AVALON BAY WATER QUALITY IMPROVEMENT PROJECT, CATALINA ISLAND, CALIFORNIA

A final report for the

Clean Beaches Initiative Grant

Agreement # 07-582-550-2

Submitted to the City of Avalon and the State Water Resources Control Board on 3/10/11 by

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Funded by

The City of Avalon, Los Angeles Regional Water Quality Control Board, and State of California Clean Beaches Initiative

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Summary

Background and Problem statement

The City of Avalon, located on Catalina Island, is a recreational destination for boaters, fisherman, divers, beach goers, and other ocean oriented visitors. In 1999 the County of Los Angeles began testing Avalon Bay for fecal indicator bacteria in accordance with AB 411. The test results frequently exceeded California single-sample standards for fecal indicator bacteria in coastal bathing waters, and as a result beaches in Avalon are frequently posted as unfit for swimming.

In response, a series of studies and mitigations efforts were undertaken:

a) In 2000, Ms. Alison Davis in Jed Fuhrman's laboratory at USC was hired to conduct a microbial source tracking study, to determine if there was evidence of human fecal pollution in Avalon Bay. This study, which was very small in scope, found no evidence of human viruses in Avalon Bay. Based on the results of this very limited study, the City concluded that the fecal indicator bacteria problem in Avalon Bay was due to fecal material produced by birds, in particular pigeons. Accordingly, the City focused on controlling bird populations in and around the City

b) In 2001, the City received a $500,000 grant from the State of California's Clean Beaches Initiative to further investigate the water quality problem in Avalon Bay, and pursue mitigation measures. This grant had three goals: 1) to determine the sources of fecal indicator bacteria in the Bay, 2) to conduct further microbial source tracking studies, and 3) to characterize circulation in Avalon Bay. These studies, which were carried out by Professors Stanley Grant (UCI), Burt Jones (USC), and Jed Fuhrman (USC) between September and November 2001, concluded that:

    i. Fecal indicator bacteria in Avalon Bay appear to originate from several land-side sources, including bird and animal fecal droppings, broken plumbing under wharf structures, run-off from street wash down activities, and contaminated shallow groundwater.
    ii. Within Avalon Bay, fecal indicator bacteria concentrations are highest in ankle depth water along the shoreline. Fecal indicator bacteria concentrations in the water and sediment are generally below detectable levels a very short distance (<10 m) bayward of the shoreline.
    iii. Microbial indicators of human fecal pollution (including the human-specific bacteria *Bacteroides/Provetella* and human enterovirus) were detected at several locations in Avalon Bay and in groundwater sampling pits, suggesting that human sewage may contribute to water quality impairment of Avalon Bay.
    iv. The rates of advection and turbulent diffusion within Avalon Bay (*ca*. 1 to 6 cm/s and 1 m^2/s, respectively) is sufficient to disperse contaminants introduced to the Bay within an hour or so, provided that the source of contamination is not continuous.

v. A significant fraction of the water in Avalon Bay is exchanged with the ocean over a single tide cycle.
vi. The region of the Bay impacted by the storm drain (near the beach site called “Channel”) does not appear to have a circulation problem. Within one hour, pollutants released into this area of the Bay are transported 80 to 100 m into the Bay and diluted by a factor of 100 or more.

Based on these results, the City implemented the following mitigation measures:

i) Sewer mains and manholes in the first three blocks from the waterfront were slip-lined and sealed; this effort was completed in May, 2002.
ii) Bird control measures were intensified; this ongoing effort was initiated in 2001.
iii) Plumbing under the wharfs was repaired and a regular twice per year inspection program initiated.
iv) Street wash down procedures were modified to prevent run-off.
v) Sewer laterals in the first three blocks from the waterfront were repaired and sealed; this effort was initiated in May 2005 and completed in November 2005.

Current Project Purpose, Scope, Goals, and Activities

The City was also awarded a follow-up grant from the Clean Beaches Initiative (Agreement No. 07-582-550) to support the following activities:

Task B.1.: Characterize the extent of the sewage-contaminated shallow groundwater

Task B.2.: Conduct bench-scale pilot remediation study on sewage contaminated shallow groundwater.

Task B.3.: Identify the sources of fecal indicator bacteria in ankle-depth waters.

Task B.4.: Carry out capital improvement of the sewer infrastructure in Avalon

Below is a brief summary of the main findings and accomplishments associated with the first three sub-tasks. Work carried out under the last sub-task (Task B.4.) is described in a separate report prepared by the consulting firm Robert Bien and Frost (RBF).

Task B.1. Characterize sewage-contaminated shallow groundwater

In this task a set of studies were carried out collectively aimed at characterizing fecal pollution in the shallow groundwater beneath the City of Avalon, and the exchange of shallow groundwater with Avalon Bay. Major results obtained are summarized as follows (Figure 1 is a map showing the location of field studies described below):

1. Electrical resistivity surveys--including marine electrical resistivity (MER) surveys

and electrical resistivity tomography (ERT) studies--revealed several areas of the Avalon Bay shoreline where brackish shallow groundwater is discharged to the Bay, including near the Pleasure Pier, at Busy Bee Wharf, and at Step Beach. Repeated ERT measurements at Pleasure Pier, Busy Bee, and Step Beach indicate that shallow groundwater discharge at these locations is modulated by the tides. Saline water from Avalon Bay flows into the shallow aquifer during rising tides, and brackish groundwater flows out of the shallow aquifer into Avalon Bay during ebbing tides. The resistivity surveys cannot determine the source of high resistivity (lower salinity) water in the shallow aquifer. Possible sources include meteoric water (i.e., from rainfall), infiltration of surface water, and sewage from leaking sewer lines.

2. A total of 27 shallow groundwater wells were installed in the City of Avalon. 20 of these wells were arranged in a "picket fence" along the Avalon Bay shoreline. The remaining 7 wells were installed at various inland locations, including landward of the Pleasure Pier along Catalina Avenue, and landward of Step Beach. All wells were screened between 1 and 2 m below ground surface, and surveyed to within sub-meter accuracy; well head elevations were also determined for a subset of wells. The location of the wells, relative to Avalon Bay and the sewer line infrastructure in the downtown area, is displayed in Figure 1.

3. The 27 shallow groundwater wells were sampled over a range of time scales (hours to months) and weather conditions (dry to wet). Shallow groundwater samples were assayed for salinity and the culture dependent fecal indicator bacteria (FIB) *Escherichia coli* (cEC) and enterococci bacteria (cENT). Most of the shallow groundwater samples had FIB concentrations at or below the detection limit (10 MPN/100 mL). FIB concentrations above the detection limit, and in some cases above the AB411 criteria for marine bathing waters, were measured in shallow groundwater near the Pleasure Pier, in front of Busy Bee, and at Step Beach. Salinity at these sites varied from oceanic (ca., 32) at the Pleasure Pier, to slightly fresher in front of Busy Bee (ca., 28), to brackish at Step Beach (ca., 15 to 20). The salinity of shallow groundwater also varied significantly in the cross-shore direction. For example, along Catalina Avenue the salinity of shallow groundwater increased from less than 10 to more than 30 over a horizontal distance of less than 30 m.

4. Shallow groundwater sampled from wells near Step Beach, and in front of the Busy Bee Wharf, had a number of additional characteristics consistent with sewage contamination, including: (1) elevated orthophosphate (upwards of 10 μM); (2) low dissolved oxygen (<0.2 mg/L); (3) elevated ammonia concentration (upwards of 10 μM); (3) a sulfidic smell; and (4) an unusual gray color.

5. Several advanced microbial source tracking (MST) methods were employed to determine the source of FIB in the shallow groundwater beneath the City of Avalon. 61 putative ENT isolates were cultured from inland wells. These isolates were identified to genus and species using an automated biochemical substrate utilization system. Of the 61 isolates analyzed, 46 belonged to the genus *Enterococcus*, and of the confirmed *Enterococcus* isolates 100% were identified as *E. faecium*. The fact that *E. faecium* was

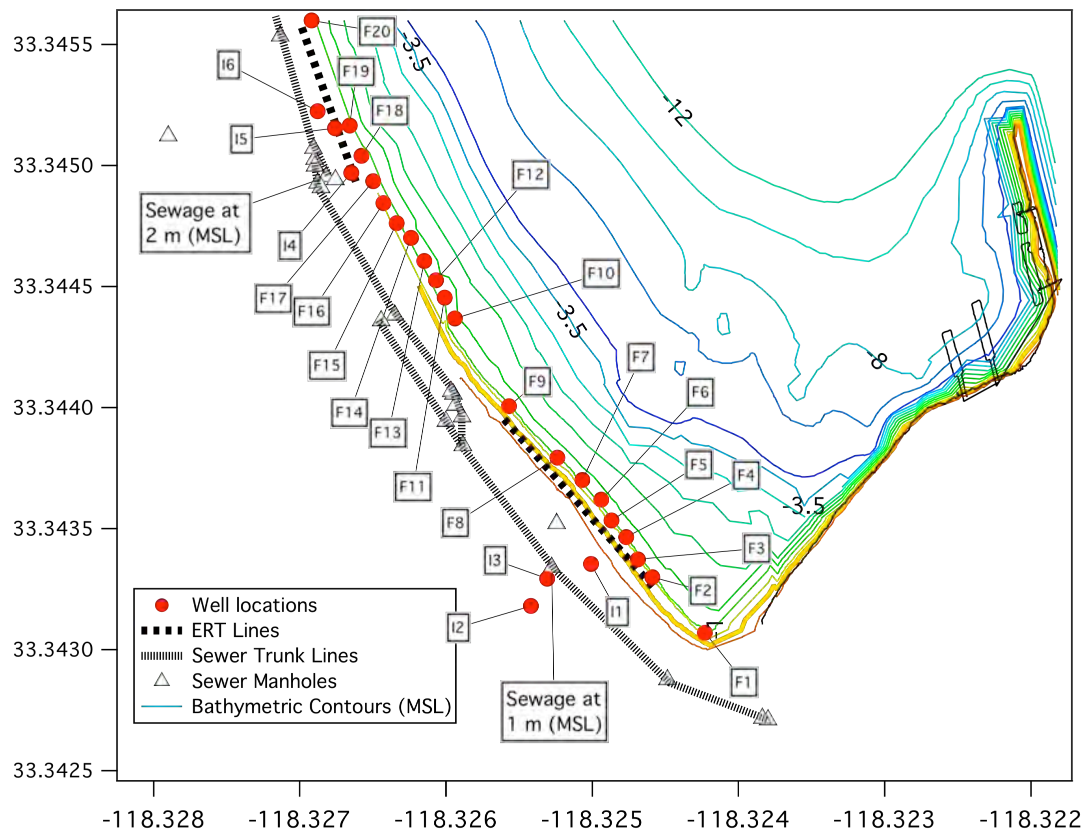

Figure 1. Map of Avalon Bay showing the location of studies carried out as part of Task B.1. Bathymetric contours of the Bay are in meters relative to mean sea level (MSL). Also shown are the elevation of the sewer trunk line at 2 locations along the waterfront

the only *Enterococcus* species isolated from the inland wells is consistent with the differential survival, or perhaps even environmental proliferation, of *E. faecium* in the shallow groundwater. Unfortunately, a relatively low number of isolates were cultured from foreshore wells, so it is not known if the low enterococci species diversity associated with inland wells also applies to shallow groundwater closer to the Bay, including wells located near Pleasure Pier, Busy Bee Wharf, and Step Beach where the shallow groundwater may be contaminated with sewage.

6. Samples collected from foreshore wells, inland wells, raw sewage, and the ocean were tested, using quantitative polymerase chain reaction (qPCR), for four groups of *Bacteroidales* spp., including universal, human-specific, dog-specific, and cow-specific; in addition, groundwater samples were tested for the bird-specific organism *Catellicoccus marimmalium*. Furthermore, all samples were divided in two and tested with and without the addition of propidium monoazide (PMA), which inhibits the qPCR amplification of nucleic acid from cells with compromised cell membranes or present extracellularly. The universal *Bacteroidales* marker, which is generally associated with fecal waste of one

form or another, was detected in all water samples collected from foreshore wells, inland wells, and the ocean. The human-specific *Bacteroidales* marker was detected in an inland well and in an ocean sample but not in foreshore wells. The dog-specific *Bacteroidales* marker, which can cross-react with both human stool samples and with sewage, was detected in all samples, but at particularly high concentrations in water collected from an inland well and the ocean. The cow-specific *Bacteroidales* marker was measured at high concentration in an inland well and in the ocean, but not in the foreshore wells. The bird-specific *Catellicoccus marimmalium* was not detected in any shallow groundwater samples. PMA results yielded conflicting information (e.g., in some cases addition of PPM lowered the qPCR signal, while in other cases it increased the qPCR signal), and consequently further studies are needed to interpret the PMA results. Collectively, these results demonstrate that *Bacteroidales* is relatively ubiquitous in the shallow groundwater beneath the City of Avalon, and point to locations near specific inland wells where further testing may be warranted.

7. Water level was monitored continuously (every 15 min.) for approximately 1 month in six foreshore wells, and four inland wells. Water levels measured in all ten wells displayed tidal and fortnightly (spring-neap) variability, although the timing and magnitude of fluctuating water levels varied in both cross-shore and along-shore directions. As expected from other studies of tidally influenced flow in unconfined aquifers, tidal fluctuations in the shallow groundwater are progressively attenuated and time delayed with increasing distance landward of the beach. Water levels measured in closely spaced wells near Step Beach exhibit significant well-to-well variability in the timing and attenuation of tidal fluctuations, suggesting that subsurface flow in that region is complex and three-dimensional.

8. Overall, these results are consistent with the hypothesis that FIB contamination along the shoreline in Avalon Bay is caused, at least in part, by the discharge of sewage-contaminated shallow groundwater into the Bay. Based on the results presented in this chapter, future mitigation efforts should focus on three areas along the Avalon Bay shoreline—Pleasure Pier, Busy Bee Wharf, and Step Beach. A number of lines of evidence indicate that shallow groundwater at these sites may be contaminated with sewage, and geophysical measurements suggest that shallow groundwater in these areas undergo significant exchange with Avalon Bay.

Task B.2.—Pilot Disinfection Studies

Activites in this task were center around pilot testing several different strategies—including chemical disinfection, permeable treatment barriers, and subsurface mobilization of fecal pollution using linear alkylbenzene sulfonates—for remediating fecally polluted shallow groundwater beneath the City of Avalon. These studies support the following conclusions:

1. A series of laboratory-scale studies were carried out to evaluate four disinfection strategies for removing sewage-associated FIB (in particular, culture-dependent measurements of enterococci bacteria (cENT) and *Escherichia coli* (cEC)) from shallow groundwater in Avalon Bay: (1) aeration alone, (2) aeration with

addition of brine, (3) aeration with addition of peracetic acid (PAA), and (4) aeration with addition of peroxymonosulfate (Oxone). The effectiveness of these different disinfection strategies was evaluated by reporting the log reduction in FIB concentration achieved after a 15 minute exposure time. A schematic of the laboratory set-up used in these experiments is shown in Figure 2.

2. Aeration alone and aeration with brine did not significantly reduce cEC and cENT concentrations in mixtures of raw sewage and shallow groundwater; i.e., no reduction in either cEC or cENT was achieved after 15 minutes of exposure.
3. Four to 5 mg/L of PAA achieved > 3 log reduction of cEC and cENT in mixtures of raw sewage and shallow groundwater after 15 minutes of exposure. The biocidal properties of PAA do not appear to be affected by the salinity of the mixture.
4. Disinfection of cEC and cENT by Oxone depends significantly on salinity; all else being equal, greater log-reduction was achieved at higher salinities.
5. In general, cENT was more resistant to disinfection by both Oxone and PAA than cEC.
6. The formation of hypohalous oxidants probably accounts for the enhanced biocidal properties of Oxone at high salinity, and implies that Oxone is likely to form toxic disinfection by products (DBPs) in marine waters.
7. Based on these results, it does not appear that Oxone would be appropriate for any application in which the disinfectant, or its DPBs, might find their way into Avalon Bay.
8. Particulate matter naturally present in shallow groundwater strongly interferes with PAA disinfection. Therefore, the turbidity of ambient waters must be factored into the design of a successful strategy for remediating sewage-contaminated shallow groundwater in Avalon.
9. For above-ground pump and treat remediation to be effective, a procedure must be developed for effectively mobilizing FIB out of sewage contaminated sediments into the pore fluids, where they can be pumped to the surface and treated. We hypothesized, based on previously published studies involving the mobilization of viruses in sewage contaminated groundwater, that injection of linear alkylbenzene sulfonates (LAS) might mobilize FIB out of sewage-

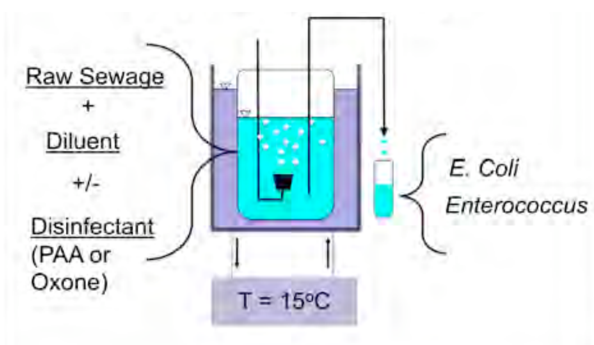

Figure 2. Schematic of the batch experiments used to evaluate the disinfection of sewage-contaminated shallow groundwater.

contaminated sediments, but that does not appear to be the case based on packed column experiments carried out with both coarse and fine-grained sediments from Avalon's main beach area. Interestingly, we found that a significant fraction (50 to 99%) of FIB in sewage contaminated groundwater were removed by passage through just 28 cm of beach sand, suggesting that the native sediments have significant filtration capacity, even when the pore fluids possess brackish salinities (15).

10. Within the resolution of the filtration set-up used here, granular activated carbon (GAC) did not remove sewage-derived FIB to any appreciable degree. While better filter media could probably be found, permeable treatment barriers are probably not a viable option in any case, given the spatially complex and temporally variable nature by which sewage contaminated shallow groundwater is exchanged with Avalon Bay.

Based on the data obtained from these pilot studies, the most promising remediation approach would appear to involve the use of the chemical disinfectant PAA, either applied directly to sewage contaminated sediments, or injected into high-risk laterals, like those that pass through foreshore sands (e.g., connecting sewage lines at the Pleasure Pier to sewer mains in the downtown area of Avalon). Pump and treat methods and permeable treatment barriers are less promising, because of unresolved difficulties associated with mobilizing FIB and pathogens out of sewage contaminated sediments, and proper placement of in situ filter media in the face of a contamination plume that is highly variable in both space and time.

Task B.3.—Source Identification of FIB in Ankle Depth Waters in Avalon Bay

The field investigations described in this task were intended to identify sources of FIB in ankle deep water in Avalon Bay, and determine how these bacteria are moblilized into shoreline waters by either "overbeach" or "through beach" transport processes. Primary findings from this effort are summarized as follows:

1. FIB concentrations in surficial sand pore fluids are consistently elevated at two locations: (A) in front and upcoast of the Busy Bee Wharf, and (B) downcoast of the Pleasure Pier. It also appears that culturable enterococci bacteria (cENT) concentrations are frequently elevated in pore fluids with brackish salinity. FIB measured in waist deep Bay waters are frequently elevated near the Busy Bee Wharf, and more rarely near the Pleasure Pier.
2. Radon-222 activity measured along the Avalon Bay shoreline lends credence to the idea that shallow groundwater is discharged into the Bay on falling tides.
3. There is additional evidence that FIB may be associated with Bay water containing elevated radon activity and depressed salinity. During one of the shoreline surveys (on 11/12/08), two locations were identified as radon "hot spots" and likely areas of significant shallow groundwater discharge during low tides: southeast of the Pleasure Pier, and near the Busy Bee Wharf.

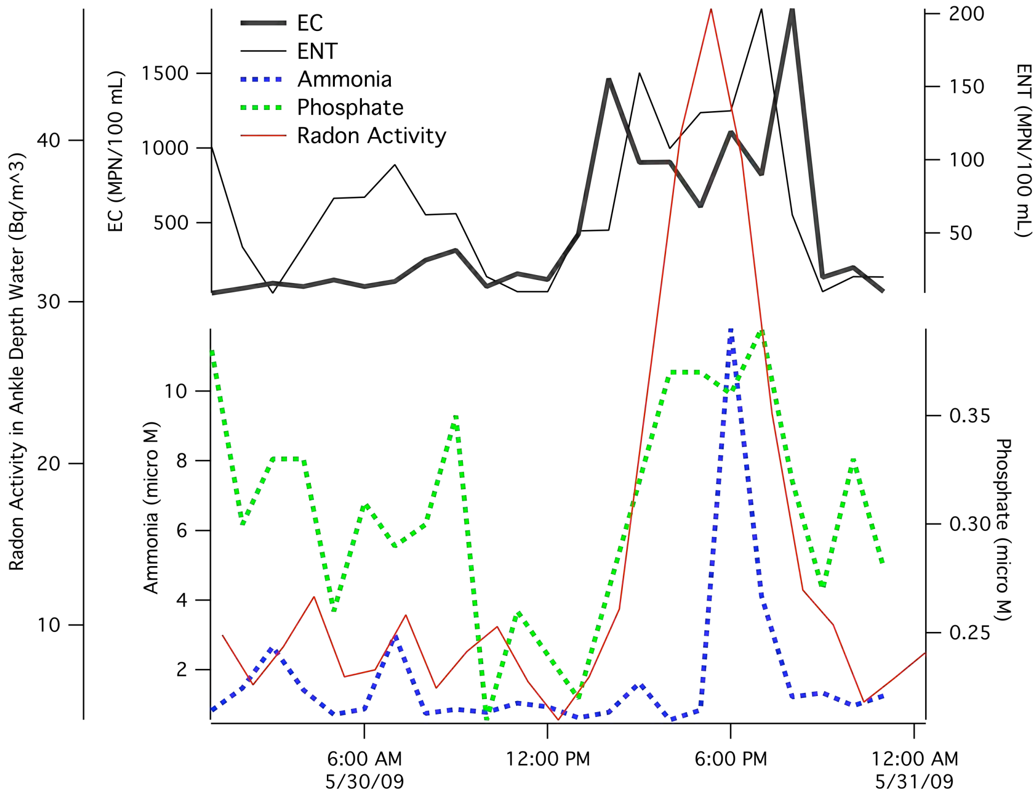

Figure 3. Comparison of Radon-222 activity, FIB concentrations, and nutrient concentrations measured in ankle deep waters at the Pleasure Pier.

4. Nearshore currents along the shoreline in Avalon Bay are dominated by boat traffic, including boats docked at the Pleasure Pier and large passenger ferries that run their reverse thrusters continuously while docked at the Mole. Nearshore currents generated from these docking activities typically manifest as westerly current pulses that last approximately 1.5 hours and have peak velocities of approximately 25 cm/s. The nearshore currents could affect FIB concentrations in ankle depth waters in several ways; e.g., by resuspending particle-associated bacteria off of the sediment bed, and by advecting clean (or polluted) water toward the main beach area. A research article describing the influence of boat currents in Avalon Bay on shoreline water quality was accepted for publication in the journal *Environmental Science and Technology*.[1]
5. Conductivity-Temperature-Depth (CTD) profiles in the nearshore region of Avalon Bay revealed little in the way of temperature, salinity, or depth stratification, as evidenced by relatively low Buoyancy Frequencies (0.013/s). There is a subtle but consistent increase in Bay water salinity during large ebb tides, suggesting that at least a portion of the shallow groundwater discharged to the Bay is hypersaline (i.e., salinity in excess of oceanic salinity).
6. Water samples were collected along a groundwater-to-ocean transect, and analyzed for nitrogen species (nitrate, nitrite, ammonia) and orthophosphate. In

[1] Ho, L.C., Litton, R.M., Grant, S.B. (2011) "Anthropogenic currents and shoreline water quality in Avalon Bay, California", *Environmental Science and Technology*, in press.

addition, samples were analyzed for the relative distribution of the ^{16}O and ^{18}O of oxygen in water. The oxygen isotope studies indicate that, to a first approximation, shallow groundwater beneath Avalon is a variable mixture of meteoric groundwater and recirculated Bay water. Street runoff was isotopically similar to ocean water, probably reflecting the fact that the domestic water supply in the City of Avalon is generated by reverse osmosis desalination. Raw sewage had an isotopic signature intermediate between ocean water and meteoric groundwater, perhaps reflecting the infiltration of meteoric groundwater into the sewage collection system.

7. The different nitrogenous species measured (nitrate, nitrite, and ammonia) were summed to yield the total dissolved inorganic nitrogen (DIN), and compared to the dissolved inorganic phosphate (DIP) as orthophosphate. Sewage, groundwater, and Avalon Bay water can be distinguished by their DIN and DIP concentrations. The DIN and DIP concentrations measured in several shallow groundwater wells (including inland well IW3 located near the Marlin Club and foreshore well W19 near Step Beach) were consistent with significant levels of sewage contamination, ranging from 1 to 20% by volume.
8. High frequency measurements of FIB, Radon-222 activity, and nutrients next to the Pleasure Pier support the hypothesis that foreshore sands and ankle depth water infuse with FIB-laden shallow groundwater as the hydraulic gradient tilts toward the Bay with the falling tide. Measurements of ammonia and orthophosphate in ankle deep water at the Pleasure Pier also increase with the falling tide (Figure 3).
9. FIB concentrations along the shoreline of Avalon Bay appear to be correlated with several environmental variables, including temperature (negative correlation), onshore wind (positively correlated), and wave period (positively correlated). These associations may reflect the influence of environmental conditions on the sourcing, fate, and transport of FIB in Avalon Bay.
10. Measurements of temperature profiles in foreshore sands reveal that, at specific times during the tidal cycle, pore fluids in the foreshore exhibit an inverse temperature gradient (i.e., colder water sits on top of warmer water) sufficient to cause the convective overturning of pore fluids. Convective turnover of foreshore pore fluids may “eject” FIB laden pore waters into the Bay.
11. Overall, these data support the hypothesis that sewage-contaminated shallow groundwater is discharged to Avalon Bay at specific locations along the shoreline—specifically Pleasure Pier, Busy Bee, and Step Beach. Furthermore, evidence is presented that the seepage face—which forms when water level in the Bay drops below the shallow groundwater table—is contaminated with sewage markers.
12. The possibility that foreshore sediments in Avalon are periodically infused with sewage-contaminated shallow groundwater raises the possibility that human-sand contact may represent a route for the transmission of fecal-oral disease at this site.

AVALON BAY WATER QUALITY IMPROVEMENT PROJECT, CATALINA ISLAND, CALIFORNIA

A final report on Shallow Groundwater Characterization
Task B.1 of the Clean Beaches Initiative Grant

Submitted to the City of Avalon and the State Water Resources Control Board on 8/24/10 by

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Summary of Task B.1 Results

This Task B.1 report describes a set of studies collectively aimed at characterizing fecal pollution in the shallow groundwater beneath the City of Avalon, and the exchange of shallow groundwater with Avalon Bay. Major results obtained are summarized as follows:

1. Electrical resistivity surveys--including marine electrical resistivity (MER) surveys and electrical resistivity tomography (ERT) studies--revealed several areas of the Avalon Bay shoreline where brackish shallow groundwater is discharged to the Bay, including near the Pleasure Pier, at Busy Bee Wharf, and at Step Beach. Repeated ERT measurements at Pleasure Pier, Busy Bee, and Step Beach indicate that shallow groundwater discharge at these locations is modulated by the tides--saline water from Avalon Bay flows into the shallow aquifer during rising tides, and brackish groundwater flows out of the shallow aquifer into Avalon Bay during ebbing tides. The resistivity surveys cannot determine the source of the lower salinity water in the shallow aquifer. Possible sources include meteoric water (i.e., from rainfall), infiltration of surface water, and sewage from leaking sewer lines.

2. A total of 27 shallow groundwater wells were installed in the City of Avalon. 20 of these wells were arranged in a "picket fence" along the Avalon Bay shoreline. The remaining 7 wells were installed at various inland locations, including landward of the Pleasure Pier along Catalina Avenue, and landward of Step Beach. All wells were screened between 1 and 2 m below ground surface, and surveyed to within sub-meter accuracy; well head elevations were also determined for a subset of wells.

3. The 27 shallow groundwater wells were sampled over a range of time scales (hours to months) and weather conditions (dry to wet). Shallow groundwater samples were assayed for salinity and the culture dependent fecal indicator bacteria (FIB) *Escherichia coli* (cEC) and enterococci bacteria (cENT). Most of the shallow groundwater samples had FIB concentrations at or below the detection limit (10 MPN/100 mL). FIB concentrations above the detection limit, and in some cases above the AB411 criteria for marine bathing waters, were measured in shallow groundwater near the Pleasure Pier, in front of Busy Bee, and at Step Beach. Salinity at these sites varied from oceanic (ca., 32) at the Pleasure Pier, to slightly fresher in front of Busy Bee (ca., 28), to brackish at Step Beach (ca., 15 to 20). The salinity of shallow groundwater also varied significantly in the cross-shore direction. For example, along Catalina Avenue the salinity of shallow groundwater increased from less than 10 to more than 30 over a horizontal distance of less than 30 m.

4. Shallow groundwater sampled from wells near Step Beach, and in front of the Busy Bee Wharf, had a number of additional characteristics consistent with sewage contamination, including: (1) elevated orthophosphate (upwards of 10 μM); (2) low

dissolved oxygen (<0.2 mg/L); (3) elevated ammonia concentration (upwards of 10 μM); (3) a sulfidic smell; and (4) an unusual gray color.

5. Several advanced microbial source tracking (MST) methods were employed to determine the source of FIB in the shallow groundwater beneath the City of Avalon. 61 putative ENT isolates were cultured from inland wells. These isolates were identified to genus and species using an automated biochemical substrate utilization system. Of the 61 isolates analyzed, 46 belonged to the genus *Enterococcus*, and of the confirmed *Enterococcus* isolates 100% were identified as *E. faecium*. The fact that *E. faecium* was the only *Enterococcus* species isolated from the inland wells is consistent with the differential survival, or perhaps even environmental proliferation, of *E. faecium* in the shallow groundwater. Unfortunately, a relatively low number of isolates were cultured from foreshore wells, so it is not known if the low enterococci species diversity associated with inland wells also applies to shallow groundwater closer to the Bay, including wells located near Pleasure Pier, Busy Bee Wharf, and Step Beach where the shallow groundwater may be contaminated with sewage.

6. Samples collected from foreshore wells, inland wells, raw sewage, and the ocean were tested, using quantitative polymerase chain reaction (qPCR), for four groups of *Bacteroidales* spp., including universal, human-specific, dog-specific, and cow-specific; in addition, groundwater samples were tested for the bird-specific organism *Catellicoccus marimmalium*. Furthermore, all samples were divided in two and tested with and without the addition of propidium monoazide (PMA), which inhibits the qPCR amplification of nucleic acid from cells with compromised cell membranes or present extracellularly. The universal *Bacteroidales* marker, which is generally associated with fecal waste of one form or another, was detected in all water samples collected from foreshore wells, inland wells, and the ocean. The human-specific *Bacteroidales* marker was detected in an inland well and in an ocean sample but not in foreshore wells. The dog-specific *Bacteroidales* marker, which can cross-react with both human stool samples and with sewage, was detected in all samples, but at particularly high concentrations in water collected from an inland well and the ocean. The cow-specific *Bacteroidales* marker was measured at high concentration in an inland well and in the ocean, but not in the foreshore wells. The bird-specific *Catellicoccus marimmalium* was not detected in any shallow groundwater samples. PMA results yielded conflicting information (e.g., in some cases addition of PPM lowered the qPCR signal, while in other cases it increased the qPCR signal), and consequently further studies are needed to interpret the PMA results. Collectively, these results demonstrate that *Bacteroidales* is relatively ubiquitous in the shallow groundwater beneath the City of Avalon, and point to locations near specific inland wells where further testing may be warranted.

7. Water level was monitored continuously (every 15 min.) for approximately 1 month in six foreshore wells, and four inland wells. Water levels measured in all ten wells displayed tidal and fortnightly (spring-neap) variability, although the timing and magnitude of fluctuating water levels varied in both cross-shore and along-shore

directions. As expected from other studies of tidally influenced flow in unconfined aquifers, tidal fluctuations in the shallow groundwater are progressively attenuated and time delayed with increasing distance landward of the beach. Indeed, an estimate of the aquifer's hydraulic conductivity—a key parameter that determines how easily water flows through a porous media—can be obtained from the slope of the time delay vs distance curve. Water levels measured in closely spaced wells near Step Beach exhibit significant well-to-well variability in the timing and attenuation of tidal fluctuations, suggesting that subsurface flow in that region is complex and three-dimensional.

8. Overall, these results are consistent with the hypothesis that FIB contamination along the shoreline in Avalon Bay is caused, at least in part, by the discharge of sewage-contaminated shallow groundwater into the Bay. Based on the results presented in this chapter, future mitigation efforts should focus on three areas along the Avalon Bay shoreline—Pleasure Pier, Busy Bee Wharf, and Step Beach. A number of lines of evidence indicate that shallow groundwater at these sites may be contaminated with sewage, and geophysical measurements suggest that shallow groundwater in these areas undergo significant exchange with Avalon Bay.

Groundwater characterization

This report describes activites collectively aimed at characterizing shallow groundwater beneath the City of Avalon. This effort was carried out under Task B.1 of the Clean Beaches Initiative (CBI) contract. For clarity, the results are organized by contract sub-task.

Task B.1.1. Prepare Draft Work Plan for groundwater characterization

A draft work plan for groundwater characterization was submitted to City of Avalon Staff and State Water Board personnel on August 15, 2008. Based on feedback, the draft plan was revised and resubmitted as a revised draft plan on September 26, 2008.

Task B.1.2. Submit Final Work Plan for groundwater characterization

Based on feedback provided in Task B.1.1., a final work plan for groundwater characterization was prepared and submitted to City of Avalon Staff and State Water Board personnel on December 12, 2008.

Task B.1.3: Install wells to monitor shallow groundwater underlying Avalon

Twenty seven (27) 2-inch diameter monitoring wells were installed along the waterfront and inland areas in the City of Avalon. Well locations were sited in consultation with City and State Board staff, and in conjunction with subsurface geophysical investigations described below, with the goal of sampling the shallow groundwater in locations most likely impacted by the City's sewage infrastructure, from the downtown area to the shoreline. The shallow groundwater wells were installed with considerable help from the City of Avalon's Public Works Department.

Task B.1.3.1: Conduct geophysical characterization of buried sewer lines and shallow water/seawater exchange

Goal and Approach. Marine Electrical Resistivity (MER) and Electrical Resistivity Tomography (ERT) surveys were carried out to identify regions of the subsurface beneath the City of Avalon where the shallow groundwater may be contaminated by leaks from buried sewer lines, and to characterize the tidal exchange of shallow groundwater with Avalon Bay. Because many water consumers in the City of Avalon use seawater to flush their toilets, influent to the City of Avalon's sewage treatment plant varies in salinity between 14 and 26 (data not shown). While the salinity of the City's raw sewage is higher than normal for most communities, it is still less than the near oceanic salinities (~35) measured in the shallow groundwater along the perimeter of Avalon Bay (see groundwater results presented later). Consequently, regions of the shallow groundwater contaminated with sewage may be characterized by anamolously low salinities, and higher than normal electrical resistivities (the resistivity of a subsurface formation increases with decreasing salinity of the pore fluid, all else being equal). It is precisely this variation in subsurface resistivity that both the MER and ERT surveys are intended to reveal.

Because the electrical resistivity of a sediment is strongly correlated with its physical properties—most notably mineralogy, grain size distribution, pore space structure, degree of saturation, and pore fluid salinity— remotely sensed variations in electrical conductivity or resistivity can be used to assess subsurface variations in sediment and pore fluid properties[1]. Electrical resistivity surveys have been used for the nondestructive assessment of sediment properties in a wide variety of applications. These range from estimating the porosity and water saturation of oil producing formations[2], to assessing the moisture, clay content and salinity of agricultural soils[3], to characterizing the subsurface structure of landfills[4], to identifying preferential pathways for water flow in the unsaturated zone[5], to characterizing the location and flow direction of groundwater pollution[6], to even locating badger burrows[7] and characterizing the size distribution of sediment micro-cracks[8]. Closer to the application of interest here, electrical resistivity surveys are used to map fresh and saline-saturated sediments[9,10], to characterize saltwater intrusion in groundwater aquifers[11], and, more recently, to study the tidal exchange of shallow groundwater with the coastal ocean[12,13, 14].

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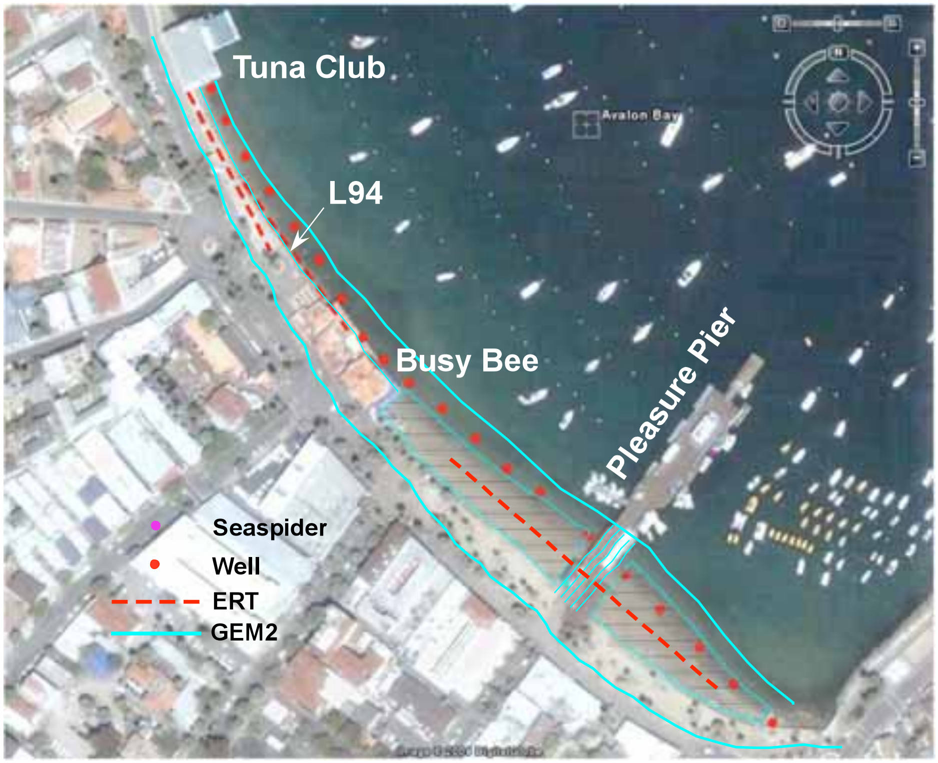

Figure 2-1. Location of Electrical Resistivity Tomography (ERT, red dashed lines) and Marine Electrical Resistivity (MER) surveys (green lines and green-hatched areas). GEM 2 refers to the instrument used in the MER surveys. Also shown are the approximate locations of shallow groundwater wells discussed later in the report.

MER Field Methods. The MER field surveys were carried out with a GEM-2 multi-frequency Broadband EMI Sensor (Geophex Ltd. Geophex Ltd., 2010). To minimize noise induced by powerline harmonics—a major ambient electromagnetic noise in urban areas—the

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into the freshwater aquifer in the eastern shore of Virginia: a reconnaissance electrical resistivity survey. *J. Appl. Geophys*. 42, 1-22; Acworth, R.I., 1999. Investigation of dryland salinity using the electrical image method. *Aust. J. Soil Res*. 37, 623-626. Yaramanci, U., 2000. Geoelectric exploration and monitoring in rock salt for the safety assessment of underground waste disposal sites. J. Appl. Geophys. 44, 181-196.

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Figure 2-2. MER survey being conducted in Avalon Bay by research assistant Jordan Monroe. In this picture, the GEM-2 sensor is deployed across the back of the zodiac.

frequencies chosen for the GEM-2 should be odd multiples of half the powerline frequency. For example, in 60-Hz areas (U.S., Canada), the first few possible frequency choices are 90, 150,210, 270 Hz corresponding to 3, 5, 7, and 9 times 30 Hz (=60Hz/2). The total transmitter energy is shared equally among all frequencies and, therefore, a reduced signal-to-noise ratio may be encountered if too many frequencies are added. The manufacturer of the GEM-2 recommends that no more than 5 frequencies be used at one time. The last factor that must be considered is the subsurface depth range of interest, because sensing the resistivity at shallower depths requires higher frequencies. Taking all of these factors into account, the following five frequencies were chosen for the MER surveys in Avalon: 3270Hz, 13170Hz, 28650Hz, 37890Hz, and 45870Hz. MER surveys were carried out along two survey lines (Fig. 2-1): (1) parallel to the strike of the beach from Tuna Club (upcoast) to Channel (downcoast); (2) parallel to the first MER line but a short distance offshore. The second survey was conducted from an inflatable zodiac, as illustrated in Fig. 2-2. Additional MER surveys were were conducted in the hatched areas, but these surveys are not described here.

