Olema Creek Watershed

Water Quality Analysis and Condition Assessment

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I. Introduction

This report analyzes water quality data collected by the U.S. National Park Service (NPS) in the Olema Creek watershed at two scales: (1) long-term trends at 6 primary sampling stations over the period spanning water years (WY = October 1 – September 30) 1999 to 2017; and (2) a watershed condition assessment at 13 sampling stations (the 6 primary plus 7 additional) over the period spanning January 2016 to May 2018. The focus of the analysis is on fecal indicator bacteria (FIB) concentrations (fecal coliform and *E. coli*) in the context of grazed lands and conservation practices implemented on those lands in an effort to improve water quality. The goals of the report are to address the following questions:

(1) What have FIB conditions been in the Olema Creek watershed over the period of record?

(2) What is the spatiotemporal context in terms of season (storm, winter baseflow, summer baseflow) and land use/land cover including completed conservation practices?

(3) Are there any trends in the data (e.g. decreasing concentrations with time, sites with consistently higher concentrations, or higher or lower concentrations in different stream reaches)?

(4) How do existing data fit into a hydrologic context (e.g. constituent loading based on flow)?

(5) How do the data compare to regulatory objectives?

Background

Watershed Overview and Regulatory Context

The 560 square kilometer Tomales Bay Watershed (TBW) is located on the central California coast approximately 64 kilometers northwest of San Francisco, predominantly in rural western Marin County. Its three primary tributaries Lagunitas, Walker, and Olema Creeks provide habitat for multiple listed species, including Coho salmon (*Oncorhynchus kisutch*), steelhead (*O. mykiss*), California freshwater shrimp (*Syncharis pacifica*), tidewater goby (*Eucyclogobius newberryi*) and California red-legged frog (*Rana draytonii*). Due to its unique ecological significance as a major estuary on the California coast, Tomales Bay has numerous designations and protections. It is listed as a wetland of international importance under the Ramsar Convention, included in the Golden Gate Biosphere, is part of the Greater Farallones National Marine Sanctuary, and partially within the boundaries of Point Reyes National Seashore.

Land use in the TBW includes: nearly 55% grazing livestock and other agriculture; an estimated 3% of urban lands with limited commercial development and no industry; and roughly 42% parks, recreation and open space (SFRWQCB 2005). Additionally, about 70% of Marin Municipal Water District's water supplies originate in the Lagunitas Creek watershed. This report examines the 38 square kilometer Olema Creek watershed. Olema Creek, the largest undammed tributary of Lagunitas Creek, flows north through the Olema Valley along the San Andreas Fault Zone. Land use in this subwatershed is 99% NPS land (56% of which is under grazing leases) and 1% non-park land with rural residential and commercial development (**Figure 1**). The NPS lands encompass both the North District Golden Gate National Recreation Area (GGNRA) and Point Reyes National Seashore (PRNS).

The Clean Water Act of the United States requires states to define beneficial uses of water bodies and apply water quality standards to protect these uses. Water bodies that do not meet applicable standards are placed on the US Environmental Protection Agency (USEPA) Section 303(d) list of impaired water bodies, requiring development of a Total Maximum Daily Load (TMDL). In California, the development and implementation of TMDLs is delegated by the USEPA to the California State Water Resources Control Board and the Regional Water Quality Control Boards. TMDLs identify pollutant source areas and set the maximum pollutant loading capacity a given water body can receive while still meeting water quality standards.

Beneficial uses of Tomales Bay include contact and non-contact recreation, shellfish harvesting, commercial and sport fishing, marine habitat, wildlife habitat, fish migration, fish spawning, preservation of rare and endangered species, and navigation. Additional beneficial uses of tributaries include water supply (agricultural, municipal and domestic), freshwater replenishment, and warm and cold freshwater. Under the Clean Water Act, Tomales Bay and its tributaries have been listed as impaired for pathogens, nutrients and sediment (as well as mercury on Walker Creek). A TMDL for pathogens was adopted by the San Francisco Regional Water Quality Control Board (SFRWQCB) in 2006, as a result of the impaired beneficial uses of water contact and non-contact recreation and shellfish harvesting.

Under the Pathogen TMDL, pathogen sources in the TBW are identified as grazing lands, dairies, equestrian facilities, on-site wastewater treatment systems, small wastewater treatment facilities, boat discharges, and municipal runoff (SFRWQCB 2005). Although the TMDL lists pathogen sources and water quality targets, it does not discuss relative contributions of each source to pollutant loading.

Water quality objectives for bacteria are listed in **Table 1**. The lower target for each range is based on the geometric mean of a minimum of five consecutive samples equally spaced over a 30-day period. If there are not at least five samples in a six week period, the 90^{th} percentile is used as the objective value, which shall not be exceeded by more than 10% of samples collected in a single month's time. Thus, for a single monthly sample, the 90^{th} percentile is the applicable numeric target (SFRWQCB 2017). Note that the *E. coli* objectives are provisional; they are in the process of being adopted by the State Water Board and subsequently by the SFRWQCB (Farhad Ghodrati, pers. comm. 4/24/2018).

Table 1: Water quality objectives for bacteria (provisional for *E. coli*) from the San Francisco Bay Regional Water Quality Control Board.

Beneficial Use	Fecal Coliform*	*E. coli*^
Freshwater contact recreation	geometric mean <200	geometric mean <100
	90th percentile <400	90th percentile <320
Freshwater non-contact recreation	mean <2000	
	90th percentile <4000	

*Most probable number (MPN) per 100 ml. Based on a minimum of five consecutive samples equally spaced over a 30-day period

^Colony forming units (CFU) per 100 ml. Provisional objective not yet approved by the SFRWQCB

In July of 2008, a Conditional Waiver of Waste Discharge Requirements for Grazing Lands in the Tomales Bay Watershed (Grazing Waiver) was adopted to aid in implementing the Pathogen TMDL on grazed lands (SFRWQCB, 2013). Grazing Waiver conditions include development of Ranch Water Quality Plans, implementation of conservation practices identified in these plans that minimize delivery of pathogens, nutrients and sediments to surface waters, annual monitoring, and annual adaptive management adjustments to the plans.

Recent water quality management efforts

PRNS has worked with ranch operators in the TBW under grazing lease/permit to comply with all Grazing Waiver requirements. PRNS staff and ranchers have been implementing water quality improvement projects, hereafter conservation practices (CPs), for decades. These CPs have largely been based on USDA Natural Resource Conservation Service conservation practice standards (USDA 2016) including fencing, rocked stream crossings and watering facilities, as well as erosion control projects such as road treatment and headcut repair. Major efforts from 1998 to 2007 focused on the mainstem of Olema Creek, Lagunitas Creek and major tributaries (John West Fork Creek, Cheda Creek). Since 2007, efforts have shifted to the many tributaries of Olema and Lagunitas Creeks. Studies to increase understanding of agricultural systems in the TBW, including where to focus CPs to reduce indicator bacteria concentrations and loading have identified and confirmed the benefit of working on high use areas and pastures that receive manure (Lewis et al. 2005; Lewis et al. 2009; Lewis et al. 2010).

In addition to CP implementation, dramatic floodplain changes and operational decisions regarding cattle management resulted in removal of grazing from sensitive watershed lands during the study period. The majority of these changes involved the transition of a single ranch operator away from Olema mainstem: in the early to mid-2000s, floodplain changes in the lower Olema Creek watershed resulted in grazing cessation on more than 290 acres (accounting for about 63 animal units), and additional voluntary reductions occurred on grazing lands adjacent to lower Olema Creek in 2013. In total, the number of animal units authorized in the Olema Creek watershed were reduced by approximately 20% (about 138 animal units) for an overall reduction in permitted grazing lands of roughly 10% (about 600 acres) over the study period.

Watershed response to rainfall

Mean annual precipitation over the water year was estimated at 986 mm (1972-2017) based on data primarily from the Bear Valley weather station (PRNS Olema Valley, OVYC1), which is located within the Olema Creek watershed. Rainfall is highly variable with periods of pronounced drought (e.g. 2012-2016) and periods of high precipitation (e.g. 2005-2006) (**Figure 2**; **Figure 3**) during the rainy season from October to April, the period in which approximately 95% of the precipitation occurs (USNPS unpublished data). This annual variability, coupled with the variation caused by individual winter storm duration and intensity, contribute to flashy runoff and stream flows within the winter season and across multiple years. Discharge at Olema Creek ranges from less than 0.014 cubic meters per second (cms) in summer/fall to more than 70 cms in winter (data from 1996-2001; Ketcham 2001). Measured lag time between peak rainfall and runoff on lower Olema Creek is approximately 3 to 4 hours, whereas the response time for most Olema Creek tributaries is between 15 to 45 minutes, depending on watershed size. In general and in the absence of an extreme rain event or protracted dry period, 178 to 229 mm of cumulative rainfall are required to initiate significant in-stream flow response and hydrologic connectivity within the watershed. If this rainfall is spread across more than 60 days, additional precipitation is necessary to establish connectivity (Ketcham 2001). This priming dynamic between precipitation and stream flow generation has been documented in other California rangeland watersheds (Lewis et al. 2000).

Under saturated conditions, it takes less rainfall to initiate increases in runoff that result in hydrologic connectivity and potential for delivery of water quality constituents downstream. For example, in the winter of 2001, a time-series analysis was conducted to identify lag times between peak runoff and peak FIB delivery in the Olema Creek watershed (Ketcham 2001; SFRWQCB 2001). Over the course of 3 storm events and 1 dry season event, 56 water quality samples were collected from station OLM 11 (Bear Valley Road Bridge) at a rate of one sample every one to four hours for the duration each event (up to four days.) Samples were analyzed for *E. coli* in MPN/100ml. Lag time between peak discharge and peak *E. coli* level during first flush was approximately 2 hours, after which levels declined through the duration of the storm. However, as saturation occurred, the lag time between peak runoff and peak *E. coli* concentration was reduced. In subsequent consecutive storm events, an increase in *E.coli* concentration was seen in response to each peak in rainfall over a 4 day sample period. During this study, Olema Creek had one of the lowest contributions of fecal coliform and *E. coli* pollutant loading to Tomales Bay. Although Lagunitas fecal coliform concentration levels were lower than Olema, due to greater streamflow, the loading from Lagunitas was actually higher than loading from Olema (Ketcham 2001; SFRWQCB 2001).

Water quality sampling

Within the TBW, PRNS has conducted water quality monitoring since 1999 on Lagunitas and Olema creeks and their tributaries. Over the period of record, this has included a number of different objectives, stations, and regimes, including targeted monitoring to search for potential sources, CP monitoring before and after implementation, and TMDL compliance monitoring. From these multiple monitoring efforts comes a long-term data set for 6 primary stations in the Olema Creek watershed, where water samples were collected at 5 stations with grazing upstream, and 1 (referent) station with no grazing upstream (**Figure 1**; **Table 2**). FIB sampling and analysis was initiated in 1999 for fecal coliform (FC) at sites OLM11, OLM14, and OLM1. OLM 18 was added in 2001 and OLM10B and OLM6A (referent station) were added in 2003. *E. coli* (EC) sampling and analysis was initiated in 2007 at all 6 stations. All water samples were collected as grab samples following standard operating procedures outlined in Cooprider and Carson (2006). Sampling frequency changed across the monitoring time span and is generally characterized by two distinct periods: 1999-2003 with samples collected quarterly and during up to three storms per water year, if possible; and 2003-2017 with samples collected monthly, during one storm per water year if possible, with additional samples collected weekly for five weeks in winter and summer as part of the TMDL monitoring program (**Table 2**).

