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Small Drains, Big Problems: The Impact of Dry Weather Runoff on Shoreline Water Quality at Enclosed Beaches

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S Supporting Information

ABSTRACT: Enclosed beaches along urban coastlines are frequent hot spots of fecal indicator bacteria (FIB) pollution. In this paper we present field measurements and modeling studies aimed at evaluating the impact of small storm drains on FIB pollution at enclosed beaches in Newport Bay, the second largest tidal embayment in Southern California. Our results suggest that small drains have a disproportionate impact on enclosed beach water quality for five reasons: (1) dry weather surface flows (primarily from overirrigation of lawns and ornamental plants) harbor FIB at concentrations exceeding recreational water quality criteria; (2) small drains can trap dry weather runoff during high tide, and then release it in a bolus during the falling tide when drainpipe outlets are exposed; (3) nearshore turbulence is low (turbulent diffusivities approximately $10^{-3} \text{ m}^2 \text{ s}^{-1}$), limiting dilution of FIB and other runoff-associated pollutants once they enter the bay; (4) once in the bay, runoff can form buoyant plumes that further limit vertical mixing and dilution; and (5) local winds can force buoyant runoff plumes back against the shoreline, where water depth is minimal and human contact likely. Outdoor water conservation and urban retrofits that minimize the volume of dry and wet weather runoff entering the local storm drain system may be the best option for improving beach water quality in Newport Bay and other urban-impacted enclosed beaches.



■ INTRODUCTION

Enclosed beaches are found inside sheltered coastal embayments such as tidal estuaries, lagoons, and harbors. Protection from winds and waves makes these beaches a popular destination for families with small children. In Southern California, enclosed beaches receive more than 24 million visitors annually, but are five times more likely to exceed State and Federal water quality standards than beaches located along the open coastline.¹ An analysis of shoreline monitoring data collected from 600 public beaches along the west coast of the United States found that enclosed beaches were substantially more polluted than beaches directly impacted by storm drain outlets or beaches located along open coastlines.² Similar conclusions have been reported nationally: over 50% of marine

coastal beaches on the Natural Resources Defense Council's "repeat offenders" list are enclosed.³

Why are enclosed beaches so polluted? It is often assumed the underlying cause is poor circulation, although to our knowledge no published studies have specifically addressed this issue. Indeed, circulation enhancement devices have been trialed at several enclosed beaches in California with little documented efficacy,^{1,2} suggesting that additional factors (beyond circulation) may influence water quality at these sites. Unfortunately, insights gained from studies of pollutant

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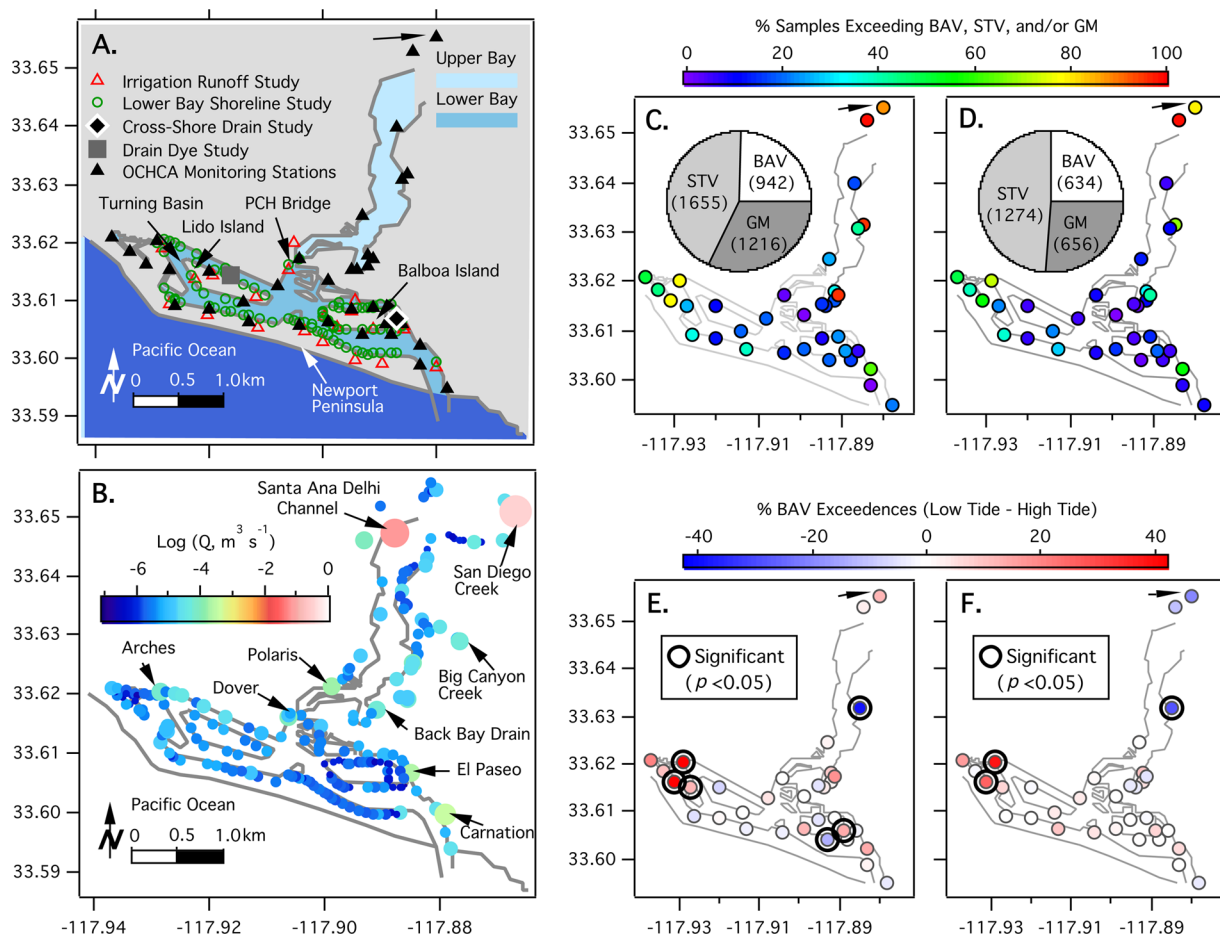