ERT Field Methods. The ERT surveys were carried out using a resistivity meter (Sting R1), controller (Swift) and 28 smart electrodes manufactured by Advanced Geoscience Instruments (AGI, see http://www.agiusa.com/index.shtml). The electrodes were pushed into wet foreshore sand in a dipole-dipole array configuration that is optimal for shallow depth groundwater investigations. Each ERT survey required approximately 70 minutes to complete. With the exception of the survey on Upper Step Beach (between Tuna Club and Busy Bee Wharf, see Fig. 2-3) the electrode array was deployed on wet foreshore sands during low tides. At Upper Step Beach, the electrodes were located above the high-high tide line. As indicated in Fig. 2-1, the following ERT surveys were conducted: (1) four rounds of

Figure 2-3. ERT set-up at Upper Step Beach, between Busy Bee Wharf and Tuna Club, at the upcoast (northwest) end of Avalon Main Beach.

surveys were conducted at the Pleasure Pier site; (2) one round was conducted on Lower Step Beach; and (3) 18 rounds were conducted on the Upper Step Beach.

MER Results. The offshore MER survey yielded little subsurface information, because the GEM-1 signal was completely attenuated within the water column. The land MER survey, on the other hand, identified high resistivity (low conductivity) regions at two locations: (1) ~3 m below ground surface near the Pleasure Pier and Busy Bee Wharf, and (2) ~ 20 m below ground surface beneath the Pleasure Pier. These MER results were used to help plan the ERT surveys described next.

ERT Results: Pleasure Pier. Following the MER surveys, ERT was carried out at multiple locations along Avalon Main Beach (see Fig. 2-1 and methods above). Inversion of the ERT data collected at the Pleasure Pier yields the cross-sections of electrical resistivity displayed in Fig. 2-4. The cross-sections in this figure were collected just before (top panel) and after (bottom panel) a low-low tide on March 11 (2009). A high resistivity region is evident in both cross-sections, approximately 20 m southwest of the Pleasure Pier at a depth of approximately 3 meters. Resistivity in this region nearly doubles over the hour time difference between the first and second section (note change in scale from the top to bottom panel), consistent with the idea that the shallow groundwater in this region freshens (i.e., becomes more resistive) as the tide drops. While the downcoast feature is the most dramatic, there are several other low resistivity features that warrant mention, including: (1) a shallow feature directly below the Pleasure Pier, and (2) multiple shallow (<5 m) features upcoast of the Pleasure Pier. From the shape of the ERT images we can also infer that the

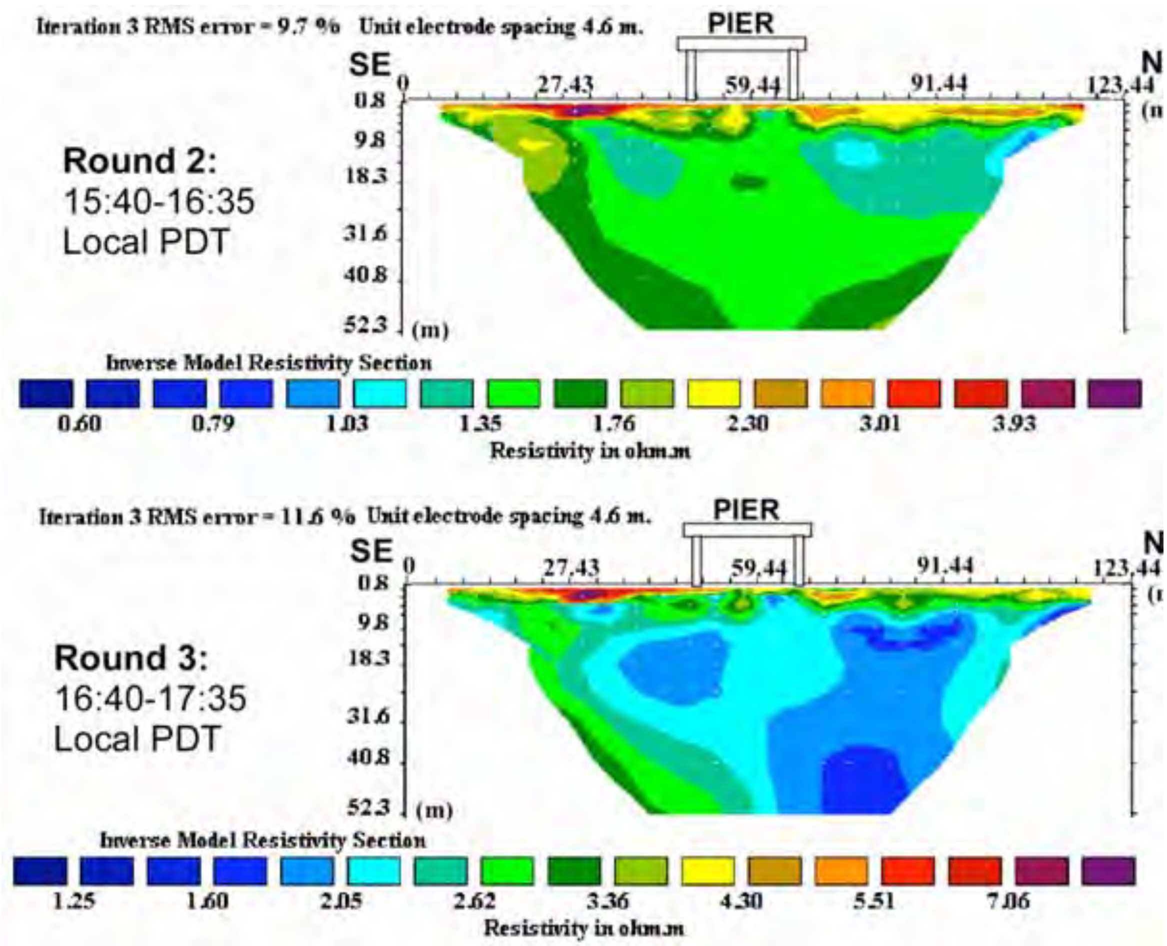

Figure 2-4. ERT cross-section of subsurface resistivity upcoast (left side of figures) and down-coast (right side of figures) of the Pleasure Pier. Rounds 2 and 3 were conducted just before and just after a low-low tide on March 11 (2009).

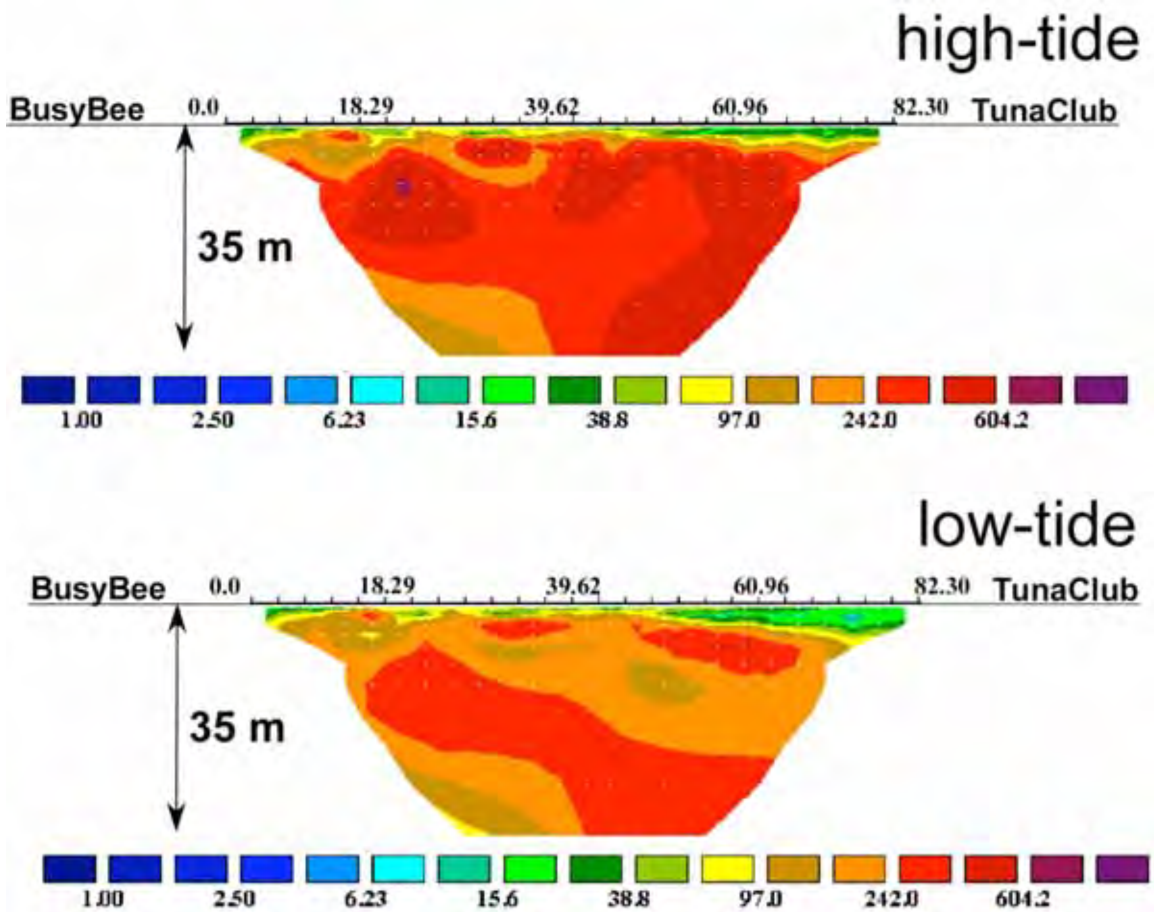

Figure 2-5. ERT cross-section of subsurface conductivity at Upper Step Beach, between Busy Bee and Tuna Club. Measurements occurred during high-high (top panel) and low-low (bottom panel) tides on March 12 (2009).

top 5 m of the subsurface near the Pleasure Pier consists of porous beach sand or other coarse fluvial material, while deeper down the lithology may be less porous (i.e., more conductive). If this is in fact the case, then the flow of shallow groundwater at the shoreline may be confined to a fairly thin (<5 m) veneer of surficial sediment. This would tend to minimize dilution of pollutants that enter the shallow groundwater (e.g., from leaking sewer lines) and maximize the exchange of shallow groundwater with the Bay—precisely the set of conditions that might make a coastal embayment highly vulnerable to pollution from sewage contaminated shallow groundwater.

ERT Results: Busy Bee to Tuna Club. ERT data collected at Upper Step Beach, along a line from the Busy Bee to Tuna Club, were inverted to yield the cross-sections of electrical resistivity displayed in Fig. 2-5. These cross-sections were collected at a high-high (top panel) and low-low (bottom panel) tide on March 12 (2009). A prominent low-conductivity (high resisitivity) feature is evident on the upcoast (northwest) side of Step Beach near the Tuna Club. This feature becomes substantially less conductive (more resistive) as the tide falls (compare top and bottom ERT sections in Fig. 2-5). Measurements of shallow groundwater, described later in this report, document the existence of a freshwater lens at this location, which almost certainly accounts for the low conductivity feature in the ERT sections. The 50 mS/m conductivity contour line (roughly denoted by the transition from green to yellow in Fig. 2-5) drops by approximately 2 m over the 6 hours from the high-high to low-low tide, which is roughly equivalent to the tide level change over the same period. The feature's conductivity also decreased by approximately 0.36 S/m over the 6 h, consistent with a relatively high rate of seepage into Avalon Bay at this location. Although less pronounced, there is a low conductivity feature at ~3 m below ground surface at the downcoast (southeast) side of Step Beach, near the Busy Bee Wharf.

Interpretation of Electrical Resistivity Surveys. Resistivity measurements in Avalon identified several regions where the shallow groundwater is more resistive (i.e., less conductive), including: (1) approximately 20 m downcoast of the Pleasure Pier at a depth of ~3 m; (2) Upper Step Beach near the Busy Bee Wharf at a depth of ~3 m; and (3) Upper Step Beach near Tuna Club at a depth of 3 to 5 m. These high resistivity features probably represent areas of the shallow groundwater where porewater salinities are relatively fresh, reflecting the input and mixing of water from meteoric and/or urban infrastructure such as leaking storm sewer and/or sanitary sewer systems.

Repeated ERT measurements at Pleasure Pier and Upper Step Beach suggest that tides control the exchange of salt (and presumably other mass, including pollutants) between shallow groundwater and Avalon Bay. The ERT surveys reveal a complex and heterogenous subsurface environment, in which resitivity anamolies tend to be highly localized in space, and variable in time. These data also suggest that shallow groundwater flow may be confined to a relatively thin veneer of highly porous sediments, which could exacerbate the impact of subsurface pollution (e.g., from leaking sewer lines) on nearshore water quality. Collectively, these geophysical data provide an excellent context within which to interpret the shallow groundwater sampling results presented next.

Task B.1.3.2: Install Shallow Groundwater Monitoring Wells

Goal and Approach. According to the Work Plan, twenty (20) shallow groundwater-monitoring wells were to be sited and installed in the downtown and main beach areas of Avalon. To minimize the cost per well and thus maximize the number of wells installed, the wells were installed by hand, using an auger and manual slide hammer. Therefore, monitoring wells could not be installed in areas underlain by hard rock, and could not extend significantly deeper than 10 feet (or 2 m) below ground surface. This is noteworthy, because many of the highly resistive features detected with the ERT were located at a depth of ~3 m below ground surface. Thus the groundwater wells installed here may have just "skimmed the surface" of these resistive features.

Methods. Monitoring wells consisted of 4 ft sections of stainless steel (SS) pipe affixed to a SS drive-point piezometer with a 12" screened bottom (Solinst Canada Ltd., Georgetown, Ontario). The wells were installed using a soil auger (AMS Inc., American Falls, ID) and manual slide hammer (Solinst Canada Ltd, Georgetown, Ontario). The length of pipe varied by well, as documented in Table 2-1. The top of each well was secured by a locking PVC enclosure. Well installation followed standard procedure for shallow groundwater wells, as described elsewhere (USGS WRI 96-4233). Wells were developed by a combination of bailing, surging, and pumping methods.

Well Construction Permits and Long-Term Disposition of Wells. Based on previous CBI sampling efforts, and consistent with the ERT data presented above, the salinity of shallow groundwater beneath Avalon varies from oceanic to brackish. The shallow groundwater wells installed in Avalon are therefore "saltwater wells" and explicitly excluded from the State of California's definition of a "water well" (Section 11.38, Title 11 L.A., California Health and Safety Code). Thus permits were not required for the construction and sampling of monitoring wells installed as part of this study. Per prior agreement with the City of Avalon, some monitoring wells were not removed at the end of the contract period.

Location and Configuration of Wells. Based on discussions with City of Avalon and State Water Board personnel, 27 sites were selected for installation of shallow groundwater wells (Fig. 2-6). Because only 20 wells were budgeted in the CBI contract, the 27 wells were installed in two different configurations as follows. In the first configuration, which lasted from January to April (2009), 20 wells were installed in a "picket fence" arrangement along the foreshore of Avalon Bay (wells labeled FW1 through FW20 in Fig. 2-6, where "FW" refers to Foreshore Well). In April (2009), six of the foreshore wells (FW1, FW2, FW6, FW7, FW8, and FW9) were removed and reinstalled at the following locations: 1) one well in upper beach at Main Beach, 2) two in planter boxes in front of the Marlin Club, 3) two at Upper Step Beach (one was filled with sand by kids, and thus could not be sampled); 4) in the lawn directly inland of Step Beach, near the pathway to the Casino; and 5) behind City Hall (although this well, which was screened at 13' below surface, is not deep enough to sample groundwater). Inland wells are indicated with the prefix "I". Information on the

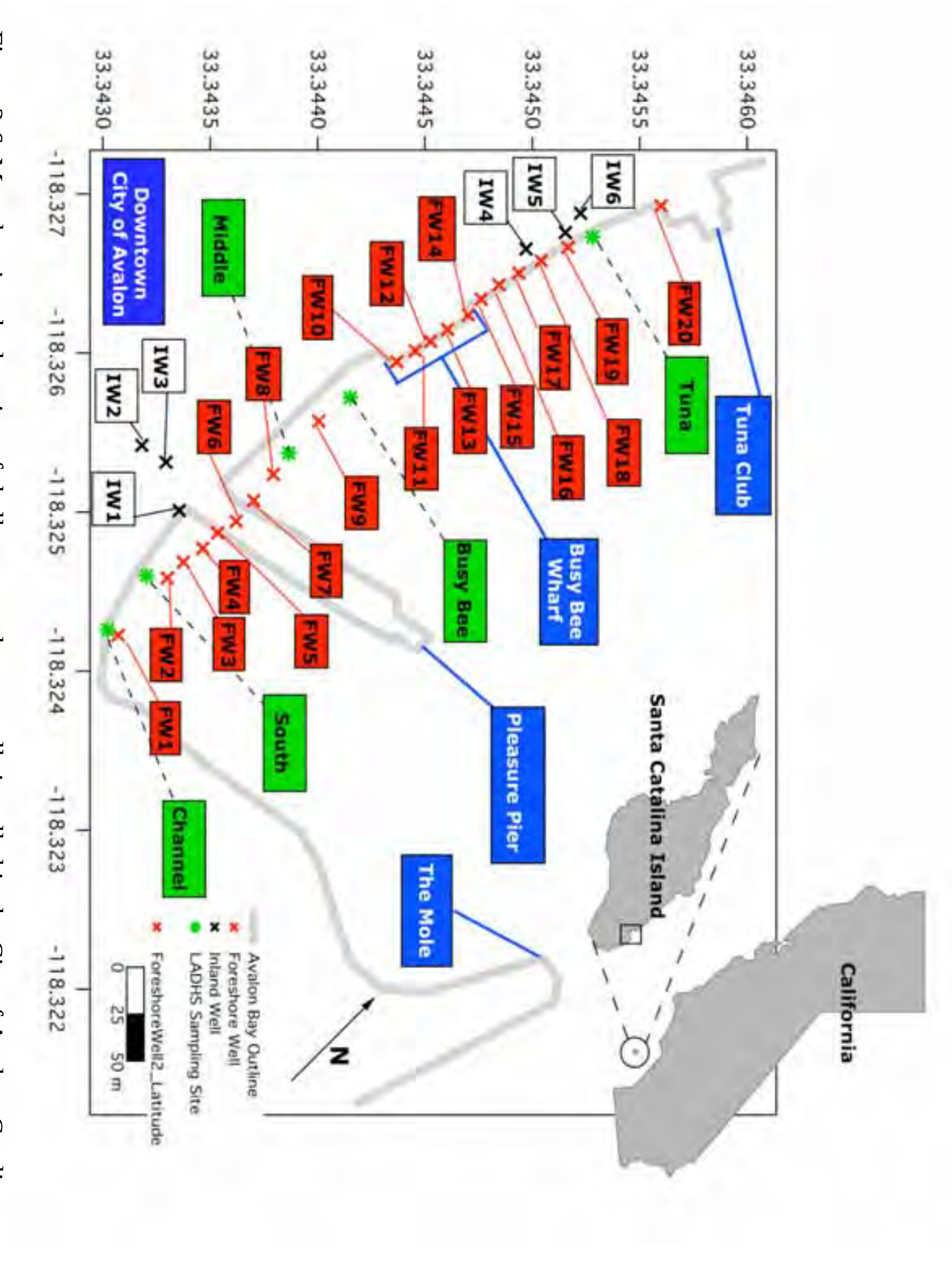

Figure 2-6. Map showing the location of shallow groundwater wells installed in the City of Avalon, Catalina Island, California.

Table 2-1: Features of shallow groundwater monitoring wells.

Well Name	Well Type	Long.	Lat.	Elev. well head (m, MSL)	Length of Pipe (m)			Elev. of screen (m, MSL)
					Total	Above Ground	Below ground	
FW1	F	-118.32423	33.343071	N/D	2.8			
FW2	F	-118.32459	33.343300	N/D	2.8			
FW3	F	-118.32469	33.343374	3.15	2.8	1.9	0.9	0.35
FW4	F	-118.32477	33.343465	3.06	2.8	1.9	0.9	0.26
FW5	F	-118.32487	33.343535	3.06	2.8	1.8	1.0	0.26
FW6	F	-118.32494	33.343621	N/D	2.8			N/D
FW7	F	-118.32507	33.343702	N/D	2.8			N/D
FW8	F	-118.32524	33.343794	N/D	2.8			N/D
FW9	F	-118.32557	33.344006	N/D	2.8			N/D
FW10	F	-118.32594	33.344368	N/D	2.8			N/D
FW11	F	-118.32601	33.344455	2.46	2.8			-0.34
FW12	F	-118.32607	33.344527	2.18	2.8			-0.62
FW13	F	-118.32615	33.344606	2.34	2.8			-0.46
FW14	F	-118.32624	33.344701	2.28	2.8			-0.52
FW15	F	-118.32634	33.344762	2.66	2.8	1.7	1.1	-0.14
FW16	F	-118.32643	33.344845	2.64	2.8	1.6	1.2	-0.16
FW17	F	-118.32650	33.344936	2.70	2.8	1.7	1.1	-0.10
FW18	F	-118.32658	33.345041	2.74	2.8	1.7	1.1	-0.06
FW19	F	-118.32666	33.345166	2.64	2.8	1.8	1	-0.16
FW20	F	-118.32692	33.345600	2.69	2.8	1.8	1	-0.11
IW1	I	-118.32501	33.343355	4.32	4.1			0.22
IW2	I	-118.32531	33.343294	4.74	4.1	0.55		0.64
IW3	I	-118.32542	33.343182	4.84	4.1	0.69		0.74
IW4	I	-118.32665	33.344970	4.90	4.1			0.80
IW5	I	-118.32676	33.345154	4.78	4.1			0.68
IW6	I	-118.32688	33.345225	5.00	4.1	0.16		0.90
IW7	I	-118.32818	33.34021	N/D	4.1			N/D

wells, including their latitude and longitude, elevation above mean sea level, depth below ground surface, and elevation of the screen, are provided in Table 2-1.

Task B.1.3.3: Characterization of Sediment and Well Tailings

Approach. Subsurface sediments in the foreshore area of Avalon were collected near each of the 20 foreshore wells, and separately analyzed for grain size distribution, percent organic content based on loss on ignition (LOI), and porosity. Small trenches were dug near each well, and approximately 5 L of sediment was collected from each trench at approximately 0.3 m below ground surface. While the original study plan called for collecting well tailings (instead of sediment from a trench), the former approach proved infeasible because of the small volume of well tailings produced by each well. Sediment samples were transported back to UCI where they were dry sieved (using sieve sizes 1 inch, 0.5 inch, No. 4, No. 10, No. 16, No. 35, No. 60, and No. 120) and assayed for porosity and % organic content by LOI.

Results: Mineralogy. Reflecting the granitic nature of the parent rocks surrounding the City of Avalon, sediment collected from the foreshore area consisted mostly of quartz-rich sand. Examination of sediment grains by optical microscopy did not reveal the presence of oxide coatings, and therefore further characterization of the grain surfaces (e.g., by SEM-EDX) was not carried out.

Results: Sieving. Grain size distribution data are plotted in Fig. 2-7. The median grain size varied over a relatively narrow range of values, from 3 to 8 mm. Sediments collected from south (downcoast) of the Pleasure Pier (foreshore wells 1-5) were generally more fine-grained than sediments collected north (upcoast) of the Pleasure Pier (foreshore wells 6-20). The upper quartile (75^{th} percentile) grain size exhibited greater variability, from 5 mm to >2.5 cm, reflecting significant sample-to-sample differences in the largest grain sizes present. In general, the largest grain sizes tended to be larger in sediment samples collected north (upcoast) of the Pleasure Pier, and smaller in sediment samples collected south (downcoast) of the Pleasure Pier.

Percent Organic Content (LOI) Results. The organic content was relatively low (< 1.6%) in all sediment samples. Sediment collected in front, and to the north (upcoast), of the Busy Bee Wharf (Wells 11, 13, and 16) may have higher organic content (Fig. 2-8).

Porosity Results. Porosity of sediment collected from the Avalon Bay foreshore varied from a low of 0.21 to a high of 0.32, and averaged 0.27 +/- 0.032. As indicated in Fig. 2-9, there are no obvious alongshore trends in measured porosity.

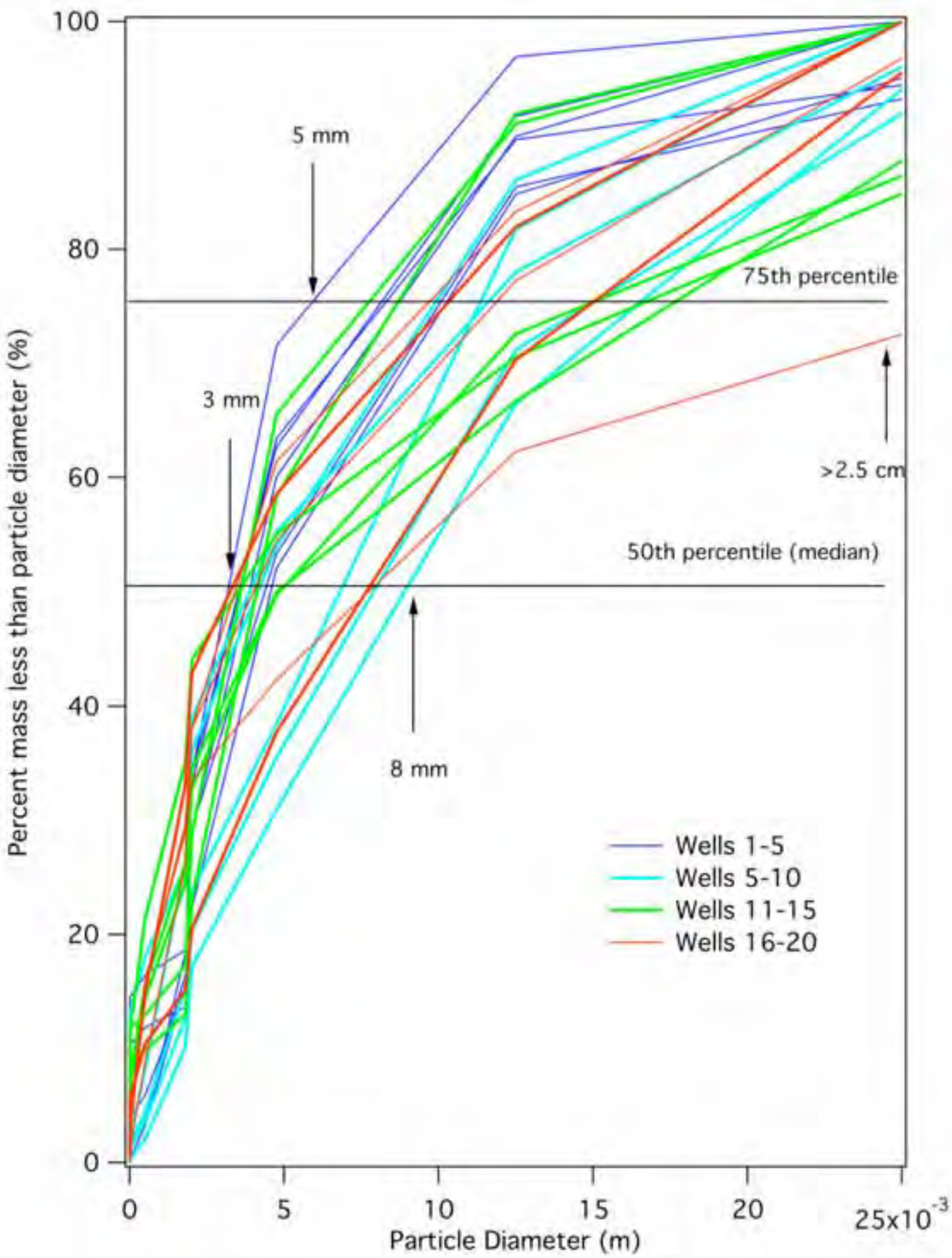

Figure 2-7. Sieve analysis measurments on sediment samples collected from the 20 foreshore sites (plus two duplicates) indicated.

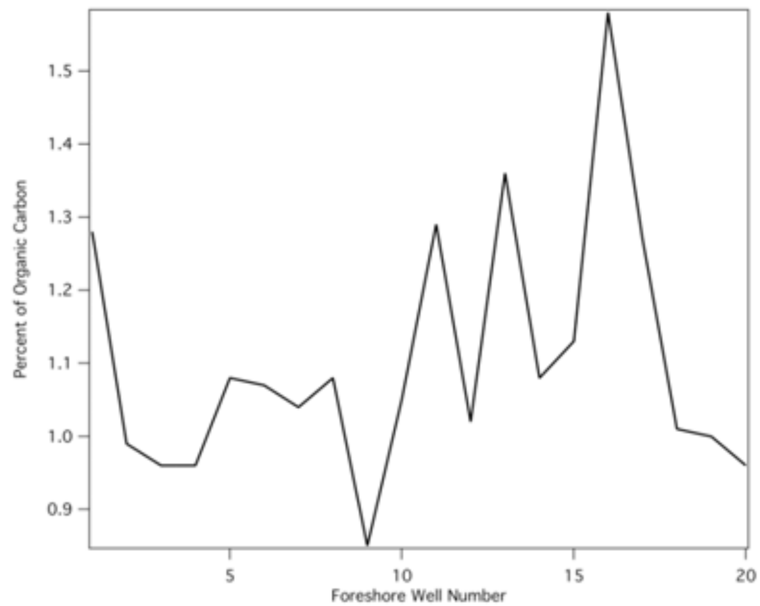

Figure 2-8. Organic content (%) measured on foreshore sediment samples using the Loss on Ignition method.

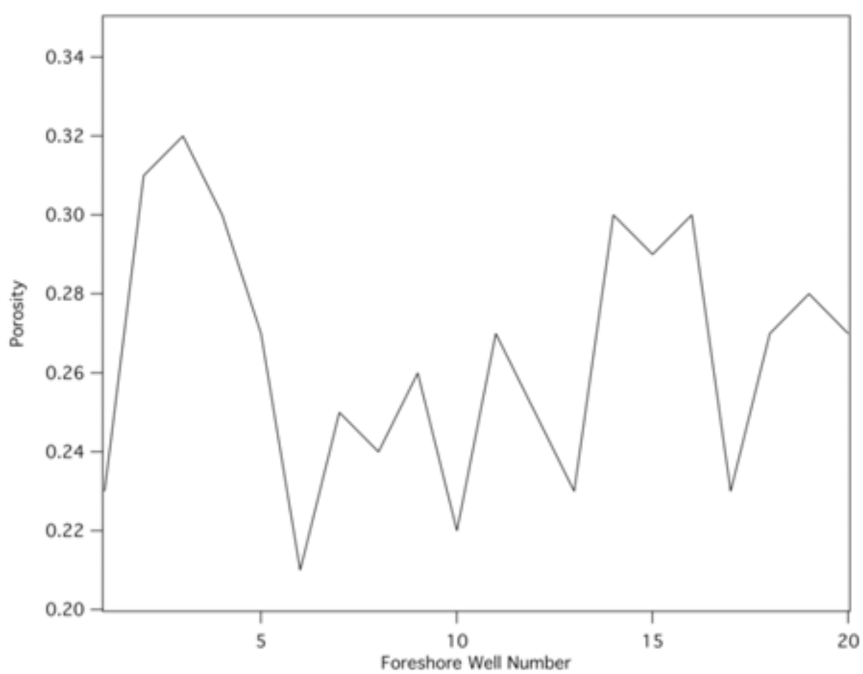

Figure 2-9. Measured porosity of sediment collected from the foreshore area of Avalon Bay.

Task B.1.4.1: Sample Monitoring Wells for FIB

Shallow groundwater was sampled and tested in three phases, as described below.

Phase I Foreshore Sampling: Approach. During the first phase of sampling, which occurred from January 14 to February 22 (2009), shallow groundwater samples were collected from the 20 foreshore wells four separate times, all during low-low tides. The Work Plan called for sampling the wells twice during a high-high tide and twice during a low-low tide. However, high-high tide sampling proved impractical because, during high tides, many foreshore wells were completely submerged beneath the Bay or otherwise inaccessible. Shallow groundwater samples were transported on ice to the temporary laboratory in Avalon City Hall where they were analyzed, using culture-dependent methods, for the FIB *Escherichia coli* (cEC) and enterococci bacteria (cENT) using the same procedure utilized by Los Angeles County for their routine monitoring of the Avalon coastline; namely, IDEXX Colilert-18 and Enterolert tests, respectively, implemented in a 97 well quantitray format. All samples were also analyzed for water temperature (at the time of collection) and salinity (at the City Hall laboratory). The work plan called for screening a subset of samples with ammonia- and nitrate-specific electrodes. However, despite manufacturer's claim to the contrary, the near oceanic salinity of the groundwater samples precluded accurate electrode measurements of nitrate and ammonia. Therefore, an additional sampling effort was carried out in which shallow groundwater samples were collected and analyzed by the UCSB Marine Science Institute Analytical Laboratory for nitrate, nitrite, ammonia, and orthophosphate. A subset of samples were analyzed for dissolved organic carbon (DOC) by TestAmerica (Irvine, CA). Dissolved oxygen was measured with a downhole probe.

Phase I Foreshore Sampling: Results. Measurements on shallow groundwater collected from the foreshore wells during five rounds of Phase I sampling are plotted in Fig. 2-10. FIB concentrations in shallow groundwater were above the detection limit (10 MPN/100 mL) at two locations: (1) downcoast of the Pleasure Pier (foreshore wells FW3 through FW5); and (2) upcoast of the Busy Bee Wharf at Step Beach (foreshore wells FW16 through FW19). The salinity of shallow groundwater was oceanic (ca., 32) at most sites located downcoast of the Busy Bee Wharf, fresher (ca., 28 to 30) in front of Busy Bee Wharf (foreshore wells 12 through 17), and brackish (ca., 15) at Step Beach (foreshore wells 18 and 19). The wells where brackish groundwater was detected (F18 and F19) are a couple of meters bayward of the highly resisistive feature detected by the ERT (Compare Figs. 2-5 and 2-10), suggesting that our earlier interpretation of the ERT results (i.e., that these resistive features were caused by lower than normal pore water salinity) was correct. While the ERT and shallow groundwater sampling seem self-consistent at Step Beach, they are less so downcoast of the Pleasure Pier. With the exception of one sampling event (February 22, 2009), shallow groundwater collected from foreshore wells located downcoast of the Pleasure Pier (FW2, FW2, FW3, FW4, and FW5) had near oceanic salinities (~33), despite the highly resistive feature detected by the ERT at this location (compare Figs. 2-4 and 2-10). A closer inspection of the ERT sections, however, reveal that the highly resistive feature downcoast of the Pleasure Pier is characterized by closed contours (Fig. 2-11), implying that

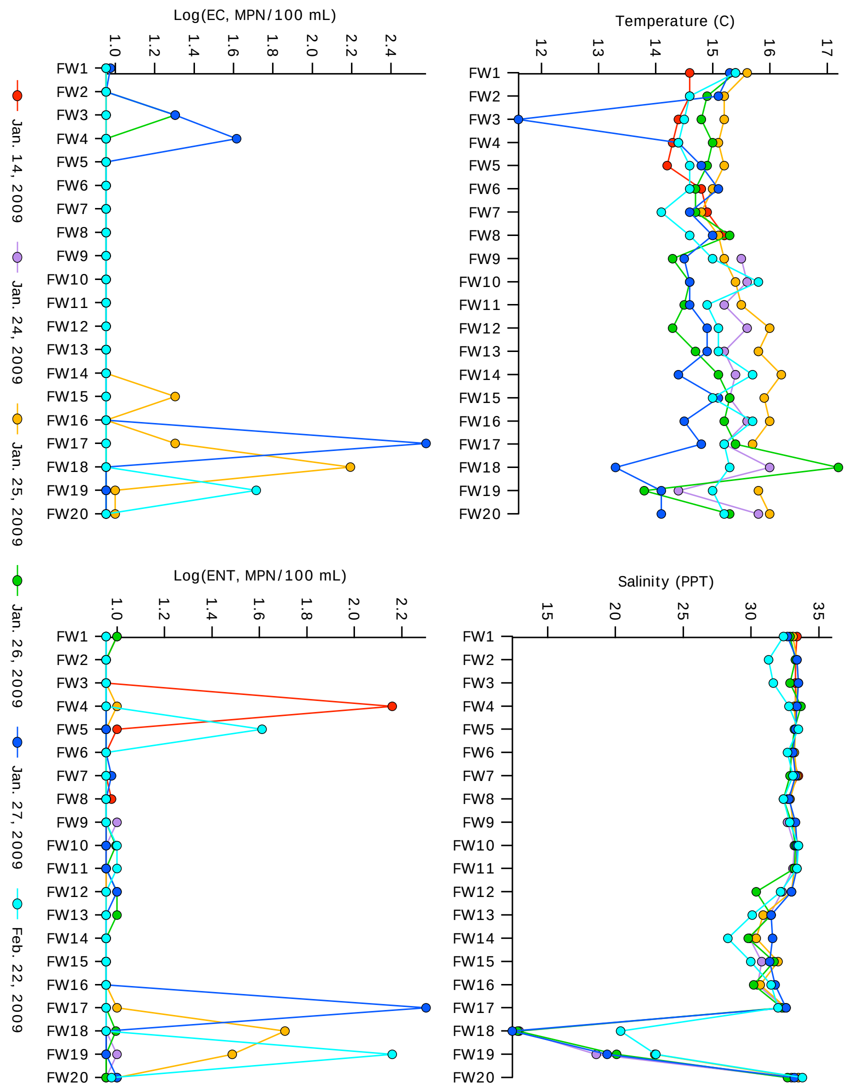

Figure 2-10. Measurements of temperature, salinity, and FIB concentrations measured on water samples collected from the 20 foreshore wells during Phase I sampling.

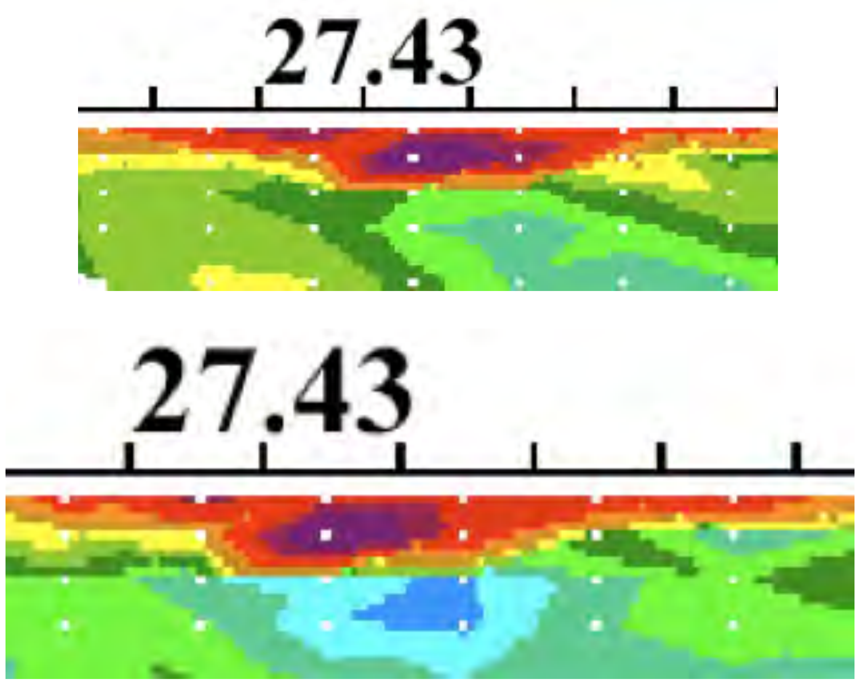

Figure 2-11. A close-up view of the highly resistive feature evident in the ERT sections collected downcoast of the Pleasure Pier. Note that the resistivity contours close (i.e., form a bullseye), suggesting that resistivity increases with depth down to about 3 m below ground surface (the second row of white dots is at 3 m bgs).

resistivity increases down to about 3 m below ground surface. Because shallow groundwater wells were screened at ~1 m belowground surface (see Table 2-1), these wells probably did not sample the highly resistive feature evident on the ERT sections. Given that Bay water quality is historically poor at this site, follow-up groundwater studies to evaluate the nature of these resisitive features would appear warranted.

Nutrient measurements on shallow groundwater are plotted in Fig. 2-12. Shallow groundwater in front of the Busy Bee Wharf (foreshore wells FW12 through FW16) is characterized by relatively high concentrations of orthophosphate (>4 µM) and ammonia (>5 µM), low concentrations of nitrite + nitrate (<1 µM), and low dissolved oxygen levels (<2 mg/L). DOC concentrations were above the detection limit in the two foreshore wells flanking Busy Bee Wharf (wells FW11 and FW17).

