Coastal Runoff Impact Study III: Scaling and Management of Fecal Indicator Bacteria From the Talbert Watershed: Huntington Beach, California

A final report prepared for the National Water Research Institute and the County of Orange

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ACKNOWLEDGMENTS

This work was supported by the National Water Research Institute (NWRI) 02-EC-003 and matching funds from the County of Orange. We gratefully acknowledge the many people involved in the collection of data described in this paper. Special thanks to the following individuals who supervised data collection efforts and/or provided critical feedback and support: N. Gardiner, J. Kim, S. Ensari, J. Redman, M. Anderson, R. Linksy, C. Crompton, C. McGee, K. Hauptly and Y. Jeong.

Executive Summary:

This report describes a series of field studies aimed at identifying the sources and environmental 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, consistent with the idea that urban runoff from this watershed is a source of 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 $\mathcal{L} \sim Q^n$, where Q is the volumetric flow rate and the exponent n ranges from 1 to 1.5. This power-law, and observed range of exponent values, are consistent with a mathematical model that assumes fecal indicator bacteria in storm runoff originate from the erosion of contaminated sediments. 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 storm water conveyance system from which the pollution derives. This raises the possibility that the scaling properties of pollutants in storm water runoff (i.e., the value of n) may harbor information about the origin of non-point source pollution.

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. Management strategies to reduce the downstream impacts of fecal indicator bacteria shedding are needed, but there is a paucity of knowledge regarding the exact sources of these organisms, how these sources react to environmental forcing (e.g., storms), and how fecal indicator bacteria loads scale with runoff volumes.

To address this problem we carried out field studies in a coastal urban watershed, 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[4, 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) What are the sources of fecal indicator bacteria in surface water

from an urban watershed, and do different sources dominate during dry and wet weather conditions? (2) How do fecal indicator bacteria loads shed from an urban landscape vary in space and time? (3) How are fecal indicator bacteria concentrations forced by storms and other environmental factors? (4) How effective is the Talbert watershed diversion program in mitigating fecal indicator bacteria pollution?

FIELD SITE DESCRIPTION

The Talbert and Lower Santa Ana watersheds encompass 80 km^2 of urban landscape in the cities of Huntington Beach, Fountain Valley, Costa Mesa, Santa Ana, and Newport Beach, in central Orange County, California (Appendix I Fig.1). The coastal edge of the watershed is divided into 13 sub-drainages, each of which drains 0.8-8 km^2 (Appendix II 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, and hence pollutants in the runoff can have a large and negative impact on the surfzone water quality[8]. 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: (1) transfer to the sanitary sewer system of runoff accumulating in the forebays (forebay diversions), and (2) 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[9].

METHODS AND MATERIALS

A series of field studies were carried out to define the dry weather sources of fecal indicator bacteria in the watershed (*Source Study*), and characterize spatial and temporal variability of fecal indicator bacteria shedding during dry and wet weather (*Spatial Studies* and *Temporal Study*, respectively). The timing of these different investigations is in Appendix I Fig. 2, where the source investigation is denoted as *Study S*, the spatial investigations are denoted as *Studies A, B, D* and *E* and the temporal investigation is denoted as *Study C*.

Of the 3629 samples collected for this set of studies, over 88% (3220) were analyzed for fecal indicator bacteria using defined substrate tests known commercially as Colilert and Enterolert (IDEXX, Westbrook Maine), all implemented in a 97 well quantitray format (*Method 1*). 2.5% (90) of the samples were analyzed by membrane filtration and multiple tube fermentation (EPA method 9230 C and 9221 B, E respectively) (*Method 2*). 8% (283) of the samples were analyzed by membrane filtration and multiple tube fermentation (EPA method 9222 B, D and 9230 B respectively) (*Method 3*). Sediment samples were analyzed using EPA method 9221 A.3 (*Method 4*). 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 of bacteria (MPN) per 100 mL of sample (Colilert and Enterolert procedure from *Method 1*, EPA method 9221 B, and E from *Method 2*, EPA method 9230 B from *Method 3*), colony forming units (CFU) of bacteria per 100 mL of sample (EPA method 9230 C from *Method 2*, and EPA method 9222 B, and D from *Method 3*),

and MPN per 100 g of wet sediment (EPA method 9221 A.3 from *Method 4*). Samples were also analyzed for turbidity (*Study B*: HACH 21000N, Loveland, Colorado; *Study D*: HF Scientific DRT-15CE, Fort Meyers, Florida), conductivity (*Studies A* and *B*: Thermo Orion 160 Conductivity Meter, Beverly, MA), and salinity (*Study D:* Thermo Orion 162A Conductivity Meter, Beverly, MA). All conductivity measurements were temperature corrected to 25°C and converted to salinity using equations derived from the 1978 practical salinity scale[10].

Although bacterial concentration obtained by these different methods are comparable[11], care was taken to draw conclusions based only on comparisons between sub-groups 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 non-parametric statistical tests. The Kruskal-Wallis[12] test was used to assess whether differences between population medians were significant. Correlation between variables was assessed using Spearman's rank correlations[12]. All statistical tests were implemented with Statistical Packages for the Social Sciences (Chicago, Illinois).

Source Study (*Study S*)

The goal of this study was to measure the concentration of fecal indicator bacteria in specific potential sources of dry-weather runoff. Over the period 12-28 April 2000, samples of dry weather runoff were collected from 283 sites in the Talbert watershed and surrounding area. Over the same period of time 36 sediment samples were collected from areas that served as known sources of dry weather runoff. Specific locations where these samples were collected are

indicated as light blues dots on the map in Appendix I Fig. 1. The type of land-use associated with each sample site was noted at the time of collection. Specific categories of land-use included: Residential, Industrial, Commercial, Agricultural, Parks, Channels and Storm Drains, and Other. Water samples from each site were collected in sterile 100 mL plastic bottles. The samples were labeled and placed in a cooler on ice and transported (within the 6-hour holding time limit) to Sierra Analytical Laboratory (Laguna Hills, CA) where they were analyzed using *Method 2* (for surface water) and *Method 4* (for sediment). Altogether 319 samples were collected, including 283 and 36 water and sediment samples respectively.

Spatial Study (*Studies A, B, D*, and *E*)

The goal of *Studies A, B*, and *D* was to characterize how the concentration of fecal indicator bacteria in dry weather runoff varied across sub-drainages within the Talbert watershed, and along a salinity gradient from inland to coastal sites. These spatial measurements were repeated three times over the course of three years (from 1999 to 2001), as progressively more dry weather runoff was being diverted (compare the number of active diversions with the timing of *Studies A, B,* and *D* on the timeline in Appendix I Fig. 2). During *Studies A, B,* and *D*, 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 Appendix I Fig. 1), eight forebays in 2000 (same as in 1999 with the addition of HB), and ten forebays in 2001 (same as 2000 with the addition of M and H); (2) daily from two to three 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 Appendix I Fig. 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 Appendix I Fig. 1). Sampling at the coastal outlet was conducted hourly (instead of daily as was done at the inland sites), to capture the rapid variation in bacterial concentrations caused by the tidally driven flow reversals, as described elsewhere [6, 13]. The first two spatial studies (*Studies A* and *B*) were two weeks in duration; the third study (*Study D*) was three weeks in duration (See Appendix I Fig. 2).

Water samples from the forebay and channel sites were collected and processed as follows. Approximately 500 mL of sample was collected in a sterile Nalgene bottle (Rochester, New York), capped, placed on ice, and transported to a laboratory within a 6 h holding time for processing (*Study A*: Truesdail Laboratories, Inc; Tustin, CA; *Study B*: Orange County Sanitation District Laboratory, Fountain Valley, CA.; *Study D*: UCI Environmental Engineering Laboratory). Either 10 or 1 mL of each sample (depending on expected concentration) was analyzed using *Method 1*. Samples processed by Orange County Sanitation District and UC Irvine were also analyzed for salinity and turbidity as described earlier.

Water from the coastal outlet (CO in Appendix I Fig. 1) was collected and analyzed as follows. Samples were collected using programmable sampling units (3700 and 6700 programmable samplers, ISCO, Lincoln, Nebraska) installed on an overhead bridge. The sampler was connected to 6.5 mm vinyl tubing that

terminated in a strainer located at a fixed position in the water column. The number and locations of the strainers employed varied by study. *Study A*: Four different positions in the water column, two at fixed distances relative to the water surface (8 cm and 40 cm below the water surface), and two at fixed distances above the bed (50 cm and 90 cm). *Study B*: Two different positions in the water column, 8 cm below the water surface and 50 cm above the bed, little variation between the different positions was observed (for Spearman's correlation coefficients of measured water quality parameters between the various positions in the water column for *Study A* and *B* see Appendix II Table 2.a and b respectively), hence the reduction in the number of sampling positions. *Study D*: One position in the water column, 50 cm above the bed. Each sample (total volume 1L) was a composite of four 250 mL sub-samples collected every 15 minutes. Altogether, 2785 samples were collected and analyzed for the spatial studies, including 50 (*Study A*), 125 (*Study B*), and 440 (*Study D*) from the forebays; 0 (*Study A*), 30 (*Study B*) and 130 (*Study D*) from the channel sites; and 805 (*Study A*), 695 (*Study B*), and 510 (*Study D*) from the coastal outlet.

