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Salt Marsh Reduces Fecal Indicator Bacteria Input to Coastal Waters in Southern California

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Abstract.—We investigated fecal indicator bacteria (FIB) concentrations in water and sediment from Carpinteria Salt Marsh, a medium-sized (93 ha), mostly natural southern California coastal wetland. High FIB concentrations, exceeding recreational water quality standards, were found at inlet sites after winter storm events and during a summer dry weather sampling event. Runoff entering the wetland had the highest concentrations of FIB after large rain events and after rain events following extended periods without rain. The watersheds with the greatest agricultural and urban development draining into the wetland generally contributed the highest loads of FIB, while the largest and least developed watershed contributed the lowest FIB concentrations. Surface water exiting the wetland at the ocean contained relatively low concentrations of FIB and only exceeded recreational water quality standards after the largest rain event of the year. Bacterial concentrations in sediment were only elevated after rain events, suggesting wetland sediment was not a reservoir for bacteria. Our results provide evidence that moderate-sized tidal wetlands at the base of moderately urbanized watersheds can attenuate FIB, improving coastal water quality.

Runoff from coastal watersheds carries bacteria to the ocean, causing human health risks. Fecal indicator bacteria (FIB), including *Enterococcus* (ENT) and *Escherichia coli* (EC), are natural components of human and other mammal, reptile and bird intestinal fauna used to indicate the likely presence of human pathogens that cause unhealthy conditions for people recreating in coastal water (Balarajan et al. 1991; Haile et al. 1999). Sources of FIB include faulty or overflowing sewage systems, homeless populations and domestic and wild animals (including birds) (Mallin et al. 2001; Crowther et al. 2002). FIB are generally present in high concentrations in sewage and in urban and agricultural runoff during wet weather conditions (Wyer et al. 1994, 1996, 1998; Kay et al. 2005). They may be concentrated on fine (<6μm) particles (Brown et al 2013), and can come from streambed sediments (Wilkinson et al. 1995; Solo-Gabriele et al. 2000), intertidal sediments (Obiri-Danso and Jones 2000; Ferguson et al. 2005) and watershed stores that are flushed by rainfall (Sanders et al. 2005).

For example, stormwater runoff from the Santa Ana River in California was identified as a significant source of near-shore pollution, carrying sediment, FIB, fecal indicator viruses, and human pathogenic viruses (Jeng et al. 2005). FIB concentrations are used as a guide to determine when Southern California beaches should be closed to recreational

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activities. In one of the only epidemiological studies of coastal ocean bathing water, Haile et al. (1999) determined that thresholds of 10,000 cfu of total coliform (TC), 104 cfu of E. coli (EC) and 400 cfu of enterococcus (ENT) per 100 ml of sample had potentially harmful human health effects at southern California beaches. These values are incorporated in California Department of Health Services regulations, which furthermore state that if the TC/EC ratio is <10, then TC must be ≤ 1000 cfu/100ml.

Coastal tidal wetlands could mitigate the risk of bacterial contamination. It is well known that freshwater wetlands perform water treatment functions (Kay and McDonald 1980; Breen et al. 1994; Kadlec and Knight 1996; Davies and Bavor 2000). Constructed freshwater wetlands may remove over 85% of FIB (Kadlec and Knight 1996; Davies and Bavor 2000). While tidal wetlands may perform similar functions, few studies have addressed this topic. Dorsey et al. (2010) found bacterial loads were significantly reduced in a southern California coastal wetland during daylight hours. A tidal wetland behind a flood defense wall reduced flux and concentration of fecal indicator bacteria (FIB) in coastal waters by 97% (Kay et al. 2005). An analysis of 32 years of coliform data for Newport Bay wetland and tidal embayment in southern California revealed a gradient of reduced bacterial concentration between inland sites and the ocean (Pednekar et al. 2005). The highly urbanized Talbert Salt Marsh watershed had a gradient of high to low FIB during dry weather run off, with highest concentrations in the upstream watershed and lowest at adjacent coastal waters (Reeves et al. 2004).