Phase I Inland Well Sampling: Approach. Shallow groundwater was collected from the six inland wells (IW1 through IW6) during four dates in April (2009), and analyzed for temperature, salinity, cEC, and cENT following the procedure outlined above for the foreshore wells. Sampling of the inland wells occurred exclusively during high-high tides, because many of the inland wells were dry, and thus could not be sampled, during low tide.

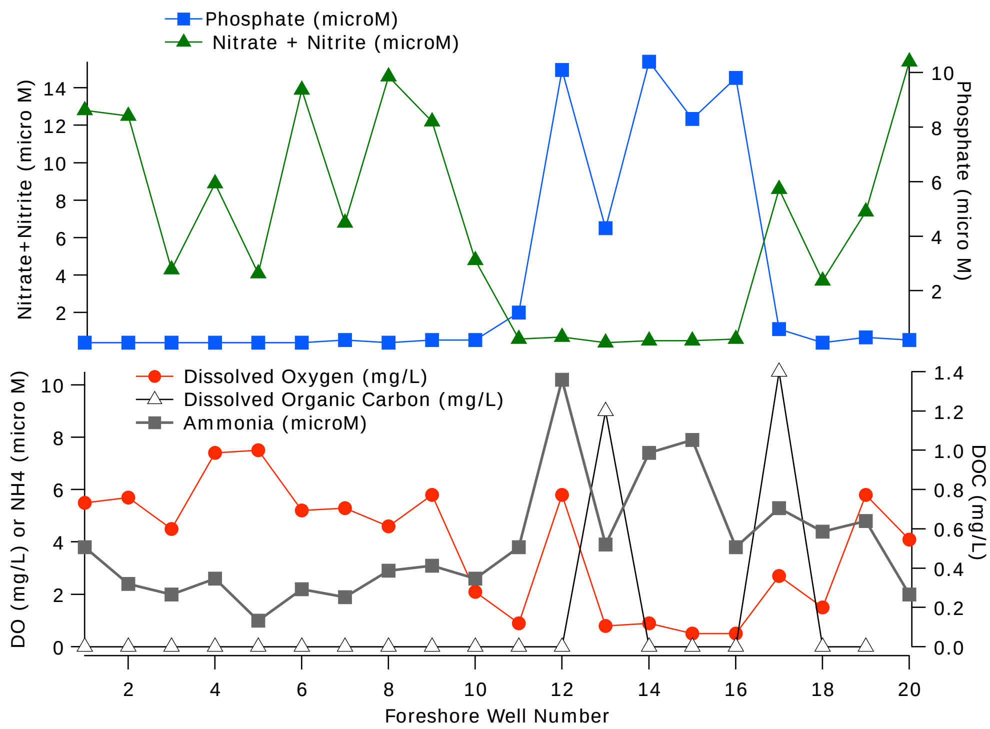

Figure 2-12. Measurements of nutrients and dissolved oxygen on water samples collected from the 20 foreshore wells during Phase I sampling.

Phase I Inland Well Sampling: Results Measurements on shallow groundwater collected from the inland wells during the four rounds of Phase I sampling are plotted in Fig. 2-13. The temperature of shallow groundwater varied between sampling events, but was relatively consistent across wells during any particular sampling event. Near the Pleasure Pier, the shallow groundwater exhibits steep cross-shore salinity gradients, from <10 (at IW2) to >30 (at IW1), a cross-shore horizontal distance of <30 m. FIB concentrations in the inland wells were, with a few exceptions, at or below detection limits (10 MPN/100 mL, or log-transformed value equal to 1).

Phase II and III Sampling: Approach Phase II and III involved intensive sampling of shallow groundwater wells located where, based on the results from the Phase I sampling, shallow groundwater was most likely to be impacted by sewage. The Phase II effort involved sampling select shallow groundwater wells daily for two weeks, once during a dry weather period (April 29 to May 12, 2009) and once during a wet weather period (May 28 to June 9, 2009). The Phase III effort was carried out on June 6 and 7 (2009), and involved sampling select shallow groundwater wells hourly for 48 hours. Five wells were chosen for inclusion in the Phase II and III sampling effort: FW4, FW5, FW17, FW18, and FW19.

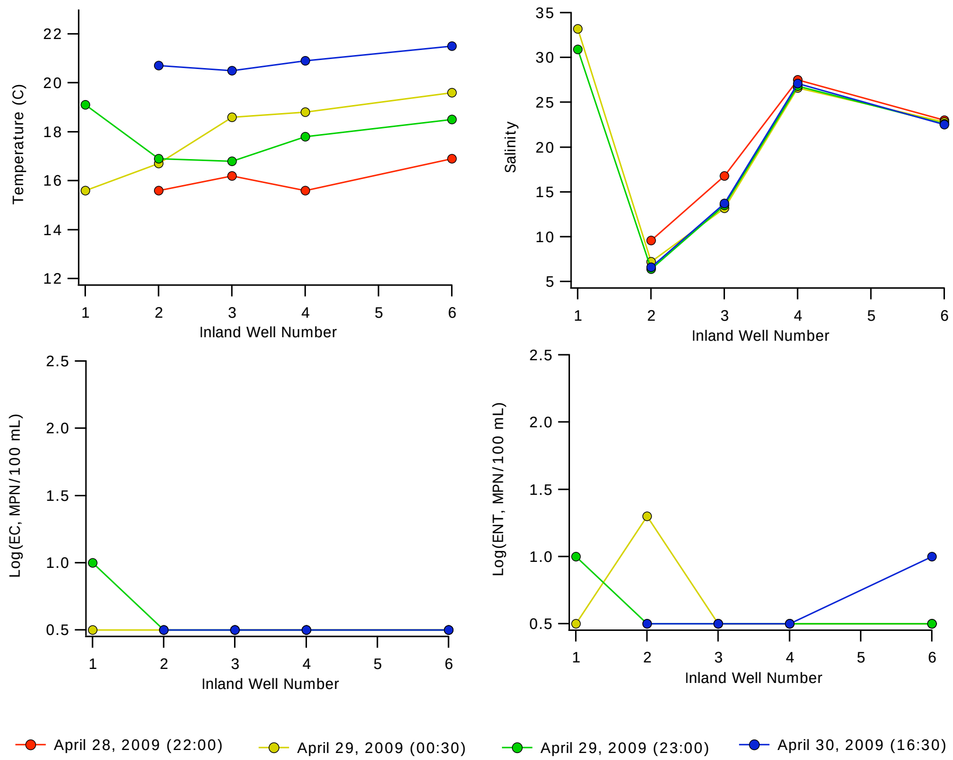

Figure 2-13. Measurements of temperature, salinity, and FIB concentrations measured on water samples collected from the 6 inland wells during Phase I sampling.

All shallow groundwater samples were analyzed for FIB and salinity.

Phase II: Results Phase II data are plotted in Fig. 2-14. During the wet weather study, salinity varied across wells, but was relatively constant within a given well. Shallow groundwater downcoast of the Pleasure Pier (wells FW4 and FW5, yellow and red curves in Fig. 2-14) had near oceanic salinities (ca., 32), while shallow groundwater upcoast of Busy Bee Wharf at Step Beach (FW17, FW18, and FW19, grey, green, and blue curves in Fig. 2-14) had more brackish salinities (ca., 20). As might be expected, the salinity of shallow groundwater near Busy Bee Wharf and Step Beach is higher during dry weather, compared to wet weather, and salinities during dry weather are more temporally variable. FIB concentrations in these wells were generally below the detection limit (<10 MPN/100 mL) during the wet weather study, and sporadically above the detection limit during the dry weather study (bottom left and right panels, Fig. 2-14). Consistent with the findings of the Phase I study, FIB concentrations

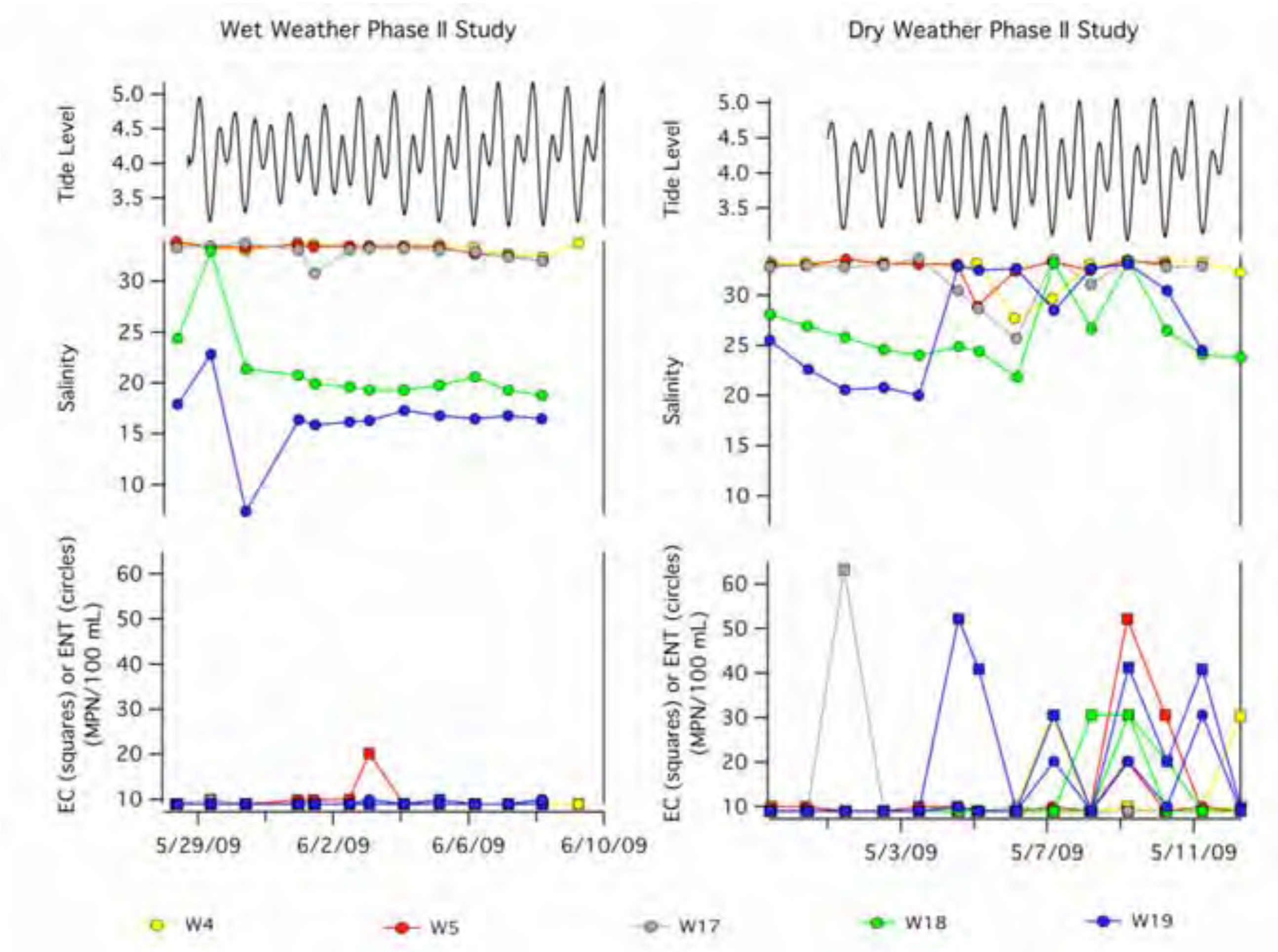

Figure 2-14. Measurements of salinity and FIB concentrations in five foreshore wells (FW4, FW5, FW17, FW18, FW19) during the Phase II sampling effort.

were most frequently above the detection limit in samples collected from foreshore well FW19.

<u>Phase III: Results</u> Phase III data are plotted in Fig. 2-15. Shallow groundwater sampled downcoast of the Pleasure Pier has near oceanic salinities (ca., 32) while shallow groundwater sampled at Step Beach is more brackish (15 to 20). Based on the data presented in Fig. 2-15, the salinity of the shallow groundwater does not appear to change over diurnal time scales, although the results of this very limited effort cannot be extrapolated to all wells and all times. FIB concentrations were generally below the detection limit (10 MPN/100 mL), with the exception of FW19 for which EC concentrations were above the detection limit in a few samples.

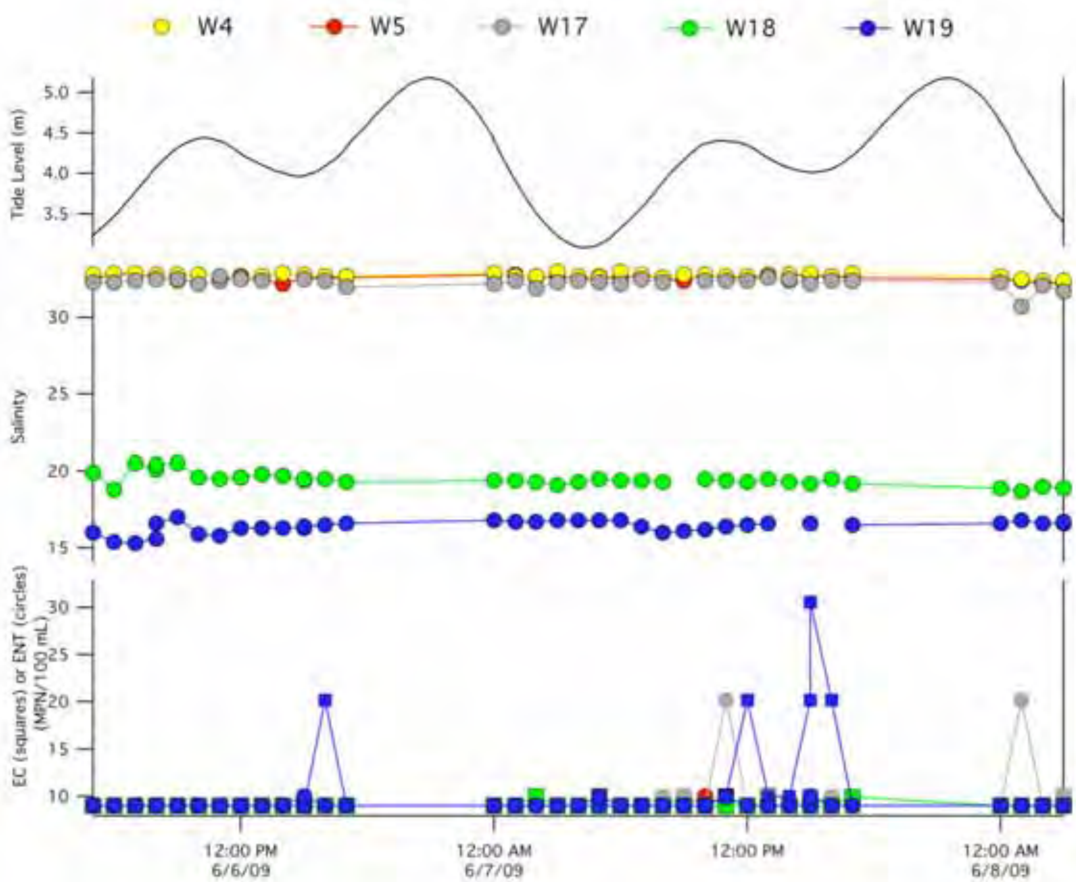

Figure 2-15. Measurements of salinity and FIB concentrations in five foreshore wells (FW4, FW5, FW17, FW18, FW19) during the Phase III sampling effort.

<u>*Task B.1.4.1: Summary*</u> Shallow groundwater beneath the City of Avalon exhibits significant along-shore and cross-shore variability in salinity and FIB concentrations. In the cross-shore direction, salinity of the shallow groundwater can increase from brackish (ca., 10) to oceanic (ca., 32) over a distance of less than 30 m. In the alongshore direction, salinity of shallow groundwater is mostly oceanic, except at Step Beach where brackish salinities were detected in front of the Busy Bee Wharf and downcoast of the Tuna Club. FIB concentrations were generally below detection limits in shallow groundwater collected from inland wells, and higher at three locations along the foreshore: downcoast of the Pleasure Pier, in front Busy Bee Wharf, and at Step Beach.

Collectively, this study presents several lines of evidence that are consistent with sewage contamination of the shallow groundwater at Step Beach and in front of the Busy Bee Wharf, including: (1) FIB concentrations above the detection limits, (2) high concentrations of ammonia and phosphate, (3) low dissolved oxygen, (4) lower salinity, and (5) crew observations of gray coloring and sulfidic smell of shallow groundwater samples. While foreshore groundwater near the Pleasure Pier does not have as strong as a sewage signature (i.e., concentrations of orthophosphate and ammonia were low, dissolved oxygen levels were high, oceanic salinities), the presence of measureable EC and ENT in shallow groundwater implies that sewage contamination cannot be ruled out at this location. Indeed, as noted earlier, wells were screened above a highly resistive feature at this location, and therefore it is possible that a stronger sewage signal is present at depths below 1 m.

Task B.1.4.2: Test Monitoring Wells with high concentrations of FIB for markers of human sewage

In this task, shallow groundwater samples collected from inland and foreshore wells were tested for indicators of fecal pollution using several advanced Microbial Source Tracking (MST) methods. MST is increasingly used to determine host-specific contributions of fecal contamination to waterbodies, thus helping resolve these unknown sources. This information can, in turn, guide decisions regarding the appropriate corrective measures for affected waters. One emerging MST method is the detection of host-specific 16S rRNA markers that target the order *Bacteroidales*, which are found exclusively in feces, animal rumen, and other cavities of humans and animals, often in greater abundance than traditionally used coliform bacteria[15]. Samples of shallow groundwater collected from the wells described in the last section were analyzed for three microbial/molecular markers of human and non-human sewage: (1) speciation of *Enterococcus* isolates, (2) universal, human-specific, cow-specific, and dog-specific fecal *Bacteroidales* spp., and (3) a recently developed molecular assay targeting *Catellicoccus marimammalium* in feces of sea gulls[16].

<u>*Speciation of Enterococcus isolates: Approach*</u>. Shallow groundwater samples were collected from wells IW3, IW4, FW5, and FW16 on May 31 (2009), and analyzed by membrane filtration for enterococci bacteria using EPA Method 1600. From this effort, 70 putative ENT isolates were cultured from shallow groundwater, streaked onto blood agar plates, picked, and stored on streak slants. The original CBI contract called for a third party laboratory (Orange County Health Care Agency) to carry out the speciation of ENT isolates; however, a contract could not be worked out between UCI and OCHCA. Consequently, in collaboration with the Orange County Sanitation District (C. McGee) and the Southern

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[15] Currently, there is a transition toward culture independent and library independent methods using host-specific polymerase chain reaction (PCR) assays based on alternative targets. The most desirable aspect of host-specific PCR assays is that they generally do not require cultivation, which can save much time and expense. PCR assays can be performed in a matter of hours, and they have the potential of being sensitive, inexpensive, quantitative, and amenable to automation. Another advantage of PCR-based techniques is that multiple assays targeting multiple microbial targets and microbial populations can be performed against the same DNA extract. Furthermore, DNA extracts from environmental and fecal samples can be preserved for future analyses should more sensitive assays, or assays for other hosts of interest, become available. While archival of DNA is not indefinite, the addition of an internal DNA control of known concentration to the extracts can be used to estimate the rate of DNA degradation when samples are analyzed at a later stage.

[16] Lu, L., JW. Santo Domingo, R. Lamendella, T.Edge, S. Hill.(2008) Phylogenetic diversity and molecular detection of gull feces. Appl. Environ. Microbiol. 74: 3969–3976

California Coastal Water Research Project (Donna Ferguson), UCI personnel performed the speciation studies using an automated biochemical substrate bacterial identification system (Vitek, Biomerieux, Durham, NC). Coincident with the groundwater speciation studies described here, ENT cultures were also isolated from Avalon runoff, foreshore sediments, and Bay water. Speciation results for these results are presented in Chapter 4, which is devoted to Source Identification of FIB in Ankle Depth Water (Task B.3).

Speciation of Enterococcus isolates: Results A total of 61 ENT isolates were cultured from inland wells IW3 (N=33) and IW4 (N=29). Of these 61 isolates, 46 belonged to the genus *Enterococcus*, 11 belonged to the genus *Aerococuccus*, 3 were non-*Enterococcus* species, and 1 was unidentified. Remarkably, 100% of the confirmed *Enterococcus* isolated from IW3 and IW4 were identified with a high degree of certainty as *Enterococcus faecium*. A much smaller number of isolates were cultured from foreshore wells W5 (N=7), W16 (N=1, later idenitified as *E. casseliflavus*), and W19 (N=1). Of these 9 isolates, 7 were identified as *E. faecium*, one could not be identified, and another was a non-enterococci species. The low diversity of enterococci species observed in IW3 and IW4 is consistent with the differential survival, or perhaps even environmental proliferation, of *E. faecium* in the shallow groundwater. Unfortunately, a relatively low number of isolates were cultured from foreshore wells, so it is not known if the low enterococci species diversity associated with inland wells also applies to the foreshore wells, including wells located near Pleasure Pier, Busy Bee, and Step Beach where the shallow groundwater may be contaminated with sewage.

Bacteroidales spp.: Approach. The original sub-contract called for collecting up to 35 groundwater samples and analyzing them for *Bacteroidales* by quantitative polymerase chain reaction (qPCR). However, because of the large volumes required to conduct this assay, and the limited volumes of water that could be extracted from most wells, water samples were analyzed for seven wells in total, including five foreshore wells (FW4, FW5, FW17, FW18, FW19), two samples from one inland well (IW3), two samples from offshore, and two samples of sewage influent to the Avalon wastewater treatment plant. Additional water samples were collected and analyzed as part of an intertidal study described in the report for Task B.3. The sample analysis involved two steps: (1) filter immobilization of the nucleic acid in a water sample (carried out by UCI personnel); and (2) analysis of the immobilized nucleic acid by qPCR (carried out by UCD personnel). The filtration step also involved calculation of recovery of bacteria based on a surrogate *Acinetobacter* strain and a correction for nucleic acid extraction efficiency. For *Bacteroidales*, two types of DNA extraction and qPCR analysis were performed to distinguish between molecular markers present in viable cells and those in dead cells or present as extracellular DNA. This approach is based on a recently developed method[17] that permits the assessment of the extent of recent fecal pollution vis-à-vis persistence of DNA after cell death. For each run of *Bacteroidales* assays, both negative and positive controls

[17] Bae, S., S. Wuertz. (2009) Discrimination of viable and dead fecal Bacteroidales bacteria by quantitative PCR with propidium monoazide. *Appl. Environ. Microbiol*. 75:2940-2944.

Table 2-2. *Bacteroidales* and *Catellicoccus marimammalium* testing of shallow groundwater

Sample ID	Universal	Human	Dog	Cow	Bird *C. marimammalium*
FW4 (-PMA)	3300	n.d.	190	n.d.	n.d.
FW4 (+PMA)	n.d.	n.d.	n.d.	17	n.d.
FW5 (-PMA)	1900	n.d.	42	n.d.	n.d.
FW5 (+PMA)	2200	n.d.	690	n.d.	n.d.
FW17 (-PMA)	2000	n.d.	710	n.d.	n.d.
FW17 (+PMA)	140	n.d.	21	n.d.	n.d.
FW18 (-PMA)	3500	n.d.	270	n.d.	n.d.
FW18 (+PMA)	5100	n.d.	930	n.d.	n.d.
FW19 (-PMA)	140	n.d.	27	n.d.	n.d.
FW19 (+PMA)	340	n.d.	91	n.d.	n.d.
IW3-1 (-PMA)	3800	4200	3400	16000	n.d.
IW3-1 (+PMA)	800	n.d.	780	n.d.	n.d.
IW3-2 (-PMA)	300	5400	1400	2900	n.d.
IW3-2 (+PMA)	500	2600	1600	2400	n.d.
Offshore (-PMA)	2100	10000	28000	14000	n.d.
Offshore (+PMA)	1800	2300	11000	9000	n.d.
Sewage (+PMA)	720000000	130000000	4400	17000	n.d.
Sewage (-PMA)	100000000	65000000	82000	25000	n.d.

were included. Monitoring data for host marker concentrations (human, dog, cow, and universal marker) were analyzed by a statistical model to estimate true concentrations of host-specific genetic markers. Detailed assay procedures are described in the QAPP for this project.

Bacteroidales and C. marimammalium Testing: Results The *Bacteroidales* and *C. marimammalium* results are summarized in Table 2-2. Entries in the table represent the concentration (in gene copies per mL of water) of genetic markers. The results are further broken down by the source of sample (foreshore well, inland well, offshore ocean sample, or sewage influent sample), and whether propidium monoazide (PMA) was included in the assay or not (+/- PMA). As noted earlier, inclusion of PMA causes the qPCR assay to detect only live cells, and hence a comparison of qPCR concentrations obtained in the presence and absence of PMA may provide insights into how recently the water was fecally contaminated.

As expected, the gene copy concentration of *Bacteroidales* was highest in the sample of raw sewage collected from the influent of the Avalon wastewater treatment plant. All sub-groups of *Bacteroidales* were measured at high concentrations in the sewage sample, while *C. marimammalium* was not detected in the sewage sample. However, the raw sewage results also reveal a problem with the interpretation of the PMA data: in some cases (e.g., Universal and Human-specific) the *Bacteroidales* concentrations decrease when PMA is included in the qPCR assays, while in other cases (e.g., dog- and cow-specific) the *Bacteroidales* concentrations increase when PMA is included in the qPCR assay. For this reason, the PMA results will not be discussed further here.

Next we focus on the non-sewage samples; i.e., samples collected from foreshore wells, inland wells, or the ocean. The universal *Bacteroidales* marker, which is generally associated with fecal waste of one form or another, was detected in all water samples collected from foreshore wells, inland wells, and the ocean. The human-specific *Bacteroidales* marker was not detected in foreshore wells but was detected in inland well IW3, and in the ocean sample. The dog-specific *Bacteroidales* marker, which can cross-react with both human and sewage, was detected in all samples, but at particularly high concentrations in water samples collected from inland well IW3 and the ocean sample. The cow-specific *Bacteoridales* marker was measured at high concentration in inland well IW3 and in the offshore samples, but not in the foreshore well samples. None of the groundwater, ocean, or sewage samples collected as part of this task tested positive for the bird-specific marker *Catellicoccus marimammalium*.

Generally speaking, these results are consistent with the previous CBI study that found shallow groundwater beneath Avalon tests positive for human-specific *Bacteroides*. The results presented in Table 2-2 go beyond the original CBI study, however, by providing concentration estimates, and employing a set of specific animal markers, in addition to the human-specific fecal marker. On its face, it is hard to explain how the cow-specific *Bacteroidales* would find its way into inland well IW3. The cow marker can cross-react with feces from other bovine species and with horse feces (Kildare et al. 2007; Silkie and Nelson 2009) and therefore it is possible that an unknown animal source exists at IW3.

Task B.1.5: Conduct geophysical characterization of the shallow groundwater underlying Avalon

Shallow Groundwater Level: Approach. Levelogger sondes (Solinst Canada Ltd., Georgetown, Ontario) were installed in a subset of inland and foreshore wells for unattended continuous monitoring every 15 minutes over one month. The sondes were hung from a thin-stainless steel wire attached at the top of the well pipe, and periodically removed (every 2 weeks) for data capture and recalibration. Independent measurements of the groundwater level in the wells were performed once a week per well using a water level meter (Slope Indicator Standard Water Level Meter, Mukilteo, WA) to calibrate and confirm the Levelogger readings. The sondes were disinfected prior to emplacement in the well, by swabbing with ethanol and rinsing thoroughly in distilled water. Table 2-3 provides summary information on the wells where leveloggers were deployed, together with key

Table 2-3. Wells selected for levelogger deployment.

Monitoring-Well Name	Elevation of well head (m, MSL)	Latitude	Longitude	Length of wire suspending sonde (m)	Elev of sonde sensor (m, MSL)[1]
FW4	3.06	33.34346576	-118.3247715	2.23	0.63
FW5	3.06	33.34353473	-118.3248697	2.26	0.6
FW11	2.46	33.34445499	-118.3260146	2.44	-0.18
FW17	2.70	33.34493634	-118.3265026	2.35	0.15
FW18	2.74	33.34504087	-118.3265801	2.42	0.12
FW19	2.64	33.34516639	-118.3266649	2.27	0.17
IW1	4.32	33.34335549	-118.3250091	2.32	1.8
IW2	4.74	33.34329414	-118.3253129	3.74	0.8
IW3 (Barologger)	4.84	33.34318172	-118.3254199	1.36	3.28
IW4	4.90	33.34497001	-118.3266535	3.79	0.91
IW6	5.00	33.34522492	-118.3268787	3.77	1.03

[1]This calculation assumes that the sonde sensor is located 0.2 m below where the sonde attaches to the suspending wire.

information about about each deployment. Note that a Barologger was deployed at IW3, and data from this instrument was used to correct for the barometric pressure in wells, following manufacturer's recommended procedures.

Shallow Groundwater Level: Results. The top panel in Fig. 2-16 is a time series plot of water levels measured in wells FW4, IW1 and IW2 (light blue, red, and black curves, respectively). Referring to the well map in Fig. 2-8, these three wells form a cross-shore transect at the Pleasure Pier. Water levels measured in these wells have a distinct tidal signature, and the peak of the tide wave progressively shifts to later times with distance inland. The time lag between peaks was calculated for a single tide wave (lower left panel of Fig. 2-17) and plotted against distance inland from well FW4 (lower right panel of Fig 2-17). The time lag appears to increase linearly with distance inland (lower right panel, Fig. 2-14), as predicted by an elementary solution to tidal groundwater flow[18].

[18] Erskine, A.D. (1991) "The effect of tidal fluctuationon a coastal aquifer in the UK" Ground Water 29: 556-562.

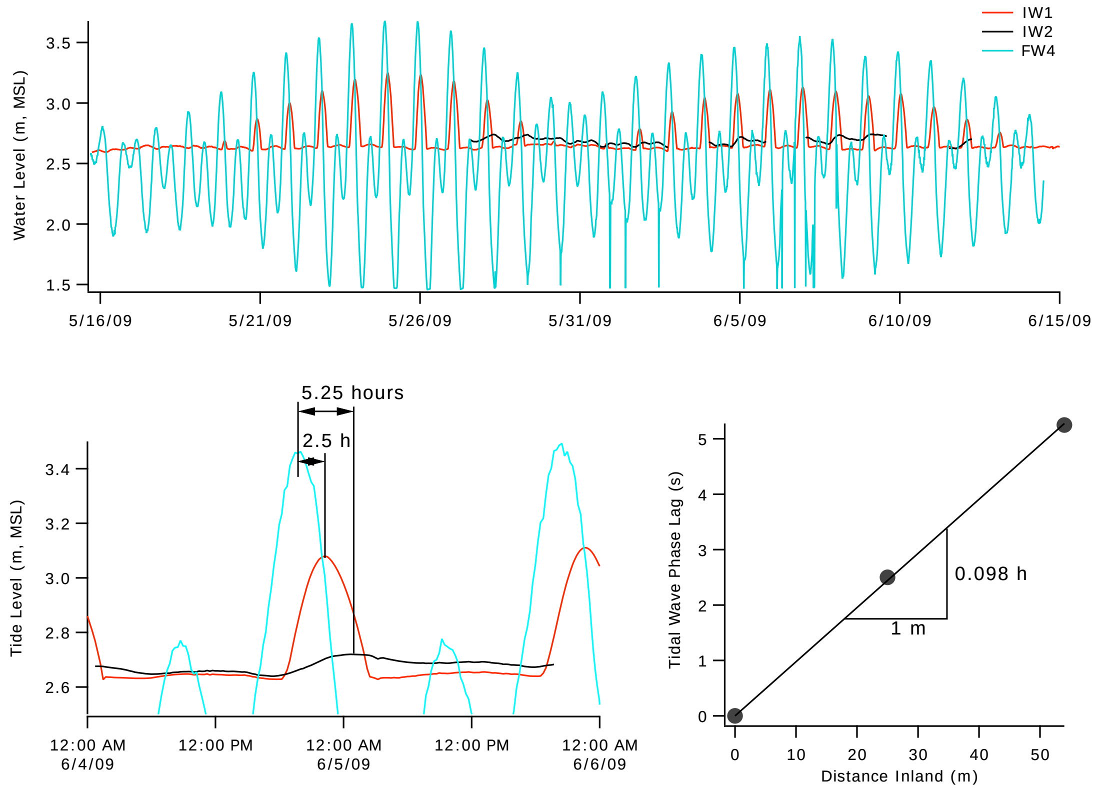

Figure 2-16. Water level measurements in three shallow groundwater wells along a cross-shore transect near the Pleasure Pier.

Water levels measured in foreshore wells FW17 and FW19 at Step Beach look very similar to the water level measured in FW5 near the Pleasure Pier. The water level measured in foreshore well FW18 is both attenuated and time lagged, relative to FW 17 and FW19, perhaps reflecting complex (i.e., non-tidal) subsurface flow at this location. Water levels measured at the two inland wells IW4 and IW6 are time-lagged relative to foreshore wells FW17 and FW19, consistent with the time lag observed at the cross-shore transect near the Pleasure Pier. It is also interesting to note that the water level at IW4 and IW6 is elevated above foreshore wells FW17 and FW19 during all but the highest tide levels, consistent with the idea that the hydraulic gradient is tilted toward the Bay during most of the tidal cycle. This last result would be consistent with the ERT and groundwater sampling at this site (see earlier), that collectively support the idea that freshwater of meteoric or other (e.g., sewage) origin is discharged to the Bay at this location.

Task B.1.6. Prepare Draft Report for Pilot Remediation Study

This task is satisfied with the submission of this report.

AVALON BAY WATER QUALITY IMPROVEMENT PROJECT, CATALINA ISLAND, CALIFORNIA

A final report on Pilot Disinfection Studies Task B.2 of the Clean Beaches Initiative Grant

Submitted to the City of Avalon and the State Water Resources Control Board on 8/24/10 by

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Summary of Task B.2 Results

Results presented in this chapter center around pilot testing several different strategies—including chemical disinfection, permeable treatment barriers, and subsurface mobilization of fecal pollution using linear alkylbenzene sulfonates—for remediating fecally polluted shallow groundwater beneath the City of Avalon. These studies support the following conclusions:

1. A series of laboratory-scale studies were carried out to evaluate four disinfection strategies for removing sewage-associated FIB (in particular, culture-dependent measurements of enterococci bacteria (cENT) and *Escherichia coli* (cEC)) from shallow groundwater in Avalon Bay: (1) aeration alone, (2) aeration with addition of brine, (3) aeration with addition of peracetic acid (PAA), and (4) aeration with addition of peroxymonosulfate (Oxone). The effectiveness of these different disinfection strategies was evaluated by reporting the log reduction in FIB concentration achieved after a 15 minute exposure time.
2. Aeration alone and aeration with brine did not significantly reduce cEC and cENT concentrations in mixtures of raw sewage and shallow groundwater; i.e., no reduction in either cEC or cENT was achieved after 15 minutes of exposure.
3. Four to 5 mg/L of PAA achieved > 3 log reduction of cEC and cENT in mixtures of raw sewage and shallow groundwater after 15 minutes of exposure. The biocidal properties of PAA do not appear to be affected by the salinity of the mixture.
4. Disinfection of cEC and cENT by Oxone depends significantly on salinity; all else being equal, greater log-reduction was achieved at higher salinities.
5. In general, cENT was more resistant to disinfection by both Oxone and PAA than cEC.
6. The formation of hypohalous oxidants probably accounts for the enhanced biocidal properties of Oxone at high salinity, and implies that Oxone is likely to form toxic disinfection by products (DBPs) in marine waters.
7. Based on these results, it does not appear that Oxone would be appropriate for any application in which the disinfectant, or its DPBs, might find their way into Avalon Bay.
8. Particulate matter naturally present in shallow groundwater strongly interferes with PAA disinfection. Therefore, the turbidity of ambient waters must be factored into the design of a successful strategy for remediating sewage-contaminated shallow groundwater in Avalon.
9. For above-ground pump and treat remediation to be effective, a procedure must be developed for effectively mobilizing FIB out of sewage contaminated sediments into the pore fluids, where they can be pumped to the surface and treated. We hypothesized, based on previously published studies involving the mobilization of viruses in sewage contaminated groundwater, that injection of linear alkylbenzene sulfonates (LAS) might mobilize FIB out of sewage-

contaminated sediments, but that does not appear to be the case based on packed column experiments carried out with both coarse and fine-grained sediments from Avalon's main beach area. Interestingly, we found that a significant fraction (50 to 99%) of FIB in sewage contaminated groundwater were removed by passage through just 28 cm of beach sand, suggesting that the native sediments have significant filtration capacity, even when the pore fluids possess brackish salinities (15).

10. Within the resolution of the filtration set-up used here, granular activated carbon (GAC) did not remove sewage-derived FIB to any appreciable degree. While better filter media could probably be found, permeable treatment barriers are probably not a viable option in any case, given the spatially complex and temporally variable nature by which sewage contaminated shallow groundwater is exchanged with Avalon Bay.

Based on the data obtained from these pilot studies, the most promising remediation approach would appear to involve the use of the chemical disinfectant PAA, either applied directly to sewage contaminated sediments, or injected into high-risk laterals, like those that pass through foreshore sands (e.g., connecting sewage lines at the Pleasure Pier to sewer mains in the downtown area of Avalon). Pump and treat methods and permeable treatment barriers are less promising, because of unresolved difficulties associated mobilizing FIB and pathogens out of sewage contaminated sediments, and proper placement of in situ filter media in the face of a contamination plume that is highly variable in both space and time.

Pilot Disinfection Studies

This report describes a set of pilot disinfection studies carried out under Task B.2 of the Clean Beaches Initiative Avalon Bay Water Quality Improvement Project. For clarity, the results presented below are organized by contract sub-task.

Task B.2.1. Prepare Draft Work Plan for pilot remediation study

A draft work plan for groundwater characterization was submitted to City of Avalon Staff and State Water Board personnel on August 15, 2008. Based on feedback, the draft plan was revised and resubmitted as a revised draft plan on September 26, 2008.

Task B.2.2. Submit Final Work Plan for groundwater characterization

Based on feedback provided in Task B.2.1., a final work plan for the Pilot Remediation Study was prepared and submitted to City of Avalon Staff and State Water Board personnel on December 12, 2008.

Task B.2.3: Obtain all necessary permits if needed by State and Local jurisdictions

After consultation with State Board personnel, pilot studies carried out under this sub-task will involve bench-scale tests only, and therefore no field permits are required.

Task B.2.4: Build and operate pilot remediation facilities

Goal and Approach. Remediation of sewage-contaminated shallow groundwater beneath Avalon could be accomplished using a number of techniques, including pump-and-treat, in situ treatment, and permeable treatment barriers. With the pump-and-treat approach, contaminated groundwater is pumped to the surface through one or more wells, disinfected (e.g., using UV or ozone treatment), and then pumped back into the shallow groundwater, discharged to the Bay, or discharged to the sanitary sewer system. With in situ treatment, one or more disinfectants are pumped directly into the contaminated region of the shallow groundwater, thus accelerating the die-off of sewage-associated microbial pollutants. A permeable treatment barrier could be installed parallel to main beach, to remove microbial pollutants as they flow with the shallow groundwater to the Bay. Finally, disinfection could be added directly to high-risk areas of the sewage collection network, such as laterals that pass through the foreshore area of Avalon Bay. Pilot scale-studies described below were carried out to evaluate the potential efficacy of these different approaches.

Chemical disinfection of Shallow Groundwater: Background A series of pilot-scale studies were carried out to evaluate three in situ disinfection strategies for removing sewage-associated FIB from shallow groundwater in Avalon Bay: (1) aeration alone, (2) aeration with addition of brine, and (3) aeration with addition of peracetic acid

Fig. 3-1. Left: schematic of the batch experiments used to evaluate the disinfection of sewage-contaminated shallow groundwater. Right: a photograph of experimental set-up.