The goal of *Study E* 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 Appendix I Figs. 1 and 2 for channel diversion locations and study timing, respectively). Water samples were collected 3 times per month approximately 65 meters inland and coastward of the Talbert and Greenville Banning dams for five (Talbert) to nine (Greenville-Banning) months. The samples were analyzed for fecal indicator bacteria using *Method 3*. Altogether 90 samples were collected during *Study E*, including 34 in the Talbert Channel and 56 in the Greenville-Banning Channel.

Temporal Study (*Study C*)

The goal of *Study C* 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 five days per week for six months (from 1 January 2001 to 12 June 2001, see timeline in Appendix I Fig. 2) from the Yorktown and Flounder forebays (designated F and Y in Appendix I Fig. 1), and one channel site in the Fountain Valley Channel (designated FV in Appendix I Fig. 1). Water was collected from the forebay by lowering sample bags (Isco ProPak) into the forebays, and collecting 1 L from the surface of the water column. Approximately 1L of water was collected from the Fountain Valley Channel site by placing the sample bag directly into the channel (which was rarely >15 cm deep). Once the samples were collected, they were immediately capped, placed on ice, and transported back to the laboratory at UCI where they were analyzed for fecal indicator bacteria using *Method 1*, and salinity and turbidity as described earlier.

In addition to the daily sampling just described, depth profiles were also conducted once per week for 3 months (from 3/6/01 to 6/12/01) at the Yorktown forebay. Water samples were collected at fixed depth intervals throughout the water column using a profiling apparatus that consisted of ten Norprene 3mm (outside diameter) tubes strapped to the outside of a 5 cm (outside diameter) Poly-vinyl Chloride (PVC) pipe. The Norprene tubes were arranged so that they terminated at different positions on the PVC pipe. At the time of sample collection, the PVC pipe was lowered into the forebay in a vertical orientation, and the Norprene tubes were connected to a multi-head Cole Parmer L/S pump (Vernon Hills, Illinois). To minimize mixing of the forebay water during sample collection, the pump was set to slowly ($\approx$10 mL/min) draw water up from various depths in the forebay. Water (1 L total volume) from each depth was deposited in sterile bottles (or sample bags) on the deck of the forebay. After collection, samples were immediately placed on ice and returned within a holding time of 6 hrs to the UCI Environmental Engineering laboratory for fecal indicator bacteria analysis using *Method 1,* and turbidity and salinity as described above. In addition to the weekly sampling at discrete depths, depth profiles of salinity, pH, temperature, and dissolved oxygen were measured on a daily basis for the entire six month study using a YSI 600XL Multi-Parameter Sonde (Yellowsprings, Ohio) connected to an Isco 4250 data logger (Lincoln, Nebraska). Altogether, 435 samples were collected and analyzed for the temporal study, including 110 from the Flounder forebay, 215 from the Yorktown forebay, and 110 from the Fountain Valley Channel.

The instantaneous load (in units of most probable number 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 the map, Appendix I Fig. 1). Dry weather flows from the two forebays and one channel site were diverted to the sanitary sewer system, and hence the daily dry weather flow rate $Q_B(t)$ could be estimated directly from City and County diversion records. 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, Talbert and Huntington Beach Channels, see Appendix I Fig. 1). The rational method was used to estimate the magnitude of volumetric flow rate during storms[14]: $Q_S(t) = KR(t)A_s$ where K is the dimensionless runoff coefficient (assumed to be $K = 0.75$, which is typical for highly urbanized drainage areas[14]), $R(t)$ is measured rainfall intensity (units of mm/h), and A_s is the total sub-drainage area (See Appendix II Table 1). The rational method can be used to calculate storm runoff because, at our study site, 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 $R(t)$. The rainfall data are available from NOAA's National Climatic Data Center (Asheville, NC)[15].

RESULTS

Source Study (*Study S*)

The results of *Study S* are summarized in Appendix II Table 3. The concentration of fecal indicator bacteria in dry-weather urban runoff are very high (geometric means of 15,000, 1,000, and 1,800 CFU/100 mL for TC, FC, and ENT, respectively). By way of comparison, the 30-day geometric mean standards for coastal beaches in California are 1,000, 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, channels and storm drains, and the other category ($p < 0.05$, Kruskal-Wallis). The fecal indicator bacteria concentrations in the sediment samples are also very high (geometric means of 63,000, 1,000, and 3,000, 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).

Spatial Study (*Studies A, B, D,* and *E*)

Forebays in the Talbert watershed receive dry weather runoff from a well-defined area, as indicated by the sub-drainage boundaries drawn on the map in Appendix I Fig. 1. Residential areas dominate the land-use in all of the sub-drainages of the Talbert watershed (Appendix II Table 1). Water samples collected from the forebays during dry weather periods harbor very high concentrations of fecal indicator bacteria, although no single forebay (or set of

forebays) is consistently higher than the rest (Appendix II 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 D* (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 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 (Appendix II Table 1), and the high concentration of fecal indicator bacteria detected in residential runoff during the *Study S* (Appendix II 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 (Appendix I Fig. 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 Appendix II Table 5). Referring to Table 5, over the three year 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, B*, and *D* 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, 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 $p < 0.01$) (See Appendix II Table 6). The relatively weak correlation between fecal indicator bacteria and turbidity in the dry weather runoff is apparent in Appendix I Fig. 3, where the turbidity of each sample is denoted by color ranging from blue (low turbidity) to red (high turbidity)

To assess the efficacy of the two in-channel diversions, in *Study E* 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 (Appendix I Fig. 4). 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, see Appendix II Table 7).

Temporal Study (*Study C*)

Based on the depth profiling studies, runoff in the forebays is generally well-mixed (especially notable in the later part of the study) over the vertical relative to fecal indicator bacteria, salinity, dissolved oxygen, pH, and temperature. Physical parameters ranged from 0 to 6 ppt (salinity), 0 to 8 mg/L (dissolved oxygen), 6.8 to 8.4 (pH), and 16 to 22 °C (temperature). Over the course of the depth profiling study (6 March through 12 June, 2001), temperature increased, dissolved oxygen decreased, and salinity and pH showed no clear trend (Appendix I, Fig. 5).

Appendix I Fig. 6 illustrates the effect of rainfall on turbidity, salinity, and the concentration of fecal indicator bacteria during the six-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/day), 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 to 10^6 MPN/100 mL), EC (10^1 to 10^5 MPN/100 mL), and ENT (10^1 to 10^5 MPN/100 mL) (Appendix I Fig. 6). 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, see Appendix II Table 8) in samples collected during base flow conditions, on the 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, compared to samples collected during trace rainfall and dry-weather periods ($p < 0.01$, Kruskal-Wallis, see Appendix II Table 8). 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, see Appendix II Table 9).

Appendix I Fig. 7 presents time series plots of the fecal indicator bacteria load entering the Yorktown forebay (first column of panels), Flounder forebay (second column), and the 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 rate at these sites are highly variable, ranging over five (TC) and six (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 near the end of *Study C*,

increased steadily over the last three months of the study (e.g., see the TC loading rates in the third column of Appendix I Fig. 7).

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 a year. This result is illustrated in Appendix I Fig. 8, where the fecal indicator bacteria load diverted from the Yorktown and Flounder forebays is plotted as a percentage of the total load shed over the course of the six-month study. The diverted load ranges from approximately 0.1% for ENT to near 1% for EC. Over the course of this six month study, >99% of the fecal indicator bacteria load shed from the Yorktown and Flounder sub-drainages made its way to the ocean.

Previous studies[16] have noted that pollutant loading $\mathcal{L}$ in storm runoff sometimes scales as a power-law of the volumetric flow rate Q:

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

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: $\alpha = C_B/(Q_B/A_s)^{n-1}$. Eq. 1 predicts that a log-log plot of $\mathcal{L}/A_s$ versus Q/A_s will yield a straight line

with slope n and intercept α. As illustrated in Appendix I Fig. 9, fecal indicator bacteria loading from the Fountain Valley, Yorktown, and Flounder sub-drainages conform reasonably well to eq. 1. Spearman's correlation coefficients computed between $Log(\mathcal{L}/A_s)$ 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 Appendix I Fig. 9 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 Appendix I Fig. 6).