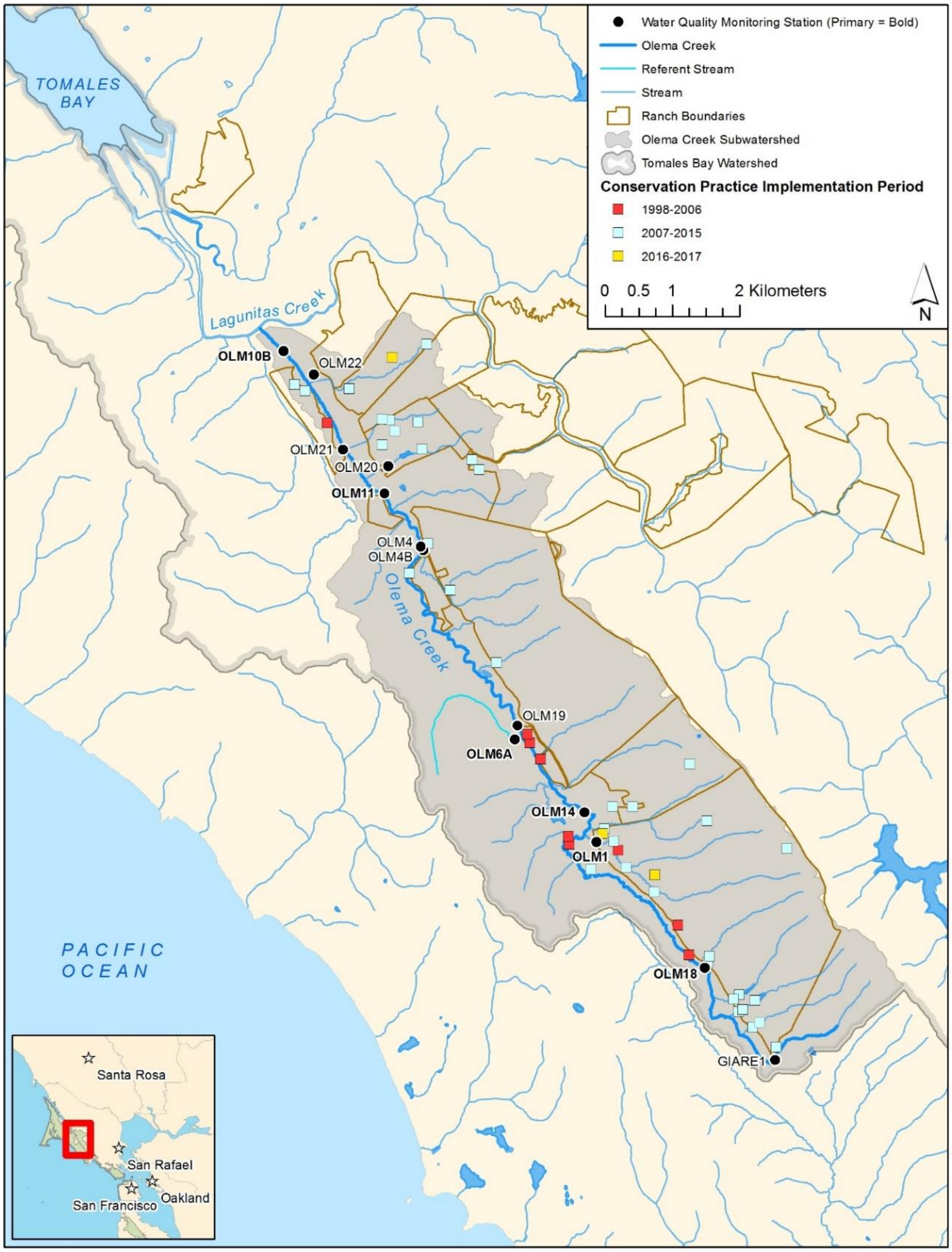


Figure 1: Overview of Olema Creek water quality sampling stations in the Tomales Bay Watershed within the context of grazing lease/permit boundaries and implemented conservation practices. Yellow boxes indicate practices implemented during the watershed condition assessment study period. The 6 primary stations for the long-term assessment are shown in bold.

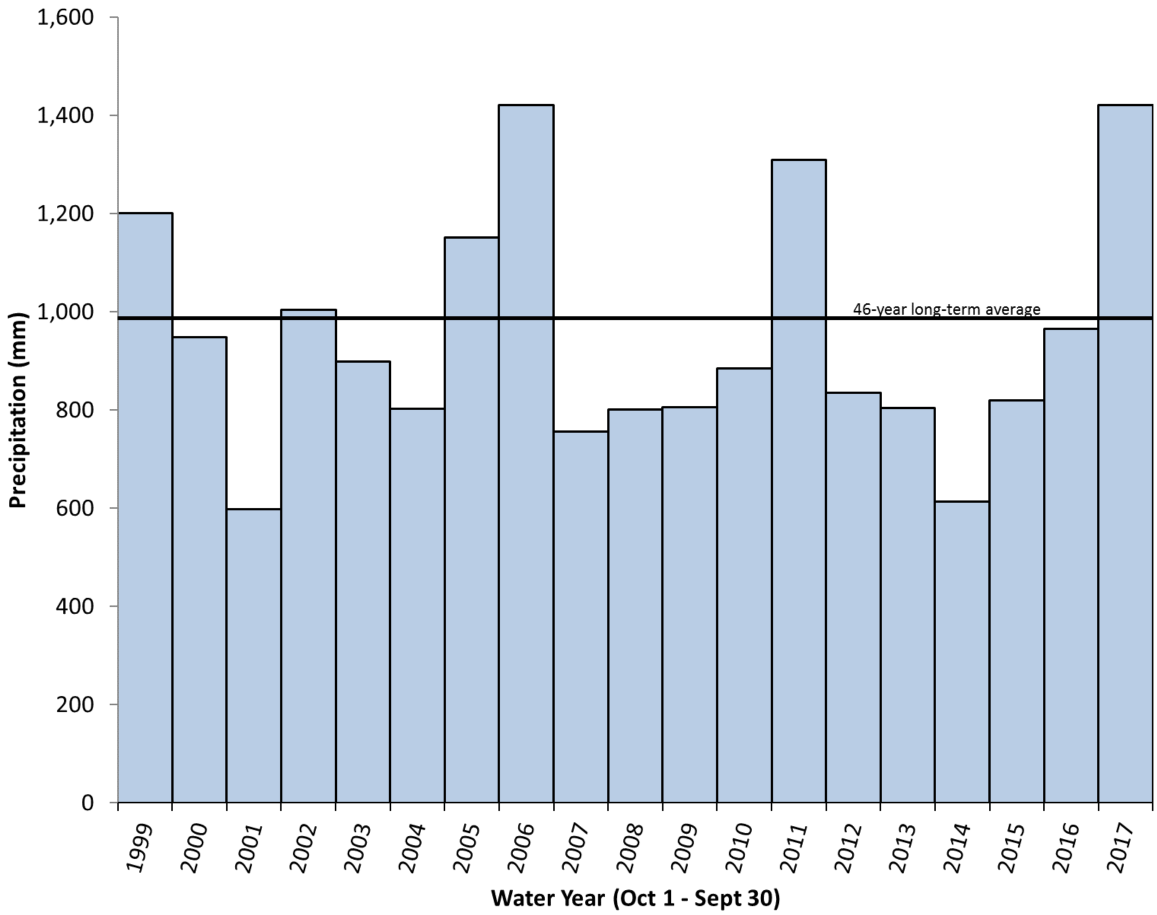


Figure 2: Annual total precipitation from water year 1999 to 2017 and long-term average annual total precipitation (986mm) for the Olema Creek watershed.

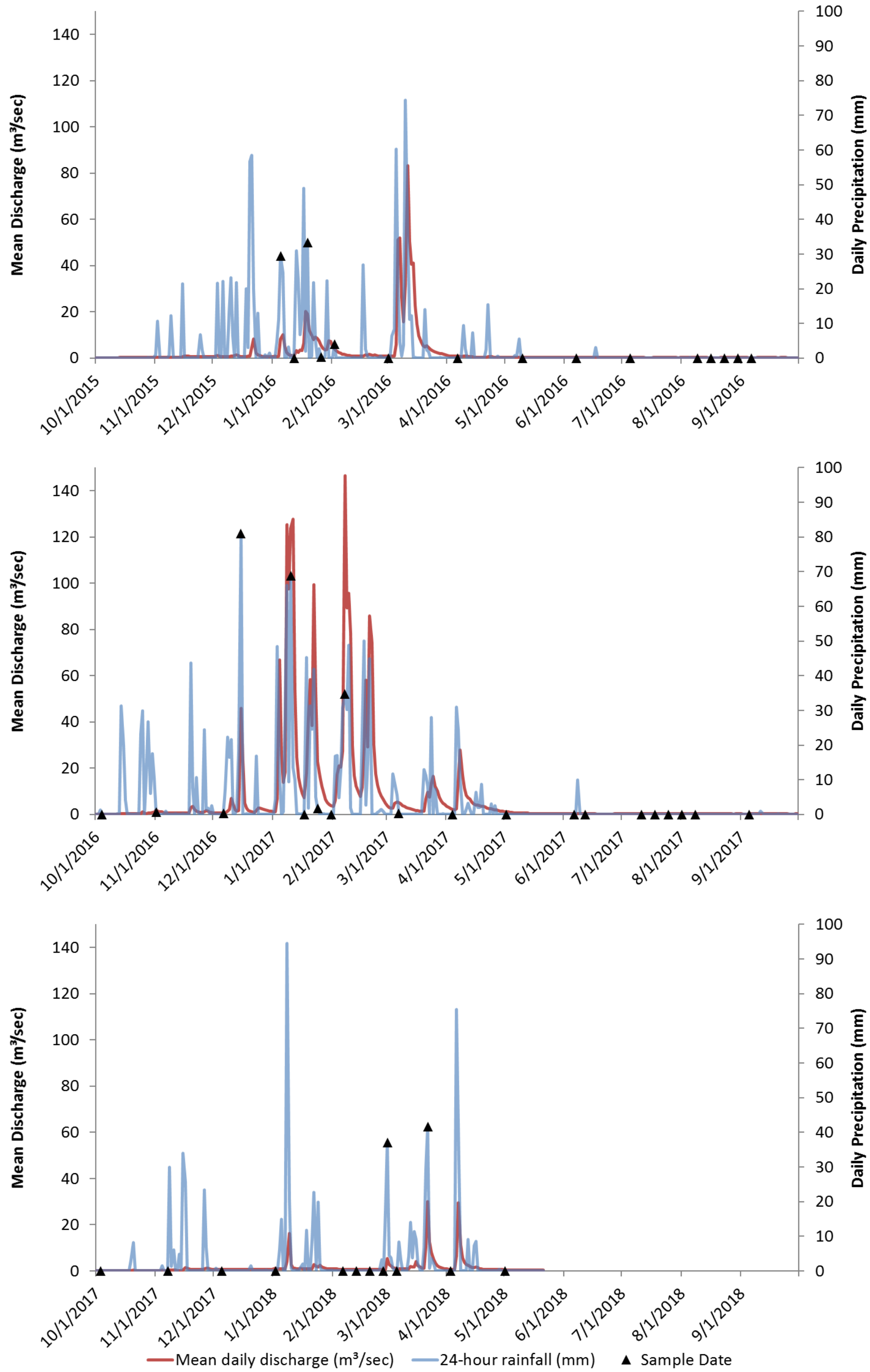


Figure 3: Mean daily discharge at Lagunitas Creek (USGS 11460600), 24-hour rainfall and water quality sample dates for the watershed condition assessment study period, January 2016 to May 2018.

Table 2: Station ID, location, attributes, period of record and sample frequency for Olema Creek watershed sampling stations analyzed in this study. Primary long-term monitoring stations are shown in bold.

Station ID	Location	Attributes†	Period of Record*	Frequency^	X[¥]	Y[¥]
GIARE1	Olema Creek headwaters (at SR1 culvert)	M,G	02/2007 - 02/2008 01/2016 - 05/2018	Storms Monthly + storms + 5/5	524266	4202067
OLM18	Olema Creek (above Randall Gulch confluence)	M,G	01/2001 - 5/2003 05/2003 - 05/2018	Quarterly + storms Monthly + storms** + 5/5	523219	4203442
OLM1	John West Fork Creek	T,G	05/1999 - 05/2003 05/2003 - 05/2018	Quarterly + storms Monthly + storms** + 5/5	521606	4205314
OLM14	Olema Creek (North Five Brooks bridge)	M,G	09/1999 - 05/2003 05/2003 - 05/2018	Quarterly + storms Monthly + storms** + 5/5	521429	4205752
OLM6A	Davis Boucher Creek	T,U	06/2003 - 05/2018	Monthly + storms** + 5/5	520387	4206839
OLM19	Olema Creek (Below Stewart Ranch)	M,G	01/2016 - 05/2018	Monthly + storms + 5/5	520431	4207043
OLM4B	Olema Creek (Upstream of Quarry Gulch)	M,G	01/2016 - 05/2018	Monthly + storms + 5/5	518988	4209711
OLM4	Quarry Gulch	T,G	05/1999 - 05/2003 03/2004 - 09/2013 01/2016 - 05/2018	Quarterly + storms Monthly Monthly + storms + 5/5	519026	4209659
OLM11	Olema Creek (Bear Valley bridge)	M,G	08/1999 - 05/2003 05/2003 - 05/2018	Quarterly + storms Monthly + storms** + 5/5	518453	4210500
OLM20	Unnamed tributary on Rogers Ranch	T,G	01/2016 - 05/2018	Monthly + storms + 5/5	518504	4210907
OLM21	Olema Creek (downstream of town of Olema)	M,G	01/2016 - 05/2018	Monthly + storms + 5/5	517827	4211151
OLM22	Olema floodplain channel at CalTrans	M,G	01/2016 - 05/2018	Monthly + storms + 5/5	517398	4212268
OLM10B	Olema Creek (Below Res. #530)	M,G	06/2003 - 05/2018	Monthly + storms** + 5/5	516948	4212620

†M=Mainstem of Olema Creek; T=Tributary; G=Grazed upstream; U=Ungrazed upstream

*EC analysis began 1/2007; Gaps in FC data at all sites between 05/2007-07/2008; 08/2009-10/2009; 07/2010-02/2011; 08/2013-06/2014; 08/2014-12/2014

^5/5=Five consecutive weeks in winter, five consecutive weeks in summer

**Generally 1 targeted storm with only EC analysis after 01/2007; multiple targeted storms with EC+FC analysis 01/2016-05/2018 for the watershed assessment

[¥]NAD 1983 UTM Zone 10N

II. Methods

Conservation Practice Documentation

A list of known CPs completed in the TBW between 1998 and 2017 was compiled based on the PRNS range project management database (**Table 3**). Additional practices were implemented prior to the start of water quality monitoring, however, this analysis and documentation examines only practices implemented from 1998 to 2017. Each CP was assigned water quality monitoring stations both upstream and downstream from the practice, and the kilometers of stream influenced by each CP were calculated using the calculate geometry tool for linear distance along a local NHD Flowline shapefile in ESRI® ArcMap™. To determine stream length influenced by implemented CPs, projects that were intended primarily to reduce sediment input (road and crossing) were not included, as opposed to projects that primarily remove or reduce cattle residence time in riparian areas (e.g. fencing, water development). In the case that multiple CPs were directed at the same stream reach, the reach was counted only once.