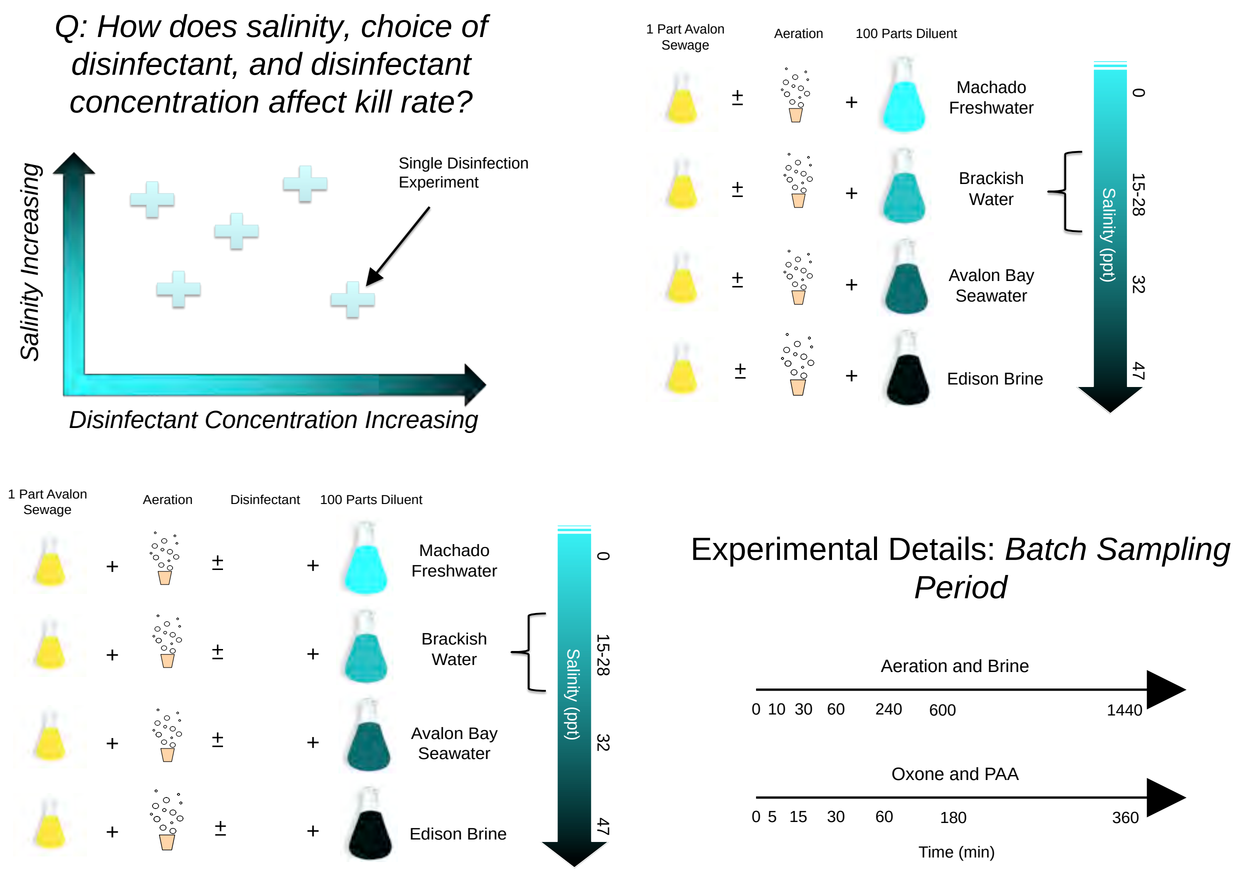

Fig. 3-2. Upper Left: matrix design of the disinfection experiments. Upper Right: mixtures prepared to test disinfection by aeration and brine. Lower Left: mixtures prepared to test chemical disinfection. Lower Right: timing of sample collection.

and/or peroxymonosulfate. These three disinfectant strategies were chosen because they were thought, at the start of the project, to be unlikely to produce harmful disinfection by-products, pose relatively little in the way of human safety considerations, and can be scaled-up for treatment in the field. The choice of brine as a candidate disinfectant was motivated by the fact that it is environmentally friendly, and it is produced on Avalon as an effluent from the desalination plant there. Peracetic acid appears promising, because it produces little or no toxic disinfection by-products when mixed with seawater (it rapidly degrades into acetic acid, vinegar), it is a strong biocide in marine waters as evidenced by its use as an antifouling agent in cooling water systems for coastal power plants, and it is safe for discharge to sensitive marine waters, including the highly regulated Italian Lagoon of Venice[1]. To our knowledge, peroxymonosulfate (Oxone) has not been tested as a biocide in coastal marine settings, but its application to this particular problem seemed worth exploring based on the fact that, upon addition to water, it generates hydroxyl radicals and sulfate. The former should accelerate the die-off of bacteria and viruses in the shallow groundwater, and the latter is already present at high concentrations in marine waters. Some commonly used disinfectants (e.g., ozone, chlorine gas, sodium hypochlorite) were excluded from consideration because, although highly effective biocides, they readily react with bromide and organics in sewage-contaminated groundwater to form toxic disinfection byproducts (e.g., bromoform and haloforms)[2,3]. If these by-products washed into the Bay, for example through tidal exchange, they could negatively impact the sensitive ecology of Avalon Bay. We also excluded from consideration the disinfectant chlorine dioxide. Although chlorine dioxide is a strong biocide (it was used decontaminate several buildings in Washington DC after the 2001 anthrax attacks), is very water soluble, and generates relatively few disinfection byproducts, it must be made onsite and its handling presents explosion, contact, and inhalation hazards.

Chemical disinfection of Shallow Groundwater: Approach. Fig. 3-1 includes a schematic of the pilot-scale disinfection studies, and a photograph of the actual experimental set-up. The experiments involved measuring the loss of culturable *Escherichia coli* (cEC) and enterococci bacteria (cENT) concentrations after the addition of disinfectant to raw (untreated) Avalon sewage diluted 1:100 into various mixtures (with various final salinities) of fresh groundwater from an inland well (Machado Well), Avalon Bay water, and brine from a local desalination plant. As noted above, two chemical disinfectants were evaluated: peracetic acid (PAA) and peroxymonosulfate (Oxone). The reaction vessel was immersed in a water bath held at a constant temperature (15^{o}C) using a temperature controlled recirculating water bath.

Over 50 separate experiments were run with different choices of disinfectant (PAA, Oxone, or no added chemical disinfectant), disinfectant concentration, and sewage/groundwater/brine

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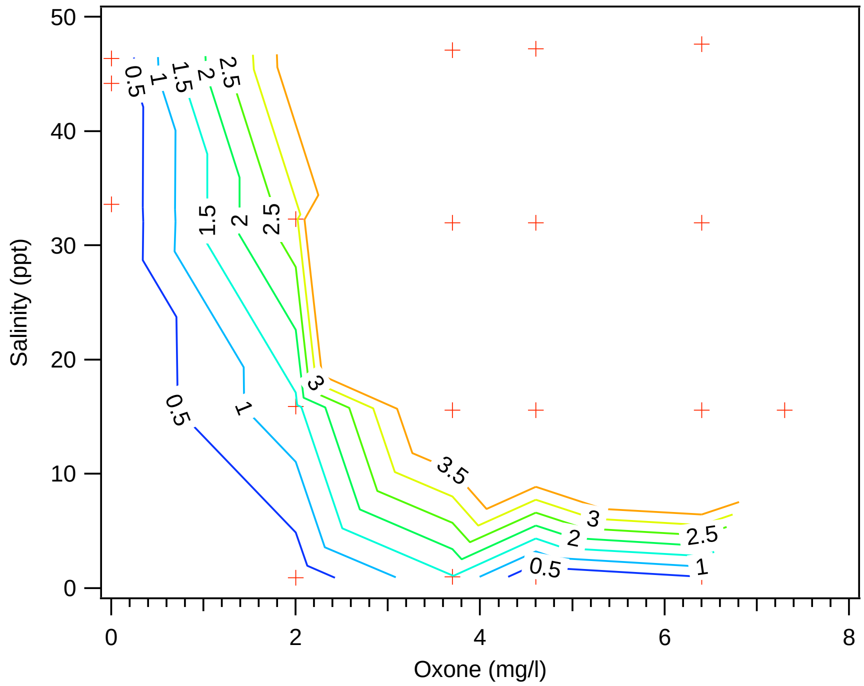
[1] Pierangela, C. (2005) Solutions to fouling in power station condensers *Applied Thermal Engineering* v. 25:2630-2640.

[2] Abarnou, A., L. Miossec (1992) Chlorinated waters discharged to the marine environment chemistry and environmental impact. An overview. *The Science of the Total Environment*: **126**:173-197.

[3] Allonier, A.S., M. Khalanski, V. Camel, A. Bermond (1999) Characterization of chlorine by-products in cooling effluents of coastal nuclear power stations *Marine Poll. Bull.* v. 38:1232-1241.



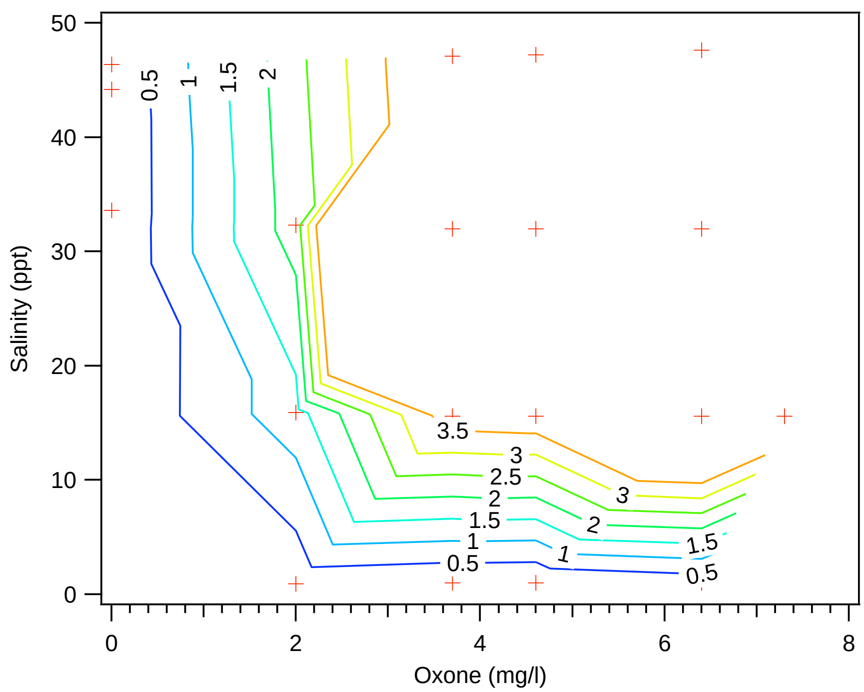


Fig. 3-3. Contour plots of the log-reduction in culturable *Escherichia coli* (cEC, top panel) or enterococci bacteria (cENT, bottom panel) achieved after 15 minutes of disinfection at the Oxone concentration and salinity noted.

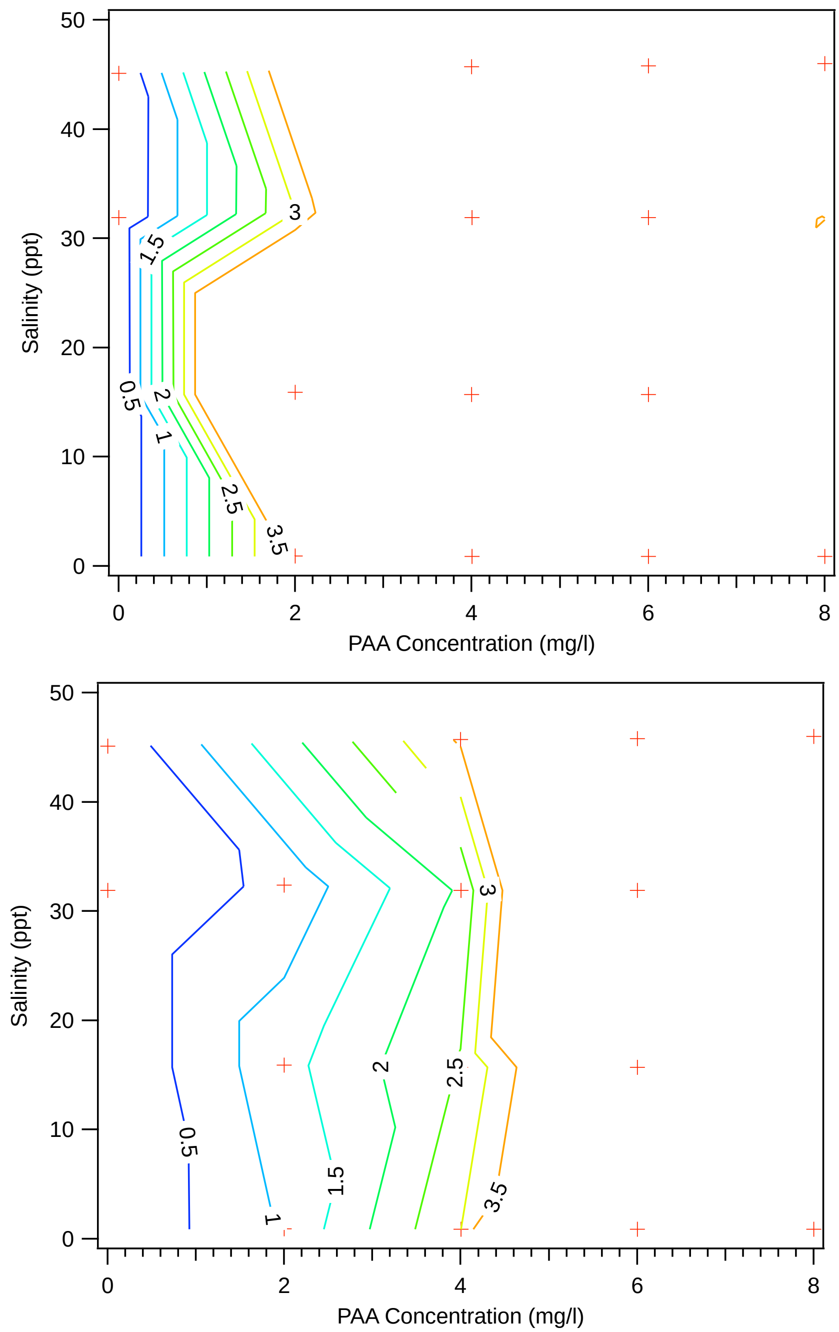


Fig. 3-4. Contour plots of the log-reduction in culturable *Escherichia coli* (cEC, top panel) or enterococci bacteria (cENT, bottom panel) achieved after 15 minutes of disinfection at the PAA concentration and salinity noted.

mixtures. To capture a representative range of potential salinities and disinfectant concentrations, a matrix design was adopted as illustrated in Fig. 3-2 (upper left panel). Also shown in the figure is the experimental approach adopted to evaluate the biocidal potential of aeration and brine (upper right panel) and Oxone and PAA (lower left panel), and the timing of water samples collected from the batch experiments (lower right panel).

Chemical disinfection of Shallow Groundwater: Results. While the Work Plan called for using Chick's law to estimate disinfection rate constants, in practice we found this approach required subjective interpretation of the raw data (e.g., estimating lag times). Instead, disinfection was quantified using the following simple metric: the log removal of cEC or cENT achieved after 15 minutes of exposure to disinfectant. Contour plots of 15-min. log-removal results are shown for Oxone and PAA in Figures 3-3 and 3-4, respectively. Each contour line in these figures represents a fixed level of log-reduction after 15 minutes of disinfectant exposure. The data presented in these two figures can be summarized as follows:

1. Aeration alone and aeration with brine did not significantly reduce cEC and cENT concentrations in the diluted sewage after 15 minutes of exposure; i.e., no reduction in either cEC or cENT was achieved after 15 minutes of exposure (points along the vertical axis, corresponding to a disinfectant concentration of 0, in Fig. 3-3 or 3-4).
2. Four to 5 mg/L of PAA achieved > 3 log reduction of cEC and cENT after 15 minutes of exposure (Fig. 3-4). The biocidal properties of PAA do not appear to be affected by the salinity of the mixture, based on the near vertical nature of the contour lines in Fig. 3-4.
3. Disinfection of cEC and cENT by Oxone depends significantly on salinity; i.e., the contour lines are not vertical in Fig. 3-3. Greater log-reduction was achieved at higher salinities for a fixed Oxone dose.
4. In general, cENT was more resistant to disinfection by both Oxone and PAA than cEC.
5. Although not shown, studies conducted with ternary mixtures of groundwater, sediments, and sewage, we found that cENT was more susceptible to disinfection than cEC (a trend also observed in the packed column filtration experiments described below).

To determine why Oxone disinfection is salinity dependent, follow-up studies were carried out by mixing Oxone with artificial seawater, and then following the oxidant concentration over time by the colormetric indicator *N,N*-diethyl-*p*-phenylenediamine (DPD). These DPD experiments (data not shown) support the hypothesis that, when mixed with seawater, Oxone oxidizes trace bromide and iodide in the seawater to form hypohalous oxidants (HOBr and I_2/HOI), along with hypochlorous acid, hypochlorite ion, and chlorate from the oxidation of chloride[4]. The formation of hypohalous oxidants probably accounts for the enhanced biocidal properties of Oxone at high salinity, but it also means that Oxone is likely to form toxic disinfection by products (DBPs) in marine waters. Based on these results, Oxone would not be appropriate for any applications in which the disinfectant, or its DPBs, might find their way into Avalon Bay.

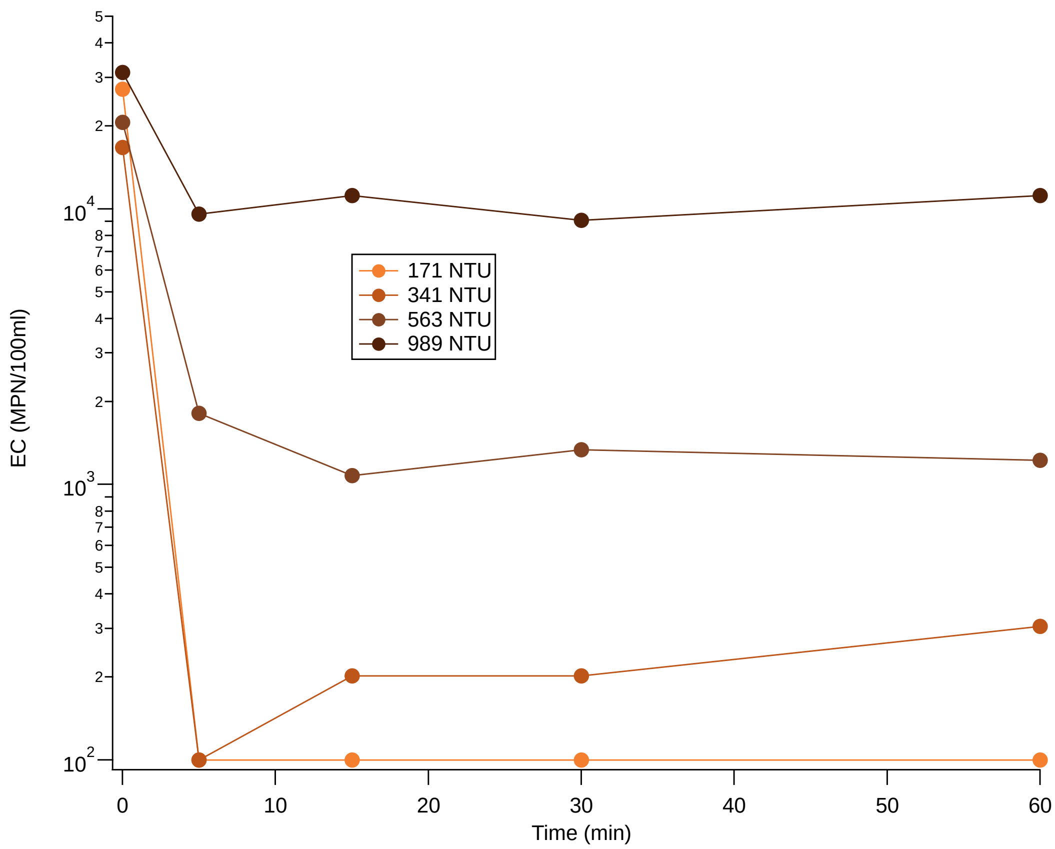


Fig. 3-5. The impact of particulate matter in shallow groundwater on the disinfection of cEC by PAA. Groundwater with different particulate concentrations (as indicated by the turbidity values shown) were prepared by mixing filtered and unfiltered groundwater from shallow groundwater from well IW1.

Additional disinfection experiments were conducted to determine how PAA disinfection of cEC and cENT is affected by ambient temperature and the presence of particulate matter. In one of these experiments, shallow groundwater from inland well 1 (IW1) was collected, and half of the sample passed through a 0.45 micron filter to remove particulate matter. Various

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[4] Delcomyn, C.A., Bushway, K.E., Henley, M.V. (2006) "Inactivation of biological agents using neutral oxone-chloride solutions" Environ. Sci. Technol., **40**: 2759-2764.

mixtures of the filtered and unfiltered shallow groundwater were prepared, with raw sewage from the Avalon wastewater treatement plant (1 part sewage to 100 parts groundwater), and assayed for FIB over time following the addition of PAA. The impact of particle turbidity on the PAA disinfection of cEC is shown for one set of experiments in Fig. 3-5. Based on the data presented in this figure, particulate matter present in the shallow groundwater strongly interfered with the PAA disinfection of EC. Therefore, turbidity of ambient waters should be factored into the design of remediation strategies for sewage-contaminated shallow groundwater in Avalon.

Linear Alkylbenzene sulfonate (LAS) Mobilization Experiments. If Avalon adopts a pump-and-treat approach, microbial contaminants will need to be desorbed from the contaminated sediment matrix so that they can be pumped to the surface for treatment. Injection of linear alkylbenzene sulfonates (LAS) into a sewage contaminated aquifer can mobilize previously attached viruses in a field setting[5], and it may have a similar effect on both previously attached fecal indicators and pathogens in the shallow groundwater beneath Avalon.
Pilot studies described in this section were designed to evaluate the mobilization of FIB from sewage contaminated sediments using LAS.

LAS Mobilization Experiments: Approach. Glass columns were wet packed in deionized (DI) water using either coarse or fine-grained sediment collected from Avalon Main Beach. After packing, the columns were flushed with 5 pore volumes of DI water, followed by 2 pore volumes of a synthetic shallow groundwater prepared from a 1:1 mixture of Machado groundwater and Avalon Bay water (final salinity of 15). Three pore volumes of sewage-contaminated synthetic groundwater (consisting of a 1:100 dilution of raw sewage from the City of Avalon wastewater treatment plant) were then passed through the column, followed by two pore volumes of sewage-free groundwater, and finally three pore volumes of sewage-free groundwater containing 10 mg/L of LAS. Effluent from the columns was collected in 10 mL fractions, and analyzed for cEC and cENT using procedures described earlier. After the experiments were completed, the columns were drained, and the sediment from the columns was extruded into a series of 5 to 10 cm segments, each of which was analyzed for cEC and cENT.

Mobilization of Microbial Pollution for Pump and Treat: Results. The grain size distribution of the coarse and fine grain sand samples are displayed in Figure 3-6. The median diameters are 2 mm and 0.12 mm for the coarse and fine-grained sediments, respectively. Loss on ignition (LOI) estimates of organic carbon content are similar for the coarse (0.85%) and fine (1.03%) sediment samples. Experimental conditions used for the packed column experiments are summarized in Table 3-1. Normalized FIB breakthrough curves are plotted for the coarse-grained (upper left panel) and fine-grained (lower left panel) sediments in Fig. 3-7. cEC and cENT concentrations in the sewage-contaminated groundwater were reduced

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[5] Pieper, A.P., J.N. Ryan, R.W. Harvey, G.L. Amy, T.H. Illangasekare, D.W. Metge (1997) "Transport and recovery of bacteriophage PRD1 in a sand and gravel aquifer: effect of sewage derived organic matter" *Environmental Science and Technology* **31**:1163-1170.

Table 3-1. Experimental parameters for LAS mobilization experiments

Experimental Parameter	**Coarse Sand**	**Fine Sand**
Sand Source	Avalon Main Beach	Avalon Main Beach
Loss on Ignition (Organic Carbon)	0.85 %	1.03 %
Median Grain Size	2 mm	0.12 mm
Column length	27.5 cm	26 cm
Column diameter	5 cm	5 cm
Pore Volume	127 mL	226 mL
Influent salinity	15	15
Influent pH	7.85	7.89
Sewage Influent (EC)	16,000 MPN/100 mL	14,000 MPN/100 mL
Sewage Influent (ENT)	2600 MPN/100 mL	3000 MPN/100 mL
LAS Influent	10 mg/L	10 mg/L
Flow rate	0.54 mL/min	0.53 mL/min
Volumetric flux	0.4 m/d	0.4 m/d
Column temperature	14 C	14 C

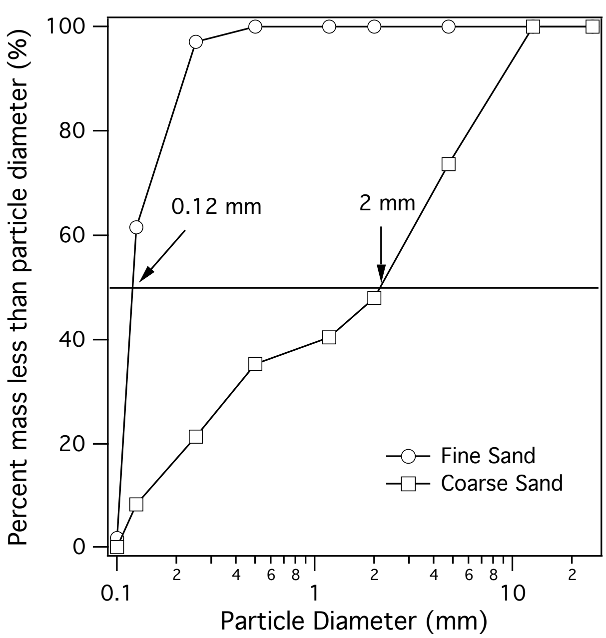

Figure 3-6. Sieve analysis of coarse and fine-grained sediment samples collected from Avalon Main Beach and used in the LAS mobilization experiments (median , or 50th percentile, grain sizes are indicated on the graph).

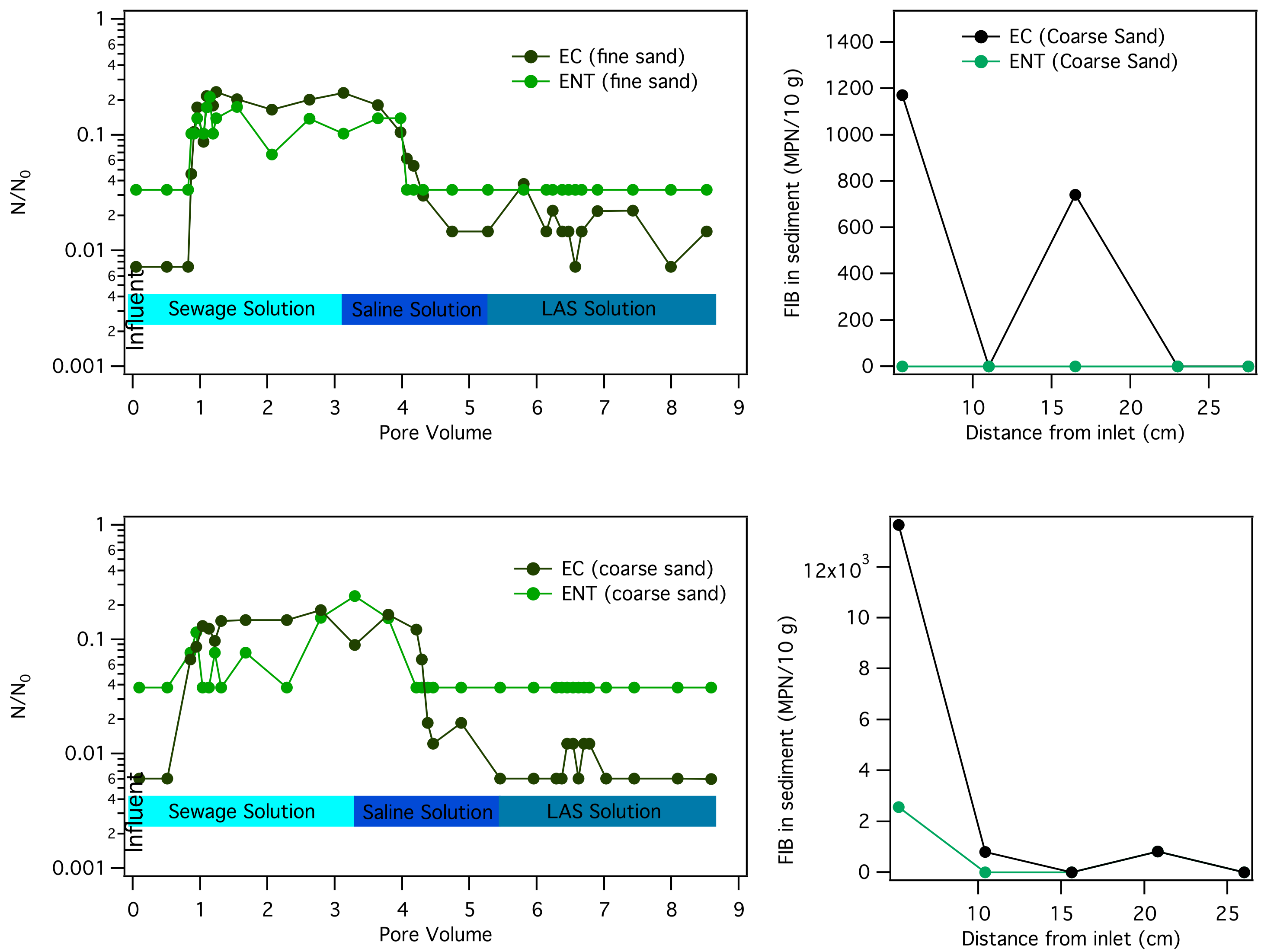

Figure 3-7. Left Panels: EC and ENT breakthrough curves in filtration experiments conducted with coarse (top penal) and fine (bottom panel) grained sediments. Right panels: Concentration of FIB measured on sediment samples extruded from packed columns containing fine (top panel) and coarse (bottom panel grained sediments.

five to ten-fold by passage through the packed columns. Remarkably, the level of FIB removal was similar for cEC and cENT, and relatively insensitive to the grain size of the packing material (coarse or fine-grained) (left hand panels, Fig. 3-7). No tailing is evident as the sewage-free groundwater breakthrough curves at pore volume 4 to 5, suggesting that FIB are irreversibly attached to sediments in the column. Application of the LAS mixture did not obviously mobilize either cEC or cENT out of the column; i.e., FIB concentrations remained near or below the lower limit of detection after the application of a sewage-free LAS/groundwater mixture. When sediments from the columns were extruded and analyzed for FIB, a very low fraction (<1%) of filtered FIB was recovered (right panels, Fig. 3-7). Contrary to expectations, application of the LAS to sewage-contaminated sediment did not mobilize either cEC or cENT into the pore fluid. Instead, it appears that LAS facilitated the rapid loss of culturability (and perhaps die-off) of cEC and cENT in the sewage-contaminated sediment. It should be noted that the flow rate chosen for these experiments (see Table 3-1) corresponds to a volumetric flux (volume of water passing per unit time per unit area of sediment) of 0.4 m/s. This particular volumetric flux is very similar to peak upwelling rates reported for shallow groundwater discharge both in Avalon Bay[6] and in Two Harbors[7], Catalina Island.

Permeable Treatment Barrier. Based on the results presented in the last chapter (Task B.1), the exchange of shallow groundwater with Avalon Bay is likely to be temporally and spatially variable, which raises questions about how a permeable treatment barrier would be implemented in practice, even if a perfect filter media could be found. Nevertheless, as called for in the contract, filtration experiments were carried out in which 1:100 mixtures of sewage and either fresh groundwater (from the Machado well) or Avalon Bay water were continuously applied to the influent of a 20 cm glass column (7 cm o.d.) packed with granular activated carbon (GAC). Column effluent was collected in 10 mL fractions over 6 hours at a flow rate of 3 mL/min., and analyzed for cEC and cENT using Colilert-18 and Enterolert. As documented in Fig. 3-8, cEC and cENT exhibit complete breakthrough (i.e., the final effluent concentration is equal to the influent concentration, $N/No \sim 1$) and therefore, within the resolution of these experiments, GAC did not remove FIB to any appreciable degree. Indeed, it is remarkable to note that GAC is a less effective filter for FIB than is Avalon Bay sediment, based on the coarse and fine grained packed column studies described in the previous section. While better filter media could certainly be found, as noted above permeable treatment barriers are probably not a viable option in any case, given the complex and temporally variable nature by which sewage contaminated shallow groundwater is exchanged with Avalon Bay.

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[6] Boehm, A. B. Y., K.M.; Love, D.C.; Peterson, B.M.; McNeill, K.; Nelson, K.L., Covariation and Photoinactivation of Traditional and Novel Indicator Organisms and Human Viruses at a Sewage-Impacted Marine Beach. *Environmental Science & Technology* **2009,** *43*, (21), 8046-8052.

[7] Colbert, S.L.; Hammond, D.E.; Berelson, W.M. Radon-222 budget in Catalina Harbor, California: 1. Water mixing rates. *Limnology and Oceanography* **2008**, *53*(3)

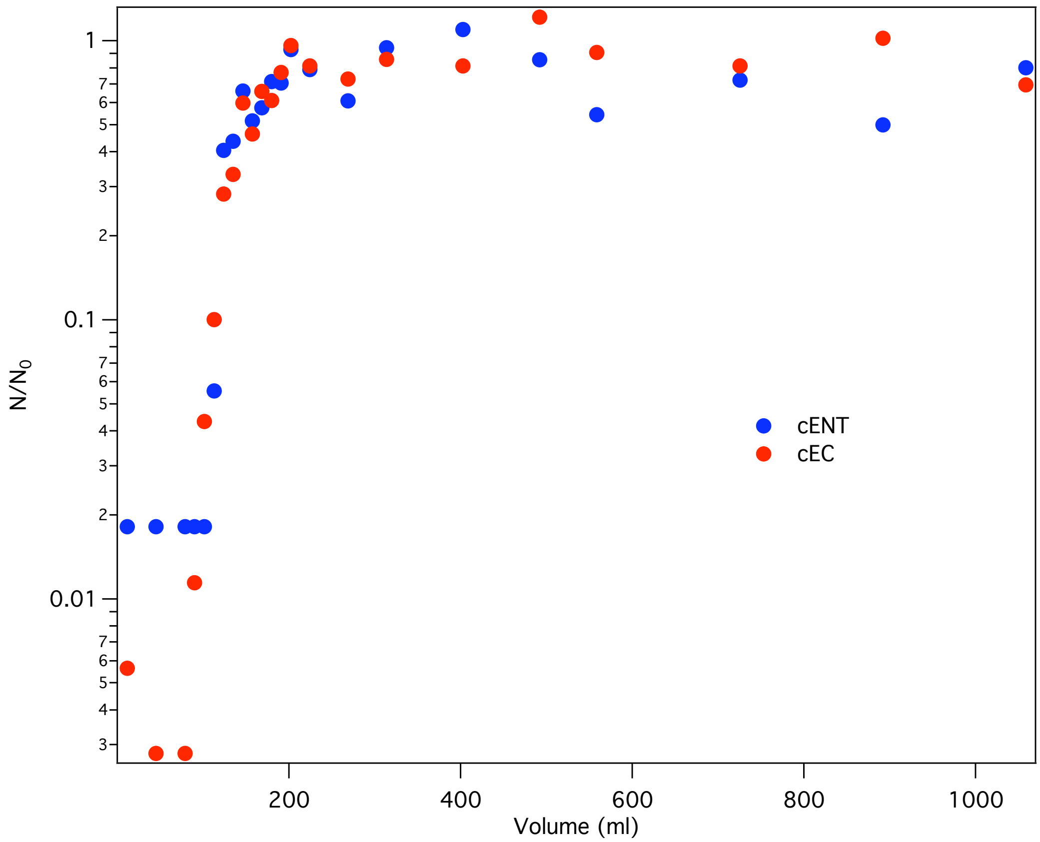

Figure 3-8. Breakthrough of culturable *Escherichia coli* (cEC) and enterococci bacteria (cENT) in a glass column packed with granular activated carbon (GAC). The vertical axis represents the concentration of FIB measured in the effluent (*N*) divided by the concentration of FIB measured in the influent (*No*). The horizontal axis represents the volume of water passed through the column (the pore volume of the column is approximately 100 mL). In this experiment the influent consisted of a 1:100 mixture of raw sewage and a 50:50 mixture of Bay water and Machado well water (final salinity 15).

Task B.2.5. Prepare Draft Report for Pilot Remediation Study

This task is satisfied with the submission of this report.

AVALON BAY WATER QUALITY IMPROVEMENT PROJECT, CATALINA ISLAND, CALIFORNIA

A final report on Source Identification of FIB in Ankle Depth Waters in Avalon Bay
Task B.3 of the Clean Beaches Initiative Grant

Submitted to the City of Avalon and the State Water Resources Control Board on 8/24/10 by

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Funded by

The City of Avalon, Los Angeles Regional Water Quality Control Board, and State of California Clean Beaches Initiative

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Summary of Task B.3 Results

The field investigations described in this sub-task were intended to identify sources of FIB in ankle deep water in Avalon Bay, and determine how these bacteria are moblilized into shoreline waters by either "overbeach" or "through beach" transport processes. Primary findings from this effort are summarized as follows:

1. FIB concentrations in surficial sand pore fluids are consistently elevated at two locations: (A) in front and upcoast of the Busy Bee Wharf, and (B) downcoast of the Pleasure Pier. It also appears that culturable enterococci bacteria (cENT) concentrations are frequently elevated in pore fluids with brackish salinity. FIB measured in waist deep Bay waters are frequently elevated near the Busy Bee Wharf, and more rarely near the Pleasure Pier.
2. Radon-222 activity measured along the Avalon Bay shoreline lends credence to the idea that shallow groundwater is discharged into the Bay on falling tides.
3. There is additional evidence that FIB may be associated with Bay water containing elevated radon activity and depressed salinity. During one of the shoreline surveys (on 11/12/08), two locations were identified as radon "hot spots" and likely areas of significant shallow groundwater discharge during low tides: southeast of the Pleasure Pier, and near the Busy Bee Wharf.
4. Nearshore currents along the shoreline in Avalon Bay are dominated by boat traffic, including boats docked at the Pleasure Pier and large passenger ferries that run their reverse thrusters continuously while docked at the Mole. Nearshore currents generated from these docking activities typically manifest as westerly current pulses that last approximately 1.5 hours and have peak velocities of approximately 25 cm/s. The nearshore currents could affect FIB concentrations in ankle depth waters in several ways; e.g., by resuspending particle-associated bacteria off of the sediment bed, and by advecting clean (or polluted) water toward the main beach area.
5. Conductivity-Temperature-Depth (CTD) profiles in the nearshore region of Avalon Bay revealed little in the way of temperature, salinity, or depth stratification, as evidenced by relatively low Buoyancy Frequencies (0.013/s). There is a subtle but consistent increase in Bay water salinity during large ebb tides, suggesting that at least a portion of the shallow groundwater discharged to the Bay is hypersaline (i.e., salinity in excess of oceanic salinity).
6. Water samples were collected along a groundwater-to-ocean transect, and analyzed for nitrogen species (nitrate, nitrite, ammonia) and orthophosphate. In addition, samples were analyzed for the relative distribution of the ^{16}O and ^{18}O of oxygen in water. The oxygen isotope studies indicate that, to a first approximation, shallow groundwater beneath Avalon is a variable mixture of meteoric groundwater and recirculated Bay water. Street runoff was isotopically similar to ocean water, probably reflecting the fact that the domestic water supply in the City of Avalon is generated by reverse osmosis desalination. Raw sewage had an isotopic signature

intermediate between ocean water and meteoric groundwater, perhaps reflecting the infiltration of meteoric groundwater into the sewage collection system.

7. The different nitrogenous species measured (nitrate, nitrite, and ammonia) were summed to yield the total dissolved inorganic nitrogen (DIN), and compared to the dissolved inorganic phosphate (DIP) as orthophosphate. Sewage, groundwater, and Avalon Bay water can be distinguished by their DIN and DIP concentrations. The DIN and DIP concentrations measured in several shallow groundwater wells (including inland well IW3 located near the Marlin Club and foreshore well W19 near Step Beach) were consistent with significant levels of sewage contamination, ranging from 1 to 20% by volume.
8. High frequency measurements of FIB, Radon-222 activity, and nutrients next to the Pleasure Pier support the hypothesis that foreshore sands and ankle depth water infuse with FIB-laden shallow groundwater as the hydraulic gradient tilts toward the Bay with the falling tide. Measurements of ammonia and orthophosphate in ankle deep water at the Pleasure Pier also increase with the falling tide.
9. FIB concentrations along the shoreline of Avalon Bay appear to be correlated with several environmental variables, including temperature (negative correlation), onshore wind (positively correlated), and wave period (positively correlated). These associations may reflect the influence of environmental conditions on the sourcing, fate, and transport of FIB in Avalon Bay.
10. Measurements of temperature profiles in foreshore sands reveal that, at specific times during the tidal cycle, pore fluids in the foreshore exhibit an inverse temperature gradient (i.e., colder water sits on top of warmer water) sufficient to cause the convective overturning of pore fluids. Convective turnover of foreshore pore fluids may “eject” FIB laden pore waters into the Bay.
11. Overall, these data support the hypothesis that sewage-contaminated shallow groundwater is discharged to Avalon Bay at specific locations along the shoreline—specifically Pleasure Pier, Busy Bee, and Step Beach. Furthermore, evidence is presented that the seepage face—which forms when water level in the Bay drops below the shallow groundwater table—is contaminated with sewage markers.
12. The possibility that foreshore sediments in Avalon are periodically infused with sewage-contaminated shallow groundwater raises the possibility that human-sand contact may represent a route for the transmission of fecal-oral disease at this site.

