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Scaling and Management of Fecal Indicator Bacteria in Runoff from a Coastal Urban Watershed in Southern California

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This paper describes a series of field studies aimed at identifying the spatial distribution and flow forcing of fecal indicator bacteria in dry and wet weather runoff from the Talbert watershed, a highly urbanized coastal watershed in southern California. Runoff from this watershed drains through tidal channels to a popular public beach, Huntington State Beach, which has experienced chronic surf zone water quality problems over the past several years. During dry weather, concentrations of fecal indicator bacteria are highest in inland urban runoff, intermediate in tidal channels harboring variable mixtures of urban runoff and ocean water, and lowest in ocean water at the base of the watershed. This inland-to-coastal gradient is consistent with the hypothesis that urban runoff from the watershed contributes to coastal pollution. On a year round basis, the vast majority (>99%) of fecal indicator bacteria loading occurs during storm events when runoff diversions, the management approach of choice, are not operating. During storms, the load of fecal indicator bacteria in runoff follows a power law of the form $\mathscr{L} \sim Q^n$, where $\mathscr{L}$ is the loading rate (in units of fecal indicator bacteria per time), Q is the volumetric flow rate (in units of volume per time), and the exponent n ranges from 1 to 1.5. This power law and the observed range of exponent values are consistent with the predictions of a mathematical model that assumes fecal indicator bacteria in storm runoff originate from the erosion of contaminated sediments in drainage channels or storm sewers. The theoretical analysis, which is based on a conventional model for the shear-induced erosion of particles from land and channel-bed surfaces, predicts that the magnitude of the exponent n reflects the geometry of the stormwater conveyance system from which the pollution derives. This raises the possibility that the scaling properties of pollutants in stormwater runoff (i.e., the value of n) may harbor information about the origin of nonpoint source pollution.

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Introduction

A growing number of the nation's rivers, estuaries, and coastlines are impaired for fecal indicator bacteria (*1*−*3*). This problem is particularly acute in southern California, where the shedding of fecal indicator bacteria and pathogens from urbanized watersheds routinely triggers swimming advisories at coastal saltwater and inland freshwater beaches and the closure of shellfish harvesting areas in estuarine and coastal systems. There are many different management strategies that can be implemented to reduce the downstream impacts of fecal indicator bacteria pollution; however, it is unlikely that any single approach will be effective at all urban sites and under all environmental conditions. The goal of this study was to provide baseline data for watershed managers on the occurrence patterns and shedding rates of fecal indicator bacteria from an urban coastal watershed. The field investigations focused around the Talbert watershed that is thought to play a role in the beach postings and closures at Huntington State Beach, a popular swimming resort in southern California, as described in a companion paper (*4*) and an earlier study (*5*). This watershed, like many in southern California, has separate storm and sanitary sewer systems. Prior to 1999, both dry and wet weather runoff from the Talbert watershed drained to the ocean through a series of gutters, forebays, and channels (*6*). After 1999, local agencies began diverting dry weather runoff to the sanitary sewer system for treatment in an attempt to reduce the downstream impacts of fecal indicator bacteria on coastal water quality at Huntington State Beach (*7*). In this paper, we describe three years of data collection in and around the Talbert watershed that collectively answer the following questions: (1) How does the concentration of fecal indicator bacteria in this watershed vary spatially and temporally during dry weather and in response to storms? (2) How effective is the current management strategy of diverting dry weather runoff to the sanitary sewer system? (3) How does the load of fecal indicator bacteria scale with runoff volume? (4) What role does sediment erosion play in the loading of fecal indicator bacteria? (5) What are the management implications of these results?

The paper is organized as follows. A description of the field site is presented, followed in the next section by the methods and materials employed in the field investigations. Results and discussion of the field experiments are then presented. Next, we show that the loading of fecal indicator bacteria closely follows a theoretical model, which assumes that the bacteria originate from the shear-induced erosion of contaminated sediments. The paper concludes with a discussion of the management implications of the field data and theoretical results presented in the paper. To make the results of the paper accessible to a wide audience, we begin some sections with the primary questions to be addressed, immediately followed by answers supported by the data and analysis.

Field Site

The Talbert and Lower Santa Ana watersheds encompass 80 km^2 of urban landscape in the cities of Huntington Beach,

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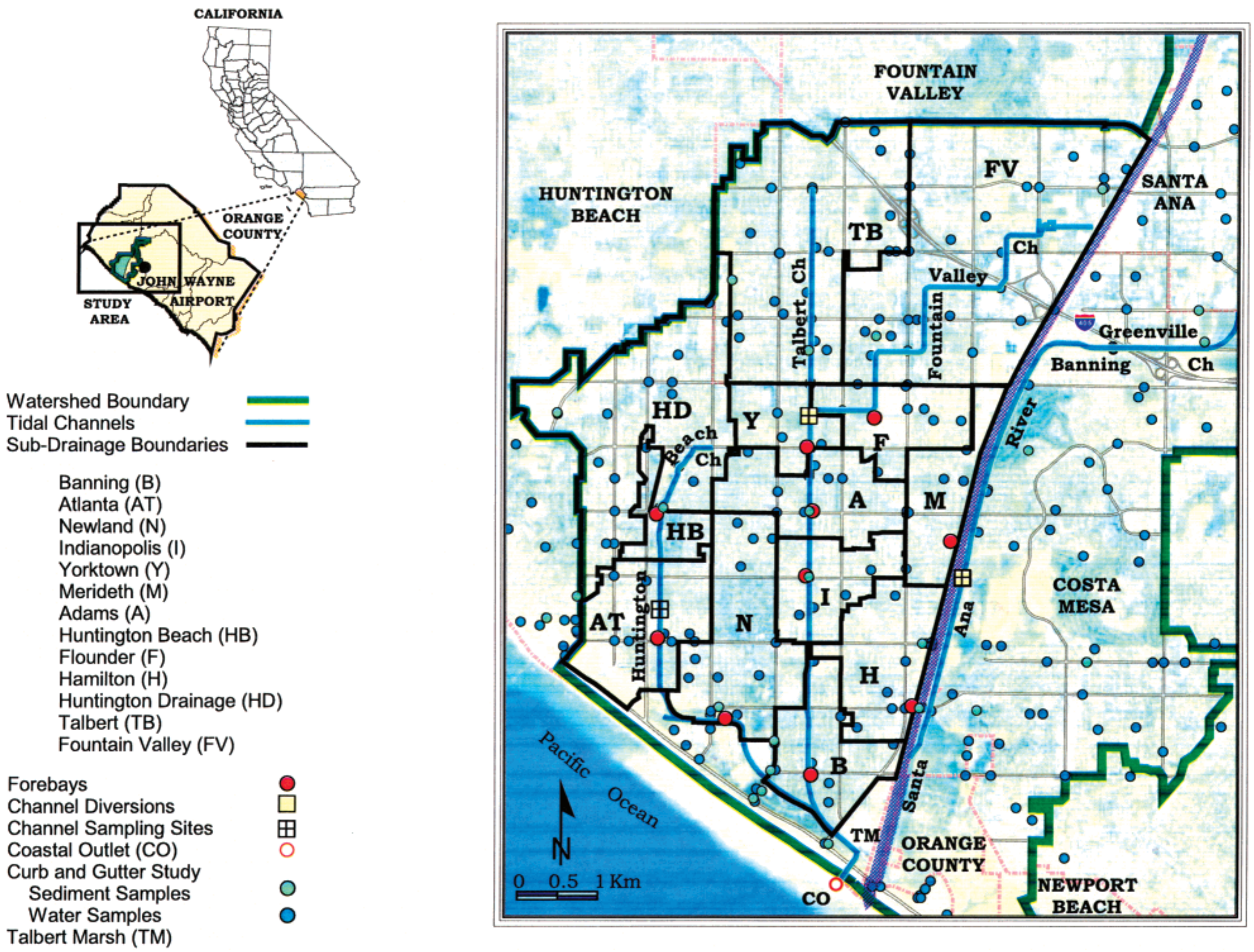

FIGURE 1. Map of the Talbert watershed study area and the locations of sampling sites and sites where dry weather runoff was diverted to the sanitary sewer system.

TABLE 1. Sub-Drainages in the Talbert Watershed Study Area

sub-drainage	dominant land-use	% of total[a]	sub-drainage area (km^2)	baseflow (m^3/d)
Banning	residential	83	1.8	610
Atlanta	residential	72	2.4	1490
Newland	residential	48	2.9	700
Indianapolis	residential	84	1.5	210
Yorktown	residential	75	1.1	40
Merideth	residential	67	1.4	100
Adams	residential	75	2.1	180
Huntington Beach	residential	48	0.8	320
Flounder	residential	79	1.6	60
Hamilton	residential	77	2.0	640
Huntington Drainage	residential	68	5.1	nd[b]
Talbert	residential	81	5.8	300
Fountain Valley	residential	51	8.2	500

[a] Percentage of total sub-drainage area that has the dominant land-use designation. [b] No data available.