DISCUSSION

Diversion Efficacy. Urban runoff is increasingly recognized as a significant cause of coastal water quality impairment [13, 17-20]. 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. Based on the data presented above, the efficacy of this diversion program is mixed. On the 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: (1) 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) (*Studies A, S, B, C,* and *D*). (2) 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 (*Studies A, B,* and *D*). (3) 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 (*Study E*). On the other hand, when the entire six-month study is considered, the vast majority (>99%) of fecal indicator bacteria from the Flounder and Yorktown sub-drainages was shed during rainstorms when diversions were not operating (*Study C*). 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, 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[21-25]. Indeed it is interesting to note that elevated concentrations of fecal indicator bacteria in the surfzone 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[18, 26].

The increase in the inland-to-coastal fecal indicator bacteria gradient during *Studies A, B, and D* 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 Appendix II 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 particular, air temperature increased in the order: *Study A* (14 °C), *Study B* (18 °C) and *Study D* (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 D* (277 mm) (see Appendix I Fig. 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[27, 28]. Regardless of what caused the dry weather concentration of fecal indicator bacteria in the forebays to increase over the three-year 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 (non-runoff) sources of fecal indicator bacteria, such as regrowth in sediments and/or bird droppings deposited in the channel network and Talbert marsh[13, 28].

Origins of Storm Loading. Why does so much of the fecal indicator bacteria loading occur during storm events? Loading increases nonlinearly with rainfall intensity because both the 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 $m^3/day/km^2$ during dry weather (see Appendix II Table 1) to peak values of nearly $500{,}000\, m^3/day/km^2$. 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 (Appendix I Fig. 6). The fact that the concentration of fecal indicator bacteria increases, or holds steady, during heavy storms is at odds with the traditional build-up/wash-off paradigm which predicts that pollutant concentration in runoff should scale with the time between storms[29], not rainfall intensity. Indeed, a large fecal indicator bacteria loading event occurred late in the storm season, and was proceeded by a short (5 day) antecedent dry period (March 6, 2001, Appendix I Fig. 7).

Because the build-up/wash-off paradigm is widely employed in surface water quality models[30,31], it is important to explore what other process may be at work in our system. One promising paradigm envisions that most of thc 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 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[32,33]. Further, fecal indicator bacteria accumulate, die-off and perhaps grow, in storm sewer sediments[34]. 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 six month study (*Study C*), and the relatively high concentrations of fecal indicator bacteria measured in sediments collected from drainage channels in the Talbert watershed (*Study S*, Appendix II Table 3). 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 section. Relative to measurements conducted in forebay samples during *Studies A, B, C* and *D,* it is interesting to note that while there is a strong correlation between fecal indicator bacteria concentration and turbidity during storms (Spearman's correlation coefficients of 0.63 to 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 Appendix I Fig. 3), suggest that different processes may drive fecal indicator bacteria concentrations during dry and wet weather. 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.

Model of Pollutant Loading from Sediment Erosion. Modified versions of eq. 1 have been employed to characterize the relationship between pollutant loading

(usually conservative pollutants, e.g. heavy metals) and volumetric flow rate in previous studies[16]. 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 [35] 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):

$$\mathcal{L} = A_1 P R_h^{2.52} \quad (2)$$

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

The parameters in eq. 2a 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 [14]:

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

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 $\mathcal{L}$ 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 only require that $\mathcal{L}$, P, and R_h can be represented as power-laws of Q:

$$\mathcal{L} = A_2 Q^n \quad (4a)$$

$$P = A_3 Q^p \quad (4b)$$

$$R_h = A_4 Q^r \quad (4c)$$

where A_2, A_3, and A_4 are fixed multiplicative constants. Substituting 4a,b ,c into eqs. 2 and 3 yields the following constraints on the exponents n, p, and r:

$$n = p + 2.52r \quad (5a)$$

$$p + 1.5r = 1 \quad (5b)$$

Excluding the possibility that wetted perimeter and hydraulic radius decrease with increasing flow rate (i.e., $p \geq 0$ and $r \geq 0$), eqs. 5a and b yield the following bounds on the power-law exponent n:

$$1 \leq n \leq 1.68 \quad (6)$$

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 (for a complete derivation see Appendix III).

Based on 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. Further, 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, and 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, and 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 ($n = 1$ to 1.5) are within the range predicted by our simple erosion model ($n = 1$ to 1.68). Intriguingly, the exponents for TC and EC ($n = 1$ to 1.2) are closer to the lower bound, while the exponent for ENT ($n = 1.5$) is closer to the upper bound. One interpretation 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). Further research is needed to 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.

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APPENDIX I

Figures

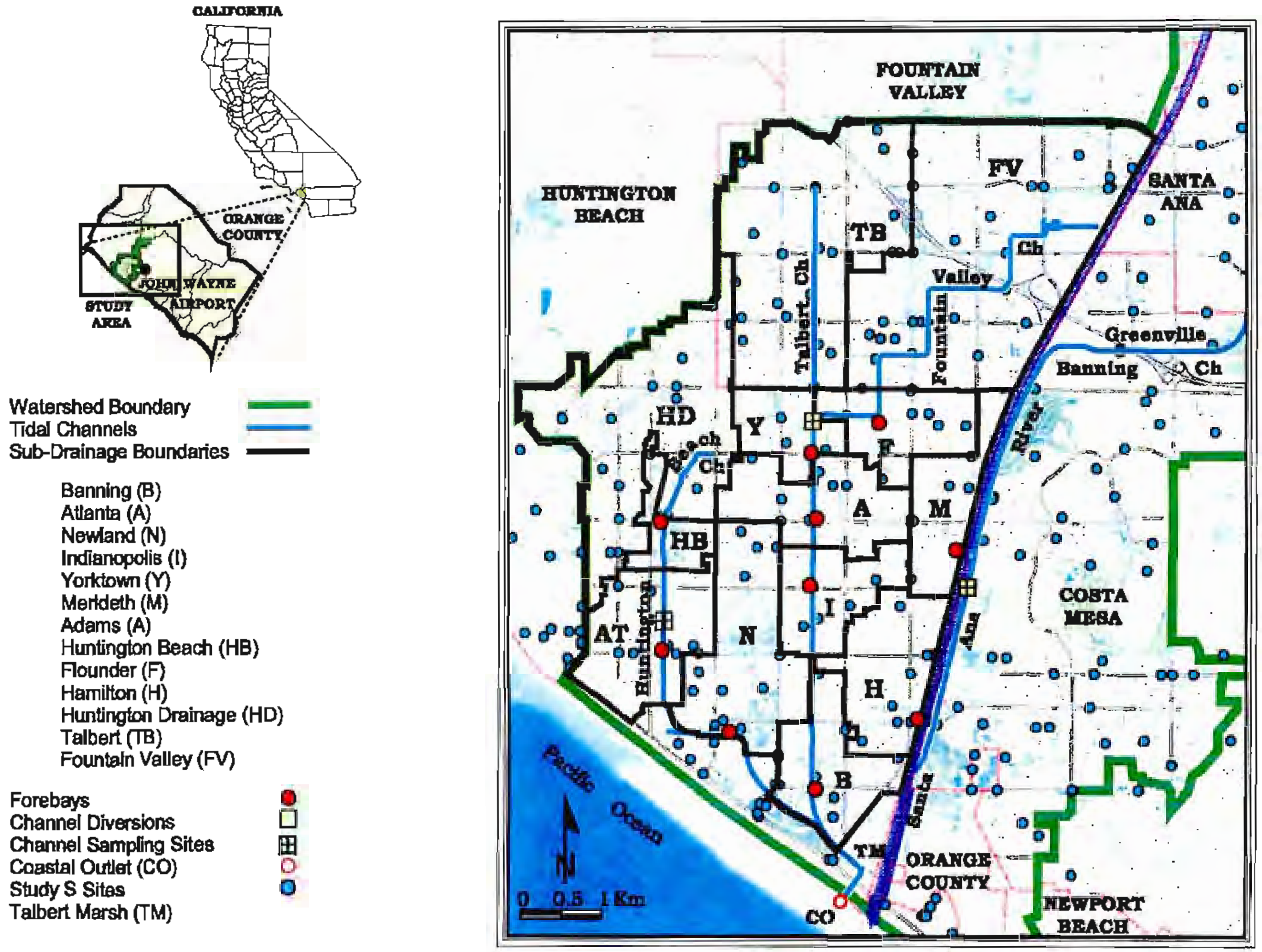

Figure 1. Map of the Talbert watershed study area and the number and approximate locations of sampling sites and sites where dry weather runoff was diverted to the sanitary sewer system.