Coastal wetlands are a potential source of FIB since animals, such as birds, attracted by the wetland produce FIB-laden feces. Bacteria either from within wetland or outside sources may settle in slow-moving wetland waters where they can accumulate in sediment and possibly re-grow (Solo-Gabriele et al. 2000; Desmarais et al. 2002; Ferguson et al. 2005). Bacteria harbored in the sediment may be tidally flushed out to coastal bathing waters (Sanders et al. 2005). High concentrations of FIB were observed in California coastal wetlands when sediments were resuspended during strong ebb flows (Dorsey et al., 2010; Dorsey et al., 2013). At Talbert Salt Marsh, a small (10 ha), restored southern California tidal wetland, outflow from the wetland increased bacterial concentration in coastal waters (Grant et al. 2001). The reduced size of this wetland, less than 1/100th its original 1200 ha, and restored condition likely affected its ability to attenuate bacterial populations. This study and others pointed to bird populations as a potentially important bacteria source (Abulreesh et al. 2004). However, a modeling study of the same wetland by Sanders et al. (2005) indicated that bird feces were a minor contributor to surface water contamination, although they suggested that feces contributed to sediment FIB loads and tidal flushing deposited bacteria in coastal waters.

Water entering the ocean from coastal wetlands is most likely to cause poor ocean water quality after large rain events, when runoff flowing into the wetland has high volume and FIB concentrations, or when water has been stored for long periods in the wetland without tidal flushing (Reeves et al. 2004; Gersberg et al. 1995). For example, immediately following the breaching of San Elijo Lagoon in San Diego County, water quality close to the wetland mouth at an adjacent marine bathing beach was unhealthy (Gersberg et al. 1995); the authors predicted healthy bathing conditions would return to coastal waters within two weeks after breaching and one week after any large rain events. Jeong et al. (2008) found that as the volume of runoff entering Talbert Salt Marsh declined, the wetland was better able to attenuate FIB loads and coastal water quality improved.

Table 1. Land uses, areas and elevations of subwatersheds that drain into Carpinteria Salt Marsh. Table adapted from Page and Court (unpublished data).

	Drainage area	Maximum elevation	Greenhouse		Orchard	
Subwatershed	km^2	m	ha	%	ha	%
Western Creek	3.41	1175	36.7	10.8	91	26.7
Franklin Creek	11.60	533	63.3	5.4	68.8	5.9
Santa Monica Creek	15.61	1192	6.1	0.4	8.1	0.5

The capacity of a wetland to remove FIB is affected by a variety of physical and ecological factors including: wetland size, sediment size, tidal flow, bird and other animal populations, vegetation type, size and abundance and tidal creek length and shape. Larger, more pristine wetlands, with longer tidal creeks for runoff to travel through and longer residence time of bacteria and sediment-attached bacteria, likely are better at reducing FIB loads to the coastal ocean. Carpinteria Salt Marsh (CSM) was selected as the study location because it is a moderate-sized, mostly natural southern California wetland. To determine if CSM acted to attenuate or exacerbate FIB loads to coastal waters, we evaluated FIB concentrations at all the inlet sites where watershed runoff entered the wetland and at the wetland-ocean interface where watershed runoff flowed to the ocean after passing through the wetland. Our purpose was to investigate whether this wetland protected coastal water quality.

Materials and Methods

Study Area

CSM is a 93 ha (230 acre) wetland of pickleweed habitat [*Sarcocornia pacifica* (=*Salicornia virginica*)]. Located at 34°24’N and 119°31’30"W in Santa Barbara County, California, it is influenced by a Mediterranean climate with heavy, intermittent rainfall in the winter and dry, usually rainless summer months. Nearly 90% of average annual rainfall occurs between November and April, carrying materials stored during the summer from the watershed into the wetland[1]. The bird population, estimated by monthly two-hour bird counts at high and low tides in 2003, is estimated to be between 150 (June) and 1000 (October) including all bird species (shorebirds, water fowl etc.)[2]

The watershed of CSM is composed of three subwatersheds that are drained by Franklin and Santa Monica creeks and a western coastal plain area (Table 1; Fig. 1). Land use cover within sub-watersheds was delineated by Page and Court[3] using a Geographic Information System (GIS) and a USGS 30 m digital elevation model (DEM). By combining the GIS with a 1999 aerial photograph of the study area, they divided land use within each sub-watershed into five categories, 1) greenhouse agriculture, 2) open-field agriculture, 3) orchard, 4) urban/residential and 5) undeveloped (Table 1).

Franklin and Santa Monica Creeks originate in the Los Padres National Forest, a mountainous area whose foothill communities are composed of chaparral vegetation,

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[1] Ferren, W.R, Page, H.M. and Saley, P. 1997. Carpinteria Salt Marsh: Management Plan for a Southern California Estuary, Environmental Report No. 5, Museum of Systematics and Ecology, Department of Ecology, Evolution, and Marine Biology, University of California, Santa Barbara.

