An Analysis of Water Circulation in Pillar Point Harbor, Half Moon Bay, California, based on the Dye Distribution Study of September 27, 2008

Report prepared for:

San Mateo County Resource Conservation District

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Scope of Work

The San Mateo County Resource Conservation District (SMCRCD) has contracted Dr. Wuertz per agreement dated November 1, 2010, to summarize and interpret the Dye Release Study carried out on September 27, 2008 by Balance Hydrologics, Inc. The study involved the release of two dyes, Rhodamine and Fluorescein, at specific locations in the harbor to track how dyes dissipate, providing information about how water constituents travel within the harbor.

The following items were provided for review of the study:

- Draft Internal Report by Balance Hydrologics to SMCRCD (per Barry Hecht, Principal, Balance Hydrologics)
- A range of technical and nontechnical documents pertaining to the study

Sections of the Balance Hydrologics internal report are included verbatim by permission.

Acknowledgements

Carolann Towe, of the San Mateo County SMCRCD, conceived the idea of a circulation study and developed and implemented the complex programs to coordinate the volunteers, under the direction of Kellyx Nelson, and with the assistance of Ellen Gartside. Ms. Towe, who has studied fecal coliform along the San Mateo Coast for many years, collected samples during the study in addition to coordinating volunteers. Technical design and execution of the study was by Dr. Carla Grandy, Travis Baggett and Bonnie de Berry at Balance Hydrologics, under the leadership of Barry Hecht. We gratefully acknowledge their help and willingness in providing information for this report.

Members of the Technical Advisory Board of the ongoing research study “Identification of Sources of Fecal Pollution Impacting Pillar Point Harbor” by SMCRCD provided helpful advice during the planning stages of the study. In particular, John Oram gave key advice during preliminary dye release experiments and Steve Peters participated as volunteer kayaker. Dan Temko and harbor staff assisted throughout all stages by sharing their knowledge and providing logistical support such as placing the buoys. Saul Chaikin, veteran pilot, volunteered throughout the trial and main studies with air support, dodging the fog, while remaining at the elevation of 3000 feet required by the Federal Aviation Administration. Kellyx Nelson (SMCRCD) served as photographer from the air. Last but not least this study involved a great number of dedicated volunteers (listed by name in the Appendices) who spent many hours taking samples and helping with logistical aspects of the study. They came from diverse professional backgrounds, making the harbor circulation investigation a truly interactive event with significant input from the local community. The Balance Hydrologics project staff particularly wishes to thank their 8 co-workers from the various Balance offices and their families who volunteered.

We gratefully acknowledge the following persons who contributed time and effort to the Dye Distribution Study: Sheri Almeda, Greg Ames and Corey Ames, Ed Ballman and Alex Ballman, Allison Barden, Jim Blanchard, Rita Bosnich, Nathan Boyd, Nyssa Brennan, Gretchen Bringas, Ione Burge, Annette Cayot, Laurie Chaikin, Pat Conroy, K. Adem Cooper, Kevin Cooper, Tim Costello, Miguel Cunha, Brendan Downing, Chris Dunham, Carmen Fewless, Jeff Grandy, Andrea Grech, Rich Gruber, Richard Hagy, Leila Harris, Jennifer Heit, Mary Lou Holding, Linda Jacobson, Clive Jones, Marie Kazan-Komarek, Mary Sue Kelly, Steven King, Rosemary Lanyon, Jonathan Lear, Wendell Lee, Barry Lifland, Charlotte Lingo, Kaya MacMillen, Brian McBride, Susan McCarthy, Jeannie McDermott, Laurie McDonough, Mike Mead, Greg Merkes, Larry Miller, Carrie-Andrea Moresi, Ivan Navarro, Jill K. Newburn, Michael Newburn,

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EXECUTIVE SUMMARY

A Dye Distribution Study was conducted in Pillar Point Harbor (PPH) from September 27 to 29, 2008. The objective was to observe flow direction, velocity and mass transport in the harbor and to allow estimation of expected residence times of constituents in the harbor at key identified locations under late-summer or early-fall dry conditions. There were no prior studies of currents and circulation due to interaction of tide, wave and wind regarding the harbor. Microbial water quality in PPH is poor and the State Water Resources Control Board has listed the location as impaired by coliform bacteria on the 303(d) list submitted to the United States Environmental Protection Agency. In 2005 and 2006, San Mateo County Department of Environmental Health repeatedly posted beaches in the Harbor as potential health hazards. Capistrano Beach was posted most frequently, approximately 50 weeks in each year. At the time of the study, Capistrano Beach had elevated levels of fecal indicator bacteria (FIB), such as *E. coli* and *Enterococcus*, on over 95% of sampling events in wet and dry conditions.

Two fluorescent dyes, Fluorescein and Rhodamine, were released at selected locations in the harbor. Circulation of these dyes was recorded by taking samples from 3 kayaking circles A, B and C that covered the entire outer harbor, two sites D and E in the inner harbor, and 9 sites outside the harbor over the course of 3 days. The two dyes have slightly higher density than water. When they were sampled 6” below the water surface, their movement indicated the prevailing water current.

The dyes were used to check the circulation in the inner and outer harbor, flow between inner and outer harbor, and flow between the outer harbor and the open ocean. Both dyes are commonly used for environmental tracking because they are visible to the naked eye at high concentrations and remain detectable by a fluorometer even at very low concentrations. They are environmentally benign at the levels used in the study and decay naturally in ultraviolet light within days to weeks of being released.

Fluorescein and Rhodamine dyes were released concurrently at four locations throughout the harbor at 8 a.m. on September 27, 2008:

- Rhodamine was released to analyze the circulation of potential contaminants near the marsh.

- Fluorescein was released approximately 100 feet offshore of Denniston Creek to track circulation near the creek and outfall pipes at Capistrano Beach.

- Rhodamine dye was dispersed throughout the inner harbor in the vicinity of the liveaboard boats at the western end of the inner harbor.

- Fluorescein dye was released to monitor circulation from and around the side of the harbor as well as to ascertain some information about the permeability of the outer breakwater.

In addition, four types of fruit (25 each) were deployed at the identical sites used for dye release. Oranges were released evenly in the Western inner harbor; tangerines were released at the dye release site in circle A, lemons in circle B and limes in circle C. They were collected and counted once they reached the shore or the harbor wall. The drogues appeared to move downwind more quickly than the dye, implying that the surface water was moving in a different direction than the underlying water.

Dye distribution patterns suggest zones of differential velocities and hence propensities of mixing in the harbor. Consequently, the outcomes of fecal contamination released at different points in the harbor are likely to be different with respect to their residence time in the harbor. Taking into consideration the limitations of the study, which did not consider vertical stratification of dyes within the harbor or provide direct wind and wave measurements, it can be concluded that the distribution of dyes was not affected appreciably by wave action or wind speed. Consequently, the observed dye distribution patterns reflect the force of tidal flows. Given that the known contributions of freshwater inflows into the harbor throughout the seasons are minor it can be concluded that flushing will generally be determined by the action of tides. It should be noted that freshwater flows may still provide considerable pollutant loads into the harbor.

Assuming that Pillar Point Harbor (PPH) can be approximately represented by a rectangle, the average per cycle exchange coefficient for PPH is of the order of 0.42, indicating that the harbor possesses a high degree of interchange of waters with the ocean, facilitating the elimination of pollutants.

Yet there is no uniform pattern of flushing with some harbor areas less likely to depurate pollution levels. The Fluorescein plume, which was released at the Northern zone of the harbor, completely washed out in five tidal cycles (2.5 tidal days). However, any constituents which are released in the shallow waters of the Northwestern side of the basin would not be flushed out after six tidal cycles (3 days), because a considerable amount of tracer mass remained inside the harbor. In case of a future tracer study, the other release point to consider for a tracer study is the Eastern end of the harbor. The general pattern of incoming jet from the ocean and ebb tide currents flushing the harbor showed the general mode of circulation in the tidal prism to be clockwise.

Besides the two fluorescent dyes and the drogues, FIB and the alternate indicator *Bacteroidales* were measured inside the harbor and at beach control sites to gain knowledge of their general abundance at the time of the experiment. In general, FIB levels were below the single maximum and geometric mean standards. Capistrano Beach (PPH3) was the exception. This site is under direct influence of two (PPH1, Capistrano Outfall Pipe; PPH2, Bathhouse Outfall Pipe) of the four freshwater inflows into the harbor; these two freshwater sources typically exceed the geometric mean water quality objectives and even the single sample maximum objectives.

1 BACKGROUND

1.1 Fecal Pollution in Pillar Point Harbor and Motivation for Harbor Circulation Study

1.1.1 Geographical Setting

Pillar Point Harbor, located on the northern side of Half Moon Bay and adjacent to the small town of Princeton along the central coast of California in San Mateo County, is an enclosed watershed with complex inputs and water flows. It contains an inner boat harbor, pier, and saltwater/brackish tidal marsh (Pillar Point Marsh). It receives drainage from Denniston and Deer Creeks, storm drains, outflow pipes, and large, mixed-use areas including an airport, agricultural, commercial and residential sections. Pillar Point Harbor contains five beaches: Capistrano Beach, Yacht Club Beach, Marsh Beach, Mavericks Beach, Inner Harbor Beach, and Beach House Beach.

Pillar Point Harbor comprises an inner harbor and outer harbor. The boat-berthing basin is approximately 45 acres, contains approximately 400 slips, and is located within a set of breakwaters, herein referred to as the "inner" breakwaters. The inner breakwaters were constructed in 1982. South of the inner breakwaters there is another set of breakwaters, herein referred to as the "outer" breakwaters. The outer breakwaters were built in 1961 with an extension to the west breakwater across the opening added in 1967. The outer harbor area (between the inner and outer breakwaters) encompasses approximately 279 acres resulting in an entire harbor area of 324 acres.

The harbor area houses commercial ventures including several restaurants, hotels, shops, a fertilizer plant, three commercial fish buyers, sport fishing concessions, a yacht club, two kayak rental companies, a recreational vehicle park, and a Naval Station situated on the bluff overlooking the Outer Harbor. Outside of the Outer Harbor area but within the project study area are conference facilities, residential areas, and additional commercial ventures as well as a pump station for the Sewer Authority Mid-coastside.

1.1.2 Water Quality

Microbial water quality in Pillar Point Harbor (PPH) is poor and the State Water Resources Control Board has listed the location as impaired by coliform bacteria on the 303(d) list submitted to the United States Environmental Protection Agency. Capistrano Beach has elevated levels of fecal indicator bacteria (FIB), such as *E. coli* and *Enterococcus* on over 95% of sampling events in wet and dry conditions. This beach has been ranked for several years by Heal the Bay's Report Card as a "Beach Bummer," meaning that it is in the top ten most polluted beaches in California in dry weather conditions. In 2005/2006, Capistrano Beach ranked sixth on the "Beach Bummer" list. It was the worst ranked beach in Northern California and is a Clean Beaches Task Force Priority Beach with regard to fecal pollution. Capistrano Beach is permanently posted by the San Mateo County Environmental Health Department as a potential health hazard.