Fountain Valley, Costa Mesa, Santa Ana, and Newport Beach in central Orange County, California (Figure 1). The coastal edge of the watershed is divided into 13 sub-drainages, each of which drains 0.8–8 km^2 (Table 1). To prevent flooding in the low elevation sub-drainages, dry and wet weather flow is routed to underground tanks (called forebays) where runoff accumulates until it exceeds some predetermined level. From there, the runoff is pumped into a channel network where it flows to the ocean under tidal control (*6*). The channels discharge at the shoreline; hence, pollutants in the runoff can have a large and negative impact on the surf zone water quality (*4*, *8*, *9*). To reduce the downstream impact of runoff from the Talbert watershed, beginning in 1999 the City of Huntington Beach and the County of Orange began diverting dry weather runoff to the sanitary sewer system for treatment and offshore disposal. The diversions took two forms: (i) transfer to the sanitary sewer system of runoff accumulating in the forebays (forebay diversions) and (ii) transfer to the sanitary sewer system of runoff accumulating upstream of temporary dams in the Talbert and Greeenville–Banning Channels (channel diversions). To prevent failure of the sewage treatment plant, all diversions are terminated during storm periods, which for this region typically occur in the November to March time frame (*10*).

Materials and Methods

A set of field studies were carried out between December 1999 and January 2003. The name of each study is indicated in Figure 2; this figure also indicates the timing of each study relative to local precipitation, air temperature measurements, and the number of forebay and channel diversions in effect. The experimental design of each study is described below. Sample processing methods varied somewhat between studies, as summarized in Table 2. These different methods yielded the concentration of total coliform (TC), *Escherichia coli* (EC), fecal coliform (FC), and *Enterococci* bacteria (ENT) in units of most probable number (MPN) or colony forming units (cfu) per 100 mL of sample. A detailed description of the sample collection and processing methods can be found in the Supporting Information.

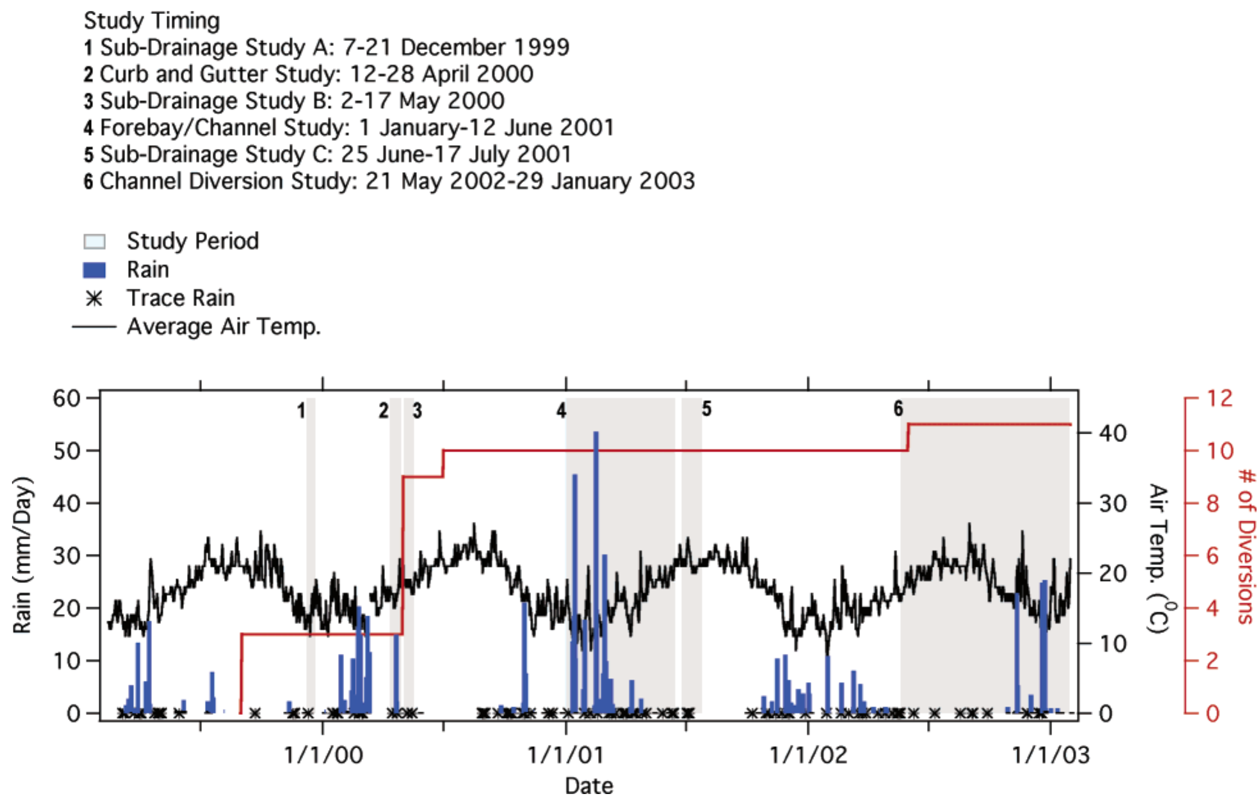

FIGURE 2. Timeline of the various studies conducted in the Talbert watershed. Also shown are rainfall history and average air temperature recorded at the nearby John Wayne Airport and the number of forebay and channel diversion structures operating within the study area.

TABLE 2. Study Methods Summary

study	fecal bacteria methods[a]	physical properties methods[b]	no. of samples	study timing	sample collection frequency
sub-drainage study A				12/7–21/99	
forebays	1		49		daily
coastal outlet	1	A	805		hourly
sub-drainage study B				5/2–17/00	
forebays	1	A	124		daily
tidal channels	1	A	30		daily
coastal outlet	1	A	697		hourly
sub-drainage study C				6/25–7/17/01	
forebays	1	B	439		daily
tidal channels	1	B	130		daily
coastal outlet	1	B	508		hourly
curb & gutter study				4/12–28/00	once/study
water samples	2		283		
sediment samples	4		36		
channel & forebay study					
forebays	1	B	217	1/11–6/12/01	daily
tidal channels	1	B	111	1/11–6/12/01	daily
bacteria forebay profile	1	C	108	3/6–6/6/01	weekly
physical forebay profile		D	782	3/6–6/6/01	daily
channel diversion study	3		90	5/21/02–1/29/03	triweekly

[a] Method 1: Samples were analyzed for total coliform (TC), *E. coli* (EC), and *Enterococci* bacteria (ENT) using defined substrate technology commercially known as Colilert and Enterolert (IDEXX, Westbrook, ME). Method 2: Samples were analyzed for ENT by membrane filtration and for TC and fecal coliform (FC) by fermentation. Method 3: Samples were analyzed for TC and FC by membrane filtration and for ENT by fermentation. Method 4: Sediment samples were analyzed for TC, FC, and ENT by fermentation. [b] Method A: The conductivity and turbidity of the water samples were measured using a Thermo Orion 160 conductivity meter (Beverly, MA) and a HACH 21000N (Loveland, CO), respectively. Method B: The conductivity and turbidity of the water samples were measured using Thermo Orion 162A conductivity meter (Beverly, MA) and a DRT-15CE (Fort Meyers, FL), respectively. Method C: Turbidity measurement was made using a DRT-15CE (Fort Meyers, FL). Method D: The conductivity, temperature, pH, and dissolved oxygen were measured in-situ with a YSI (Yellow Springs, OH) 600 xl multi-parameter water quality sonde connected to an ISCO (Lincoln, NE) 4250.

Curb and Gutter Study. The goal of this study was to measure the concentration of fecal indicator bacteria in dry weather runoff from various locations in the watershed. Over the period April 12–28, 2000, samples of dry weather runoff were collected from 283 sites in the Talbert watershed (light blue dots in Figure 1) and surrounding area and analyzed for fecal indicator bacteria (TC, FC, and ENT). Over the same period of time, 36 sediment samples were collected from areas that served as conveyance structures (i.e., channels and storm drains) and analyzed for the same suite of fecal indicator bacteria (light green dots in Figure 1). The type of land-use associated with each sample site (both runoff and sediment samples) was noted at the time of collection. Specific categories of land-use included: residential, industrial, commercial, agricultural, parks, channels and storm drains, and other.