[2] Brooks, A.J. 2003. Unpublished data. Marine Science Institute University of California, Santa Barbara, CA 93106-6150

[3] Page, H.M. and Court, D. 1997. Unpublished data. Marine Science Institute University of California, Santa Barbara, CA 93106-6150

Table 1. Extended.

Open field		Total agriculture		Urban		Undeveloped		Total
ha	%	ha	%	ha	%	ha	%	ha
26.3	7.7	154	45.1	50.9	14.9	136.4	40	341
45.6	3.9	177.4	15.3	270.7	23.3	714.9	61.5	1163
5.5	0.4	19.7	1.3	32.5	2.1	1509	96.7	1561

with several kilometers of downstream coastal plain that are covered by a mixture of urban and agricultural development, including greenhouses and fields for commercial flower production and lemon and avocado orchards. The Franklin Creek sub-watershed (1107 ha) is the furthest east and has the lowest elevation, lying partially in the foothills but primarily within the coastal plain, where a large portion of the land is developed with multi-use agriculture, residential areas and light commercial facilities[4]. The Franklin Creek watershed is the most developed of the three subwatersheds, with 271 ha of urban development and 177 ha of agricultural land. Most of Franklin Creek (75%) is concrete lined with a concrete bottom (Robinson et al. 2002). Franklin Creek provides water to a restored section of CSM. Both Franklin and Santa Monica creeks have been dredged by County Flood Control, creating wide, deep, straight channels through the wetlands. The Santa Monica Creek sub-watershed (1561 ha) is the largest and least-developed sub-watershed, with over 90% composed of undeveloped land in the foothills and southern slopes of the Santa Ynez Mountains. The portion of Santa Monica Creek flowing from the northern edge of the city of Carpinteria into the salt marsh is channelized and concrete lined with a concrete bottom.

The Western creeks drain a much smaller area (340 ha) that lies entirely within the coastal plain. The Western subwatershed is nearly 50% agricultural and 15% urbanized (Robinson et al. 2002). The creek water is entirely from coastal plain runoff, flowing through a riparian corridor before entering the western side of CSM at three locations. Two of these creeks (Creeks B1 and B2) flow together, but upon intersecting with the railroad track located just outside the wetland border, Creek B1 diverges and flows easterly until it enters the salt marsh at a separate location. The most northwestern creek (Creek A) primarily drains greenhouse runoff. Degradation of the salt marsh due to anthropogenic pollutants entering from urban and agricultural runoff has been documented since the 1970s[5] (Page et al. 1995; Hwang et al. 2006).

Field Sampling

To investigate the change in FIB concentrations as water moves through CSM, we sampled water and sediment at the main water inlet and outlet sites to the wetland. Inlet sites included one site each from Franklin Creek and Santa Monica Creek and three sites from the Western subwatershed (Fig. 1). The mouth was sampled approximately 100 m upstream from the wetland/ocean interface.

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[4] Ferren, W.R. 1985. Carpinteria Salt Marsh: Environment, History, and Botanical Resources of a Southern California Estuary, Santa Barbara, CA: Herbarium, Dept. of Biological Sciences, University of California, Santa Barbara.

[5] MacDonald, K. 1976. The natural resources of Carpinteria Marsh. Their status and future. Report to the California Department of Fish and Game. Coastal Wetland Series #13.

Fig. 1. Carpinteria Salt Marsh with inlet sites where creeks drain into the marsh and the mouth site identified. (Image from Google Earth.)

Tidal cycle may affect ENT loads, with highest populations occurring during spring ebb tides (Boehm and Weisberg 2005), so collection of all samples was initiated within an hour after the tide had changed from in-coming to out-going. Samples were always collected during daylight but at different times of day to accommodate the tide. Thus, different samples may have been exposed to UV radiation for different lengths of time on different sampling dates. This would have had little influence on differences among sites for a sampling date since all samples were collected within a few hours of each other, but could potentially lead to differences between dates. However, UV exposure did not appear to have an overriding influence on results since high FIB concentrations exceeding health standards occurred in samples taken in the afternoon after extended UV exposure. There were also differences in cloud cover, stream flow, and other environmental variables that could have led to variability in FIB concentrations.

One surface water sample was collected at each site except on February 26, 2004 and March 3, 2004 when five water samples were collected, and July 8, 2004 when three water samples were taken in Franklin Creek (site F). No water sample was collected from Franklin Creek in December. Samples were placed in sterile 50 ml Falcon tubes and maintained on ice in a dark container immediately after collection until they were processed within 6-8 hours. Water column salinity was measured at each site using a YSI 85 meter.