The threshold for stream influence of water developments was set at 1,250 meters based on a study by Rigge et al. (2013) that showed increases of in-channel vegetation values within this distance. We selected the longest or most directly influenced unfenced stream segment adjacent to each trough and included the mainstem reach of this segment within same pasture up to 1,250 meters away.

Sample Collection

Based on preliminary analysis of the long-term data set from the 6 stations, an additional 7 stations were added in the Olema Creek watershed to conduct a condition assessment of FIB concentrations across the watershed (**Figure 1**; **Table 2**). Sampling and analysis was conducted from January 2016 through May 2018 following the TMDL sampling regime, with the addition of synoptic monitoring (at least two sampling teams visiting all stations in generally < 3 hours) of storms occurring opportunistically at the 7 new stations plus the 6 primary stations (**Figure 3**). Additionally, Microbial Source Tracking (MST) was conducted at a subset of stations (OLM10B, OLM21, OLM11, OLM4B, OLM19, and OLM18) during 1 summer baseflow event (June 12, 2017) and 1 storm event (March 22, 2018).

Monitoring of core parameters (water temperature, dissolved oxygen, conductivity, specific conductance, pH) was conducted using a variety of field probes over the sample period. Instrument calibration was conducted according to manufacturer specifications and the San Francisco Bay Area Network Freshwater Quality Monitoring Protocol (Cooprider and Carson 2006).

Field sample collection methods for EC and FC included the use of sterile bottles and gloved hands. Samples were kept on blue ice during station visits and in transport to analytical laboratories. Samples were processed within eight hours of collection for both parameters. Fecal coliform analysis was performed using the SM 9221E Multiple Tube Technique (Most Probable Number) in "Standard Methods for the Examination of Water and Wastewater" (APHA-AWWA-WEF, 1998). *E. coli* analysis was performed using method SM 9223 B (with the IDEXX Quanti-Tray™ System) at a state certified lab or the PRNS in-house lab with proper quality control as outlined in the monitoring protocol and Quality Assurance Project Plan (Cooprider and Carson 2006). MST was conducted utilizing provisional EPA

Method B (USEPA 2010) and Source Identification Protocol Project guidelines (*see* Boehm et al. 2013 and Stewart et al. 2013) with the following assays: universal (UniB), ruminant (Rum2Bac; BacCow_CF123), human (HF183) and horse (HoF597).

Parameter Analysis

Several additional variables were incorporated into the dataset to account for watershed and climate conditions the have the potential to influence water quality. Each sample date was assigned a categorical variable for sample period, either "storm", "winter" or "summer", with "summer" being defined by date (June 1 – September 30) and "storm" being defined by reviewing the following factors as available: 24-hour precipitation, 5-day precipitation sum, qualitative flow severity rating, discharge, station turbidity and Total Suspended Solids results, station visit photos, and visit comments. All other dates were labelled "winter". Precipitation (PPT) data (cumulative 24-hour, 5-day and annual by WY) was compiled and assigned to each sample. Priority for PPT data selection was given to the most proximate weather station (PRNS Olema Valley; OVYC1), however gaps in the data were filled in with values collected at the adjacent Barnaby (BBEC1) or Point Reyes Station (Marin County 38029) weather stations. For the watershed condition assessment, many of the factors listed above for determining "storm" were assessed in real-time, with post-sample event "storm" defined by assigned 24-hour PPT exceeding 26 mm. Kilometers upstream from station LAG4 at the headwaters of Lagunitas Creek in Tomales Bay to each water quality sampling station were derived using the calculate geometry tool in ESRI® ArcMap™ along a local NHD Flowline shapefile.

While both analyses investigated PPT, they differed in their treatment of categorical classification of monitoring periods. For the long-term study, we only designated storm (yes or no) while for the watershed condition assessment we created a finer classification (storm, summer, winter) since the goal of the latter project was to better understand spatial and temporal patterns.

Substitution methods were used for censored data (results that were reported as above or below detection limits for the given laboratory analytical procedure). Laboratory results reported above quantification limits were substituted with the upper limit and those below the quantification limits were set to either half of the lower limit (watershed analysis) or effectively zero (long-term trend analysis) for the indicator bacteria parameters used (Helsel and Hirsch, 2002).

Statistical Analysis

Graphical analysis and linear mixed-effects modeling (LME) were used for both the long-term and watershed condition assessment data sets. Long-term trend analysis was conducted using data from 1999 to 2017 collected at the 6 primary stations: OLM1, OLM6A, OLM10B, OLM11, OLM14, and OLM18 (**Table 2**). Graphical analysis was conducted to facilitate understanding of the underlying relationships between water quality constituent values (i.e. indicator bacteria,) and factors such as cumulative precipitation and watershed position. In addition to graphical analysis, LME was employed to test for statistical significance between response and predictor variables (Pinheiro and Bates, 2000). Unique models were developed for trends over time, with each sampling station set as a group effect to adjust the P-values for repeated sampling at the same site. Final model selection was based upon system understanding and Akaike Information Criterion (AIC; Akaike, 1974).

The watershed condition assessment was conducted using data from January 2016 to May 2018 collected at 13 sampling stations (6 primary plus 7 additional; **Table 2**). In addition to graphical analysis and LME, percent exceedances of SFRWQCB upper water quality thresholds were calculated for each station. LME explored the dataset for trends associated with sample date, rainfall (or sample period classification), stream location (km upstream) and grazing status (grazed/ungrazed subwatershed) using R v3.5 (R Core Team 2018) statistical software, with statistical analysis using the lme4 package (Bates et al. 2015). We tested a limited set of competing explanatory models and ranked them using AICc to account for overdispersion (Hurvich and Tsai 1989)

III. Results

Cumulative Implementation of Conservation Practices

A total of 48 documented conservation practices were implemented between 1998 and 2017 in the Olema Creek watershed, all of which have sample stations above and/or below the implementation locations (**Table 3**). Two practices were completed in the late fall of 2017, so they were not included in discussion of the long term-trend analysis as that data set was only analyzed through 09/30/2017. The frequency and number of projects increased, with more than 4 times as many practices completed in the last 10 years as compared with the first 10 years of the study period. The 2007 program year represents a dividing point marking the acceleration of practice implementation, with 9 implemented before 2007 compared to 39 implemented from 2008 to 2017. Combined these implemented practices are estimated to influence more than 30 kilometers of stream (**Table 3; Figure 1**).

Table 3: Conservation practices implemented in the Olema Creek watershed by year, with practice location and estimated stream kilometers influenced.

Year Completed	Conservation Practice	Stream Kilometers Influenced	Practice Location
1998	Exclusion Fencing	1.11	Tributary
2001	Bioswale	0.20	Mainstem
2002	Exclusion Fencing	0.89	Mainstem
2003	Exclusion Fencing	0.19	Tributary
2003	Bank Stabilization*		Mainstem
2003	Bank Stabilization	0.16	Mainstem
2005	Exclusion Fencing	0.52	Mainstem
2006	Controlled Crossing*		Mainstem
2006	Exclusion Fencing	1.10	Mainstem
2008	Seasonal Exclusion Fencing	0.46	Tributary
2008	Exclusion Fencing	0.53	Mainstem
2008	Stream Restoration	0.32	Tributary
2008	Water Development	0.71	Tributary
2008	Exclusion Fencing	0.25	Tributary

Year Completed	Conservation Practice	Stream Kilometers Influenced	Practice Location
2008	Headcut Repair	0.09	Tributary
2008	Headcut Repair	0.12	Tributary
2008	Headcut Repair		Tributary
2008	Headcut Repair	0.14	Tributary
2008	Road Repair*		Tributary
2008	Seasonal Exclusion Fencing	0.24	Tributary
2009	Water Development	0.61	Tributary
2009	Exclusion Fencing	0.21	Tributary
2009	Exclusion Fencing	0.08	Tributary
2009	Water Development	2.41	Tributary
2009	Water Development	1.17	Tributary
2009	Exclusion Fencing	1.54	Mainstem
2010	Controlled Crossing*		Tributary
2010	Road Repair*		Tributary
2010	Exclusion Fencing	0.80	Mainstem
2011	Water Development	5.96	Tributary
2012	Controlled Crossing*		Tributary
2012	Controlled Crossing*		Tributary
2012	Controlled Crossing*		Tributary
2012	Controlled Crossing*		Tributary
2012	Exclusion Fencing	0.13	Tributary
2012	Exclusion Fencing	0.30	Tributary
2012	Exclusion Fencing	0.20	Tributary
2012	Exclusion Fencing	0.31	Tributary
2013	Exclusion Fencing	0.08	Tributary
2013	Seasonal Exclusion Fencing	0.19	Tributary
2013	Exclusion Fencing	0.39	Tributary
2013	Seasonal Exclusion Fencing	0.64	Tributary
2014	Water Development	3.01	Tributary
2014	Water Development	0.69	Tributary
2015	Water Development	1.75	Tributary
2016	Water Development	0.87	Tributary
2017	Structures for Water Control	0.06	Tributary
2017	Exclusion Fencing	1.69	Tributary

*CP focused on sediment delivery, no calculation for stream kilometers influenced

Trend Analysis at 6 Primary Stations

Review of the existing water quality monitoring data determined that there was an existing long-term data set from 1999 to 2017 for fecal coliform at 6 primary monitoring stations in the Olema Creek watershed, including data collected during the watershed assessment period. Monitoring for *E. coli* began after significant CP implementation occurred, precluding the analysis of long-term trends over this same period.

Sampling effort across the entire study period was variable, including percent of storm, winter and summer baseflow sampling conducted (**Table 4**; **Appendix Table A-1**). Annual fecal coliform concentrations at these 6 stations demonstrated a wide range through 2006 (**Figure 4**). From 2007 to 2017 the range of fecal coliform concentrations decreased.

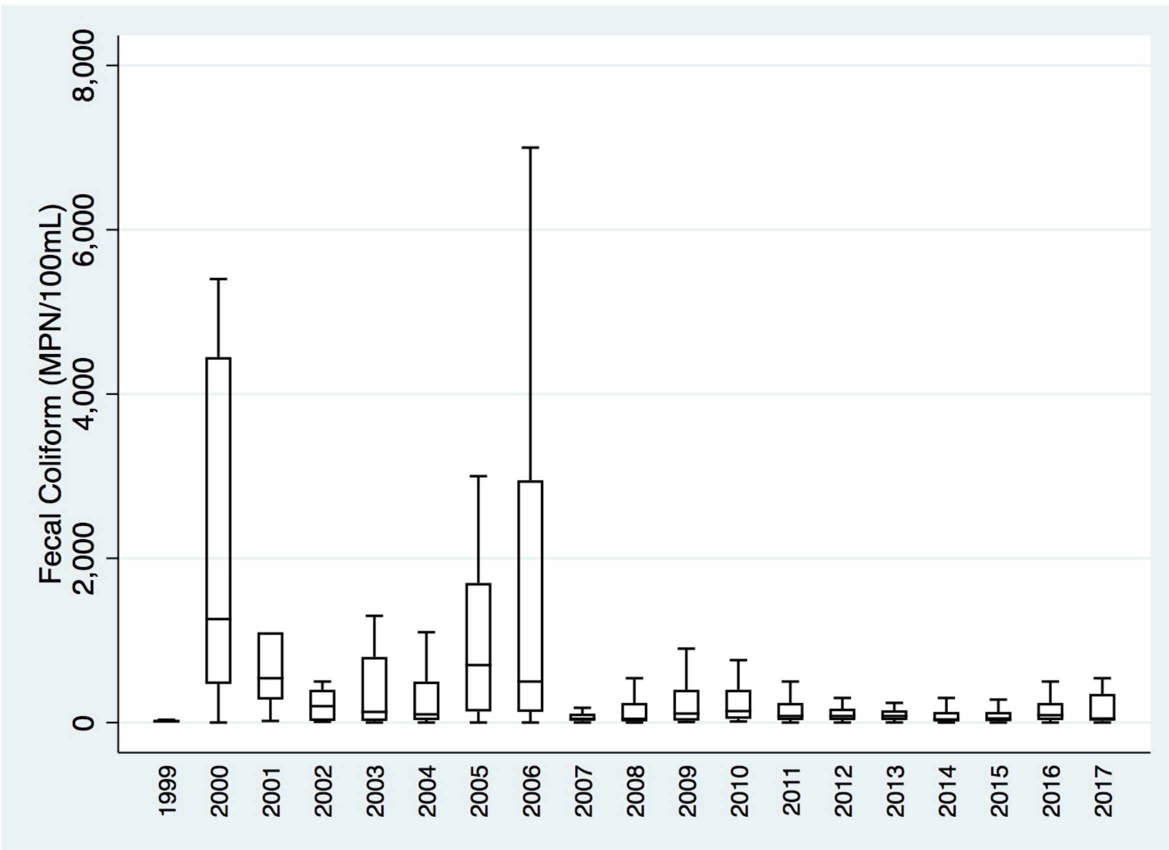


Figure 4: Box and whisker plots for fecal coliform concentrations from 1999 to 2017 at 6 primary sampling locations in the Olema Creek watershed. Bottom and top of each box are the 25th and 75th percentile of the data, horizontal line within the box is the median value, and the vertical lines extending from the box are the 10th and 90th percentiles of the data. Observations below the 10th percentile and above the 90th percentile (outlier observations) are excluded from this figure, but are included in the statistical analysis.