Source Identification of FIB in Ankle Depth Waters

A number of recent studies have implicated beaches—either the beach sand itself, or shallow groundwater discharge through the beach face—as the source of FIB impairment in ankle depth waters along the shore[1,2,3,4,5,6]. Yamahara et al[1] describes two scenarios by which FIB from a sandy beach can contaminate near shore waters: *over-beach transport* and *through-beach transport*. During *over-beach transport*, FIB transfer into shoreline waters from the surface of the beach, where they are present in solid materials deposited on the beach surface (e.g., bird droppings, decaying seaweed) or in the interstitial fluids (e.g., from FIB-contaminated runoff). In over-beach transport, FIB are mobilized into the water column as the sand is washed by the tides, and hence ankle-depth water quality should worsen during rising tides, as was observed at Lover's Point beach in ref. 1. During *through beach transport*, FIB transport into nearshore waters by the discharge of shallow groundwater from an FIB-contaminated beach aquifer. Potential sources of FIB in the beach aquifer include regrowth of environmentally adapted FIB strains and/or sewage contamination from leaking sewer lines. Because the marine discharge of shallow groundwater should occur more rapidly during low tide (when the hydraulic gradient of the beach aquifer slopes toward the ocean), in this scenario FIB impairment of nearshore waters should worsen during falling tides, as was observed previously in Avalon Bay.

In Task B.3, field experiments were carried out to determine which of these two scenarios—*over-beach transport* or *through-beach transport*—are responsible for the water quality problems in Avalon Bay. In Task B.3.3, the focus is on evaluating *through-beach transport*, using a combination of natural isotope tracers, nutrient and FIB tests. In Task B.3.4, a set of studies similar to those described in Yamahara et al. are used to evaluate *over-beach transport*.

Task B.3.1. Prepare Draft Work Plan for Source Identification Study

A draft work plan for the FIB Source Identification Study was submitted to City of Avalon Staff and State Water Board personnel on August 15, 2008. Based on feedback, the draft plan was revised and resubmitted as a revised draft plan on September 26, 2008.

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[1] Yamahara, K.M., Layton, B.A., Santoro, A.E., Boehm A.B. (2007) "Beach sands along the California Coast are diffuse sources of fecal bacteria to coastal waters" *Environ. Sci. Technol*. **41**:4515-4521.
[2] Oshiro, R., Fujioka, R. (1995) "Sand, soil, and pigeon droppings—Sources of indicator bacteria in the waters of Hanauma Bay, Oahu, Hawaii" *Water Sci. Technol*. **31**:251-254.
[3] Desmarais, T.R.; Solo-Gabriele, H.M., Palmer, C.J. (2002) "Influence of soil on fecal indicator organisms in a tidally influenced subtropical environment" *Appl. Environ. Microbiol*. **68**:1165-1172.
[4] Whitman, R.L.; Nevers, M.B. (2003) "Foreshore sand as a source of *Escherichia coli* in nearshore water of a Lake Michigan beach" *Appl. Environ. Microbiol*. **69**:5555-5562.
[5] Ferguson, D.M., Moore, D.F., Getrich, M.A., Zhowandai, M.H. (2005) "Enumeration and speciation of enterococci found in marine and intertidal sediments and coastal water in southern California" *J. Appl. Microbiol*. **99**:598-608.
[6] Lee, C.M., Lin, T., Lin, C.C., Kohbodi, G.A., Bhatt, A., Lee, R., Jay, J.A. (2006) "Persistence of fecal indicator bacteria in Santa Monica Bay beach sediments" *Water Res*. **40**:2593-2602.

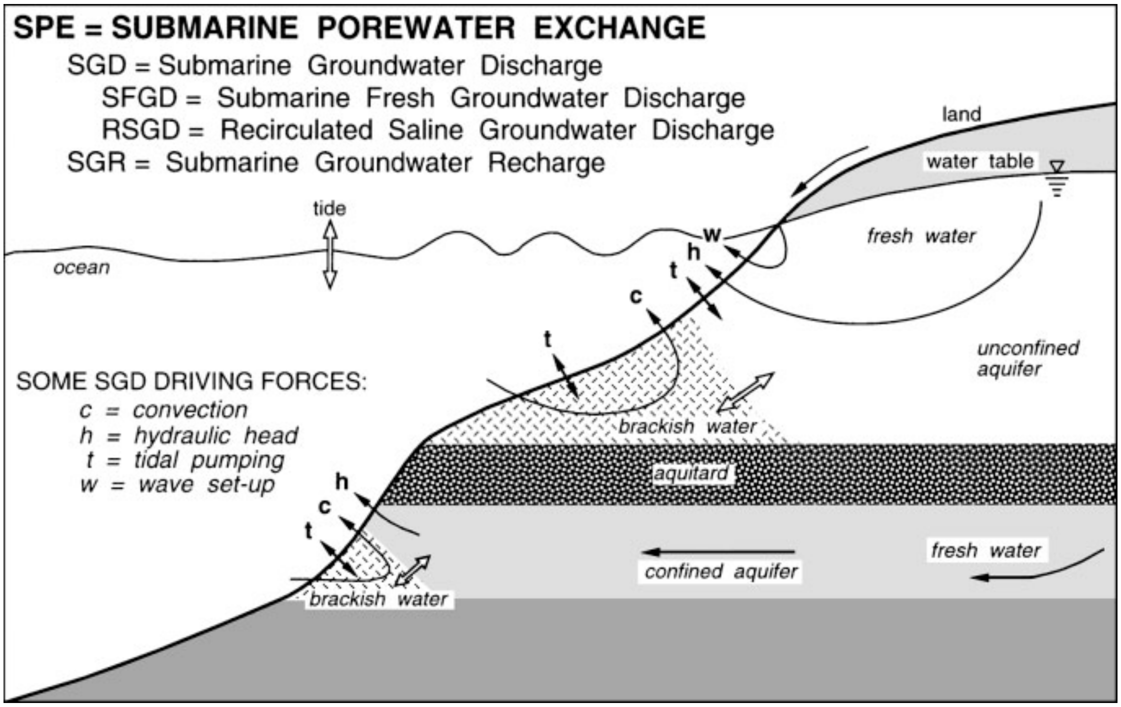

Figure 4-1. Saline groundwater circulation in a coastal groundwater system (taken from Taniguchi et al**)**

Task B.3.2. Prepare Draft Work Plan for Source Identification Study

Based on feedback provided in Task B.3.1, a final work plan for the FIB Source Identification Study was prepared and submitted to City of Avalon Staff and State Water Board personnel on December 12, 2008.

Task B.3.3: Determine if Tidal Exchange of Shallow Groundwater is Source of FIB Contamination

Goal and Background. The field investigations described here are intended to test the hypothesis that sewage contaminated shallow groundwater is the cause of FIB impairment in Avalon Bay. Fig. 4-1, taken from Taniguchi et al[7], summarizes the possible pathways by which shallow groundwater and associated pollutants might flow into Avalon Bay. As described in Burnett et al.[8], these pathways can be described by the source of water discharged to the Bay (meteoric, recirculated seawater, connate waters, or water from human sources, such as leaking sewer lines), the driving force for exchange across the

[7] Taniguchi, M., Burnett, W.C., Cable, J.E., Turner, J.V., 2002. Investigation of submarine groundwater discharge, *Hydrological Processes* 16, 2115-2129.
[8] Burnett, W.C., Bokuniewicz, H., Huettel, M., Moore, W.S., Taniguichi, M. (2003) Groundwater and pore water inputs to the coastal zone, *Biogeochemistry*, 66, 3-33.

sediment/water interface (hydraulic gradient, tidal pumping, wave set-up, density and thermal gradients), and contributing factors (topography, transmissivity, precipitation, evapotranspiration, the frequency and periodicity of tides, geological processes).

Based on the data and results presented in Chapter 2 (Task B.1), it is likely that transfer of water and pollutants across the sediment/water interface along the Avalon Bay shoreline is facilitated by recirculation of seawater through tides and wave set-up (pathways “t” and “w” in Fig. 4-1) and/or flow of meteoric groundwater down the hydraulic gradient (pathway “h” in Fig. 4-1).

Task B.3.3.1: Radon-222 concentrations in ankle depth waters

In this sub-task we set out to answer the following question:

Is there substantial submarine groundwater discharge across the sediments in Avalon Bay, and is that discharge associated with markers of sewage contamination—most notably FIB?

To answer this question, four complementary studies were carried out: (1) alongshore surveys of FIB in waters collected from foreshore pore fluids and waist deep water in the Bay; (2) alongshore surveys of the natural isotope Radon-222 (^{222}Rn) which is a measure of shallow groundwater discharge; (3) measurements of currents in Avalon Bay very near to the shore; and (4) measurements of the vertical structure of salinity, temperature, and density in the shallow region of the Bay. Results of these field studies efforts are described below.

Shoreline Surveys of Fecal Indicator Bacteria.

Approach. Bay water samples were collected from an inflatable boat, and from beach seepage adjacent to the boat. These water samples were analyzed for culturable FIB (cEC and cENT); a subset of samples were analyzed for salinity, and temperature[9]. These shoreline surveys were repeated several times during a period of large spring tides on 11/12/08 and 11/13/08 (Figure 4-2). On each of these dates, field personnel conducted two rounds of sampling. The first round occurred during a large falling tide, and the second round occurred during the subsequent rising tide.

[9]Note that the Work Plan called for screening samples using a nitrate specific probe, but despite manufacturer’s claim to the contrary, the probe was did not function in the oceanic salinity of the Bay water

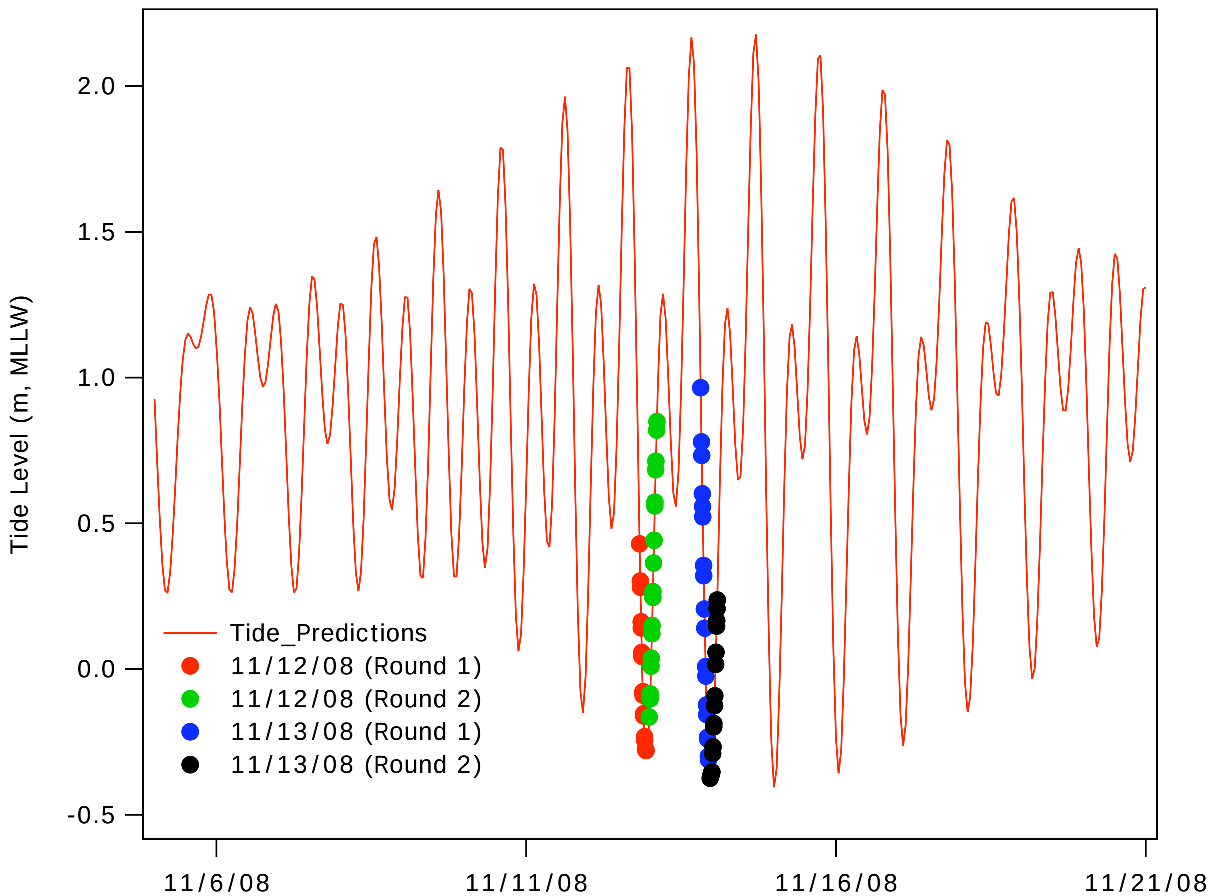

Figure 4-2. Timing of shoreline surveys carried on 11/12/08 and 11/13/08 (in GMT). Two surveys were conducted on each day, during consecutive falling and rising tides.

Results: Round 1 on 11/12/08. Shoreline sampling started at the downcoast (southeast) end of the beach near the Channel site, and progressed upcoast (northwestward) as the tide fell (left panels, Fig. 4-3). cEC and cENT concentrations measured in pore fluids from surficial beach sand exhibit two peaks (top right panel, Fig. 4-3): one peak upcoast of the Busy Bee Wharf (282-326m), and a second peak on the southeast side of the Pleasure Pier (72m). The concentration of pore fluid FIB at these two locations is near, or above, the single sample standards for cEC and cENT in marine bathing waters[10]. Because the tide was falling (see red

[10] The California single sample standards for EC and ENT in marine bathing waters are 400 and 104 MPN/100 mL, respectively. After log-transform, the single-sample regulatory limits equal Log(400)= 2.6 and Log(104)=2.01, respectively.

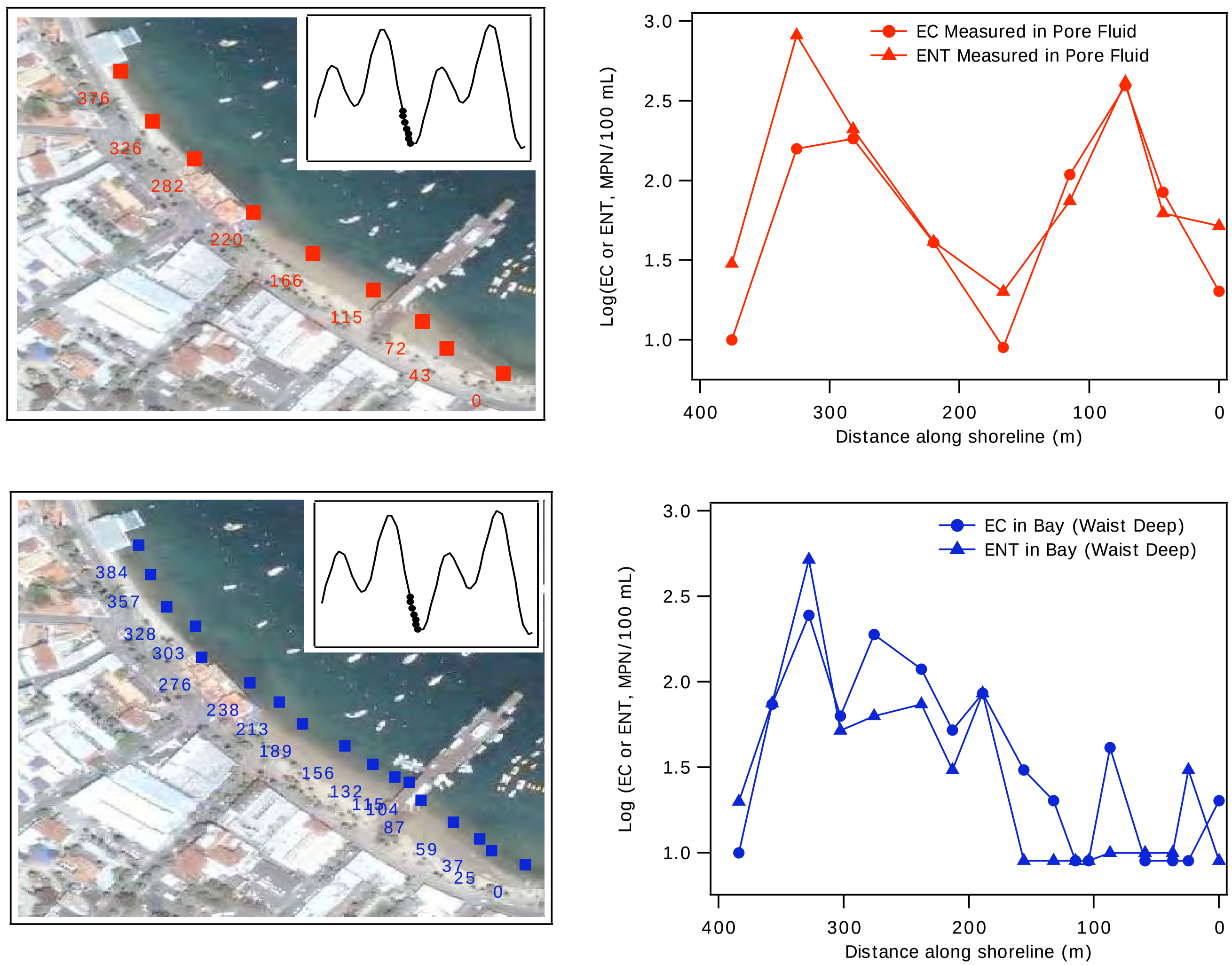

Figure 4-3. Shoreline survey of FIB (EC or ENT) in pore fluids (top two panels) and waist depth water (bottom two panels) during round 1 of sampling on 11/12/08. Figures on left denote sampling locations (numbers indicate distance in meters from the start of the survey, and inset indicates tide level at time of sampling). Right panels represent the log-transformed FIB concentration in the pore fluids of surficial sands (top panel) and in waist depth water (bottom panel).

circles, Figure 4-2), the pore waters collected during this sampling round are probably representative of shallow groundwater seeping out of the beach face into the Bay during low tide. The cENT concentration in waist deep Bay water exceeds the single-sample regulatory limit at one location, upcoast of the Busy Bee Wharf (328 m, bottom right panel, Fig. 4-3). While the rest of the Bay samples were below the regulatory limits for EC and ENT, the concentration of these two indicator bacteria are elevated over a 139 m stretch of shoreline centered on the Busy Bee Wharf (189 To 328 m, bottom right panel, Fig. 4-3).

Round 2 on 11/12/08. Shoreline sampling started at the upcoast end of the beach near the Tuna Club site, and progressed downcoast as the tide rose (left panels, Fig. 4-4). cEC concentrations measured in surficial sand pore fluids were below the single-sample criteria at all sites. cENT concentrations in the pore fluids, on the other hand, are above or near single-sample criteria at three sites: (1) upcoast of Busy Bee Wharf (51 m), (2) on the southeast side of the Pleasure Pier (292 m), and (3) near Channel (369 m). In waist deep Bay water, cENT concentrations exceeded single-sample criteria over a 141 m stretch of shoreline centered on the Busy Bee Wharf. cENT concentration in waist deep Bay water were higher over a broader region of the shoreline during the rising tide, compared to the falling tide (compare bottom right panels in Figs. 4-3 and 4-4).

Round 1 on 11/13/08. Sampling for this round progressed downcoast during a falling tide, but different regions of the shoreline were sampled for surficial sand pore fluid and waist deep Bay water. In the former case, sampling was limited to ~200 m stretch of beach centered at the Pleasure Pier, from Busy Bee Wharf to Channel (top left panel, Figure 4-5). Sampling of waist deep Bay water, on the other hand, took place over the same stretch of shoreline sampled previously, from Tuna Club to Channel (bottom left panel, Figure 4-5). With one exception, pore fluids collected from surficial sands had oceanic salinities (34.5) and FIB concentrations below the single-sample criteria. The exception was pore fluid collected from the southeast side of the Pleasure Pier, for which the salinity was very low (0) and cEC concentration was very high (2,800 MPN/100 mL) (top right panel, Fig. 4-5). Interestingly, the cENT concentration in this pore water sample was below the detection limit (<10 MPN/100 mL). In waist deep Bay water, the concentration of cEC exceeded regulatory criteria at one location—on the northwest corner of the Busy Bee Wharf at 110 m (lower right panel, Fig. 4-5). Although below the criteria, cEC is also elevated in waist deep Bay water collected upcoast of the Pleasure Pier at 255 m (lower right panel, Fig. 4-5). cENT in waist deep Bay water was below the single-sample criteria at all sites, and salinities were oceanic in all cases (lower right panel, Fig. 4-5).

Round 2 on 11/13/08. Sampling for this round progressed from downcoast during a rising tide, from Tuna Club to Channel (left panels, Fig. 4-6). cENT concentrations in surficial sand pore fluids were above the single-sample regulatory standards at two locations: (1) in front of, and to the northwest of, Busy Bee Wharf (0 to 141 m); and (2) on the southeast edge of the Pleasure Pier (290 m). Interestingly, the salinity of pore fluids at these two locations is brackish, indicating that the pore waters there are a mixture of Bay water

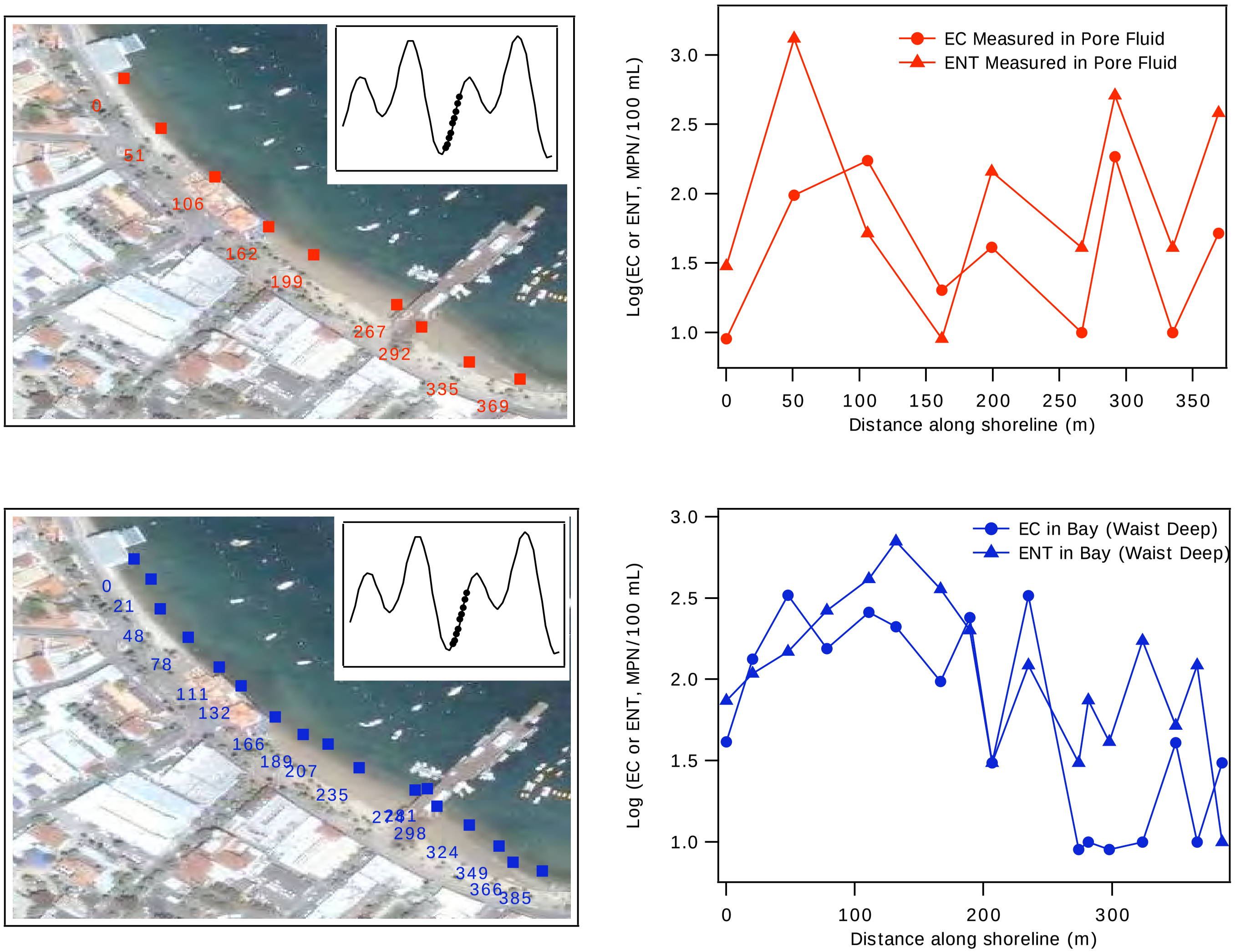

Figure 4-4. Shoreline survey of FIB (EC or ENT) in pore fluids (top two panels) and waist depth water (bottom two panels) during round 2 of sampling on 11/12/08. Figures on left denote sampling locations (numbers indicate distance in meters from the start of the survey, and inset indicates tide level at time of sampling). Right panels represent the log-transformed FIB concentration in the pore fluids of surficial sands (top panel) and in waist depth water (bottom panel).

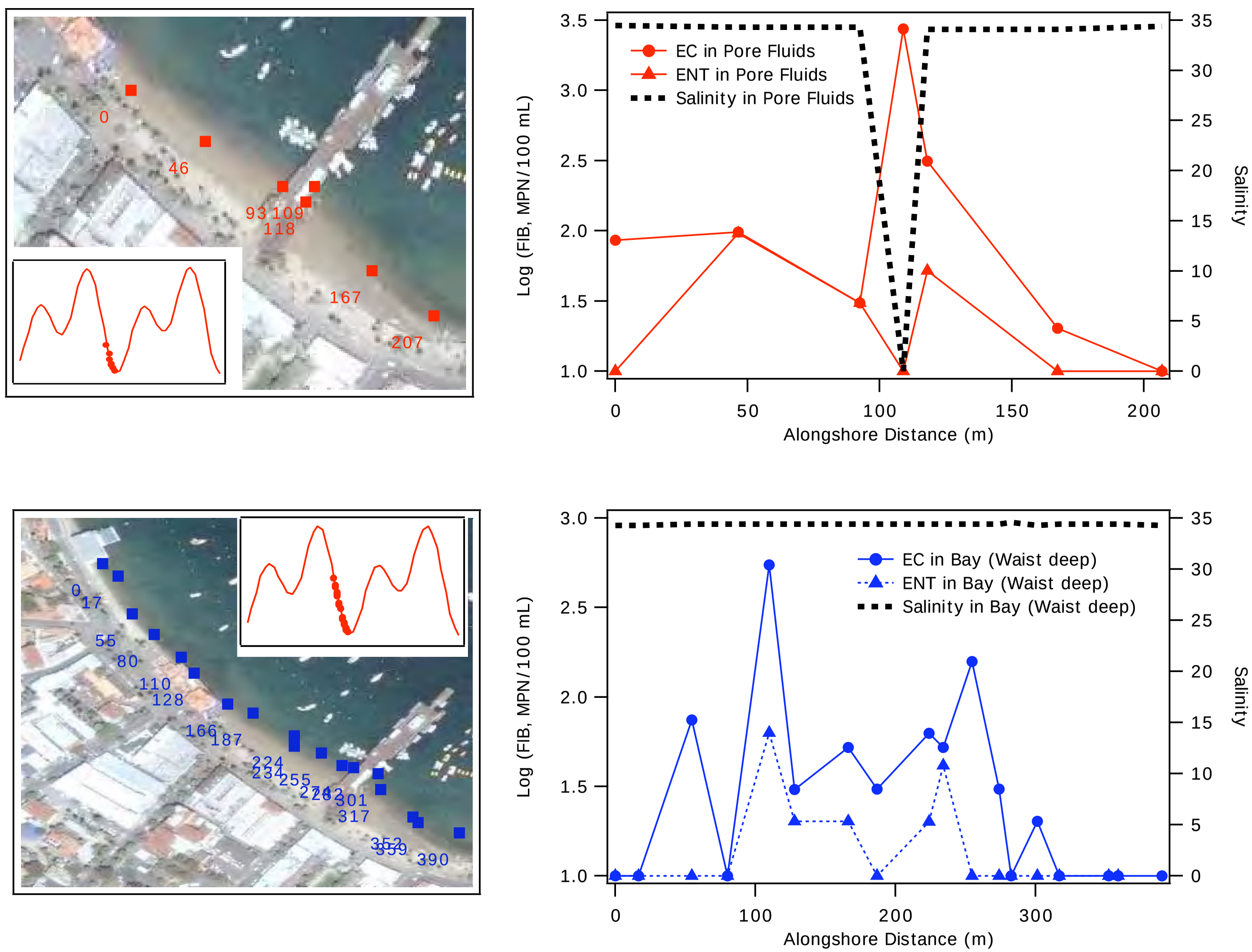

Figure 4-5. Shoreline survey of FIB (EC or ENT) in pore fluids (top two panels) and waist depth water (bottom two panels) during round 1 of sampling on 11/13/08. Figures on left denote sampling locations (numbers indicate distance in meters from the start of the survey, and inset indicates tide level at time of sampling). Right panels represent the log-transformed FIB concentration in the pore fluids of surficial sands (top panel) and in waist depth

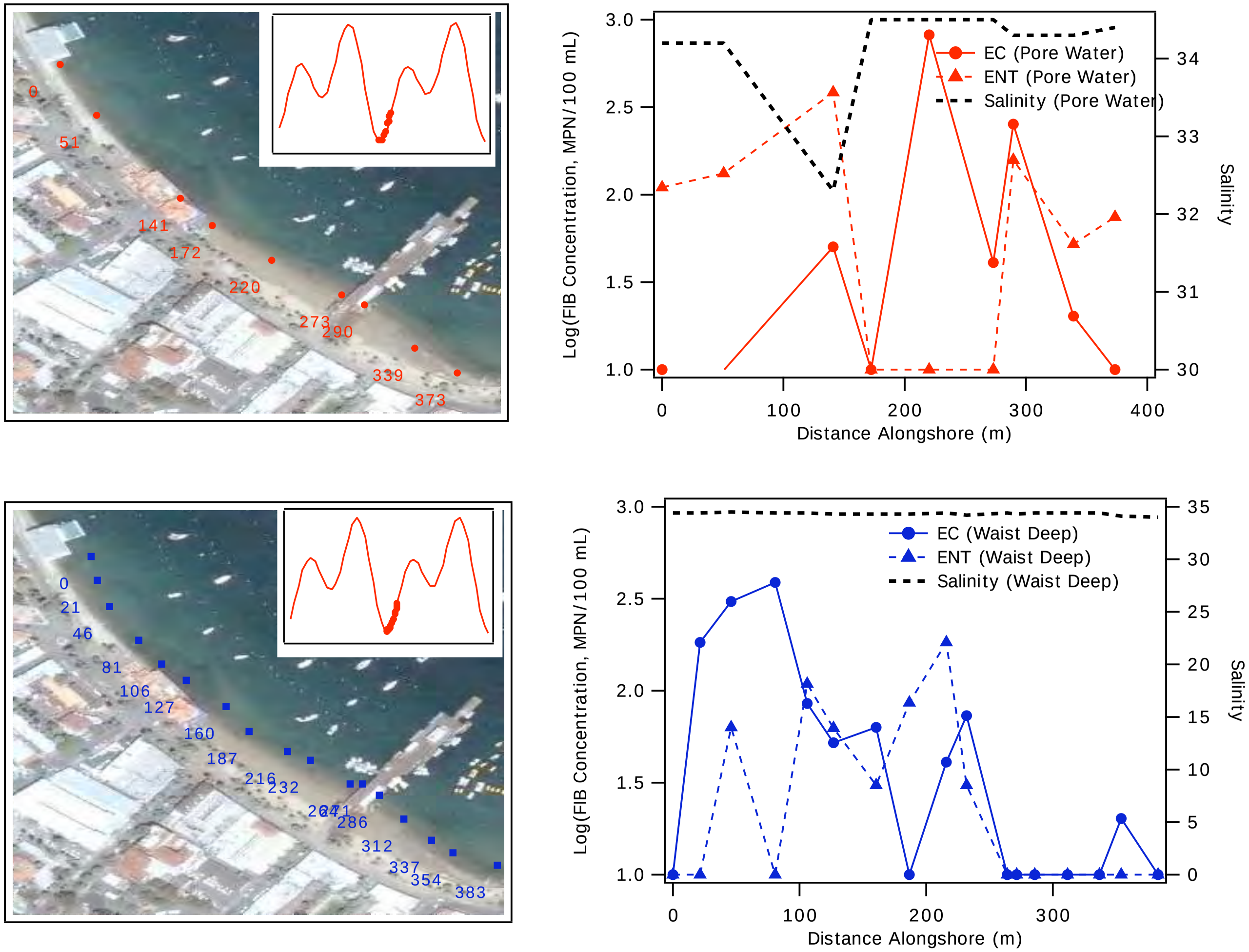

Figure 4-6. Shoreline survey of FIB (EC or ENT) in pore fluids (top two panels) and waist depth water (bottom two panels) during round 2 of sampling on 11/13/08. Figures on left denote sampling locations (numbers indicate distance in meters from the start of the survey, and inset indicates tide level at time of sampling). Right panels represent the log-transformed FIB concentration in the pore fluids of surficial sands (top panel) and in waist depth water (bottom

and lower salinity water. cEC concentration in surficial sand pore fluids is above regulatory single-sample limits at a single location, between the Busy Bee Wharf and Pleasure Pier at 220 m. In waist deep Bay water, cEC concentrations are elevated in a 40 m region of the shoreline northwest of the Busy Bee Wharf (21 through 81m, lower right panel, Fig. 4-6). cENT concentrations in waist deep Bay water are above regulatory single-sample limits at two locations, on the northwest edge of the Busy Bee Wharf (106 m) and between the Busy Bee Wharf and the Pleasure Pier (216 m) (lower right panel, Fig. 4-6). Salinity in waist deep Bay water is oceanic, except near Channel where it is slightly brackish (ca., 32).

Summary and Overall Assessment. FIB concentrations measured in pore fluids collected from surficial sands were near or above single-sample criteria for marine bathing waters at the following sites:

- Upcoast of the Busy Bee Wharf and on the southeast side of the Pleasure Pier (both cEC and cENT, sampling round 1, 11/12/08). No salinity measurements available for this round.
- Upcoast of the Busy Bee Wharf, on the southeast side of the Pleasure Pier, and at Channel (cENT only, sampling round 2, 11/12/08). No salinity measurements available for this round.
- On the southeast side of the Pleasure Pier (cEC only); salinity very low at this site (sampling round 1, 11/13/08)[11].
- Northwest edge of the Busy Bee Wharf and on the southeast edge of the Pleasure Pier (cENT only); salinity brackish at these two sites (sampling round 2, 11/13/08).

FIB concentrations measured in samples collected from waist deep Bay Water were near or above single-sample criteria for marine bathing waters in California at the following sites:

- 139 m stretch of shoreline centered on the Busy Bee Wharf (both cEC and cENT, sampling round 1, 11/12/08). No salinity measurements available for this round.
- 141 m stretch of shoreline centered on the Busy Bee Wharf (cENT only, sampling round 2, 11/12/08). No salinity measurements available for this round.
- Northwest edge of Busy Bee Wharf (cEC only, sampling round 1, 11/13/08). All samples had oceanic salinities.
- 40 m region of the shoreline upcoast of the Busy Bee Wharf (cEC only), northwest edge of the Busy Bee Wharf (cENT only), and between the Busy Bee Wharf and the Pleasure Pier (cENT only) (sampling round 2, 11/13/08). Salinities are oceanic at all sites, except near Channel where salinities are slightly brackish.

Based on the above evidence, FIB concentrations in surficial sand pore fluids are consistently elevated at two locations: (1) in front of, and upcoast of, the Busy Bee Wharf, and (2) on the

[11] Note also that the region around Busy Bee Wharf was not sampled during this round.

southeast edge of the Pleasure Pier. It also appears that ENT concentrations are frequently elevated in pore fluids that have brackish salinity, indicating that the contaminated pore water consists of a mixture of Bay water and lower salinity water of unknown origin. FIB measured in waist deep Bay waters are frequently elevated near the Busy Bee Wharf, and more rarely near the Pleasure Pier.

Shoreline Surveys of Radon-222.

Approach. A naturally occurring isotope of radon (^{222}Rn) is used here to obtain information on the flow of shallow groundwater into Avalon Bay from both recycled and meteoric water (pathways "t", "w", and "h" in Fig. 4-1). This particular isotope is well suited for assessing inputs of shallow groundwater to the Bay for three primary reasons: (1) it is typically 100 to 1000 fold enriched in groundwater, relative to coastal waters, (2) its half-life (of 3.83 days) is long enough to yield information on the tidal exchange of shallow groundwater with the Bay, and (3) it lacks chemical reactivity and does not adsorb to particle surfaces. Its primary disadvantages are that it partitions readily into the atmosphere (at equilibrium, there is about 4 times as much radon is in the air phase relative to the water phase), and there are several potential sources, in addition to the advective input from groundwater, that must be accounted for. However, methods have been developed to address the disadvantages just listed, and as a result ^{222}Rn is finding increasing use as both a qualitative and quantitative[12] tracer of shallow groundwater inputs to the coastal ocean, including on Catalina Island at Catalina Harbor [13].

Methods. To obtain in situ and real time estimates of the ^{222}Rn activity in Avalon Bay, we used a RAD-7 radon-in-air sensor combined with a RAD AQUA air/water exchanger (Durridge Company, Bedford, MA).[14] The instrument works by equilibrating a stream of water (in our case from Avalon Bay) with a stream of air that is continuously circulated through the RAD-7 instrument. A silicon detector in the RAD-7 senses the alpha decay of Polonium 218, a daughter of ^{222}Rn. Because the half-life of ^{218}Po is relatively short ($t_{1/2}$=3.10 min.), the RAD-7 instrument equilibrates quickly to new activities of ^{222}Rn in the water, in approximately 20 to 30 minutes[15,16,]. For the set of experiments described below, we used a

[12] Santos, I.R., Niencheski, F., Burnett, W., Peterson, R., Chanton, J., Andrad, C.F.f., Milani, I.B., Schmidt, A., Knoeller, K. (2008) "Tracing anthropogenically driven groundwater discharge into a coastal lagoon from southern Brazil" *J. Hydrology* v. **353**, 275-293.

[13] Colbert, S.L., Berelson, W.M., Hammond, D.E. "Radon-222 budget in Catalina Harbor, California: 2. Flow dynamics and residence time in a tidal beach" *Limnology and Oceanography*, in press.

[14] Kim, G., Burnett, W.C., Dulaiova, H., Swarzenski, P.W., Moore, W.S. (2001) "Measurements of ^{224}Ra and ^{226}Ra activities in natural waters using a radon-in-air monitor" *Environmental Science and Technology* **35**, 4680-4683.

[15] Burnett, W.C., Dulaiova, H. (2003) "Estimating the dynamics of groundwater input into the coastal zone via continuous radon-222 measurements" *J. Environ. Radioactivity* **69**: 21-35.

[16] Dulaiova, H., R. Peterson, W.C. Burnett, D.Lane-Smith (2005) "A multi-detector continuous monitor for assessment of 222Rn in the coastal ocean" *J. Radioanalytical and Nuclear Chemistry* **264**:361-365.

single Rad-7 (together with the RAD AQUA) deployed in a small zodiac to obtain measurements of ^{222}Rn along the shoreline of Avalon Bay.

The RAD-7 and RAD AQUA were installed in a small (5 foot) zodiac, which was rowed from site-to-site along the perimeter of Avalon Bay. Water was pumped (Portable Peristaltic Pump, Cole Parmer, City, State) from a point approximately 5 cm below the water surface off the stern of the boat into a RAD AQUA water/air exchanger affixed to the stern bulkhead. The RAD-7 was placed in the boat near the stern, and encased in a plastic bag to keep the instrument dry. The RAD-7 was configured with a cycle time of 15 minutes. The sampling protocol was as follows. The zodiac was paddled to a particular location along the shore and anchored in waist deep water. RAD-7 counting was commenced, and allowed to continue for 15 minutes. At the end of 15 minutes, the RAD-7 reported a ^{222}Rn activity, the anchor was lifted, and the boat was paddled to the next site where the entire process just described was repeated. This protocol was repeated every ~100 m along the shoreline, until most of the main beach area in Avalon Bay had been traversed[17]. Sampling of ^{222}Rn from the zodiac was coincident with sampling of surficial sand pore water and waist deep Bay water for FIB, as described above.