Samples were collected three times during dry weather between Nov 30, 2003 and Dec 10, 2003 and during dry weather on July 8, 2004. Samples also were taken seven times during the winter rainy season in 2003/2004. Samples were taken immediately following significant rain events of 0.5” or greater on Feb 3 (0.85”), Feb 19 (0.5”), Feb 26 (2.8”) and Mar 3 (0.5”) in 2004; on Dec 16, 2003, one day following a small 0.12” rain event that occurred after a month without rain; and on Jan 16 and 17, 2004 during the wet season but not following a significant rain event. Precipitation measurements were taken from the Carpinteria Fire Station (34°23’53” N, 119°31’06”W) (Santa Barbara County Flood Control District 2004; http://www.countyofsb.org/pwd/water/hydro.htm).

Table 2. Salinity during water and sediment sampling. Dashes indicate no salinity reading was taken. **Bold text** indicates 5 sediment samples taken, normal text indicates 3 sediment samples were taken, and sites with grey text boxes were not sampled for sediment. Asterisk indicates that lab tests failed on Dec 4 for Western Creek B2 although salinity was measured.

	Dry weather				Wet weather						
Station	Nov 30	Dec 4	Dec 10	Jul 8	Dec 16	Jan 16	Jan 17	Feb 3	Feb 19	Feb 26	Mar 3
Mouth	**36**	35	36	-	36	35	35	34	34	6	32
Franklin Creek	**35**	36	33	-	35	-	-	35	32	2	2
Santa Monica Creek	-	32	32	-	37	-	-	19	4	2	2
Western Creek B2	-	25*	23	-	7	-	-	4	8	3	2
Western Creek B1	**29**	25	11	-	5	-	6	5	3	2	5
Western Creek A	**30**	15	21	-	14	11	-	10	5	3	7

Sediment samples of at least 5 g of material were scraped from the top 1-3 cm of the tidal creek substrate closest to the water's edge during an outgoing low tide. In an unpublished experiment, we found no difference in sediment bacterial concentrations at different lateral locations on the tidal creek bank. The samples from each location were stored in individual plastic bags. In general, three sediment samples one meter apart were collected at each site, although this varied somewhat with five sediment samples taken at most sites on Nov 30, 2003 and no samples on Feb 26 and Mar 3, 2004 (see Table 2).

Sample Analysis

Each sediment sample was homogenized and a 5 g sample was suspended in 35 ml of phosphate buffer solution (0.3mM KH_2PO_4, 2mM $MgCl_2$) based on Standard Method 9221 A-3 (Greenberg et al. 1992). Samples were shaken by hand for one minute and then centrifuged at 4°C for five minutes at 1000 rpm (Evanson and Ambrose 2006). Three sediment samples and one water sample were processed per site. Using standard procedures for Idexx Colilert®-18 and Enterolert® 97-well Quanti-trays, ten ml of each sample of sediment supernatant and water were added to 90ml of dilution water and analyzed for TC, EC and ENT. The highest value of FIB that could be measured was 2500 MPN/100 ml since sample dilutions were not made; bacteria levels exceeding this maximum detection limit were not quantified.

Results

The Santa Monica Creek subwatershed, which was the largest (15.6 km^2) but least developed (97% undeveloped) catchment draining into Carpinteria Salt Marsh (Table 1), generally had the cleanest water and sediment (Fig. 2 and 3). Santa Monica Creek water EC levels were below health standards at all times and TC was relatively low. The subwatersheds with high amounts of urbanization and agricultural development (Table 1), Franklin Creek and the Western subwatersheds, had runoff with higher FIB concentrations. Franklin Creek subwatershed was the most developed and had the highest FIB in runoff entering the wetland. High levels of TC and ENT were present in Franklin Creek water during wet and dry weather, with ENT exceeding health standards during each sampling event except on December 10 and 16, 2003. The Western subwatershed also had high FIB levels with water exceeding ENT health standards on at least one occasion at each site during both wet and dry weather.