Figure 1. (A) Beach water quality studies conducted in Newport Bay, California, including the irrigation runoff study (red open triangles), Lower Bay shoreline study (green open circles), cross-shore drain study (white-rimmed black diamond), drain dye study (gray square), and Orange County Health Care Agency (OCHCA) historical beach water quality monitoring stations (black triangles). (B) Dry weather freshwater inputs to Newport Bay from two tributaries (San Diego Creek and Santa Ana Delhi Channel), 12 large drains (the five largest are Carnation, El Paseo, Polaris, Dover, and Arches), and 207 small drains. All drain outlet sites are sized and color-coded by their (log-base 10 transformed) average dry-weather flow rate. (C,D) Percent of samples collected at OCHCA historical monitoring sites that exceeded one or more EPA criteria for enterococci bacteria (ENT, part C) or *E. coli* (EC, part D). (E, F) Difference in percent of samples exceeding the Beach Action Value (BAV) criteria at low and high tide for ENT (part E) and EC (part F). Red and blue circles correspond to more exceedences at low tide and high tide, respectively. Black open circles mark sites where the low/high tide difference is statistically significant. The OCHCA monitoring station located in San Diego Creek has been moved 2 km west so it can be shown on the map (station indicated by arrow in the upper right corner of panels A and C–F).

transport and mixing along open coastal beaches (e.g., refs 4–10) may not inform our understanding of pollution at enclosed beaches, given their different physical dynamics (e.g., high vs low wave energy).^{1,11}

Measurements of fecal indicator bacteria (FIB) in shoreline water samples are typically used to assess water quality at both beach types. FIB are a broad group of organisms including enteric bacteria such as *Escherichia coli* (EC) and *Enterococcus* species (ENT) that are used as a proxy for sewage-associated waterborne pathogens and recreational waterborne illness risk.^{12,13} At enclosed beaches, FIB can originate from point sources (sewage outfalls, storm drains, creeks, and rivers), nonpoint sources (bather shedding, bird and dog feces, tidal washing of sediments, decaying vegetation, shallow groundwater discharge, and runoff from drains), or some combination of the two.^{1–3,11,14–18}

In Southern California, precipitation outside of the winter storm season is rare. Consequently, landscape irrigation occurs throughout the year to maintain vegetation. Dry weather runoff from excess irrigation flows into the storm drain system and

from there is discharged to local receiving waters with minimal or no treatment. In this paper, we investigate the impact of urban irrigation runoff from storm drains on shoreline water quality at enclosed beaches in Newport Bay, Southern California. Concentrations of FIB in irrigation runoff are reported, spatiotemporal patterns of nearshore FIB and salinity are identified (and linked back to dry weather discharge), and the role of tides, winds, turbulence, and buoyancy on FIB mixing and transport is evaluated. Furthermore, a flow and transport model is developed to investigate how shoreline water quality is affected by the timing and magnitude of storm drain discharge. Our study provides insight into how civil infrastructure and physical processes combine to make enclosed beaches a “perfect storm” of water quality impairment. While our study concerns a single embayment, the results should be of general interest to managers and researchers focused on improving water quality at enclosed beaches worldwide.

SITE DESCRIPTION

Newport Bay is an 8 km² tidal saltwater embayment located in Orange County, California. The bay is divided into two geographic regions: one inland and the other oceanward of the Pacific Coast Highway (denoted PCH bridge in Figure 1A). The upper region of the bay (Upper Bay) is a state ecological reserve and provides refuge, foraging areas, and a breeding ground for a number of threatened and endangered species. The lower portion (Lower Bay) is a regionally important recreational area with chronically impaired beaches.^{19,20} Newport Bay is one of the largest pleasure craft harbors in the United States and is surrounded by one of the most densely populated communities in the United States.²¹ The bay experiences mixed tides (dominant constituents M2, S2, K1, and O1) with a daily tide range of approximately 1.65 m. The primary tidal currents are oriented along the main axis of the bay from the harbor jetty, along the south side of Balboa Island, and into Upper Bay. Residual currents circulate counter clockwise around Lido Island on the west side of Lower Bay and clockwise around Balboa Island on the east side of Lower Bay.²²

Three primary sources of dry weather runoff flow into Newport Bay (Figure 1B): (1) two major tributaries [San Diego Creek (SDC) and Santa Ana Delhi Channel (SAD)] drain 352 km² of residential, industrial, agricultural, and open space land in nine cities, (2) 12 large drains (drain diameters >1.2 m) receive flows from 14.8 km² of residential and commercial land in the cities of Newport Beach and Costa Mesa (the five largest are Arches, Dover, Polaris, El Paseo, and Carnation, Figure 1B), and (3) 207 small drains (drain diameters 0.15 to 1.2 m) receive flows from 10.7 km² of residential land along the perimeter of Lower ($N = 151$) and Upper ($N = 56$) Newport Bay (all drains are shown in Figure 1B, color-coded and sized by their log-10 transformed dry weather volumetric flow rate). Measured dry weather volumetric flow rates from both tributaries (SDC and SAD) exceed those from large drains by approximately 1 order of magnitude [0.39 and $1.7 \times 10^{-2} \text{ m}^3 \text{ s}^{-1}$, respectively (see the Supporting Information)]. Dry weather volumetric flow rates from small drains are approximately 1 order of magnitude less than large drains and 2 orders of magnitude less than tributaries (see the Supporting Information). In what follows we describe a set of coordinated studies intended to characterize (1) spatial and tidal patterns of FIB pollution in Newport Bay based on historical monitoring data (historical monitoring study), (2) FIB concentrations in surface runoff urban areas surrounding Newport Bay (irrigation runoff study), (3) the spatiotemporal variability of FIB concentrations along the Lower Bay perimeter (Lower Bay shoreline study), (4) vertically resolved cross-shore distributions of FIB and salinity adjacent to a single storm drain (cross-shore drain study), (5) mixing and dilution of runoff plumes by nearshore turbulent diffusion (nearshore turbulence study), (6) the timing and physical transport processes associated with drain discharge (drain dye study), and (7) the relative contribution of proximal drains and distal tributaries to beach water quality in Lower Bay (flow and transport modeling).