The public health conditions of the impaired waters may affect commercial ventures, harbor activities, tourism, recreation, and ecological habitat in the watershed. The harbor area has approximately 100,000 visitors annually and is heavily used recreationally by boating enthusiasts, kayakers, windsurfers, campers, hikers, dog walkers, bird watchers, swimmers, waders, families, clam diggers, surfers, and thousands of spectators for the world famous Mavericks big wave surf break.

In 2005 and 2006, San Mateo County Department of Environmental Health repeatedly posted beaches in the Harbor as potential health hazards. Capistrano Beach was posted most frequently, approximately 50 weeks in each year. Marsh Beach was posted over 20 weeks in each year i.e. 42% to 51% of sampling events. Mavericks Beach was posted approximately 15 weeks each year, approximately 30% of sampling events. The county terminated sampling for Capistrano Beach and permanently posted the beach as a potential health hazard in March of 2006.

Within the local community there are numerous opinions as to the primary sources of fecal pollution impacting the harbor, including but not limited to human contamination from leaking sewer lines, avian contamination from resident and migratory bird populations including large flocks of gulls and other birds, and lack of flushing in the harbor due to the presence of two break walls. Although much effort has been expended on studying the locations of fecal pollution impacting the harbor, including water sampling and fecal indicator enumeration studies, data on identification of primary sources and their relative contributions to the overall magnitude of the pollution problem are lacking. There is an urgent need for a comprehensive study of all of the possible sources of pollution in this watershed and how these flows interact in the confines of the enclosed Pillar Point Harbor Bay.

1.2 Objectives of Harbor Circulation Study

A fluorometric dye tracing study was designed by Balance Hydrologics, Inc., in coordination with San Mateo County Resource Conservation District (SMCRCD) and Prof. Stefan Wuertz at UC Davis who is the lead scientist in the ongoing research study "Identification of Sources of Fecal Pollution Impacting Pillar Point Harbor" by

SMCRCD. The objective was to observe flow direction, velocity and mass transport in the harbor and to allow estimation of expected residence times of constituents in the harbor under late-summer or early-fall conditions. During this period surface runoff is negligible, uncoupled from specific meteorological events. By sampling close to the onset of the winter rainy season, a period when surface runoff is negligible, uncoupled from specific meteorological events, the intention was to characterize the water quality characteristics of the harbor under prevailing conditions.

There were substantial outreach activities to local community members resulting in active participation by kayakers and other interested parties. The information gathered will be used in the abovementioned research study to determine the effects of harbor circulation dynamics on the fate and transport of FIB. There were no prior studies of currents and circulation due to interaction of tide, wave and wind regarding the harbor. Also there were no previous reports of variability of currents or flushing time either. In 1994 and 2006 two surveys of bathymetry were conducted by Gahagan & Bryant Associates (GBA) as part of design phase for maintenance deranging and also building 71 new berths.

2 STUDY DESIGN

The main objective of the study was to inspect the water exchange through the mouth of the harbor, movement through and around the breakwater and nearshore circulation, and residency times at key identified locations. The experiment was conducted on September 27, 2008 and measurements were taken through September 29, 2008. These were quiescent days at the end of the dry season with minimum inflow from land use; therefore, the circulation results obtained from this study were under no influence of freshwater inflow. Two fluorescent dyes, Fluorescein and Rhodamine, were released at selected locations in the harbor. Circulation of these dyes was recorded by taking samples from 3 kayaking circles A, B and C that covered the entire outer harbor, two sites D and E in inner harbor and 9 sites outside the harbor (Figure 1) over the course of 3 days. The two dyes have slightly higher density than water. When they were sampled 6” below the water surface, their movement indicated the prevailing water current. Drogues including orange, tangerine, lemon and lime were also released at the dye release location to check the impact of wind.

Fecal indicator bacteria including total coliform, *E. coli* and enterococci were also measured at these sites and at the routine monitoring sites PPH1 to PPH10. The microbial source tracking (MST) indicator *Bacteroidales* for total, human-associated, cow-associated and dog-associated fecal pollution was measured at the four dye release sites and four sites outside of the harbor. *Bacteroidales* are highly abundant bacteria in the gut of warm-blooded animals and contain genetic markers that can be used to pinpoint specific animal fecal sources. Neither FIB measurements not MST analysis were expected to contribute new information in addition to the concentration profiles of the two fluorescent dyes because of the relatively low concentrations found in the harbor compared to beaches and freshwater discharge points. Rather, FIB and *Bacteroidales* were measured as part of the ongoing research project in Pillar Point Harbor. The information is included in this report as ancillary information.

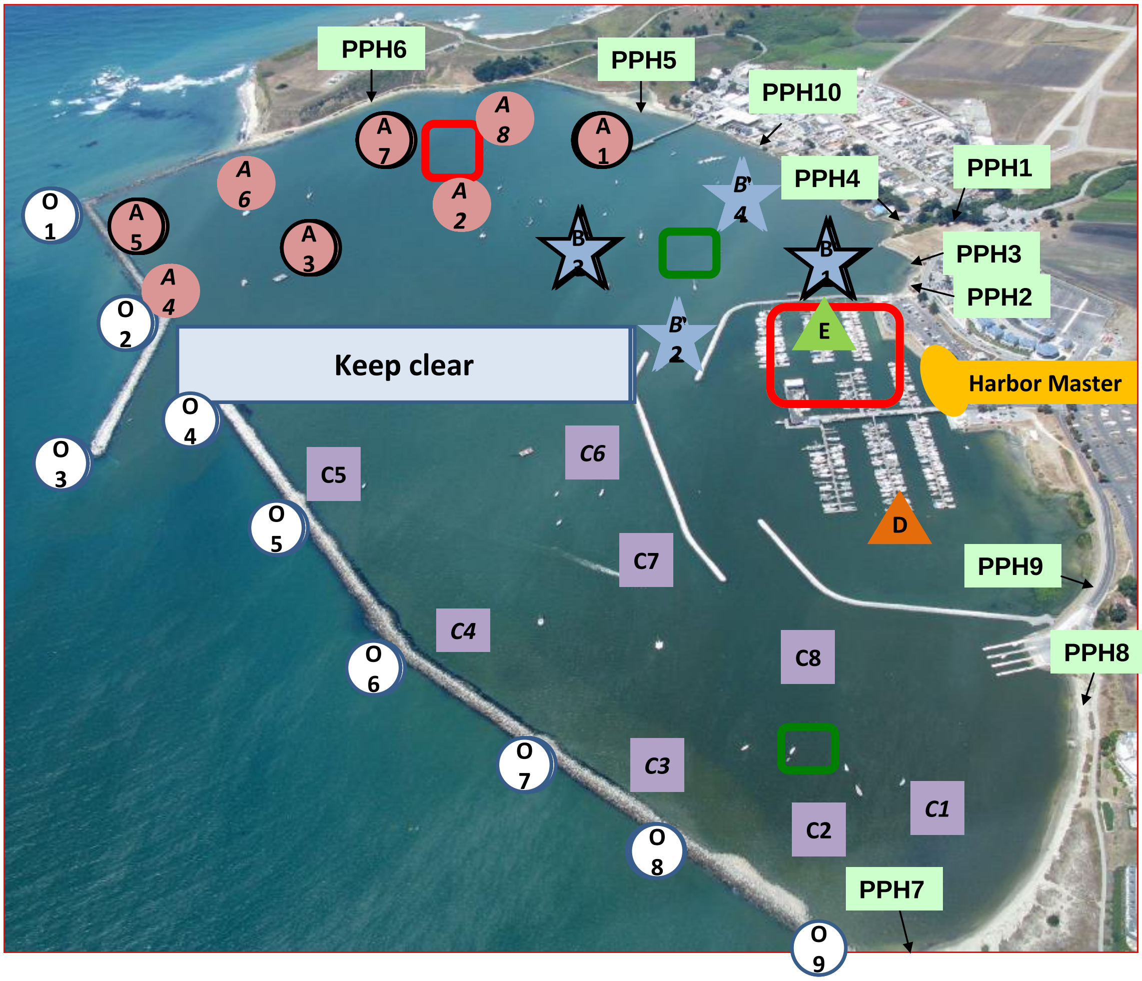

Figure 1: Dye release and sampling sites. Green square: Fluorescein release site; red square: Rhodamine release site. Circle A with sites A1 to A8, circle B with sites B1 to B4 and circle C with sites C1 to C8 are sampling sites in outer harbor. Site D and E are sampling sites in inner harbor. Sites O1 to O9 are control sites outside of the harbor. PPH1 to PPH10 are the 10 sites for routine monitoring in the research study "Identification of Sources of Fecal Pollution Impacting Pillar Point Harbor". PPH1: Capistrano Outfall Pipe, PPH2: Bathhouse Outfall Pipe, PPH3: Capistrano Beach, PPH4: Denniston Creek, PPH5: Pillar Point Marsh Beach, PPH6: Mavericks Beach, PPH7: Beach House Beach, PPH8: Deer Creek Outlet, PPH9: Inner Harbor Beach, PPH10: Yacht Club Beach.

3 MATERIALS AND METHODS

3.1 Dye Sampling and Measuring Procedure

The dyes Fluorescein and Rhodamine (Bright Dyes, OH and Keystone Dyes, IL) were used to check the circulation in the inner and outer harbor, flow between inner and outer harbor, and flow between outer harbor and the open ocean. These two dyes were selected as tracers to monitor circulation within the harbor. Both dyes are commonly used for environmental tracking because they are visible to the naked eye at high concentrations and remain detectable by a fluorometer even at very low concentrations. They are environmentally benign at the levels used in the study and decay naturally in ultraviolet light within days to weeks of being released.

Rhodamine was released at one location in circle A (released equidistant between sites A1, A2, A7, and A8 to analyze the circulation of potential contaminants near the marsh) and evenly distributed in the western inner harbor (in the vicinity of the liveaboard boats at the western end of the inner harbor) at 8:00 Sep. 27th. Fluorescein was released at one location in circle B (100 feet offshore of Denniston Creek between sites B1 and B4 to track circulation near the creek and outfall pipes at Capistrano Beach) and one location in circle C (equidistant from sites C1, C2, C3 and C8 to monitor circulation from and around the eastern side of the harbor as well as to ascertain some information about the permeability of the outer breakwater) at 8:00 Sep. 27th. Two batches of dyes (one batch from each company) were ordered and released at each location (Table D-1). Volunteer kayakers took samples every 15 minutes from 8:00 to 16:00 on Sep 27th and from 8:00 to 10:00, 12:00 to 14:00 and 16:00 to 18:00 on Sep 28th and 29th at circle A, B and C, site D and E. At each location and sampling time, water samples were grabbed 6" below water surface using a 100-ml plastic bottle; the bottles were immediately put in 2-liter black zip lock bags to avoid exposure to sun. The bottles were then returned to the harbor master for analysis. A Turner Designs 10--AU--005--CE Field Fluorometer was used to measure dye concentrations.