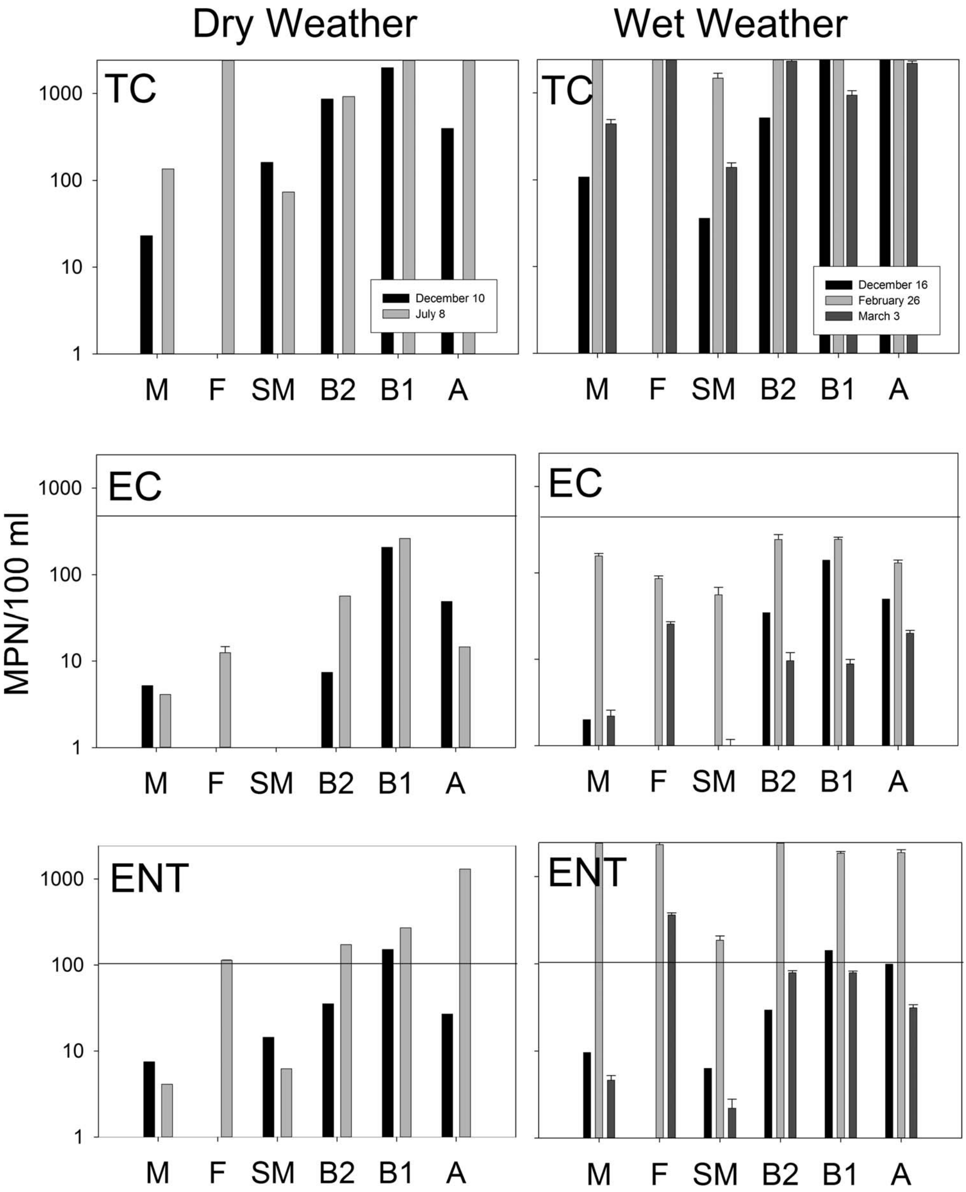

Fig. 2. Concentrations of total coliform (TC), *E. coli* (EC) and *Enterococcus* (ENT) bacteria in Carpinteria Salt Marsh water samples. Five inlet sites [Western Creek A (A), Western Creek B (B1 and B2), Franklin Creek (F), Santa Monica Creek (SM)] and one mouth (M) site were sampled during two dry weather (Dec 10 and Jul 8) and three wet weather (Dec 16, Feb 26 and March 3) sampling events. No water sample was collected from Franklin Creek in Dec. Error bars indicate MPN confidence interval based on SE of five method replicates for Feb 26 and Mar 3, three for Jul 8. Horizontal lines indicate the single-sample water quality standards for EC and ENT; the single-sample standard for TC (10,000 cfu) is above the maximum detection limit (2,500 MPN/100 ml) for the samples.

