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Reduction of fecal indicator bacteria (FIB) in the Ballona Wetlands saltwater marsh (Los Angeles County, California, USA) with implications for restoration actions

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ABSTRACT

A benefit of wetland preservation and restoration is the ecosystem service of improving water quality, typically assessed based on bacterial loading. The Ballona Wetlands, a degraded salt marsh of approximately 100 ac located on the southern border of Marina Del Rey (Los Angeles County, California, USA) are currently the focus of publicly funded restoration planning. The wetlands receive tidal water, usually contaminated with fecal indicator bacteria (FIB: total and fecal coliforms, *Escherichia coli*, enterococci) from the adjacent Ballona Creek and Estuary. During the summer of 2007, two 24-h studies were conducted to determine FIB tidal dynamics within the wetland. Measurements of water flow and mean FIB concentrations ($n = 3$) were measured every 1.5 h to determine total FIB load estimates. FIB loading rates (MPN/s) were greatest during flood tides as water entered the wetlands, and then again during spring tide conditions when sediments were resuspended during swifter spring ebb flows. During daylight hours, the wetland acted as a sink for these bacteria as loads diminished, presumably by sunlight and other processes. Conversely, during late afternoon and night, the wetlands shifted to being a source as excess FIB departed on ebb flows. Therefore, the wetlands act as both a source and sink for FIB depending on tidal conditions and exposure to sunlight. Future restoration actions would result in a tradeoff – increased tidal channels offer a greater surface area for FIB inactivation, but also would result in a greater volume of FIB-contaminated resuspended sediments carried out of the wetlands on stronger ebb flows. As levels of FIB in Ballona Creek and Estuary diminish through recently established regulatory actions, the wetlands could shift into a greater sink for FIB.

1. Introduction

Maintaining good water quality along beaches is a prime goal of resource managers. Contamination of recreational waters by sewage or runoff can lead to increased swimmer illness from exposure to water-borne pathogens and consequential loss of millions of dollars for a region (Given et al., 2006). A variety of measures to reduce microbial loads impacting coastal waters have been implemented with varying levels of success (e.g. Dorsey, 2009). Among these, the use of natural or constructed wetlands appears to be a good strategy to reduce levels of pathogenic bacteria or fecal indicator bacteria (FIB:

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total and fecal coliforms, *Escherichia coli*, enterococci). For example, in studying a series of constructed wetlands, Rifai (2006) documented an average FIB removal efficiency of 88%.

Coastal salt marsh systems have been shown to be both sinks and sources of FIB. Steets and Holden (2003) found that a small coastal lagoon-wetland system in Santa Barbara, California, acted as a sink for FIB during the dry summer months. However, during wet-weather winter months, the system switched to a source of FIB to the adjacent surf zone. In this situation, bacteria were associated with sediments resuspended by increased runoff flowing through the lagoon system. During dry weather, Grant et al. (2001) determined that increased densities of enterococci in tidal water flowing from the Talbert Marsh system significantly impacted surf zone water quality along Huntington Beach, California. Later studies at this site showed that as increased volumes of contaminated runoff were diverted from the marsh into the sanitary sewers, indicator bacteria were more efficiently removed within the marsh by the natural processes (Jeong et al., 2008). Further, Jeong et al. (2008) calculated that the wetland could receive runoff equaling <1% of the average tidal prism volume (about 2×10^5 m^3/d) before becoming a source of FIB to coastal waters.

These studies imply that an urban saltwater marsh system could act as either a sink or source for FIB depending on tidal flows and the amount of urban runoff it receives. Here, we define a sink as an area whereby loads of FIB are reduced through various wetland processes. Conversely, the wetland would act as a source if FIB loads increase and are released to adjacent receiving waters. A management goal would be to understand factors influencing whether a wetland acts as a sink or source of FIB, and if these systems can be utilized to clean contaminated runoff, thus improving water quality along adjacent ocean beaches. In turn, this information can affect restoration design considerations, particularly for urban wetlands.

1.1. The Ballona Wetlands

The Ballona Wetlands in Los Angeles County offer a good opportunity to address these questions. These wetlands are the last remaining major saltwater marsh in Los Angeles County (West, 2001). Surrounded by urban areas, the marsh has been degraded from numerous past activities, chief of which was construction of the Ballona Creek flood control channel, a largely cemented box or trapezoidal channel that diverted water from the Creek straight to Santa Monica Bay, thus severely limiting tidal flow to the marsh system (Phillip Williams & Associates, Ltd., 2006). Presently, the Ballona Wetlands are undergoing restoration planning under the direction of the California Coastal Conservancy (http://www.scc.ca.gov).

These wetlands comprise a saltwater marsh system of approximately 100 ac located just south of Marina Del Rey (Fig. 1). Based on a series of recent monitoring studies by the City of Los Angeles and Keane Biological Consulting (2005), the marsh flat was characterized by a low diversity plant community dominated by the pickle weed *Salicornia virginica*, while the upper banks of the tidal channels are covered by stands of Fleshy jaumea, *Jaumea carnosa*. Invasive plant species were prevalent throughout the marsh habitat and upland areas. Plants dominating the intertidal sediments mainly were the algae *Enteromorpha* and *Ulva*. Within the tidal channels, corophid amphipods, spionid and capitellid polychaetes, and the California horn snail *Cerithidea californica* dominated a low diversity animal assemblage. Common fish included the California killifish *Fundulus parvipinnis*, the Topsmelt *Atherinops affinis*, and several species of goby (Arrow goby *Clevelandia ios*, Longjaw mudsucker *Gillichthys mirabilis*). Feeding on the infaunal and fish assemblage were a variety of shorebirds, particularly the Willet *Catoptrophorus semipalmatus*, and several species of larger wading birds, mainly the Great blue heron *Ardea herodias*, Snowy egret *Egretta thula* and Great egret *Ardea alba*.

The marsh is subjected to mixed semidiurnal tidal flows through approximately 3.2 ac of tidal channels. Water enters wetlands from the Ballona Creek Estuary through a single self-regulating east tide gate during flood flows. This gate was constructed in 2003 replacing an older, non-functioning gate. The tidal flow is muted as the gate allows only a tidal height of up to 1.1 m. At medium to high tides, the water column within the tidal channels is stratified with the surface being more brackish (Dorsey, unpublished data), reflecting the input of freshwater from Ballona Creek upstream from the estuary. During ebb flows, water departs wetlands via the east tide gate and a second smaller west tide gate. This latter gate is a flap-valve system allowing water to flow out of the wetlands. At the lowest spring tides, the tidal channels are nearly completely drained with water depths of 10 cm or less.

Dorsey (2006) found that FIB concentrations within the wetland tidal channels vary greatly with tidal flows and that the wetlands may act as a sink for FIB under flood-tide conditions. Four 12-h surveys within the wetlands to generate preliminary data on FIB tidal dynamics similarly demonstrated that densities changed by several orders of magnitude over the period, and that densities tended to diminish during daylight hours (Dorsey, unpublished data).

