



Freshwater Quality Monitoring in the San Francisco Bay Area Network

2009-2010 Biennial Report

Natural Resource Technical Report NPS/SFAN/NRTR—2013/720



ON THE COVER

First storm sampling event in the San Francisquito Creek watershed (West Union Creek, site WU1). February 24, 2009.
Photograph by: Katie Booth

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Executive Summary

The San Francisco Bay Area Inventory and Monitoring Network (SFAN) monitors freshwater streams in John Muir National Historic Site (JOMU), the Presidio of San Francisco (PRSF), Muir Woods National Monument (MUWO), Pinnacles National Park (PINN), Point Reyes National Seashore (PORE), and Golden Gate National Recreation Area (GOGA). The SFAN has identified vital signs (indicators of ecosystem health) which represent a broad suite of ecological phenomena operating across multiple temporal and spatial scales. Freshwater quality ranks among the most important vital signs being monitored by the SFAN. The SFAN has many unique aquatic resources that are significant in an ecological and economic context, supporting a variety of federally protected species. Furthermore, the National Park Service (NPS) has a legal obligation to ensure that streams meet minimum water quality standards.

Water years (WYs) run from October 1st to September 30th of each year. This report summarizes water quality data from GOGA, PORE, and MUWO, collected during WYs 2009 and 2010 (10/1/2008 – 9/30/2010). Twenty-five sites in three watersheds were monitored during WYs 2009-2010, including 11 sites in the Redwood Creek watershed (GOGA/MUWO), nine sites in the Lagunitas Creek watershed (PORE/GOGA), and five sites in the San Francisquito Creek watershed (GOGA). Sampling events included collection of field and laboratory water quality parameters, employing the methods set forth in the peer-reviewed SFAN Freshwater Quality Monitoring Protocol (Coopridge and Carson 2006). Core parameters measured in the field included temperature (air and water), dissolved oxygen, pH, specific conductance, turbidity, and discharge. Pathogenic bacteria parameters included *Escherichia coli* (*E. coli*) and total coliform (monitored at all sites) in addition to fecal coliform (only at select sites). Nutrient parameters included nitrate (as nitrogen), ammonia (as nitrogen) and total Kjeldahl nitrogen (TKN).

During WYs 2009-2010, a total of 587 visits were made to 25 monitoring sites monthly and during storm events. Additionally, staff conducted weekly visits to the Olema Creek watershed sites (within the Lagunitas Creek watershed) during five-week sampling regimens (once each winter and summer) in collaboration with the San Francisco Bay Regional Water Quality Control Board's (RWQCB) Tomales Bay Pathogen Total Maximum Daily Load (TMDL) program.

The SFAN water quality results from WYs 2009-2010 commonly met the water quality objectives established by the United States Environmental Protection Agency (EPA) and the San Francisco Bay RWQCB Basin Plan (CA RWQCB 2010). Out of all SFAN water quality parameters, the total coliform, pH, nitrate (as nitrogen), and ammonia (as nitrogen) results most frequently met the established objectives: only 5% of the total coliform results exceeded the recreational objective maximum (10,000 MPN/100 mL); 3% of all pH results fell outside the objective range of 6.5 – 8.5 pH units; less than 2% of nutrient samples exceeded the ecological objective maximum of 1.1 mg/L nitrate (as nitrogen); and no single ammonia sample was above the water quality objective maximum of 0.025 mg/L. Only 1.5% of all SFAN water temperature results were above the range for optimal growth of juvenile coho salmon (10 – 15.6°C) (Armour 1991). Twenty-nine percent of water temperature results were below this optimal range, however, most of the lowest temperatures were recorded in the Lagunitas Creek watershed during December and January, which is not during peak rearing season. Water temperatures in

these SFAN streams (monitored during WYs 2009-2010) are generally capable of supporting salmonids.

Among all parameters measured during WYs 2009-2010, the dissolved oxygen and *E. coli* results most frequently failed to meet water quality objectives (although program-wide results were often weighted by one watershed). The dissolved oxygen results from the San Francisquito Creek watershed sites failed to meet the objective of 7 mg/L with a 32% frequency, while the Lagunitas and Redwood Creek watershed sites had 11% and 6% failure rates, respectively. The two watersheds that most commonly met the dissolved oxygen objective, are the two that still support viable populations of coho salmon and steelhead trout. Within all WY 2009 and 2010 *E. coli* results, the Lagunitas Creek watershed results failed to meet the recreational objective (235 MPN/100 mL) at a rate of 22%, while the Redwood and San Francisquito Creek watershed sites had 9% and 1% failure rates, respectively. High levels of pathogenic indicator bacteria in the Lagunitas Creek watershed have been documented for many years, which is why the state-mandated TMDL program requires additional sampling of the six Olema Creek watershed sites (within the Lagunitas watershed); the fecal coliform results from these sites failed to meet the recreational objective (400 MPN/100 mL) at a rate of 16%.

Two additional parameters – turbidity and specific conductance – do not have established water quality objectives, but they produced a significant number of failures when compared to ecological objectives. Twelve percent of all SFAN turbidity samples (monitored during WY 2010 only) were above the ecological objective maximum of 25 NTU, a level that has been shown to cause reductions in salmonid growth (Sigler et al. 1984); all of these failures were found in the Lagunitas Creek watershed, except for one high result from a tributary to Redwood Creek. Although the San Francisquito Creek watershed had zero turbidity failures, it had the highest percentage of specific conductance failures. The ecological objective for specific conductance is 150 – 500 μ S/cm, in order to support diverse aquatic life (Behar 1997). The San Francisquito watershed sites failed to fall within this range at a rate of 39%, while the Lagunitas and Redwood Creek watersheds failed at rates of 24% and 11%, respectively.

WYs 2009 and 2010 produced a clear depiction of water quality status in these three SFAN watersheds. Due to the two-year rotating basin design of the SFAN Freshwater Quality Monitoring Protocol, this specific set of 25 sites will not be monitored again until WYs 2013-2014 (Coopridge and Carson 2006). The only exception to the rotating basin design is the set of six Olema Creek watershed sites, which require year-round monitoring under the Tomales Bay Pathogen TMDL Program. This freshwater quality monitoring program will continue at sites within PORE, GOGA, JOMU, and PINN during WYs 2011-2012.