Regression analysis was conducted using 1,247 FC observations (**Table 4**). As a first step, a test for distribution of the Logarithmic 10 transformed data was conducted and confirmed normal distribution.

Final model selection included time (represented by sample date), 24-hour and 5-day cumulative PPT (**Table 5**). The time coefficient was negative confirming decreases in bacteria concentrations over time. In contrast, the coefficients for the two PPT variables were positive indicating increases in bacteria concentrations with increases in PPT over the 24-hour and 5-day time periods.

Other descriptor variables that were tested and proved to be insignificant (p>0.1) were water year, tributary or mainstem, and annual cumulative PPT. Additionally, the categorical variable of storm sample (yes or no) was tested and was significant but also found to be collinear with the PPT variables, forcing a selection of one or the other in the final model. Similarly, the variable for stream length was dropped from the model once the random effects variable for sampling stations was included. The PPT variables provided more mechanistic explanations for concentrations than did the general storm (yes or no) categorical value and therefore they were retained. Additionally, two interactions were tested to explore how watershed position could be interacting with time and practice implementation. The first interaction was for time and stream length, which was not significant. The other interaction that was tested was the categorical variable of practice implementation (pre or post 2008) with stream length. This interaction was also not significant.

Table 4: Samples by assigned sample period and total samples by station for fecal coliform (FC) over the long-term Olema Creek watershed data set (1999 – 2017).

Station ID	Storm	Winter	Summer	Total
OLM18	17	106	78	201
OLM1	20	111	84	215
OLM14	20	108	87	215
OLM6A	13	97	84	194
OLM11	21	111	89	221
OLM10B	15	101	85	201

Table 5: Linear mixed effects model for associations of logarithmic 10 transformed fecal coliform concentrations with 24-hour cumulative precipitation, 5-day cumulative precipitation, and sample collection timing (date) for the long-term Olema Creek watershed data set (1999-2017).

Factor	Coefficient	Standard Error	95% Confidence Intervals[a]		*P*-value[a]
Constant or intercept term for the model	6.6	0.5	5.6	7.6	<0.0001
24-hour cumulative precipitation (mm)	0.014	0.002	0.009	0.018	<0.0001
5-day cumulative precipitation (mm)	0.006	0.0007	0.005	0.007	<0.0001
Sample timing (date)	-0.00012	0.00012	-0.00014	-0.00009	<0.0001

[a] Adjusted for potential lack of independence due to repeated sampling of stations.

Watershed Condition Assessment

For the Olema Creek watershed condition assessment, data was grouped into three categorical monitoring periods based on the following assigned sample period field to account for observed differences in watershed response: (1) *winter baseflow*, generally characterized by connectivity of Olema Creek with tributaries draining grazed and ungrazed lands and fast moving clear water; (2) *storm*, characterized by connectivity of Olema Creek with tributaries draining grazed and ungrazed lands as well as overland flow from compacted and impervious surfaces, and fast moving turbid water; and (3) *summer baseflow*, characterized by limited to no connectivity of Olema Creek with tributaries draining grazed and ungrazed lands, slow moving water and low flow. A snapshot of measured FIB concentrations during these three periods is shown in **Figure 5**, with representative station photos in **Appendix Figure A-4**. A total of 47 sample events were conducted over the course of the study period (January 2016 to May 2018), including 7 storm events (with the exception of one less storm for OLM6A due to site access) with a total sample size of 517 for FC and 523 for EC (**Table 6**). Samples were taken and analyzed for EC but not FC concentration during lack of flowing water, which only occurred sporadically in the upper watershed (7 samples at OLM1 and 10 samples at OLM 18). The sampling included a series of 5 evenly spaced consecutive weekly samples during two summers and three winters to assess compliance with SFRWQCB objectives. These consecutive sample events contained 2 storm events in both WY 2016 and WY 2017. Graphical analysis demonstrates the differences in observed FIB values within the different assigned categorical monitoring periods (**Figure 6**; **Figure 7**).

Synoptic monitoring consisted of two or more sample teams dividing up the 13 monitoring stations and completing all monitoring generally within 3 hours. Out of the 47 sample events, only 5 events were >3 hours (4 sample events took approximately 3 hours and 20 minutes and 1 summer sample event took 3 hours and 40 minutes to complete).

Exceedances of SFRWQCB objectives for FC and EC were calculated based on values presented in **Table 1**: (1) the geometric mean of the consecutive 5-week winter and summer samples was compared to the lower geometric mean objective; and (2) any monthly sample not in the 5-week series was compared to the higher (90th percentile) objective (**Table 7**). Storm samples that occurred within the 5-week series were also compared to the higher objective in addition to being included in the 5 week geometric mean for the lower objective.

A correlation plot was generated to explore all monitoring parameters and their relationship (included in **Appendix Figure A-1**). Strongest correlations were between *E. coli* and fecal coliform, turbidity and FIB concentration, precipitation and turbidity, and water temperature and dissolved oxygen. Precipitation and FIB concentration were significantly correlated as was shown in analysis of the long-term data, but not as strongly as the above-mentioned parameters.

For the LME models we looked at residual plots and at AICc from log10, Poisson, and negative binomial models, with negative binomial models displaying by far the best residual behavior and lower AICc (see **Appendix Figure A-2** and **Figure A-3** for residuals). A priori hypotheses explaining FC and EC included time trend (date), storm condition, distance upstream, and grazing status of adjacent lands. In addition to assigned sample period, we also examined daily and 5-day cumulative rainfall. Continuous variables were scaled with mean zero and 1 standard deviation to improve model fitting. The best fitting (lowest AICc) negative binomial mixed effects model for both FC and EC included scaled sample date, and assigned sample period ("storm", "winter", "summer") by stream km (**Table 8**; **Table 9**; **Figure 8**; **Figure 9**). There was no collinearity among covariates for this model and model coefficients are presented as log values and odds ratios (**Table 10**; **Table 11**). For both FIB models, concentrations showed a decreasing trend moving upstream. This was true of all 3 assigned sample periods ("storm", "winter", and "summer"), with "winter" generally showing lower variation and concentrations across stream km, and "storm" generally trending highest. For the entire data set for each FIB type, a weak downward trend over the study period was also detected after accounting for storm status (period). However, the short 3-year duration of this study precludes considering this a long-term trend. All lower ranked models having AICc weights > 0.01 included distance upstream and sample period with similar coefficients, and showed a small potential effect of grazed/ungrazed. However, grazing status had a small effect and was limited to only one site, and therefore inferences should be made with caution

Table 6: Samples by assigned sample period and total samples by station for fecal coliform (FC) and *E. coli* (EC) over the Olema Creek watershed condition assessment sample period (01/2016 – 05/2018). The table includes 5-week summer and winter sampling, monthly sampling, targeted storm sampling and MST sampling. Primary long-term sampling stations are indicated in bold.

Station ID	Storm		Winter		Summer		Total #	Total #
	FC	EC	FC	EC	FC	EC	Samples FC	Samples EC
GIARE1	7	7	17	16	0	0	24	23
OLM18	7	7	23	25	7	14	37	46
OLM1	7	7	23	25	10	14	40	46
OLM14	7	7	26	25	14	14	47	46
OLM6A	6	7	25	25	14	14	45	46
OLM19	7	7	26	25	14	14	47	46
OLM4B	7	7	26	25	14	14	47	46
OLM4	7	7	21	20	2	2	30	29
OLM11	7	7	26	25	14	14	47	46
OLM20	7	7	19	18	0	0	26	25
OLM21	7	7	26	25	14	14	47	46
OLM22	7	7	23	22	3	3	33	32
OLM10B	7	7	26	25	14	14	47	46

Note: site conditions precluded sampling of station OLM6A during one storm event.

Table 7: Exceedances of SFRWQCB upper water quality thresholds by station for single sample and 5-week winter and summer monitoring for fecal coliform (FC) and *E. coli* (EC) for the Olema Creek watershed condition assessment study duration (01/05/2016 – 05/01/2018). Single samples are separated into the three assigned sample periods. Total percent exceedance by assigned sample period is included at the bottom of each FIB type. Primary long-term sampling stations are indicated in bold. If <4 samples were taken during any of the 5-week periods, they are included in the single sample exceedance.

	Storm*				**Winter**				**Summer^**				**Winter 5-Week**				**Summer 5-Week**			
Station ID	**FC >400**	**FC Total**	**EC >320**	**EC Total**	**FC >400**	**FC Total**	**EC >320**	**EC Total**	**FC >400**	**FC Total**	**EC >320**	**EC Total**	**FC >200**	**FC Total**	**EC >100**	**EC Total**	**FC >200**	**FC Total**	**EC >100**	**EC Total**
GIARE1	1	7	3	7	0	11	0	10	--	0	--	0	0	2	0	2	--	0	--	0
OLM18	6	7	7	7	1	12	1	14	0	3	0	4	1	3	2	3	0	1	0	2
OLM1	6	7	7	7	0	12	0	14	0	5	0	4	1	3	1	3	0	1	0	2
OLM14	5	7	7	7	0	15	1	14	0	4	1	4	1	3	1	3	0	2	0	2
OLM6A	2	6	1	7	0	17	0	14	0	4	0	4	0	2	0	3	0	2	1	2
OLM19	6	7	7	7	2	15	1	14	0	4	1	4	1	3	2	3	0	2	1	2
OLM4B	6	7	7	7	1	15	1	14	1	4	1	4	2	3	2	3	0	2	2	2
OLM4	7	7	7	7	1	10	2	9	1	2	1	2	2	3	2	3	--	0	--	0
OLM11	6	7	7	7	1	15	2	14	1	4	1	4	1	3	2	3	1	2	2	2
OLM20	7	7	7	7	3	13	8	12	--	0	--	0	2	2	2	2		0	--	0
OLM21	7	7	7	7	3	15	5	14	2	4	2	4	1	3	3	3	2	2	2	2
OLM22	7	7	7	7	2	12	1	11	0	3	2	3	1	3	2	3	--	0	--	0
OLM10B	7	7	7	7	1	15	2	14	0	4	1	4	2	3	3	3	0	2	0	2
%Exceedance	81%		89%		8%		14%		12%		24%		42%		59%		19%		44%	

*5-week consecutive sampling for winter included 2 storms in both WY 2016 & WY 2017, which are also included under storm here
^No flow at stations GIARE1 and OLM20 during the assigned sample period "summer"

Table 8: FC model selection for the Olema Creek watershed condition assessment based on AICc with R^2 for lowest AICc model.

Factor	K	ΔAICc	AICc Wt	R^2
Date+Period*Km	10	0.00	0.50	0.46
Period*Km	9	1.62	0.22	
Period+Km+Grazed	8	1.92	0.19	
Period+Km	7	3.71	0.08	
5-day PPT*Km	7	16.32	0.00	
Date+PPT*Km	8	16.63	0.00	
PPT+Km	6	17.85	0.00	
Period	6	18.39	0.00	
Km	5	50.77	0.00	
Date	5	64.62	0.00	

Table 9: EC model selection for the Olema Creek watershed condition assessment based on AICc with R^2 for lowest AICc model.

Factor	K	ΔAICc	AICc Wt	R^2
Date+ Period*Km	10	0.00	0.87	0.63
Period*Km	9	4.44	0.09	
Period+Km+Grazed	8	7.88	0.02	
Period+Km	7	8.02	0.02	
Period	6	20.99	0.00	
PPT+Km	6	29.23	0.00	
Date+PPT*Km	8	40.15	0.00	
5-day PPT*Km	7	40.16	0.00	
Km	5	71.97	0.00	
Date	5	84.18	0.00	

Table 10: Fixed effects log coefficients for the Olema Creek watershed condition assessment FC model with lowest AICc. Note that Date and StreamKm are scaled to mean zero and 1 standard deviation, therefore each unit change in those covariates results in change shown in the coefficient column. The *Odds Ratio* is the exponentiated coefficient and illustrates proportional change with each one unit increase in standard deviation. For example, a one standard deviation increase in date results in a 19% (or 1 * 0.81) decline in FC and a one standard deviation increase in stream km results in a decline of 39% (or 1 * 0.61). The categorical variable "storm" shows that summer and winter values are only 9% and 5% of winter storm (which was treated as the baseline) values, respectively. Categorical values were not scaled and therefore do not change with standard deviations.