1.2. This study

Previous work by Dorsey (2006) to describe FIB tidal dynamics within the Ballona Wetlands was based on samples collected only at peak flood and ebb tides, and four subsequent 12-h surveys (Dorsey, unpublished data) captured only a portion of the tidal cycle. In this study we ask under what tidal conditions does the Wetland act as a FIB sink or source. To address this question, we determined FIB loading and total FIB loads throughout 24-h tidal cycles by coupling measurements of FIB densities with water flow within the tidal channels. This approach enabled us to determine how the loading of bacteria changed over tidal periods.

2. Methods

2.1. Station locations

Water samples for FIB analyses, flow rate, and water quality measurements were collected at BW2 in the Ballona Wetlands positioned 35 m south of the East Tide gate (Fig. 1). This

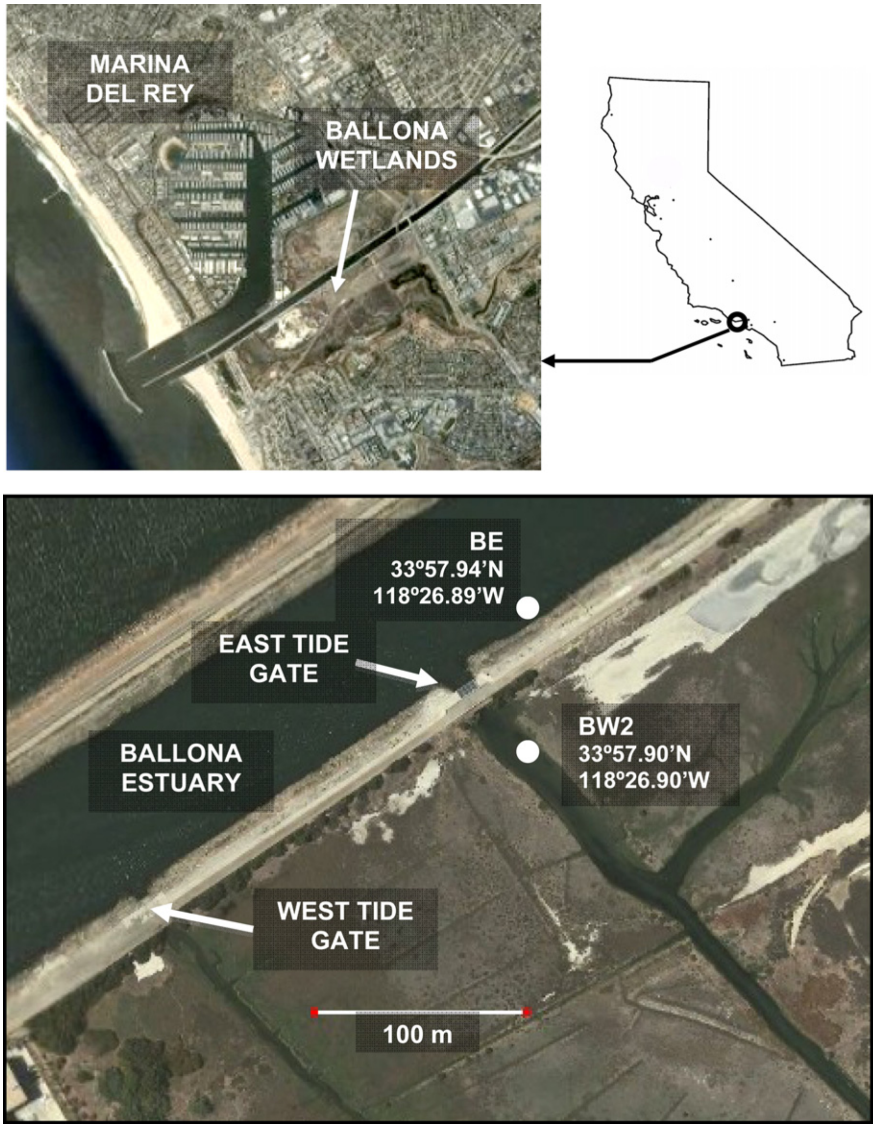

Fig. 1 – Location of sampling sites in the Ballona Wetlands (BW2) and Estuary (BE). Images from Google Earth.

location was selected to measure water entering and leaving the wetlands. A second station (BE) was positioned in the Ballona Estuary 60 m east of the tide gate as a reference point to measure concentrations of FIB upstream of the gate. Sampling events were conducted only during dry weather conditions in an attempt to clarify FIB tidal dynamics. Previous studies showed that during rain events, concentrations of all FIB groups could increase by several orders of magnitude throughout the wetland (Dorsey, 2006).

2.2. *Sampling frequency*

Two 24-h sampling events were conducted during the summer of 2007 to elucidate trends over several tidal cycles (Table 1). Replicate water samples ($n = 3$) were collected every 1.5 h during each sampling event at the two wetland stations, and every 4.5 h at the estuary station. Water for bacterial and turbidity tests was collected in 125 ml sterile polypropylene jars, placed on ice, and transported to the nearby laboratory at Loyola Marymount University for analyses.

2.3. *Bacterial and turbidity tests*

Concentrations of FIB (total coliforms, *E. coli*, enterococci) were determined using defined substrate technology (APHA et al., 1998: Standard Methods Section 9223 B). Idexx media Colilert®-18 was used for total coliforms and *E. coli*, and Enterolert® media for enterococci (http://www.idexx.com). For each sample, 10 ml of sample was added to 90 ml of dilution water, sealed into Quanti-Tray® 2000 97-well trays, then incubated 18–22 h at 35 °C for total coliforms/*E. coli*, and 24 h at 41 °C for enterococci. After incubation, reactive wells in the trays were counted and the most probable number (MPN) of bacteria/100 ml was determined for each sample. Turbidity (NTU) was determined using a HACH 2100N turbidimeter.

Table 1 – Sampling dates and tidal information for the 24-h FIB surveys in the Ballona Wetlands (BW2) and Estuary (BE). Samples were collected every 1.5 h at BW2 and 4.5 h at BE.

Date	Start time (h)	Time period (h)	Tidal flow	Tidal range (m)
12–13 Jul'07	0445	0310–0952	Flood	1.44
		0952–1404	Ebb	0.39
		1404–2025	Flood	1.29
		2025–0353	Ebb	2.40
2–3 Aug'07	0600	0624–1253	Flood	1.49
		1253–1839	Ebb	0.99
		1839–0030	Flood	0.98
		0030–0657	Ebb	1.30

2.4. *Chemical and physical electronic measurements*

During each sampling event, water quality measurements of depth (m), temperature (°C), salinity (ppt), pH, and dissolved oxygen (mg/L) were measured using a YSI 6600 EDS sonde positioned in the deepest part of the channel, and with the bottom of the sonde resting on the sediment surface. Measurements were made every 5 min during sampling events. Light intensity (lums/ft^2) was measured during the 24-h sampling events in 2007 at Station BW2 using a HOBO data logger positioned on the west channel bank where each set of water samples were collected.