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List of Acronyms and Abbreviations

CFS	Cubic Feet per Second
DO	Dissolved Oxygen
EPA	(United States) Environmental Protection Agency
GOGA	Golden Gate National Recreation Area
JOMU	John Muir National Historic Site
MPN	Most Probable Number (of colony-forming units per 100 mL)
MUWO	Muir Woods National Monument
MQO	Measurement Quality Objectives
NO ₂ -N	Nitrite as nitrogen
NO ₃ -N	Nitrate as nitrogen
NPS	National Park Service
NPStoret	National Park Service's version of the EPA STORET database
PINN	Pinnacles National Park
PORE	Point Reyes National Seashore
PRSF	The Presidio of San Francisco
QC	Quality Control
RDL	Reporting Detection Limit
ROS	Regression on Order Statistics
RPD	Relative Percent Difference
RWQCB	Regional Water Quality Control Board
SFAN	San Francisco Bay Area Network (of the National Park Service)
SOP	Standard Operating Procedure
STORET	Storage and Retrieval (EPA's water quality database)
TC/EC	Total coliform and <i>E. coli</i>
TKN	Total Kjeldahl Nitrogen
TMDL	Total Maximum Daily Load
USGS	United States Geological Survey
WY	Water Year

Introduction

Background

The National Park Service (NPS) Management Policies document (NPS 2006) states that parks will “use qualitative and quantitative techniques to monitor key aspects of resources and processes at regular intervals.” The Inventory and Monitoring (I&M) program was established to help accomplish those policies. Freshwater quality ranks among the most important vital signs being monitored by the San Francisco Bay Area Network (SFAN) I&M Program. The SFAN has many unique aquatic resources that are significant in an ecological and economic context. Freshwater systems within the network support a variety of federally protected species including the California freshwater shrimp (*Syncaris pacifica*) [FE¹], coho salmon (*Oncorhynchus kisutch*) [FE/SE²], steelhead trout (*Oncorhynchus mykiss*) [FT³], and the California red-legged frog (*Rana draytonii*) [FT]. Beneficial uses of freshwater bodies within the SFAN include contact and non-contact recreation, fish spawning and migration, cold freshwater habitat, and wildlife habitat. Freshwater quality also has a direct impact on several other resources including marine water quality, federally protected stream species and fish assemblages, amphibians and reptiles, riparian habitat, wetlands, and aquatic macroinvertebrates.

The NPS has a legal obligation to ensure streams meet minimum water quality standards. The SFAN monitors freshwater quality in six national park service units: John Muir National Historic Site (JOMU), the Presidio of San Francisco (PRSF), Muir Woods National Monument (MUWO), Point Reyes National Seashore (PORE), Golden Gate National Recreation Area (GOGA), and Pinnacles National Park (PINN) (Figure 1). The California Environmental Protection Agency regulates water quality through the State Water Resources Control Board which is divided into nine Regional Water Quality Control Boards (RWQCBs). All SFAN park units, with the exception of PINN, fall under the regulation of the San Francisco Bay RWQCB; PINN is within the Central Coast RWQCB area. Through Basin Plans, the RWQCBs have set beneficial uses for water bodies and numerical and narrative objectives (also referred to as standards) to meet the uses. There are specific numerical objectives for ammonia, pH, dissolved oxygen, and pathogenic indicator bacteria listed by each RWQCB; however, there are no established objectives for nitrates, temperature, specific conductance, or turbidity. Freshwater quality monitoring is conducted under the SFAN Freshwater Quality Monitoring Protocol, which contains a thorough narrative and twelve standard operating procedures (SOPs) describing sampling locations, field and laboratory methods, quality assurance procedures, and data management procedures (Coopridier and Carson 2006).

¹ FE – federally endangered

² SE – state endangered

³ FT – federally threatened



Figure 1. Map of the San Francisco Bay Area Inventory and Monitoring Network. (Pinnacles National Monument became Pinnacles National Park in January 2013.)

Objectives

Monitoring objectives as stated in the SFAN Freshwater Quality Monitoring Protocol are:

- Determine variability and long-term trends in water quality through monthly summaries of select parameters (water temperature, pH, conductivity, dissolved oxygen, total nitrogen, nitrate, ammonia, discharge, fecal and total coliform) at selected sites in priority freshwater streams within SFAN.
- Determine the existing ranges and diurnal variability of water temperature, pH, conductivity, and dissolved oxygen at selected sites in priority streams within SFAN.
- Determine the extent that selected sites in priority streams within SFAN meet federal and state water quality standards for fecal indicator bacteria, un-ionized ammonia, dissolved oxygen, and pH through monthly sampling.
- Determine the annual, seasonal, and 30-day mean fecal coliform load to Tomales Bay (an impaired water body) from Olema Creek as required by the San Francisco Bay RWQCB's Tomales Bay Pathogen Total Maximum Daily Load (TMDL) Program

Several of the monitoring questions and program objectives set forth in the protocol are not addressed in this report. Diurnal variability has not been measured because of significant needs for additional funding, staff time, and continuous monitoring equipment. Additionally, loading is not calculated as part of the RWQCB's TMDL program, and long-term trends can not be studied until there is a larger dataset. The goal of this report is to present data collected at the SFAN water quality sites during two consecutive water years (WYs) of monitoring. This report presents physical, chemical, and biological ranges found at the SFAN water quality sites during WYs 2009-2010 (October 1, 2008 – September 30, 2010).

Overview of Aquatic Resources

Watershed conditions in the SFAN range from coastal wilderness to an urbanized watershed managed as a public water supply. Land uses within the rural watersheds include agricultural and commercial operations (e.g., beef and dairy cattle ranching, oyster harvesting, and equestrian operations) as well as protected wilderness areas.

The Mediterranean climate of the San Francisco Bay Region is characterized by wet winters and dry summer months. The hydrologic systems are very flashy, with high runoff in the winter, and very low to intermittent flow during summer and early fall. In response to flashy hydrologic conditions and the highly active geologic processes associated with the San Andreas Fault, stream channels are highly dynamic. Chalone Creek in PINN includes a highly mobile sand bed that is typically dry in the summer months. Watersheds within JOMU and portions of GOGA are greatly altered by development and urbanization, with natural processes engineered out of the stream system. Watersheds within PORE, and the Marin and San Mateo County portions of GOGA, are less constrained and more ecologically functional, with most of the smaller watersheds supporting anadromous steelhead. The larger PORE/GOGA watersheds including Lagunitas Creek, Olema Creek, Redwood Creek, and Pine Gulch Creek, are documented to support both coho salmon and steelhead trout. Stream systems in these areas have been impacted by historic or current agricultural activities as well as dispersed development.