	Log Coefficient	Standard Error	Odds Ratio	P-value
Intercept	7.48	0.29	1764.59	<0.01
ScaleDate	-0.21	0.11	0.81	<0.05
Storm2Summer	-2.45	0.34	0.09	<0.01
Storm2Winter	-3.00	0.31	0.05	<0.01
scaleStreamKm	-0.50	0.16	0.61	<0.01
Storm2Summer:scaleStreamKm	-0.41	0.18	0.66	<0.02
Storm2Winter:scaleStreamKm	-0.27	0.13	0.77	<0.04

Table 11: Fixed effects coefficients for the Olema Creek watershed condition assessment EC model with lowest AICc. See Table 10 for explanation.

	Log Coefficient	Standard Error	Odds Ratio	P-value
Intercept	7.69	0.26	2189.37	<0.01
ScaleDate	-0.24	0.09	0.79	<0.01
Storm2Summer	-2.71	0.28	0.07	<0.01
Storm2Winter	-3.36	0.25	0.04	<0.01
scaleStreamKm	-0.53	0.18	0.59	<0.01
Storm2Summer:scaleStreamKm	-0.45	0.17	0.64	<0.01
Storm2Winter:scaleStreamKm	-0.29	0.13	0.75	<0.04

Microbial Source Tracking

MST results (**Table 12**) indicated no detection of human, ruminant or horse markers at the upstream site (OLM18) on either sample date. Markers were positively detected and quantified for human at OLM19 and ruminant at OLM4B on both sample dates. A mix of marker detections occurred downstream, with human marker detections during the 03/22/2018 storm at all sites but OLM18.

Table 12: Results of MST analysis for the selected subset of Olema Creek mainstem stations on 06/12/2017 summer baseflow and 03/22/2018 storm. Stations sorted from upstream to downstream locations.

Station ID	Human	Ruminant	Horse
OLM18			
OLM19	[+] {+}		
OLM4B	[DBLOD] {+}	[+] {+}	
OLM11	[DBLOD] {+}	[DNQ] {+}	{DBLOD}
OLM21	[DNQ] {+}	[DBLOD]	
OLM10B	{+}	[DBLOD]	[+]

DBLOD=Signal detected below limit of detection but could still indicate presence of marker
DNQ=Signal detected between limit of detection and lab reporting limit, indicating marker is present but cannot be quantified
+=Signal above limit of detection and lab reporting limit, indicating marker is present and quantified
[ ]=06/12/2017 during summer baseflow
{ }=03/22/2018 during storm conditions

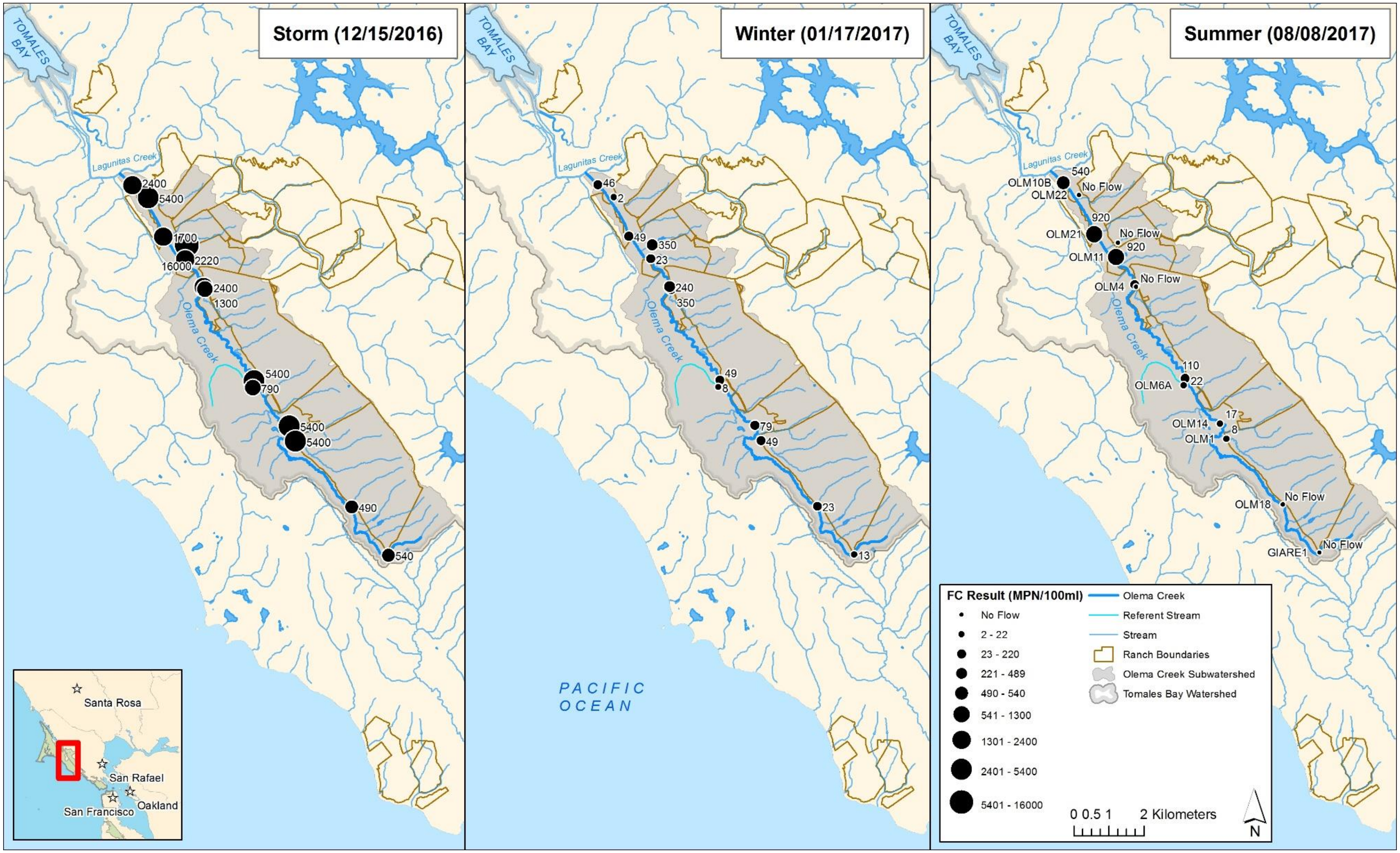


Figure 5: Watershed snapshot of fecal coliform concentration (MPN/100ml) results on 12/15/2016 during storm conditions (left), 01/17/2017 during winter baseflow (center) and 08/08/2017 during summer baseflow (right) at all 13 stations in the Olema Creek watershed (note: the 16,000 result on 12/15/2016 was censored data > upper quanitification limit so substitituion of the upper limit was used for this figure to characterize conditions.

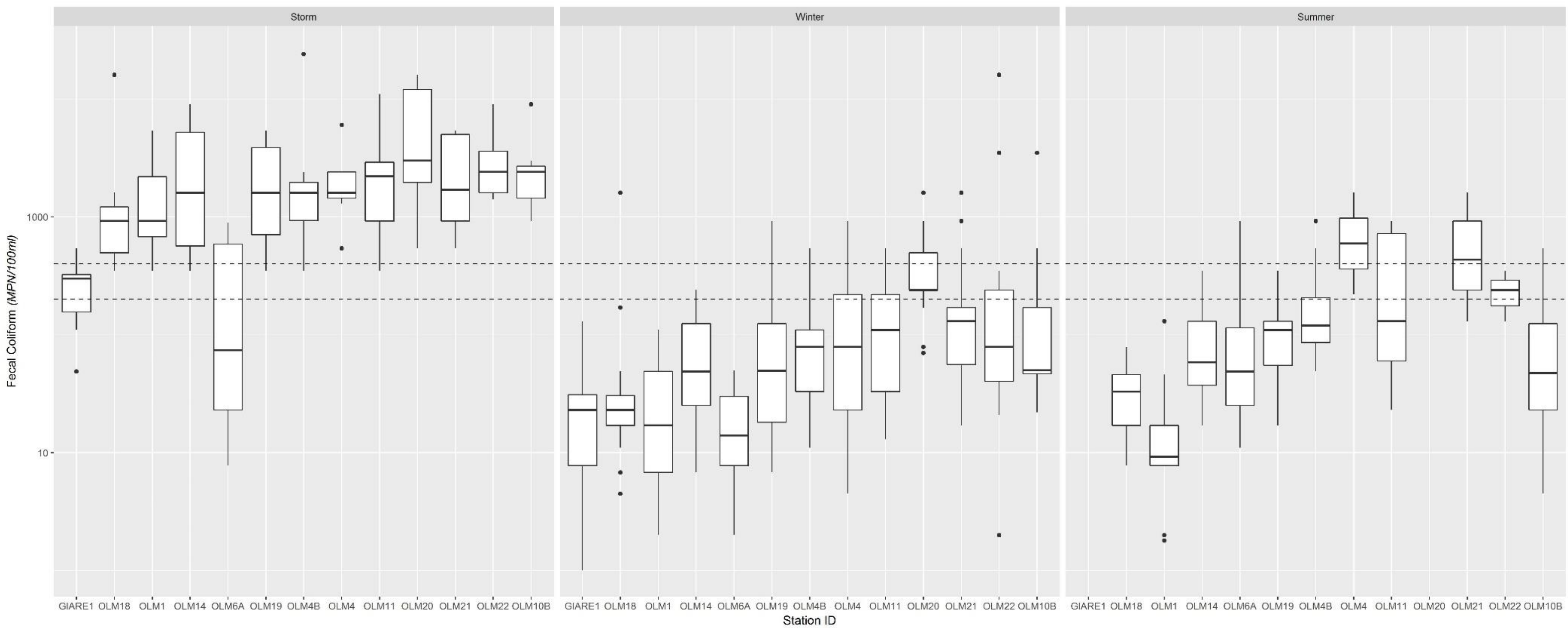


Figure 6: Box plots for fecal coliform concentration in the Olema Creek watershed at all 13 stations from upstream to downstream over the sample period 01/2016 to 05/2018 during storms (left), winter baseflow (center), and summer baseflow (right). Horizontal lines represent SFRWQCB water quality targets at 200 and 400 MPN/100ml. The middle horizontal line within the box is the median. The lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles). The upper whisker extends from the hinge to the largest value no further than 1.5 * IQR from the hinge (where IQR is the inter-quartile range, or distance between the first and third quartiles). The lower whisker extends from the hinge to the smallest value at most 1.5 * IQR of the hinge. Data beyond the end of the whiskers are called "outlying" points and are plotted individually.

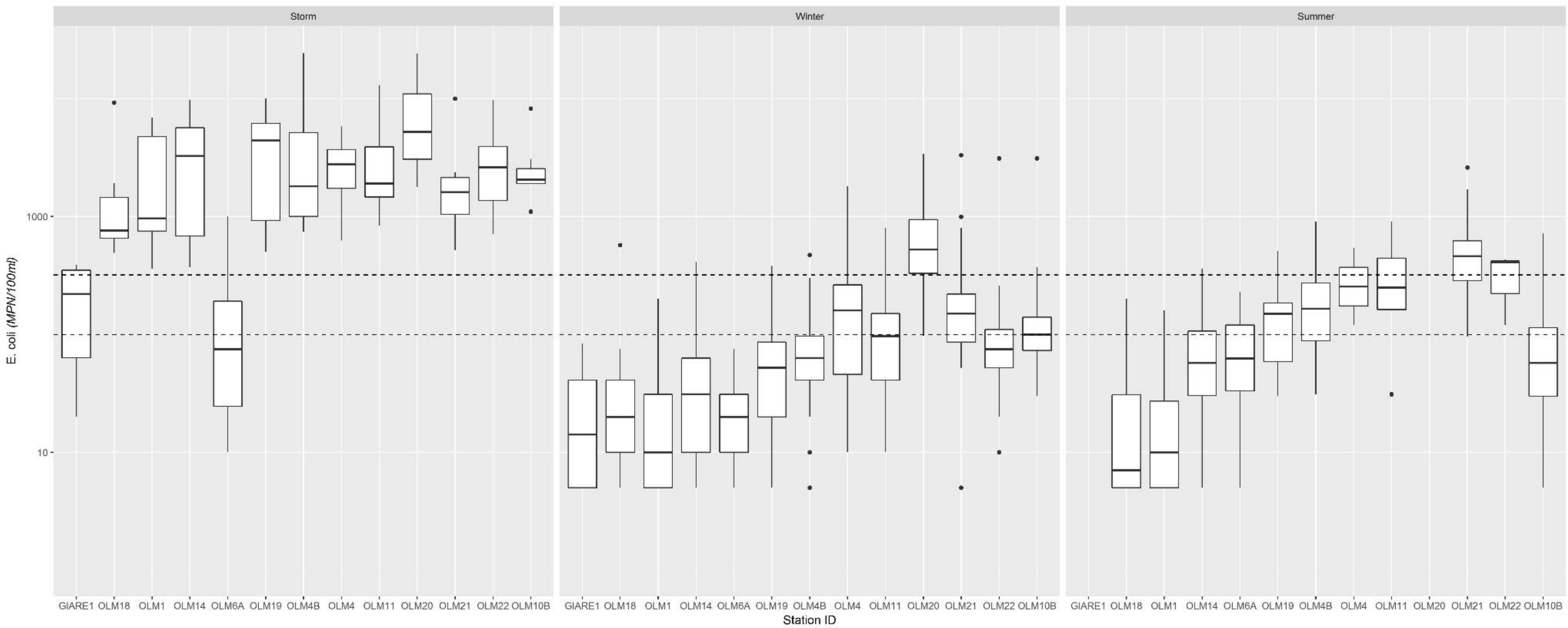


Figure 7: Box plots for *E. coli* concentration in the Olema Creek watershed at all 13 stations from upstream to downstream over the sample period 01/2016 to 05/2018 during storms (left), winter baseflow (center), and summer baseflow (right). Horizontal lines represent provisional SFRWQCB water quality targets at 100 and 320 cfu/100ml. See Figure 6 for boxplot description.