Table 1 Fluorescein and Rhodamine Manufacturer and Dosage Used

Manufacturer	**Fluorescein**	**Rhodamine**
Bright Dyes	Yellow/Green	Rhodamine Red (50)
Concentration	7.7%	5%
Volume released per station	3 gallons	3 gallons
Keystone Dyes	Uranine K liquid	Rhodamine WT liquid
Concentration	40%	20%
Volume released per station	0.96 gallon	0.96 gallon

The Turner Designs 10--AU--005--CE Field Fluorometer was used to analyze the samples. This fluorometer was chosen because of its portability, ability to analyze samples at different temperatures, and because of the availability of support from Turner Designs. Before analyzing the samples the fluorometer was calibrated by Balance Hydrologics staff. A standard of fluorescein was created by diluting the dye as received with deionized water to a concentration of 200 ppb. That standard was further diluted using harbor water to a concentration of 50 ppb. The fluorometer was calibrated using the 50 ppb standard. The 10--AU also allows a "blank" value to be set which acts as the zero point for the analysis and subtracts the value of the fluorescence of the blank standard from all other samples. Harbor water collected prior to the release of the dye was used as the blank sample. This was done to account for the natural fluorescence present in the harbor water. The reporting range of the instrument in this configuration is from 0 to150 ppb with greatest accuracy around 50 ppb. The 50 ppb standard was further diluted with harbor water to 25 ppb. The 25 ppb standard was used to check the calibration of the fluorometer periodically while analyzing samples and the value was recorded.

The fluorometer was set to analyze discrete samples (rather than continuous flow). Samples were transferred to a cuvette that was triple rinsed with distilled water. Once the filled cuvette was placed into the discrete sample chamber, the fluorometer was allowed to stabilize until the "time constant" reached 2 seconds, typically 10 seconds. No more than 60 seconds was allowed to pass before recording the value reported by the fluorometer. Once analyzed the sample in the cuvette was disposed of. The sample remaining in the sampling container was resealed and packed in boxes. The used cuvette was triple rinsed with distilled water, wiped clean and returned to stock to be filled with the next sample.

On September 27, 2011 the fluorometer was set up for discrete sample analysis of Fluorescein. All samples collected on this date were analyzed on site for Fluorescein and samples remaining in the sampling container were returned to the Berkeley office of Balance Hydrologics by Balance staff. Samples collected on September 28th and 29th were packed by San Mateo SMCRCD and mailed to the Balance Hydrologics office in Berkeley. All samples remained in plastic bags and cardboard boxes to minimize photo--degradation of the Fluorescein and Rhodamine. Most samples were received in acceptable condition with a few samples lost in transport. All lost samples were marked as lost in the lab notes. Samples collected on 28th, and 29th of September were analyzed for Fluorescein with no adjustments made to the set--up of the Turner 10--AU from the initial September 27th configuration.

Once all samples were analyzed for Fluorescein, the fluorometer was converted for Rhodamine analysis. This involved changing internal filters and lamps and recalibration.

Calibration procedures used for the Rhodamine were the same as the procedure used for Fluorescein. The samples were reanalyzed for Rhodamine using the same methods used for Fluorescein.

In addition to samples of harbor water, QA/QC blank samples and duplicate samples were also collected. The procedure of the QA/QC samples was handled by San Mateo SMCRCD staff. Analysis of the QA/QC samples was done intermittently during the regular sample analysis and without adjustment to the fluorometer. Results of those analyses were recorded in the onsite lab book and transcribed into the electronic spreadsheet. Additional QA/QC was performed on the transcription procedure to ensure that the electronic spreadsheet of results matched the original lab notes.

3.2 Drogue Release and Counting

Four types of fruit (25 each) were released at the identical sites used for dye release. Oranges were released evenly in the western inner harbor; tangerines were released at the dye release site in circle A, lemons in circle B and limes in circle C (see Figure 2). They were collected and counted once they reached shore or the harbor wall.

3.3 Fecal Indicator Bacteria (FIB) Sampling and Analytical Procedure

Hundred-milliliter water samples for fecal indicator bacteria (FIB) including total coliform, *E. coli* and enterococci were collected at the same sites where samples for dye monitoring were collected. FIB were measured four times for circle A, B and C, site D and E (8:00 and 14:00 on Sep. 27th, 9:00 on Sep. 28th and 9:00 on Sep. 29th); twice for the 10 routine sampling sites PPH1 to PPH10 (9:00 on Sep. 28th and 9:00 on Sep. 29th); and once for the control sites O1 to O9 (9:00 on Sep. 28th). Water samples were sent on ice to the San Mateo County Public Health Lab and enumerated using Colilert and Enterolert (IDEXX, Maine) within 6 h. Total coliform and enterococci were measured for all water samples; *E. coli* was measured for fresh water sites. About 10% of samples for FIB included duplicates and blanks, which were analyzed in parallel.

3.4 *Bacteroidales* Sampling and Analytical Procedure

Ten-liter water samples for the microbial source tracking (MST) target *Bacteroidales* were collected at the four dye release sites and four control sites outside of the harbor (O1, O3, O6 and O9) at 8:00 on Sep. 27th. The water samples were driven to the Wuertz laboratory at UC Davis within 2 h and immediately concentrated to 100 ml using hollow fiber ultrafiltration according to a previously tested procedure (Rajal et al. 2007). DNA was extracted from the concentrated samples and four *Bacteroidales* qPCR genetic assays (universal, human-associated, cow-associated and dog-associated) were conducted as described elsewhere (Kildare et al. 2007).

4 RESULTS

4.1 Fecal Indicator Bacteria

FIB concentrations in water samples taken inside the harbor and at control sites were generally below the water quality objectives, only site C1 had a one-time exceedance of enterococci on Sep. 29th. The MPN value was 52/100 ml, which is higher than the allowed geometric mean of 35/100 ml for this indicator, but lower than the allowable single sample maximum value of 104/100ml. The geometric mean of a site must be calculated from the five most recent samples from that site in a 30-day period. Because site C1 was not routinely sampled but only tested during this circulation study, the water quality objective based on the geometric mean does not apply to it. Hence the site was in compliance. Of the six beach sites, which are monitored as part of the research project study "Identification of Sources of Fecal Pollution Impacting Pillar Point Harbor" by San Mateo Resource Conservation District (SMRCD), only PPH3 had ever exceeded the geometric mean water quality objective but not the single sample maximum objective, once for coliform and twice for the enterococci geometric mean (the geometric mean was calculated based on routine PPH3 monitoring data from the five most recent samples before and during the circulation study). This is because PPH3 is under direct influence of two (PPH1 and PPH2) of the four freshwater inflows into the harbor; these two freshwater inflows typically exceed the geometric mean water quality objectives and even the single sample maximum objectives.

This circulation study was done in September under dry weather condition. There was minimum freshwater input into the harbor for the previous few months. Their impact on water quality inside the harbor is small due to the dilution effect and most FIBs were below detection limit. Only site PPH3 exceeded the geometric mean water quality objectives occasionally. Details are in Tables 2, 3 and 4 and Figures 2, 3, 4 and 5.

Table 2 Exceedance Rate of Total Coliforms (see Figures 2 and 5)

Site/ Objective	**No. exceedances/sample size[a]**	**No. exceedances/sample size[b]**
A circle	0/32	0/32
C circle	0/32	0/32
B circle	0/16	0/16
Site D and E	0/8	0/8
Control site	0/9	0/9
MST beach site	1/12 (PPH3)	0/12
MST inflow site	7/8 (PPH1,2,4,8)	3/8 (PPH1,8)

[a] Allowable geometric mean = 1000/100 ml

[b] Single sample maximum = 10000/100 ml

Table 3 Exceedance Rate of *E. coli* for Fresh Water Only (see Figure 3)

Sites/ Objectives	No. exceedances/sample size[a]	No. exceedances/sample size[b]
A circle	Not applicable	Not applicable
C circle	Not applicable	Not applicable
B circle	Not applicable	Not applicable
Site D and E	Not applicable	Not applicable
Control sites	Not applicable	Not applicable
MST beach sites	Not applicable	Not applicable
MST inflow sites	5/8 (PPH1,4,8)	5/8 (PPH1,4,8)

[a] Allowable geometric mean = 126/100 ml
[b] Single sample maximum = 235/100 ml

Table 4 Exceedance Rate of Enterococci Levels (see Figures 4 and 5)

Sites/ Objectives	No. exceedances/sample size[a]	No. exceedances/sample size[b]
A circle	0/32	0/32
C circle	1/32 (site C1)	0/31
B circle	0/16	0/16
Site D and E	0/8	0/8
Control sites	0/9	0/9
MST beach site	2/12 (PPH3)	0/12
MST inflow site	6/8 (PPH1,4,8)	6/8 (PPH1,4,8)

[a] Allowable geometric mean = 35/100 ml for marine or 33/100 ml for fresh water
[b] Single sample maximum = 104/100 ml for marine or 61/100 ml for fresh water

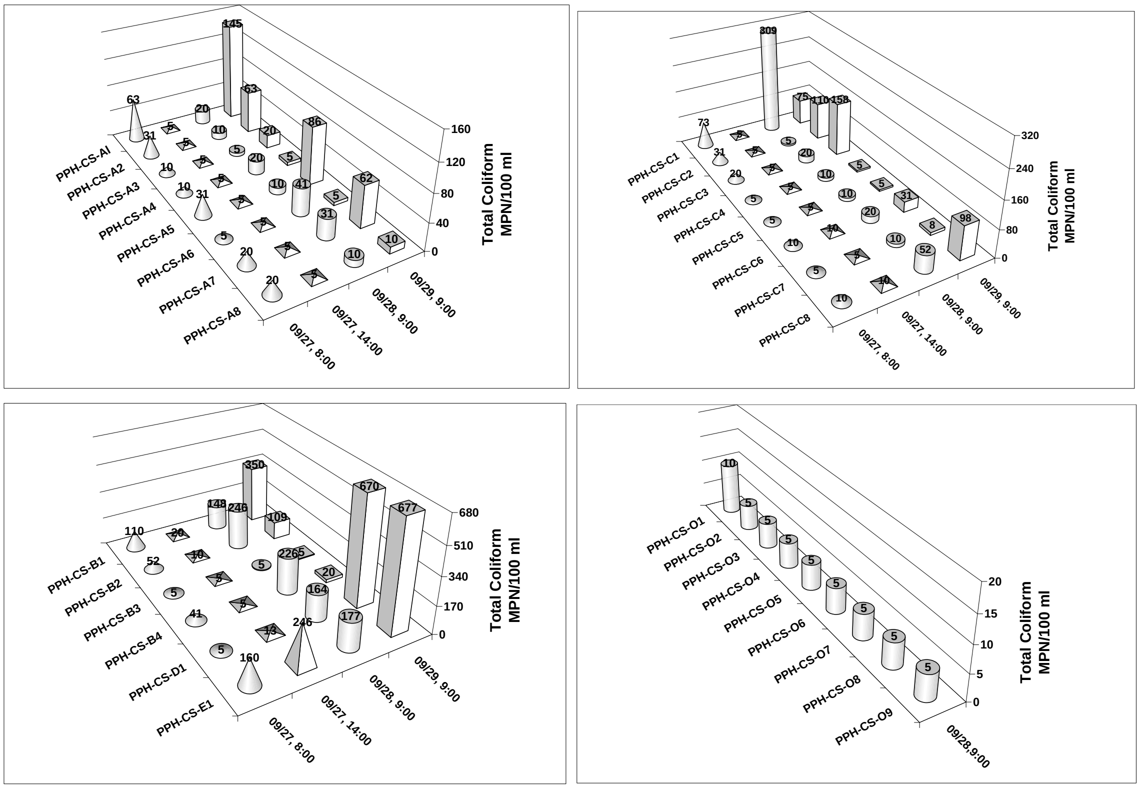

Figure 2: Total coliform concentrations at the dye monitoring sites and control sites (upper left panel: A circle; upper right panel: C circle; lower left panel: B circle and site D and E; lower right panel: control sites outside of the harbor)