Several NPS efforts to improve water resources within SFAN are underway. The Redwood Creek watershed (MUWO/GOGA) is currently the focus of a variety of projects including

watershed planning, transportation planning, water quality and water rights investigations, sensitive species monitoring, riparian restoration projects, invasive/non-native plant removal, and habitat restoration. Several stream restoration projects are on-going at PORE including implementation of rangeland water quality Best Management Practices, as well as fish passage and habitat restoration projects. Restoration efforts for Chalone Creek (PINN) and its floodplain are also on-going.

Study Area

Due to the rotating basin design of the SFAN Freshwater Quality Monitoring Protocol, the type of sites and number of watersheds monitored, alternate during each two-year rotation. During WYs 2007-2008, there were 32 monitoring sites in eight different watersheds, which were located in four different SFAN parks (JOMU, PINN, GOGA, and PORE). Larger watersheds were selected for the alternate rotation. During WYs 2009-2010 there were 25 monitoring sites in three different watersheds, located in three SFAN parks (GOGA, MUWO, and PORE). Monitoring of the previous 32 sites will resume during WYs 2011-2012, and this alternating sampling routine will continue throughout the life of this long-term monitoring program. The watersheds monitored during WYs 2009-2010 are introduced briefly below; more background information on site selection criteria, rationale, and sampling design can be found in the SFAN Freshwater Quality Monitoring Protocol (Coopridier and Carson 2006). The protocol and its maps (see Figures 2-5) identify sites as proposed or alternate, but in this report they will be referred to as primary and secondary sites, respectively. Primary and secondary sites are monitored at the same frequency, but involve slightly different parameters (see Methods section for more information.)

Redwood Creek Watershed

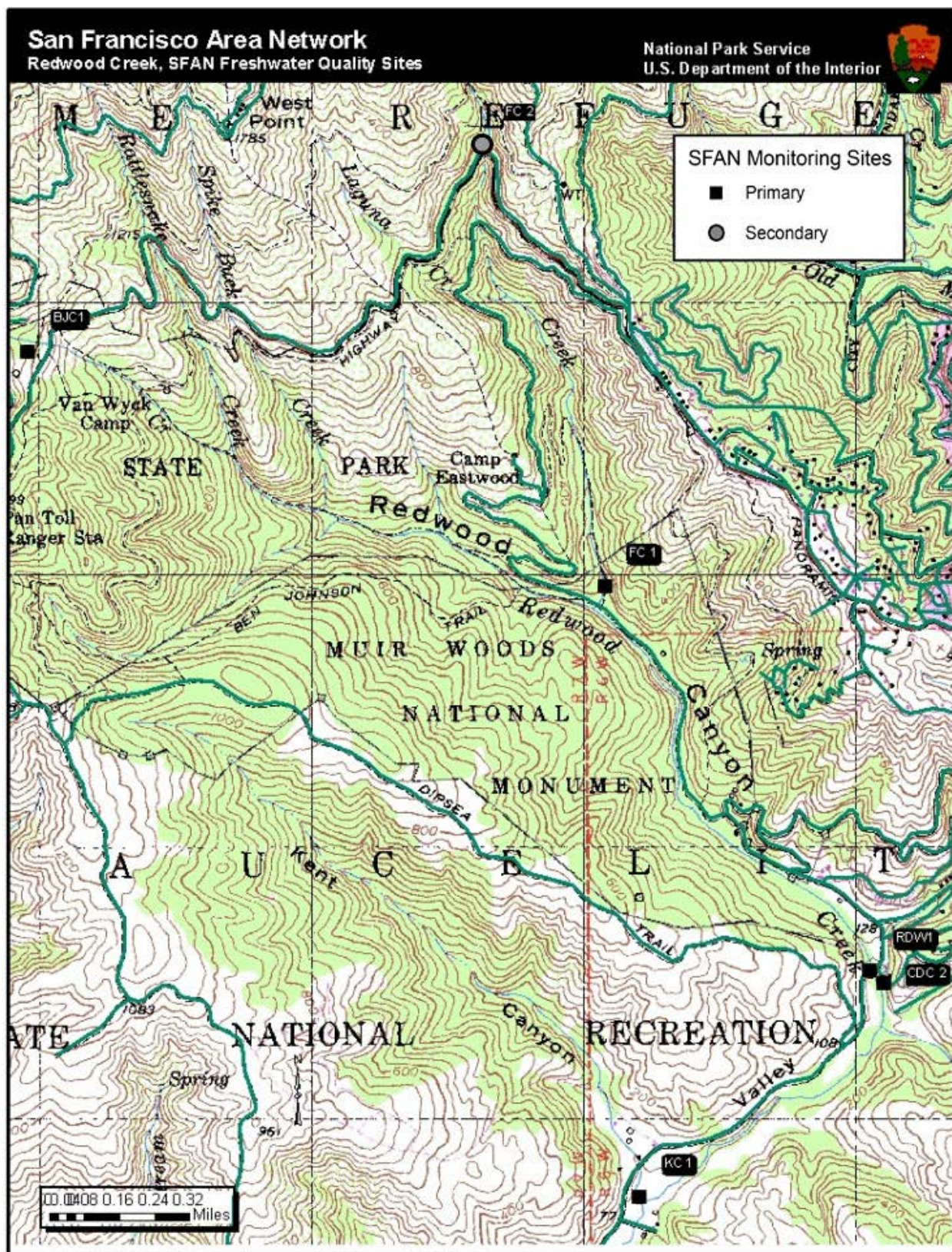
The Redwood Creek watershed is approximately 7.5 mi². Its headwaters originate on the south side of Mount Tamalpais, where the creek flows through Mount Tamalpais State Park, through MUWO, under Highway 1, and eventually into the Pacific Ocean at Muir Beach. The largest tributary of upper Redwood Creek is the Bootjack Branch (1.96 mi²), followed by Fern Creek (1.11 mi²) and Kent Creek (0.99 mi²) (Coopridier 2004). There are seven other minor tributaries (including Spike Buck Creek, Rattlesnake Creek, and Camino del Canyon) in what is considered the upper Redwood Creek area (Coopridier 2004). In addition, Green Gulch (1.26 mi²) is the largest tributary of the lower Redwood Creek area (Lehre and Wahrhaftig 1974). Green Gulch and another tributary (often referred to as the Golden Gate Dairy tributary) join Redwood creek less than half of a mile upstream of the mouth. The area near the mouth of the creek is known historically as Big Lagoon, and has been the focus of extensive restoration efforts. The beneficial uses for Redwood Creek, defined by the San Francisco Bay RWQCB, include agricultural supply, coldwater habitat, freshwater replenishment, municipal supply, contact and non-contact recreation, fish spawning, and wildlife habitat.