2.5. *FIB loading estimates*

2.5.1. *Tidal channel flow rate measurements*

Tidal channel flow rate measurements were recorded every 1.5 h. Velocity in ft/s was determined at 1-ft intervals across the channel using a McBirney Flo-Mate (Model 2000) electromagnetic flow meter positioned approximately 2/3 of the distance between the channel bottom and water surface. For each interval, the flow rate (Q) in ft^3/s was calculated as follows:

$$Q = (w)(d)(v) \quad (1)$$

where w was the interval width (ft), d was the depth (ft), and v was the flow velocity (ft/s). The flow rates for each interval were then summed as follows to yield a total flow rate for the channel, Q_T, and then converted to metric units (m^3/s):

$$Q_T = \sum_{i=1}^{n} (Q)_i \quad (2)$$

For each of the total flow rates, a volume (V) in m^3 of water moving into or out of the wetlands at that sample time was calculated by simply multiplying the total flow rate (Q_T) by the duration of flow (in seconds).

2.5.2. *FIB loading estimates*

A loading rate of bacteria (MPN/s) was determined by multiplying the concentration of bacteria by the flow rate measured at each sample time. This approach needed to be modified since incoming/outgoing flows do not occur simultaneously and the concentration of bacteria and the flow rates are constantly changing. Therefore, no direct comparison of influent and effluent loading rates is applicable. To mitigate this situation, a total load of bacteria entering the wetlands over the course of a flood tide and a total load of bacteria leaving the wetlands over the course of an ebb tide was calculated. The beginning and end of a tidal cycle from low to high and back to low tide was sampled for this experiment, and based on direct measurements of water depth collected with the YSI sonde (Section 2.4 above). The resulting flood load was divided by the ebb load to determine whether the wetlands acted as a source or sink. Similarly, Shellenbarger et al. (2008) used total loads of FIB to determine a source or sink term for system of managed tidal ponds in San Francisco Bay.

The total load of each FIB group per sample (L) was determined by multiplying the volume of water moving (calculated above) by the mean FIB concentration (FIB$_c$) measured at the sampling time. For example, FIB loads for Sample 1 (L_1) would be calculated as follows:

$$(L_1) = V_1(\mathrm{FIB}_{c1}) \quad (3)$$

where V_1 was the volume in m^3, and FIB_{c1} was the indicator group's concentration (MPN/100 ml) collected at a specific time t_1.

To calculate total FIB load for each flood (L_F) and ebb (L_E) tidal flows, the total ebb volume of water departing the wetlands from both tidal gates needed to be estimated. Of the total flow entering the wetlands, most of the ebb flow exits the wetlands from the east gate with the remainder exiting from the west gate. For the total load calculations described below, the ebb volume from the West Gate over the entire ebb period was estimated by subtracting the East Gate ebb volume from the Total Flood Volume:

$$V_{EBB\ WG} = V_{FLD} - V_{EBB\ EG} \quad (4)$$

The Total Ebb Volume for each time interval was then estimated by adding the East Gate Ebb volume and the West Gate Ebb volume together.

$$\text{Total Ebb Volume} = V_{EBB\ EG} + V_{EBB\ WG} \quad (5)$$

Where $V_{EBB\ EG}$ is the ebb volume measured at the East Tide Gate, $V_{EBB\ WG}$ is the ebb volume calculated for the West Tide Gate and V_{FLD} is the total flood volume at the East Tide Gate. Depending on the tide characteristics and the operating condition of the tide gates, the percentage of the water leaving via each tide gate can vary significantly from day to day. Because of this, these calculations were performed for each time interval during each 24 h study. It is important to note that equal volumes of flood and ebb water were used in calculating the total load of bacteria. This was achieved by only using samples taken between the same depths in the tidal channel. Also note that that the infiltration, evapotranspiration, and inputs from other sources were not included in the model because in this system, which is overwhelmingly driven by tidal inputs and outflows from Ballona creek and the Pacific Ocean, these factors are relatively insignificant (Phillip Williams & Associates, Ltd., 2006).

Tidal load ratios for each FIB group were calculated between similar depths in the tidal channel from low tide through the high tide crest then back through the following equivalent low tide. Load estimates for each sampling time (L) were summed for each flood-flow and ebb-flow period over this truncated tidal cycle. For example, the total loading during the flood tide (LF_F) would be calculated by the expression $L_1 + L_2 ... + L_x = L_F$.

The total load for the flood flow then was divided by the total load for the ebb flow to yield a FIB tidal ratio (FIB_R) for each indicator group as follows:

$$FIB_R = L_F/L_E \quad (6)$$

2.5.3. *Correlations*

Pearson correlation analyses were performed between FIB concentrations, YSI measured water depth at the time of sampling, and averaged data from the YSI sonde measurements. For each YSI parameter, means were determined by averaging three readings prior to each FIB collection time, the reading at the time of collection, and the subsequent three readings to yield $n = 7$.

3. Results

3.1. *Tidal flow rates and volumes*

Flow rates ranged from <0.01 m^3/s during slack water periods to 1.24 m^3/s during the July sampling event (Fig. 2). The most rapid flow rates occurred approximately midway between the high and low tide peaks, especially when tidal ranges (Table 1) exceeded 1 m during spring tides. Maximum flow rates during each flood and ebb flow period were positively correlated with corresponding tidal ranges (Spearman $r = 0.67$), but this relationship was not significant ($p = 0.08$).

Based on calculated flood and ebb volumes (equation (4) above), we estimated that during the two tidal cycles of the July survey, 93% of the ebb flow departed the wetlands through the east tide gate during the first cycle followed by 70% during the second cycle. The first cycle had a relatively smaller tidal range compared to the second cycle that day (Fig. 2). During August, the two tidal cycles were more similar in their tidal ranges (Fig. 2) with similarly proportioned volumes leaving the wetlands through the east tide gate (first tide cycle equaled 77%, the second equaled 67%).

3.2. *Water quality measurements*

Nearly 500 sets of measurements for temperature (°C), salinity (ppt), dissolved oxygen (mg/L) and pH were collected with the YSI sonde during the two 24-h sampling events. Summary statistics for these variables are presented in Table 2. In addition to the YSI recordings, 102 turbidity measurements were made in samples collected for bacterial analyses (Table 2).