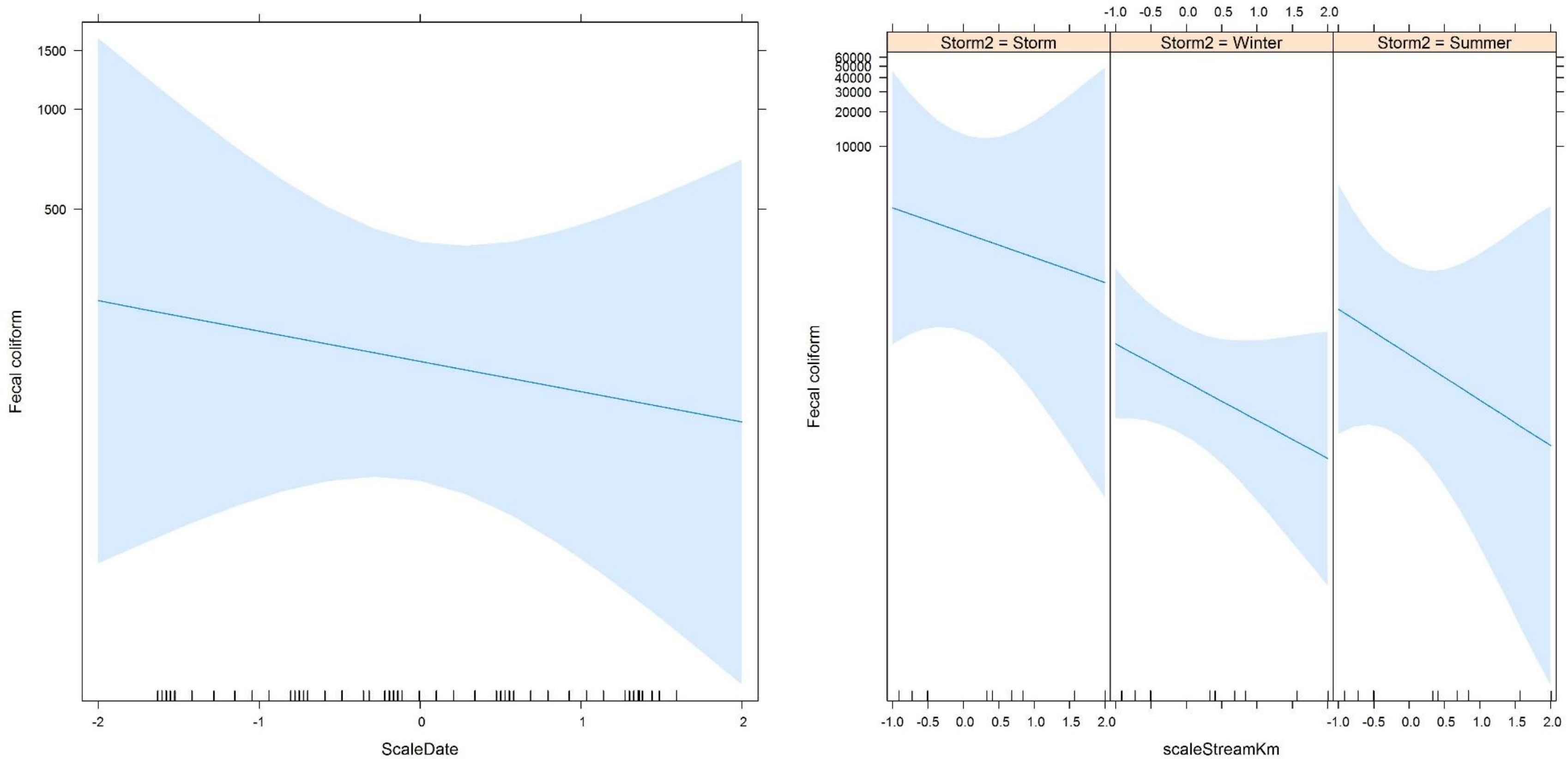


Figure 8: Olema Creek watershed condition assessment LME marginal (once other covariates have been removed) effects for the lowest AICc model for FC over time (left) and by assigned sample period (“storm”, “winter” or “summer”) from downstream to upstream (right). Note that the variables have been normalized to zero for the model fitting and that each unit represents one standard deviation. The dark blue line indicates the modeled trend in FC over time (left) or from downstream to upstream during the three assigned sample periods (right). Lighter blue shading indicates one standard error associated with the model. See Table 10 for model coefficients and odds ratios.

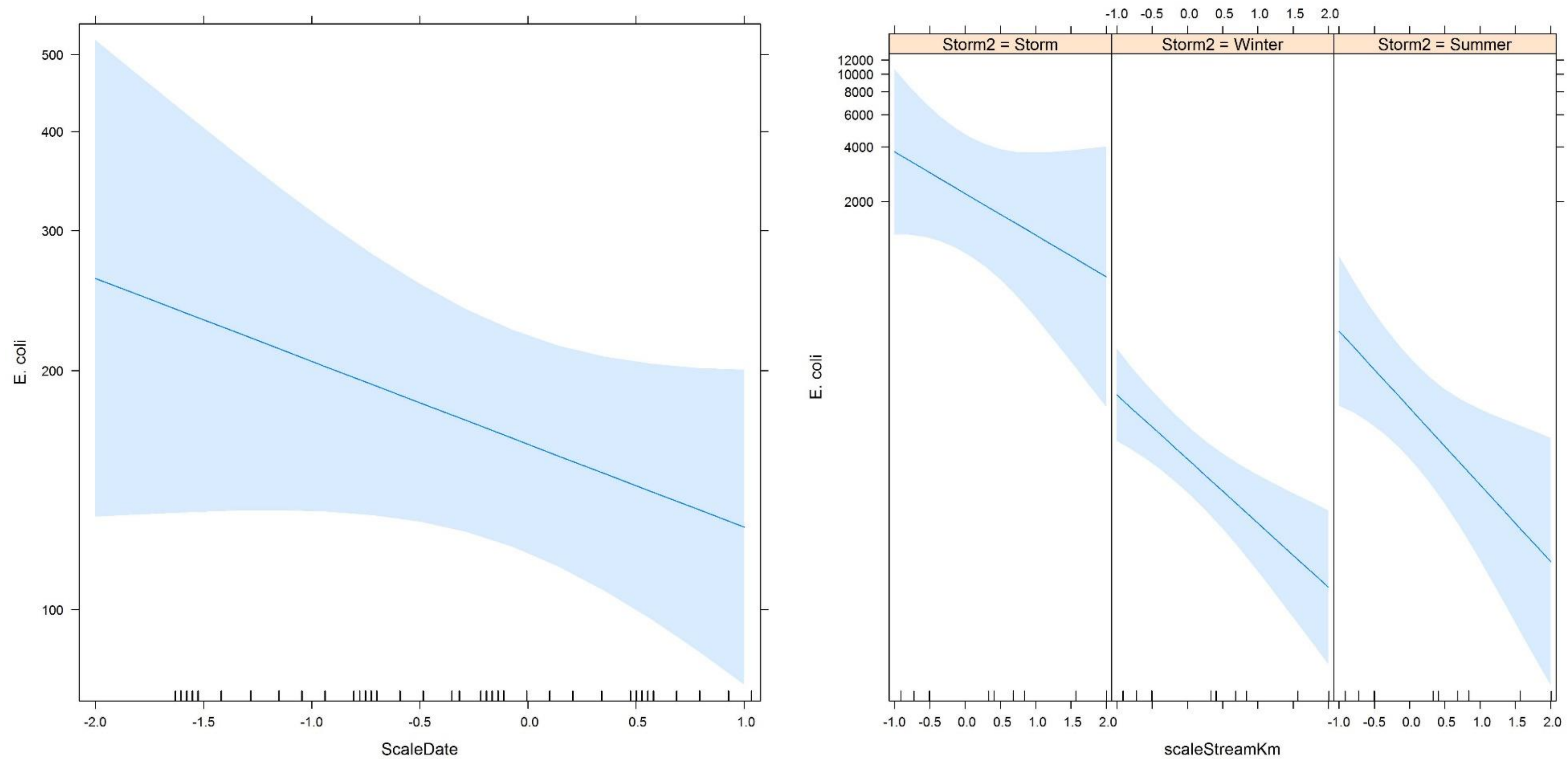


Figure 9: Olema Creek watershed condition assessment LME marginal (once other covariates have been removed) effects for the lowest AICc model for EC over time (left) and by assigned sample period ("storm", "winter" or "summer") from downstream to upstream (right). Note that the variables have been normalized to zero for the model fitting and that each unit represents one standard deviation. The dark blue line indicates the modeled trend in EC over time (left) or from downstream to upstream during the three assigned sample periods (right). Lighter blue shading indicates one standard error associated with the model. See Table 11 for model coefficients and odds ratios.

IV. Discussion

An Opportunity to Couple Conservation Practice Implementation and Water Quality Monitoring

The management of nonpoint source pollution from potential sources like grazing livestock agriculture through the implementation of conservation practices is an adaptive management exercise that land managers achieve through iterations of planning and execution. This is the case for the PRNS and operating ranches within the Olema Creek watershed. Seashore staff and livestock agriculturalists have collaborated on the development of ranch water quality management plans and subsequent implementation of conservation practices through funding support from State and Federal agencies.

Concurrent to this endeavor, PRNS has conducted water quality monitoring from 1999 to the present. This monitoring is comprised of multiple phases and initiatives to understand cold water fisheries habitat conditions and ambient water quality relative to nonpoint source pollution.

Nationally, there has been a formal call to confirm conservation practice effectiveness, along with organized research and synthesis to provide that assessment (Briske et al. 2011; Maderik et al. 2006). In the case of Tomales Bay and the Olema Creek watershed, there are corollary systems internationally and across the United States such as the River Conwy (Bussi et al. 2017), Tillamook Bay (Dorsey-Kramer 1996), Morro Bay (McNeil et al. 2003) and the Stemple Creek Watershed (Binger et al. 2008) with corresponding land use and endeavors to implement and assess the benefit of conservation practices. Evaluating the effectiveness of these implemented conservation practices is typically done through monitoring consisting of pre and post project photographs, design and as-built comparisons, and post project field inspections for three to five years after construction (Lewis et al. 2008).

Often missing from such assessment and evaluation endeavors is validation monitoring and the confirmation of a change in conditions like increased wildlife use of restored habitat. This is largely because costs for field studies and monitoring over the longer time frames required for changes to be detected are prohibitive and generally not funded. Detecting changes in water quality within a watershed is an example of validation monitoring that requires forethought to establish a monitoring network and plan, as well as the financial bandwidth to implement it in coordination with conservation practice implementation. Here then, in the Olema Creek watershed, is a rare opportunity to couple the PRNS water quality monitoring programs with conservation practice planning and implementation on grazing livestock operations.

Results from the long-term study document a significant level of CP implementation paralleling decreases in fecal coliform concentrations. The 48 conservation practices, that were designed and constructed to reduce delivery of sediment, nutrients, and pathogens, are estimated to influence cumulatively more than 30 kilometers of stream (**Table 3**). The graphically demonstrated reduction of fecal coliform concentrations after 2007 (**Figure 4**) coupled with the trend analysis confirmation of decreases in concentrations over time (**Table 4**) mirror the rates and timeline of CPs implementation. The influence of dry and wet years or the interannual variability in PPT as well as the influence of sampling effort on detection of concentration ranges deserve consideration. Examining annual PPT in **Figure 2** and the FC ranges in **Figure 4**, it is interesting to note that the decrease in the range of observed FC concentrations persists from 2007 on, during prolonged dry periods (2007-2010 and 2012-2016) and through wet years (2011, 2017). This relationship is also confirmed and documented in the case of 2016 and 2017 when sampling effort to capture storm conditions increased.

The relationship between decreases in fecal coliform concentrations and CP implementation is an acknowledged correlation. However, in the light of confirmed site scale benefits for CPs implementation (Smolders et al. 2015; Briske et al. 2011), the inference that CPs implemented in Olema Creek have provided benefits to the management of grazing livestock sources for NPS is reasonable. Additional trend analysis using alternative distributions, such as negative binomial, and also further exploration of interactions with grazed and ungrazed sampling locations could offer more insight on this correlation and potential confirmation of causation.