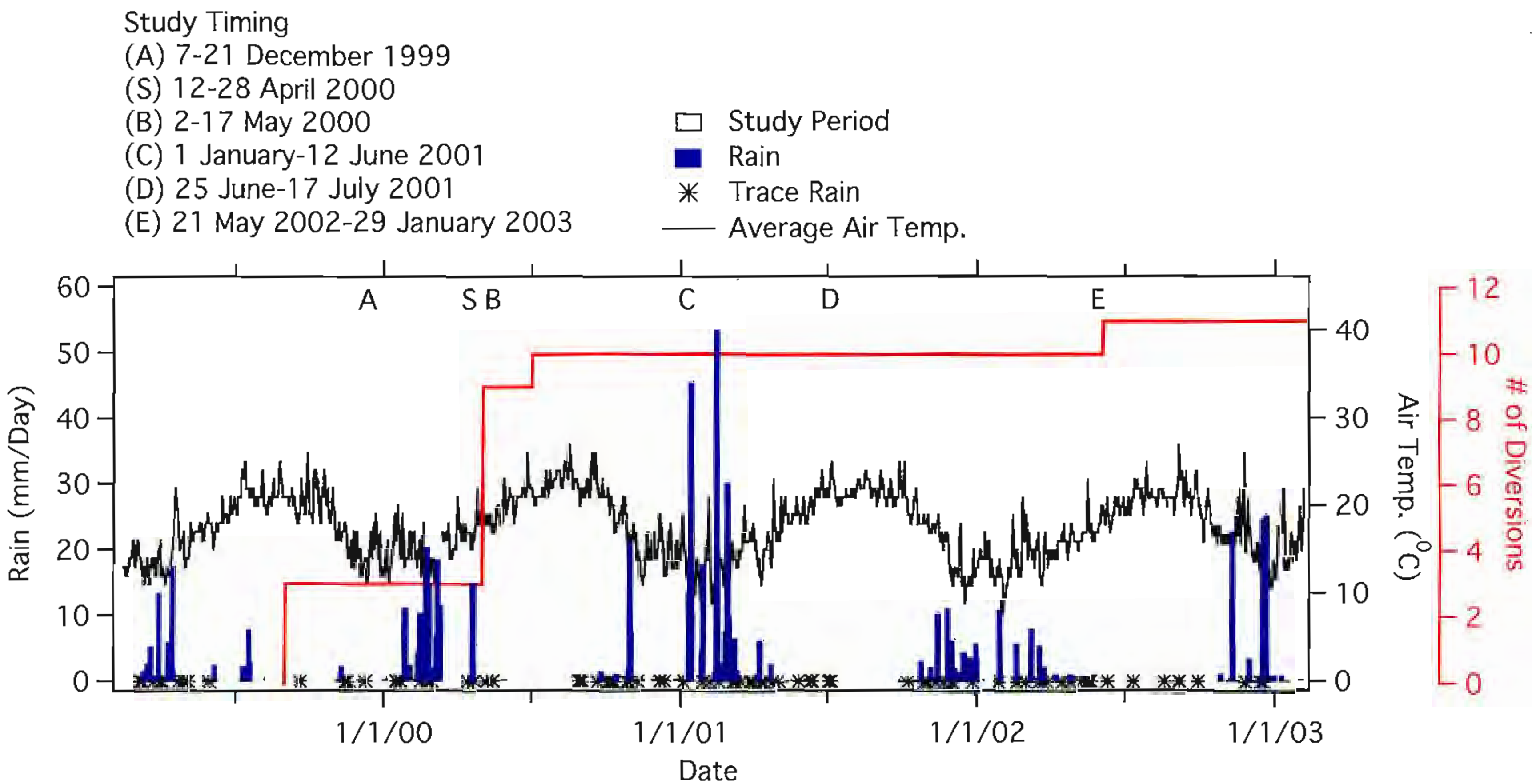

Figure 2. Timeline of the various studies conducted in the Talbert watershed. Also shown on the time line are rainfall history, average air temperature recorded at the nearby John Wayne Airport, and the number of forebay and channel diversion structures operating within the study area.

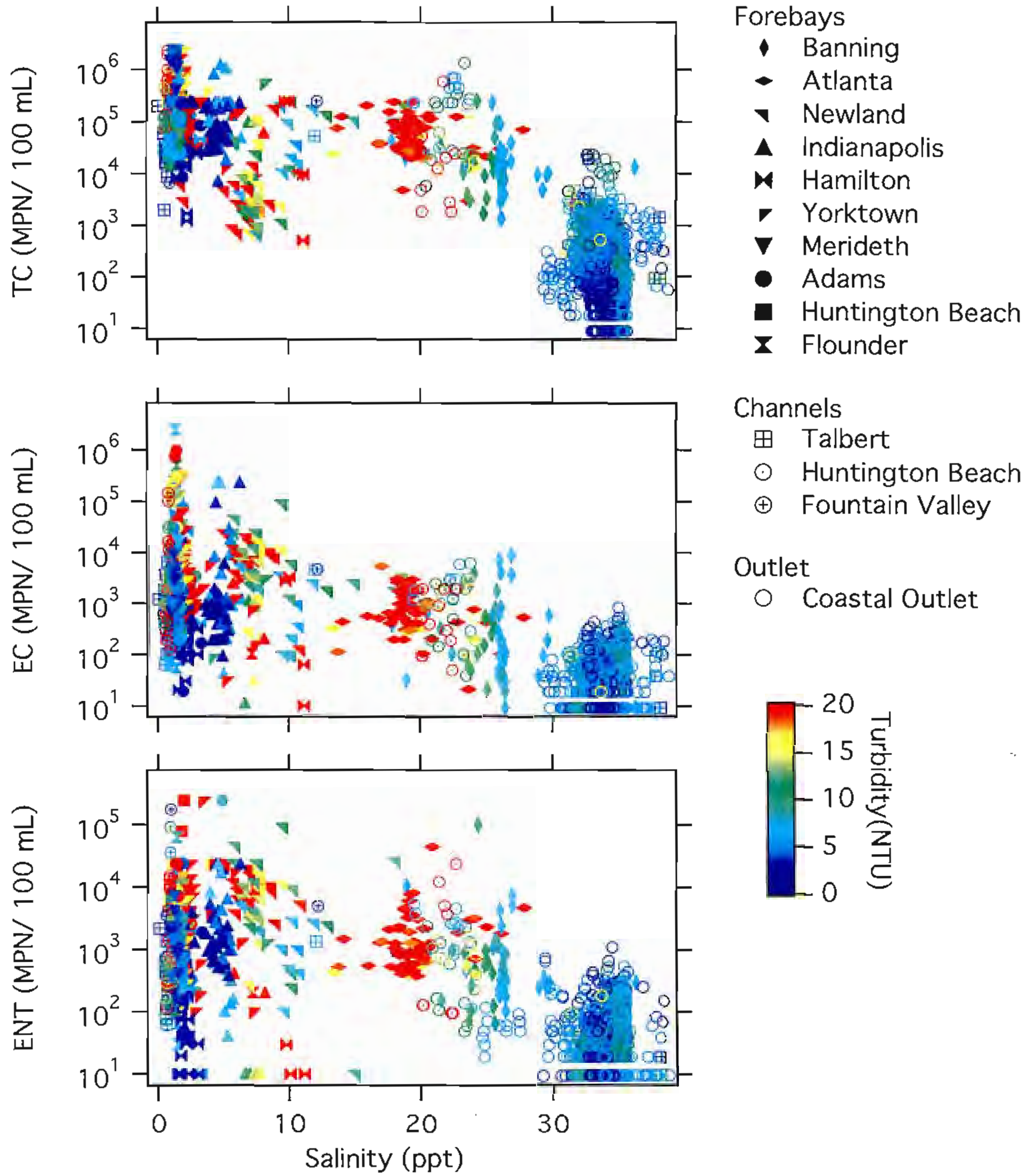

Figure 3. The concentration of fecal indicator bacteria and turbidity measured in forebays and channels, and at the coastal outlet of the Talbert watershed, during a series of dry weather studies conducted from 1999 to 2001 (*Studies A, B, and D*).