METHODS

Historical Monitoring Study. Five years of FIB monitoring data from Newport Bay (2001–2005) were analyzed to (1) provide a snapshot of baywide bacteriological

water quality when our field studies began in 2006 and (2) determine if historical water quality is impacted by tide height. Samples were collected weekly by the Orange County Health Care Agency (OCHCA) at 35 sites within the bay (black triangles in Figure 1A) and analyzed for ENT ($N = 5791$) and fecal coliform (FC, $N = 5741$) by membrane filtration.²³ For comparison to 2012 EPA recreational water quality criteria,²⁴ EC concentrations were calculated from historical FC data assuming $EC = FC/1.1$.²⁵ Reflecting our interest in dry weather water quality, samples collected during wet weather were removed. The remaining data were checked for errors, censored data were assigned values, and (for the tidal analysis) samples were filtered into low- and high-tide groups (see the Supporting Information). The following 2012 U.S. EPA ENT and EC criteria were applied to these data retroactively (so the data can be evaluated in light of current EPA guidelines): the 30 day geometric mean standard (GM, 35 ENT or 126 EC per 100 mL), the single sample beach action value (BAV, 70 ENT or 235 EC per 100 mL), and the 30 day statistical threshold value (STV, 130 ENT or 410 EC per 100 mL).²⁴ The EPA EC criteria are for freshwater beaches, but were applied to the estuarine waters of Newport Bay (see results section). Only the BAV was used to evaluate the relationship between tide height and dry weather exceedence frequency, because 30 day criteria (such as the STV and GM) cannot be applied to tidally filtered data.

Irrigation Runoff Study. Dry weather runoff from landscape irrigation in residential communities surrounding Lower Bay can contain FIB and other contaminants.^{15,19,20} This runoff collects in curbside gutters, flows by gravity through the local drainage system, and discharges to the bay with little or no treatment. Most of the discharge occurs through small pipes (diameters 0.45–0.61 m; referred to here as “small drains”) that extend a short distance down the beach, terminating at a drainpipe outlet located near the mean tide line. In this field effort, samples of irrigation runoff ($N = 23$) and water from (or near) drainpipe outlets ($N = 30$) were collected during dry weather on November 16, 2006 (open triangles, Figure 1A, see the Supporting Information for sampling details). Irrigation runoff samples were collected at 7 a.m. local time, coincident with peak irrigation runoff from the surrounding landscape (personal observations). Drainpipe outlet samples were collected at low tide (12 p.m. local time) when drainpipe outlets were exposed and accessible (details in the Supporting Information). All water samples were stored on ice and analyzed within 6 h for conductivity, EC (IDEXX Colilert-18), and ENT (IDEXX Enterolert). Conductivity measurements (model 162A, Thermo Orion, Waltham, MA) were converted to salinity using the practical salinity scale.

Lower Bay Shoreline Study. To characterize the spatiotemporal variability of FIB concentrations in Lower Bay, 334 nearshore water samples were collected during dry weather (August, 2006) at 77–85 sites along the Lower Bay shoreline (open circles, Figure 1A). Sample collection occurred at night/early morning (to minimize solar effects on FIB concentrations^{26,27}) during two different tide conditions (high and low tide) and at two cross-shore locations at each site (shoreline and 30 m bayward) (see the Supporting Information). All water samples were analyzed for conductivity, EC, and ENT using the methods described above.

Cross-Shore Drain Study. Cross-shore transects were carried out on May 30, 2008 to assess the variability of conductivity and FIB bayward of small drains. The study was

centered on a single drain at Park Avenue Beach, Balboa Island (solid blue diamond, Figure 1A). The drain is adjacent to a public dock, which was used as a platform to collect water samples ($N = 49$; nine stations, 2.2–3.7 m spacing). Surface water was sampled at all stations, and bottom samples were also collected where water depth exceeded 0.5 m (see the Supporting Information). All samples were analyzed for conductivity, EC, and ENT using the methods described above. Transect sampling occurred four times over a 24 h period (6 a.m., 12 p.m., 5 p.m., and 10 p.m. local time), roughly corresponding to low–high tide (LHT), high–low tide (HLT), high–high tide (HHT), and low–low tide (LLT), respectively.

Nearshore Turbulence Study. Nearshore turbulence was measured coincident with the cross-shore drain study (diamond in Figure 1A) using an acoustic doppler velocimeter (ADV, SonTek/YSI, Inc., San Diego, CA). The ADV was mounted on a metal frame and lowered over the side of the Park Avenue Beach pier until the frame rested on the sediment bed. The ADV was deployed 11 times (10 min per deployment); velocity measurements were collected at a sampling frequency of 25 Hz. Three components of velocity were measured (U , along-shore; V , cross-shore; W , vertical) in a small sensing volume located ~25 cm above the sediment bed.

Data were screened for signal strength/quality (details in the Supporting Information) and used to estimate along and across-shore turbulence intensities (I , a measure of turbulent fluctuations in the velocity signal) and Lagrangian time scales (T_L , time scale over which velocity fluctuations are decorrelated). These were then used to calculate along and across-shore Lagrangian length scales ($L = IT_L$) and eddy diffusivities ($\epsilon = LI$), assuming a homogeneous turbulence field (see the Supporting Information). A nondimensional transverse mixing coefficient was also estimated: $\bar{\epsilon} = \epsilon/(du_*)$, where u_* is a measure of turbulent bed shear called the shear velocity (estimated from the covariance of ADV velocities) and d is water depth.²⁸ The nondimensional transverse mixing coefficient was used to parametrize horizontal diffusion in the Newport Bay flow and transport model described below.