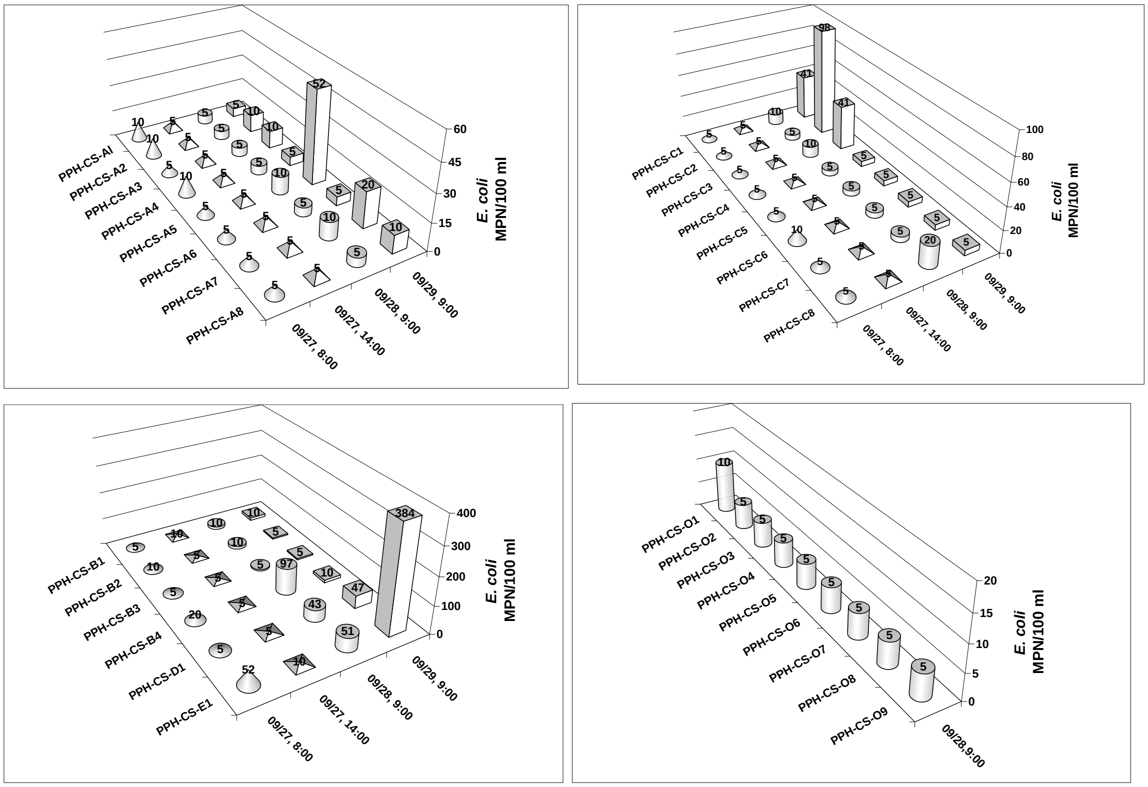

Figure 3: *E. coli* concentrations at the dye monitoring sites and control sites (upper left panel: A circle; upper right panel: C circle; lower left panel: B circle and site D and E; lower right panel: control sites outside of the harbor)

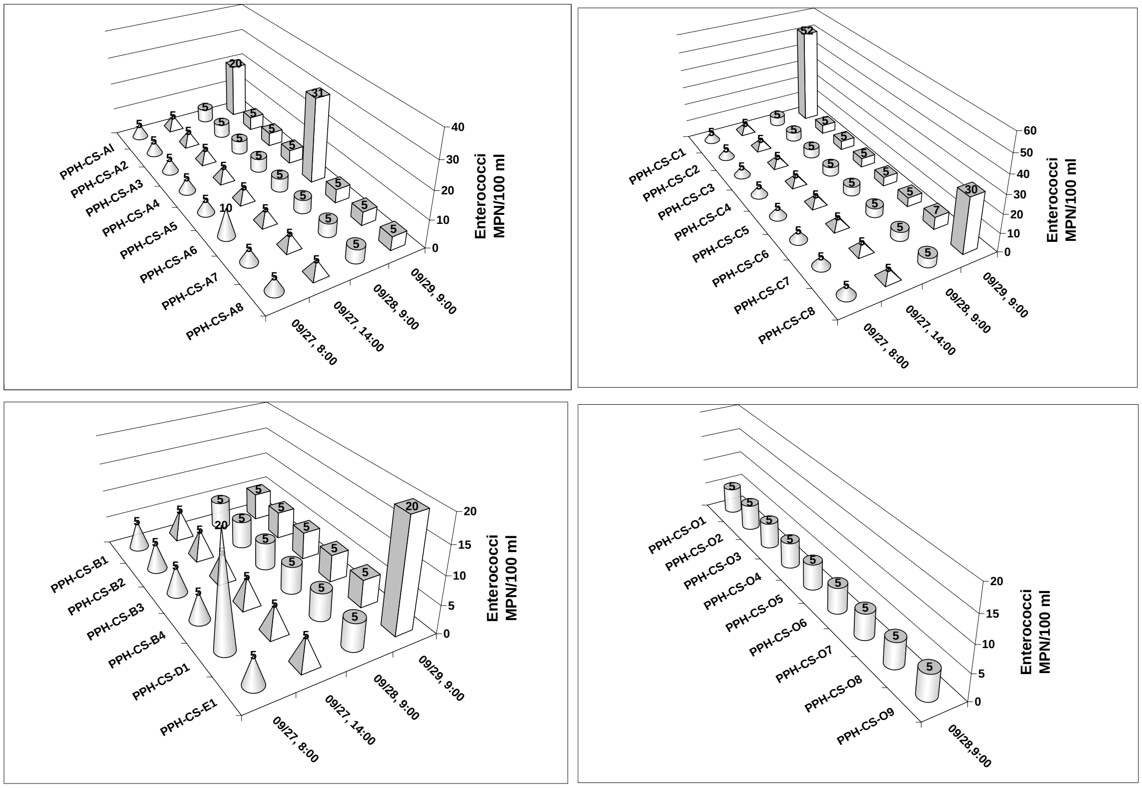

Figure 4: Enterococci concentrations at the dye monitoring sites and control sites (upper left panel: A circle; upper right panel: C circle; lower left panel: B circle and site D and E; lower right panel: control sites outside of the harbor)

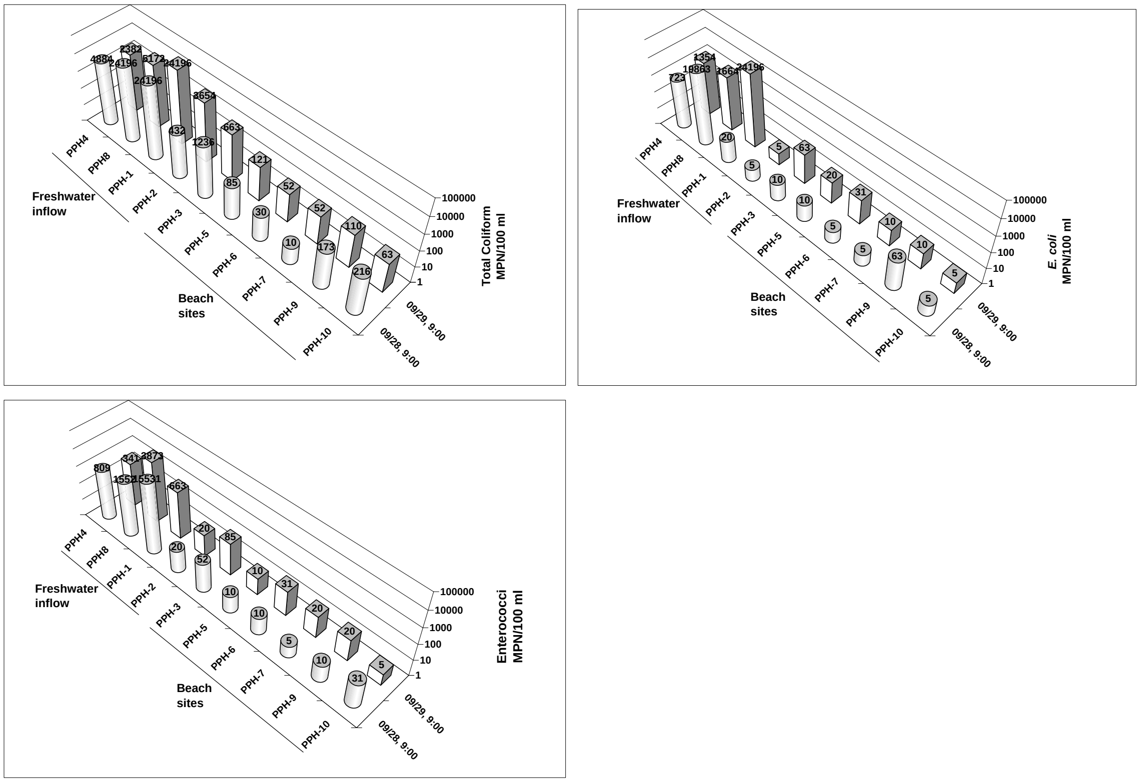

Figure 5: Fecal indicator bacteria levels at the 10 microbial source tracking sampling sites (upper left panel: total coliform; upper right panel: *E. coli*; lower left panel: enterococci)

4.2 Fate of Drogues Released

Fruit was chosen because it is biodegradable, non-toxic, and has a density that allows it to float with most of the fruit under water. Prior observations in the harbor had shown that floating fruit moved in a different direction than the dye, which disperses slowly through the water column. The drogues appeared to move downwind more quickly than the dye, implying that the surface water is moving in a different direction than the underlying water. Some of the tangerines released in the A circle reached the beach locations PPH5 and PPH6 about 6 h later, whereas others escaped the confines of the outer harbor as measured after 7 h (Figure 6). Lemons released inside the B circle reached beaches PPH5 and PPH6 4.5 h later, and some of them had migrated towards the opening of the break wall. Oranges released in the west inner harbor reached the beach location PPH3 in the east harbor 6 to 8 h later. Limes released in the C circle reached the outer harbor wall 1 to 5 h later.