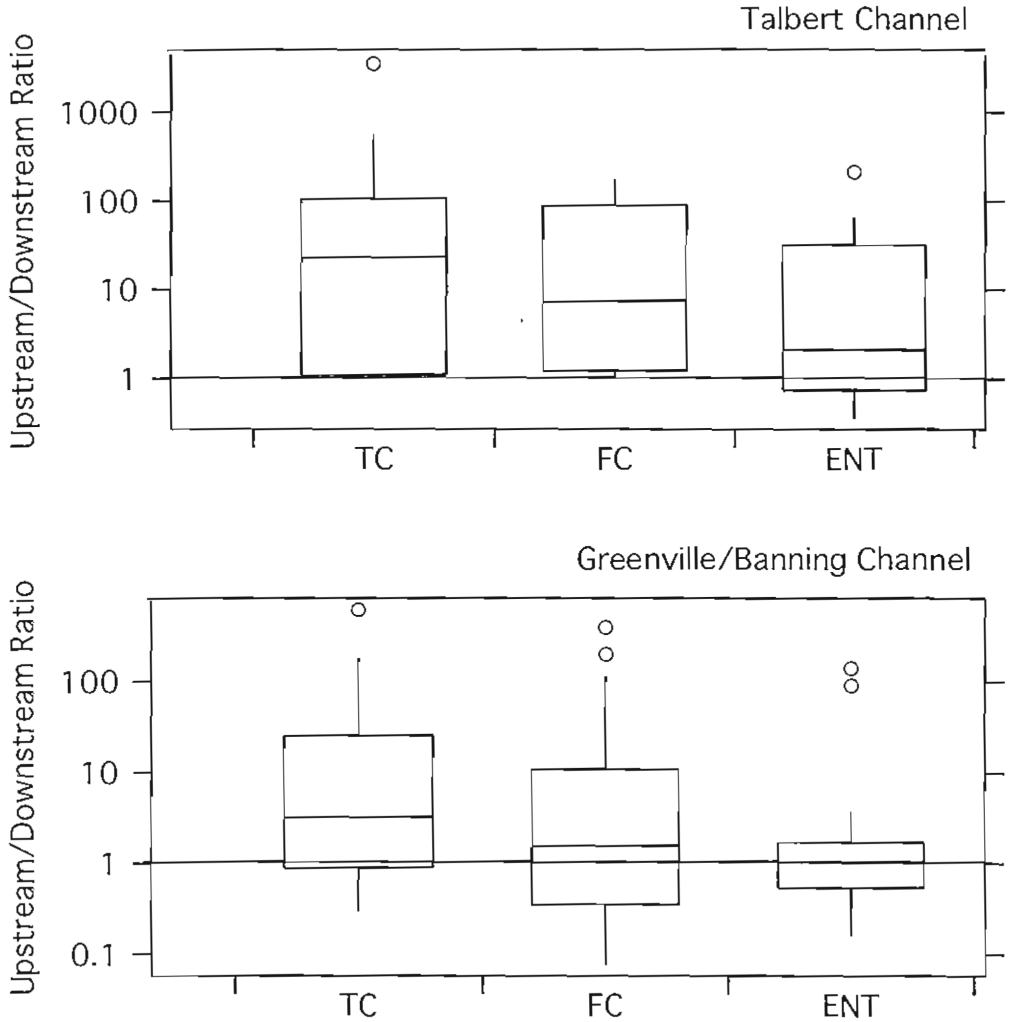

Figure 4. Comparison of fecal indicator bacteria concentrations measured inland and coastward of temporary diversion dams installed in the Talbert and Greenville-Banning channel (*Study E*). In this graph, median values are denoted by horizontal lines, the box encompasses all values falling in the 25th to 75th percentiles, the whiskers encompass all data falling in the 10th to 90th percentiles, and the circles denote extreme values (<10th or >90th percentiles).

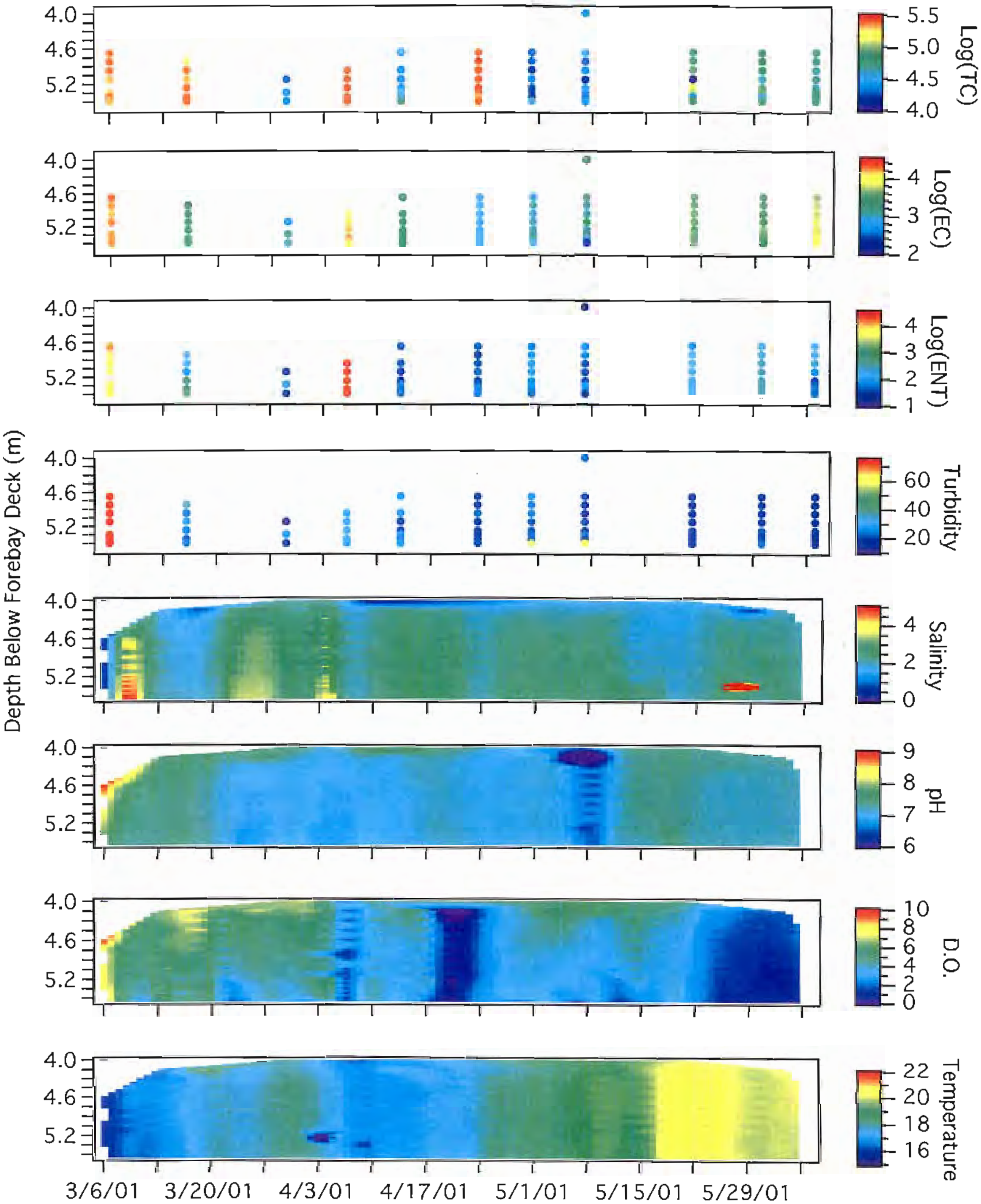

Figure 5. Time series measurements of Yorktown forebay profiling studies. Units of fecal indicator bacteria (TC, EC, and ENT) are MPN/100 mL, units of turbidity are NTU, units of salinity are ppt, and units of temperature are °C. Note that water quality parameters are generally well mixed over the vertical.