Hydrologic monitoring in Redwood Creek began in 1997 with the installation of a stream gaging station at the Highway 1 bridge. Water quality monitoring within the Redwood Creek watershed had been conducted sporadically since the mid 1980s and was mainly short-term and project-based. Fisheries monitoring (focused on coho salmon and steelhead trout) has been conducted in the watershed since the early 1990s. In WYs 2009-2010, the SFAN initiated long-term water quality monitoring in the Redwood Creek watershed.

Eleven sites within the Redwood Creek watershed were selected as part of the SFAN Freshwater Quality Monitoring Program (Table 1). Two of the monitoring sites are in the upper watershed area, and nine are scattered around the lower Redwood Creek area (Figures 2 and 3). Out of these eleven sites, three are located on the mainstem of Redwood Creek, and each of these exhibits perennial flow. The remaining eight sites are located on tributaries of Redwood Creek, and they all exhibit low or intermittent flows in the summer and early fall.

Table 1. Redwood Creek watershed monitoring site locations, approximately in order from upstream to downstream.

Site	Site Type	Flow Regime	Location	Site Description
BJC1	Primary	Intermittent	Tributary	Bootjack Creek: in Bootjack picnic area, Mt. Tamalpais State Park
FC2	Secondary	Intermittent	Tributary	Fern Creek: upstream of Panoramic Hwy (near milepost 3.22) in Mt. Tamalpais State Park
FC1	Primary	Intermittent	Tributary	Fern Creek: off of Fern Creek Trail in MUWO, above confluence with Redwood Creek
CDC2	Primary	Intermittent	Tributary	Camino del Canyon Creek: off of Frank Valley Road, above confluence with Redwood Creek
RDW1	Primary	Perennial	Mainstem	Redwood Creek mainstem: downstream of MUWO entrance, under the Frank Valley Road concrete bridge
KC1	Primary	Intermittent	Tributary	Kent Creek: upstream of Kent Creek culvert (milepost 2.67), approximately 50 ft from confluence with Redwood Creek
RDW2	Primary	Perennial	Mainstem	Redwood Creek mainstem: at stream gaging station under Hwy 1 bridge
GGD	Primary	Intermittent	Tributary	Golden Gate Dairy tributary: upstream of the Hwy 1 culvert at intersection with Pacific Way
GG2	Secondary	Intermittent	Tributary	Green Gulch: in Green Gulch Zen Center, upstream site next to guest parking lot
GG1	Primary	Intermittent	Tributary	Green Gulch: in Green Gulch Zen Center, downstream site near horse pasture
RDW3	Primary	Perennial	Mainstem	Redwood Creek mainstem: upstream of Muir Beach Pedestrian bridge



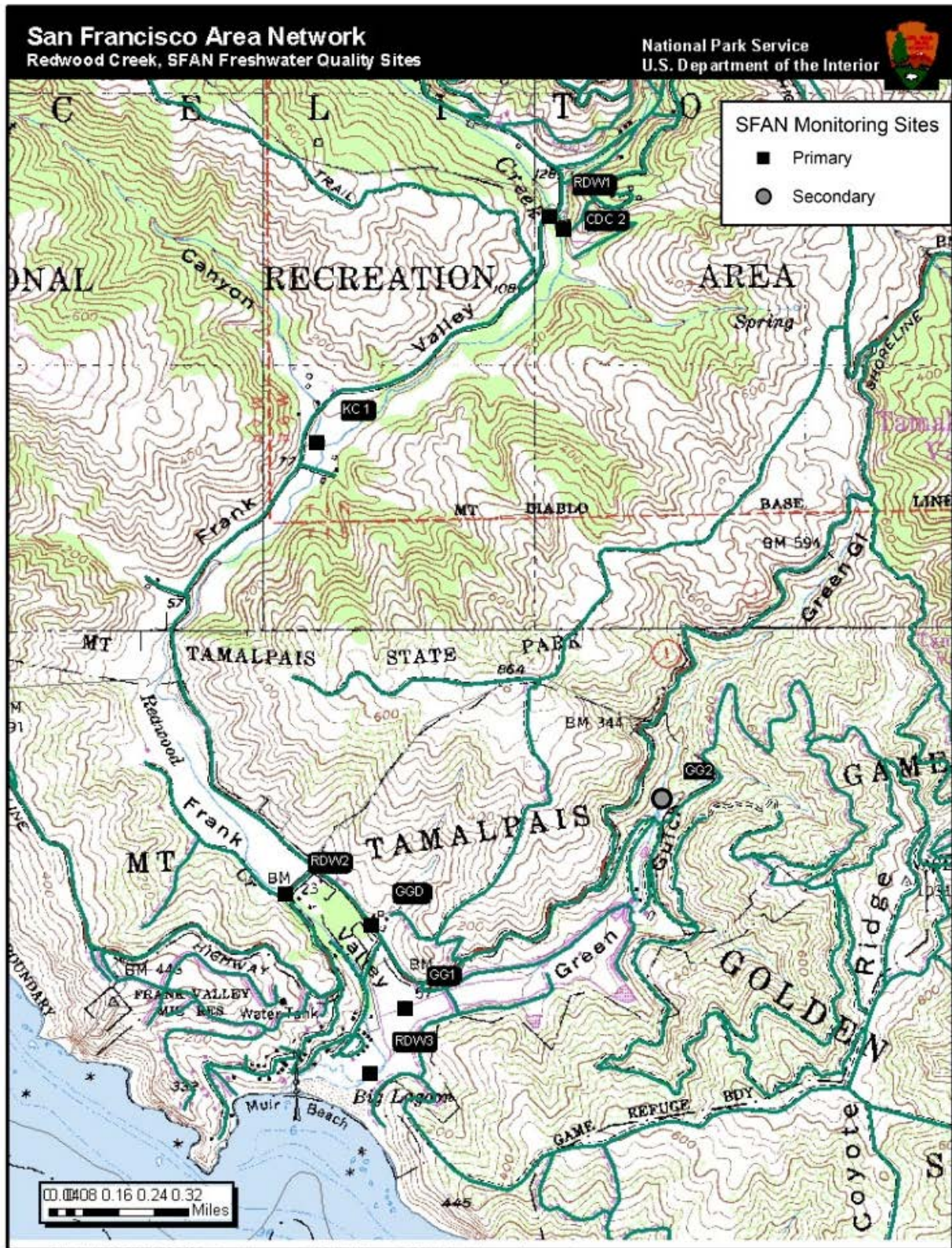


Figure 3. Map of the five lower Redwood Creek watershed sites (and three upper watershed sites).