Sub-Drainage Studies A−C. The goal of these studies was to measure the concentration of fecal indicator bacteria in dry weather runoff from sub-drainages of the Talbert watershed and to document how the concentration of fecal indicator bacteria varies across different sub-drainages and along a salinity gradient from inland to coastal sites. A set of three studies were carried out (designated sub-drainage studies A−C), each lasting 2−3 weeks, in which water samples were collected daily (or more frequently) from a set of forebay, channel, and outlet sites, and analyzed for fecal indicator bacteria (TC, EC, and ENT) and physical parameters (salinity and turbidity). Sampling sites are denoted in Figure 1 as red filled circles (forebay sites), crossed squares (channel sites; note that the yellow filling denotes in-channel diversions), and red unfilled circles (coastal outlet site). The sub-drainage studies were repeated three times over the course of 3 years (from 1999 to 2001), as the number of dry weather diversions increased (compare the number of active diversions with the timing of sub-drainage studies A−C in Figure 2). During sub-drainage studies A−C, water samples were collected (1) daily from forebays in the Talbert watershed, including seven forebays in 1999 (designated B, AT, N, I, Y, A, and F in the map in Figure 1), eight forebays in 2000 (same as in 1999 with the addition of HB), and 10 forebays in 2001 (same as 2000 with the addition of M and H); (2) daily from 2−3 sites in the channels that convey runoff to the coastal outlet, including two sites in 2000 (the Talbert and Fountain Valley channel sites in the map in Figure 1) and three sites in 2001 (same as 2000 with the addition of the Huntington Beach channel); (3) hourly from the coastal outlet of the Talbert watershed (designated CO in Figure 1).

Channel and Forebay Study. The goal of this study was to assess the long-term (6-month) variability of fecal indicator bacteria concentrations in wet and dry weather runoff shed from three sub-drainages within the Talbert watershed. Water samples were collected approximately 5 d/week for 6 months (from January 1 to June 12, 2001; see timeline in Figure 2) from the Yorktown and Flounder forebays (designated F and Y in Figure 1) and from one channel site in the Fountain Valley channel (designated FV in Figure 1). In addition to the daily sampling just described, two types of depth profiles were conducted at the Yorktown forebay (from March 6 to June 6, 2001) to determine the degree to which water in the forebay was well-mixed over the vertical (see Table 2 and Supporting Information for details). The instantaneous load (in units of MPN per time) of fecal indicator bacteria passing through the Fountain Valley channel site and the Yorktown and Flounder forebays was calculated as follows: $\mathcal{L}(t) = (Q_B(t) + Q_S(t))C(t)$ where $C(t)$ represents the daily measured concentration of fecal indicator bacteria (either TC, EC, or ENT) and $Q_B(t)$ and $Q_S(t)$ represent the instantaneous volumetric flow rate (units volume per time) of dry weather and storm runoff, respectively. The Yorktown and Flounder forebays and Fountain Valley channel receive dry weather and storm runoff from defined sub-drainage areas (see the sub-drainage boundaries drawn around the symbols Y, F, and FV in Figure 1). Dry weather flows from the two forebays and one channel site were diverted to the sanitary sewer system; hence, the daily dry weather flow rate $Q_B(t)$ could be estimated directly from City and County diversion records (Table 1). When diversions were not operating (e.g., during storms), water from the forebays was discharged directly to the channels in the Talbert watershed (Fountain Valley and Talbert channels; see Figure 1). The rational method was used to estimate the magnitude of volumetric flow rate during storms (*11*): $Q_S(t) = KR(t)A_s$ where K is the dimensionless runoff coefficient (assumed to be $K = 0.75$, which is typical for highly urbanized drainage areas (*11*)), $R(t)$ is measured rainfall intensity (units of mm/h), and A_s is the total sub-drainage area (see Table 1). The use of the rational method is justified at our study site because the sub-drainages are relatively small (see Table 1 for drainage areas). Rainfall intensity time−series measured at the nearby NOAA station (located at the John Wayne Airport) was substituted for $R(t)$. Rainfall data are available from NOAA's National Climatic Data Center (Asheville, NC) (*12*).

Channel Diversion Study. The goal of this study was to monitor the effectiveness of in-channel diversion structures, which consisted of temporary dams and conveyance infrastructure designed to capture and divert runoff flowing down the channel. Two in-channel diversion structures were installed in May 2002, one in the Talbert channel (replacing a previous temporary diversion structure, in operation since June 2000) and another in the Greenville−Banning channel. Because these diversion structures were located within the tidal prism, it was possible to sample water both inland and coastward of the dams (see Figures 1 and 2 for channel diversion locations and study timing, respectively). Water samples were collected 3 times per month approximately 65 m inland and coastward of the Talbert and Greenville−Banning dams for 5 (Talbert) to 9 (Greenville−Banning) months and analyzed for fecal indicator bacteria (TC, FC, and ENT).

Statistical Analysis of Field Data and Comparison between Studies. As indicated in Table 2, different sample collection and processing methods were used in the different studies. Of the 3627 samples collected for this set of studies, over 89% (3218) was analyzed for fecal indicator bacteria using defined substrate tests known commercially as Colilert and Enterolert (IDEXX, Westbrook ME), all implemented in a 97-well quantitray format (method 1); 2.5% (90) of the samples was analyzed by membrane filtration and multiple tube fermentation (EPA Method 9230 C and 9221 B, E respectively) (method 2); and 8% (283) of the samples was analyzed by membrane filtration and multiple tube fermentation (EPA Method 9222 B, D and 9230 B, respectively) (method 3). Some researchers have raised concern that the Colilert method, when implemented for marine waters, may give a significant number of false TC positives (*13*); however, another marine water study found that these different methods yield comparable results (*14*). To avoid any cross-method comparability problems in this study, care was taken to draw conclusions based only on comparisons between subgroups of data collected using the same analysis methodology (e.g., samples analyzed using method 1 were not compared against samples analyzed using method 2). Comparisons were evaluated using nonparametric statistical tests. The Kruskal−Wallis (*15*) test was used to assess whether differences between population medians were significant. Correlation between variables was assessed using Spearman's rank correlations (*15*). All statistical tests were implemented with Statistical Packages for the Social Sciences (Chicago, IL).

Results and Discussion

Spatial and Temporal Variability of Fecal Indicator Bacteria in Dry Weather Runoff.

Question: *How does the concentration of fecal indicator bacteria in this watershed vary spatially and temporally during dry weather and change in response to storms?*

TABLE 3. Concentrations of Fecal Indicator Bacteria Measured in Samples of Dry Weather Runoff and Sediment (Sed) from Talbert Watershed (Curb and Gutter Study

land-use	TC[a]		FC[a]		ENT[a]		no. of samples	
	runoff[b]	Sed[c]	runoff[b]	Sed[c]	runoff[b]	Sed[c]	runoff	Sed
residential	42, (44, 190)[d]	1440 (3564, 224 730)	2.9 (2.6, 14)[d]	1.8 (42, 6658)	5.6 (5.1, 17)[d]	1530 (422, 12598)	150	7
agricultural	27, (3.7, 77)	4500 (1696, 13 410)	0.75 (0.4, 6)	90 (49, 3148)	1.6 (0.5, 7)	99 (181, 12598)	6	7
commercial	26 (33, 166)	9459 (583, *)	1.2 (1.2, 9)	279 (99, *)	1.75 (1.8, 6)	60 (42, *)	52	2
industrial	17 (16, 0)	450000 (*, *)	3 (3, 0)	36000 (*, *)	11.1 (6.8, 0)	3330 (*, *)	3	1
channels	0.6 (1, 1.2)[e]	2070 (1321, 4860)	0.1 (0.2, 0.25)[e]	50 (56, 2563)	0.1 (0.2, 0.6)[e]	230 (243, 18311)	25	8
parks	0.7 (2.1, 17)[e]	4500 (3803, 17 325)	0.1 (0.1, 0.1)[e]	99, (41, 179)	0.1 (0.2, 0.69)[e]	99 (57, 580)	11	5
other	20 (22, 88)	8100 (11 516, 701 368)	0.5 (0.8, 5.1)	99 (42, 380)	1.7 (1.8, 10)	58 (46, 2162)	36	6
all	19 (15, 118)	4500 (3140, 20 475)	0.7 (1, 8.8)	95 (58, 516)	2.4 (1.8, 11)	99 (155, 2874)	283	36

[a] Median (geometric mean, inner quartile region) all values × 1000. An asterisk (*) indicates insufficient data. [b] TC and FC units of cfu/100 mL of water; ENT units of MPN/100 mL of water. [c] Units of MPN/100 g of wet sediment. [d] Significantly greater than all other land-use categories in a given year ($p < 0.05$, Kruskal−Wallis), based on comparing the median of each land-use to the median computed from measurements of all other land-uses. [e] Significantly less than all other land-use categories in a given year ($p < 0.05$, Kruskal−Wallis), based on comparing the median of each land-use to the median computed from measurements of all other land-uses.