The scale of these decreases may not afford complete year-round achievement of water quality criteria. This has been observed in other water quality management programs (Inamdar et al. 2002) and is part and parcel of adaptive management. Multiple factors may be contributing to this including background loading and delivery of indicator bacteria, seasonal and watershed position dynamics, and the need to implement CPs for other sources of indicator bacteria in the watershed.

Complexities of a mixed-use watershed

Adding to the complexity of improving surface water quality is the context of a mixed-use watershed that includes other wildlife and human sources of nonpoint source pollution. This too is the case for the Olema Creek watershed, including rural residential and developed areas with impervious surfaces. The confirmation of higher FIB concentrations during storm periods relative to winter and summer baseflow periods (**Figure 5**; **Figure 6**; **Figure 7**) during the watershed condition assessment is consistent with the relations of 24-hour and 5-day cumulative PPT regression coefficient values in the long-term trend analysis (**Table 5**). It is also consistent with previous research on FC and EC fate and transport in the Tomales Bay Watershed (Lewis et al. 2005). Although also consistent with the long-term study, the weak downward trend in FIB concentration indicated by the model for the short-term watershed assessment (**Figure 8**; **Figure 9**) should be interpreted with caution, as the study duration was not long enough to account for long-term seasonal variation. Classifying the samples by categorical monitoring period during the watershed condition assessment provided better model fit that PPT, likely due to the observed differences in FIB concentrations during summer baseflow, especially in the lower portions of the Olema Creek watershed (**Figure 5**; **Figure 6**; **Figure 7**). These spatial and temporal observations of higher concentrations in the lower watershed are consistent with results from other previous monitoring efforts (*see* Carson 2013) and not dissimilar from observations in other watersheds (Stocker et al. 2016; Pandy et al. 2014). With most tributaries draining grazing lands dry during summer, higher concentrations could be caused by the flow of groundwater through the hyporheic zone, mobilizing environmental bacteria in stream sediments (Pachepsky and Shelton, 2011; Stocker et al. 2016). There also is the potential for other non-agriculture or background sources in this multi-use watershed to facilitate delivery of FC and EC to Olema Creek. The MST results indicate that the three sources analyzed (human, ruminant, horse) are present under different conditions with the implication that fate and transport for each source is different. Most notable is that human markers were identified during both summer and storm sampling events at nearly all stations, but not detected at station OLM18, furthest upstream and above any known human sources.

Monitoring Recommendations

The correlations presented for the watershed condition assessment are consistent with long-standing fundamentals for water quality relationships (e.g. TSS and Turbidity, D.O. and temperature, etc., *see* **Appendix Figure A-1**). Of note is the consistently high and even higher concentrations of *E. coli* relative to fecal coliform. Typically, as a subset of the fecal coliform bacterial population, *E. coli* has lower concentrations in any given water sample (Atwill et al. 2012). This should be investigated further to ensure monitoring consistency. It is also worth pointing out that the Quanti-Tray™ methodology gives an estimate reported in Most Probable Number (MPN), while guidelines and methodology for water quality objective exceedance testing are developed with analytical results based on laboratory protocols using Colony Forming Unit (CFU) enumeration.

The watershed condition assessment results are helpful for directing future CP implementation and the ability to utilize this data to potentially conduct subsequent watershed condition assessment comparisons in future years. Implementation of future CPs to derive additional improvements to water quality should focus on the lower reaches of the Olema Creek watershed and its tributaries. This may include CPs for grazing livestock and also will invariably include practices to address human sources in that portion of the watershed. Once that implementation has occurred, and also as a recurring evaluation effort, subsequent watershed condition assessments could be conducted, repeating the sampling and analysis conducted during this study.

In addition to planning and preparation for future CP implementation and watershed condition assessment, trend sampling and analysis should continue. With a now 20-year record for fecal coliform and a 12-year record for *E. coli* at the 6 primary sampling stations, the NPS, cooperating agriculturalists, and other partners in the watershed can benefit from this long-term feedback on water quality status and continued management efforts to improve it. As part of this program, descriptor variables and data should continue to be collected including cumulative precipitation (and streamflow where possible), stream kilometer, and sample period designations ("storm", "winter", "summer") for samples among others. Additionally, coordination with the SFRWQCB monitoring programs should continue. This includes the TMLD 5-week winter and summer monitoring for fecal coliform, as well as participating in any future modifications to parameters and/or sampling frequency and duration.

V. References

American Public Health Association, American Water Works Association, and Water Environment Federation. 1998. Standard methods for the examination of water and wastewater (18th ed.), pp. p. 2-8 to 2-11, American Public Health Association, Washington, D.C.

Akaike, H. 1974. A new look at the statistical model identification. IEEE transactions on Automatic Control 19: 716-723.

Atwill, E.R., M. Partyka, R.F. Bond, X. Li, C. Xiao, B. Karle, and L.E. Kiger. 2012. An introduction to waterborne pathogens in agricultural watersheds. Nutrient Management Technical Note No. 9. Natural Resources Conservation Service, United States Department of Agriculture. pp 1-84.

Bates, D., M. Maechler, B. Bolker, and S. Walker. 2015. Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software, 67(1), 1-48. doi:10.18637/jss.v067.i01.

Binger, R., R.R. Lowrance, and D.J. Lewis. 2008. Natural Resources Conservation Service Stemple Creek Conservation Effects Program (CEAP) Final Report. United States Department of Agricutlure, Agricultural Research Service. 115 pp. http://naldc.nal.usda.gov/naldc/download.xhtml?id=38073&content=PDF.

Boehm, A.B., L.C. Van De Werfhorst, J.F. Griffith, P.A. Holden, J.A. Jay, O.C. Shanks, D. Wang, and S.B. Weisberg. 2013. Performance of forty-one microbial source tracking methods: a twenty-seven lab evaluation study. Water Research 47: 6812-6828.

Briske, D.D. (Editor). 2011. Conservation Benefits of Rangeland Practices: Assessment, Recommendations, and Knowledge Gaps. United States Department of Agriculture, Natural Resources Conservation Service. 429 pp.

Bussi, G., P.G. Witehead, A.R.C. Thomas, D. Masante, L. Jones, B.J. Cosby, B.A. Emmett, S.K. Malham, C. Prudhomme, and H. Prosser. 2017. Climate and land-use change impact on faecal indicator bacteria in a temperate maritime catchment (the River Conwy, Wales). Journal of Hydrology. 553 (2017): 248-261.

California Regional Water Quality Control Board, San Francisco Bay Region. 2001. Controlling Pathogens in Tomales Bay, California – Total Maximum Daily Load: Sources and Loadings. 77pp.

California Regional Water Quality Control Board, San Francisco Bay Region. 2005. Pathogens in Tomales Bay Watershed Total Maximum Daily Load (TMDL) Staff Report. Prepared by Farhad Ghodrati & Rebecca Tuden. 144 pp.

California Regional Water Quality Control Board, San Francisco Bay Region. 2013. Renewal of Conditional Waiver of Waste Discharge Requirements for Grazing Operations in the Tomales Bay Watershed (Tomales Bay, Lagunitas Creek, Walker Creek, and Olema Creek) in the San Francisco Bay Region. Resolution No. R2-2013-0039.

California Regional Water Quality Control Board, San Francisco Bay Region. 2017. Water Quality Control Plan (Basin Plan) for the San Francisco Bay Basin. https://www.waterboards.ca.gov/sanfranciscobay/basin_planning.html (accessed 5/31/2018).

Carson, R. 2013. Tomales Bay Wetlands Restoration and Monitoring Program 2007-2012 Final Water Quality Technical Report and Program Summary. Tomales Bay Watershed Council Foundation prepared for California State Water Resources Control Board SRF Project No. C-06-6926-110. http://www.tomalesbaywatershed.org/assets/2011_12_tbwc_finalwqreport_complete_finalv4_sm.pdf

Cooprider, M.A. 2004. San Francisco Area Network Preliminary Water Quality Status Report. National Park Service. December 2004.

Cooprider, M.A., and Carson, R.G. 2006. San Francisco Bay Area Network Freshwater Quality Monitoring Protocol, Version 2.11. National Park Service, Point Reyes Station, CA. 64 pp. plus appendices.

Dorsey-Kramer, J. 1995. A Statistical Evaluation of the Water Quality Impacts of Best Management Practices Installed at the Tillamook County Dairies. Master of Science Theses, Oregon State University. 90 pp.

Helsel, D.R. and R. M. Hirsch. 2002. Statistical Methods in Water Resources Techniques of Water Resources Investigations, Book 4, chapter A3. U.S. Geological Survey. 522 pages.

Hurvich, C.M. and C-L. Tsai. 1989. Regression and time series model selection in small samples. Biometrika 76:297-307.

Inamdar, S.P., S. Mostaghimi, M.N. Cook, K.M. Brannan, and P.W. McClellan. 2002. A long-term, watershed-scale, evaluation of the impacts of waste BMPs on indicator bacteria concentrations. Journal of the American Water Resources Association. 38(3): 819-833.

Ketcham, B.J. 2001. Point Reyes National Seashore Water Quality Monitoring Report: May 1999 - May 2001. National Park Service, Point Reyes National Seashore. November 2001.

Lewis, D.J., M.J. Singer, K.W. Tate, and R.A. Dahlgren. 2000. Hydrology in a California oak woodland watershed: Journal of Hydrology, 240:106-117.

Lewis, D.J., E.R. Atwill, M.S. Lennox, L. Hou, B. Karle, and K.W. Tate. 2005. Linking On-Farm Dairy Management Practices to Storm-Flow Fecal Coliform Loading for California Coastal Watersheds. Environmental Monitoring and Assessment, 107:407-425.

Lewis, D.J., M. Lennox and S. Nossaman. 2008. Developing a monitoring program for riparian revegetation projects. University of California Agriculture and Natural Resources Communication Services Publication #8363. Davis, California. 16pp.

Lewis, D.J., E.R. Atwill, M.S. Lennox, M.D.G. Pereira, W.A. Miller, P.A. Conrad, and K.W. Tate. 2009. Reducing microbial contamination in storm runoff from high use areas on California coastal dairies. Water Science & Technology, 60.7:1731-1734.

Lewis, D.J., E.R. Atwill, M.S. Lennox, M.D.G. Pereira, W.A. Miller, P.A. Conrad, and K.W. Tate. 2010. Reducing microbial contamination in storm runoff from pastures on California coastal dairies. Journal of Environmental Quality, 39:1782-1789.

Maderik, R.A., S.R. Gagon, and J.R. Makuch. 2006. Enivornmental Effects of Conservation Practices on Grazing Lands: A Conservation Effects Assessment Project (CEAP) Bibliography. Special Reference Briefs Series no SRB 2006-02. United States Department of Agriculture, Agricultural Research Service, National Agricutlural Library, Water Quality Information Center. 390 pp.

McNeill, K., J.H. Davis IV, K. Worcester, L.E. Moody, B.C. Dietteick, and J. Beckett. 2003. Morro Bay National Monitoring Program: Nonpoint Source Pollution and Treatment Measure Evaluation for the Morro Bay Watershed. Final Report 1992-2002. Prepared for the U.S. Environmental Protection Agency by the Central Coast Regional Water Qualitiy Control Board and California Polytechnic State University.

Pachepsky, Y.A. and D.R. Shelton. 2011. *Escherichia Coli* and Fecal Coliforms in Freshwater and Estuarine Sediments. Critical Review in Environmental Science and Technology. 41:1067-1110.

Pandey, P.K., P.H. Kass, M.L. Soupir, S. Biswas, and V.P. Singh. 2014. Contamination of water resources by pathogenic bacteria. AMB Express. 4:51.

Pinheiro, J.C. and D.M. Bates: 2000, *Mixed-effects models in S and S-plus*, Statistics and computing series, Springer, New York, 528 pgs.

R Core Team. 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rigge, M., A. Smart and B. Wylie. 2013. Optimal placement of off-stream water sources for ephemeral stream recovery. Rangeland Ecology & Management, 66(4):479-486.

Smolders, A., R.J. Rolls, D. Ryder, A. Watkinson, and M. Mackenzie. 2015. Cattle-derived microbial input to source water catchments: An experimental assessment of stream crossing modification. Journal of Environmental Management. 156(2015):143-149.

Stewart, J.R., A.B. Boehm, E.A. Dubinsky, T. Fong, K.D. Goodwin, J.F. Griffith, R.T. Noble, O.C. Shanks, K. Vijayavel, and S. B. Weisberg. 2013. Recommendations following a multi-laboratory comparison of microbial source tracking methods. Water Research, 47(18): 6829-6838.

Stocker, M.D., J.G. Rodriguez-Valertin, Y.A. Pachepsky, and D.R. Shelton. 2016. Spatial and temporal variation of fecal indicator organisms in two creeks in Beltville, Maryland. Water Quality Research Journal of Canada. 51.2: 167-179.

U.S. Environmental Protection Agency. 2010. Method B: Bacteroidales in Water by TaqMan® Quantitative Polymerase Chain Reaction (qPCR) Assay. EPA-822-R-10-003. USEPA Office of Water. Washington, DC.

U.S. Department of Agriculture. 2016. NRCS Electronic Field Office Technical Guide. Technical references and information on soil, water, air, plant, animal and energy resources to support conservation planning. Marin County, CA. Updated 5/6/2016. https://efotg.sc.egov.usda.gov/treemenuFS.aspx. Accessed 9/15/2016.