Drain Dye Study. Three dye release experiments were conducted in Lower Bay (Genoa Beach, Lido Island) during dry weather conditions on February 25, 2010 (solid gray square, Figure 1A). These experiments were qualitative and used to determine (1) the timing of runoff released from small drainpipe outlets and (2) the extent to which runoff plume dispersal is influenced by buoyancy, tidal currents, and wind.

The first two experiments evaluated freshwater release from small drainpipe outlets. Dye-labeled freshwater (1700 L) (acid yellow 73, Norlab, Inc., Amherst, OH; specific gravity = 1.0) was pumped into a curbside gutter that drains into Lower Bay through a pipe. Experiment 1 was conducted during morning high tide when the drainpipe outlet was submerged, and experiment 2 was conducted during afternoon low tide when the outlet was exposed. In both experiments, the flow rate of dye-labeled freshwater was 0.50–0.63 L s⁻¹ to mimic peak (early morning) dry weather runoff from neighboring residential communities. Dye-tagged water flowed quickly (within minutes) from the curbside gutter to the storm drain outlet, but the timing of its release to the bay differed for the two experiments (detailed later). Experiment 3 evaluated dye dispersal offshore of drainpipe outlets. Here, ~5 mL of undiluted dye was poured off the end of the Genoa Beach public pier, forming an offshore dye patch. Dye plumes generated by all three experiments were observed and

photodocumented for approximately 30 min after dye entered the bay; time-stamped images from experiment 2 were used to estimate along-shore transport velocity of the plume.

Flow and Transport Modeling. A two-dimensional flow and transport model was developed for Newport Bay to evaluate (1) the relative importance of large drains and tributaries versus small drains and (2) the importance of intermittent discharges from small drains. The model predicts embayment currents and water depths in response to forcing by a time series of water levels recorded 30 km northwest of the study site (NOAA Los Angeles tide gage) and specified at the offshore boundary of the model domain, several kilometers seaward of the Newport Bay tidal outlet. The model is also forced by freshwater inputs from the two tributaries (SDC and SAD), 12 large drains, and 207 small drains. See the Supporting Information for a detailed description of the setup, parametrization, forcing, calibration, and limitations of the model.

The model was used to compare three runoff scenarios: scenario 1, runoff entered the bay only from tributaries and large drains (i.e., small drains were “turned off”); scenario 2, runoff entered the bay from a full inventory of inputs (tributaries, large and small drains), and small drains discharged runoff continuously throughout the tidal cycle; scenario 3, runoff inputs were the same as scenario 2, but small drains only discharged runoff at low tide, when the drainpipe outlet was exposed (what we refer to throughout the paper as “trap-and-release” discharge). The trap-and-release simulation was inspired by the results of dye and FIB field studies, described later. The model was run separately for each scenario, with model-predicted FIB concentrations (EC and ENT) tabulated at two locations (shoreline and 30 m bayward) at all drainpipe outlets in Lower Bay ($N = 159$). Model scenarios were determined to be significantly different if the number of outlet sites with model-predicted FIB concentrations above a specified threshold was significantly different (significance determined using bootstrap techniques, see the Supporting Information). Multiple thresholds were evaluated, including (1) presence/absence ($>$ or <10 EC or ENT per 100 mL) and (2) the BAV (see the Supporting Information).

RESULTS

Historical Monitoring Study. One or more EPA criteria (BAV, STV, and/or GM, see the Methods section) were exceeded in 33% (ENT) and 27% (EC) of samples collected from Newport Bay. The frequency of sample exceedence varied by region (colored circles in Figure 1, parts C and D), increasing in the following order: (1) beach sites on Lido and Balboa Islands (<24% of samples exceeded one or more criteria), (2) beach sites west and south of the Turning Basin (23–78% of samples exceeded one or more criteria), and (3) creek sites in San Diego Creek, Santa Ana Delhi Channel, Big Canyon Creek, and Back Bay Drain (46–100% of samples exceeded one or more criteria). Across all sites, samples most often exceeded the STV followed by the GM and BAV; this trend applied to both ENT and EC (see pie charts, Figure 1, parts C and D). While the EPA criteria for EC are for freshwater beaches, Newport Bay is under a total maximum daily load for fecal coliform (FC) and the FC water quality objectives are similar to the current EPA STV and GM recommendations for EC (see the Supporting Information). Regulatory considerations aside, similar patterns of FIB pollution (i.e., sample exceedence frequency) are obtained