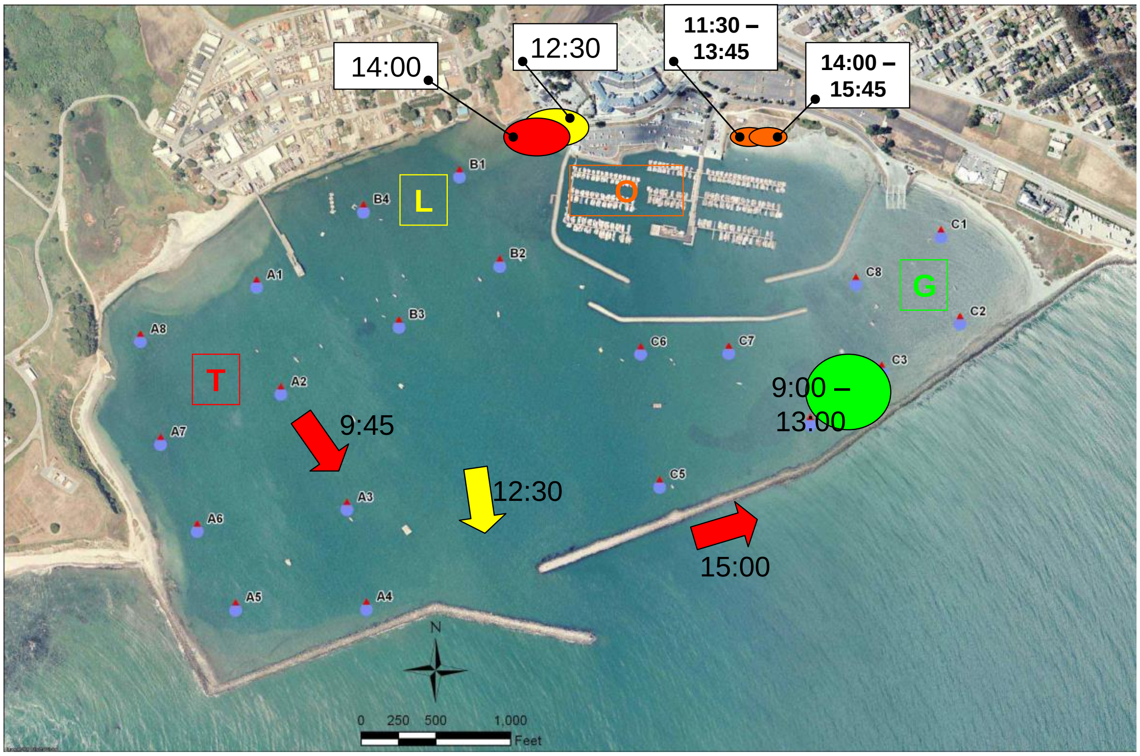

Figure 6: Drogue release sites and migration. (Box T: tangerine release site, Box L: lemon release site, Box O: orange release site, Box G: lime release site. Arrow: drogue moving direction. Ellipses: locations of beaching or repeated observations)

4.3 *Bacteroidales*

Microbial source tracking (MST) using *Bacteroidales* as source indicator was conducted at two groups of sites: group one consists of the 4 dye release sites in circle A, B, C and site E; group two contains the 4 control sites in the open ocean right outside of the harbor O1, O3, O6 and O9. The total *Bacteroidales* concentration was generally higher at the control sites outside of the harbor than at the sites inside the harbor (dye release sites). Our hypothesis is that kelp and fish, which have higher density at the control sites, might harbor some *Bacteroidales* species that can be detected by the universal *Bacteriodales* assay. This hypothesis remains to be verified. The human-associated *Bacteroidales* concentration was slightly higher at sites B and E than at other sites, but on the same order of magnitude than at sites A and O6. Site B is next to the most contaminated beach site PPH3, which is under direct influence of fresh water inflow PPH1 and PPH2. Site E is in the inner harbor with much less circulation. It is also close to the liveaboard boats. Long-term monitoring is needed to identify the exact reason for this human-associated signal. The dog-associated and cow-associated *Bacteroidales* concentrations in both groups of sites were at minimum level (Figure 7).

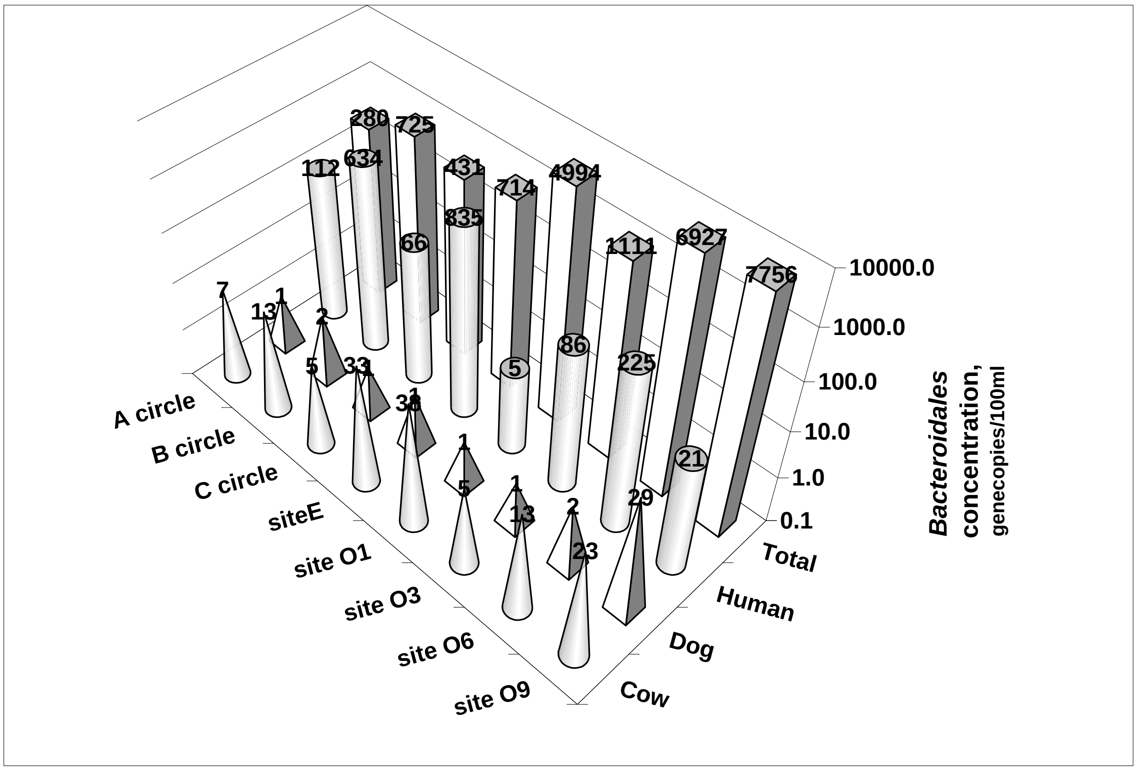

Figure 7: *Bacteroidales* concentration at the four dye release sites and four control sites outside the harbor (sampled at 8 a.m. on 9/27/2008)

4.4 Dispersion of Fluorescent Dyes in Inner and Outer Harbor

Fluorescein and Rhodamine dyes were released concurrently at four locations throughout the harbor at 8 a.m on September 27, 2008. The release sites were chosen by Balance Hydrology, with input from members of the Technical Advisory Committee for the research project "Identification of Sources of Fecal Pollution Impacting Pillar Point Harbor" by San Mateo Resource Conservation District (SMRCD). The four sites were strategically selected to gain information about circulation from and within the areas suspected to be potential sources of bacterial contamination within the harbor as follows:

- Rhodamine was released equidistant from sites A1, A2, A7, and A8 to analyze the circulation of potential contaminants near the marsh (see Figure 1).

- Fluorescein was released approximately 100 feet offshore of Denniston Creek between sites B1 and B4 to track circulation near the creek and outfall pipes at Capistrano Beach.

- Rhodamine dye was dispersed throughout the inner harbor in the vicinity of the liveaboard boats at the western end of the inner harbor.

- Fluorescein dye was released equidistant from sites C1, C2, C3 and C8 to monitor circulation from and around the eastern side of the harbor as well as to ascertain some information about the permeability of the outer breakwater.

Beginning at 8:15 a.m. and continuing until 16:00 on September 27th samples were collected by volunteer kayakers at 15-minute intervals from each of the 22 pre-identified sites within the harbor. For the two succeeding days (September 28 and 29) samples were collected approximately hourly from each of the locations. Samples were collected in bottles that were pre-labeled for the site locations. Volunteers wrote the time the sample was collected on the bottle and stored the bottles in black plastic bags, which were collected at the end of their two-hour kayaking shift. At the same time samples were being collected from the harbor, aerial photographs were obtained to monitor the movement of the visible plume. As there was heavy fog on the day of the field operation, the pilot was only able to fly during a limited period of time.

4.4.1 Fluorescein Movement Observation

Fluorescein was released at 8:00 a.m. (27th) almost at the end of flood tide (Figure B-1, Figure 8). In the 10:00 -11:00 a.m. measurement window, a considerable amount of the Fluorescein was found at point C4 but not at the stations C7, C5, and C6. This could possibly be explained as follows: the constituent traveled from the gap between the inner harbor's breakwater (Figure B-3). From 12:00-13:00, in the middle of ebb tide, both Fluorescein mass distributions in zones B and C are carried by the ebb tide into the ocean and move toward the harbor's mouth (Figure B-3 to B-5). By the time span 13:00 to 14:00 (end of ebb tide) a portion of the Fluorescein mass passed the harbor entrance and was likely released into the ocean (Figure B-5). From 14:00 to 17:00 (slack tide) the

Fluorescein masses are pushed back to the stagnation points (B1, B2, B4 and C1, C2, C3, C8; Figures B-7; 8; 9).

By the next morning (8:00-10:00 a.m. on September 28, 2008) the center of mass in the B1, B2, B4 triangle was pushed to the western edge of the harbor due to the another flood tide in the night. Interestingly, the mass is dispersed within the harbor except for points A5, A6, A7 and A8 (Figure B-10). The points A5, A6, A7 and A8 are shallower than the average of the other sampling points, and the tracer was not found there. The authors assume the currents might not be too strong at the west end of the basin. By 2:00 p.m. (28th) the remainder of tracer mass again moved to the mouth in the ebb tide from the following two corridors: 1) North to west from B3 to the harbor mouth, 2) parallel to the eastern breakwater from C3, and C4 to the mouth (Figure B-11). In the period 16:00-18:00 (28th September 2008), the rest of Fluorescein mass was pushed back to the stagnation points by the flood tide (Figure B-12). Then, by 10:00 a.m. of the last day of study (29th September 2008) the remaining mass of Fluorescein is located at the stagnation points B1, B2, B4 and C1, C2, C3, C8 (Figure B-13). Finally, by 2:00 p.m. of September, 29th no more Fluorescein was detected at the sampling points (Figures B-14, B-15).

