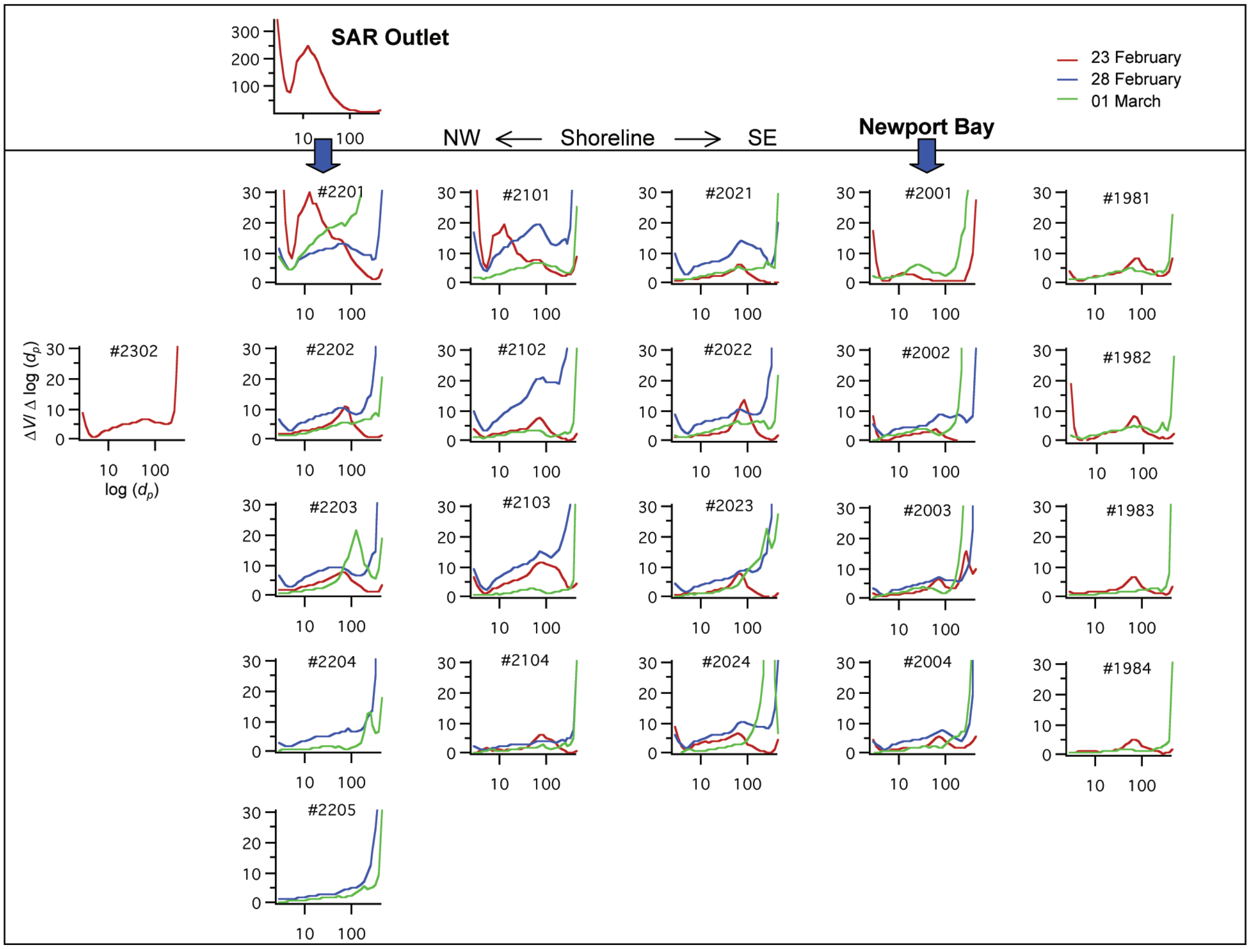

FIGURE 7. Particle size spectra measured during the three offshore cruises; numbers at the top of each panel denote the station number where the particle size spectra were measured (see Figure 1). The vertical axis in each plot represents the particle volume resident in logarithmically spaced particle diameter bins; the horizontal axis represents the diameter of the particles (in μm). These plots are arranged so that the stations progress from onshore to offshore (top to bottom) and up-coast to down-coast (left to right). The single plot labeled "SAR Outlet" corresponds to a particle size spectrum measured in stormwater runoff flowing out of the Santa Ana River outlet, just upstream of where it flows over the beach and into the ocean.