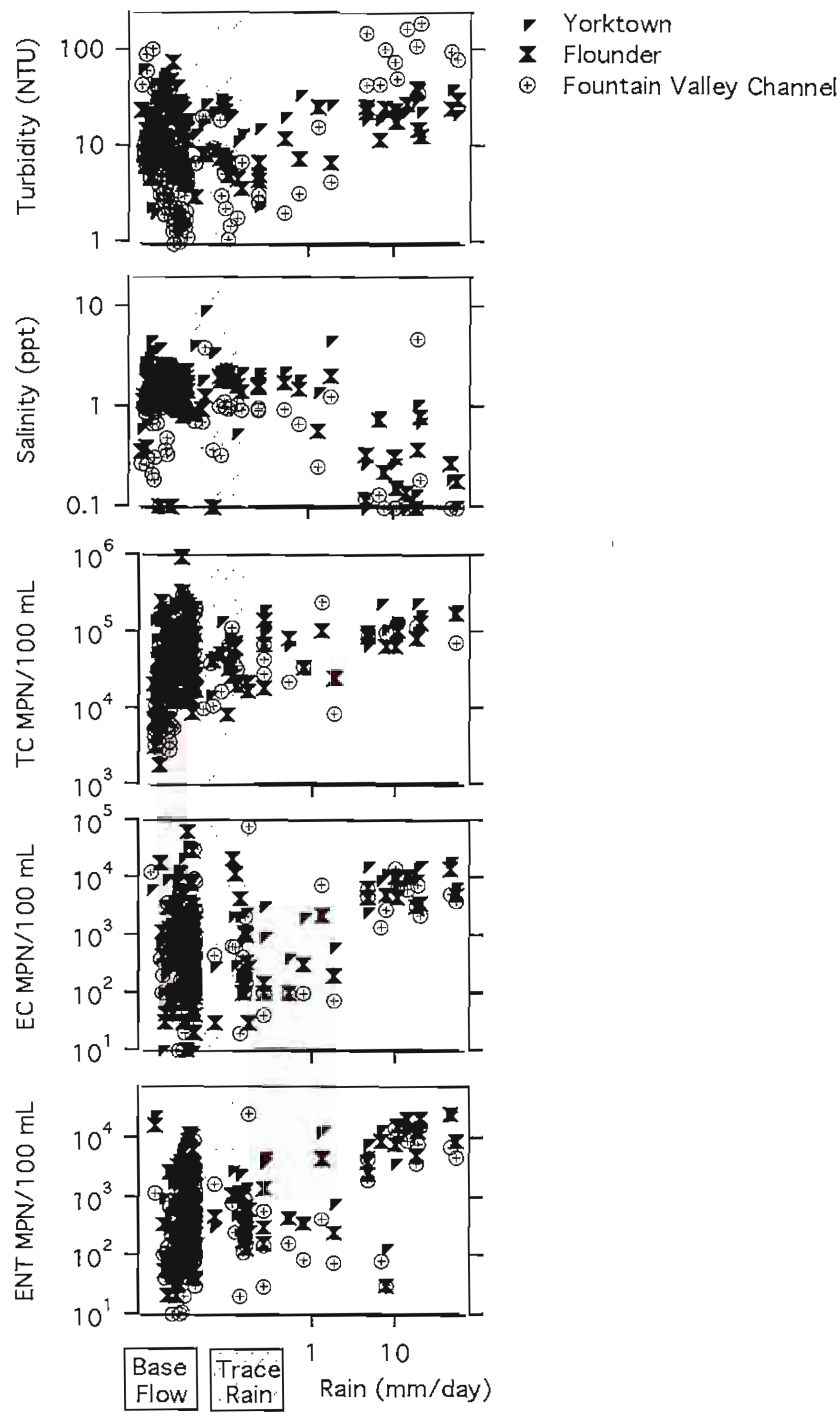

Figure 6. Effect of rainfall intensity on turbidity, salinity, and fecal indicator bacteria concentrations in runoff from the Yorktown, Flounder, and Fountain Valley Channel sub-drainages (Study C).

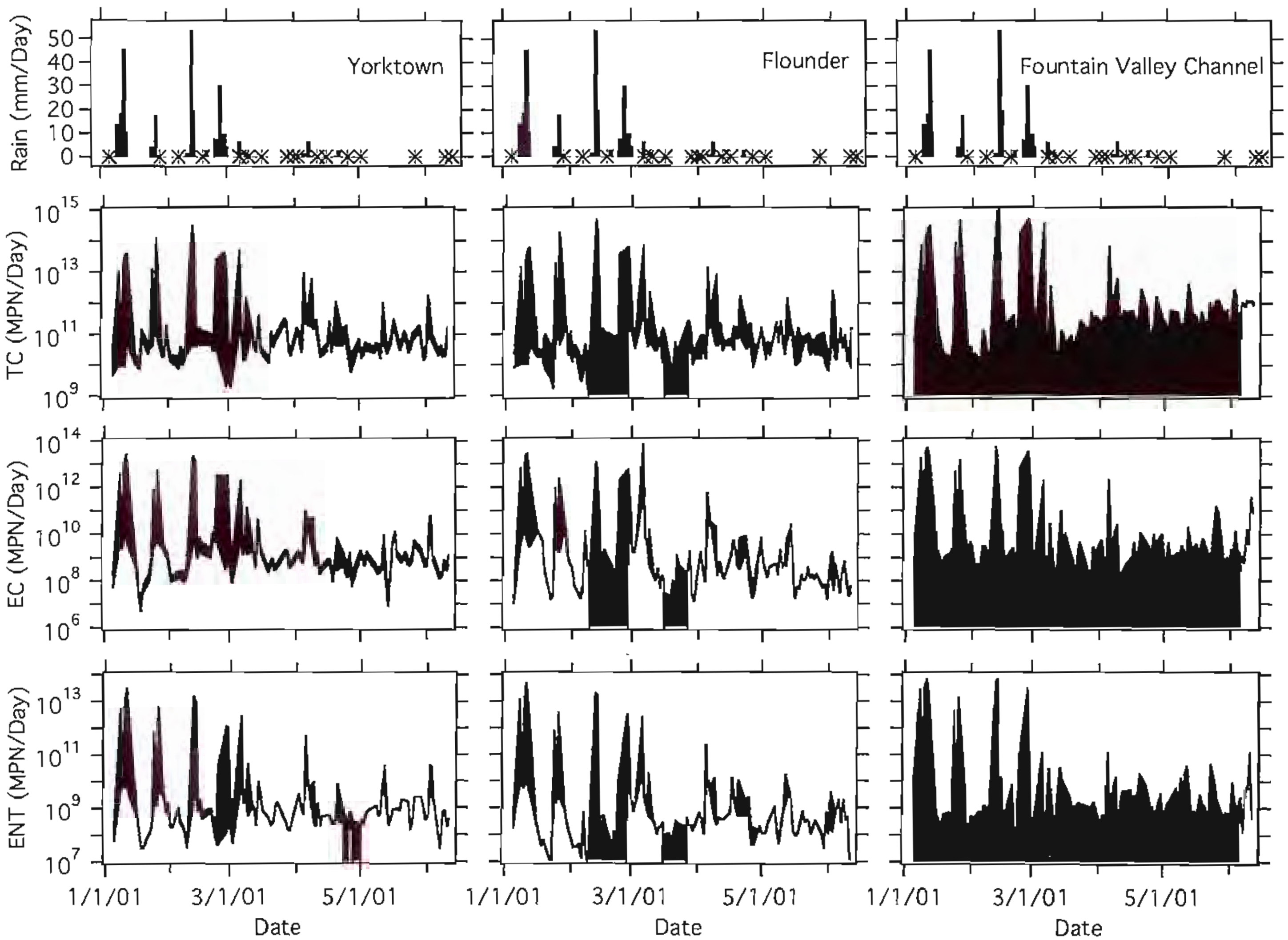

Figure 7. Instantaneous loading of fecal indicator bacteria from the Yorktown, Flounder, and Fountain Valley sub-drainages during dry and wet weather (*Study C*). shading denotes fraction of load diverted to the sanitary sewer system (light grey) and fraction released to the ocean (black). Also shown (top panels) rainfall intensity (bars) and trace rain events (asterisks).

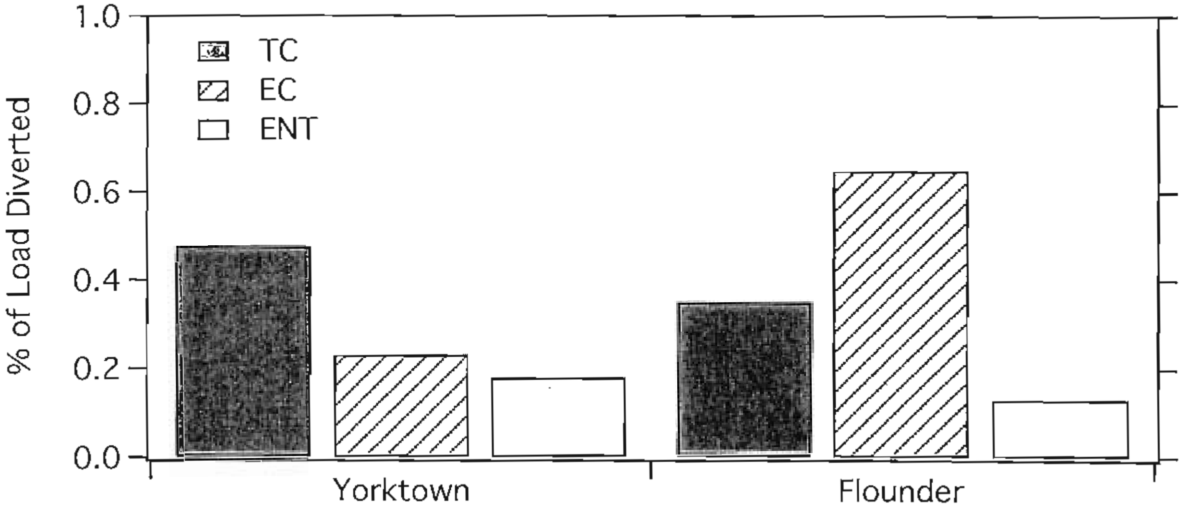

Figure 8. Fraction of fecal indicator bacteria load shed from the Yorktown and Flounder sub-drainages over the six-month time frame (1 January to 12 June 2001) for *Study C.*