Answer: *The concentration of fecal indicator bacteria in dry weather runoff (1) varies systematically across an inland-to-coastal gradient, with the highest concentrations at inland sites harboring low-salinity runoff and the lowest concentrations at coastal sites harboring variable mixtures of urban runoff and ocean water; (2) is highest in runoff from residential land-use and lowest in runoff from parks; (3) exhibits significant day-to-day and year-to-year variability; and (4) is poorly correlated with turbidity. During storms, rainfall intensity is positively correlated with both concentration of fecal indicator bacteria and turbidity. Fecal indicator bacteria are present at high concentrations in sediments collected from the storm drain infrastructure.*

The answer above is based on the collective results of the curb and gutter study, the three sub-drainage studies (A−C), and the channel and forebay study as described below.

Curb and Gutter Study. The results are summarized in Table 3. The concentration of fecal indicator bacteria in dry weather urban runoff are very high (geometric means of 15 000, 1000, and 1800 cfu/100 mL for TC, FC, and ENT, respectively). By way of comparison, the 30-d geometric mean standards for coastal beaches in California are 1000, 200, and 35 cfu/100 mL. When sorted by land-use, the median concentration of all three fecal indicator bacterial groups is highest in runoff from residential sites ($p < 0.05$, Kruskal−Wallis). The median concentrations of one or more groups of fecal indicator bacteria are significantly lower in runoff from parks and channels ($p < 0.05$, Kruskal−Wallis). The fecal indicator bacteria concentrations in the sediment samples are also very high (geometric means of 63 000, 1000, and 3000, MPN/100 g for TC, FC, and ENT, respectively). However, no single category of land-use stands out as having significantly higher or lower sediment concentrations of fecal indicator bacteria ($p > 0.05$, Kruskal−Wallis).

Sub-Drainage Studies (*A−C*). Forebays in the Talbert watershed receive dry weather runoff from a well-defined area, as indicated by the sub-drainage boundaries drawn in Figure 1. Residential areas dominate the land-use in all of the sub-drainages of the Talbert watershed (Table 1). During dry weather periods, forebay runoff harbors very high concentrations of fecal indicator bacteria, although no single forebay (or set of forebays) is consistently higher than the rest (Table 4). For example, the median concentration of TC was highest in the Atlanta forebay during study A (in 1999), in the Adams forebay during study B (in 2000), and in the Meridith forebay during study C (in 2001). Moreover, the different fecal indicator bacteria in groups are highest in different forebays. During study A, for example, TC and EC were highest in the Atlanta forebay, while ENT was highest in the Banning forebay. These two observations—that the concentrations of fecal indicator bacteria in dry weather runoff are high in all forebays and that there is no single forebay where the concentrations are always highest—are consistent with the relative predominance of residential land-use in the Talbert watershed sub-drainages (Table 1) and the high concentration of fecal indicator bacteria detected in residential runoff during the curb and gutter study (Table 3).

During dry weather, the concentrations of fecal indicator bacteria in surface water vary systematically across an inland-to-coastal salinity gradient. The concentrations are highest in forebays and channel sites that harbor low-salinity urban runoff, intermediate at forebay and channel sites that harbor a variable mixture of runoff and ocean water, and lowest at the coastal outlet (Figure 3). The inland-to-coastal fecal indicator bacteria gradient increased from 1999 to 2001 as progressively more dry weather runoff from the Talbert watershed was diverted to the sanitary sewer system (see Table 5). Referring to Table 5, over the 3-yr study period the concentrations of fecal indicator bacteria in the forebays increased nearly an order of magnitude, while concentrations of fecal indicator bacteria at the outlet remained constant or declined slightly. When all forebay, channel, and outlet data collected during studies A−C are included, the Spearman's correlation coefficients calculated between salinity and fecal indicator bacteria are −0.65 (TC), −0.50 (EC), and −0.49 (ENT) (all significant at $p < 0.01$). For the entire data set (including the forebay, channel, and outlet samples), there is also a weak to moderate positive correlation between turbidity and fecal indicator bacteria: 0.58 (TC), 0.45 (EC), and 0.38 (ENT) (all significant at $p < 0.01$). The correlation between fecal indicator bacteria and turbidity is much weaker if only measurements on forebay samples are considered: −0.08 (TC), 0.2 (EC), and 0.32 (ENT) (EC and ENT significant at $p < 0.01$). The relatively weak correlation between fecal indicator bacteria and turbidity in the dry weather runoff is apparent in Figure 3, where the turbidity of each sample is denoted by color ranging from blue (low turbidity) to red (high turbidity).

The increase in the inland-to-coastal fecal indicator bacteria gradient during studies A−C merits discussion. Over the course of these three studies, the concentration of fecal indicator bacteria in the forebays steadily increased, while the concentrations in the channels and outlets remained constant or decreased slightly (see Table 5 for significance values). Environmental conditions that may have triggered the increasing concentration of fecal indicator bacteria in the forebays include ambient air temperature and/or the total rainfall that preceded the dry weather studies. In

TABLE 4. Concentrations of Fecal Indicator Bacteria Measured in Dry Weather Runoff Collected from Forebays in the Talbert Watershed

forebays	study A (1999)	study B (2000)	study D (2001)
		TC (MPN/100 mL)[a]	
Banning	10 (23, 124)	18 (16, 12)[c]	11 (13, 11)[c]
Atlanta	173 (114, 143)[b]	37 (41, 67)	45 (52, 61)[c]
Newland	46(42, 81)	98 (60, 155)	3 (4, 5)[c]
Indianapolis	20 (20, 13)	61 (46, 61)	179 (118, 188)
Yorktown	112 (65, 118)	65 (63, 112)	317 (431, 574)[b]
Merideth			532 (494, 1859)[b]
Adams	24(28, 90)	130 (106, 130)[b]	202 (205, 294)[b]
Huntington Beach		52 (53, 37)	242 (187, 182)[b]
Flounder	3 (4, 1)[c]	52 (92, 214)	84 (106, 195)
Hamilton			73 (70, 213)
		EC (MPN/100 mL)[a]	
Banning	0.32 (0.32, 0.41)	0.34 (0.32, 0.41)[c]	0.1 (0.15, 0.2)[c]
Atlanta	1.1 (0.98, 0.73)[b]	0.41 (0.33, 0.39)[c]	0.92 (0.82, 1.2)[c]
Newland	0.1 (0.11, 0.06)	1.5 (0.85, 2.5)	6.7 (6.6, 9.3)[b]
Indianapolis	0.63 (0.93, 11)	0.58 (0.38, 0.89)	1 (2.2, 4.0)
Yorktown	0.3 (0.13, 0.41)	0.93 (0.78, 1.2)	4.3 (5.6, 7.4)[b]
Merideth			1.1 (1.3, 1.6)
Adams	0.52 (0.36, 0.51)	2.6 (3.0, 2.7)[b]	2.5 (3.6, 17.4)[b]
Huntington Beach		1.5 (1.9, 2.4)[b]	3.1 (3.0, 5.8)[b]
Flounder	0.01 (0.01, 0)[c]	8.0 (6.1, 96)[b]	1.8 (2.4, 9.0)
Hamilton			0.45 (0.78, 3.0)[c]
		ENT (MPN/100 mL)[a]	
Banning	0.63 (0.37, 0.33)[b]	0.66 (0.74, 0.57)	0.34 (0.44, 0.28)[c]
Atlanta	0.48 (0.48, 1.0)[b]	1.8 (1.8, 1.3)	0.92 (1.1, 1.1)
Newland	0.11 (0.12, 0.13)	1 (1, 2.2)	6.7 (6.6, 9.3)[b]
Indianapolis	0.12 (0.09, 0.06)	0.1 (0.07, 0.25)[c]	1.9 (2.5, 3.3)[b]
Yorktown	0.17 (0.15, 0.12)	2.5 (2.6, 23)	4.5 (3.7, 7.8)[b]
Merideth			1.1 (1.3, 1.4)
Adams	0.21 (0.26,0.2)	2.1 (1.9, 2.4)	1.7 (1.5, 3.1)
Huntington Beach		4.1 (3.8, 5.6)[b]	1.8 (2.2, 4.3)[b]
Flounder	0.03 (0.03, 0.02)[c]	5.9 (1.9, 24)	0.64 (0.83, 1.9)[c]
Hamilton			0.09 (0.11, 0.27)[c]

[a] Median (geometric mean, inner quartile region) all values × 1000. [b] Significantly greater than all other forebays in a given year ($p < 0$, Kruskal−Wallis), based on comparing the median of each forebay to the median computed from measurements of all other forebays. [c] Significantly less than all other forebays in a given year ($p < 0.05$, Kruskal−Wallis), based on comparing the median of each forebay to the median computed from measurements of all other forebays.

particular, air temperature increased in the order: study A (14 °C), study B (18 °C), and study C (22 °C). The total rain that fell in the 6 months prior to each study increased in the order: study A (23 mm), study B (154 mm), and study C (277 mm) (see Figure 2 for air temperature and rainfall time series plots). Both of these factors could have affected the re-growth of fecal indicator bacteria by, for example, redistributing nutrients throughout the watershed and providing environmental conditions more favorable for bacterial replication (*16*, *17*). Regardless of what caused the dry weather concentration of fecal indicator bacteria in the forebays to increase over the 3-yr study period, it is noteworthy that a similar increase was not observed downstream at the coastal outlet. One interpretation is that the dry weather diversions prevented a worsening of water quality at the outlet by capturing and treating the runoff before it could make its way to the coast. Alternatively, during dry weather, water quality at the watershed outlet may be dominated by other (nonrunoff) sources of fecal indicator bacteria, such as re-growth in sediments and/or bird droppings deposited in the channel network and Talbert marsh (*17*, *18*).