Lagunitas Creek Watershed

The 88 mi² Lagunitas Creek watershed is the largest within the SFAN, flowing north from Mount Tamalpais, through a series of lakes and dams, and eventually flowing through NPS lands (PORE/GOGA) before reaching the head of Tomales Bay near the town of Point Reyes Station. Stream discharge records range from 22,100 cfs, in the floods of January 1982, to 0.01 cfs during the drought of 1977 (Freeman et al., 2003). Within NPS lands there are several tributaries of Lagunitas Creek, including Olema Creek, Bear Valley Creek, Haggerty Gulch, and Tomasini Creek. The San Francisco Bay RWQCB has identified Lagunitas and Olema Creeks as impaired by pathogens, sediment, and nutrients.

Olema Creek is the largest tributary of Lagunitas Creek, with stream discharge records up to approximately 3,000 cfs (Coopridge 2004). This 14.5 mi² watershed flows north through the Olema Valley, the landward expression of the San Andreas Fault Zone. Its confluence with Lagunitas Creek lies at the head of Tomales Bay. Currently, 35-40 percent of the Olema Creek watershed is managed for cattle grazing. Two horse concessions operations, Stewart Horse Stable and Five Brooks Horse Stable, are located in the central portion of the watershed. Hydrologic monitoring in Olema Creek began in 1997 with the installation of a stream gaging station at the Bear Valley Road bridge. Water quality monitoring within the Olema Creek watershed has been conducted since 1999, and fisheries monitoring (focused on coho salmon and steelhead trout) has been conducted in the Olema Creek watershed since 1994. Water quality monitoring under the SFAN Freshwater Quality Monitoring Protocol began in the fall of 2006.

Lagunitas Creek and Olema Creek still support viable populations of coho salmon, steelhead trout, and California red-legged frogs; Lagunitas Creek supports a well-established population of California freshwater shrimp, where over 5,000 individuals were recorded during a 2011 survey (Serpa 2011). Because of its significance as habitat for threatened and endangered species, and as a source of pollutant loading to Tomales Bay, the Lagunitas Creek watershed is the subject of extensive monitoring through this water quality program as well as the SFAN Coho and Steelhead Monitoring Program, the Salmon Protection and Watershed Network, and Marin Municipal Water District's Lagunitas Creek Fisheries Program.

Nine primary and two secondary sampling sites within the Lagunitas Creek watershed were selected as part of the SFAN Freshwater Quality Monitoring Program, however, the secondary sites are monitored through the PORE Pastoral Water Quality Monitoring Program, which only collects core parameter and pathogenic bacteria data (Table 2 and Figure 4). The results from these two secondary sites are not included in this report.

Table 2. Lagunitas Creek watershed monitoring site locations, approximately in order from upstream to downstream.

Site	Site Type	Flow Regime	Location	Site Description
OLM18	Primary	Intermittent	Mainstem Olema	Olema Creek: upstream of Randall Gulch (near Hwy 1 milepost 21.06)
OLM1	Primary	Intermittent	Tributary of Olema	John West Fork: upstream of Highway 1 culvert (near milepost 22.67)
OLM2	Secondary	Intermittent	Tributary of Olema	Giacomini Gulch: downstream of Highway 1 culvert (near milepost 22.78)
OLM14	Primary	Perennial	Mainstem Olema	Olema Creek: access just downstream of the northernmost Five Brooks bridge
OLM6A	Primary	Perennial	Tributary of Olema	Davis Boucher Creek: approximately 50 m upstream of footbridge, above confluence with Olema Creek
OLM4	Secondary	Intermittent	Tributary of Olema	Quarry Gulch: at staff plate upstream of confluence with Olema Creek (near Hwy 1 milepost 26.0)
OLM11	Primary	Perennial	Mainstem	Olema Creek: at Bear Valley Road bridge
LAG1	Primary	Perennial	Tributary of Olema	Bear Valley Creek: upstream of first bridge in Bear Valley Headquarters area
OLM10B	Primary	Perennial	Mainstem Olema	Olema Creek: adjacent to Olema Marsh, below residence #530
LAG3	Primary	Perennial	Tributary of Lagunitas	Devil's Gulch: upstream of Sir Francis Drake Boulevard in Samuel P. Taylor State Park
LAG2	Primary	Perennial	Tributary of Lagunitas	Cheda Creek: upstream of Sir Francis Drake Boulevard (near milepost 19.17)