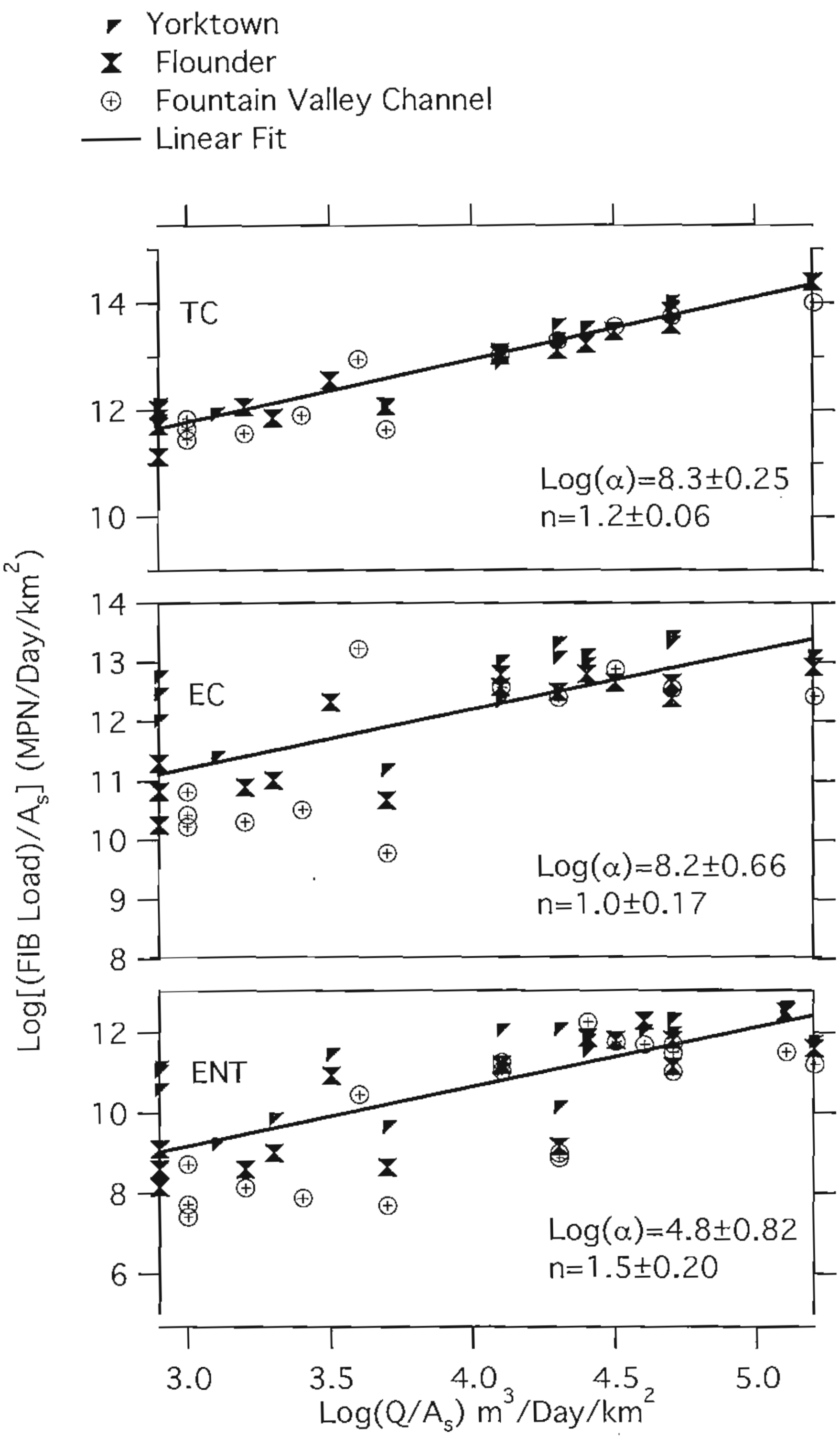

Figure 9. The scaling of fecal indicator bacteria load during storms with volumetric flow rate (*Study C*).

APPENDIX II

Tables

Table 1. Sub-drainages in the Talbert watershed study area.

Sub-drainage	Dominant Land Use	% of Total	Sub-Drainage Area (km^2)	Baseflow (m^3/day)
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	640
Huntington Drainage	Residential	68	5.1	ND*
Talbert	Residential	81	5.8	300
Fountain Valley	Residential	51	8.2	500

*No Data Available

Table 2.A. Spearman's correlation coeficients and significance values for the listed water quality parmeters between different positions in the water column (*Study A*).

	1999	Surface	Below Surface	Above Bottom
TC	Surface	1		
	Below Surface	0.75[a]	1	
	Above Bottom	0.55[a]	0.52[a]	1
	Bottom	0.75[a]	0.77[a]	0.63[a]
EC	Surface	1		
	Below Surface	0.39[a]	1	
	Above Bottom	0.39[a]	0.41[a]	1
	Bottom	0.43[a]	0.52[a]	0.46[a]
ENT	Surface	1		
	Below Surface	0.54[a]	1	
	Above Bottom	0.5[a]	0.57[a]	1
	Bottom	0.56[a]	0.62[a]	0.66[a]
Salinity	Surface	1		
	Below Surface	0.92[a]	1	
	Above Bottom	0.78[a]	0.86[a]	1
	Bottom	0.93[a]	0.91[a]	0.85[a]
Turbidity	Surface	1		
	Below Surface	0.79[a]	1	
	Above Bottom	0.69[a]	0.43[a]	1
	Bottom	0.73[a]	0.74[a]	0.55[a]

Table 2.B. (*Study B*).

	2000	Surface
TC	Bottom	0.83[a]
EC	Bottom	0.69[a]
ENT	Bottom	0.70[a]
Salinity	Bottom	0.87[a]
Turbidity	Bottom	0.82[a]

[a] correlation significant ($p<0.01$)

Table 3. Concentrations of fecal indicator bacteria measured in samples of dry weather runoff and sediment (Sed) from the Talbert watershed (*Study S*).

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]	28.8 (71,999)	2.9 (2.6,14)[d]	0.045 (1,30)	5.6 (5.1,17)[d]	30.6 (8,56)	150	7
Agricultural	27 (3.7,77)	90 (34,60)	0.75 (0.4,6)	1.8 (1,14)	1.6 (0.5,7)	1.8 (4,56)	6	7
Commercial	26 (33,166)	189 (12,0)	1.2 (1.2,9)	5.4 (2,0)	1.75 (1.8,6)	1.35 (1,0)	52	2
Industrial	17 (16,0)	9000 (*,0)	3 (3,0)	63 (*,0)	11.1 (6.8,0)	486 (*,0)	3	1
Channels	0.6 (1,2.1)[e]	41.4 (26,22)	0.1 (0.2,0.25)[e]	0.9 (1,11)	0.1 (0.2,0.6)[e]	4.5 (5,81)	25	8
Parks	0.7 (2.1,17)[e]	90 (76,77)	0.1 (0.1,0.1)[e]	1.8 (1,0.8)	0.1 (0.2,0.69)[e]	1.8 (1,2.6)	11	5
Other	20 (22,88)	162 (229,3117)	0.5 (0.8,5.1)	1.8 (1,1.7)	1.7 (1.8,10)	1.35 (1,9.6)	36	6
All	19 (15,118)	90 (63,91)	0.7 (1,8.8)	1.8 (1,2.3)	2.4 (1.8,11)	1.8 (3,13)	283	36

a Median (Geometric Mean, Inner Quartile Region) all values x1000
b TC and FC units CFU/100 mL of water, ENT units of MPN/100 mL of water
c Units MPN/ 100 g of wet sediment
d Significantly greater than all other landuse types ($p<0.05$ Kruskal-Wallis)
e Significantly less than all other landuse types ($p<0.05$ Kruskal-Wallis)
*Insufficient Data

Table 4. Concentrations of fecal indicator bacteria measured in dry weather runoff collected from forebays in the Talbert watershed.

Forebays	TC (MPN/100 mL) [a] *Study A* ('99)	*Study B* ('00)	*Study D* ('01)
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 x1000
b Significantly greater than all other forebays in a given year ($p<0.05$ Kruskal-Wallis)
c Significantly less than all other forebays in a given year ($p<0.05$ Kruskal-Wallis)

Table 5. Concentration of fecal indicator bacteria measured on an inland-to-coastal salinity gradient

	Study A ('99)	*Study B* ('00)	*Study D* ('01)
	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	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 x1000
b Significantly greater than the subsequent year ($p<0.05$ Kruskal-Wallis)
c Significantly less than the subsequent year ($p<0.05$ Kruskal-Wallis)
*No Data

Table 6. Spearman's correlation coefficients between fecal indicator bacteria and salinity and turbidity (*Studies A,B and D*).