The trends of water quality variables generally appeared to be associated with tidal conditions and time of day. The range of salinities (22.31–33.62 ppt) reflected the estuarine nature of the water entering the wetlands. Salinity tended to be positively correlated with tidal heights (Table 3) where higher salinities occurred during flood tides and lower salinities were associated with ebb flows. Several actions could account for this relationship. Most likely, the wetland salinities are

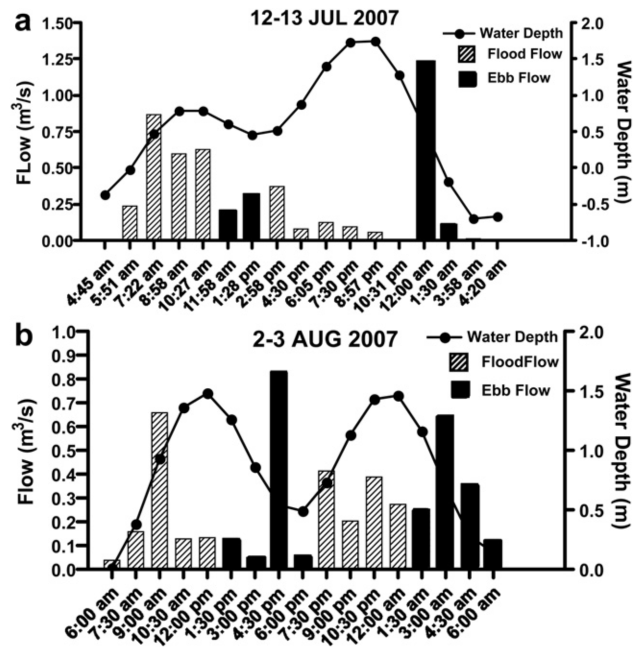

Fig. 2 – Flow rates and corresponding water depths at Ballona Wetlands Station BW2 during the 24-h surveys in a) July, and b) August.

governed by water flooding in from the estuary where the brackish/freshwater lens in the estuary first enters the wetlands during the initial flood tide followed by more saline water. During the flood tide, the water column would become water progressively more stratified. During spring ebb flows, as measured in this study, the more brackish surface lens would eventually reach the channel bottom as the water level drops to 10 cm or less in the tide channel at maximum low tide. This scenario was best demonstrated during the July sampling event as water at the bottom of the tide channel (where the YSI conductivity sensor was positioned) became progressively more saline with the flood tide, then more brackish as the tide fell later in the day (Fig. 3). We assumed

Table 2 – Summary statistics for water quality variables measured at BW2. Values for water levels < 0.2 m not used since sensors were exposed.

Date	Variables	Temp (°C)	Salinity (ppt)	DO (mg/L)	pH	Turbidity (NTU)[a]
12–13 Jul'07	Mean	22.42	30.53	6.67	8.11	3.77
$n = 228$	S.D.	1.15	2.91	2.38	0.13	2.17
	Min	21.11	22.31	2.76	7.90	1.83
	Max	25.11	33.62	13.94	8.46	9.51
2–3 Aug'07	Mean	22.52	29.36	5.63	7.96	2.92
$n = 252$	S.D.	1.31	2.01	3.53	0.20	1.92
	Min	20.62	22.57	1.00	7.64	1.27
	Max	25.73	31.85	15.48	8.47	7.60

a $n = 51$ for the July and 51 for the August 2007 surveys.

Table 3 – Matrix of Pearson correlation coefficients (*r*) for FIB groups and mean water quality variables measured during the two 24-h sampling events. Significant correlations ($p < 0.05$) indicated by bold, italicized font.

	Total	*E. coli*	Entero	Tide Hgt	Flow	Light	Wat Temp	Sal	DO	pH
12–13 July, 2007										
E. coli	***0.79***	1.00								
Entero	***0.77***	***0.99***	1.00							
Tide Hgt	−0.48	−0.47	−0.47	1.00						
Flow	0.41	0.15	0.10	−0.30	1.00					
Light	−0.16	−0.37	−0.33	−0.14	−0.02	1.00				
Wat Temp	−0.47	−0.34	−0.35	−0.34	0.00	***0.57***	1.00			
Sal	−0.45	***−0.68***	***−0.66***	***0.76***	−0.08	0.42	0.00	1.00		
DO	−0.12	−0.28	−0.25	−0.19	0.02	***0.82***	***0.65***	0.23	1.00	
pH	0.10	−0.06	−0.04	−0.39	0.18	***0.81***	***0.63***	0.05	***0.95***	1.00
Turbidity	0.42	***0.65***	***0.71***	***−0.64***	−0.09	0.01	0.11	***−0.62***	0.04	0.18
2–3 August, 2007										
E. coli	***0.79***	1.00								
Entero	***0.54***	***0.62***	1.00							
Tide Hgt	0.25	0.23	0.06	1.00						
Flow	0.00	0.14	−0.23	−0.01	1.00					
Light	0.15	0.00	0.08	0.28	−0.12	1.00				
Wat Temp	0.01	0.03	−0.14	−0.40	0.08	−0.35	1.00			
Sal	−0.19	−0.27	−0.33	0.58	0.04	***0.64***	−0.29	1.00		
DO	−0.10	−0.32	−0.19	0.17	0.07	***0.51***	0.29	0.47	1.00	
pH	0.02	−0.19	−0.04	0.25	0.08	***0.56***	0.20	0.41	***0.97***	1.00
Turbidity	0.07	0.20	0.35	−0.54	−0.26	−0.20	0.02	***−0.58***	−0.41	−0.39

that water column became fully stratified and horizontally mixed throughout the wetland as high slack water was reached. Other sources of brackish and/or freshwater entering the tidal channels could be dry-weather runoff from the surrounding community, and intrusion of shallow groundwater (Saez, 2007). These latter two sources are not significant relative to estuarine tidal water entering the wetlands, and were not included in this study.

Mean water temperatures generally reflected warmer temperatures during the summer with the greatest temperatures occurring in the afternoons during slack tide conditions. This relationship was best demonstrated during the July sampling event where water temperatures and light intensity were significantly correlated (Table 3; $r = 0.57$, $p < 0.05$). Dissolved oxygen displayed a wide range with lowest values (e.g. 1.0 mg/L during the August survey) measured during predawn hours. Dissolved oxygen and pH were positively correlated during both sampling events, and also displayed positive correlations with water temperatures and light intensity during the July sampling event (Table 3).

Turbidity negatively correlated with salinity (Table 3) indicating that more turbid water was associated with ebb flows when more brackish water was present. When mean turbidities were regressed against corresponding water flow rates (Fig. 4), the swifter flow rates corresponded with increased turbidities ($r^2 = 0.97$, $p < 0.0001$). Increased turbidities at the tide gate probably resulted from tidal scouring that resuspended sediments, mainly during spring tide ebb flows approaching minus tide conditions.