San Francisco Area Network Lagunitas & Olema Creek, Freshwater Quality Sites

National Park Service
U.S. Department of the Interior

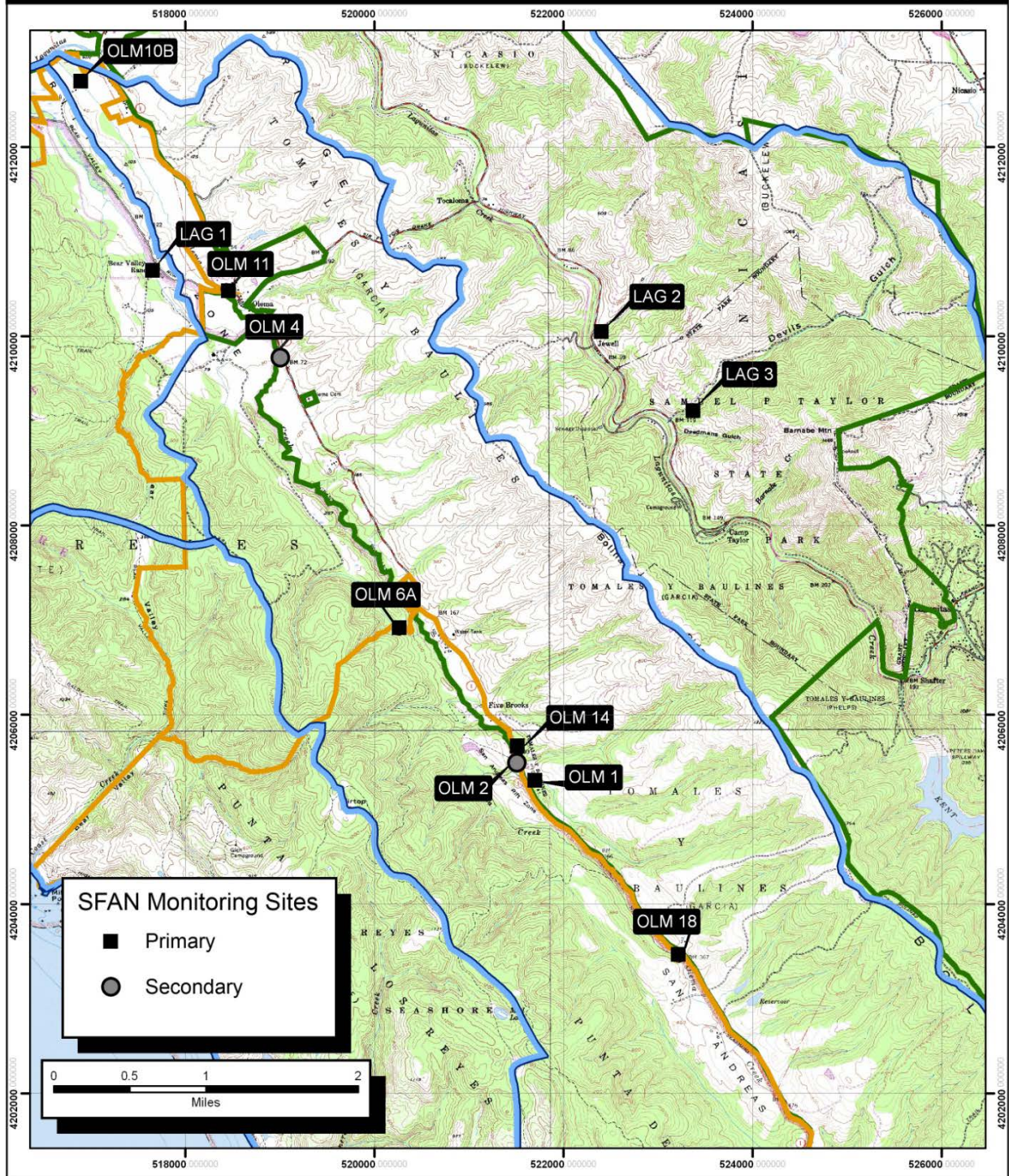


Figure 4. Map of the Lagunitas Creek watershed sites.

San Francisquito Creek Watershed

In 1992, GOGA acquired the Phleger Estate, located adjacent to Huddart County Park in the town of Woodside in central San Mateo County. The headwaters of West Union Creek are located within the 1,000-acre Phleger Estate, where the creek flows south through NPS lands into Huddart County Park. There are two minor (unnamed) tributaries of West Union Creek within the Phleger Estate, and another larger tributary, McGarvey Gulch, which flows into West Union near the Phleger/Huddart boundary. West Union Creek drains approximately five square miles of land before flowing into Bear Creek, a tributary of San Francisquito Creek, which eventually empties into the San Francisco Bay, northeast of Palo Alto and Stanford University. San Francisquito Creek is listed under Section 303(d) of the Clean Water Act for impairment by sedimentation/siltation, as well as the pesticide diazinon.

Until January 2004, no monitoring of surface water had been conducted by NPS in the southern GOGA lands. Some limited water quality monitoring had been conducted within the San Francisquito Creek Watershed, but not on NPS lands. Concerns for West Union Creek include erosion and runoff from trails, since land slides and significant bank erosion have been observed in the past (Coopridier 2004). Trails in the Phleger Estate are frequented by equestrians, which can contribute to runoff of bacteria and nutrients.

Two primary and three secondary sampling sites within the West Union Creek watershed were selected as part of the SFAN Freshwater Quality Monitoring Program (Table 3). Two sites are located on the mainstem of West Union Creek, and the remaining three sites are located on tributaries of West Union Creek. In this report, these will be referred to as the San Francisquito Creek watershed sites (Figure 5).

Table 3. San Francisquito Creek watershed monitoring site locations, in order from upstream to downstream.

Site	Site Type	Flow Regime	Location	Site Description
WU4	Secondary	Perennial	Mainstem	West Union Creek: upstream of tributary #2
WU3	Secondary	Intermittent	Tributary	Tributary #2 (second tributary upstream of McGarvey Gulch): upstream of Raymundo Bridge Trail
WU2	Secondary	Intermittent	Tributary	Tributary #1 (first tributary upstream of McGarvey Gulch): above the Miramontes trail crossing
WU1	Primary	Perennial	Mainstem	West Union Creek: ¼ mile down the trail from the Huddart County Park boundary
MGG1	Primary	Perennial	Tributary	McGarvey Gulch: between trail crossing and confluence with West Union Creek (above large boulders)