Channel and Forebay Study. Based on the depth profiling studies, runoff in the forebays is generally well-mixed over the vertical relative to fecal indicator bacteria, turbidity, salinity, dissolved oxygen, pH, and temperature (Figure S1 in Supporting Information). Physical measurements in the forebays water ranged from 0 to 6 ppt (salinity), from 0 to 8 mg/L (dissolved oxygen), from 6.8 to 8.4 (pH), and from 16 to 22 °C (temperature). Over the course of the depth profiling study (March 6−June 6, 2001), temperature increased, dissolved oxygen decreased, and salinity and pH showed no clear trend.

Figure 4 illustrates the effect of rainfall on turbidity, salinity, and concentration of fecal indicator bacteria during the 6-month study at two forebays (Flounder and Yorktown) and in the Fountain Valley channel. Data in this plot are arranged into three categories based on rain gauge records: (1) *base flow* when no rainfall was reported, (2) *trace rain* when rainfall was detected at intensities too small to quantify (i.e., >0 but <0.25 mm/d), and (3) *rain* when measurable amounts of rainfall were recorded. Samples collected during base flow conditions were highly variable with respect to turbidity (1−100 NTU), TC (10^3−10^6 MPN/100 mL), EC (10^1−10^5 MPN/100 mL), and ENT (10^1−10^5 MPN/100 mL) (Figure 4). Samples collected during trace rainfall appear to be less variable, perhaps because fewer samples are represented. The median values of turbidity, salinity, TC, EC, and ENT were not significantly different ($p > 0.05$, Kruskal−Wallis) in samples collected during base flow conditions, on one hand, and in samples collected during trace rainfall conditions, on the other hand. Samples collected during rainfall have significantly higher median fecal indicator bacteria concentrations, turbidity, and lower salinity as compared to samples collected during trace rainfall and dry weather periods ($p < 0.01$, Kruskal−Wallis). Including all samples collected during periods of measurable rainfall, rainfall intensity is negatively correlated with salinity (−0.62) and positively correlated with turbidity (0.63), TC (0.42), EC (0.67), and ENT (0.66); all of these correlation coefficients are significant ($p < 0.01$, Kruskal−Wallis).

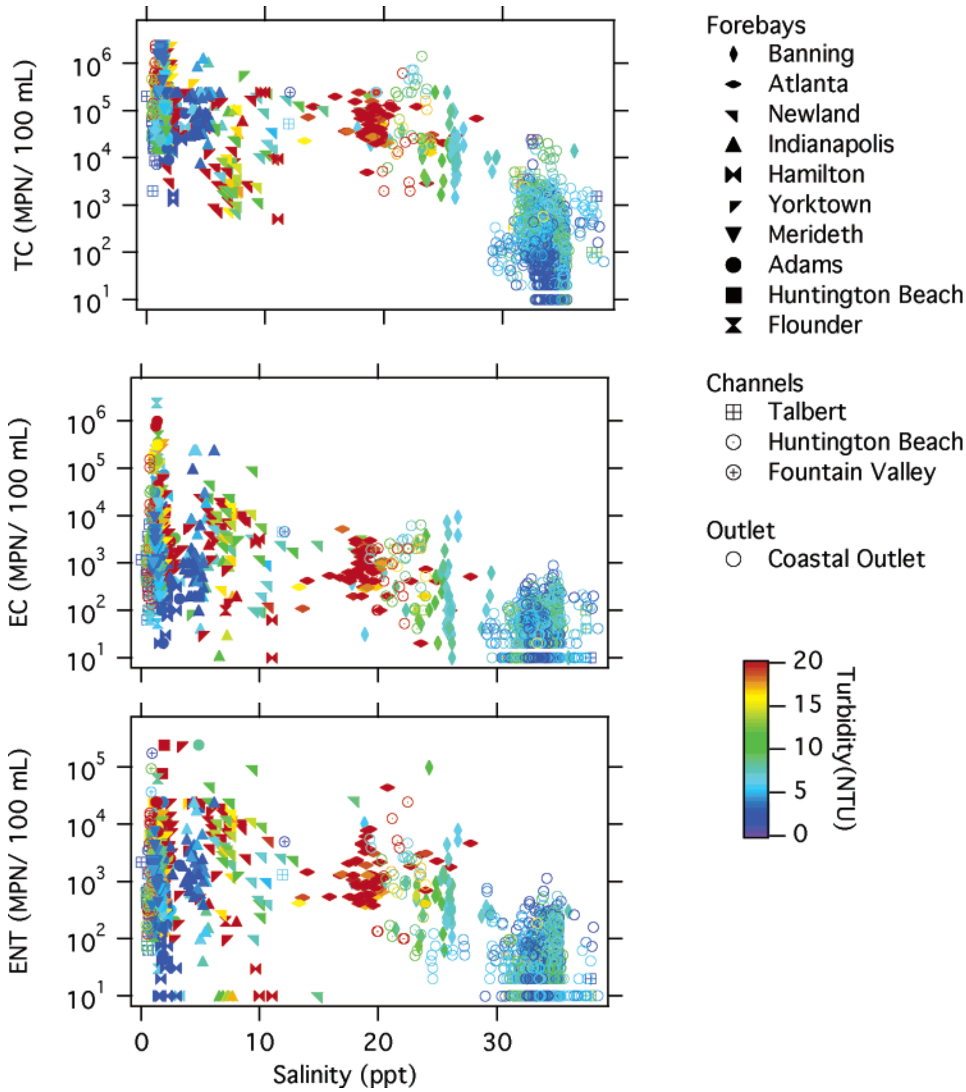

FIGURE 3. Concentration of fecal indicator bacteria and turbidity measured in forebays and channels and at the coastal outlet of the Talbert watershed, during a series of dry weather studies conducted from 1999 to 2001 (sub-drainage studies A–C).

TABLE 5. Concentration of Fecal Indicator Bacteria Measured on an Inland-to-Coastal Salinity Gradient. (Sub-Drainage Studies)

	study A (1999)	study B (2000)	study C (2001)
	TC (MPN/100 mL)[a]		
forebays	24.2 (28.2, 146)[c]	51.7 (52.7, 107.2)[c]	104.6 (85.7, 213.4)
tidal channels	nd[d]	36.5 (47, 109)	38.6 (19.5, 240.5)
coastal outlet	0.1 (0.1, 0.1)[c]	0.2 (0.2, 0.3)[c]	0.3 (0.2, 0.5)
	EC (MPN/100 mL)[a]		
forebays	0.3 (0.2, 0.6)[c]	1 (1, 2.7)[c]	1.5 (1.7, 5.3)
tidal channels	nd	0.6 (0.8, 3)[b]	0.3 (0.3, 1.9)
coastal outlet	0.02 (0.02, 0.03)[c]	0.05 (0.05, 0.1)[b]	0.03 (0.03, 0.05)
	ENT (MPN/100 mL)[a]		
forebays	0.2 (0.2, 0.3)[c]	1.2 (1.3, 4.8)	1.3 (1.3, 3.7)
tidal channels	nd	1.6 (1.2, 2.5)[b]	0.2 (0.2, 1.2)
coastal outlet	0.03 (0.03, 0.04)[c]	0.04 (0.04, 0.08)[b]	0.01 (0.02, 0.02)

[a] Median (geometric mean, inner quartile region) all values × 1000. [b] Significantly greater than the subsequent year ($p < 0.05$, Kruskal–Wallis). [c] Significantly less than the subsequent year ($p < 0.05$, Kruskal–Wallis). [d] No data.