3.3. *FIB concentrations and loading*

The mean concentrations of total coliforms, *E. coli*, and enterococci (Appendix A) generally were greater during flood-tide conditions as water entered the wetlands from the adjacent Ballona Estuary, and during the mid-point of the ebb- and flood-flows when turbidity spikes occurred. Within sampling events, mean densities of these indicator bacteria could span up to three orders of magnitude with total coliforms ranging from 10^2 to 10^4, and *E. coli* and enterococci from 10^1 to 10^3 MPN/100 ml.

Concentrations of FIB at the estuary station were elevated during early morning hours, fell throughout the day, but rose again at night. During the July sampling event, the estuary station displayed a spike during the mid-point of the ebb flow, similar to that seen within the wetland.

A ratio of mean FIB concentrations between the upstream estuary (BE) and wetland (BW2) stations was calculated for each sampling time to indicate the magnitude of estuary concentrations relative to those in the wetlands (Table 4).

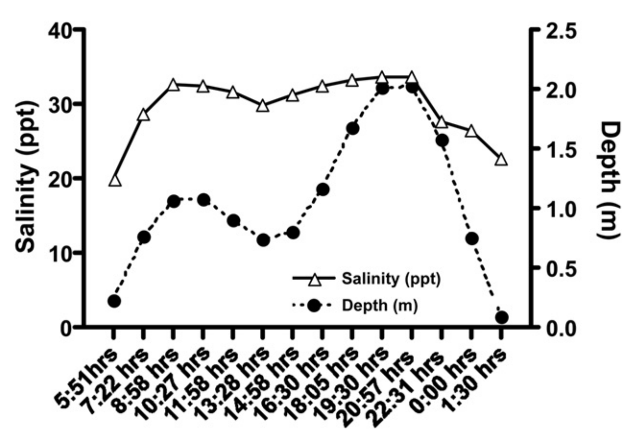

Fig. 3 – Relation between mean salinity (ppt) and water depth (m) during the July sampling event at BW2. Salinity was measured at a point approximately 5 cm off the channel bottom where the salinity sensor of the YSI sonde was positioned.

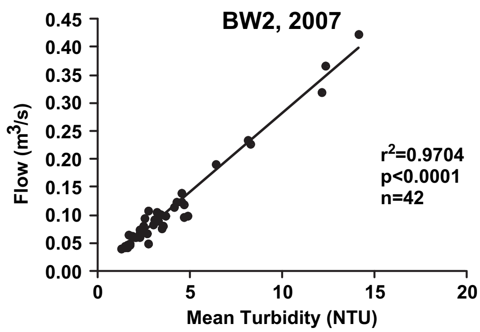

Fig. 4 – Linear regression between flow rate and mean turbidity at BW2. All data from the two surveys were pooled for the analysis.

Calculations of $R_{E:W}$ were followed by Student's *t*-tests to determine if the means used to calculate the ratios differed significantly (Table 4). In the estuary at Station BE, concentrations of all three FIB groups tended to be significantly greater than those within wetland during the July survey as indicated by values of $R_{E:W} > 1.00$ (Table 4). The highest $R_{E:W}$ values for all three FIB groups occurred during low slack water when the tidal height was less than −0.5 m (Fig. 2). Conversely, ratios of 1.0 or less tended to be associated with flood conditions as slack water was reached. Similar trends were seen during the August survey, although not as evident (Table 4). However, as in July, some of the greatest values of $R_{E:W}$ occurred during low slack water.

The FIB loading rates (MPN/s) were greatest in early mornings during flood flows as water flowed into the wetland channel from Ballona Estuary (Fig. 5). Loading rates generally diminished throughout the day for all FIB groups although mid-flow spikes occurred, especially during spring tide ebbs (e.g. July at 12:00 AM). Total load estimates for flood and ebb flows during a single tidal cycle (low tide through high then back to low) are presented in Table 5. During daylight hours, the FIB tidal ratio (FIB_R) was >1 for all three indicator groups indicating a reduction of bacteria during this period. The reduction of the total number of load of FIB during daylight hours ranged from approximately 60% total coliforms to 100% for enterococci. Conversely, during late afternoon and nighttime, the FIB_R ratios all were <1 indicating that the wetlands were acting as a source of FIB. Increases in the total load of FIB ranged from around 270% for total coliforms to 836% for enterococci. These load increases during the nighttime resulted from the spikes of suspended solids during the strong ebb flow rates (Fig. 5).

During the July survey densities of *E. coli* and enterococci displayed significant ($p < 0.05$) correlations with increased turbidity ($r = 0.65$ and 0.71, respectively) and lower salinities ($r = -0.68$ and -0.66, respectively) associated with ebb tide conditions (Table 3). In contrast, during the August sampling event, none of the FIB groups formed significant correlations with the water quality parameters.

4. Discussion

Three main points have emerged from this research: 1) densities of FIB groups can vary by up to three orders of magnitude within a 24-h period during dry weather; 2) the wetlands can act as a sink for these bacteria during daylight hours; and 3) although re-suspension of sediments during ebb flow can cause the wetlands to be a source of FIB to the estuary, water flowing from the wetlands can dilute the more contaminated receiving waters of the estuary.

4.1. *Variation in FIB densities*

Water in the Ballona Estuary is a mixture of marine water from Santa Monica Bay and freshwater flowing into the

Table 4 – Ratio of mean FIB concentrations between the Estuary (BE) and Wetland (BW2) stations. Mean concentrations for FIB groups per site and per time are given in Appendix A, and were tested for significant differences using a Student-t test on log10-transformed data.

Sample time	Total coliforms		*E. coli*		Enterococci		Tidal state
	$R_{E:W}$	*p*[a]	$R_{E:W}$	*p*	$R_{E:W}$	*p*	
July 12–13 survey							
5:51AM	1.00	Not tested[b]	1.75	0.0356*	1.08	0.4839 ns	Flood
10:27AM	2.93	0.0003*	3.58	0.0220*	3.85	0.0236*	Ebb
2:58PM	1.81	0.0322*	1.00	Not tested	1.67	0.3753 ns	Flood
7:30PM	0.24	0.0239*	1.00	Not tested	1.00	Not tested	High Slack water
12:00AM	3.40	0.0699 ns	8.37	0.0108*	9.63	0.0035*	Ebb
4:20AM	7.16	0.0003*	12.70	0.0002*	19.28	0.0033*	Low slack water
August 2–3 survey							
7:30AM	1.00	Not tested	5.85	0.0268*	0.08	0.0007*	Flood
12:00PM	1.00	Not tested	0.49	0.0666 ns	0.18	0.0266*	High slack water
4:30PM	1.64	0.0015*	1.24	0.6037 ns	2.40	0.1180 ns	Low slack water
9:00PM	0.69	0.0138*	0.41	0.0520 ns	0.82	0.4552 ns	Flood
1:30AM	0.79	0.3077 ns	2.35	0.0604 ns	0.75	0.3808 ns	High Slack water
6:00AM	1.31	0.0271*	18.51	0.0001*	6.09	0.0001*	Low slack water

a *$p \leq 0.05$; ns $p > 0$.
b Means were equal, so not tested.