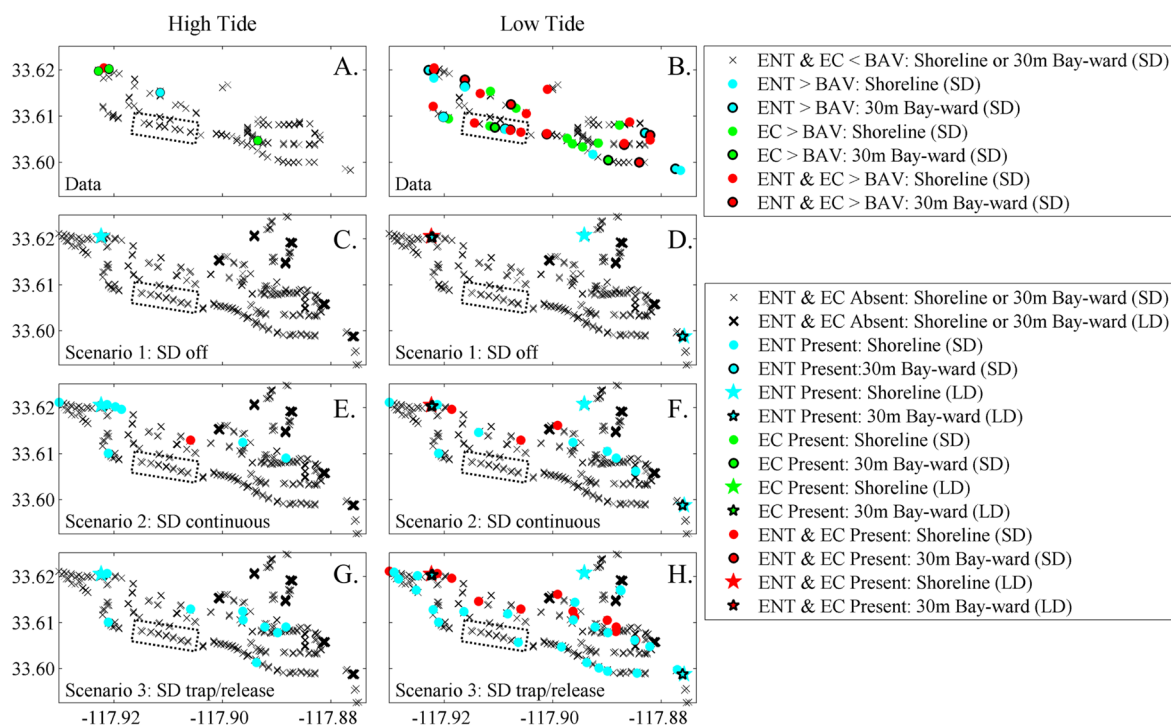


Figure 2. Spatial patterns of fecal indicator bacteria (FIB) pollution in the Lower Bay during high tide (A, C, E, G) and low tide (B, D, F, H). Plots depict field measurements collected during the Lower Bay shoreline study (A and B) or modeling simulations conducted as part of the flow and transport modeling study (C–H). Abbreviations denote small drains (SD), large drains (LD), enterococci (ENT), *E. coli* (EC), and beach action value (BAV). Colored symbols mark locations where EC (green), ENT (cyan), or both FIB groups (red) exceeded either the BAV (A and B) or the detection threshold (>10 MPN/100 mL, panels C–H) at the shoreline (solid symbols) or 30 m bayward (black edged symbols). Stars and circles represent LD and SD, respectively. The model results (C–H) correspond to different scenarios for the release of runoff from small drains: scenario 1 (SD turned off, panels C and D), scenario 2 (SD discharge continuously throughout the tidal cycle, panels E and F), and scenario 3 (SD trap-and-release dry weather runoff in response to changing tide levels, panels G and H). All three modeling scenarios include dry weather runoff from LD and tributaries. The boxed region along the Newport Bay Peninsula marks a region of FIB contamination (observed at low tide during the Lower Bay shoreline study) that is not captured by any model scenario.

when the ENT and EC criteria are applied to these historical data (compare Figure 1, parts C and D).

Tide height significantly influenced water quality at a subset of sites in Newport Bay (Figure 1, parts E and F). Samples collected at three (ENT, Figure 1E) and two (EC, Figure 1F) beach sites on the west side of the bay (near the Turning Basin) more frequently exceeded the BAV at low than high tide (red circles with outer ring, $p < 0.05$). The same was true for ENT measurements at the Grand Canal (southeast side of Balboa Island; Figure 1E). Samples collected at Big Canyon Creek displayed the opposite pattern: EC and ENT BAVs were exceeded more frequently at high tide than low tide (blue circle with outer ring in Upper Bay, $p < 0.05$, Figure 1, parts E and F). A significant (but weak) high-tide bias was also evident for ENT at one beach site on the south side of Balboa Island (blue circle with outer ring in Lower Bay, Figure 1E).

Irrigation Runoff Study. Although irrigation runoff samples were fresh (median salinity, 0.5), drainpipe outlet samples had variable salinity ranging from fresh to oceanic (salinity, <0.7–32; median 31) (Supporting Information Figure S1A). FIB concentrations were also variable, spanning 4 orders of magnitude in both irrigation and drainpipe outlet samples (<10 to >20 500 MPN per 100 mL, Supporting Information Figure S1, parts B and C). ENT concentrations were significantly higher in irrigation runoff than drainpipe outlet samples, while EC concentrations were not significantly different (permutation-based paired t test; $p < 0.05$ level, Supporting Information Table S1). Across drainpipe outlet

samples, those with “brackish” water (salinity <30) had significantly higher FIB concentrations than those that were “saline” (salinity >30) (permutation-based t test; $p < 0.05$ level, Supporting Information Table S1 and Figure S2). A detailed description of the permutation-based statistical approach is provided in the Supporting Information.

Median FIB concentrations in irrigation runoff samples were 30 MPN per 100 mL for EC and 1455 MPN per 100 mL for ENT (Supporting Information Figure S1, parts B and C). These values were rounded to the nearest 50 MPN per 100 mL and adopted as the runoff source concentrations in the flow and transport modeling study (EC, 50 MPN per 100 mL; ENT, 1500 MPN per 100 mL).

Lower Bay Shoreline Study. During early morning low tide, 31% of shoreline samples and 19% of offshore samples (collected 30 m bayward) exceeded the BAV for EC and/or ENT (Figure 2B). Fewer samples exceeded the BAV for either FIB group during high tide (5% of shoreline and 3% of offshore samples; Figure 2A). Consistent with this finding, overall FIB concentrations were significantly higher during low tide than high tide (permutation-based ANOVA; $p < 0.05$, Supporting Information Tables S2 and S3 and Figure S3, parts B and C). Nearshore contamination was variable but present along the majority of the bay perimeter during low tide. This includes an ~1 km region along the Newport Bay Peninsula (black dashed box, Figure 2).