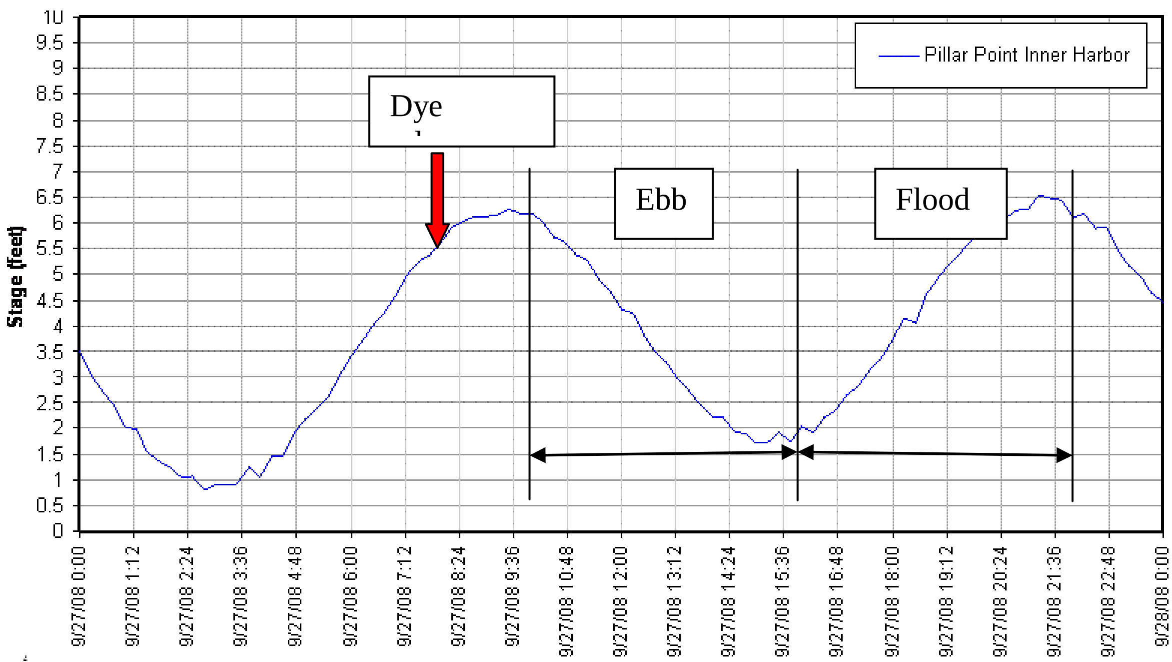

Figure 8: Fifteen-minute tide data for Pillar Point Harbor, San Mateo County, CA, September 27, 2008. Source: Balance Hydrologics Inc.

4.4.2 Rhodamine Movement Observation

Rhodamine was released at 8:00 a.m. (September 27, 2008) before the slack tide and after a flood. No tracer was detected in the first three hours (Figure C-1, 2, 3). By 11:00 a.m., the Rhodamine mass moved slowly towards the harbor mouth (with Westward direction) due to the start of ebb tide and the effect of deeper depth (Figure C-4). By 12:00-13:00 a portion of Rhodamine was taken in by the ebb tide current towards the ocean and another portion moved along the inner harbor jetty towards the point C8 (Figure C-5). At 13:00-14:00 (27th September 2008), the same behavior as pervious step up to the end of ebb tide (Figure C-6). At 14:00 – 15:00 (27th September 2008), after the beginning of flood tide, both Rhodamine mass plumes were pushed back into the basin. They remained at essentially the same location in the following sampling period, 15:00-16:00 (Figure C-7, 8). By 16:00 - 17:00 the tracer was moving towards the ocean from its previous locations (Figure C-9).

The next morning (28th September, 2008), at 8:00 to 10:00 a.m., the Rhodamine mass was almost detected everywhere in the harbor, near the end of flood tide, but the tracer concentration decreased from Northern sampling points when it came to South near harbor entrance (Figure C-10). 12:00 to 2:00 PM, 28th September, 2008, by the middle of ebb tide, Rhodamine again almost detected everywhere with about the same concentration, but the total mass was less than the last hours. The lost mass was washed out and diluted in the ocean (Figure C-11). In the period of 16:00 to 18:00, after the beginning of flood tide, Rhodamine was again detected almost everywhere with the same pattern as on the previous day. However, the mass was pushed back to the North to some extent by the incoming tidal jet (Figure C-12). At 8:00 to 10:00 a.m., 29th September, by the end of flood tide, the Rhodamine mass was once again found everywhere except in the incoming jet locus right North of the harbor mouth. The concentration of dye was higher in the zones distant from the harbor entrance (Figure C-13). Finally, during 12:00-14:00 and 16:00-18:00 on the 29th, after the end of ebb tide, the Rhodamine plume dissipated all over the harbor with the same pattern as on the previous day, but the total mass is less (Figure C-14, 15).

5 DISCUSSION

In 1994, Gahagan & Bryant Associates, Inc. (GBA) performed a hydrographic survey of the entire harbor area as part of an effort by the San Mateo County Harbor District to design and build an additional 71 berths inside the inner set of breakwaters and perform maintenance dredging. However, the project stalled until 2006. GBA again surveyed the entire berthing area in August 2006. The 2006 hydrographic survey was compared with the 1994 bathymetry to determine areas and rates of scour/accretion, which in turn facilitates planning for maintenance dredging projects and advances the understanding of sediment transport within the harbor. Both sediment entrainment and deposition are functions of shear velocity at the bottom. Shear velocity is proportional to the flow velocity. Therefore, the high velocity zones and stagnant zones in a harbor basin could be implicitly identified while considering the local scour/accretion.

The 2006 surveying report of GBA shows the annual net scour/accretion in different zones of harbor over a 12-year period of 1994-2006. Difference in depth was normalized in the repost between 1994 and 2006 when the entire harbor experienced 37,127 cubic yards (CY) of scour and 151,787 CY of accretion, resulting in a net accretion value of 114,660 CY. Each individual zone experienced scour and accretion. Zone one has the highest rate of scour in Pillar Point Harbor (Figure 10) with an average of -0.03 ft change in elevation in a year in the 12-year period of 1994-2006. Zone two with the net accretion of +0.23 ft per year has the highest amount of sediment accumulation in that period. It can be implicitly inferred that zone two in the western end of the harbor basin is a zone of low currents. This is concomitant with what one could expect based on the geometry of the harbor. Consequently, a picture emerges where there are zones of differential velocities and hence propensities of mixing in the harbor. The outcomes of fecal contamination released at different points in the harbor are likely to be different with respect to their residence time in the harbor.

Several confounding factors have to be considered when evaluating the dye tracing study. They include a limited budget, shortage of basic data, instrument precision, limited training of volunteers, and the complex multi-dimensional nature of harbor circulation. Additional field measurements and numerical modeling would be needed to reach a solid understanding of pollution migration patterns in the harbor basin. Consequently, there are some important limitations of the study:

1. Working with a limited budget while sampling a large area in a short amount of time, the sampling grid was relatively coarse. The sampling interval was 15 minutes on the first day and 2-4 h on the following two days. The latter sampling interval resulted in a relatively low resolution, and some of the samples were not useful because of mislabeling or other errors caused by short-term training of the volunteer sampling crew.

Figure 9: Critical zones for deposition and scour in Pillar Point Harbor

2. The short three-day field study period in September only provided a snapshot of the condition of the water quality in the harbor. The study was conducted in the absence of runoff and with relatively small waves and calm wind conditions; these factors determine the baseline conditions in the harbor. However, the water circulation on this day may not accurately depict the full spectrum of conditions. Preferably, there would have been several sampling periods to measure the effect of variable conditions.

3. Breakwater permeability may affect flushing and circulation of constituents within the harbor basin. The study was conducted without a full understanding of the current situation of permeability of the breakwaters. The recent hydrographic analysis that was completed for the harbor showed significant sediment accumulation along the inside of the outer harbor breakwater arm. In the dye release study samples were collected both inside and directly outside the breakwaters and very low concentrations were detected outside the breakwater, which seems to indicate that the permeability is reduced. The study team did not, however, sample specifically for the purpose of testing breakwater permeability in the harbor.

4. The wind and wave data was based on a National Buoy Data Center (NBDC) buoy number 46012, which is located approximately 35 km away from the harbor entrance towards the ocean; thus considering the same condition in Pillar Point Harbor and the buoy is a very rough assumption. But wind-induced currents are limited to the outer skin of a water-body and in most cases they have secondary influence compared to tide- induced currents.

5. In the tracer study, samples were taken at the surface to eliminate the need for special equipment and for ease of volunteers. This approach did not provide any information about the vertical distribution of the dye. As a result, effects of potential stratification within the harbor could not be considered in the analysis of motion of Fluorescein and Rhodamine dyes. In other words, there was no information on the three-dimensional conditions of flow velocities and water densities in different points of the harbor. Stratification may generate bidirectional flows in the harbor, and may thus contribute to the motion patterns of fruit and tracers. At this point, it is almost impossible to assess with some degree of certainty what those changes might be. Notwithstanding, the horizontal distribution is still useful to estimate the main trends in pollution migration in the harbor.

6. The drogue study was done utilizing fruit; therefore, it should be considered to only give a basic idea and rough qualitative inference for several reasons. First, since the size of a fruit is large compared to fecal contamination, the trajectory of fruit is the result of the integration of velocities. Second, fruit had interaction effects with the current and did not necessarily represent the constituents' transport behavior subjected to the same current. Third, fruit is buoyant in the top layer of the water-body where the influence of wind is not a secondary effect but could affect the circulation study.

5.1 Key Factors for Pillar Point Harbor Circulation

There are six mechanisms that can influence the fate of contaminants in a harbor: river inflow, marine discharge of ground water, wind-induced currents, wave effect, tidal prism, and artificial mixing. To the best of our knowledge there are no currents in PPH induced by water pumping or other anthropogenic activities, and marine discharge of ground water into the basin can in principle be assumed to be small compared to the overall harbor volume. The remaining four potential mechanisms are briefly discussed below.

5.1.1 River Inflow

Two creeks, Deer Creek and Denniston Creek, drain runoff water into the Pillar Point Harbor basin (Figure 10). The former collects the runoff from a 1.05 sq. mile watershed and the latter drains a 3.83 sq. mile watershed (almost 3.5 times larger than the Deer Creek Watershed). Based on the 2008 and 2009 hydrologic records collected in the Prospect Way station, the flow in the larger creek reached a daily peak of 5.5 cfs in January and February of 2008. That is to say the flow in Denniston Creek was less than 1 cfs in 9 out of 12 months during 2008 and 2009.

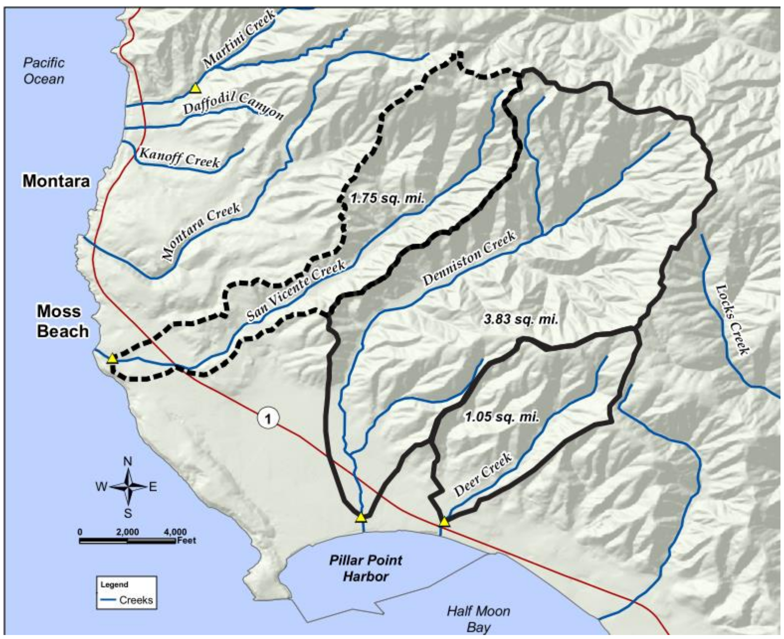

Figure 10: Deer Creek and Denniston Creek watersheds

The harbor pavement run off and the surrounding areas likely also drain directly into the harbor basin. The positive effect of the riverine fresh water inflow - for Pillar Point Harbor's flushing mechanism - is negligible when the inflow volume is compared to the volume of water and tidal prism in the harbor basin. On the other hand, we considered Deer Creek, Denniston Creek, and the harbor pavement inflow as a possible source of pollution for Pillar Point Harbor. The circulation study was conducted after more than a month of no runoff-generating rainfall. The discharge records of the creeks are shown in Figures 11 and 12. As a result, the effect of riverine inflow is concluded to be negligible in the tracer study of September 27, 2008 due to very low discharge.