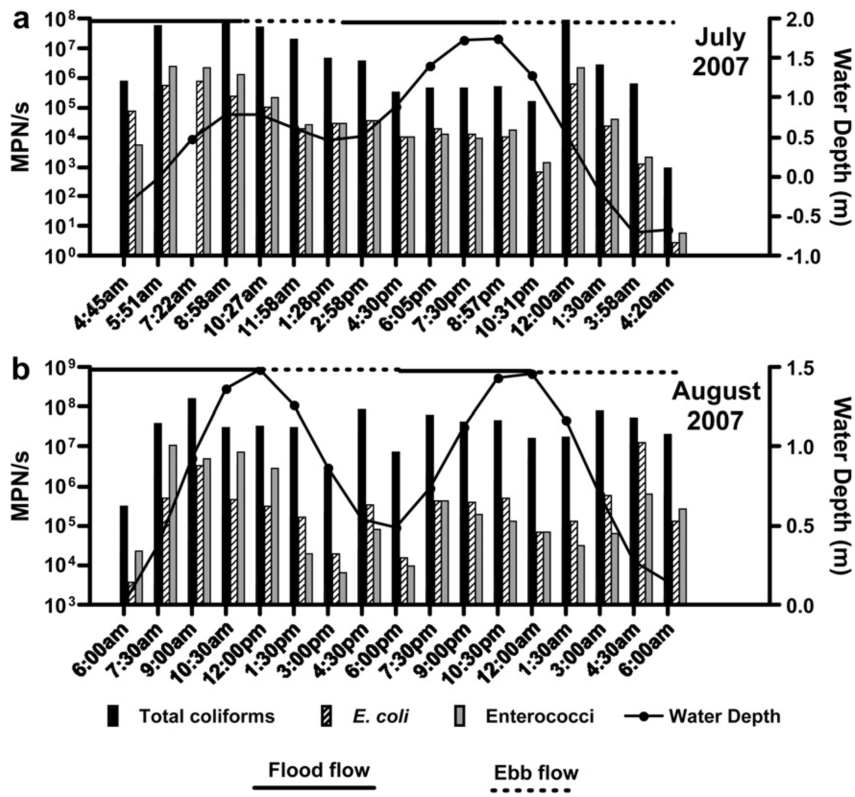

Fig. 5 – FIB loading rate estimates (MPN/s) for the two 24-h surveys conducted during 2007 at BW2 in the Ballona Wetlands: a) July sampling event, and b) August sampling event.

estuary from Ballona Creek that is contaminated by FIB. Estuarine surface salinities have been measured to range from <1 to 32 ppt depending on tidal conditions and runoff from rainfall (Dorsey, 2006), and are stratified with fresher water forming a surface lens, both within the estuary and wetland tidal channels (Dorsey, unpublished data). The main source of lower salinity water within the wetlands most likely is tidal water from the estuary. Other sources of freshwater entering the tidal channels could be dry-weather runoff from the surrounding community, or groundwater intrusion, but we assume that these sources are minimal compared to tidal flows.

Table 5 – Total tidal loads during flood (TL_F) and ebb (TL_E) flows and the corresponding FIB Tidal Ratio (FIB_R) during the 24-h surveys in 2007.

Date	Time (h)	TL_F	TL_E	FIB_R	% Reduction (−) or increase (+)
Total coliforms					
12–13 Jul 2007	0721–1321	8.93E + 13	3.71E + 13	2.41	−58.45
12–13 Jul 2007	1351–2416	3.29E + 12	2.94E + 13	0.11	793.62
3-Aug-07	0751–1825	1.57E + 14	6.43E + 13	2.44	−59.04
2–3 Aug-2007	1825–0600	1.05E + 14	1.21E + 14	0.87	15.24
E. coli					
12–13 Jul 2007	0721–1321	2.82E + 11	7.08E + 10	3.98	−74.89
12–13 Jul 2007	1351–2416	6.17E + 10	2.31E + 11	0.27	274.39
3-Aug-07	0751–1825	2.64E + 12	2.57E + 11	10.27	−90.27
2–3 Aug-2007	1825–0600	8.76E + 11	8.76E + 11	1	0
Enterococci					
12–13 Jul 2007	0721–1321	1.50E + 12	1.16E + 11	12.93	−92.27
12–13 Jul 2007	1351–2416	6.26E + 10	5.86E + 11	0.11	836.1
3-Aug-07	0751–1825	1.35E + 13	6.23E + 10	216.69	−99.54
2–3 Aug-2007	1825–0600	4.80E + 11	7.15E + 11	0.67	48.96

During this study, some of the greatest FIB concentrations were measured in water flooding in from the Ballona Estuary through the tide gates at BW2 (Fig. 5, Table 5, Appendix A). Ballona Creek is a major source of FIB entering the estuary, hence the wetlands. Upstream of the tidal prism, geometric mean densities of total coliforms have been measured to range from 10^2 to 10^3 MPN/100 ml for *E. coli* and enterococci, and 10^4 for total coliforms during dry weather (Stein and Tiefenthaler, 2004; Tiefenthaler et al., 2009). Dorsey and Lindaman (2004) measured similar FIB densities in the lower reaches of the Creek for *E. coli* and enterococci during dry weather with total coliforms averaging 10^4–10^5 MPN/100 ml. During this study, FIB concentrations in Ballona Estuary generally was an order of magnitude greater than those found in the wetlands (Appendix A), following similar trends with mean concentrations ranging from 10^2 to 10^4 MPN/100 ml for total coliforms, and 10^1 to 10^3 MPN/100 ml for both *E. coli* and enterococci.

Once FIB-contaminated water entered the wetland tidal channels, densities of FIB diminished by up to two orders of magnitude over a period of several daylight hours, presumably due to sunlight and other processes. This variability demonstrates rapidly changing FIB densities associated with tides and time of day. Grant et al. (2001) found similar enterococci variability in the Talbert Marsh saltwater system at Huntington Beach, California. Working in the same locality, Boehm et al. (2002) measured similar variability along the open ocean beach at Huntington Beach where the surf zone was impacted by runoff from various sources. Boehm's group found FIB to vary over time scales ranging from minutes to hours depending on tidal and daylight conditions.

This short-term variability emphasizes how a single grab sample taken at a monitoring locality would potentially provide misleading information on whether or not water meets standards for recreational contact (e.g. swimming, surfing). Water quality monitoring of FIB by public health and other agencies typically is done by acquiring a single grab sample, usually at the same time of the day, with results available 18–24 h later. Boehm et al. (2002) stress that this strategy is flawed given how FIB can vary over short time periods resulting from changing environmental conditions, and that a more effective strategy would be to obtain the geometric mean from a series of sample collected over a longer period, such as a week. This approach would enable beach managers to judge water quality based on 30-day standards while still being able to respond to spikes in FIB concentrations measured from instantaneous samples.