Cross-shore differences in FIB concentration were less pronounced than tidal differences. That said, at low tide FIB

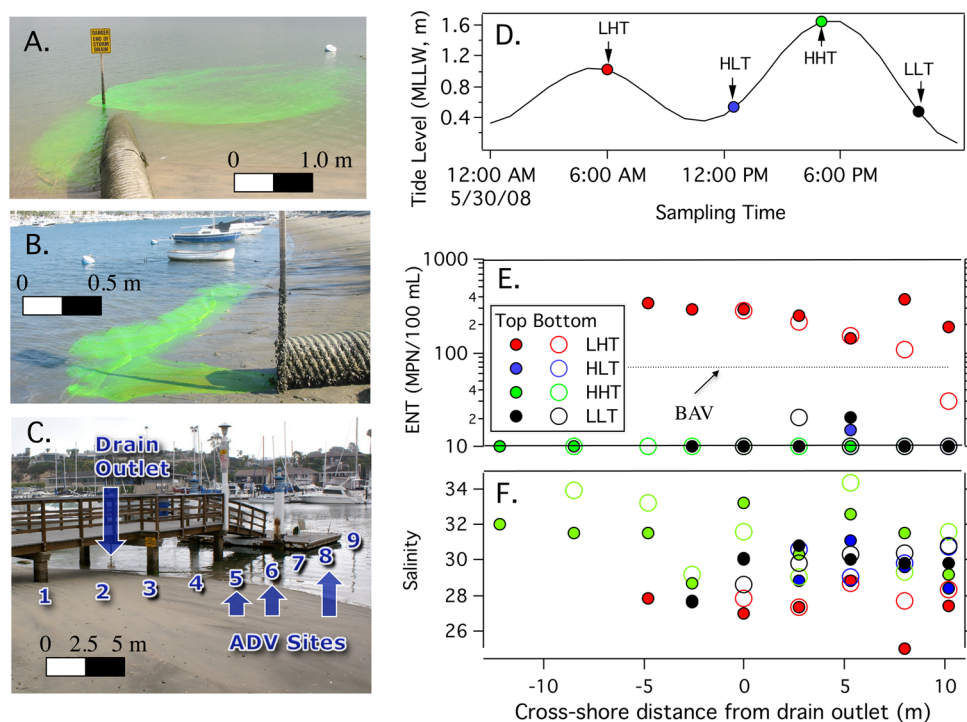


Figure 3. Drain dye study: dye discharged from the Genoa Beach storm drain on a falling tide just as the outlet is being exposed (panel A, experiment 1) or on a rising tide when the outlet is fully exposed (panel B, experiment 2). Cross-shore drain study: sampling stations along the Park Avenue Beach pier (C), tide conditions during the four transects (D), and the salinities and ENT concentrations measured during each transect at both the surface (filled circles) and bottom (open circles) of the water column (E).

concentrations were generally higher at the shoreline than 30 m bayward (Supporting Information Figure S3, parts B and C). This pattern was marginally significant for EC (Bonferroni–Holms corrected $p < 0.10$ level) and was not significant for ENT (permutation-based multiple comparison test, Supporting Information Table S3). Salinity was also lower at the shoreline and higher offshore (Supporting Information Figure S3A; marginally significant, Bonferroni–Holms corrected $p < 0.10$ level, Supporting Information Table S3). Both FIB groups exceeded the BAV in 34% of “brackish” samples (salinity < 30) and 3% of “saline” samples (salinity > 30) (Supporting Information Figure S4). In summary, FIB concentrations along the Lower Bay shoreline are generally higher (1) at low tide, (2) close to shore, and (3) in samples with salinity < 30 .

Cross-Shore Drain Study. EC concentrations were below the BAV in water samples from all transects (data not shown). ENT concentrations were also frequently below the BAV, although exceedences were observed during the early morning low–high tide (LHT, Figure 3, parts D and E). The average salinity was lowest during LHT (27.6 ± 1.0), intermediate during HLT and LLT (29.8 ± 0.9 and 29.8 ± 1.0 , respectively), and highest during HHT (31.3 ± 1.8) (Figure 3E). In short, samples collected during LHT had the lowest salinity (max < 29) and the highest ENT concentrations (11 of 12 samples exceeded the BAV, Figure 3E).

Vertically resolved samples collected during LHT reveal two patterns: (1) samples collected near the drain outlet are well-mixed over the vertical (see red circles for stations located < 5.2 m from the drain, Figure 3E), and (2) surface water samples collected at the end of the dock are fresher and have higher ENT concentrations than deep water samples (see red circles for stations located > 7 m from the drain, Figure 3E).

Nearshore Turbulence Measurements. Turbulent velocity spectra indicate that the nine of the 10 ADV deployments collected on flood tide were contaminated by interference from frame or dock piling wakes and could not be used for analysis. Uncontaminated data collected during a single ebb tide at Station 8 were used to estimate alongshore ($0.003 \text{ m}^2 \text{ s}^{-1}$) and across-shore ($0.001 \text{ m}^2 \text{ s}^{-1}$) turbulent eddy diffusivities, a quantity that parametrizes the bulk dispersal effects of turbulent velocities. The associated Lagrangian length scales along and across-shore were 30 and 16 cm, respectively. A value of 0.3 was estimated for the nondimensional transverse mixing coefficient, which falls within the range of values observed for natural channels.²⁹

Drain Dye Study. During experiment 1 (performed on falling tide), no dye was observed leaking from the drainpipe outlet when it was flooded with bay water (dye trapped, 0–1.75 h after addition to the curbside gutter). Dye began leaking from a small crack near the end of the pipe when the tide level was even with the top of the outlet (initial dye release, 1.75 h after addition to the curbside gutter). The remaining dye-tagged freshwater flowed into the bay (moving offshore and down-bay) when the tide level fell below the top of the outlet (bulk dye release, several minutes postdischarge from the crack). We refer to this drain discharge mechanism as “trap and release” (see scenario 3, flow and transport modeling results). The two dye plumes (crack and outlet) are visible in the photo taken ~ 2 h after the dye was added to the curbside gutter (Figure 3A).

During experiment 2 (performed during a low, flood tide) the drainpipe outlet was exposed and located several meters above the water line. Within minutes of addition to the curbside gutter, dye-tagged freshwater flowed out of the drain and down the beach. Upon entering the bay, the dye plume hugged the shoreline and traveled down-bay at approximately 0.07 m/s

(Figure 3B). The direction of transport opposed the average tidal current (up-bay on flood tide), but was consistent with prevailing winds (out of the northwest).