VI. Appendix –Supplemental Tables, Figures and Photos

Table A-1: Sampling frequency of storms from 1999-2007 versus 2008-2017 for the long-term fecal coliform data set.

Station ID	Sample Period	
	1999-2007	2008-2017
OLM1	12	8
OLM10B	7	8
OLM11	13	8
OLM14	12	8
OLM18	9	8
OLM6A	6	7

*No Storms analyzed for FC from 2011-2015

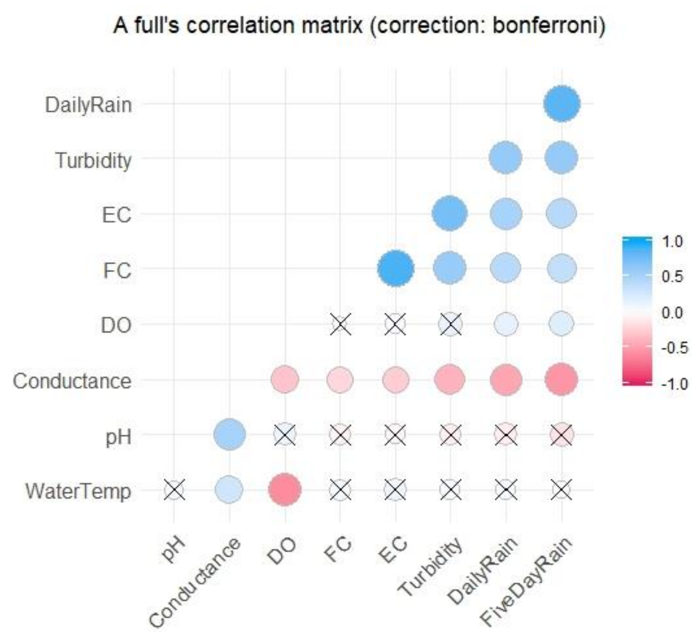


Figure A-1: Correlation plot for water quality sampling parameters during the Olema Creek watershed condition assessment study period (01/2016-05/2018). Colors indicate strength of negative or positive correlation and an X indicates no significant correlation. DO = dissolved oxygen, DailyRain = 24-hour precipitation, FiveDayRain = 5-day precipitation, Conductance = specific conductance, EC = *E. coli* concentration, and FC = fecal coliform concentration.

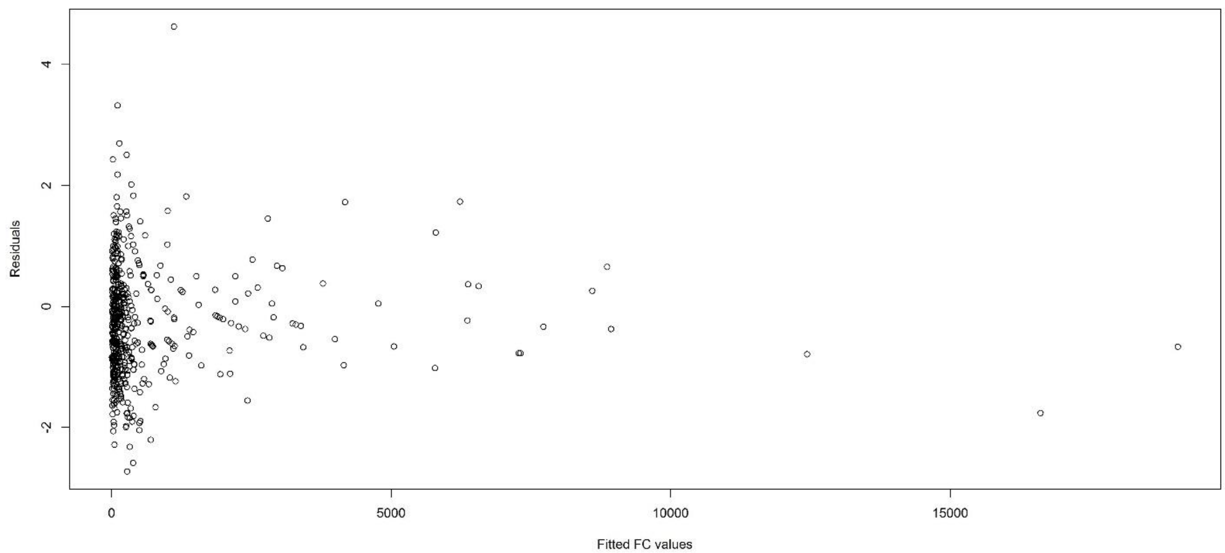


Figure A-2: Residuals from best fitting (lowest AICc) negative binomial mixed effects model for FC in the Olema Creek watershed condition assessment.

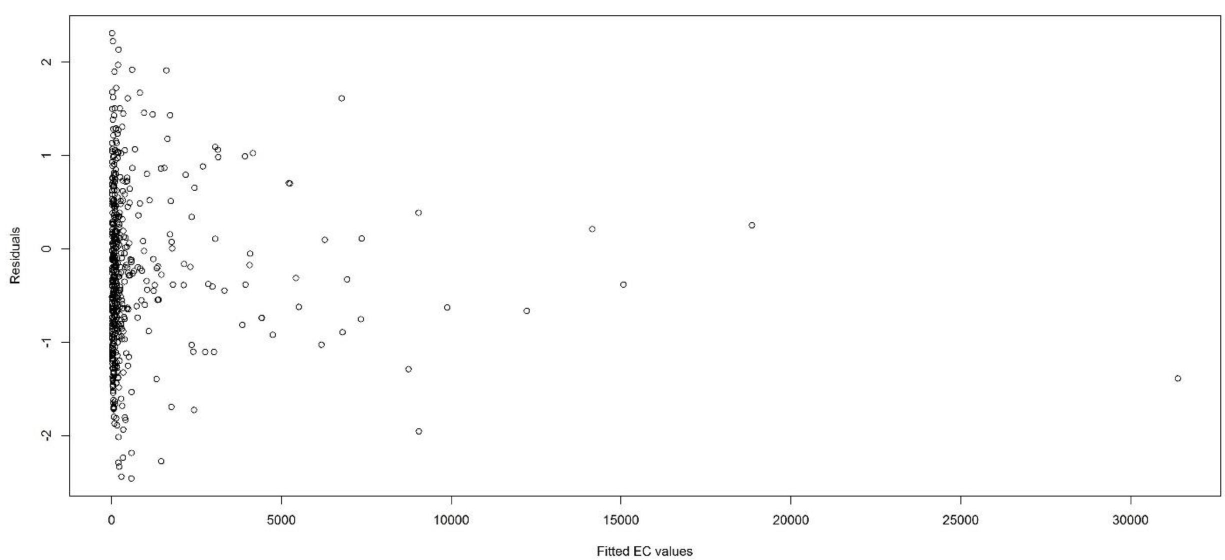
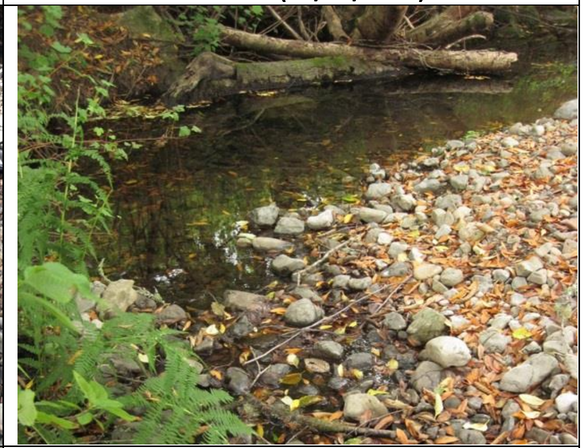
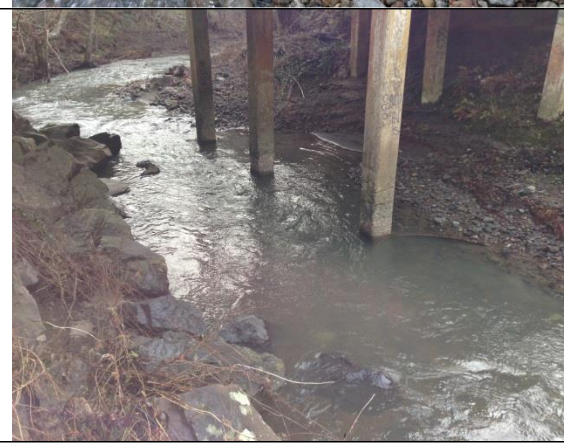
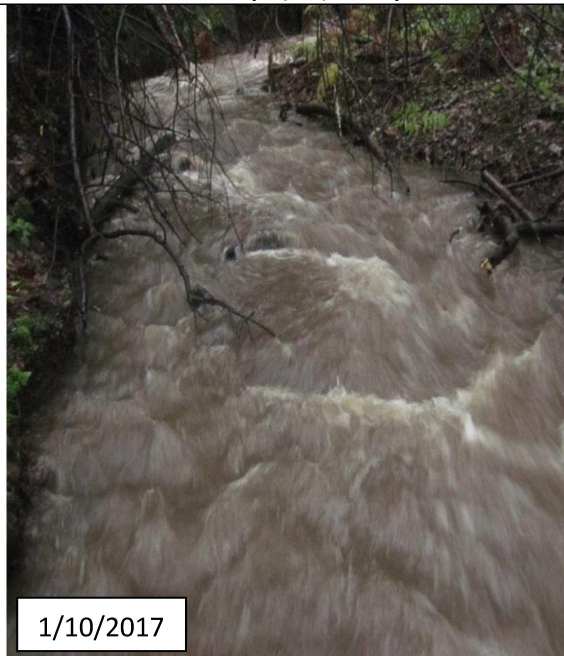
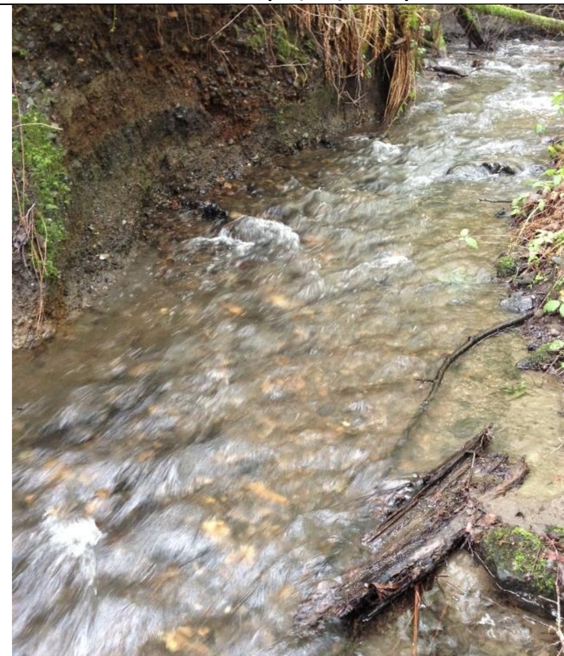
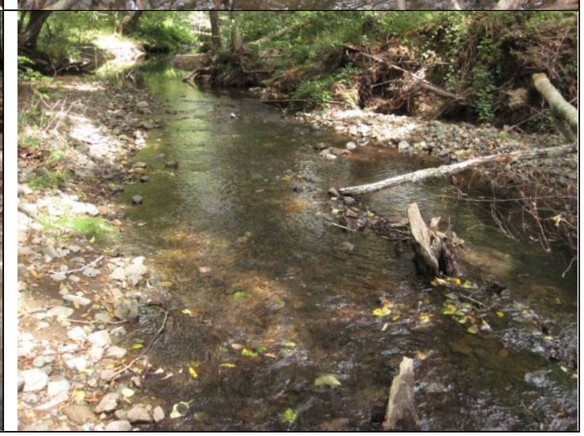


Figure A-3: Residuals from best fitting (lowest AICc) negative binomial mixed effects model for EC in the Olema Creek watershed condition assessment.

Figure A-4: Representative photos at water quality monitoring stations during categorically assigned “storm”, “winter”, and “summer” conditions.

Station ID	“Storm”(12/15/2016)	“Winter” (01/17/2017)	“Summer” (08/08/2017)
GIARE1			DRY
OLM18			

Station ID	"Storm"(12/15/2016)	"Winter" (01/17/2017)	"Summer" (08/08/2017)
OLM1			
OLM14			

Station ID	"Storm"(12/15/2016)	"Winter" (01/17/2017)	"Summer" (08/08/2017)
OLM6A			
OLM19			

Station ID	“Storm”(12/15/2016)	“Winter” (01/17/2017)	“Summer” (08/08/2017)
OLM4B	 02/07/2017		
OLM4			DRY

Station ID	“Storm”(12/15/2016)	“Winter” (01/17/2017)	“Summer” (08/08/2017)
OLM11			
OLM20			DRY

Station ID	"Storm"(12/15/2016)	"Winter" (01/17/2017)	"Summer" (08/08/2017)
OLM21			
OLM22			DRY

Station ID	"Storm"(12/15/2016)	"Winter" (01/17/2017)	"Summer" (08/08/2017)
OLM10B