Results: Round 1 and 2 Sampling on 11/12/08. Radon data collected during the mobile deployment of the RAD-7 on 11/12/08 are plotted against alongshore distance in Fig. 4-7. During the first round of sampling on 11/12/08 the zodiac was traveling in an upcoast direction (from Channel to Busy Bee Wharf) during a falling tide (see map, top right panel, Fig. 4-7). During this first round of sampling on 11/12/08 two prominent peaks in ^{222}Rn activity were observed: one on the southeast side of the Pleasure Pier (at 87 m) and another on the southeast side of the Busy Bee Wharf (at 213 m) (top left panel, Fig. 4-7). During the second round of sampling on 11/12/08, the zodiac was traveling in a downcoast direction (from Tuna Club to Channel) during a rising tide (bottom left panel, Fig. 4-7). During this second round of sampling the same two radon peaks were observed: one on the southeast side of the Busy Bee Wharf (at 166 m) and another smaller peak on the southeast side of the Pleasure Pier (at 298 m).

While the radon measurements were being carried out in the zodiac, water samples were collected from the pore fluids of surficial sands on the beach, and in waist deep waters from the zodiac (see above). Interestingly, the locations of the two radon peaks coincide with the locations of the highest FIB concentrations measured in the surficial sand pore fluids (compare top two panels in Fig. 4-3 with top two panels in Fig. 4-7). Furthermore, FIB concentrations were very high in waist deep waters in front of the Busy Bee Wharf, in the same location (and at the same time) that elevated radon activities were observed (compare Figures 4-3, 4-4, and 4-7).

[17] The aspirator in the water/air exchanger sometimes clogged with sand and small particles, reducing the flow of water through the system. This problem was eventually corrected by utilizing the largest aspirator provided with the RAD AQUA.

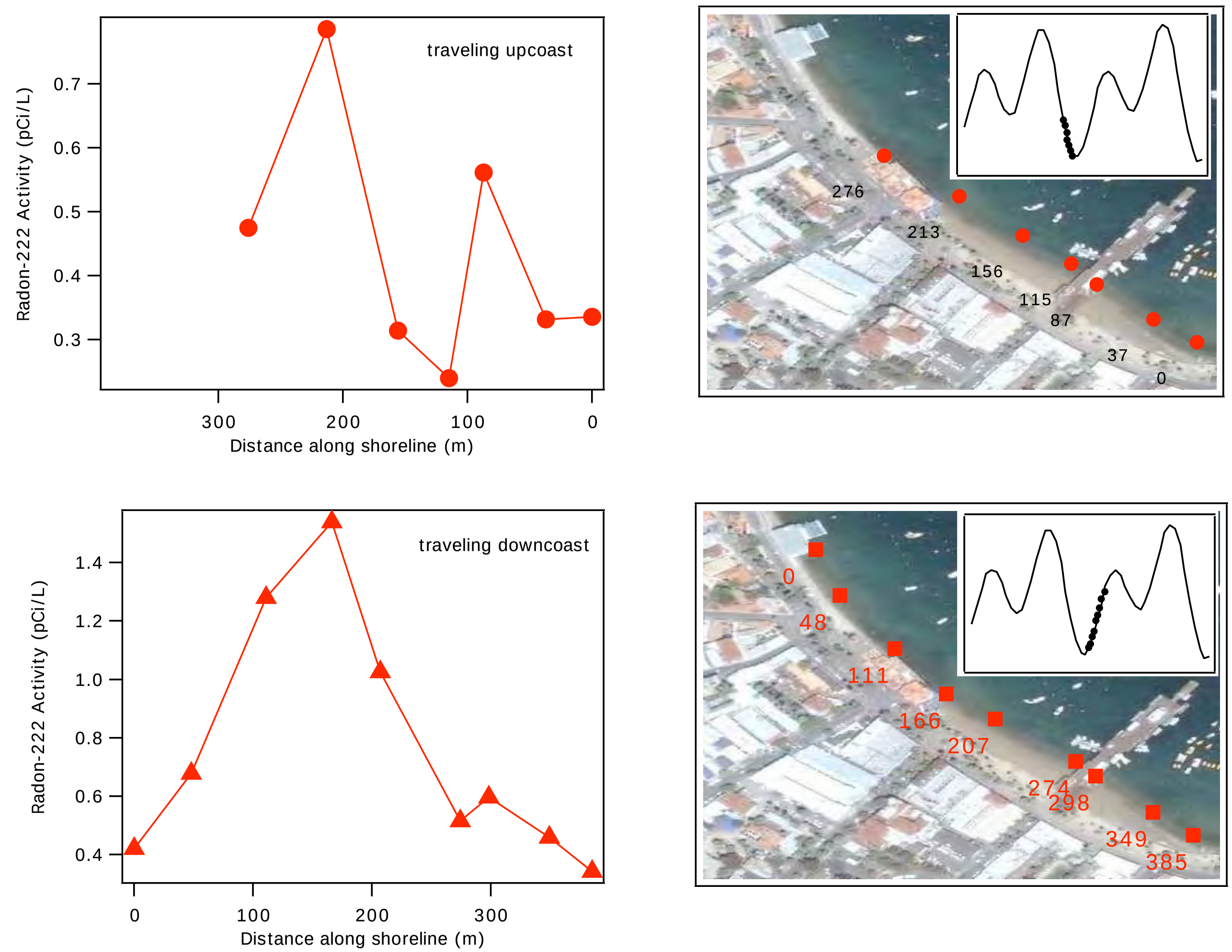

Figure 4-7. Shoreline surveys of radon activity during the mobile deployment of the Rad-7 instrument on 11/12/08. Figures on right denote sampling locations (numbers indicate distance in meters from the start of the survey, and inset indicates tide level at time of sampling). Left panels are radon in waist depth water during round 1 (top panel) and round 2 (bottom panel).

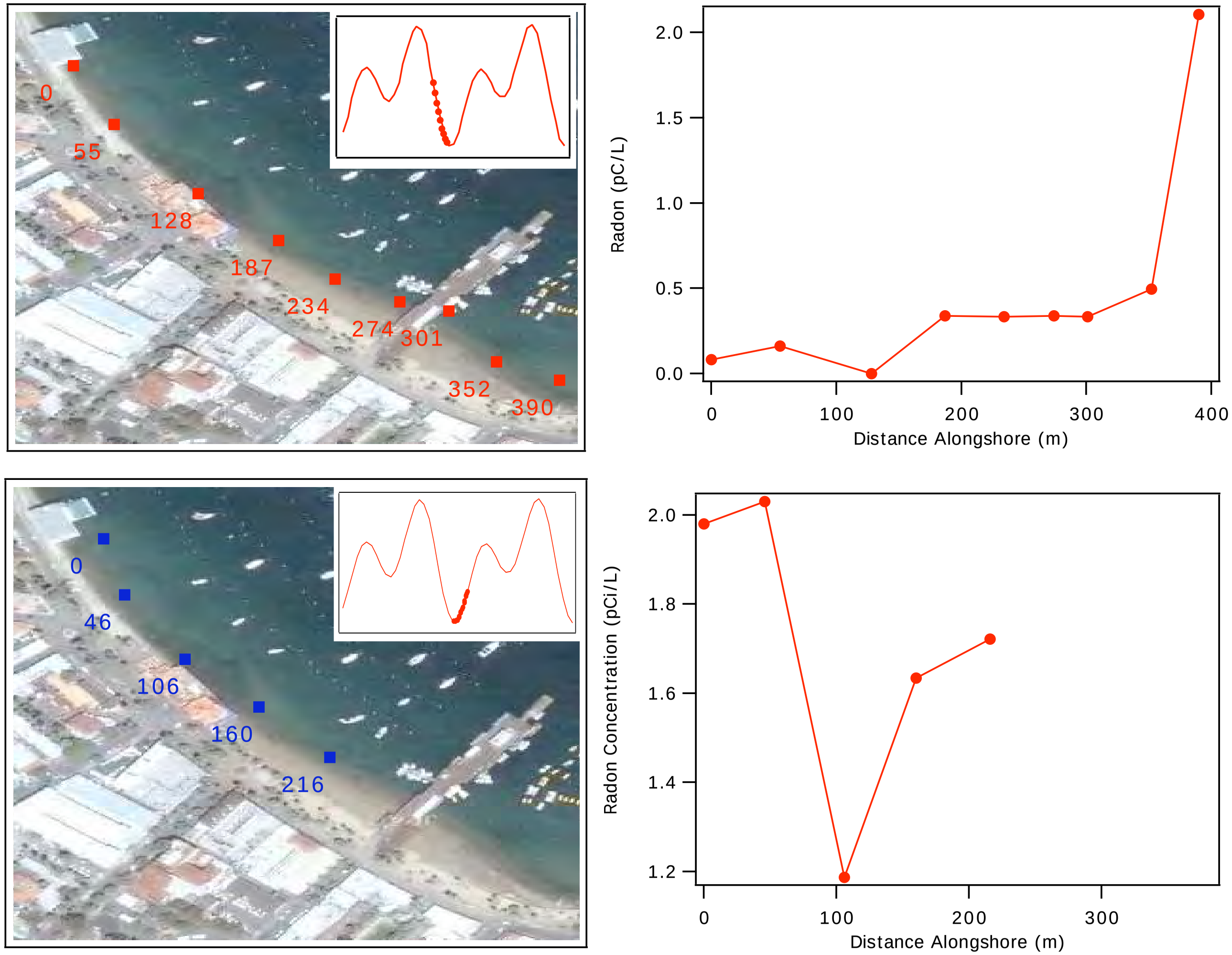

Figure 4-8. Shoreline surveys of radon activity during the mobile deployment of the Rad-7 instrument on 11/13/08. Figures on left denote sampling locations (numbers indicate distance in meters from the start of the survey, and inset indicates tide level at time of sampling). Right panels are radon measured in waist depth water during round 1 (top panel) and round 2 (bottom panel).

Results: Round 1 and 2 Sampling on 11/13/08. Radon data collected during the mobile deployment of the RAD-7 on 11/13/08 are plotted against distance alongshore in Fig. 4-8. During the first round of sampling the zodiac was traveling downcoast, from Tuna Club to Channel, on a falling tide (see map, top right panel, Fig. 4-8). Radon-222 activity was generally low between Tuna Club and Busy Bee Wharf, increased to approximately 0.5 pCi/L between Busy Bee Wharf and southeast of the Pleasure Pier, and then peaked at >2 pCi/L at Channel. This radon distribution differs from the one observed on the previous day, when distinct radon peaks were observed southeast of the Pleasure Pier and southeast of the Busy Bee Wharf (see Fig. 4-7). The zodiac was travelling upcoast on a falling tide on 11/12, and downcoast on a falling tide on 11/13. If the radon activity is tidally modulated, then we expect that the radon peak at the Busy Bee Wharf would be observed only during or following low tide, consistent with the radon pattern observed on 11/12 (when the water in front of the Busy Bee Wharf was sampled at low tide) and on 11/13 (when the water in front of the Busy Bee Wharf was sampled prior to the low tide). During the round 2 sampling on 11/13/08, the zodiac was traveling downcoast on a rising tide, but a relatively small region of the beach was sampled (from Tuna Club to northwest of the Pleasure Pier, bottom panels, Figure 4-8). Radon activities measured during this second round were elevated (> 1 pCi/L) at all sites, and especially high (~2 pCi/L) at the two sites located northwest of the Busy Bee Wharf (bottom right panel, Figure 4-8).

Summary of Radon Results. The radon data presented in this report supports the hypothesis that shallow groundwater discharge occurs at specific locations along the Avalon Bay shoreline. During one of the mobile deployments (on 11/12/08), two locations were identified as radon "hot spots" and likely areas of significant shallow groundwater discharge during low tides: southeast of the Pleasure Pier, and near the Busy Bee Wharf. In Chapter 2 of this report (Task B.1.) these two locations were identified, based on shallow groundwater sampling, as areas where sewage contaminated shallow groundwater may be present.

Currents in Avalon Bay near the Shore.

Goal. The goal of this field effort was to measure very nearshore currents in Avalon Bay, and determine if along and/or cross-shore currents very close to Main Beach might affect the distribution of FIB, and other markers of sewage contamination, along the shoreline. There were two primary current measurement efforts, referred to below as the "Pleasure Pier Study" and "Bay-Wide Study".

Pleasure Pier Study: Approach. An upward-looking acoustic Doppler current profiler (ADCP, Workhorse Monitor 1200Hz, RD Instruments, Poway, CA) was mounted to a tripod "Sea Spider" (Ocean Sciences, Oceanside, CA) and deployed from the south (downcoast) side of the Pleasure Pier in 3 to 5 m of water. The instrument was set to record water currents in 55 depth bins at a sampling frequency of 1Hz.

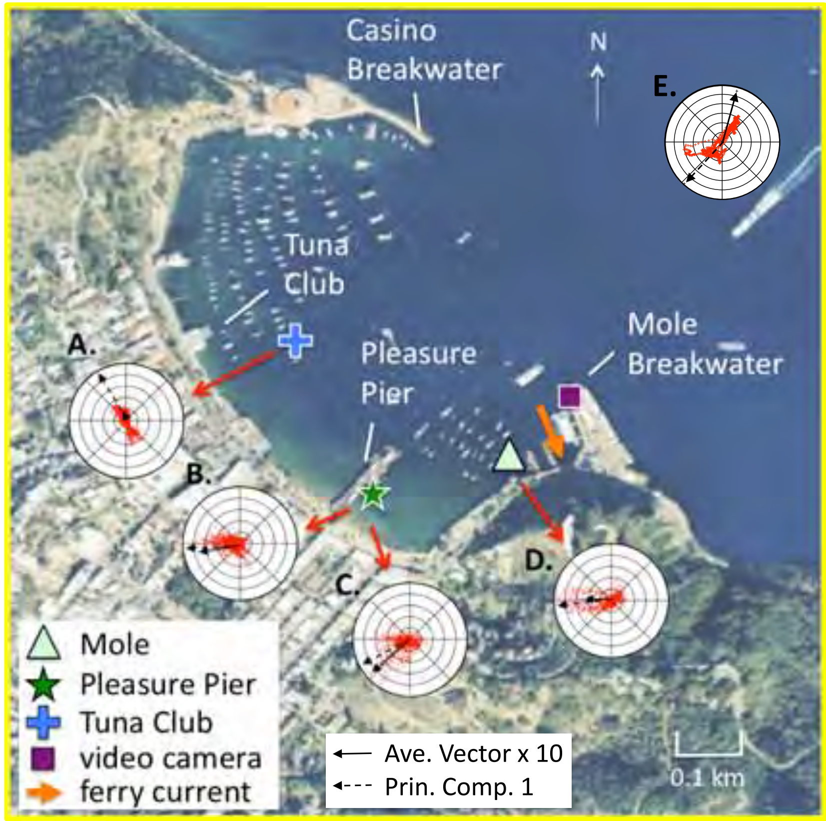

Figure 4-9. Polar plots A through D display depth-averaged current velocities measured at three sites close to the shoreline in Avalon Bay (Tuna Club, Pleasure Pier, and Mole). The outer ring of these polar plots corresponds to a velocity of 0.3 m/s. Polar plot E displays the wind velocity measured on top of the lifeguard station on the Pleasure Pier. Dashed arrow denotes first-principal component of current data.

Pleasure Pier Study: Results. ADCP measurements at the Pleasure Pier reveal a strong (10 to 30 cm/s) and persistent west to southwest current in the shallow waters close to the Main Beach area in downtown Avalon (Fig. 4-9). Westerly currents at the Pleasure Pier are oriented approximately 45° to the shore, and thus have components in both the onshore and upcoast directions. The first principal component of these data accounts for between 61 to 85% of the data variance (depending on the deployment), and is oriented west to southwest across all six ADCP deployments (Fig. 4-9).

Currents measured at the Pleasure Pier are organized into sets of 4 to 10 discrete pulses, where each pulse lasts approximately 1.5 hours. This pattern is illustrated in Fig. 4-10, where the depth-averaged westerly current measured at the Pleasure Pier is plotted against time of day. Each trace in the figure corresponds to a different day, after separating current

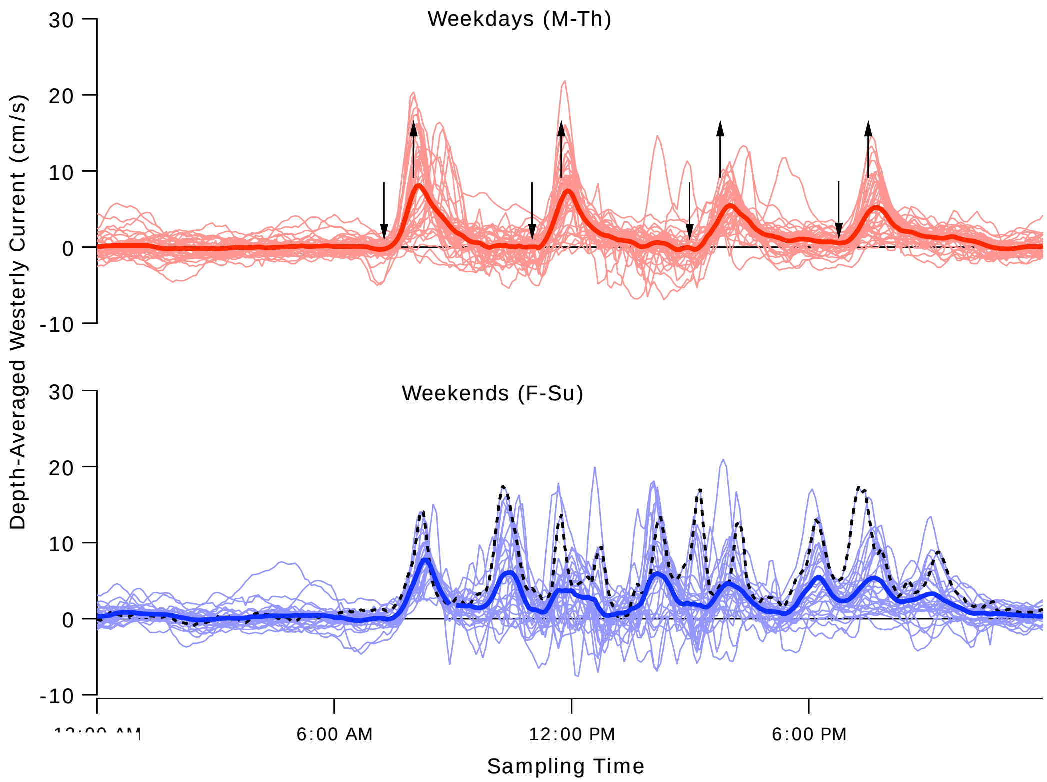

Figure 4-10. Depth-averaged westerly current measured at the Pleasure Pier, plotted against time of day. The current velocities are separated into those measured during weedays (top panel) and those measured during weekends (bottom panel).

measurements into those measured during weekdays (top panel) and those measured during weekends (bottom panel). On a typical weekday, four distinct current pulses are evident, beginning at approximately 07:00 in the morning and ending about 08:00 in the evening. The number of current pulses increases to approximately 8 per day during a typical non-holiday weekend (lower panel, Fig. 4-10) and 10 per day on holidays (e.g., Valentine's Day 2009, black dashed line in lower right panel, Fig. 4-10).

The timing of the four weekday pulses is similar to the docking schedule for large (86 to 99 ton, 97'-145') ferries that transport up to ~150 passengers each between Avalon and the mainland. These ferries do not dock at the Pleasure Pier, but rather at a dock located 200 m to the northeast at a facility referred to as the "Mole" (Fig. 4-9). The average weekday pulse pattern (denoted by the dark red line, upper panel, Fig. 4-9) coincides closely with the scheduled arrival and departures times of ferries at the Mole, which are indicated in Fig. 4-10 (upper panel) by down & up arrows, respectively. Current pulses that do not conform to the ferry schedule appear to be caused by smaller boat traffic at the Pleasure Pier near where the ADCP was deployed (data not shown).

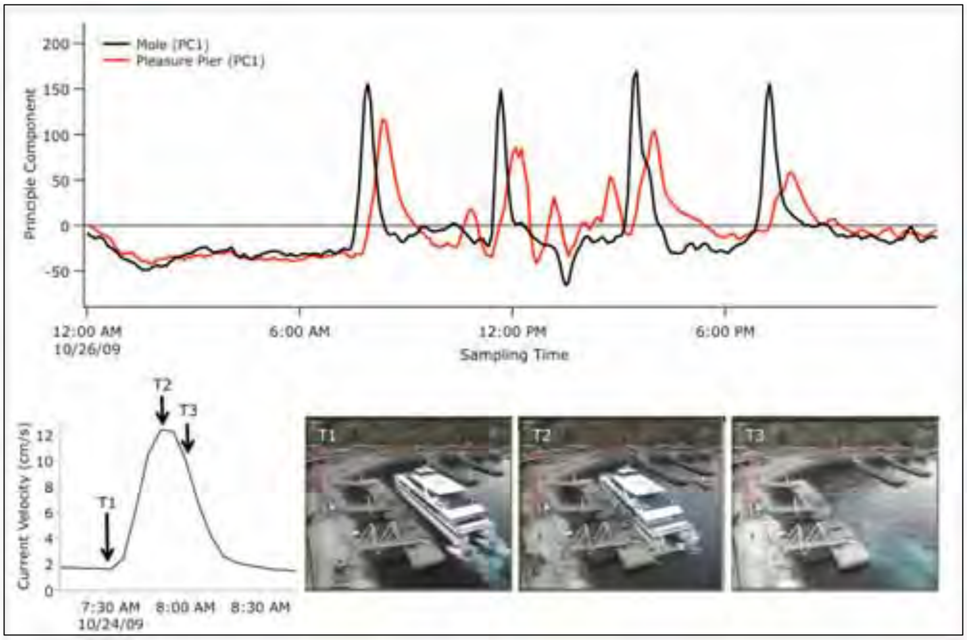

Figure 4-11. Top panel: Comparison of the depth-averaged current velocities measured at the Mole (Black line) and Pleasure Pier (red line). Bottom panel: timing of a single current pulse relative to the arrival and departure of a ferry at the Mole site.

Bay-wide Study: Approach. To better understand the relationship between ferries docking at the Mole and nearshore currents in Avalon Bay, a second study was carried out in which three ADCPs were simultaneously deployed: (1) near where the ferries dock (Mole), (2) at the Pleasure Pier site, and (3) north-west of the Pleasure Pier (Tuna Club) (Fig. 4-9). ADCP measurements at the Mole site reveal strong (upwards of 25 cm/s) and persistent westerly currents (Fig. 4-9D). The first-principal component of these data is oriented west, as is the time-averaged current. Westerly currents at the Mole exhibit a pulsing pattern very similar to the one just described for the Pleasure Pier; namely, 4 distinct pulses are evident during weekdays, and 6 to 8 pulses are evident during weekends.

When the first principal components of depth-averaged currents measured at the Mole and Pleasure Pier sites are co-plotted against time (top panel, Fig. 4-11), it is clear that the current pulse arrives first at the Mole site and then later at the Pleasure Pier site. Cross-correlation of these two signals reveals that, on average, the Pleasure Pier pulse lags the Mole pulse by approximately 30 min. Dividing the time lag between Mole and Pleasure Pier (~30 min.) into the approximate distance separating these two sites (~200 m) yields a propagation velocity of ~10 cm/s, which is close to the peak current velocities measured at both sites. Currents measured at the Tuna Club site do not exhibit a pulsing pattern described at the Mole and Pleasure Pier sites. Instead, the first principal component of depth-averaged currents at Tuna displays relatively long (>20 h) periods of either up-coast or down-coast flow.

Time stamped video images of the ferry dock (obtained from Avalon Harbor Patrol) were examined frame-by-frame and compared to measured currents. One such comparison is illustrated for a single current pulse measured at the Mole site in Fig. 4-11 (bottom panel). The onset of the westerly current pulse at the Mole site occurs several minutes after the arrival of a ferry at the dock (T1). The pulse peaks after the ferry has been docked for about 20 minutes (T2), and the pulse rapidly decays after the ferry leaves (T3) (bottom panel Fig. 3). When ferries dock at the Mole, they continuously run their reverse thrusters, pulling water from the Bay against the shoreline. This practice appears to "pile up" water along the shoreline near the mole, which in turn causes a gravitationally driven clockwise circulation to develop around the perimeter of Avalon Bay. It is this gravity-driven clockwise circulation that appears to be responsible for the westerly current pulses measured both near the Mole (Bay-wide deployment) and Pleasure Pier (both Bay-wide and Pleasure Pier deployments).

ADCP Study of Avalon Bay: Summary. Currents very close to the shoreline in Avalon Bay are dominated by boat traffic, and in particular ferries docked at the Mole. The vector of these currents at the Pleasure Pier is directed at a 45 degree angle to the shore, implying that there are both cross-shore and alongshore (upcoast) components to the flow. Analysis is ongoing to assess the degree to which these currents act to either resuspended particles off of the sediment bed, and/or transport clean (or contaminated) water from the Mole site into the main beach area of Avalon, near the Pleasure Pier.

Vertical Profiles of Water Temperature, Salinity, and Density.

Goal and Approach. Coincident with the shoreline sampling of Bay water and foreshore pore fluids described above, conductivity-temperature-depth (CTD) casts were carried out from a small (17') research vessel tied to a float on the northwest side of the Pleasure Pier in Avalon Bay. The CTD provides information on the vertical structure of temperature, salinity, and density. Briefly, CTD casts were conducted every 30 minutes for 36 hours starting in the evening of 10/29/08, and again while water samples were being collected from foreshore pore fluids and waist deep Bay water. The CTD data were captured and processed with custom programming routines written and implemented in the data analysis program Igor v. 6.1 (WaveMetric Inc., Oswego, OR). Data products generated from Igor include two-dimensional (depth and time) gridded plots of (1) temperature, (2) salinity, (3) density, and (4) Buoyancy Frequency. Buoyancy Frequency (N) is a measure of water column stratification, and is calculated from the density profile data. Values of the Buoyancy Frequency >0.2/s indicate a highly stratified water column; values <0.02/s indicate a very weakly stratified water column.[18]

[18] Mikkelsen, O.A., Milligan, T.G., Hill, P.S., Chan, R.J., Jago, C.F., Jones, S.E., Krivtsov, V., Mitchelson-Jacob, G. (2008) "The influence of schlieren on in situ optical measurements used for particle characterization" *Limnology and Oceanography: Methods* **6**:133-143.

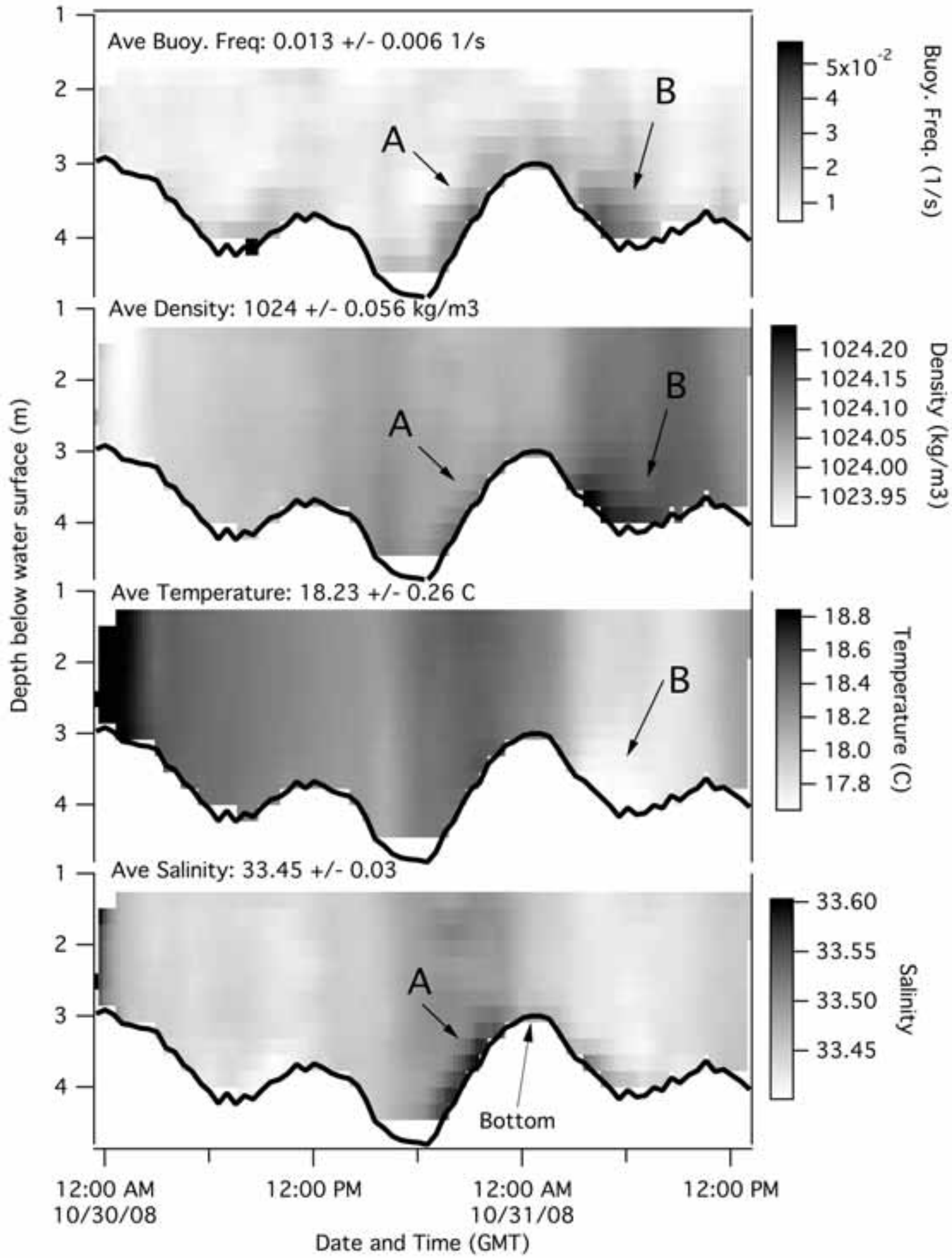

Figure 4-12. Data obtained from the first CTD study in Avalon Bay. Note all times are in GMT.

Results. Three CTD studies of Avalon Bay were conducted. The first study began on 10/29/08 (23:30 GMT) and lasted for several days. The second began during a falling tide on 11/12/08 (21:03 GMT). The third began during a falling tide on 11/13/08 (20:35 GMT). The last two CTD studies lasted approximately 6 hours each, and coincided with the shoreline surveys of surficial sand pore water and waist deep Bay water described above. Each CTD study yielded a time series of vertical profiles for four different water parameters—salinity, temperature, density, and Buoyancy Frequency. To ease interpretation, data from each CTD study were interpolated onto an evenly spaced grid, and plotted as gray scale plots (Fig. 4-12).

During the first CTD study, water parameters changed relatively little with either depth or time (Fig. 4-12). Salinity varied between 33.4 and 33.6, temperature varied between 17.6 and 18.8 C, density varied between 1023.9 and 1024.24, and the Buoyancy Frequency varied between <0.01 to 0.055 1/s (Fig. 4-12). The average Buoyancy Frequency for this study was 0.013/s, less than the threshold of 0.02/s indicative of very weak density stratification. Consistent with the low Buoyancy Frequencies, measurements of both temperature and salinity were relatively constant over the water column (Fig. 4-12). The two exceptions are a high salinity feature that forms at the bottom of the water column during a large falling tide (feature A, bottom panel, Fig. 4-12), and a low temperature feature at the bottom of the water column during a rising tide (feature B, second panel from bottom, Fig. 4-12). These salinity and temperature features result in localized regions of higher water density (features A and B, second panel from top) and higher Buoyancy Frequencies (features A and B, top panel). As expected, temperature of the water column increases during the day, and decreases at night[19]. Surprisingly, it appears that salinity of the water column increases slightly during large falling tides (especially at the bottom of the water column, as noted above), perhaps indicating that hypersaline waters are released from the shallow groundwater during large ebb tides.

The second and third CTD studies largely reinforce the patterns described above for the first CTD study. During the second CTD study, two high salinity features form on the bottom and top of the water column near the minimum tide (data not shown). Solar heating is presumably responsible for the warm surface waters that appear at about 11:00 PM GMT (3:00 PM local time)[20]. These two salinity and temperature features result in fairly significant density features and higher peak Buoyancy Frequencies, especially at the surface of the water column (ca., 0.12 1/s). As with the first CTD study, salinity increases slightly over the entire water column as the tide falls, perhaps reflecting the input of hypersaline shallow groundwater. A similar pattern is evident during the third CTD study (data not shown). Namely, a high salinity feature forms at the bottom of the water column during the

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[19] Note that to convert the GMT times plotted in Figure 11 to local time, subtract 7 hours (daylight savings was in effect during this particular study).

[20] Note that to convert the GMT times plotted in Figure 12 to local time, subtract 8 hours (daylight savings was not in effect during this particular study).

low tide, and a warm feature forms at the surface of the water column during the mid-day when solar heating is maximal. The peak Buoyancy frequency calculated for the third CTD study (0.007 1/s) indicates little density stratification.

Task B.3.3.2: Groundwater-to-Ocean Isotope Study

Overview. To assess the possible contribution of sewage to the shallow groundwater, and to determine the extent to which sewage contaminated shallow groundwater contaminates the near shore coastal waters in Avalon Bay, 76 water samples were collected along a groundwater-to-Bay transect and analyzed for a suite of nutrients (ammonia, nitrate, nitrite, orthophosphate) and several stable isotopes, including ^{18}O and ^{16}O in water, and dual isotope analysis of the nitrogen and oxygen in nitrate; the latter results are pending, and will be included in a future research article written on this work.

Stable Isotopes of Oxygen in Water. Following standard convention, the relative abundance of ^{18}O and ^{16}O in water are reported in terms of "delta O-18", which indicates the extent to which the heavier isotope (^{18}O) is enriched relative to the lighter isotope (^{16}O) compared to the Vienna Standard Mean Ocean Water (VSMOW):

$$\delta^{18}O = \left[\frac{\left({}^{18}O / {}^{16}O \right)_{sample}}{\left({}^{18}O / {}^{16}O \right)_{VSMOW}} - 1 \right] * 100$$

Because the lighter isotope (^{16}O) preferentially evaporates, meteoric groundwater will be, generally speaking, isotopically lighter (i.e., more negative $\delta^{18}O$) than ocean water (i.e., more positive $\delta^{18}O$). Thus, the value of $\delta^{18}O$ can yield information on the relative contribution of meteoric groundwater and ocean water in a given water sample.

Of the 76 water samples collected along the groundwater-to-Bay transect, 47 were analyzed for the stable isotopes ^{18}O and ^{16}O of oxygen in water. The resulting $\delta^{18}O$ values are plotted against sample salinity in Fig. 4-13. Because both $\delta^{18}O$ and salinity are conservative tracers (i.e., they do not undergo chemical transformations), most water samples collected along the groundwater-to-Bay transect array along a single mixing line (black line in the figure) between pure meteoric groundwater (asterisk) and pure Avalon Bay water (diamond) (Fig. 4-13). The meteoric groundwater sample, which was collected from the Machado Well located inland of City Hall, is characterized by low salinity (~0) and isotopically light oxygen in water ($\delta^{18}O \approx -5$ parts per thousand, or "parts per mill", represented by the symbol ‰). Avalon Bay water, on the other hand, is characterized by oceanic salinity (~34) and isotopically heavy oxygen in water ($\delta^{18}O \approx +0.5$‰). The plotting position of all other water samples, relative to the mixing line between pure groundwater and pure Bay water (black line in Fig. 4-13) supports the following conclusions:

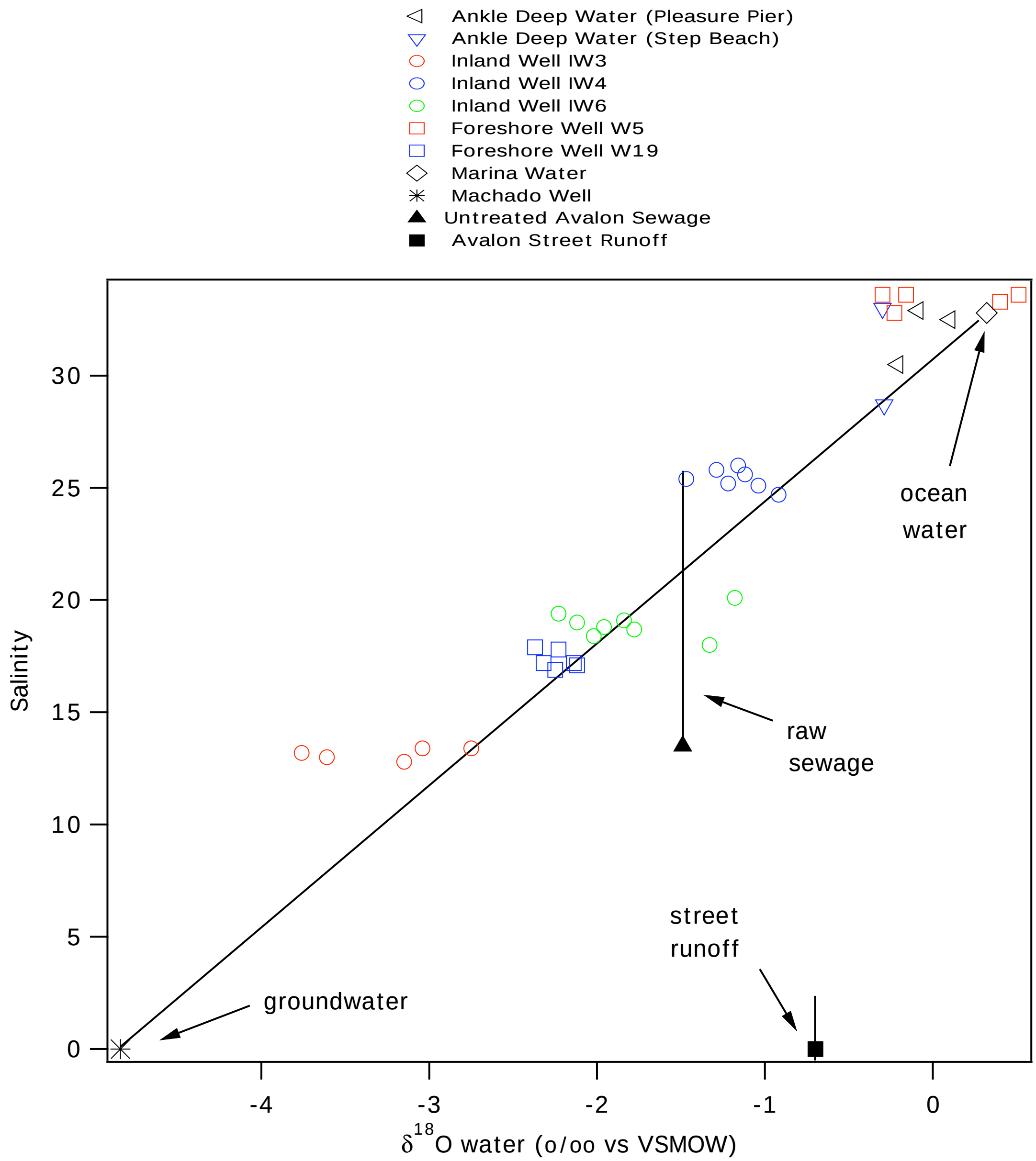

Figure 4-13. Plot of salinity versus delta O-18 of water (in units of parts per thousand) measured on water samples collected along a groundwater-to-Bay transect study.

1. Water from inland well IW3 consists of a ~ 70:30 mixture of meteoric groundwater and Bay water.
2. Water from inland well IW4 consists of a ~50:50 mixture of meteoric groundwater and Bay water.
3. Water from inland well IW6 consists of a ~30:70 mixture of meteoric groundwater and Bay water.
4. Water from foreshore well W5 consists mostly (>90%) of Bay water.
5. Water from foreshore well W19 consists of a ~50:50 mixture of meteoric groundwater and Bay water.
6. Water from ankle deep water at Pleasure Pier and Step Beach consists mostly (>90%) of Bay water.

Relative to the last point, ankle deep water at Step Beach is isotopically lighter than ankle deep water at Pleasure Pier, perhaps signaling the presence of meteoric groundwater in the nearshore water samples collected at Step Beach.

The salinity and isotopic composition of raw sewage and street runoff samples are denoted by the black triangle and square, respectively, in Fig. 4-13. Street runoff generally has low salinity (<5) but its $\delta^{18}O$ value is closer to ocean water than meteoric groundwater ($\delta^{18}O$ of runoff and meteoric groundwater of -0.7 and -4.8‰, respectively). The fact that street runoff and ocean water have similar $\delta^{18}O$ signatures is reasonable, given: (1) street runoff probably originates from the City of Avalon's domestic water supply system (e.g., from hosing down streets, over irrigation, etc.); (2) City of Avalon employs a desalination plant for most of its domestic water supply; and (3) previous studies have shown that desalination by reverse osmosis does not affect the $\delta^{18}O$ of water[21]. The $\delta^{18}O$ of water in the raw sewage sample is somewhat more negative than street runoff (-1.5 ‰ compared to -0.76 ‰), perhaps reflecting the infiltration of meteoric groundwater into the sewage collection system. Note that the vertical lines associated with the street runoff and raw sewage symbols in Fig. 4-13 denote the range of salinities reported in a previously published study[22], or measured with a water qualty sonde deployed at the City of Avalon's WWTP.