During experiment 3, the dye bolus released from the end of the Genoa Beach pier formed a vertically sheared plume (data not shown). Tide and wind conditions were the same as in experiment 2. The upper portion (top 20 cm) of the plume moved down-bay and shoreward (parallel to the prevailing wind direction), and the bottom portion moved up-bay (parallel to the average tidal current) (Supporting Information Figure S5).

Flow and Transport Modeling. Dry weather freshwater discharge from drains (calculated from catchment area using an experimentally derived correlation, Supporting Information Figure S6) ranged over 7 orders of magnitude, from $<10^{-9}$ to 10^{-2} $\text{m}^3 \text{ s}^{-1}$. Fate and transport modeling was carried out assuming small drains were turned off (scenario 1), turned on and discharging continuously (scenario 2), or turned on and discharging at low tides (“trap and release”, scenario 3). Average volumetric discharge from small drains was equal under scenarios 2 and 3 (see Supporting Information Figure S7). The three model scenarios yield distinct spatial and temporal FIB patterns (Figure 2). The number of detection events predicted in Lower Bay (>10 EC or ENT per 100 mL) was highest under scenario 3 and lowest under scenario 1. Only under scenario 3 were FIB detected along the entire Lower Bay perimeter (consistent with experimental measurements) (Figure 2, parts B and H). Note that all scenarios underestimated FIB concentrations, especially 30 m bayward of small drains (where simulated FIB concentrations were never above the detection limit, Supporting Information Figures S8 and S9 and Figure 2). All scenarios also failed to reproduce FIB excursions observed along the Newport Peninsula [Lower Bay shoreline study (black dashed box, Figure 2) and historical monitoring study (Figure 1, parts C and D)].

Model-predicted FIB concentrations exhibit the strongest tidal signature under scenario 3 (Supporting Information Figure S8), although both scenarios 2 and 3 had more FIB detects at low tide than high tide, consistent with field measurements (Figure 1, parts D and E, Figure 2, parts A, B, and E–H). No significant differences were observed between any model scenarios at high tide (statistical details in Supporting Information Figure S9, parts A and C). At low tide, however, significantly more stations exceeded detection limits and the BAV criteria for ENT under scenario 3 than scenario 1 (Supporting Information Figure S9B). Significantly more stations also exceeded ENT detection limits under scenario 3 than scenario 2, and under scenario 2 than scenario 1 (Supporting Information Figure S9B). In summary, scenario 3 comes closest to capturing the tidal cycling of ENT observed during the Lower Bay shoreline study.

Differences between model scenarios were less distinct for EC, reflecting the low EC concentration assumed for irrigation runoff in the model (50 MPN per 100 mL). Only scenarios 1 and 3 were significantly different, and only at EC thresholds below recreational criteria (<20 MPN per 100 mL, Supporting Information Figure S9D).

DISCUSSION

Small drains account for $\sim 1\%$ of the total freshwater volumetric flow to Newport Bay on a typical dry weather day (Figure 1B and Supporting Information Figure S6). Nevertheless, the field and modeling results presented here suggest that runoff from

small drains could be a significant source of episodic fecal pollution at Lower Bay beaches during dry weather conditions. This conclusion is supported by the following: (1) dry weather runoff from the surrounding urban landscape contains higher concentrations of FIB than bay water [curbside vs near-drain samples (irrigation runoff study) and creek versus beach sites (historical monitoring study)], (2) FIB concentrations in Lower Bay are typically high at the shoreline and low offshore, consistent with a beachside bacterial source (Lower Bay shoreline study, cross-shore drain study, flow and transport modeling study); (3) FIB concentrations in Lower Bay are highest when salinity is <30 , consistent with a freshwater bacterial source such as irrigation runoff (irrigation runoff study, Lower Bay shoreline study, and cross-shore drain study), (4) dead-end regions of the bay with high drain density (e.g., Turning Basin) have the highest FIB exceedence frequencies in Lower Bay (historical monitoring study), and (5) FIB patterns are modeled most accurately when small drains trap-and-release runoff (scenario 3) (flow and transport modeling study).

Because most drainpipe outlets are located at the mean tide line, they are typically submerged at high tide and exposed at low tide. One consequence of this outlet design is that FIB can accumulate in the drainpipe when the outlet is flooded at high tide and then discharge to the bay when the outlet becomes exposed at low tide; in other words, the drain pipes “trap-and-release” dry weather runoff to Lower Bay. This trap-and-release process was directly observed during the drain dye study at Genoa Beach (Figure 3A), and its tidal signature is consistent with field and modeling studies of Lower Bay: (1) of the beach monitoring sites that had tidal signatures, two-thirds had significantly more FIB exceedences at low tide (historical monitoring study), (2) more stations exceeded BAV criteria during the Lower Bay shoreline study at low tide (outlets exposed) than high tide (outlets submerged) (Figure 2, parts A and B), and (3) model predicted FIB concentrations and shoreline distributions had the strongest tidal signature when trap-and-release discharge was simulated (scenario 3, Supporting Information Figure S5 and Figure 2, parts G and H).

Several exceptions to the trap-and-release mechanism were noted: (1) not all routinely monitored beach sites in Newport Bay have significantly higher exceedence frequency at low tide compared to high tide (historical monitoring study), (2) scenario 3 was unable to reproduce FIB contamination along a central region of the Newport Bay Peninsula (Lower Bay shoreline and historical monitoring studies), and (3) FIB concentrations measured during the cross-shore transect study were higher at low–high tide (LHT; 6 a.m.) than low–low tide (LLT; 10 p.m.) (Figure 3, parts D and E). Relative to exception 1, the historical monitoring program was not designed to elucidate tidal effects (e.g., solar effects were not controlled for, as they were in the Lower Bay shoreline study). Nevertheless, of the five Lower Bay stations where ENT had a significant tidal signature, four were more likely to exceed EPA criteria at low tide, consistent with the trap-and-release mechanism. The lone station in Upper Bay where exceedences were more likely at high tide (Big Canyon Creek, compare Figure 1, parts B, E, and F) is not a drain site; therefore, different processes (e.g., wetting of wracklines at high tide) may contribute to tidal cycling of FIB at this location. Relative to exception 2, FIB pollution along the peninsula may be from non-runoff sources such as bird or dog droppings, sediments, and/or contaminated shallow groundwater.^{11,14} There might also exist synergies between storm drain discharge and other nonpoint sources of FIB; e.g.,

the drains could provide an inoculum for the sediments that, in turn, episodically yield FIB by erosion and/or drainage across the beach face. Exception 3 likely reflects prevailing irrigation schedules in residential communities surrounding Lower Bay. Yard irrigation often occurs during the night or early morning (personal observation). Indeed, samples collected during LHT had lower salinity than those collected during LLT, suggesting a larger irrigation runoff signal during the former (Figure 3).