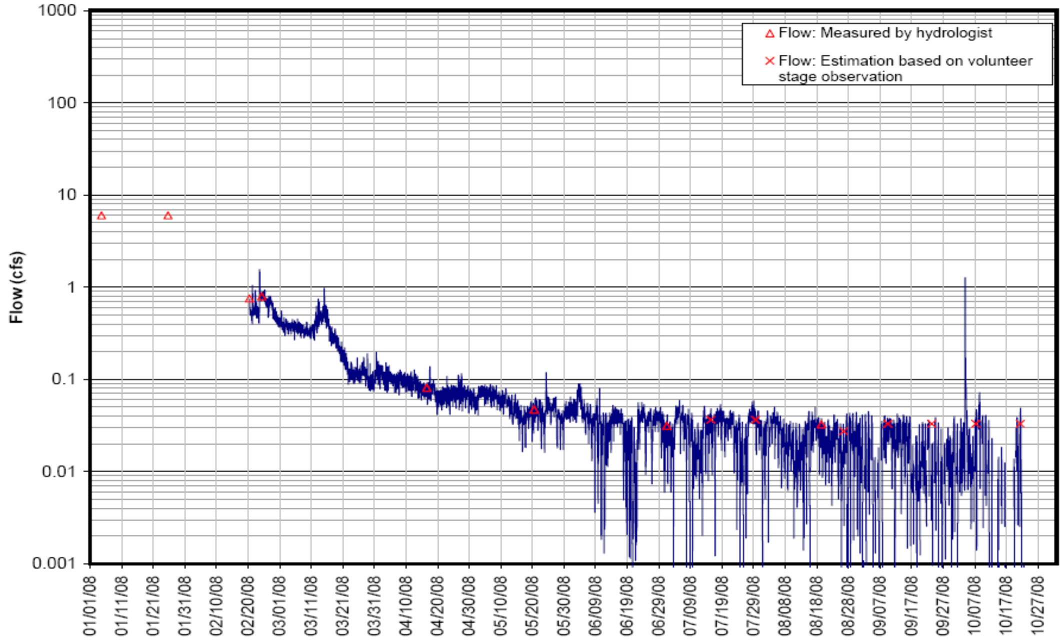

Figure 11: Deer Creek gage 15-minute flow, San Mateo County, California. Source: Balance Hydrologics, Inc.

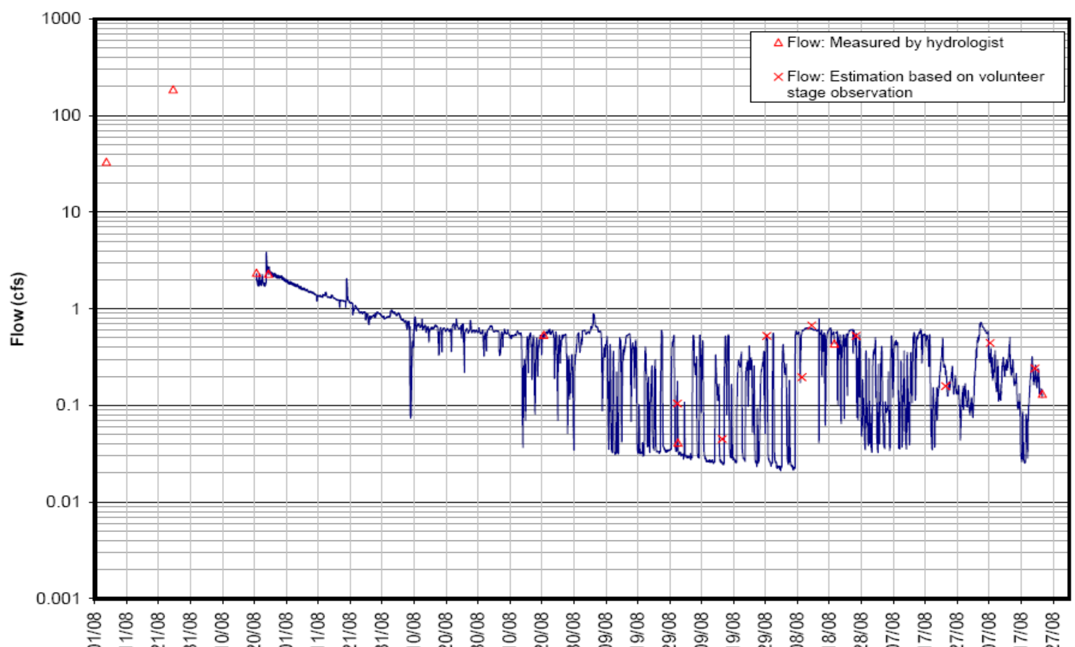

Figure 12: Denniston Creek gage 15-minute flow, San Mateo County, California, Hydrograph through 10-23-2008. Source: Balance Hydrologics, Inc.

5.1.2 Wind Effect

During the field study period (9/27/08 - 9/29/08) the prevailing wind direction was 50% of the time coming from the North-West, ≈10% from the North, and ≈12% from the West at Station #46012 of National Buoy Data Center (NBDC, Figures 13 and 14). The buoy is located approximately 35 km away from the harbor entrance in the ocean. Therefore, the data cannot be applied directly and need to be corrected to account for hills and vegetation around the harbor. (Perhaps the wind data from the Half Moon Bay Airport could be employed for future studies.) The wind-induced currents are important only on the free surface of a water body (1-2 m) and they will be between 2-4 % of the wind speed at the surface (Shore Protection Manual, 1984). The wind speed at the Station 46012 was between 5.9 m/s to 0.5 m/s in the study period. Since a correction factor for PPH is not available the authors roughly assumed the wind would have a secondary role (in principle) compared to tidal prism in the harbor flushing process.

To determine the duration of winds, the definition of constant wind presented in the Coastal Engineering Manual (2003) and Shore Protection Manual (1984) was used. In this way, wind duration at the *ith* hourly data point was considered to be equal to the number of preceding consecutive and acceptable hours, which satisfies the following conditions:

$$|D_i - \bar{D}| < 15^o$$
$$|U_i - \bar{U}| < 2.5\ m/s$$

where $\bar{U}$ and $\bar{D}$ are the average of preceding consecutive and acceptable hourly wind speed and direction, respectively. U_i and D_i are wind speed and direction at the *ith* hourly data point. As can be seen from Figures 13 and 14, wind duration in the study period (27th to 29th September, 2008) was more than 45 min[1] most of the time. On the other hand since the dimensions of wind fetch in Pillar Point Harbor is relatively short (1.4 km × 2 km) there is always a fetch-limited situation within the harbor. As recommended by the Coastal Protection Manual (2003) and Sorenson (1993), with these numbers (Fetch length about 1.5 kilometer and minimum duration of one hour) wind wise currents in the range of 1% of the standard 10 m wind speed could be expected in the harbor. From Figure 14 and the basic calculation we have:

$7\ knots = 3.6\ \frac{m}{s}$: Average wind speed

$3.6 \times 60 \times 60 \times 0.01 \cong 130\ m/hr$: Maximum of wind induced current speed

[1] $t_{min} = 77.23\,\frac{(Fetch\ Length)^{0.67}}{(U_a)^{0.33}} = 77.23\,\frac{(1400)^{0.67}}{(4.1 \cdot 9.81)^{0.33}} = 45\ minute$

One might expect wind to play the second most important role in the circulation of water and its constituents within Pillar Point Harbor; yet it is still a secondary mechanism compared to tidal prism (Coastal Engineering Manual, 2003; Sorenson, 1993).

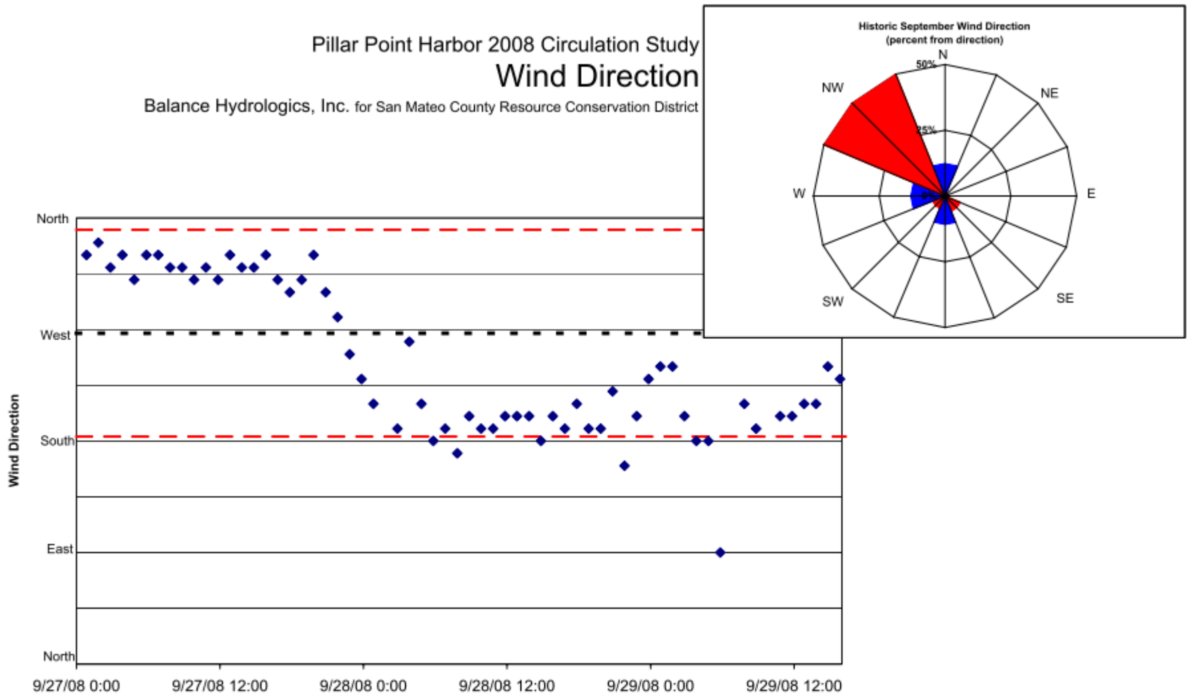

Figure 13: Wind direction observed in the tracer study period (27-29 Sept 2008) and monthly mean wind direction averaged over the period of 1980-2001 (NBDC Station #46012)