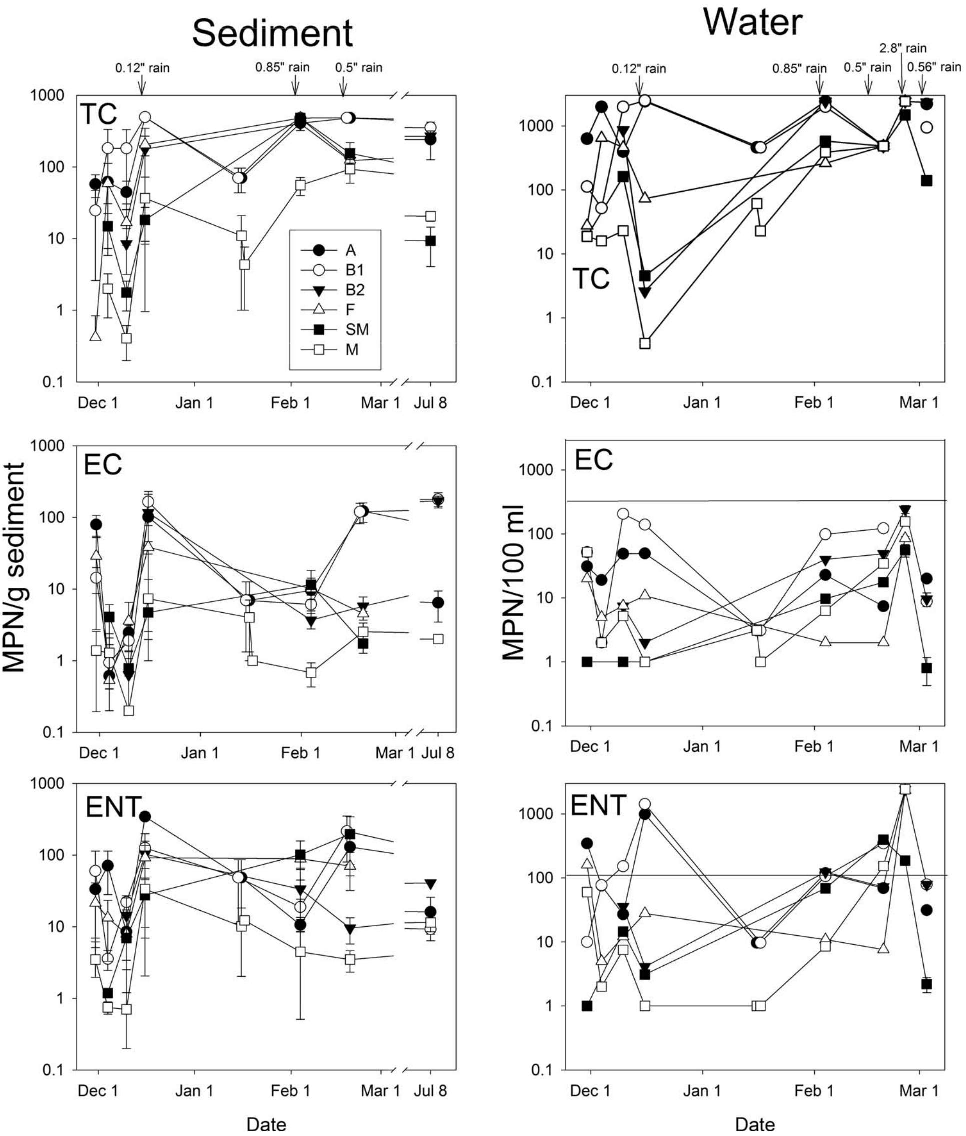

Fig. 3. Concentrations of total coliform (TC), *E. coli* (EC) and *Enterococcus* (ENT) bacteria in sediment samples taken between November 30, 2003 and July 8, 2004 and in water samples taken between November 30, 2003 and March 3, 2004. Five inlet sites [Creek A (A), Creek B (B1 and B2), Franklin Creek (F), Santa Monica Creek (SM)] and one mouth (M) site were sampled. For sediment samples, error bars are based on SE of three replicate samples; where error bars do not show, the error bar is smaller than the symbol except for B2 for July 8, when only one replicate analysis was successful. Arrows indicate rainfall events, with amount of rain noted. Horizontal lines indicate the single-sample water quality standards for EC and ENT; the single-sample standard for TC (10,000 cfu) is above the maximum detection limit for the samples (2,500 MPN/100 ml). Standards have not been established for sediment.

The largest winter rain event [7.1 cm (2.8”) on February 26, 2004] produced the highest ENT and TC values at all sites (Fig. 2). The ENT health standard was exceeded at all sites. This was the only occasion when site B2, which generally had the lowest bacteria concentrations in the Western subwatershed, had similar or higher FIB levels than A and

B1. Only after this largest rain event did Santa Monica Creek water entering the wetland exceed ENT standards. It also was the only occasion when water draining from the wetland mouth into the ocean exceeded health standards and had concentrations of TC over 2500 MPN/100 ml (Fig. 2).