Upon release from small drains, FIB plumes are diluted by ambient turbulence and transported horizontally and vertically by tide- and wind-driven currents. Because the initial dilution step is characterized by relatively small eddy diffusivities (ADV study, approximately $0.001 \text{ m}^2 \text{ s}^{-1}$), FIB released from small drains may linger at the shoreline, where they are more likely to trigger water quality exceedences (beach monitoring samples are collected in ankle depth water). To put the measured eddy diffusivities in context, previously published estimates at open coastal beaches range from approximately 0.1 to $10^2 \text{ m}^2 \text{ s}^{-1}$,^{7,8} at least 100-fold greater than our measurements. Compared to small drains, tributaries (e.g., SDC and SAD, Figure 1B) contribute relatively little to shoreline FIB pollution in Lower Bay (scenario 1, flow and transport modeling study, Figure 2, parts C and D). This may be due to (1) large effective mixing coefficients (approximately $10^2 \text{ m}^2 \text{ s}^{-1}$) associated with estuarine scale mixing processes (tidal trapping, longitudinal shear dispersion, and baroclinic exchange)^{28,29} and/or (2) long transit times which increase the opportunity for non-conservative processes (e.g., bacterial mortality) to attenuate FIB concentrations prior to reaching Lower Bay.^{21,26}

Because irrigation runoff (median salinity 0.5) is less dense than bay water (median salinity >30) it can form a buoyant surface plume upon entering the bay. Given their location near the air–water interface, buoyant plumes are likely to respond to local winds. Wind-driven plume transport was observed in the drain dye study at Genoa Beach (experiments 2 and 3, Figure 3A). It is also likely that an ENT-laden freshwater plume was present during the LHT transect of the cross-shore drain study, as offshore surface water (Stations 8 and 9) had higher ENT concentrations and lower salinities than subsurface water. Notably, ENT was well-mixed over the vertical in samples collected closer to shore (<5.2 m bayward, Figure 3E), highlighting the three-dimensional and temporal complexity of FIB plumes. Because bacterial die-off is a function of both salinity (low in surface plumes³⁰) and light intensity (high at the air–water interface³¹), plume structure may have implications for FIB survival as well as transport and mixing in the bay.

Model-predicted FIB concentrations in Lower Bay were generally below measured concentrations (Supporting Information Figures S8 and S9 and Figure 2). This could be a consequence of model oversimplification of biology or fluid dynamics (e.g., our model does not consider the possibility of wind-driven buoyant plume transport, as noted above), the way in which source concentrations were parametrized, or because FIB concentrations in the bay are dominated by other (non-runoff) sources. Field measured FIB concentrations in irrigation runoff were highly variable (<10–20 762 MPN per 100 mL), yet the model was run assuming they were fixed (EC 50 and ENT 1500 MPN per 100 mL) (Supporting Information Figures S3 and S5, Figure 2). Given the highly variable nature of FIB concentrations in runoff, future modeling efforts might benefit from adopting a probabilistic framework for source characterization.³²

From an urban infrastructure perspective, the design of small drains in Lower Bay is (unintentionally) optimized to impact nearshore water quality and expose beachgoers to dry weather runoff. The human health risk posed by this engineering design will ultimately depend on the nature of contaminants entering and exiting the storm drain system. Numerous studies support a dose–response relationship between ENT concentrations in sewage-impacted waters and recreational waterborne illness.³³ The dose–response relationship weakens, however, when FIB have nonsewage sources including nonhuman feces (e.g., birds and animals) and environmental regrowth (on vegetation, sediments, and storm drain pipes).³⁴ Multiple lines of evidence suggest that dry weather runoff in Orange County contains FIB from nonsewage sources.^{35,36} Thus, storm drain discharge of dry weather runoff may not contribute significantly to recreational waterborne illness, even if it is (as our study suggests) a significant source of FIB pollution. This is not meant to imply that storm drain discharge is “safe”, as storm drains may occasionally contain untreated sewage from illicit cross-connections, sanitary sewer exfiltration, and/or sewage spills and overflows.^{37–39} Furthermore, the storm sewer system is a conduit through which illicitly disposed chemicals (e.g., motor oil, detergents) can enter the bay.

Our study suggests that Lower Bay water quality might be improved by re-engineering the drainage system and/or drainpipe outlets. Indeed, Newport Bay water quality has dramatically improved since 2006²³ reflecting efforts to reduce dry weather flows into the bay through dry weather diversions and outdoor water conservation—a trend reinforced by the ongoing drought in Southern California.² Further water quality benefits might be obtained by extending drainpipe outlets bayward to minimize human contact with runoff plumes and/or by building green infrastructure aimed at collecting, retaining, evapotranspiring, treating, and/or reusing dry weather runoff (e.g., biofilters, porous pavement).^{40–42} A number of large-scale studies are currently underway to evaluate the performance (and incentivize the adoption) of green infrastructure for capturing both dry and wet weather runoff in urban streams.⁴³ The results of these latter studies may prove useful for managing dry weather runoff at enclosed beaches, as technologies and incentive strategies that are effective in urban streams may also be effective in urban-impacted coastal embayments.

■ ASSOCIATED CONTENT

📄 Supporting Information

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

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Notes

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