4.2. *The Ballona Wetlands as both source and sink for FIB*

It appeared that densities of the FIB groups diminished throughout the daylight hours (Table 5), although the poor correlation between FIB and light intensity (Table 3) suggests that the relationship between light and FIB densities is complex. Sunlight has been demonstrated to be a prime factor in reducing FIB densities within wetland and other water systems. Boehm et al. (2002) measured a one- to two-order log reduction of enterococci and *E. coli* in mesocosm experiments exposing unseeded FIB-contaminated water from an open coastal beach to sunlight. Other studies have demonstrated the ability of sunlight to destroy FIB within experimental mesocosms (Noble et al., 2004), treatment wetlands (Jillson et al., 2001; Karathanasis et al., 2003; Mayo, 2004; Vymazal, 2005) and ponded treatment systems (Stinton et al., 2002; Whitman et al., 2008). Photochemically produced oxidants from the reaction of sunlight with organic matter appear to be the active agents that destroy bacteria (Chamberlin and Mitchell, 1978).

Data presented herein suggest that various FIB reduction processes are at play within the Wetlands, and that effects of sunlight may interact with tidal flows and turbidity. Other FIB reduction processes likely include settling onto submerged plant surfaces (e.g. Karathanasis et al., 2003) and predation by protozoans (e.g. Surbeck et al., 2010). Further studies are needed to develop a model of FIB reduction and input pathways, similar to the box-model approach used by Shellenbarger et al. (2008) in modeling the FIB dynamics in ponds and sloughs bird habitats.

The wetlands also acted as a source of FIB to the adjacent estuary as evident by the total load ratios during late afternoon (2:00 PM on) through nighttime hours (Table 5). Increased loads leaving the wetlands probably were associated with spikes in turbidity during swifter spring tide ebb flows when sediments harboring FIB were resuspended. During spring tide ebb flows, water depth in the tidal channel at BW2 was only about 10–15 cm. Therefore, it is possible that the lens of contaminated brackish surface water would add more bacteria to the FIB associated with resuspended sediments. Although FIB concentrations during the spikes were one to two orders of magnitude lower compared with night and early morning flood flows (Appendix A), the greater flow rate of water moving out of the wetlands resulted in higher loading estimates. At nearby Del Rey Lagoon, a similar association was found where concentrations of FIB correlated with increased turbidity during strong ebb flows (Dorsey et al., 2008).

Resuspended sediments have proven to be a source of sediment-dwelling FIB. For example, Ferguson et al. (2005) showed that densities of enterococci were much greater in sediments impacted by contaminated runoff, indicating retention and growth. Similarly, FIB were found to be two to four times more concentrated in intertidal sediments impacted by sewage effluents than densities measured in the overlying water column (Shiaris et al., 1987). Evanson and Ambrose (2006) found that within a wetland system adjacent the Santa Ana River mouth (California), the sediment-associated FIB populations may be distinct from those in the overlying water column based on the ratio of Total Coliforms: *E. coli* (TC:EC). Sediment populations generally had ratios >10 compared to overlying water where TC:EC ratios were <10, suggesting possible human fecal contamination (Haile et al., 1999). Based on this ratio, resuspended sediments from this wetland were determined not to impact the adjacent coastal beach using this ratio. Rather, water quality along the beach was impacted by discharge from the Santa Ana River (Evanson and Ambrose, 2006). Within the Ballona Wetlands, additional studies like that of Evanson and Ambrose (2006) would be required to conclusively determine if increased FIB during ebb flows is caused by resuspended sediments.

A key question here is if FIB outwelling from the Ballona Wetlands could impact the adjacent surf zones along Playa Del Rey to the south, and Venice Beach to the north, similar to the situation described at Huntington Beach by Grant et al. (2001). This scenario is unlikely because the concentrations of FIB within the estuary tend to be greater relative to those outwelling from the wetlands (Table 4), even during strong ebb flows when the wetlands contributed their greatest loads of FIB (Fig. 5, Table 5). In essence, water exiting the wetland may act to dilute the more FIB-contaminated estuary water, thus reducing potential contamination of adjacent coastal beaches.

4.3. *Implications for wetland restoration*

Presently, tidal channels within the main Ballona Wetlands encompass approximately 3.2% of the area. Restoration planning, now underway by the California Coastal Conservancy, calls for increasing the number of tidal channels. To date, three options have been developed of increasing in complexity and area covered by tidal or open water (http://www.ballonarestoration.org). Increasing the tidal channels along with surface area of flooded banks will greatly increase FIB reduction. Channels should be designed to maximize flooding during high tides by grading channels to have gentle slopes of 5:1 or more. Gentler slopes also will create more intertidal area, thus increasing extent of plants and biodiversity of infauna and bird and fish predators.

Increasing the extent of tidal channels comes with a tradeoff – increased FIB entering the estuary during spring tide ebb flows associated with resuspended sediments. Therefore, channels should be designed to reduce flow velocity, thus minimizing re-suspension. Further, increasing the extent of intertidal areas will increase diversity and abundance of birds, especially waders and shorebirds that have proven to be a significant source of FIB (Ricca and Cooney, 1998; Alderisio and DeLuca, 1999).

We predict that this balance of FIB sink vs. source may shift to that of the wetlands acting primarily as a sink particularly as concentrations of FIB diminish in Ballona Creek and Estuary due to pollution abatement measures. A Total Maximum Daily Load (TMDL) to control levels of FIB in Ballona Creek and Estuary was adopted by the California State Water Resources Control Board and the U.S. Environmental Protection Agency in 2007 (http://www.waterboards.ca.gov/losangeles/water_issues/programs/tmdl/tmdl_list.shtml).

This TMDL establishes the maximum limit of FIB that can be discharged into these waters during dry weather without requiring corrective measures. Control measures will be implemented over about a 13–14 yr period via the Municipal Stormwater NPDES permit issued to the County of Los Angeles and co-permittee cities within the Ballona Watershed. Water quality within the Creek should improve as control measures are adopted, resulting in less contaminated water flowing into the adjacent wetlands. As the pressure from contaminated runoff diminishes, we would expect that the natural disinfection processes within the wetland would shift it into a predominantly "sink" mode. This situation would be similar to conditions Jeong et al. (2008) documented for the Talbert Marsh as urban runoff was increasingly rerouted from the wetland into the sanitary sewers via low-flow diversion structures.