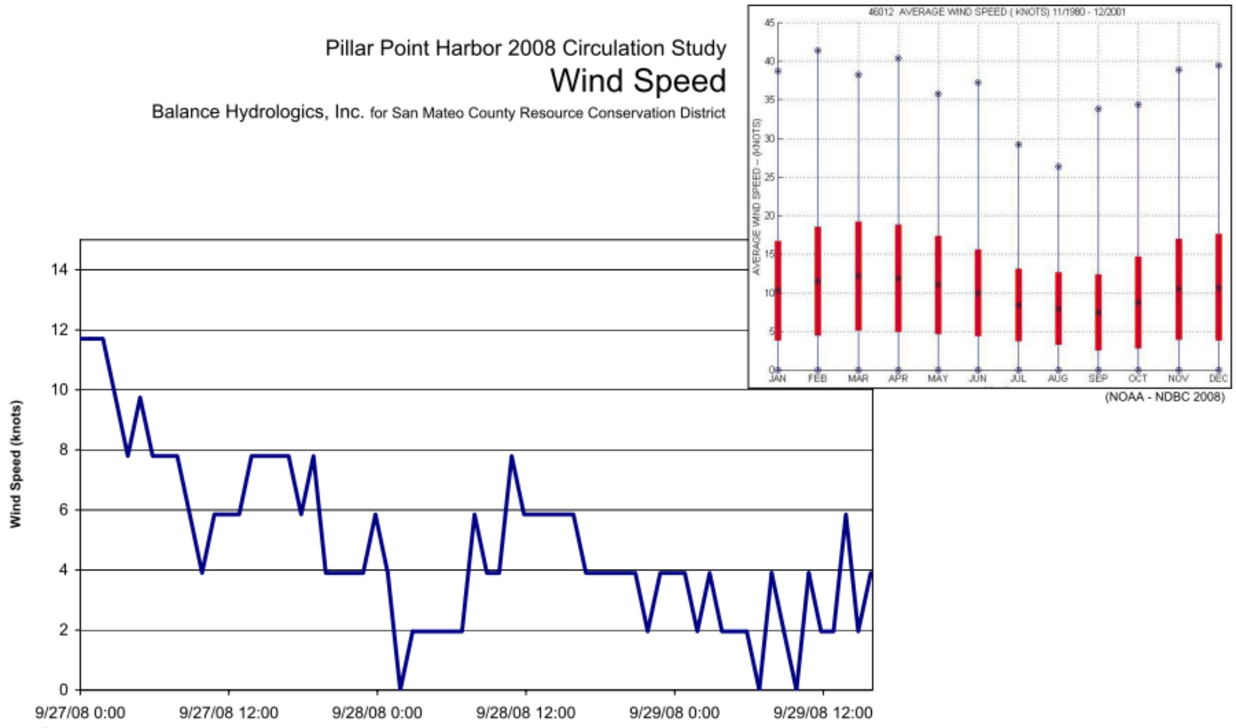

Figure 14: Wind speed observation 27-29, September 2008 and monthly mean wind speed averaged over the period of 1980-2001 (NBDC Station # 46012)

5.1.3 Wave Effect

Currents are the main means of transport of pollutants in water bodies. Although waves have a secondary effect in constituent transport they still play a role in the mixing process. In the tracer study period (9/27/08 to 9/29/08) the wave height at the NBDC station number 4601 was between 1 and 2 m (Figure 15). This buoy is far from the harbor entrance and for the present analysis, we did not have the means to convert the waves of buoy 4601 to waves at Pillar Point Harbor. However, since the harbor entrance is inclined with respect to the N-S direction and also covered by a breakwater arm, and considering the small opening of the entrance compared to the breakwater length, the diffracted waves inside the harbor would not be of a significant height. With simple "back-of-the-envelope" calculations using common refraction formulas and tables it could be concluded that the harbor is likely well protected from waves. The field observations of kayakers taking water samples also confirmed that the height of diffracted waves in the harbor was short during the tracer study.

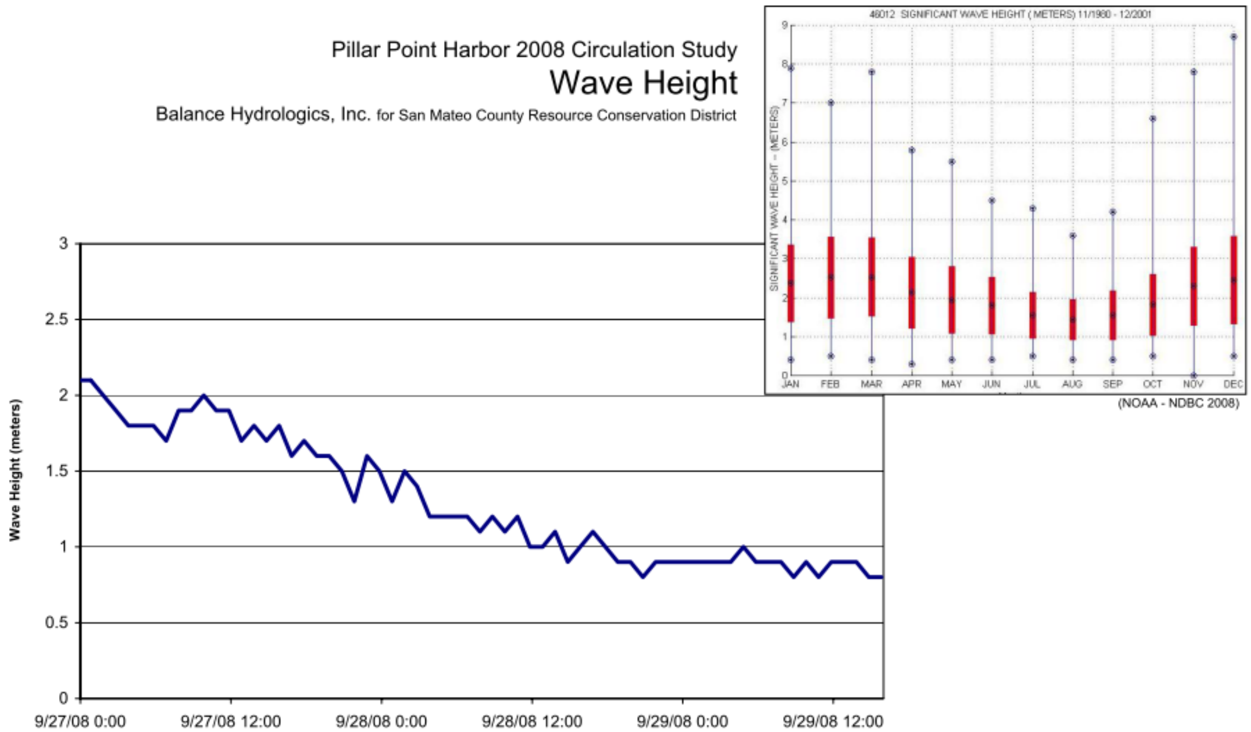

Figure 15: Wave height measured by NBDC station # 40612 (27-29 Sept 2008), H_s in the period of 1980-2001 same buoy station (Top right)

5.1.4 Tidal effect

Tides constitute the main driving mechanism of flushing and circulation in Pillar Point Harbor. With finer resolution measurements and longer periods of measurement the pattern recognition techniques could be employed to establish the correlation between tidal currents and flushing of pollution.

6 CONCLUSIONS

Taking into account all the relevant limitations of the study, the following inferences and suggestions are provided:

- Assuming that Pillar Point Harbor (PPH) can be approximately represented by a rectangle, the curves in Figure D-1 (Falconer 1980) are applicable. Adopting a ratio L/B of about 0.45, we can conclude that the exchange coefficient for PPH is of the order of 0.42, close to the highest value of 0.5. This analysis does not take into account the inner breakwaters, which would alter the curves given by Falconer

(1980). The value of exchange coefficient indicates that the harbor possesses a high degree of interchange of waters with the ocean, facilitating the elimination of pollutants.

- The Fluorescein plume, which was released at the Northern zone of the harbor, completely washed out in **five tidal cycles** (2.5 tidal days).
- Any constituents which are released in the shallow waters of the Northwestern side of the basin are **NOT flushed out after six tidal cycles** (3 day) because a considerable amount of tracer mass remained inside the harbor.
- In case of a future tracer study, the other release point to consider for a tracer study is the Eastern end of the harbor (points C1 and C2).
- In future studies it is recommended to add at least two sampling points for finer resolution:
  - A point in the middle of (B1, B2, C1, C8) or inner harbor
  - Another point in the middle of (A3, B3, C5, C6).
- The general pattern of incoming jet from the ocean and ebb tide currents flushing the harbor is roughly estimated as shown in Figure 16. The white arrows show the current pattern in the flood tide and the red arrows are associated with the currents during ebb tide. Arrow size is approximately proportional to the strength of flow. The general mode of circulation in the tidal prism is clockwise as indicated by black arrows.

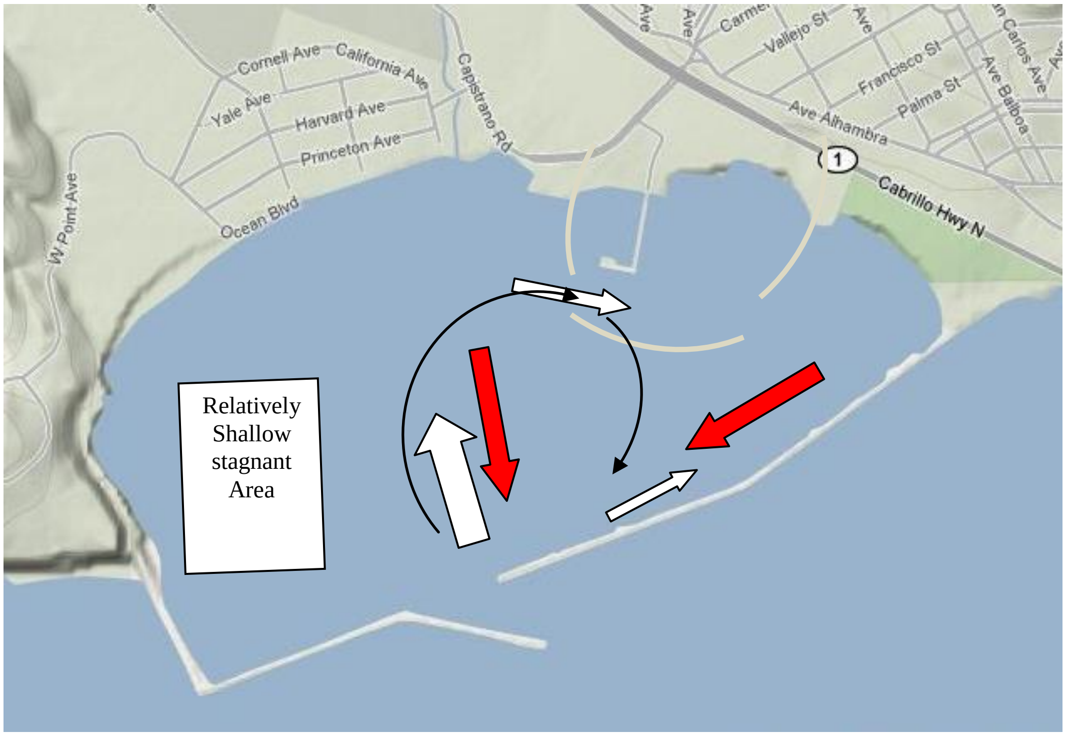

Figure 16: Schematic of tidal current patterns in Pillar Point Harbor

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