Generally, FIB levels were low during dry weather and EC levels were low, not exceeding health standards, during both wet and dry weather (Fig. 3). On December 10, 2003, both creek flow rates and FIB levels were low. Health standards were not exceeded and TC was low compared to wet weather values. However, on July 8, 2004 after several months without rain, FIB values were relatively high. ENT water quality standards were exceeded at all Western and Franklin Creek sites and TC values were over 2500 MPN/100 ml for Creeks A and B1 and Franklin Creek (Fig. 2). During this time creek flow rates were also high, indicating an upstream water source other than rainwater, likely from agricultural irrigation of greenhouses and/or field crops.

FIB loads in sediment were affected by rain events, although the pattern of increased FIB concentrations following storms was not as pronounced as in water samples, possibly due to generally low bacteria concentrations, particularly for EC and ENT (Fig. 3). At site B1 sediment mean values of EC varied between 1 and 166 MPN/g and ENT values varied between 4 and 215 MPN/g, while in water mean EC and ENT values at the same sites were as high as 1396 and 1848 MPN/g, respectively. Elevated TC was detected in both water and sediment after rain events (Fig. 3). While EC and ENT in sediment were generally low, relatively high values of ENT occurred at Western creek sites after the Dec 15 rain event, when values in water were also high. (Sediment data were not available following the largest winter rain event on February 26, 2004). Santa Monica Creek sediment also had a relatively high ENT value during dry weather (Fig. 3).

At the wetland mouth, where water entered the ocean, FIB concentrations were usually low, not exceeding recreational water quality standards (Fig. 2). FIB concentrations were only elevated at the mouth following the largest winter rain event (on February 26, 2004), when TC and ENT were over 2500 MPN/100 ml, vastly exceeding ENT health standards.

Salinity varied widely by sampling location and time (Table 2). The mouth site had near-seawater salinity during all sampling times except February 26, 2004, which was after the largest rain event. Franklin and Santa Monica Creeks also were usually close to seawater salinity, but salinities were reduced after rainfall. The Western Creek sites had lower salinities, even during dry weather, indicating their influence by persistent freshwater inflow not related to storms.

Discussion

Watershed Input to Wetland

FIB concentrations entering CSM were related to the amount of watershed urbanization rather than watershed size. The largest, least-developed watershed draining into the marsh had water with low FIB, while the smaller, more highly developed watersheds produced much higher FIB concentrations. Watershed land use has been correlated with FIB concentrations in coastal waters around the United Kingdom (Crowther et al. 2002; Kay et al. 2005). Urbanization was the primary predictor of EC concentrations in popular bathing beaches around Clacton, UK as well as for EC and ENT concentrations in surface waters of the 1583 km^2 Ribble drainage basin (Kay et al. 2005).

In CSM, high FIB values occurred after rain events, as has been found in other southern California wetlands. For example, TC in Santa Monica Bay and the Santa Ana river wetlands peaked on the same day as the rain event and decreased within one day

(Haile et al. 1999; Evanson and Ambrose 2006) and ENT and EC in the Santa Ana river wetlands peaked on the day of the storm or within several days (Evanson and Ambrose 2006). Overall the highest FIB values occurred following the largest rain event of the year on February 26, 2004 (2.8”) and after the December 15, 2003 rain event that followed over a month without precipitation, the longest dry period preceding a rain event during this study. The 7.1 cm (2.8”) rain event likely was large enough to saturate soil and produce field runoff as well as high volumes of impervious surface runoff. Although the December 15 rain event was small 0.3 cm (0.12”), it likely flushed bacteria that had accumulated over a long duration (relative to the dry period duration preceding other storms sampled).

Western Creek flow rates in July, while not quantified, appeared similar to those that occurred the day after rain events rather than the typical dry weather flow, likely due to agricultural and greenhouse irrigation runoff from facilities as close as a kilometer upstream of the wetland (Page et al. 1995). Some July dry weather values of TC, EC and ENT in water were similar to or higher than bacterial concentrations from creek water sampled directly following rain events.

Bacteria Removal

While surface waters entering CSM often had high FIB concentrations (during both wet and dry weather), they generally exited the wetland with low FIB values. Although the number of samples taken during this study was relatively low, sediment and water samples were collected simultaneously at five inlets sites and the wetland mouth, providing a synoptic view of FIB inputs and output over a season that included both wet and dry weather sampling. The lower FIB concentrations at the wetland mouth compared to water entering the wetland suggest that bacteria populations decreased as a result of flowing through the wetland.