An important ecosystem service of wetlands is maintaining good water quality, usually by removal of organic matter by settling (Gopal, 1999) and nutrient by macrophytes (Zedler and Kercher, 2005). Increasing wetland biodiversity through restoration actions has been shown to increase ecosystem services (Benayas et al., 2009) like water quality. In southern California, more natural salt marsh wetlands, or at least those receiving limited urban runoff, have been shown to retain FIB more often than acting as a source. Examples include wetlands adjacent the Santa Ana River (Jeong et al., 2008), the Carpinteria salt marsh (Ambrose, unpublished data), and the Bolsa Chica Wetlands (Moore, 2007). Therefore, restoration of urban salt marsh systems will have many benefits as ecosystem services are regained, of which water quality ranks high.

5. Conclusions

1. After two 24-h sampling events, densities of FIB varied up to three orders of magnitude over a tidal cycle.
2. These bacteria mainly are introduced into the wetland via contaminated water from the adjacent Ballona Creek.
3. During daytime, the total load of bacteria is significantly reduced, most likely by sunlight and other processes, resulting in a sink.
4. Sediment resuspension during stronger tidal flows may reintroduce FIB into the water column, or these bacteria could be enriched within the tidal channel water.
5. During stronger ebb flows, the wetlands tend to be a source of FIB entering the estuary, but because their concentrations of FIB are lower relative to those in the estuary, wetland flows can dilute the more contaminated receiving waters of the estuary.
6. By better understanding these processes, we may predict the potential outcome as more water is introduced into the wetlands through restoration projects.
7. We would anticipate that as pollution control measures are adopted within the watershed to reduce FIB contamination, the wetlands would shift primarily into a sink-mode rather than seesawing between sink- and source-mode, as they appear to do so now.

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Appendix A. Summary of FIB densities (MPN/100 ml) collected during the 24-h surveys in the Ballona Wetlands (BW2) and Estuary (BE), 2007. For each collection time, $n = 3$.

			Total coliforms		*E. coli*		Enterococci	
Date	Station	Time	Mean	S.D.	Mean	S.D.	Mean	S.D.
12-Jul-07	BW2	4:45 AM	12230.7	4668.8	1205.0	1536.6	86.3	69.2
12-Jul-07	BW2	5:51 AM	>24192.0	0.0	246.3	25.5	1074.3	186.2
12-Jul-07	BC	"	24196.0	0.0	430.0	110.0	1155.7	51.6
12-Jul-07	BW2	7:22 AM	>24192.0	0.0	89.7	35.2	264.0	73.4
12-Jul-07	BW2	8:58 AM	14119.7	2820.8	44.3	5.8	241.3	92.3
12-Jul-07	BW2	10:27 AM	8258.3	1355.8	16.7	11.5	37.3	15.8
12-Jul-07	BC	"	>24196.0	0.0	59.7	13.3	143.7	54.4
12-Jul-07	BW2	11:58 AM	10953.3	425.5	<10	0.0	13.3	5.8
12-Jul-07	BW2	1:28 PM	1461.3	330.6	<10	0.0	<10	0.0
12-Jul-07	BW2	2:58 PM	1028.3	265.2	<10	0.0	<10	0.0
12-Jul-07	BC	"	1860.7	259.2	10.0	0.0	16.7	11.5
12-Jul-07	BW2	4:30 PM	407.0	128.3	13.3	5.8	13.3	5.8
12-Jul-07	BW2	6:05 PM	388.3	191.8	16.7	11.5	<10	0.0
12-Jul-07	BW2	7:30 PM	503.3	161.8	13.3	5.8	<10	0.0
12-Jul-07	BC	"	123.0	69.9	10.0	0.0	10.0	0.0
12-Jul-07	BW2	8:57 PM	887.7	95.1	16.7	5.8	30.0	10.0
12-Jul-07	BW2	10:31 PM	2354.7	1039.6	10.0	0.0	20.3	17.9
12-Jul-07	BW2	12:00 AM	7119.0	8844.3	55.7	35.4	178.7	48.5
12-Jul-07	BC	"	>24196.0	0.0	466.0	234.6	1721.3	1025.8
13-Jul-07	BW2	1:30 AM	2326.7	1491.8	20.0	17.3	34.0	6.1
13-Jul-07	BW2	3:58 AM	5145.0	3868.5	<10	0.0	16.7	5.8
13-Jul-07	BW2	4:20 AM	3378.0	1050.4	<10	0.0	20.3	17.9
12-Jul-07	BC	"	>24196.0	0.0	127.0	37.6	392.0	112.6
2-Aug-07	BW2	6:00 AM	827.7	302.2	<10	0.0	59.0	6.1
2-Aug-07	BW2	7:30 AM	>24192.0	0.0	334.7	385.7	7094.0	2772.0
2-Aug-07	BC	"	>24192.0	0.0	1958.3	75.8	1958.3	75.8
2-Aug-07	BW2	9:00 AM	>24192.0	0.0	523.7	140.9	783.3	183.9
2-Aug-07	BW2	10:30 AM	>24192.0	0.0	358.0	24.6	6045.3	729.2
2-Aug-07	BW2	12:00 PM	>24192.0	0.0	243.0	79.5	2161.7	1293.0
2-Aug-07	BC	"	>24192.0	0.0	119.0	43.6	119.0	43.6
2-Aug-07	BW2	1:30 PM	>24192.0	0.0	125.3	28.3	15.0	14.4
2-Aug-07	BW2	3:00 PM	5252.7	685.6	41.3	18.5	13.3	5.8
2-Aug-07	BW2	4:30 PM	10535.3	1149.5	42.3	26.8	<10	0.0
2-Aug-07	BC	"	17329.0	0.0	52.7	29.3	52.7	29.3
2-Aug-07	BW2	6:00 PM	12777.3	4003.1	27.3	6.4	16.7	11.5
2-Aug-07	BW2	7:30 PM	14820.7	2245.7	110.0	70.0	106.0	33.5
2-Aug-07	BW2	9:00 PM	21307.3	2501.7	205.0	103.9	94.0	28.0
2-Aug-07	BC	"	14686.3	1463.0	83.3	11.5	83.3	11.5
2-Aug-07	BW2	10:30 PM	12178.0	1695.7	132.0	52.6	34.0	12.1
3-Aug-07	BW2	12:00 AM	5944.3	857.4	27.0	6.1	26.7	11.5
3-Aug-07	BW2	1:30 AM	7044.3	1881.4	52.0	21.5	13.3	5.8
2-Aug-07	BC	"	34903.3	44861.1	122.0	48.0	122.0	48.0
3-Aug-07	BW2	3:00 AM	12777.3	1480.8	92.0	44.2	<10	0.0
3-Aug-07	BW2	4:30 AM	14686.0	5647.1	3727.0	6266.6	184.0	38.5
3-Aug-07	BW2	6:00 AM	18419.0	2501.1	115.7	17.6	237.0	11.5
2-Aug-07	BC	"	>24192.0	0.0	2141.7	531.9	2141.7	531.9

> = Greater than method detection limits.
< = Less than method detection limits.

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