	TC				EC				ENT			
	FB	TCH	CO	All	FB	TCH	CO	All	FB	TCH	CO	All
Salinity	-0.56 [a]	-0.62 [a]	-0.21 [a]	-0.65 [a]	-0.36 [a]	-0.59 [a]	0.05 [b]	-0.5 [a]	-0.09 [b]	-0.54 [a]	0.04 [b]	-0.49 [a]
Turbidity	-0.08	-0.08	0.5 [a]	0.58 [a]	0.2 [a]	-0.15	0.29 [a]	0.45 [a]	0.32 [a]	-0.16 [b]	0.14 [a]	0.38 [a]

a=Correlation Coefficient Significant ($p<0.01$)
b=Correlation Coefficient Significant ($p<0.05$)
FB=Forebays
TCH=Tidal Channels
CO=Coastal Outlet
All=Entire data set

Table 7. Median fecal indicator bacteria concentrations in samples collected upstream and downstream of the channel diversion structures (*Study E*).

	Talbert Channel[a]		Greenville-Banning Channel[a]	
	Upstream	Downstream	Upstream	Downstream
TC (MPN/ 100 mL)	1300[b]	80	1200[c]	400
FC (MPN/ 100 mL)	170[b]	23	130	45
ENT (CFU/100 mL)	160	30	95	75

a=Median Concentration Kruskal-Wallis Significance Value

b=Significantly Different from Downstream (p<0.01)

c=Significantly Different from Downstream (p<0.05)

Table 8. Concentration of fecal indicator bacteria measured in runoff during periods of trace rain and rain events (*Study C*).

	Yorktown[a] Base Flow	Yorktown[a] Trace Rain	Base Flow + Trace Rain	Rain
TC (MPN/100 mL)	48840	46180	48840	125148[b]
EC (MPN/100 mL)	740	310	735	7890[b]
ENT (MPN/100 mL)	855	512	803.5	8164[b]
Salinity (ppt)	2.3	2.3	2.3	0.7[b]
Turbidity (NTU)	22.4	22.8	22.4	23.2
Flounder[a]				
TC (MPN/100 mL)	27550	32820	28320	81640[b]
EC (MPN/100 mL)	305	336	310	3980[b]
ENT (MPN/100 mL)	211	471	290	4352[b]
Salinity (ppt)	1.7	1.7	1.7	0.4[b]
Turbidity (NTU)	7.4	7.2	7.4	18.4[b]
Fountain Valley Channel[a]				
TC (MPN/100 mL)	43520	37215	43520	70685
EC (MPN/100 mL)	310	410	310	3100[c]
ENT (MPN/100 mL)	228	249	233	1935[c]
Salinity (ppt)	1	1	1	0.1[b]
Turbidity (NTU)	4.4	6	4.5	45[b]
ALL Stations[a]				
TC (MPN/100 mL)	41060	38730	40400	92080[b]
EC (MPN/100 mL)	406.5	336	403	3230[b]
ENT (MPN/100 mL)	300	336	305	3873[b]
Salinity (ppt)	1.7	1.9	1.7	0.6[b]
Turbidity (NTU)	7.9	9	8.2	21.1[b]

a=Median Kruskal-Wallis Significance Value
b=Significant ($p<0.01$)
c=Significant ($p<0.05$)

Table 9. Spearman's correlation coefficients between rainfall and the water quality parameters listed (*Study C*).

	Yorktown Rainfall	Flounder Rainfall	Fountain V. C. Rainfall	All Rainfall
TC	0.46	0.39	0.54	0.42[b]
EC	0.72[a]	0.73[a]	0.54[b]	0.67[b]
ENT	0.64[a]	0.78[a]	0.69[a]	0.66[b]
Salinity	-0.71[a]	-0.66[a]	-0.63[a]	-0.62[b]
Turbidity	0.53[b]	0.67[a]	0.78[a]	0.63[b]

a=$p<0.01$
b=$p<0.05$

APPENDIX III

Derivations

It has been noted that pollutant loading can scale as a power law demonstrated in Equation 1 below:

$$\frac{\mathcal{L}}{A_s} = \alpha\left[\frac{Q}{A_s}\right]^n$$

$\mathcal{L}$ = Pollutant Loading

Q = Volumetric flowrate

A_s = Drainage Surface Area

α = Empirical Scaling Constant

The following is a theoretical justification for this relationship based on the idea that pollutant loading originates from the re-suspension of deposited sediment during higher flow storm conditions.

Graf et al. (1968) approach: Developed for the prediction of bed material load in open-channels as well as closed conduits.

$$\psi_A = \frac{\left(\frac{\rho_s - \rho}{\rho} d\right)}{SR_h}$$

$$\phi_A = \frac{\overline{C}\,\overline{U}R_h}{\sqrt{\left(\frac{\rho_s - \rho}{\rho}\right) g d^3}}$$

ψ_A = Shear Intensity

ϕ_A = Transport Parameter

ρ_s = Sediment Density

ρ = Fluid Density

g = Acceleration due to Gravity

S = Channel Losses

P = Perimeter

$\mathrm{A_c}$ = Cross Sectional Area

R_h = Hydraulic Radius $\left(\frac{\mathrm{A_c}}{P}\right)$

$\overline{C}$ = Volumetric Concentration of Transported Particles

$\overline{U}$ = Horizontal Velocity

d = Diameter of a Particle

The relationship between these two parameters was developed from experimental and laboratory data.

$$\phi_A = 10.39(\psi_A)^{-2.52}$$

Note that:

$$\mathcal{L}/P = \overline{C}\,\overline{U}R_h$$

$$\mathcal{L} = \text{Sediment Load}\left(\frac{\overline{C}}{Q}\right)$$

Therefore Equation 2 is derived:

$$\mathcal{L} = A_1 P R_h^{\,2.52}$$

$$A_1 = 10.39\left[\frac{S}{\frac{\rho_s - \rho}{\rho}d}\right]^{2.52}\left[\frac{\rho_s - \rho}{\rho}gd^3\right]^{1/2}$$

From open channel-flow text books the well know Chezy Equation can be derived:

$$\overline{U} = C\sqrt{R_h S}$$

C = Chezy Coefficient

Note:

$$Q = \overline{U}R_h P$$

Therefore Equation 3 is derived:

$$PR_h^{\,1.5} = \frac{Q}{C\sqrt{S}}$$

It is desirable to obtain a relationship between Q and $\mathcal{L}$, however P and R_h have different exponents in Equation 2a and 3 therefore additional information is needed, which is obtained by requiring that $\mathcal{L}$, P, and R_h can be represented as power-laws of Q:

$$\mathcal{L} = A_2 Q^n \tag{4a}$$

$$P = A_3 Q^p \tag{4b}$$

$$R_h = A_4 Q^r \tag{4c}$$

Substitute 4a, b, and c into Equation 2 to get Equation 5a:

$$\mathcal{L} = A_1 P R_h^{\ 2.52}$$
$$A_2 Q^n = A_1 A_3 A_4^{\ 2.52} Q^{p+2.52r}$$
$$A_2 = A_1 A_3 A_4^{\ 2.52}$$

aside :

$$ax^n = bx^p \rightarrow (n-p)\log(x) = \log\left(\frac{b}{a}\right)$$

$n = p$ because x can vary so $b = a$

$$n\log(Q) = p\log(Q) + 2.52r\log(Q)$$
$$n = p + 2.52r$$

Substitute 4a, b, and c into Equation 3 to get Equation 5b:

$$PR_h^{\ 1.5} = \frac{Q}{C\sqrt{S}}$$
$$A_3 A_4^{\ 1.5} Q^{p+1.5r} = \frac{Q}{C\sqrt{S}}$$
$$A_3 A_4^{\ 1.5} = \frac{1}{C\sqrt{S}}$$
$$p\log(Q) + 1.5r\log(Q) = \log(Q)$$
$$p + 1.5r = 1$$

Excluding the possibility that P and R_h decrease with increasing flowrate (i.e., $p \geq 0$ and $r \geq 0$) one can see the possibility of two limiting cases:

Case 1 :

$n = p + 2.52r$ (5a)

$1 = p + 1.5r$ (5b)

if $r = 0$ then :

$n = p$ and $p = 1 \therefore n = 1$

Case 2:

$n = p + 2.52r$ (5a)

$1 = p + 1.5r$ (5b)

if $p = 0$ then:

$n = 2.52r$ and $1.5r = 1 \therefore n = 1.68$

So it has been shown that according to Grafs re-suspension theory pollutant loading should follow a power law model and the exponent (n) should range between 1 and 1.68.