Effectiveness of Dry Weather Diversions.
Question: *How effective is the current management strategy of diverting dry weather runoff to the sanitary sewer system?*
Answer: *The efficacy of the dry weather runoff diversion program is mixed. On one hand, the diversions are effective at reducing the flow of fecal indicator bacteria, and presumably other contaminants associated with urban runoff, into the ocean during dry weather periods. On the other hand, on a year-round basis, the vast majority (>99%) of fecal indicator bacteria is shed during rainstorms when diversions are not operating. Hence, while diversions appear to reduce the flow of fecal indicator bacteria to the ocean during dry weather periods when the vast majority of the people are at the beach,*

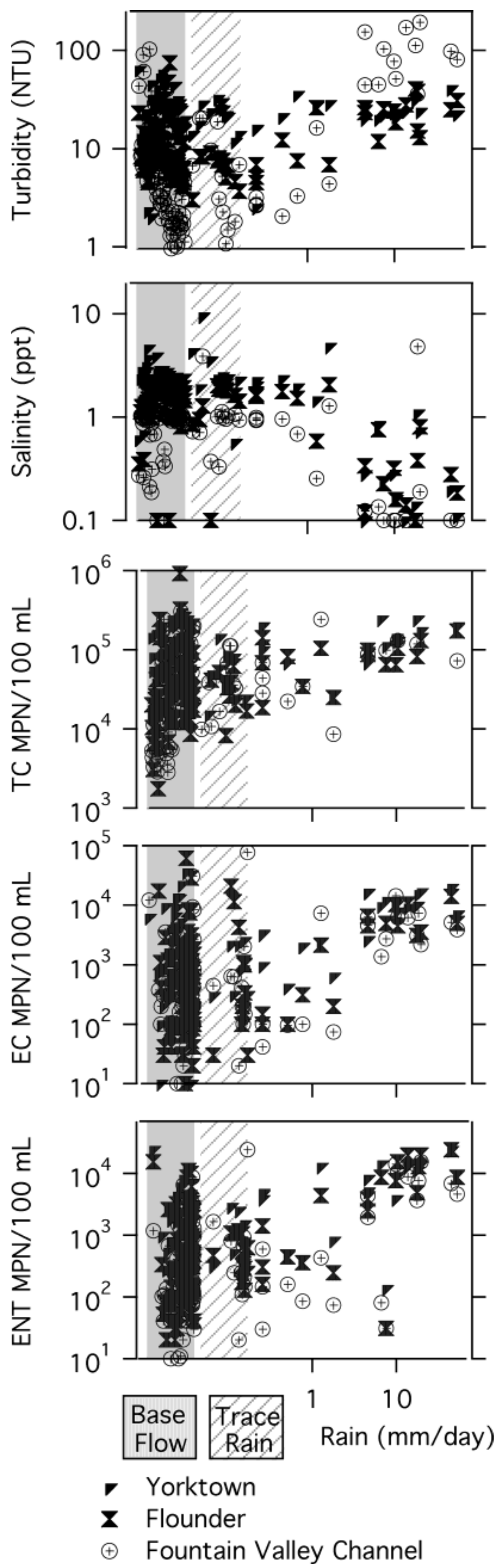

FIGURE 4. Effect of rainfall intensity on turbidity, salinity, and fecal indicator bacteria concentrations in runoff from the Yorktown, Flounder, and Fountain Valley Channel sub-drainages (channel and forebay study). Not included in the plot are fecal indicator bacteria concentrations above the maximum detection limit (24 192, 241 920, or 2 419 200 MPN/100 mL, depending on dilution) or below the minimum detection limit (10 MPN/100 mL).

they capture a remarkably small percentage (<1%) of the fecal indicator bacteria shed on a year-round basis.

The answer is based on measurements of the concentration of fecal indicator bacteria inland and oceanward of in-channel diversion dams (channel diversion study) and daily estimates of the fecal indicator bacteria load flowing through the Yorktown and Flounder forebays over the course of 6 months (channel and forebay study). These are described below.

Channel Diversion Study. To assess the efficacy of the two in-channel diversions, water samples were collected upstream and downstream of the temporary diversion dams. At both channel sites, the concentrations of fecal indicator bacteria were generally higher in the upstream sample and lower in the downstream sample, with the exception of ENT at the Greenville−Banning site (see Figure S2 in Supporting Information). However the upstream/downstream difference was only significant with respect to TC and FC at the Talbert Channel and only TC at the Greenville−Banning Channel (significant at $p < 0.05$, Kruskal−Wallis).

Channel and Forebay Study. Figure 5 presents time−series plots of the fecal indicator bacteria load entering the Yorktown forebay (first column of panels), Flounder forebay (second column), and Fountain Valley channel (third column); the light shading in these plots corresponds to the portion of load diverted to the sanitary sewer system. Also shown are measured and trace rainfall events (bars and asterisks, respectively, top panel in each column). The loading rates are highly variable, ranging over 5 (TC) and 6 (EC and ENT) orders of magnitude. Most of the loading spikes coincide with rain events that occurred during the rainy season (January to March). The loading rates do not appear to respond to trace rainfall events, despite the fact that the concentrations of fecal indicator bacteria frequently increase during trace rainfall (data not shown). The rate at which fecal indicator bacteria load was diverted to the sanitary sewer system from the Yorktown and Flounder forebays (light shading in the load plots) exhibits considerable day-to-day variability, but no month-to-month trends are evident. The dry weather fecal indicator bacteria load flowing past the Fountain Valley channel site, which was only diverted for a few weeks in the beginning of June (2001), also exhibits significant day-to-day variability (third column in Figure 5).

The cumulative load of fecal indicator bacteria diverted to the sanitary sewer system from the Yorktown and Flounder forebays is a small fraction of the total load shed from these two sub-drainages over the course of the channel and forebay study. The diverted load ranges from approximately 0.2% for ENT to near 1% for TC and EC (see Figure S3 in Supporting Information). Over the course of this 6-month study, >99% of the fecal indicator bacteria load shed from the Yorktown and Flounder sub-drainages made its way to the ocean.

Why does so much of the fecal indicator bacteria loading occur during storm events? Loading increases nonlinearly with rainfall intensity because both volumetric flow rate and concentration of fecal indicator bacteria increase during storms. Storms can increase the flow of runoff form the Yorktown and Flounder sub-drainages nearly 10 000-fold, from approximately 50 $m^3\ d^{-1}\ km^{-2}$ during dry weather (see Table 1) to peak values of nearly 500 000 $m^3\ d^{-1}\ km^{-2}$. As mentioned earlier, the concentration of fecal indicator bacteria in runoff from the Yorktown and Flounder sub-drainages remains constant, or increases, with increasing rainfall intensity (Figure 4). The fact that the concentration of fecal indicator bacteria increases, or holds steady, during heavy storms is at odds with build-up/wash-off models that predict pollutant concentration in runoff should scale with the time between storms (*19*) and not rainfall intensity. Indeed, a large fecal indicator bacteria loading event occurred