Offshore Measurements: Particle Size Spectra. Particle size spectra acquired during the three cruises are presented in Figure 7. Each plot displays the normalized particle volume (vertical axis) detected in 32 logarithmically spaced particle diameter bins ranging in size from 2.5 to 500 μm (horizontal axis). The particle size spectrum measured at a particular offshore location and time appear to be related to the specific stormwater plume the particles are associated with and, possibly, the elapsed time stormwater has spent in the ocean. Stormwater flowing out of the Santa Ana River during the February 23 cruise, for example, is characterized by two modes at the small end of the size spectrum, one in the <5 μm bin and another in the 10–50 μm bins (set of red curves, Figure 7). These modes are present in stormwater runoff sampled at several locations in the Santa Ana River watershed (*13*), in samples collected at the ocean outlet of the Santa Ana River (panel labeled "SAR Outlet" at top of Figure 7), and in samples collected just offshore (red curve at station 2201, Figure 7) and down-coast (red curve at station 2101, Figure 7) of the Santa Ana River outlet. Particles discharged from the Santa Ana River appear to dilute and merge into a background turbidity characterized by a single broad mode in the 50–300 μm size range (evident in the red curves at most stations, Figure 7).

Referring to Figure 3A and the earlier discussion of this satellite image, the 50–300 μm mode observed on February 23 may be characteristic of a large runoff plume originating from one or more up-coast sources of stormwater runoff, most likely the Los Angeles River or the San Gabriel River. Several factors can lead to artifacts in the particle size spectra estimated from the light-scattering instrument deployed in this study (*39*). However, in our case this caveat is mitigated somewhat by the observation that particle volume fractions calculated from the particle size spectra are strongly correlated (Spearman's rank correlation $Sp = 0.90$, $p = 0.02$) with independent measurements of total suspended solids (data not shown).

During the second and third cruises, the particle size spectra progressively coarsen with the result that, by March 1, virtually all of the particle volume is associated with the largest size bin (>500 μm, green curves in Figure 7). The observed temporal evolution in particle size spectra, from high turbidity and multiple modes at the lower end of the particle size spectrum to low turbidity and a single mode at the large end of the particle size spectrum, may reflect decreasing particle supply (i.e., reduced stormwater discharge from major river outlets) coupled with within-plume coagulation of particles into larger size classes and, ultimately, removal of the largest particles by gravitational sedimentation. Coagulation time scales estimated from these particle size spectra measurements are short (minutes to hours or longer) compared to time scales associated with the generation and offshore transport of stormwater plumes (hours to days), and hence coagulation cannot be ruled out as an important mechanism at our field site (see Supporting Information for details on the time scale calculations).