Nitrogen and Phosphate Concentrations. All 76 water samples collected along the groundwater-to-Bay transect were analyzed for three inorganic species of nitrogen (ammonia, nitrate, and nitrite) and orthophosphate. These data are plotted in Fig. 4-14, where dissolved inorganic nitrogen (DIN) represents the summed concentrations of

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[21] Koppmann, W.; Vengosh, A.; Guerrot, C.; Millot, R.; Pankratov, I. (2008) "Isotope and ion selectivity in reverse osmosis desalination: geochemical tracers for man-made freshwater" *Environ. Sci. Technol.* **42**, 4723-4731.

[22] Boehm, A.B., Fuhrman, J.A., Mrse, R.D., Grant, S.B. (2003) "Tiered approach for identificatin of a human fecal pollution source at a recreational beach: Case study at Avalon, Catalina Island, California" *Environ. Sci. Technol.* 37, 673-680.

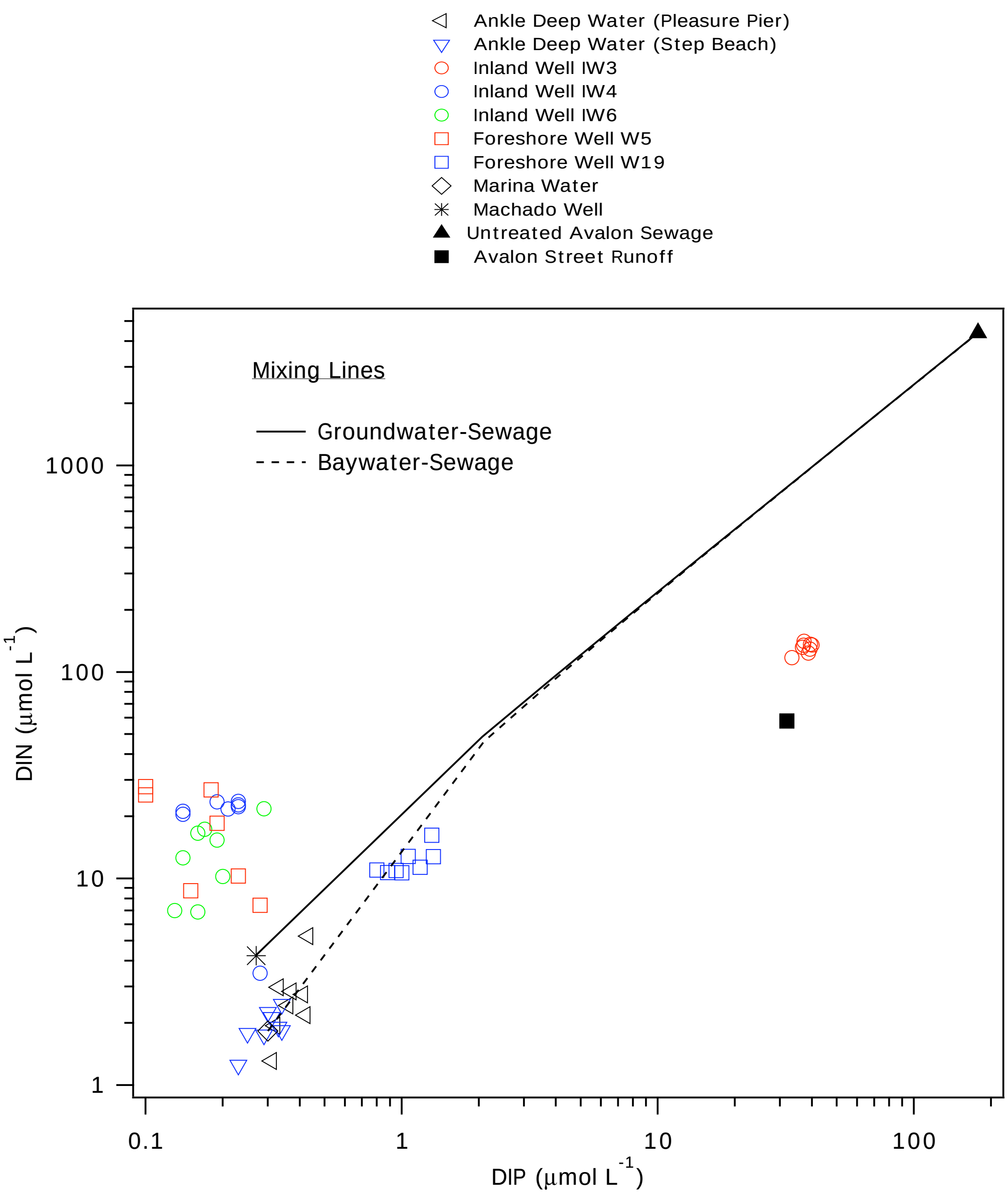

Figure 4-14. Dissolved inorganic nitrogen (DIN) vs dissolved inorganic phosphorous (DIP) along a groundwater-to-Bay transect. Two linear mixing relationships are shown in the plot, one between raw sewage and meteoric groundwater (solid line) and another between raw sewage and Avalon Bay water (dashed line)

ammonia, nitrate, and nitrite, while dissolved inorganic phosphate (DIP) represents the concentration of orthophosphate. Also shown in the plot are two mixing lines, one between meteoric groundwater and raw sewage (solid line) and one between Avalon Bay water and raw sewage (dashed line). Water samples collected from foreshore well W19 (near Step Beach) plot along the Baywater-Sewage mixing line and, from the DIN and DIP concentrations measured in the well, we estimate that approximately 1% of the water in W19 may be of sewage origin. Water samples collected from inland well IW3 have elevated DIP concentations, but fall below the DIN concentration predicted for the conservative mixing of sewage with either groundwater or Avalon Bay water. The dissolved oxygen measured in well IW3 was ~5 mg/L, although very low dissolved oxygen (<1 mg/L) was noted in some shallow groundwater wells (see Fig. 2-12 in Chapter 2). Hence, it is possible that water samples collected from IW3 are contaminated with sewage, but sewage-derived nitrogen has been removed by denitrification in the anoxic subsurface. If this is indeed the case, based on the orthophosphate concentrations measured, we estimate that approximately 20% of the water sampled from IW3 may be of sewage origin.

Task B.3.4: Determine if Resuspension of Contaminated Sediment is a Source of FIB

Goal and Background. This task investigated the hypothesis that FIB resident in the sand or interstitial pore fluids on Avalon's main beach are mobilized into ankle-depth waters on the rising tides, a type of over beach transport. Three studies were conducted, one similar to that described at an ocean beach in California (Lover's Point) by Yamahara et al. (ref. 1) and another similar to a set of studies carried out at a Lake Michigan Beach by Whitman and co-workers[23,24,25].

Tidal Cycling of FIB: Approach. Beginning May 30 (2009), water and sediment samples were collected every 20 minutes for two days from the Avalon Bay shoreline, on the northwest side of the Pleasure Pier. All water and sediment samples were analyzed for FIB using Colilert-18 and Enterolert. A subset of water samples were analyzed for culture-dependent cENT using membrane filtration (EPA Method 1600), and nutrients, including phosphate, nitrite, nitrate, and ammonia. During each sampling event, sediment samples were collected from two locations on the foreshore, just above and below the water line. Coincident with the water and sediment sampling, Radon-222 activity was measured in ankle-to-waist deep water using the small inflatable boat set-up described earlier in this report.

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[23] Whitman, R.L., M.B. Nevers (2003) "Foreshore sand as a source of *Escherichia coli* in nearshore waters at a Lake Michigan beach" *Appl. Environ. Microbiol*. **69**:5555-5562.

[24] Nevers, M.B., R. L. Whitman (2008) "Coastal strategies to predict *Escherichia coli* concentrations for beaches along a 35 km stretch of southern Lake Michigan" *Environ. Sci. Technol*. **42**:4454-4460.

[25] Nevers, M.B., R.L. Whitman, R.L., W. Frick, and Z. Ge (2007) "Interaction and influence of two creeks on *Escherichia coli* concentrations of nearby beaches: exploration of predictability and mechanisms" *J. Environ. Qual*. **36**:1338-1345.

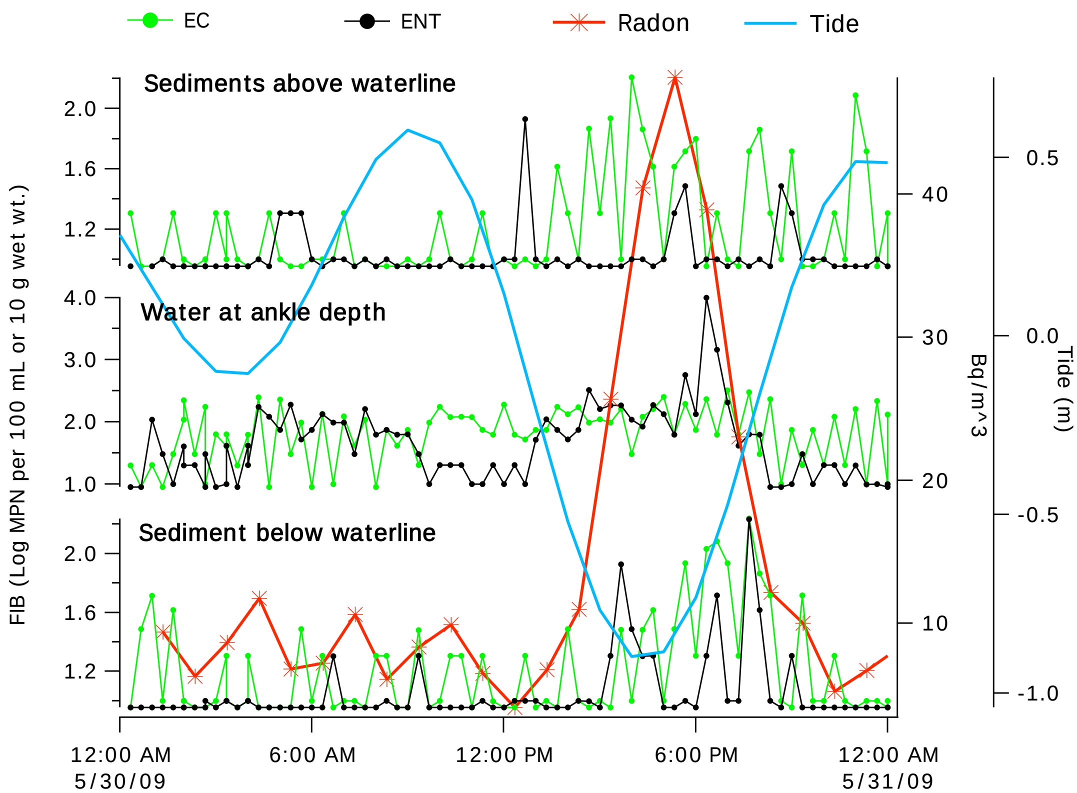

Figure 4-15. Comparison of Radon-222 activity in ankle deep waters at the Pleasure Pier and FIB concentrations measured in ankle deep waters (middle panel), and in sediments above (top panel) and below (bottom panel) the water line.

Tidal Cycling of FIB: Results. Fig. 4-15 displays measurements of the radon isotope ^{222}Rn and FIB in ankle depth waters, and FIB in sediments above and below the waterline. As noted earlier, ^{222}Rn is widely used as a marker for shallow groundwater discharge, because it has a relatively short half-life ($t_{1/2} = 3.83$ days) and is typically enriched 100 to 1000 fold in groundwater compared to the ambient ocean[26]. Based on the high frequency ($f=1/20\ min^{-1}$) results plotted in Fig. 4-15, FIB concentrations in ankle depth water and in beach sediments increase as the ^{222}Rn signal peaks at the bottom of the ebb tide, implying that foreshore sands and ankle depth water infuse with FIB laden shallow groundwater as the hydraulic gradient tilts toward the Bay with the falling tide. This conclusion is reinforced by a comparison of FIB, nutrient, and Radon-222 activity measured in ankle deep waters at the Pleasure Pier (Fig. 4-16). The increase in radon activity evident during the falling tide beginning 12:00 PM (GMT) on 5/30/09 coincides with an increase in not only culturable EC and ENT concentrations, but also ammonia and orthophosphate. Note that the peak EC concentration

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[26] Burnett, W.C., Dulaiova, H. (2003) "Estimating the dynamics of groundwater input into the coastal zone via continuous radon-222 measurements" J. Environ. Radioact., **69**: 21-35.

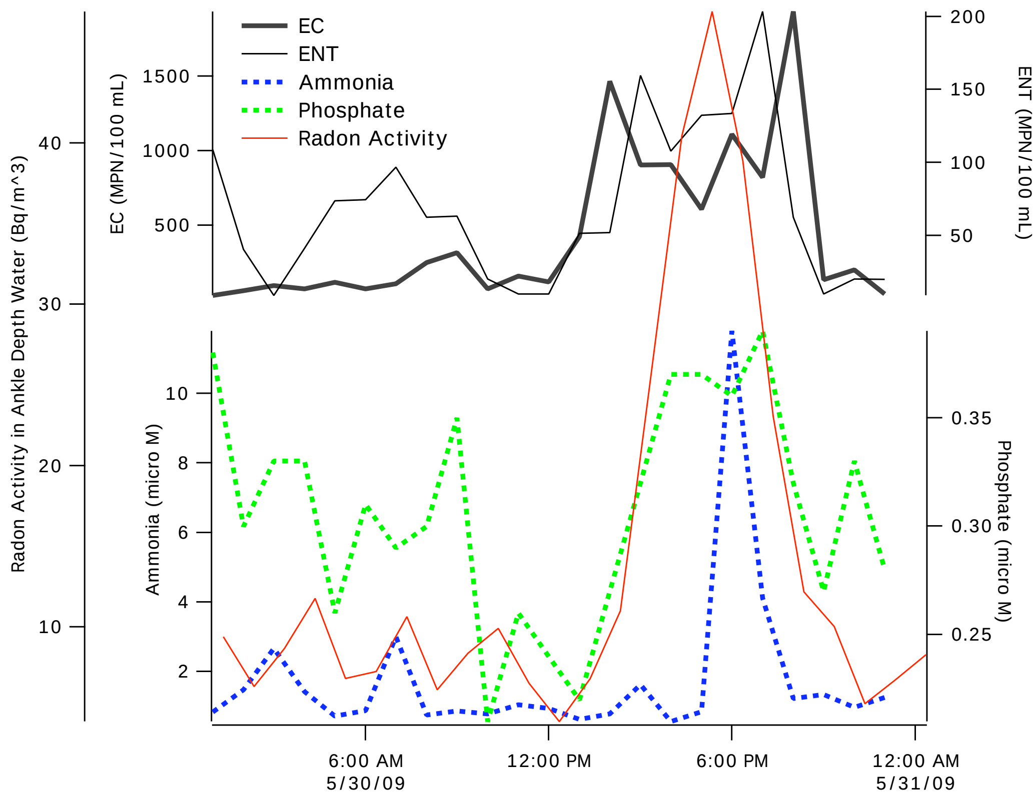

Figure 4-16. Comparison of Radon-222 activity, FIB concentrations, and nutrient concentrations measured in ankle deep waters at the Pleasure Pier.

measured during this falling tide (1900 MPN/100 mL) is nearly 10 times the California single-sample criteria for marine bathing waters. Collectively, the data plotted in Figs. 4-15 and 4-16 are consistent with the hypothesis that, during large falling tides, ankle depth waters and pore waters near the Pleasure Pier harbor multiple markers of sewage contamination during large falling tides.

Correlation with Environmental Variables: Approach Water and sediment samples were collected daily from Avalon main beach for a period of one month using random stratified sampling design (details to be presented in a future research article). The environmental variables that most influence FIB concentrations in the nearshore waters of Avalon Bay were determined by correlating, using EPA’s Virtual Beach software, FIB concentrations in nearshore water samples against a variety of environmental measurements, including: (1) air temperature, relative humidity, dew point, incident solar radiation, wind and gust speed, wind direction, precipitation, and barometric pressure (using a portable weather station, Onset Computer Corporation, Pocasset, MA); (2) water conditions, including particle size distribution, water clarity (transmissivity), salinity, temperature, and chlorophyll fluorescence (using Sequoia LISST-100 and YSI Multiparameter Water Quality Sonde); (3) wave climate, including wave height and period; and (4) current direction as measured with a downward looking Acoustic Doppler Current Profiler (ADCP Workhorse Monitor, Poway, CA).

Correlation with Environmental Variables: Results cEC concentrations along the shoreline in Avalon Bay were significantly correlated with four environmental variables, including water temperature (negatively correlated), wind direction (onshore), pressure (positively correlated), and wave period (positively correlated). ENT concentrations along the shoreline in Avalon Bay were significantly correlated with water temperature (negatively correlated), wind direction (onshore), relative humidity (positively correlated), and wave period (positively correlated). The fact that FIB concentrations are negatively correlated with water temperature is not surprising, as solar heating of the water column would also tend to be associated with increased solar inactivation of FIB during the day. The correlation of both EC and ENT concentrations with onshore winds and increasing wave period is interesting, and will be explored further in a future publication prepared from these data. Overall, these results suggest that wave climate and solar irradiance may strongly influence the sourcing, fate, and transport of FIB in the nearshore waters of Avalon Bay.

Pore Water Study: Approach. Additional studies were conducted to evaluate the "injection" of FIB trapped in sediment pore fluids into ankle depth shoreline waters, by a process called the "convective turnover pump" [27]. The convective turnover pump refers to the buoyancy-driven advection of interstitial pore fluids into overlying waters, as relatively cold Bay water inundates relatively warm sands during rising tides. The unstable thermal gradient that results can cause the rapid advective (as opposed to diffusive) transfer of pore water constituents into the overlying water. The convective turnover pump is apparently responsible for the rapid transfer of intertidal benthic nutrients into estuarine surface waters (ref 27). To evaluate the importance of the convective turnover pump as a source of FIB contamination in ankle depth waters in Avalon Bay, over several tidal cycles vertical temperature distributions in beach sediments were measured, and Rayleigh numbers were calculated from the measured temperature profiles. Rayleigh numbers are compared to the critical value (at which the tendency of the fluid to overturn due to buoyancy forces exceeds the elimination of the unstable density gradient by diffusion), to determine the likelihood that benthic pore fluids are transferred into shoreline waters by a convective turnover pump mechanism. Coincident with the temperature gradient measurements, samples of the beach sand pore fluid (collected by trenching the sand with a shovels) were tested for FIB concentrations.

Pore Water Study: Methods. Sampling of sediment pore fluids and measurements of sediment temperature-depth profiles occurred during the three hours before and after the low-tide mark on 10/1/09 from 12:00 to 17:30 and again on 10/2/09 from 00:30 to 6:00 (PDT)

[27] Rocha, C. (2000) "Density-driven convection during flooding of warm, permeable intertidal sediments: the ecological importance of the convective turnover pump" *J. Sea Research* **43**: 1-14.

(hereafter referred to as Rounds 1 and 2, respectively). Pore fluid samples were collected and temperature depth profiles were taken every half an hour, for a total of 12 pore fluid samples and 12 temperature-depth profiles per sampling round. All samples were collected on the beach just north of the Pleasure Pier, and the site of the sampling pit moved with the tide, so that it was always 0.5 m inland of the waterline (33.3437 N, 118.325 W). Sediment temperature-depth profiles were measured next to where the pore fluid sample was collected.

Pits were dug in the beach with shovels at approximately 0.5 to 1 meter above the tide line for all samples (i.e. a new pit was dug for each sample and the location moved with the tide). Digging stopped once pore fluids started to pool at the bottom of the pit; pit depth ranged from 15 to 90 cm deep, with was 31 cm deep on average. Pore fluids accumulated in the bottom of the pit were aspirated into 60 mL sterile syringes, and transferred to autoclaved 500 mL polypropolene (PP) Nalgene bottles (Rochester, NY). This process was repeated until the Nalgene bottle was nearly full for each sample. The Nalgene bottle was then capped and immediately placed in a dark cooler on ice until transport to the field laboratory for FIB processing within a six-hour holding time. During each sampling round, the temperature in the pit and the temperature of the surface bay water were measured in the field using an infrared temperature gun (Fluke, Everett, WA).

Onset Computer Corporation Stainless Steel Temperature Probes with pointed tip (Bourne, MA) was attached to a thin metal rod (because the probe itself is only 3 inches); the tip of the temperature sensor was flush with the tip of the rod, creating a "rod-thermometer." Temperature measurements were logged continuously using a HOBO 4-Channel External Data Logger (Onset Computer Corporation, Bourne, MA); the response time of the entire sensor-recording system is approximately 15 s, according to the manufacturer. For each sediment temperature-depth profile, the rod-thermometer was first pushed to a depth of 2.5 cm below the sediment surface, and allowed to equilibrate for 30 seconds, at which time the HOBO 4-Channel External Data Logger was activated. This process was repeated with increasing sediment depths until the rod-thermometer could not be driven any deeper into the ground (mainly due to obstructions such as large cobbles). To create each temperature-depth profile, the flagged temperatures were manually extracted from the time-series temperature measurments and paired with their associated depths.

Pore Water Study: Results. Pore fluids from surficial beach sediments were collected every half-hour over two six-hour periods, once during the day (hereafter referred to as 'R1') and once during the night (hereafter referred to as 'R2'). The top panel in Fig. 4-17 depicts the tide level, solar radiation, air temperature, bay surface water temperature, and pore fluid temperatures within the pits, along with FIB concentrations measured in pore fluid samples using both IDEXX (solid circles) and EPA membrane filtration methods (open squares). The bottom two panels depict contour plots of the temperature-depth profiles measured during R1 and R2 (left and right bottom panels, respectively). In addition, the Raleigh number, a dimensionless number that dictates whether buoyancy-driven free convection in the porous subsurface can occur, is overlayed on the FIB data.

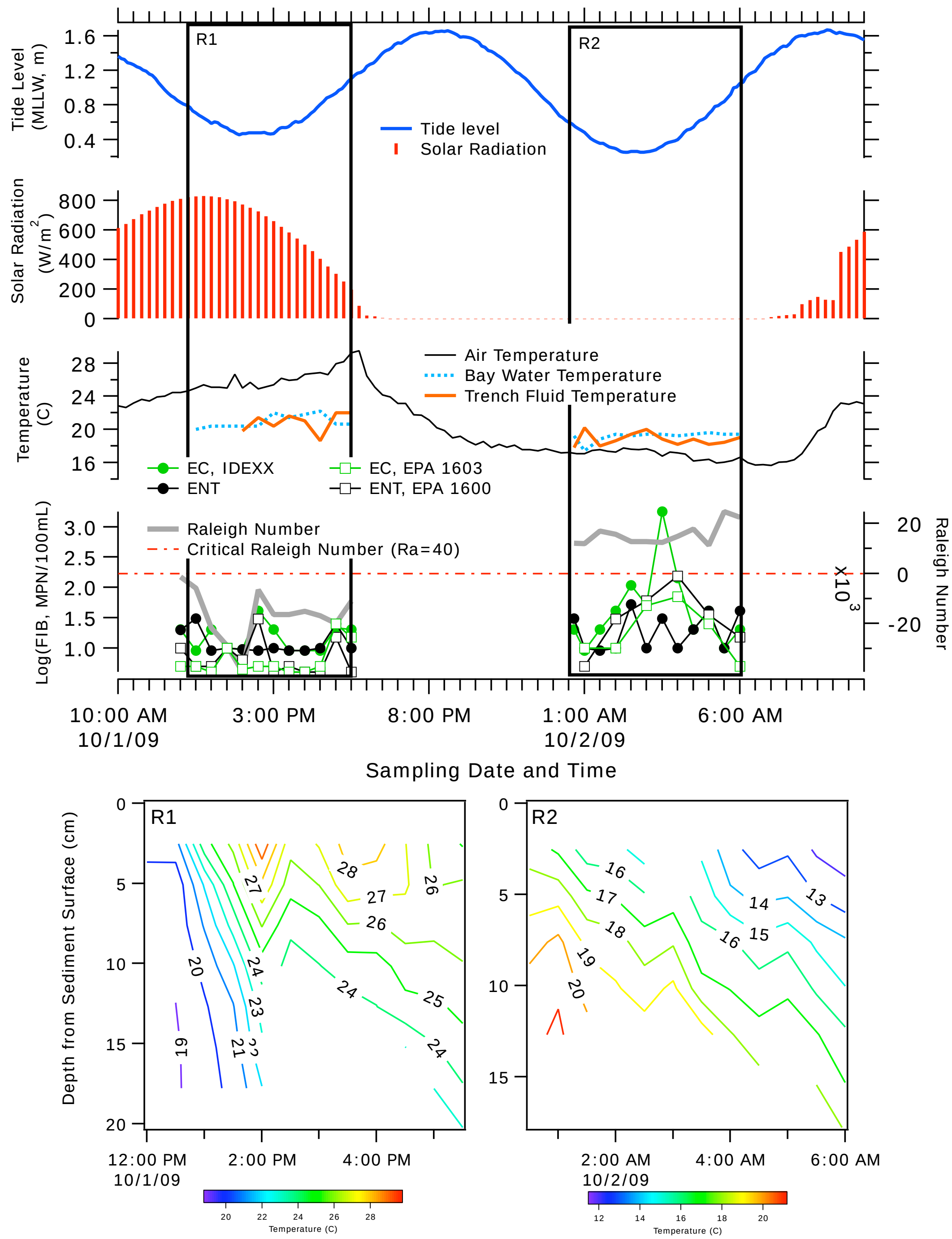

Figure 4-17. Top panel: tide level (blue solid line), solar radiation (red sticks), air temperature (black solid line), bay temperature (blue dashed line), pit temperature (orange solid line), EC (green lines), ENT (black lines), Raleigh numbers (grey solid line), and critical Raleigh number (red dashed line). Bottom panels: contour plots of the sediment temperature-depth profiles for R1 (left) and R2 (right).

When the Raleigh number exceeds 40 (the “critical Raleigh number”) buoyancy-driven free convection is possible. When Raleigh number is negative, no temperature instability exists between the fluid in the porous media and the overlying water column. The IOC UNESCO equation of state (http://ioc.unesco.org/oceanteacher/resourcekit/M3/Converters/SeaWaterEquationOfState/Sea%20Water%20Equation%20of%20State%20Calculator.htm) was used to calculate the densities at the top and bottom of the sediment temperature profile, assuming that the salinity at the top and bottom had the same salinity measured in each profile’s respective pore fluid sample. The Rayleigh number was negative during the daytime R1 sampling, indicating that buoyancy-driven free convection was unlikely to occur. During the nighttime R2 sampling, on the other hand, the pore fluids have an “inverted” temperature profile, with cooler temperatures near the surface and warmer temperature at depth. Raleigh numbers calculated during the R2 sampling indicate that convective turnover is possible. cEC and cENT concentrations measured in the pore fluids are low during the R1 sampling. During R2, cEC and cENT concentrations peak at the low tide, coincident with the increase in the Raleigh number of the critical value. These data are consistent with the hypothesis that convective turnover of pore fluids in foreshore sediments may play a role in mobilizing FIB into ankle depth waters during specific phases of the tidal and diurnal cycle.

Task B.3.5. Prepare Draft Report on the sources of FIB in ankle-depth waters

This task is satisfied with the submission of this report.

Project Assessment and Evaluation

PAEP Performance Measures

The approved PAEP for this project contained three tables (reproduced below) indicating, for each sub-task, the project goals, desired outcomes, output indicators, outcome indicators, measurement tools and methods, and targets. Project performance, as measured relative to the items listed in these tables, is assessed by sub-task below.

Assessment of Task B.1.

1. **Desired Outcomes**: The desired outcomes were achieved. Groundwater measurements collected as part of this task:
   - **a.** Support the hypothesis that FIB contamination along the shoreline in Avalon Bay is caused, at least in part, by the discharge of sewage-contaminated shallow groundwater into the Bay.
   - **b.** Highlight three areas along the Avalon Bay shoreline where future mitigation efforts should be focused—Pleasure Pier, Busy Bee Wharf, and Step Beach.
   - **c.** Confirm a relationship between "hot-spots" of shallow groundwater contamination and chemical (nutrient and geochemical isotope studies) and molecular (human and non-human *Bacteroides* tests) markers of fecal contamination.
2. **Output Indicators:** Maps of shallow groundwater contamination were obtained from a "picket fence" of shallow groundwater wells installed along the waterfront in Avalon Bay, and inland wells as permitted by the limited budget and constraints imposed by city infrastructure. As observed at other coastal sites in California, FIB (specifically, culture based measurements of enterococci bacteria, total coliform, and *Escherichia coli* by IDEXX Colilert-18 and Enterolert) concentrations are frequently decoupled from molecular and chemical markers of fecal contamination.
3. **Outcome Indicators:** As noted above, three regions of the shallow groundwater—Pleasure Pier, Busy Bee Wharf, and Step Beach—were identified as possible "hot spots" of sewage contamination. Both chemical (nutrient and isotopic) and molecular (human and non-human *Bacteroides*) measurements on shallow groundwater are consistent with this assessment.
4. **Measurement Tools and Methods**: All measurements were completed as specified in the Monitoring Plan.
5. **Targets:** Based on the data collected, the City of Avalon redoubled its efforts to identify leaks in the main sewer lines in the downtown area, and this effort led to the discovery of several potential problems. At least one of these potential problems might be responsible for the "hot spots" of sewage contaminated shallow groundwater identified at Busy Bee Wharf and Step Beach.

Table 1.
Project Performance Measures for Planning, Research, Monitoring, or Assessment Activities Project Performance Measures
Causes and Mitigation of Fecal Indicator Bacteria (FIB) Impairment of Shoreline Waters in Avalon Bay

Project Goals	Desired Outcomes	Output Indicators	Outcome Indicators	Measurement Tools and Methods	Targets
Task B1: Characterize the spatial extent of sewage-contaminated shallow groundwater beneath downtown Avalon, Catalina Is.	1. Identification of “hot spots” of FIB concentration in the shallow groundwater, and the location of hot spots relative to sewage collection infrastructure. 2. Confirmation that FIB hot spots also harbor markers of human sewage (boron, caffeine, *Bacteriodes/Provetella* spp.).	1. Reasonably complete maps of FIB concentrations in the shallow groundwater underlying downtown Avalon. 2. Data on the co-occurrence of high FIB concentrations in the shallow groundwater and markers of human sewage	1. The location of areas in downtown Avalon where the shallow groundwater is contaminated with historical and/or continuing leaks from the sewage collection system. 2. The relative persistence/prevalence of FIB and human markers of fecal pollution in the brackish shallow groundwater underlying Avalon.	Obtain samples of the shallow groundwater by installing monitoring well points at 15 locations scattered over downtown Avalon. Measurements on shallow groundwater to include salinity (conductivity and temperature), FIB using IDEXX Colilert and Enterolert, nutrients (ammonium, nitrate, TDN, phosphorous, DOC), and *Bacteriodes/Provetella* by qPCR.	Broad acceptance of the hot spots based on peer review. Broad acceptance of the source of FIB contamination in the subsurface (i.e., legacy sewage spills and/or growth of environmentally adapted strains)
Task B3: Identify source of FIB in ankle depth waters along the shoreline of Avalon Bay.	1. Determination if FIB in ankle-depth waters is from the tidal exchange of sewage-contaminated shallow groundwater with water in Avalon Bay. 2. Determination if FIB in ankle-depth waters is from the resuspension of sediments FIB contaminated foreshore sediments.	1. Estimates for the efflux of shallow groundwater into Avalon Bay (in units of volume per day per length of shoreline) 2. Evaluation of FIB transport through Avalon’s shallow groundwater matrix. 3. Evaluation of the particle-association and resuspension of FIB in ankle-depth waters.	1. Evidence that links FIB contamination of the ankle-depth waters in Avalon Bay to specific sources (sewage vs environmental growth) and transport mechanisms (tidal exchange through foreshore sands vs sediment resuspension).	Tidal efflux will be determined from dye experiments and radium isotope studies. Particle association will be determined by measuring FIB in ankle depth waters before and after passage through 2 micron filters; Resuspension of FIB will be monitored by correlating FIB concentrations and particle size measurements in the ankle depth waters.	Broad acceptance of the underlying causes of FIB contamination in the ankle depth waters along the shoreline in Avalon Bay: tidal exchange of contaminated shallow groundwater and/or growth of environmentally adapted FIB strains in the foreshore sediments.

Assessment of Task B.3.

1. **Desired Outcomes**: The desired outcomes were achieved. Nearshore studies conducted as part of Task B.3. indicate that foreshore sediments and shallow (ankle depth) waters near the Pleasure Pier infuse with sewage markers as the surface of the shallow groundwater tilts toward the bay during low-low tides. These results support the hypothesis that at least a portion of the FIB signal in the shallow waters of Avalon Bay is forced by through-beach transport of sewage-contaminated shallow groundwater. Resuspension of FIB-associated particles by Bay currents appears to be of lesser importance, although boat currents (from ferries docking at the Mole and from boats tied to the Pleasure Pier) appear to improve shoreline water quality at Avalon's main beach, by transporting relatively clean water form the middle of the Bay toward the shoreline. A research article describing these findings was recently accepted for publication in the journal *Environmental Science and Technology*[1].
2. **Output Indicators**: Data collected during the project is currently being analyzed and written up as three journal articles (in addition to the journal article mentioned above). Included in these analyses will be estimates for the flux of shallow groundwater into the Bay from Radon-222 measurements collected during the Task B.3. The mechanism by which FIB are transported through the shallow groundwater to the Bay is also under investigation; preliminary results suggest that FIB (and perhaps other sewage markers) partition at, or near, the shallow groundwater's air-water interface (or "phreatic surface"). Because the shallow groundwater wells were sampled during times when the well screen was located well below the phreatic surface, this hypothesis would explain why FIB concentrations were typically low in samples of shallow groundwater collected from the site, but much higher in groundwater sampled from trenches dug into the sand. These results have significant implications for the pathway by which humans recreating on the beach might come into contact with fecal-oral pathogens associated with the sewage-contaminated shallow groundwater. S. Grant and a colleague at UCI (R. Detwiler) submitted a pre-proposal in March (2011) to the California Sea Grant Core Research Program, outlining a research effort that would investigate this hypothesis.
3. **Outcome Indicators**: Studies carried out during this sub-task provide evidence that links the flow of shallow groundwater into Avalon Bay (Radon-222 measurements) with changes in the concentration of makers of sewage in the shallow (ankle deep) water of Avalon Bay. As noted above, the evidence support a through-beach mechanism (e.g., discharge of sewage-contaminated shallow groundwater), and less an over-beach mechanism (e.g., particle resuspension).

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[1] Ho, L.C., Litton, R.M., Grant, S.B. (2011) "Anthropogenic currents and shoreline water quality in Avalon Bay, California", *Environmental Science and Technology*, in press.

4. **Measurement Tools and Methods**: All measurements were completed as specified in the Monitoring Plan.
5. **Targets**: Results of the study are being written up for peer review and publication in scientific journals, which should constitute "broad acceptance" of the results. Furthermore, as noted above, as results from this study were coming to light, the City acted proactively by surveying (and in some cases re-surveying) portions of the sewage collection infrastructure in areas where our data indicated shallow groundwater might be contaminated with untreated sewage. These actions by the City led to the identification of previously undetected problems with the sewer lines, and these have been (or are currently being) repaired. Thus, the City staff accepted study findings, and used the results to help focus their investigations and mitigation activities.

Assessment of Task B.2.

1. **Desired Outcomes**: The desired outcomes were achieved. Data was collected to evaluate several different strategies for in situ remediation of sewage contaminated shallow groundwater, including chemical disinfection, permeable treatment barriers, and subsurface mobilization of fecal pollution using linear alkylbenzene sulfonates.
2. **Output Indicators**: Indicators include the rate at which FIB concentrations in sewage-groundwater mixture declined with time in the presence of specific chemical disinfectants (Oxone and peracetic acid, PAA), the reduction of FIB concentrations after passage through packed columns of activated granular carbon and beach sand, and the re-mobilization of previously attached FIB by passage of linear alkylbenzene sulfonates through the packed columns.
3. **Outcome Indicators**: Based on the data obtained from these pilot studies, the most promising remediation approach is the use of the chemical disinfectant PAA, either applied directly to sewage contaminated sediments, or injected into high-risk laterals, like those that pass through foreshore sands (e.g., connecting sewage lines at the Pleasure Pier to sewer mains in the downtown area of Avalon). Pump and treat methods and permeable treatment barriers are less promising, because of unresolved difficulties associated mobilizing FIB and pathogens out of sewage contaminated sediments, and proper placement of in situ filter media in the face of a contamination plume that is highly variable in space and time.
4. **Measurement Tools and Methods**. All measurements were completed as specified in the Monitoring Plan.
5. **Targets**: Results of the study are being written up for peer review and publication in scientific journals, which should constitute "broad acceptance" of the results. As a practical matter, the City's focus is currently on identifying and fixing leaks in the sewer lines. Once the sewer leaks are identified and repaired, attention may shift toward remediating residual sewage in the shallow groundwater from legacy leaks. At that point, results of the piloting testing carried out here may be of value.

Table 2
Load Reduction Activities
Performance Measures
Causes and Mitigation of Fecal Indicator Bacteria (FIB) Impairment of Shoreline Waters in Avalon Bay

Project Goals	Desired Outcomes	Output Indicators	Outcome Indicators	Measurement Tools and Methods	Targets
Task B2: Conduct pilot remediation study on sewage contaminated shallow groundwater.	1. Evaluation of several methods (disinfection by Oxone and peracetic acid) , air sparging, and emplacement of activated carbon barriers, for remediating sewage contaminated shallow groundwater	1. Data demonstrating the best approach for remediating the sewage-contaminated shallow groundwater	1. Identification of the best approach for remediating sewage contaminated shallow groundwater	Set-up laboratory in Avalon to conduct pilot treatment studies on mixtures of Avalon sewage and shallow groundwater. 2. Evaluate performance of different methods by characterizing the magnitude and rate of FIB removal by each approach.	Broad acceptance of the appropriate technology to be used for remediating sewage contaminated shallow groundwater.

Table 3
Beneficial Use Improvement and Protection Activities
Performance Measures
Causes and Mitigation of Fecal Indicator Bacteria (FIB) Impairment of Shoreline Waters in Avalon Bay

Project Goals	Desired Outcomes	Output Indicators	Outcome Indicators	Measurement Tools and Methods	Targets
Task B4: Remediate sewage contaminated groundwater interacting with Avalon Bay through sewer infrastructure improvements (specifically residential laterals in the alluvial plain).	1.Improved water quality on Avalon beaches and reduction of beach postings. Protection of existing beneficial uses of the waterbody.	1.Data on FIB in the shallow groundwater before and after lateral repairs.	1.Data that FIB concentrations in shallow groundwater and ankle deep water along the shoreline of Avalon Bay have decreased.	1.Utilize existing test wells on Avalon Beaches (installed from previous CBI grant) to test FIB concentrations in shallow groundwater and perform FIB tests in ankle deep water.	1.Reduce water quality exceedances and confirm that sewage contaminated groundwater is a major contributor to high FIB levels in Avalon Bay.

Assessment of Task B.4.

Work conducted under this sub-task is described in a separate report prepared by the consulting firm Robert Bien and Frost (RBF). To determine if sewer line repairs improved shoreline water quality in Avalon Bay, the following analysis was carried out using historical measurements by the Los Angeles Department of Public Health (LADPH).

Methods. From April to October every year, LADPH collects water samples from five locations along the shoreline in Avalon Bay, and then tests these samples for culture-dependent concentrations of total coliform (TC), fecal coliform (FC), and enterococci bacteria (ENT). The five LADPH sites in Avalon Bay are designated DPH 117, DPH 118, DPH 119, DPH 120, and DPH 121. These monitoring data, which go back to at least the year 2001, were retrieved from the county website (http://www.lapublichealth.org/eh/ehftp/) and analyzed as follows. Log-mean concentrations of TC, FC, and ENT were computed based on all data collected during the months of June, July, and August (JJA) in each year. The decision to focus on the JJA period was based on several considerations. First, to evaluate the effects of sewer line repairs on shoreline water quality, the impact of rainfall should be removed from the signal. In southern California, little rain typically falls during JJA, and therefore by focusing the analysis on JJA, the effects of rainfall on shoreline water quality should be minimized. Second, a significant fraction of Avalon's tourism and beach recreation occurs during JJA, and hence the status of water quality during this period of time is of significant interest. To ensure that rain did not impact the JJA measurements, rainfall records at the Los Angeles International Airport were checked for trace or measured rainfall, and any LADPH sampling events that occurred within 72h of a rain event were removed from the averaging step. Averaging was carried out as follows. All FIB data that met the criteria listed above (i.e., occurred during JJA and not collected within 72h of a rain event) were log-transformed to achieve normality. These data were then sorted by year, and log-means and standard deviations computed for each year. This approach generated fifteen separate time series ((3 different FIB groups) X (5 different sampling sites)) that collectively indicate how summer-time water quality in Avalon Bay changed from 2001 through 2010.