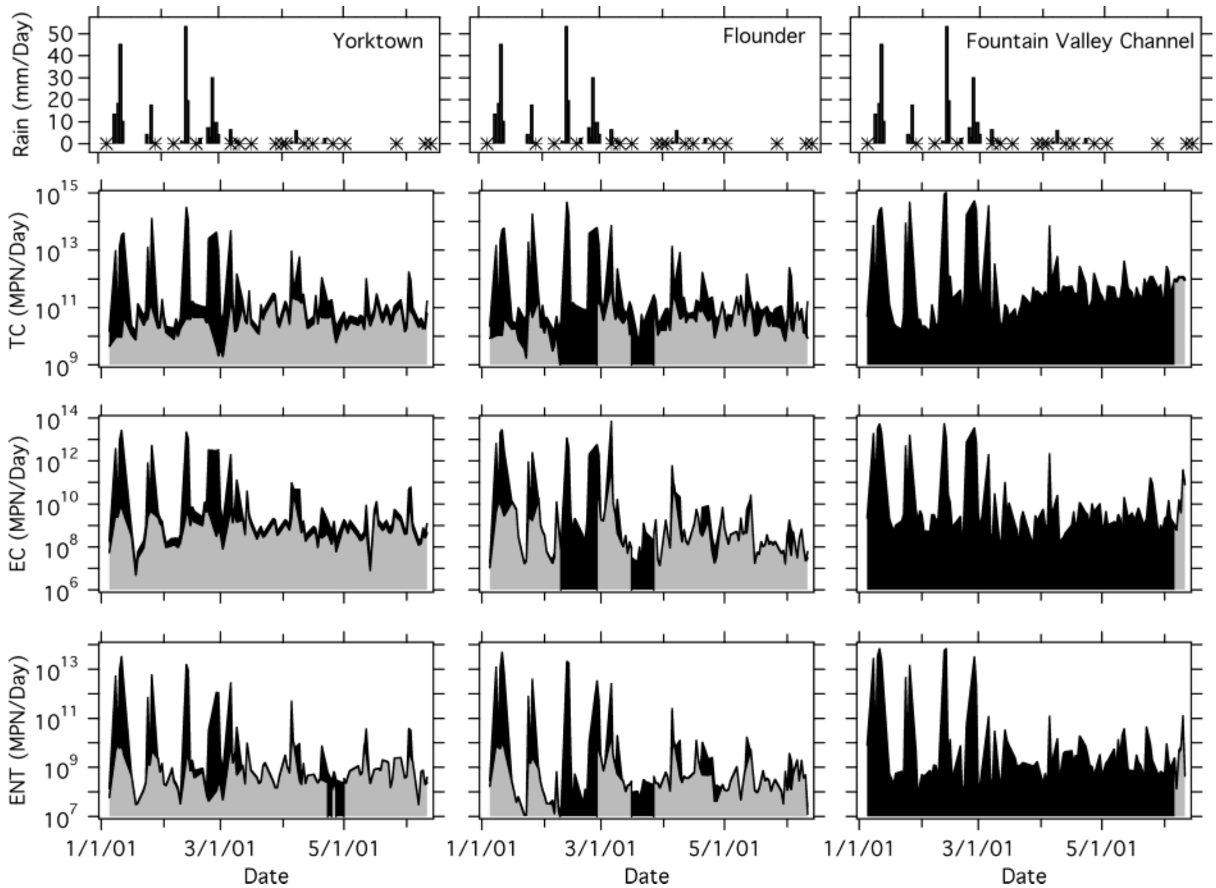

FIGURE 5. Instantaneous loading of fecal indicator bacteria from the Yorktown, Flounder, and Fountain Valley sub-drainages during dry and wet weather (channel and forebay study). Shading denotes fraction of load diverted to the sanitary sewer system (light gray) and fraction released to the ocean (black). Also shown (top panels) are rainfall intensity (solid bars) and trace rainfall events (asterisks).

late in the storm season and was preceded by a short (5-d) dry period (March 6, 2001, Figure 5).

Because the build-up/wash-off model is widely employed in surface water quality modeling (*20*, *21*), it is important to explore what other process may be at work in our system. One alternative model envisions that most of the pollution shed during storms originates from the erosion of contaminant-laden particles (from pavement erosion, automobile grease and dirt, atmospheric particle deposition, yard and soil erosion, etc.) previously deposited on the urban landscape and in the storm sewer system. The accumulation of contaminated particulates in sewer collection systems has been implicated, by other researchers, as a source of downstream pollution during storm events. For example, a significant fraction of suspended solids, volatile suspended solids, and BOD_5 in storm runoff from catchments in Paris, France, appear to originate from the erosion of in-sewer sediments (*22*, *23*). Furthermore, fecal indicator bacteria accumulate, die-off, and perhaps grow in storm sewer sediments (*24*). Relative to our study, evidence that fecal indicator bacteria in storm runoff originate from the erosion of contaminated sediment includes the positive correlations between turbidity, fecal indicator bacteria, and rainfall observed during the 6-month study (channel and forebay study), and the relatively high concentrations of fecal indicator bacteria measured in sediments collected from drainage channels in the Talbert watershed (curb and gutter study). In addition, the scaling of fecal indicator bacteria loading with volumetric flow rate (eq 1) is consistent with an erosion source for these pollutants, as described in the next sections. Relative to measurements conducted in forebay samples during sub-drainage studies A–C, it is interesting to note that while there is a strong positive correlation between fecal indicator bacteria concentration and turbidity during storms (Spearman's correlation coefficients of 0.63–0.67), the correlation is much weaker during dry weather periods (Spearman's correlation coefficients of −0.08 to 0.32). This observation together with the fact that the concentrations of fecal indicator bacteria in dry weather runoff are frequently very high when there should be little or no erosion of sediments (see Figure 3) suggest that different processes may drive fecal indicator bacteria concentrations during dry and wet weather.

Sediment Erosion Model for the Loading of Fecal Indicator Bacteria during Storms

Question: *How does the load of fecal indicator bacteria scale with storm runoff volume? What role does sediment erosion play in the loading of fecal indicator bacteria during storms?*

Answer: *Fecal indicator bacterial loads scale as a power law of runoff volume, with exponent values ranging from $n = 1$ to 1.5. This observation is consistent with a simple theoretical model that assumes fecal indicator bacteria in storm runoff originate from the erosion of contaminated sediments. The model predicts that the magnitude of the power law exponent n harbors information about the geometry of the storm conveyance system from which the pollution derives. When applied to fecal indicator bacteria loads from the Talbert watershed, the magnitude of the exponents are consistent with the following hypotheses: (i) the coliform group (TC and EC) derives from the erosion of sediments in the piping and channels of the storm sewer system and (ii) ENT originates from the erosion of sediments on the surface of urban landscapes (e.g., streets, residential yards, etc.). Further research*

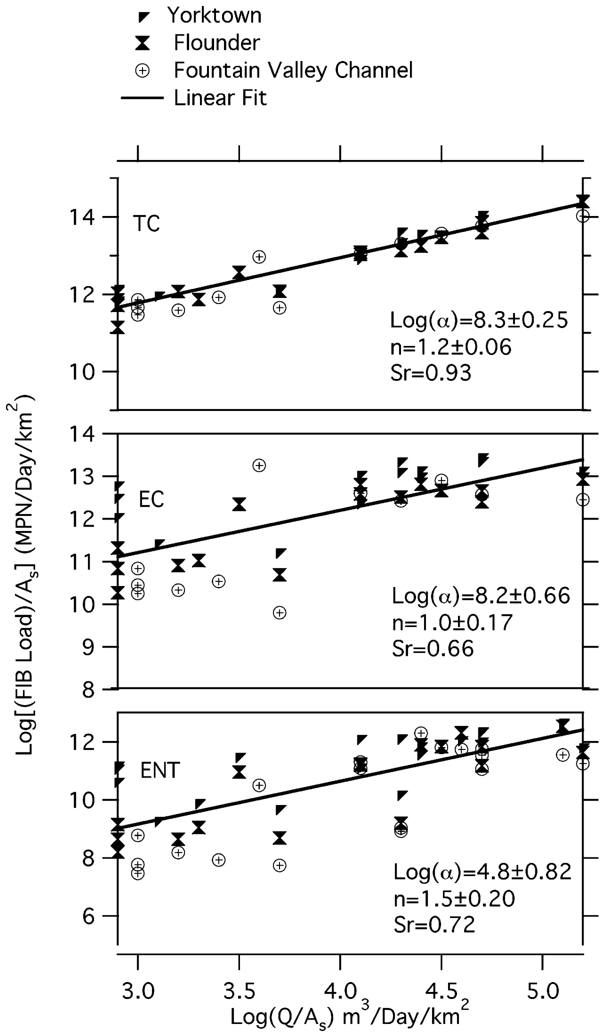

FIGURE 6. Scaling of fecal indicator bacteria load during storms with volumetric flow rate (channel and forebay study). The Spearman rank correlation coefficient (S_r), the power law exponent value (n), and the logarithm of the pre-factor (α) are shown in each graph.

is needed to test these hypotheses and, more generally, to assess whether the magnitude of the power law exponent is an accurate measure of the local-scale processes responsible for mobilizing contaminants during storm periods.

Previous studies (*25*) have noted that pollutant loading $\mathscr{L}$ in storm runoff sometimes scales as a power law of the volumetric flow rate Q:

$$\frac{\mathscr{L}}{A_s} = \alpha\left[\frac{Q}{A_s}\right]^n \qquad (1)$$

In eq 1, the load and volumetric flow rates have been normalized by the area (A_s) of the sub-drainage. The magnitude of the exponent n indicates how the concentration of fecal indicator bacteria changes with increasing flow; specifically, $n = 1$ if the concentration is constant, $n < 1$ if the concentration decreases with increasing flow, and $n > 1$ if the concentration increases with increasing flow. The pre-factor α depends on the base flow rate (Q_B) and the concentration of fecal indicator bacteria (C_B) in base flow: $\alpha = C_B/(Q_B/A_s)^{n-1}$. Equation 1 predicts that a log−log plot of $\mathscr{L}/A_s$ versus Q/A_s will yield a straight line with slope n and intercept α. As illustrated in Figure 6, during storms fecal indicator bacteria loading from the Fountain Valley, Yorktown, and Flounder sub-drainages conform reasonably well to eq 1 (data from the channel and forebay study). Spearman's correlation coefficients computed between log ($\mathscr{L}/A_s$) and log (Q/A_s) are 0.93 (TC), 0.66 (EC), and 0.72 (ENT) (all significant at $p < 0.01$). The slopes of the lines in Figure 6 range between 1 and 1.5 (see n values listed in figure). The magnitude of these empirical exponents ($n \geq 1$) are consistent with our earlier observation that the concentration of fecal indicator bacteria appears to increase with increasing rainfall intensity (see Figure 4).