Bacteria removal from CSM waters likely was the result of processes such as predation, destruction by ultraviolet light, and sedimentation (i.e. adsorbing to particles that then settle to the bottom) (Alkan et al. 1995; Noble et al., 2004; Dorsey et al., 2010, Dorsey et al., 2013). While an estimated 65-85% of the total fecal coliform, EC and ENT remain free-floating in the water column and do not settle (Jeng et al. 2005; Schillinger and Gannon 1985), the low flow rate within CSM tidal channels allows for sedimentation and increased exposure of FIB to harmful solar radiation, thereby reducing FIB concentrations in a similar manner to a reservoir system or a constructed wetland (Kay and McDonald 1980; Kay et al. 1999). As with freshwater wetlands, UV was probably important for FIB destruction since sunshine is abundant year-round in southern California and CSM tidal creeks are shallow, allowing high UV exposure. FIB concentrations also may have been reduced due to dilution by tidal water, although this factor was minimized by sampling during an outgoing tide.

FIB loads at site B2 in the Western subwatershed were generally lower than at sites A and B1, possibly because this water travelled approximately 100 yards along the wetland fringe before entering the wetland. This area beside the railroad track, while not wetland habitat, was a dirt ditch lined with plants. The extra amount of both travel time and exposure likely contributed to FIB removal.

Within-wetland sources, such as bacterial growth in the sediment or feces from bird populations, did not appear to significantly contribute to surface water FIB loads. Storm flow re-suspension during winter could have contributed to increased bacterial populations in the water (Steets and Holden 2003), but sediment FIB were generally low and unlikely a large contributor during our study. Low values of bacteria in the sediment indicated FIB were not stored there nor did they re-grow to high concentrations in wetland sediment. Grant et al. (2001) suggested that Talbert Marsh, a small (10 ha) southern California wetland with a similar bird population (1180 individuals) to CSM (a population maximum of 171-2200 individuals[6]), exacerbated FIB concentrations in coastal runoff, pointing to bird populations as an important within-wetland FIB source. A subsequent model of FIB loads to Talbert Marsh, which included urban runoff, erosion of contaminated sediments, bird feces, and combinations of these factors, indicated that direct runoff of bird feces was not likely to be a major source in this small wetland (Sanders et al. 2005). The low FIB concentrations at the mouth (wetland-ocean interface) of CSM suggest that birds in CSM were not significantly increasing FIB loads entering the ocean, despite the frequent concentration of birds near the wetland mouth (personal observations).

Besides removal of bacteria, lower FIB concentrations could be due to dilution by seawater. Salinity varied widely during sampling (range 2-37). Some dilution undoubtedly occurred at times because salinity was over 30 at many stations during at least some sampling times, particularly during dry weather and at the mouth. We minimized dilution effects by sampling on the falling tide. Nonetheless, reductions in FIB concentrations would have been due to a combination of dilution and removal processes.

The capacity of a wetland to remove contaminants is related to the volume of water flowing through the wetland and wetland size. Not surprisingly CSM, at 93 ha at the base of a 3,000 ha watershed, of which 350 ha was urbanized, was better able to attenuate FIB than Talbert Marsh, a small 10 ha marsh located at the bottom of a highly developed 3,400 ha watershed. Jeong et al. (2008) indicated that Talbert Salt Marsh was able to remove FIB more efficiently as the volume of storm water runoff entering the marsh decreased. They concluded that a wetland may have a maximum capacity to attenuate contaminants; when loads exceed this value the wetland becomes a net source of contaminants to coastal waters.

Our work suggests that a moderate-sized wetland was able to attenuate FIB during most rain events. Reducing the size of a wetland, such as occurred at Talbert Salt Marsh (historically 1200 ha, now 10 ha), reduces its capacity to remove contaminants. Expansion of existing wetland area through restoration may partially restore its capacity for attenuating FIB, although this possibility remains to be tested.

Conclusions

This work provides evidence that a 93 ha southern California wetland is an adequate size to allow for natural removal of FIB when the contributing watershed(s) have low to moderate levels of development. With relatively little loss of original wetland habitat and only moderate levels of development in its watershed, CSM is able to provide a valuable ecosystem service of improving the quality of water before it reaches the coastal ocean. Coastal water quality appeared to only be compromised by runoff during a large storm event when high volumes of bacteria-laden water overwhelmed the wetland's ability to reduce loads through sedimentation, die off, and/or dilution.

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