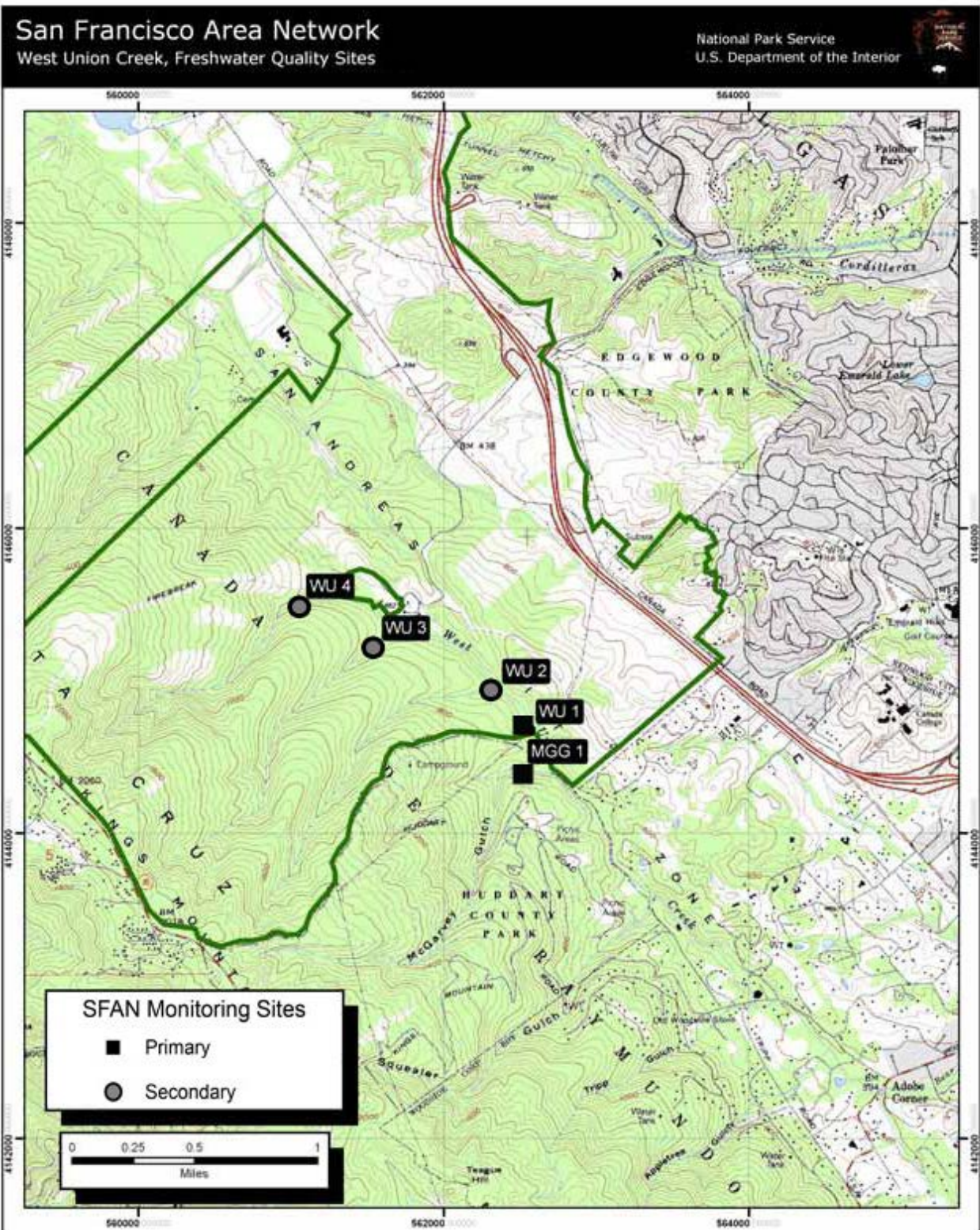


Figure 5. Map of the San Francisco Creek watershed sites.

Methods

Water Quality Criteria

In California, through Basin Plans, the RWQCBs have set “numerical and narrative objectives for surface waters” (Tables 4 and 5) (CA RWQCB 2010). The numerical objectives for bacteria are based on the national criteria established by the EPA (U.S. EPA 1986). Failure to meet these numerical objectives will be referred to as exceedances throughout this report. The Basin Plans also outline the beneficial uses assigned to each stream that is a significant surface water feature. Although the San Francisco Bay RWQCB has identified some nutrients as impairments to Tomales Bay and they are in the process of developing nutrient objectives for the region, objectives are currently not established for any nutrients except un-ionized ammonia. Although temperature, conductivity, and some nutrient parameters do not have applicable water quality objectives, they are important indicators of the effects of urbanization, climate change, atmospheric deposition, and ranching impacts on the region’s streams.

Table 4. Numerical objectives for surface waters, from the San Francisco Bay Regional Water Quality Control Board’s Basin Plan (CA RWQCB 2010).

Parameter	Water Quality Objective
Dissolved oxygen (non-tidal waters, cold water habitat)	7.0 mg/L minimum
pH	Less than 8.5 and greater than 6.5 pH units
Un-ionized ammonia (as N)	Annual median maximum 0.025 mg/L

Table 5. Pathogenic bacteria water quality criteria for contact recreation use, from the San Francisco Bay Regional Water Quality Control Board’s Basin Plan (CA RWQCB 2010).

	Marine Water	Fresh Water
Total coliform		
Single-day sample	10,000	10,000
30-day average	1,000	1,000
Escherichia coli		
Single-day sample	235	235
30-day average	126	126
Fecal coliform		
Single-day sample	400	400
30-day average	200	200

In order to assist states with the development of nutrient standards, the EPA undertook nationwide sampling of nutrients in rivers and streams, and developed regional reference values (U.S. EPA 2000). The regional reference values can be used to assess whether nutrients in the SFAN are exceeding expected conditions. The EPA regional reference values for the sub-ecoregion encompassing the SFAN are 0.36 mg/L for total Kjeldahl nitrogen (TKN) and 0.16 mg/L for nitrate and nitrite (Table 6). Monitoring in the SFAN has shown nitrite values to be insignificant, thus the SFAN only samples nitrate (Coopridier 2004).

Table 6. Ecoregion III reference values for nutrients (U.S. EPA 2000).

Parameter	Regional Reference Value
Nitrate (NO ₃)	0.16 mg/L
Nitrite (NO ₂)	0.16 mg/L
Total Kjeldahl nitrogen	0.36 mg/L

Clean Water Act Section 303(d) Listed Waters

Water bodies within and adjacent to NPS lands have been listed under Section 303(d) of the Clean Water Act as impaired by pathogens, sediment, and nutrients. With the state as the lead in development of TMDLs, the NPS has participated as an active stakeholder, along with other partners, to support development and implementation of water quality monitoring and enhancement efforts in order to address water quality pollution issues.

In 2007, the San Francisco Bay RWQCB completed a TMDL project plan for pathogens in the Tomales Bay Watershed, which set forth water quality targets for Tomales Bay and its tributaries (CA RWQCB 2011). Part of this monitoring regime is conducted through the SFAN program in conjunction with the RWQCB and other stakeholders; this includes monthly monitoring of six SFAN sites along Olema Creek, in addition to intensive weekly monitoring for five consecutive weeks during both the winter and summer. Additional information about TMDLs in the SFAN can be found in the Freshwater Quality Monitoring Protocol (Coopridner and Carson 2006) and on the San Francisco Bay RWQCB's website (<http://www.waterboards.ca.gov/sanfranciscobay/>).

Site Selection

Detailed information about the process used to select SFAN monitoring locations is documented in the SFAN Freshwater Quality Monitoring Protocol (Coopridner and Carson 2006).

Sampling Regime

The sampling design for the SFAN Freshwater Quality Monitoring Program involves a rotating basin approach in which each watershed is monitored monthly for a two-year period (Table 7). This approach allows the SFAN to collect sufficient samples for each site and watershed, in order to perform statistical analyses, while allowing for sufficient funds to perform laboratory analyses and provide representative data for each site. There are two groups of basins in this design, meaning that every four years, each site and each watershed group will have two years of data available for analysis. This design is intended to allow for the detection of both short- and long-term trends in all monitored watersheds. The only exception to the rotating basin approach is the Olema Creek watershed, which is monitored continuously, every year, because sampling is mandated by a TMDL project.