Results. The attached figures indicate how summer-time water quality along the shoreline in Avalon Bay changed from 2001 to 2010. The different figures correspond to different LADPH sites, including DPH 117 (Figure 1), DPH 118 (Figure 2), DPH 119 (Figure 3), DPH 120 (Figure 4), and DPH 121 (Figure 5). The map in each figure indicates the geographic location of the sampling site along the shore. The three plots in each figure correspond to the three different FIB groups including, from top to bottom, log-TC, log-FC and log-ENT.

From these data several observations are apparent:

- As expected, there is considerable spatial and temporal variability in the summertime concentrations of FIB measured in the shoreline waters of Avalon Bay.
- There is considerable sample-to-sample variability in FIB concentrations collected at all sites and all summers, as reflected in the relatively large error bars. Quantitatively speaking, the coefficient of variation of log-transformed data is approximately 20%.
- In a given year, summertime log-mean FIB concentrations are frequently higher at site DPH 119 compared to all other sites.
- At a given site, FIB concentrations are generally higher during the second five-year period (2006 through 2010) compared to the first five-year period (2001 through 2005).
- Within the last three years—when major repairs of the sewer lines might have improved shoreline water quality—the trends are mixed, with some site/FIB combinations showing an apparent increase in bacterial concentrations (e.g., TC at DPH 121), others showing an apparent decrease in bacterial concentrations (e.g., ENT at DPH 119), and most showing no change (e.g., ENT at DPH 118).
- Overall, the FIB concentrations displayed in these figures are high relative to the respective single-sample standards for these organisms of 104 (ENT), 400 (FC), and 10000 (TC) MPN/100 mL. These single-sample standards correspond to log-transformed values of 2.02 (ENT), 2.48 (FC), and 3 (TC).

While it is difficult to draw a single definitive conclusion from these data, it is fair to say that capital improvement of the sewage collection system has not yet resulted in dramatic improvements in the summertime concentration of FIB in the shoreline waters of Avalon Bay.

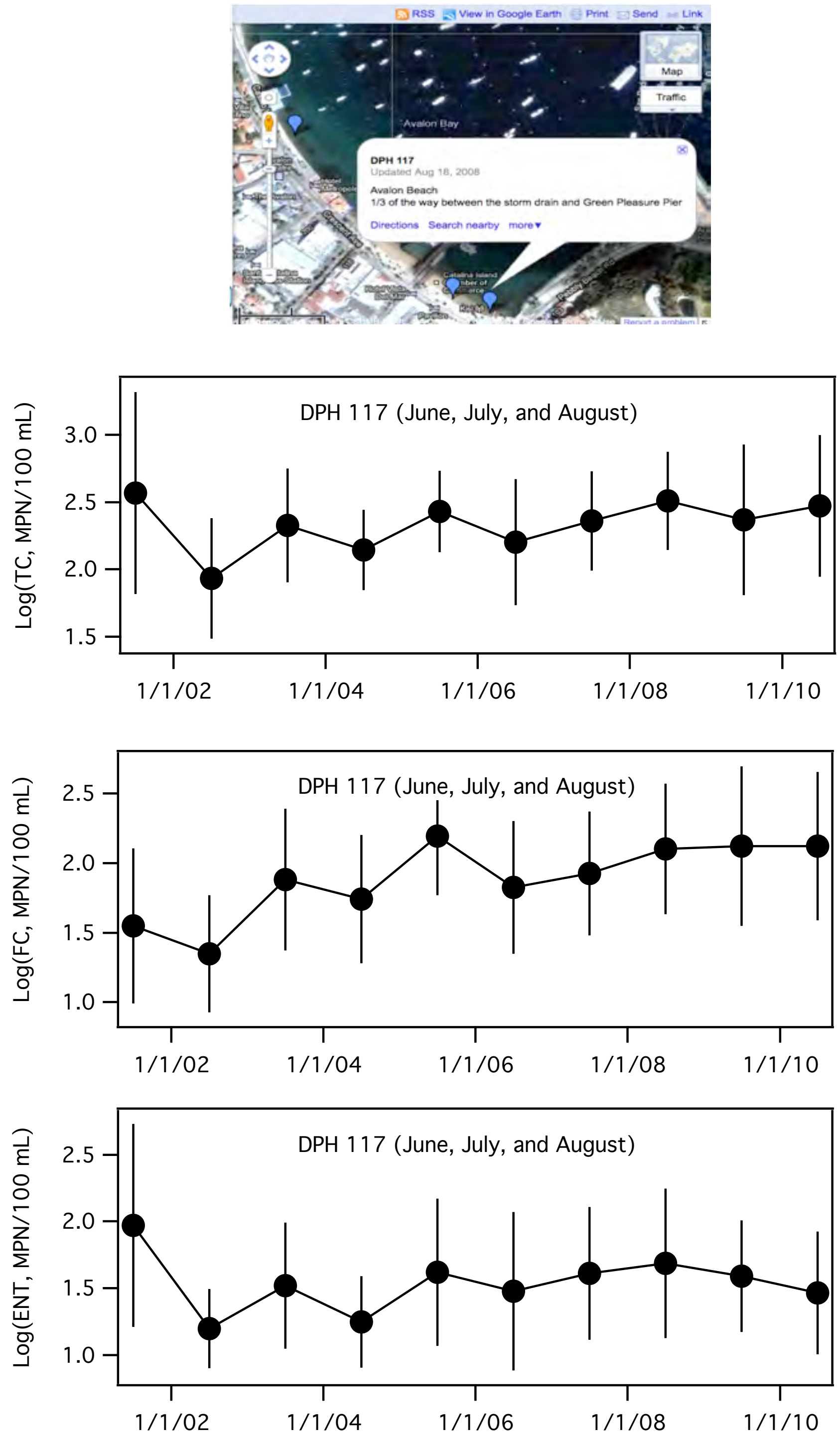


Figure 1. Mean and standard-deviation of the log-transformed FIB measured during June, July, and August at Monitoring Site 117

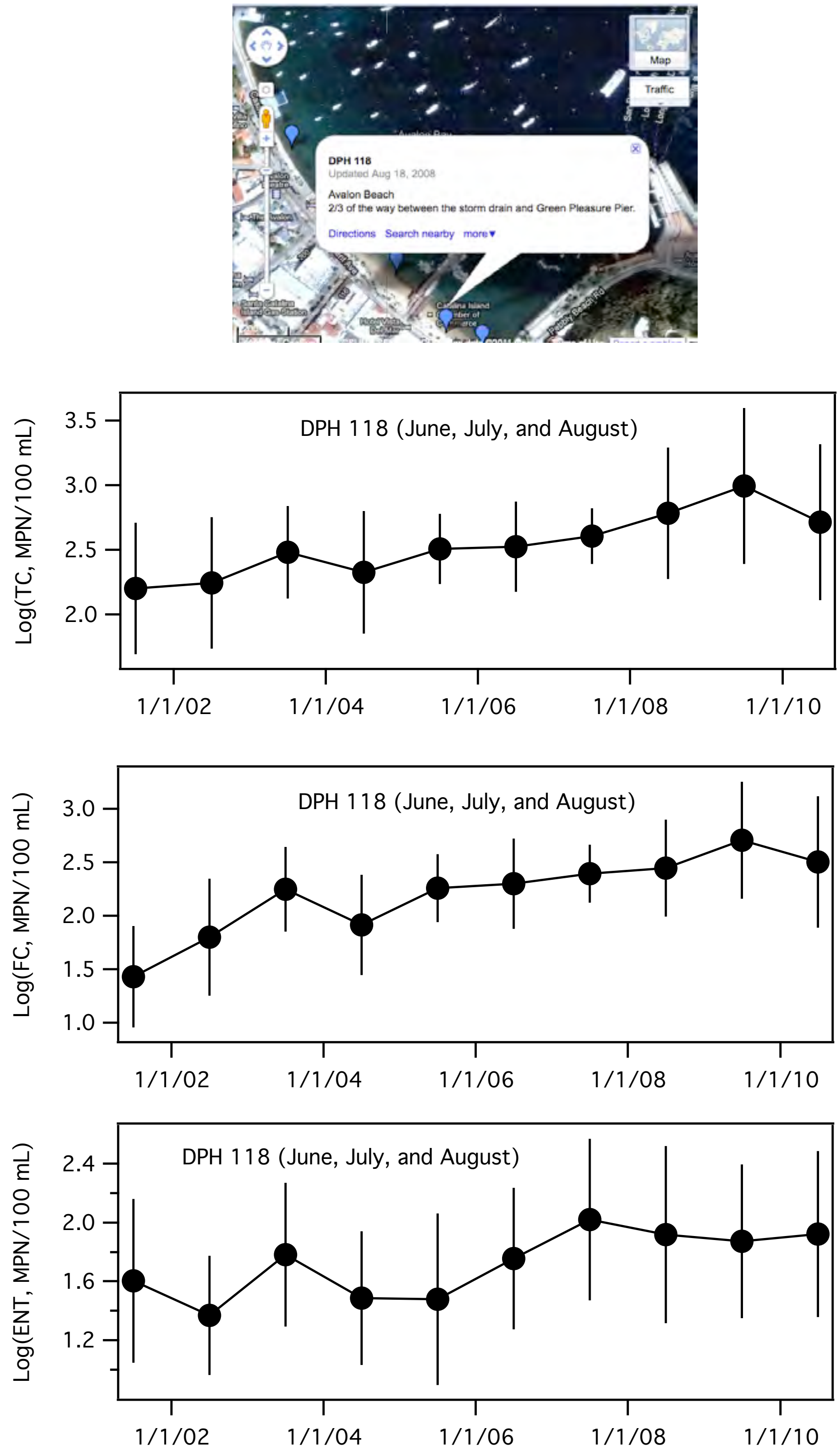
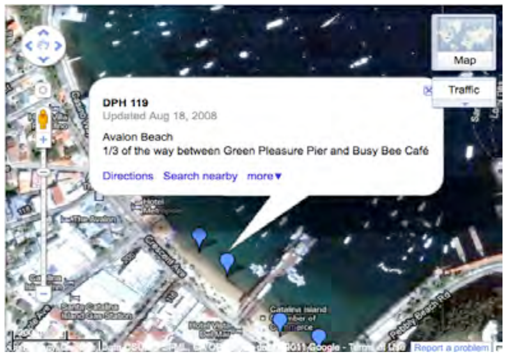


Figure 2. Mean and standard-deviation of the log-transformed FIB measured during June, July, and August at Monitoring Site 118.



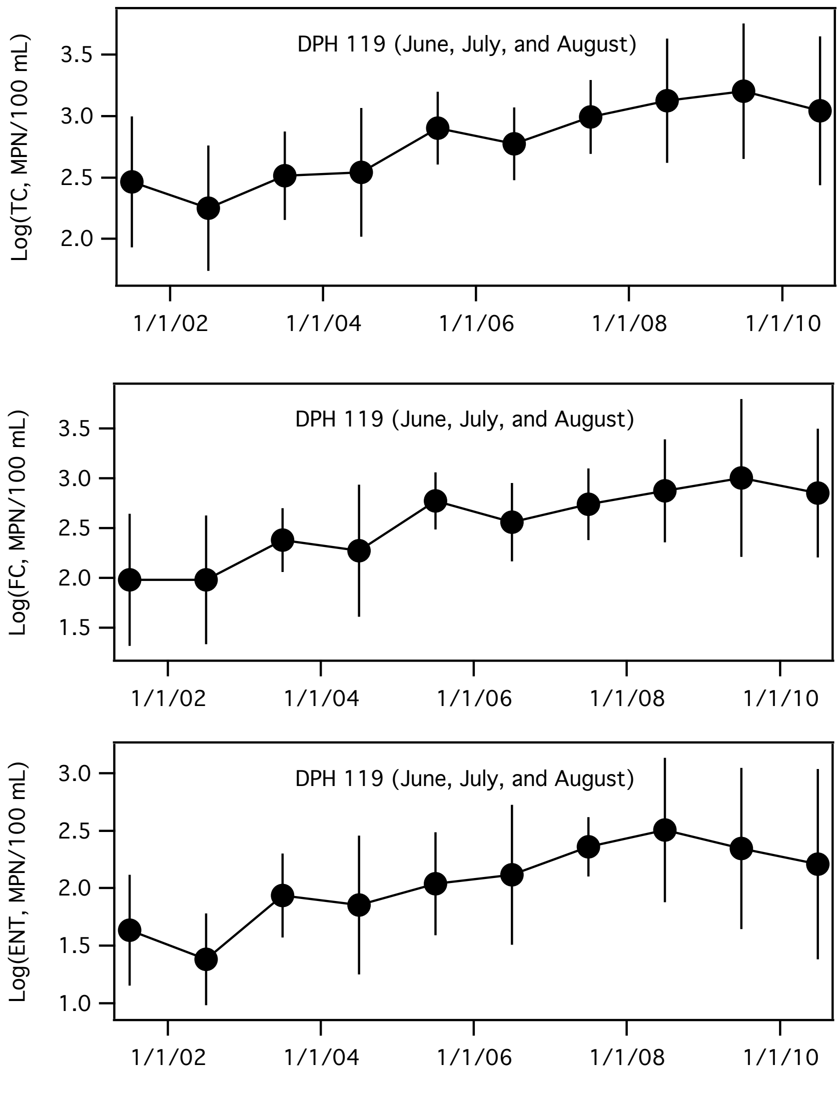


Figure 3. Mean and standard-deviation of the log-transformed FIB measured during June, July, and August at Monitoring Site 119.

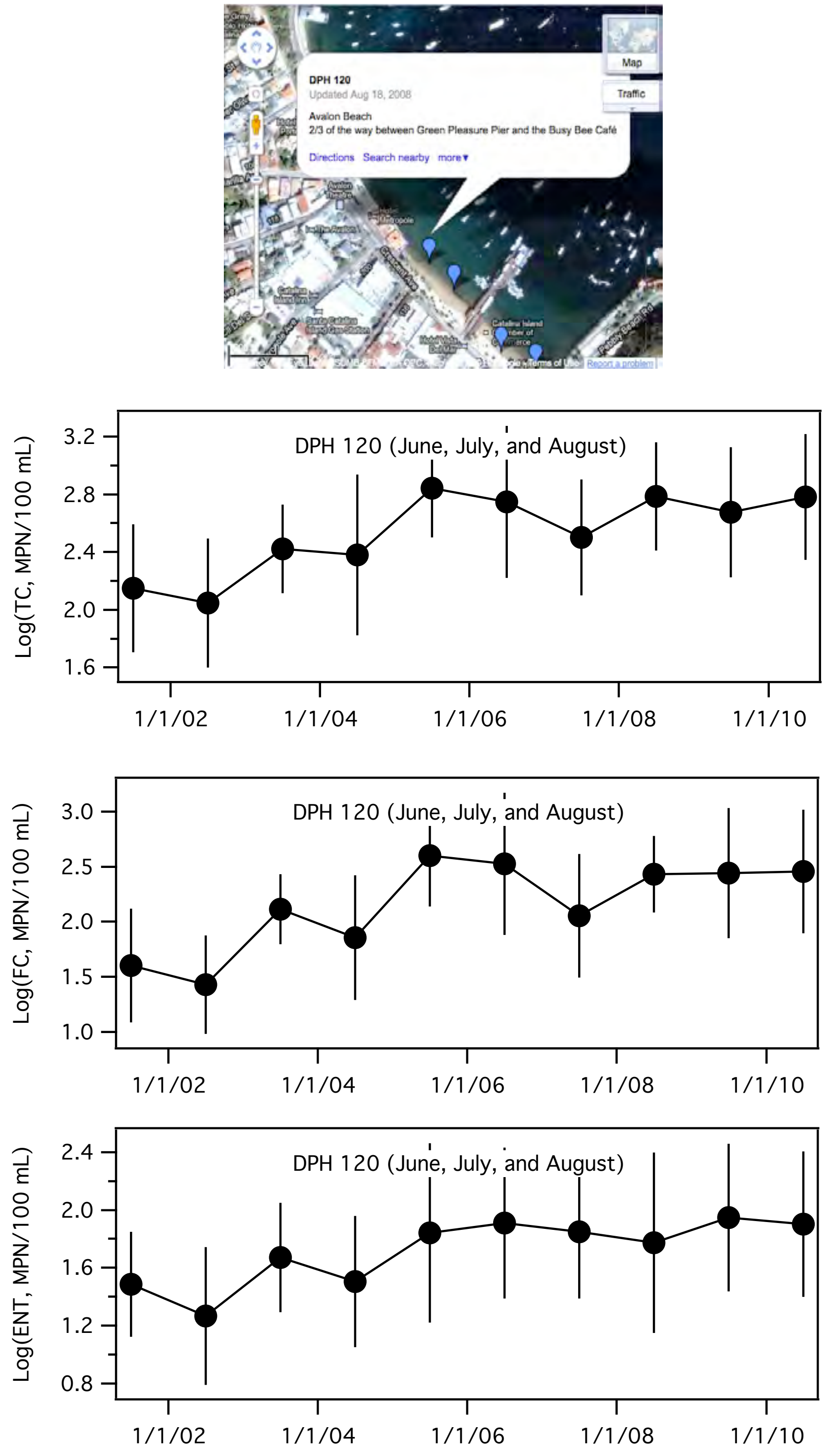


Figure 4. Mean and standard-deviation of the log-transformed FIB measured during June, July, and August at Monitoring Site 120.

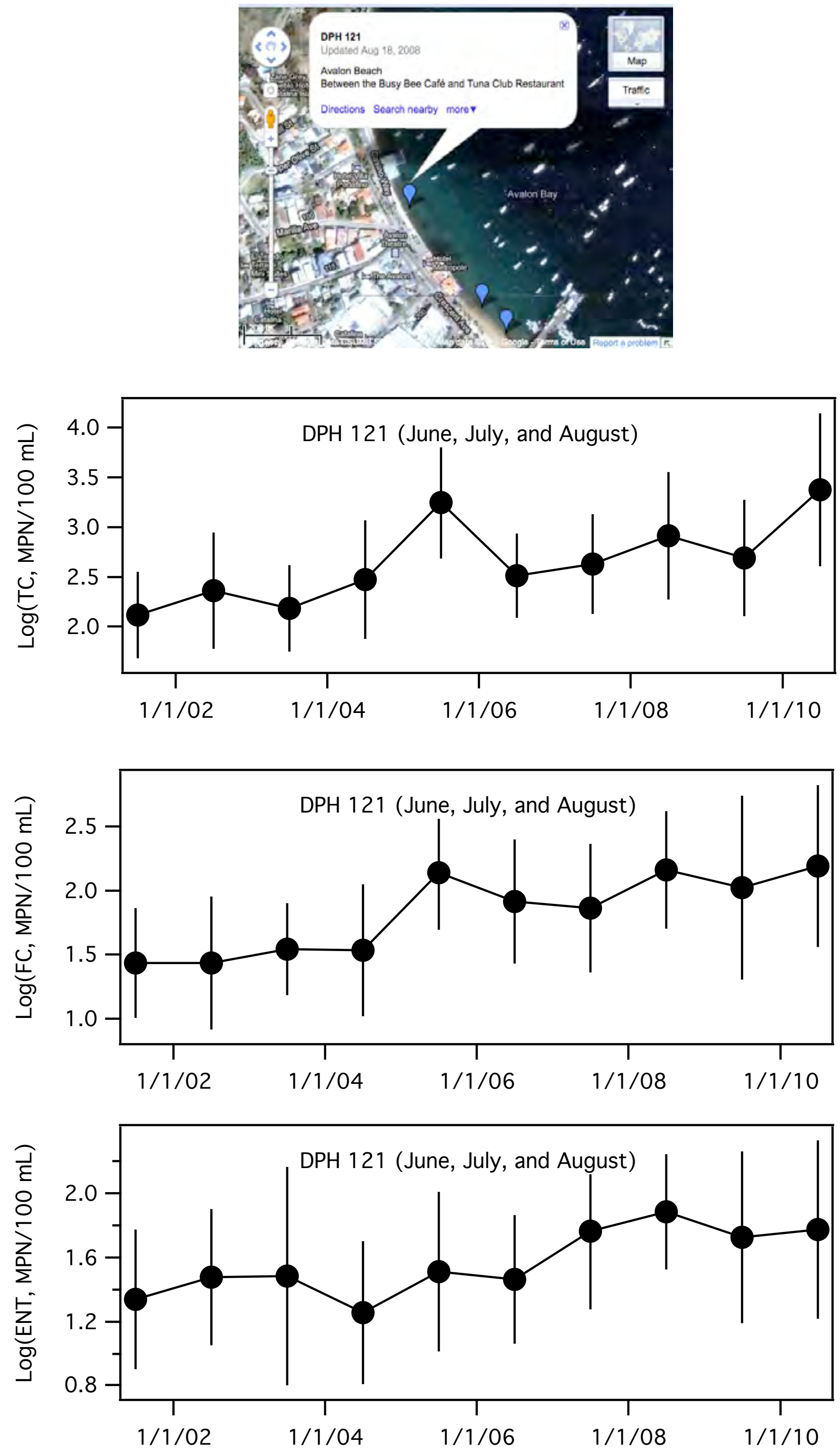


Figure 5. Mean and standard-deviation of the log-transformed FIB measured during June, July, and August at Monitoring Site 121.

Supplemental Trend Analysis

Re-Assessment of Task B.4.

As part of the PAEP element included with the original Avalon Bay Water Quality Improvement Study report, a trend analysis was carried out to determine if sewer line repairs improved shoreline water quality in Avalon Bay. This original analysis utilized FIB monitoring data collected in Avalon Bay, but only measurements collected during the months of June, July, and August of each year. This supplemental study expands on the original analysis, by including all FIB monitoring data collected in Avalon Bay during the months April through October of each year.

Methods. From April to October every year, LADPH collects water samples from five locations along the shoreline in Avalon Bay, and then tests these samples for culture-dependent concentrations of total coliform (TC), fecal coliform (FC), and enterococci bacteria (ENT). The five LADPH sites in Avalon Bay are designated DPH 117, DPH 118, DPH 119, DPH 120, and DPH 121. These monitoring data, which go back to at least the year 2001, were retrieved from the county website (http://www.lapublichealth.org/eh/ehftp/) and analyzed as follows. Log-mean concentrations of TC, FC, and ENT were computed from all data collected during the months April through October pg each year. To ensure that rain did not impact the measurements included in this analysis, rainfall records at the Los Angeles International Airport were checked for trace or measured rainfall, and any LADPH sampling events that occurred within 72h of a rain event were removed from the averaging step. Averaging was carried out as follows. All FIB data that met the criteria described above (i.e., was collected during April through October of each year and not collected within 72h of a rain event) were log-transformed to achieve normality. These data were then sorted by year, and log-means and standard deviations computed for each year. This approach generated fifteen separate time series ((3 different FIB groups) X (5 different sampling sites)) that collectively indicate how summer-time water quality in Avalon Bay changed from 2001 through 2010.

Results. The attached figures indicate how summer-time water quality along the shoreline in Avalon Bay changed from 2001 to 2010. The different figures correspond to different LADPH sites, including DPH 117 (Figure 1), DPH 118 (Figure 2), DPH 119 (Figure 3), DPH 120 (Figure 4), and DPH 121 (Figure 5). The map in each figure indicates the geographic location of the sampling site along the shore. The three plots in each figure correspond to the three different FIB groups including, from top to bottom, log-TC, log-FC and log-ENT.

From these data several trends are apparent:

- As expected, there is considerable spatial variability in the concentrations of FIB measured in the shoreline waters of Avalon Bay.

- There is considerable sample-to-sample variability in FIB concentrations collected at all sites, as reflected in the relatively large error bars.
- In a given year, log-mean FIB concentrations are frequently higher at site DPH 119 compared to all other sites.
- At a given site, FIB concentrations are generally higher during the second five-year period (2006 through 2010) compared to the first five-year period (2001 through 2005).
- Within the last three years—when major repairs of the sewer lines might have improved shoreline water quality—the trends are mixed, with some sites showing an apparent increase in bacterial concentrations (e.g., TC at DPH 121), and others showing an apparent decrease in bacterial concentrations (e.g., ENT at DPH 119).
- Overall, the FIB concentrations displayed in these figures are high relative to the respective single-sample standards for these organisms of 104 (ENT), 400 (FC), and 10000 (TC) MPN/100 mL. These single-sample standards correspond to log-transformed values of 2.02 (ENT), 2.48 (FC), and 3 (TC).

While it is difficult to draw a single definitive conclusion from these data, it is fair to say that capital improvement of the sewage collection system have not yet resulted in dramatic improvements in the measured concentration of FIB in the shoreline waters of Avalon Bay. This conclusion is consistent with the previous analysis that included only FIB measurements collected during June, July, and August of each year.

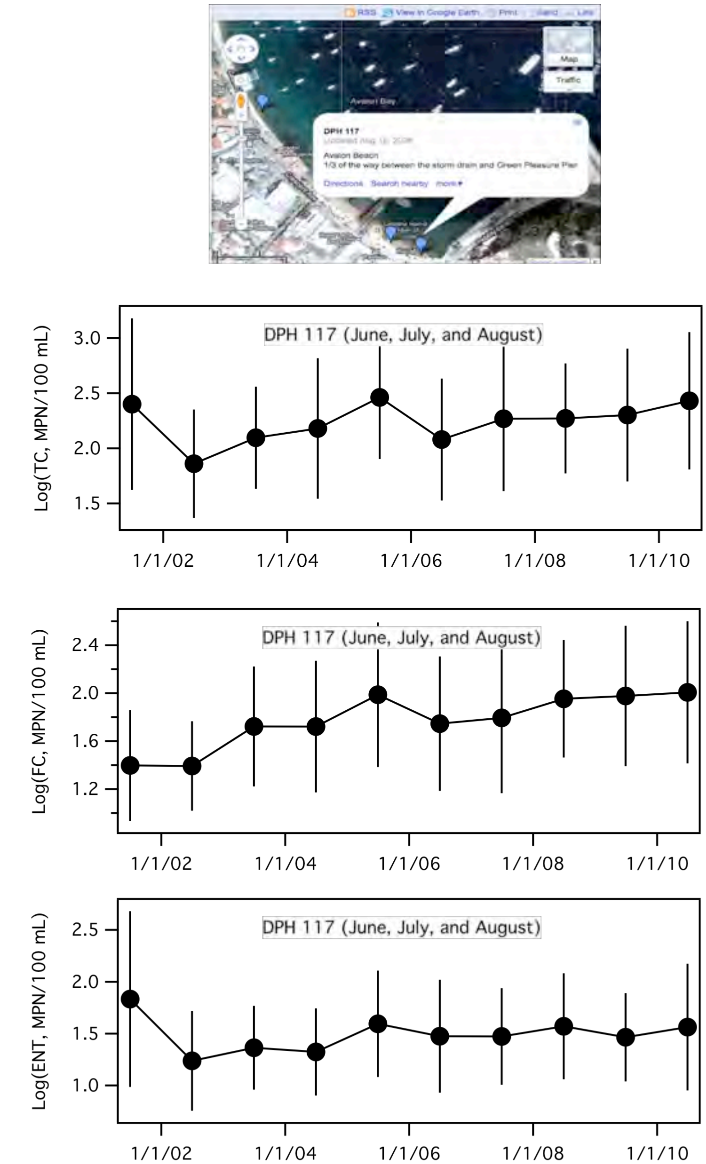


Figure 1. Mean and standard-deviation of the log-transformed FIB measured during April through October at Monitoring Site 117

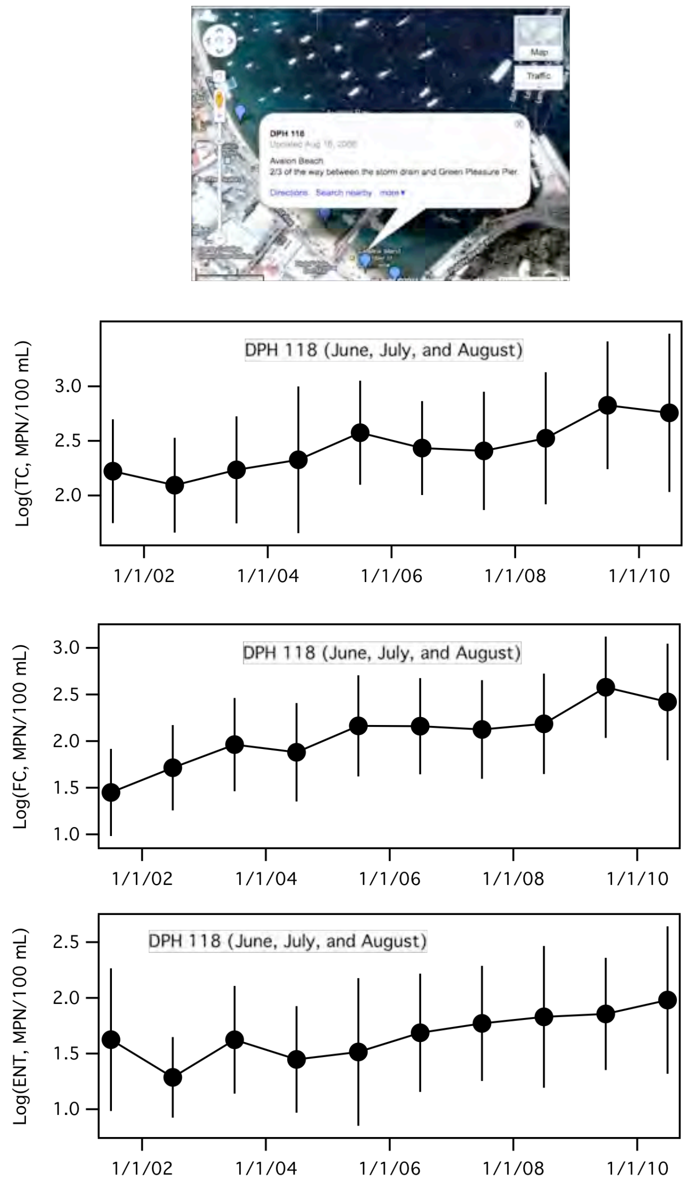


Figure 2. Mean and standard-deviation of the log-transformed FIB measured during April through October at Monitoring Site 118.

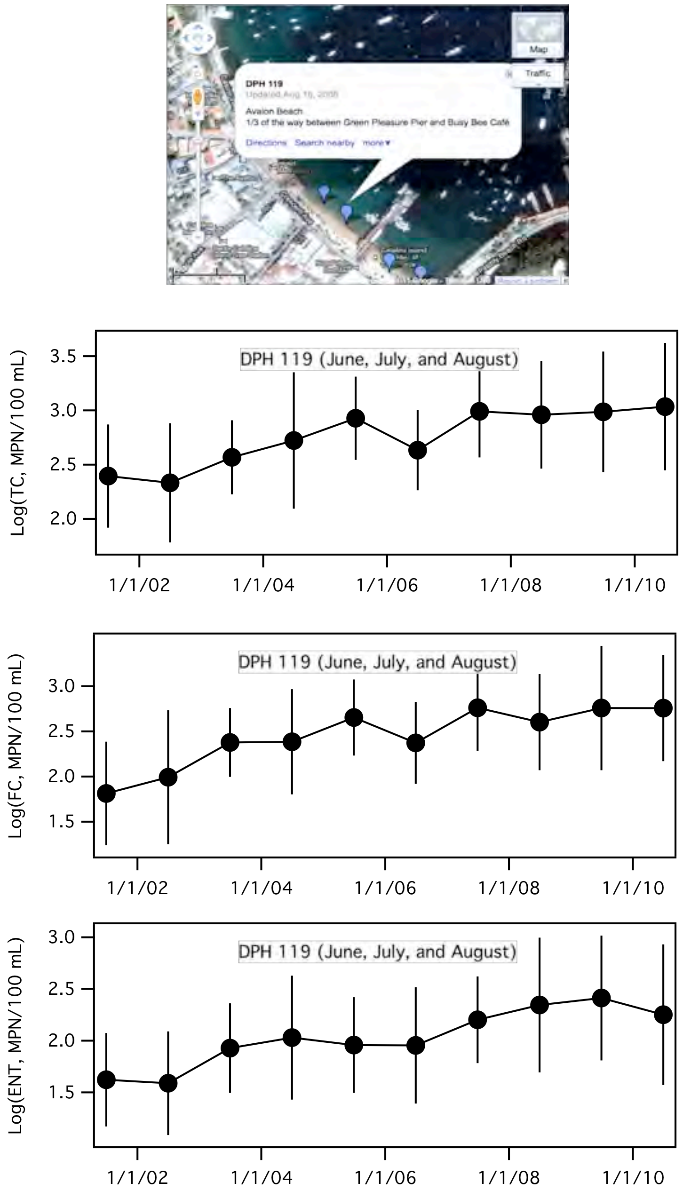
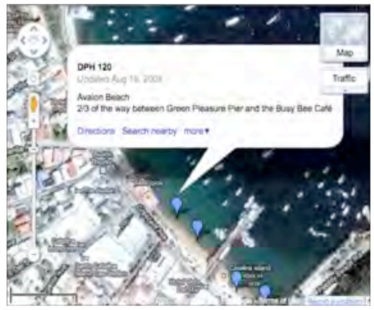


Figure 3. Mean and standard-deviation of the log-transformed FIB measured during April through October at Monitoring Site 119.



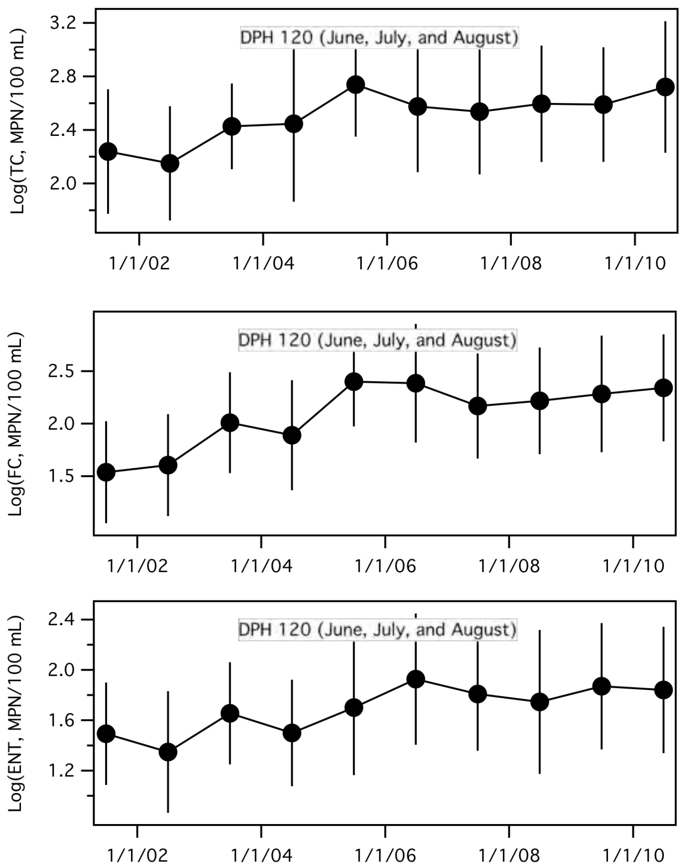


Figure 4. Mean and standard-deviation of the log-transformed FIB measured during April through October at Monitoring Site 120.

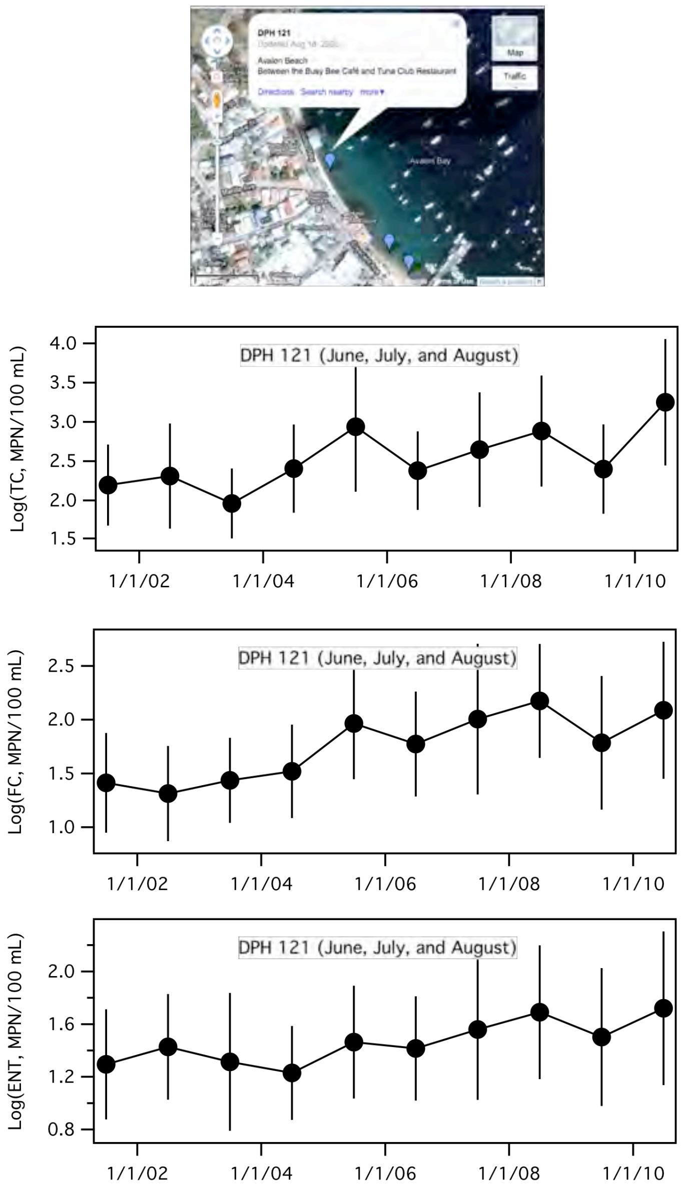


Figure 5. Mean and standard-deviation of the log-transformed FIB measured during April through October at Monitoring Site 121.

Project Outreach Activities

Outreach activities associated with this project include: (1) communicating results with residents of Avalon through one-on-one conversations during the collection of field data; (2) presentations to Avalon City Council; (3) communication of results to City staff responsible for the oversight and maintenance of the City's sewage collection and treatment system; (4) communication of results with scientists at the southern California Coastal Water Research Project (SCCWRP) who are conducting an ongoing health effects study in Avalon; (4) preparation of research journal manuscripts that describe the important aspects of the study.

As noted elsewhere in the report (the PAEP section), by identifying locations where the shallow groundwater beneath the City of Avalon had apparently high concentrations of sewage markers (so-called "hot spots"), the City was able to focus their sewer investigations, with the result that a number of significant problems with the sewage collection system were identified, and are currently being repaired. The Principal Investigator (S. Grant) has given several presentations to City Council on the study results, and he has been invited to give a final presentation to the City after the final report is approved. As noted above, SCCWRP is currently conducting a series of epidemiological studies of recreational waterborne illness (RWI) at marine beaches in southern California, and several of their study sites (City of Avalon, Catalina Island; City of Malibu and Surfrider Beach) are thought to be impacted by sewage-contaminated shallow groundwater. The results obtained from this study are informing SCCWRP's ongoing epidemiological studies, by clarifying the pathways by which sewage transports to the beach. For example, the study results in Avalon are consistent with the hypothesis that sewage markers (such as FIB) are not well-mixed in the shallow groundwater, but rather concentrated at the phreatic surface, or air-water interface. If correct, this hypothesis implies that sewage crosses the land-sea interface through foreshore sands during falling tides--precisely the location where many young children and families recreate. Indeed, preliminary results from the epidemiological study at the City of Avalon indicate that there is little difference in the RWI reported by swimmers and non-swimmers at the beach, but both groups have very high illness rates compared to the control population. One possible explanation is that human exposure to fecal-oral pathogens in Avalon is primarily through contact with sand, not contact with water. These results would have significant policy implications, including perhaps the need for new "sediment criteria" for beaches where the shallow groundwater is thought to be contaminated with sewage. Finally, data collected by this project will be written up as a series of articles, and submitted to high-impact journals. Current measurements collected in Avalon Bay were described in an article recently accepted for publication in the journal *Environmental Science and Technology*[1] It is anticipated that as many as five additional papers will come from this project.

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[1] Ho, L.C., Litton, R.M., Grant, S.B. (2011) "Anthropogenic currents and shoreline water quality in Avalon Bay, California", *Environmental Science and Technology*, in press.