Modified versions of eq 1 have been employed to characterize the relationship between pollutant loading (usually heavy metals) and volumetric flow rate in previous studies (*25*). However, to our knowledge, no published studies have justified the power law scaling of pollutant load with volumetric flow rate on theoretical grounds. Here we show that this scaling law can be justified theoretically for the case where pollutant load originates from the erosion of contaminated sediments. For this analysis we assume that the contaminated sediments are never entirely eroded, and we adopt a rearranged version of the classic equation by Graff (*26*) to express the instantaneous loading of sediments (and hence pollutants) in terms of the wetted perimeter (P) and hydraulic radius (R_h) of the water conveyance system (i.e., street, pipe, channel, etc.):

$$\mathscr{L} = A_1 P R_h^{2.52} \qquad (2a)$$

$$A_1 = 10.39\sqrt{\frac{\rho_s - \rho}{\rho} g d^3}\left[S/\left(\frac{\rho_s - \rho}{\rho}\right)\right]^{2.52} \qquad (2b)$$

The variables in eq 2b represent the density of sediment (ρ_s) and water (ρ), gravitational acceleration (g), diameter of the particles (d), and channel bed slope (S). For the purposes of this analysis, it is assumed that A_1 is constant. The wetted perimeter and hydraulic radius can be expressed as a function of the volumetric flow rate (Q) using a rearranged form of the classic Chezy equation for flow in an open channel, where C represents the Chezy coeffiecient (*11*):

$$P R_h^{1.5} = \frac{Q}{C\sqrt{S}} \qquad (3)$$

Because P and R_h have different exponents in eqs 2 and 3, these two equations cannot be combined to yield a unique relationship between pollutant loading and volumetric flow rate. To fully specify the relationship between $\mathscr{L}$ and Q, additional information on the cross-sectional geometry of the conveyance system is needed. However, to keep this analysis as general as possible, we assume no specific conveyance geometry and make the reasonable assumption that P and R_h can be represented as power laws of Q:

$$P = A_2 Q^p \qquad (4a)$$

$$R_h = A_3 Q^r \qquad (4b)$$

where A_2 and A_3 are fixed multiplicative constants. Substituting eqs 4a and 4b into eqs 2 and 3 yields a power law for the sediment (and contaminant) loading rate:

$$\mathscr{L} = A_4 Q^n \qquad (5)$$

where the exponents n, p, and r are related as follows:

$$n = p + 2.52r \qquad (6a)$$

$$p + 1.5r = 1 \qquad (6b)$$

Excluding the possibility that wetted perimeter and hydraulic radius decrease with increasing flow rate (i.e., $p \geq 0$ and r

≥ 0), eqs 6a and 6b yield the following bounds on the power law exponent n:

$$1 \leq n \leq 1.68 \quad (7)$$

The two bounds correspond to limiting cases for the geometry of the conveyance system. Specifically, the lower bound ($n = 1$) applies to the case where the hydraulic radius is relatively insensitive to changes in flow rate (i.e., $r \approx 0$); the upper bound ($n = 1.68$) applies to the case where the wetted perimeter is relatively insensitive to changes in flow rate (i.e., $p \approx 0$). If the conveyance system is an open channel, these two limits correspond to an extremely narrow channel ($n = 1$) and an extremely wide channel ($n = 1.68$), respectively.

On the basis of the analysis above, a power law relationship between pollutant loading and flow rate is expected in the case where pollutants associated with bed sediments are mobilized during storms by bed shear. Furthermore, the magnitude of the exponent n may contain information about the origin of the pollutant within the watershed or sub-drainage. In the case where the pollutants originate from the erosion of sediments in piping and channels associated with the storm sewer system, the hydraulic radius may be relatively insensitive to flow rate; hence, the power law exponent might be closer to the lower bound ($n = 1$). In the case where the pollutants originate as overland sheet flow (e.g., street and pavement runoff), one might expect that the wetted perimeter will be invariant, or nearly so, with flow rate; hence, the power law exponent should be closer to the upper bound ($n = 1.68$).

In the case of fecal indicator bacteria released from sub-drainages in the Talbert watershed, the observed range of values for the power law exponent ($n = 1-1.5$) are within the range predicted by our simple erosion model ($n = 1-1.68$). Intriguingly, the exponents for TC and EC ($n = 1-1.2$) are closer to the lower bound, while the exponent for ENT ($n = 1.5$) is closer to the upper bound. One possibility is that the coliform group of organisms (TC and EC) originate from the erosion of sediments in the piping and channels of the storm sewer system, while ENT originates from the erosion of sediments on the surface of urban landscapes (e.g., streets, residential yards, etc). However, it must be stressed that there is no direct biological evidence that one group of fecal bacteria (namely, fecal coliforms and *E. coli*) survive in sewer sediments or drainage channels, whereas another (*Enterococci*) survive as deposits on the surface of urban landscapes. Further research is needed to test this hypothesis and more generally clarify the relationship between the watershed-scale response of fecal indicator bacteria to storms as manifest by the power law relationship between pollutant loading and flow and the local-scale processes responsible for mobilizing contaminants during periods of intense rain. It should also be noted that the simple scaling model presented here does not explicitly take into account fate and transport processes, such as bacterial die-off. The relative utility of watershed-scale pollutant fate and transport models, on one hand, and simple scaling models, on the other hand, is also an interesting topic for future research.

Management Implications

Question: *What are the management implications of the field data and modeling results presented in this study?*

Answer: *Dry and wet weather runoff is a significant source of fecal indicator bacteria; hence, efforts to reduce the flow of untreated runoff to sensitive receiving water bodies are warranted. In the case of fecal pollution shed from the Talbert watershed and its impact on surf zone water quality at Huntington Beach, diversion of dry weather runoff to the sanitary sewer system is likely to reduce the health risk to recreational bathers during high-use summer time periods. However, significant reduction of fecal pollution shed from this watershed on a year-round basis will require the augmentation of dry weather diversions with alternative approaches (e.g., creating freshwater wetland treatment systems to remove contaminants near their source) and implementing watershed management strategies that minimize the loading of sediment-associated pollutants during storms.*

Urban runoff is increasingly recognized as a significant cause of coastal water quality impairment (*18, 27−30*). One approach for addressing this problem is to capture and treat urban runoff before it reaches the ocean. This strategy was adopted in the Talbert watershed after the summer of 1999 when a significant stretch, at one point encompassing 5 km of Huntington State Beach, was closed to the public due to elevated concentrations of fecal indicator bacteria in the surf zone. On the basis of the data presented above, the efficacy of this diversion program is mixed. On one hand, the diversions are effective at reducing the flow of fecal indicator bacteria, and presumably other contaminants associated with urban runoff, into the ocean during dry weather periods. The evidence includes the following: (i) The concentration of fecal indicator bacteria is extraordinarily high in sources of urban runoff, particularly residential runoff, and at collection points for urban runoff (i.e., forebays) (sub-drainage studies A−C; curb and gutter study; channel and forebay study). (ii) Fecal indicator bacteria concentrations increased in runoff from 1999 to 2001 as progressively more dry weather runoff in the Talbert watershed was diverted, while fecal indicator bacteria concentrations at the coastal outlet did not change significantly (sub-drainage studies A−C). (iii) The concentration of TC, and to a lesser extent EC and ENT, was generally higher upstream and lower downstream, of diversion dams in the Talbert and Greenville−Banning channels (channel diversion study). On the other hand, when the entire 6-month study is considered, the vast majority (>99%) of fecal indicator bacteria from the Flounder and Yorktown sub-drainages were shed during rainstorms when diversions were not operating (channel and forebay study). Hence, while diversions appear to reduce the flow of fecal indicator bacteria to the ocean during dry weather periods when the majority of the people are at the beach, they capture a remarkably small percentage (<1%) of the fecal indicator bacteria shed on a year-round basis.

The human health implication of this result is difficult to ascertain without further investigation. Beach usage is generally light during storms, when the loading of fecal indicator bacteria is highest. Hence, one might conclude that the intense loading of fecal indicator bacteria during storms poses little health threat. On the other hand, the delivery of contaminated sediments and particles to the nearshore during storms could lead to chronic contamination of beach areas located near runoff outlets (*31−34*). Indeed it is interesting to note that elevated concentrations of fecal indicator bacteria in the surf zone at Huntington State Beach began in the summer of 1998 (*5*), following an unusually wet El Nino winter in southern California. The delivery of contaminated sediment to the coastal zone during storms may also disrupt fragile nearshore ecosystems by contributing excess toxicity (*28, 35*). If erosion of sediments is driving the loading of fecal indicator bacteria from urban watersheds, then regular removal of contaminated sediments accumulating in the storm sewer system might be an appropriate management strategy. The creation of distributed wetland treatment systems, in which contaminants in urban runoff are removed near their source, might also prove useful for reducing downstream impacts.

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Supporting Information Available

Additional data including text, tables, and figures. This material is available free of charge via the Internet at http://pubs.acs.org.

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