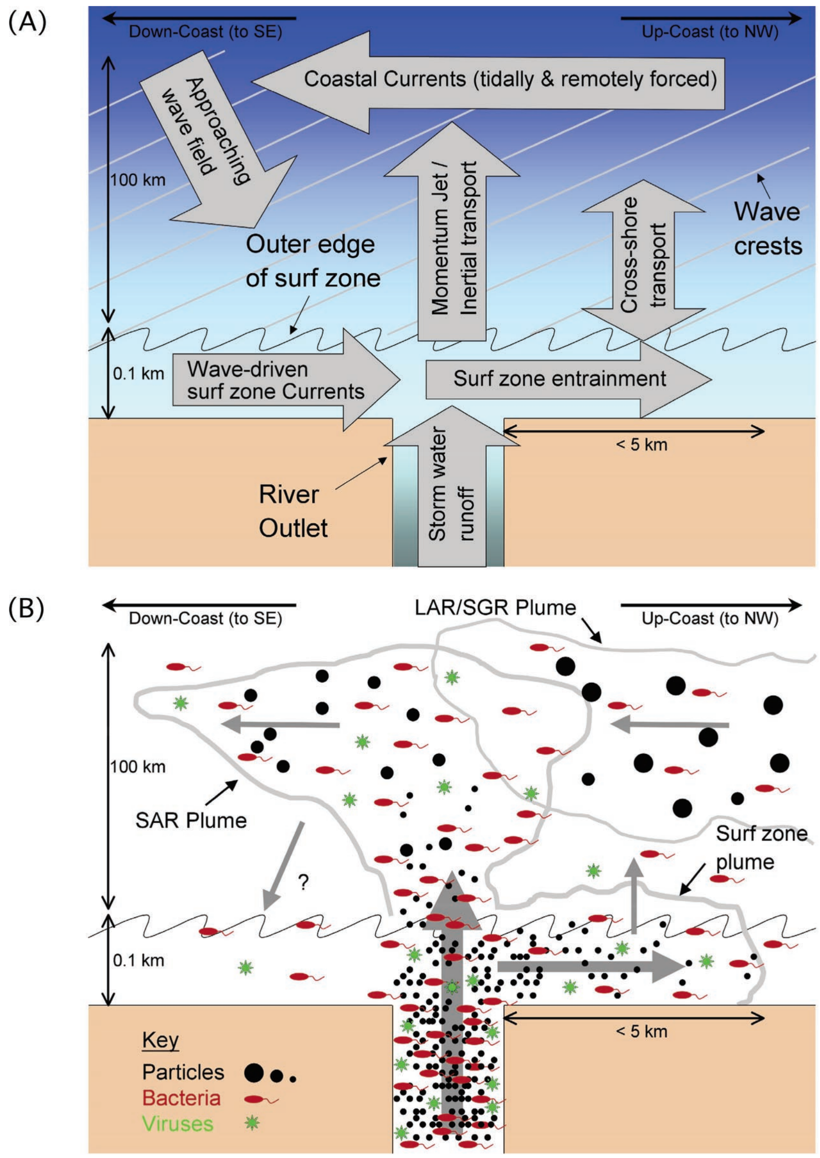

FIGURE 8. (A) Transport mechanisms that can affect the offshore distribution of contaminants discharged from river outlets. (B) Schematic representation of the spatial distribution of particles (black circles of varying size), fecal indicator bacteria (red symbols), and F^+ coliphage and human pathogenic viruses (green symbols). Abbreviations are SAR (Santa Ana River), SGR (San Gabriel River), and LAR (Los Angeles River).

Whether coagulation, in fact, plays a role in the fate and transport of particles and particle-associated contaminants in stormwater plumes will likely depend on the coagulation efficiency (i.e., the fraction of particle−particle collisions that result in sticking events) and shear rates present at a given location and time (*40*, *41*). Alternatively, the observed temporal coarsening of particles in the offshore may reflect changes in the particle size spectra of the stormwater runoff before it enters the ocean, from a predominance of smaller particles during the peak of the hydrograph, to a predominance of coarser particles during the falling limb of the hydrograph. Further studies are needed to determine whether observed coarsening of the offshore particle size spectra is caused by within-plume coagulation or by temporal evolution of the particle size spectra in stormwater runoff before it enters the ocean.

Data Synthesis. Results presented in this paper are represented schematically in Figure 8, including potential offshore transport mechanisms (panel A) and the resulting distribution of particles, bacteria, and viruses (panel B). As stormwater is discharged from the river outlet and flows over the beach, a fraction is entrained in the surf zone and the rest is ejected offshore in a momentum jet. Measurements of fecal indicator bacteria in the surf zone suggest that, once entrained, contaminants are transported parallel to shore by wave-driven currents, in a direction (i.e., up- or down-coast) controlled by the approaching wave field. When waves strike the beach so that a component of wave momentum is directed up-coast (the scenario pictured in Figure 8), fecal indicator bacteria in the surf zone are carried up-coast of the river outlet. Conversely, when waves strike the beach so that a component of wave momentum is directed down-coast, fecal indicator bacteria in the surf zone are carried down-coast of the river outlet. The buildup of water in the surf zone from breaking waves drives a cross-shore circulation cell, which can transport material between the surf zone and offshore of the surf zone. At our field site, this cross-shore circulation appears to limit the length of beach severely polluted with fecal indicator bacteria to <5 km around the river outlet, by diluting contaminated surf zone water with cleaner water from offshore. While the transport processes described here are based on measurements of fecal indicator bacteria in the surf zone, it is likely that other contaminants in stormwater runoff, in particular, human viruses and toxic contaminants associated with suspended particles (*13*, *42*), will behave similarly.

Further offshore, stormwater runoff plumes are common and readily detected through a variety of geophysical parameters (e.g., salinity, transmissivity, surface color). A clear linkage between these parameters and fecal indicator bacteria could not be established here. However, fecal indicator bacteria did appear to be associated with the smallest particle sizes, on the basis of both fractionation studies (Figure 6B) and the inverse relationship observed between fecal indicator bacteria concentrations and number-averaged particle size (Figure 6A). Particle size spectra in the offshore plumes coarsen with time post-release, and fecal indicator bacteria concentrations steadily drop (see the schematic representation of particle size in the various offshore plumes, Figure 8B). These results have several implications. First, they suggest that high concentrations of fecal indicator bacteria in the surf zone at our field site are probably not brought into the study area by coastal currents from distal sources (e.g., the Los Angeles river or the San Gabriel river). Second, cross-shore transport of water between the surf zone and offshore of the surf zone, for example, by rip cell currents, is likely to improve surf zone water quality by diluting dirty river effluent entrained in the surf zone with relatively clean ocean water from offshore.

While the concentrations of fecal indicator bacteria in the offshore plumes are generally below surf zone water quality standards, particularly during the latter two cruises, fecal indicator viruses (F^+ coliphage) were detected in nearly all offshore samples tested, and human adenoviruses and enteroviruses were detected in several offshore samples, including two collected offshore of the Santa Ana River outlet (station 2201 on February 23 and 28, see Figure 5). It is likely that the virus results presented here represent a conservative estimate of viral prevalence, because a limited numbers of samples were tested ($n = 8$). In addition, the presence of PCR inhibitors in stormwater reduces the efficiency of PCR detection of human pathogenic viruses, as mentioned earlier. At present, there are no water quality standards for fecal indicator viruses and human pathogenic viruses, largely because epidemiological data are not available to link adverse human health outcomes (e.g., gastrointestinal disease) to recreational ocean exposure to these organisms. However, the offshore detection of human pathogenic viruses begs several questions: First, do these viruses constitute a human health risk, either by contaminating the surf zone directly (see arrow with question mark, indicting the possible transfer of contaminants from offshore into the surf zone, Figure 8B) or by sequestering in offshore sediments? Second, given the fact that the Santa Ana River has separate storm and sanitary sewer systems, what is the source of human fecal pathogens in the wet weather water runoff? Many studies have shown that human fecal pathogens are associated with storm runoff from urban areas located throughout the United States (*25*, *43*−*45*), so the association between stormwater runoff and human fecal pathogens observed here is certainly not unique. Possible sources of human pathogens in stormwater runoff from urban areas include leaking sewer pipes, illicit sewage connections to the stormwater sewer system, homeless populations, and so forth.

Taken together, the results presented in this paper demonstrate that stormwater runoff from the Santa Ana River is a significant source of near-shore pollution, including turbidity, fecal indicator bacteria, fecal indicator viruses, and human pathogenic viruses. However, relationships between variables (e.g., between turbidity and fecal indicator bacteria and between fecal indicator bacteria and human viruses) vary from site to site (at the same time) and from time to time (at the same site) suggesting that the sources, fate, and transport processes are contaminant specific. The apparent exception is the inverse relationship observed between fecal indicator bacteria and number-averaged particle size, although further studies are needed to determine if this result is generalizable to other storm seasons and coastal sites and, if so, to determine the underlying mechanism at work. The relationship between water quality parameters (e.g., fecal indicator bacteria), turbidity, and other field proxies, such as number-averaged particle size, salinity, and colored dissolved organic matter, are the focus of ongoing and future regional studies, including as part of a coastal water quality observing program within the Bight '03 Project (http://www.sccwrp.org/regional/03bight/bight03_fact_sheet.html), as well as other investigations being carried out as part of the Southern California Coastal Ocean Observing System (SCCOOS).

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Supporting Information Available

Sampling and analysis protocols, calculation of the orthokinetic coagulation time scales, and additional figures. This material is available free of charge via the Internet at http://pubs.acs.org.

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