Table 7. SFAN water quality monitoring schedule. (WY = water year, M = visited monthly, S = visited during at least one storm event, W =visited 5 consecutive weeks in the winter and summer as required by the Tomales Bay Pathogen TMDL Project.)

Watershed/Stream	Park Unit	WYs 2007-2008 & 2011-2012	WYs 2009-2010 & 2013-2014	Number of Monitoring Sites
Olema Creek	PORE	M, S, W	M, S, W	6 Primary
Pine Gulch	PORE	M		3 Primary
Franklin Creek	JOMU	M		1 Primary
Strentzel Creek	JOMU	S		0 Primary / 5 Secondary
Chalone Creek	PINN	M, S		5 Primary / 3 Secondary
Rodeo Creek	GOGA	M, S		2 Primary
Tennessee Creek	GOGA	M, S		2 Primary / 1 Secondary
Nyhan Creek	GOGA	M, S		1 Primary
Oakwood Creek	GOGA	M, S		0 Primary / 1 Secondary
West Union Creek	GOGA		M	2 Primary / 3 Secondary
Lagunitas Creek	PORE/GOGA		M, S	3 Primary
Redwood Creek	GOGA/MUWO		M, S	9 Primary / 2 Secondary

Primary sites ranked as a higher priority during the site selection process, while secondary sites were identified to be of a slightly lower priority and could be integrated into the sampling regime only if funding and time allowed. Many of the secondary sampling sites are located in close proximity to primary sites, and it became apparent during the first year of monitoring that the sampling of core parameters and bacteria from the secondary sites could be conducted on each corresponding field day with little additional time. Furthermore, the SFAN was able to acquire the IDEXX Quanti-Tray system for affordable (internal) processing of pathogenic indicator bacteria samples, which kept costs low for the secondary sites. The processing of nutrient samples is one of the largest costs to the SFAN water quality program; therefore, nutrient parameters are only monitored at primary sites.

Sample Parameters

The NPS I&M Program calls for required monitoring of all basic level 1 water quality parameters. Required level 1 parameters include a qualitative description of flow, as well as the core parameters (water temperature, dissolved oxygen, pH, and specific conductance) (NPS 2002). Additionally, a quantitative discharge measurement was made at select sites (established stream gaging stations) when site conditions allowed.

An effort was made to visit each site at approximately the same time of day, once per month, and additionally during at least one storm event per year. Site visits included the measurement of core parameters and the collection of grab samples for laboratory processing, as well as documentation of air temperature, weather, flow severity, number of days since last rain, and photo monitoring (Table 8). All instantaneous measurements and grab samples were collected in the centroid of flow. Samples were analyzed for nutrients (nitrate (as N), ammonia (as N), and TKN at primary sites only), turbidity, and pathogenic indicator bacteria (total coliform and *Escherichia coli* (*E. coli*), as well as fecal coliform in the Olema Creek watershed). All

parameters were monitored monthly, except for ammonia (as N). Due to the low (and often undetectable) levels of ammonia (as N) in SFAN streams, it was decided to reduce ammonia monitoring to a quarterly frequency (January, April, July, and October), with additional storm sampling, instead of monthly (Skancke 2011). All water quality sampling followed the methods laid out in the SFAN Freshwater Quality Monitoring Protocol (Coopriider and Carson 2006), manufacturer's equipment manuals, and U.S. Geological Survey (USGS) guidance.

Table 8. SFAN water quality monitoring parameters.

Parameter Groups	Specific Parameters
Core	Water temperature, dissolved oxygen, pH, and specific conductance
Bacteria	Total coliform & <i>E. coli</i> at all sites, fecal coliform at Olema Creek sites only
Sediment	Turbidity
Nutrients	Total Kjeldahl nitrogen (TKN), nitrate (as N), and ammonia (as N)
Discharge	Qualitative flow description (& quantitative stream discharge at select sites)

Table 9 lists the processing methods used for all parameters. Core parameter data were collected in-situ, using various handheld instruments; a YSI 85 was used to collect temperature, dissolved oxygen, and specific conductance data for the majority of this monitoring period (October 2008 – July 2010), while pH data were collected with either an Oakton pH Tester 30 or a YSI EcoSense pH10 meter (often overlapping for quality control checks). During the last two months of WY 2010, the equipment was upgraded to employ the YSI ProPlus (Professional Series multiprobe sonde) to collect all core parameter data. This entailed two months of equipment overlap (at every site visit) for quality control comparison.

Table 9. Water quality testing methods used in the SFAN.

Parameter	Method
Core parameters	Instantaneous readings collected in the centroid of flow with handheld multiparameter instruments and pH probes.
Total coliform bacteria	Enzyme substrate coliform test: 9223B enzyme substrate test using IDEXX Quanti-Tray with colilert
<i>E. coli</i> bacteria	Enzyme substrate coliform test: 9223B enzyme substrate test using IDEXX Quanti-Tray with colilert
Fecal coliform bacteria	Total coliform by multiple tube fermentation: 9221B
Ammonia (as N)	SM 4500-NH ₃
Nitrate (as N)	EPA method 300
TKN	SM 4500-Norg C
Turbidity	Hach 2100P Portable Turbidimeter
Discharge	Following 'USGS Measurement of Stream Discharge by Wading' (Rantz 1982) using a Marsh-McBirney Flowmate or a Gurley Pygmy meter.

The IDEXX Quanti-Tray system was installed at the Pacific Coast Science and Learning Center in Point Reyes National Seashore in January 2007; all total coliform and *E. coli* samples were processed by SFAN staff at this location. Fecal coliform samples, collected only for the Olema Creek watershed, were processed at TestAmerica Laboratory in San Francisco, CA, a private laboratory contracted by the RWQCB. All nutrient samples were processed at Analytical Sciences, in Petaluma, CA, and turbidity samples were processed in-house with a Hach 2100P Portable Turbidimeter.

Ammonia (as N) samples were analyzed using Standard Method 4500-NH₃ with a detection limit of 0.10 mg/L, nitrate (as N) samples were analyzed using EPA method 300 with a detection limit of 0.15 mg/L, and TKN samples were analyzed using standard method 4500-Norg C with a detection limit of 0.25 mg/L. Ammonia (as N) results above the detection limit were converted to un-ionized ammonia (as N) using the pH, temperature, and specific conductance results that were recorded at the time of sample collection, in order to determine whether the results fell below the objective established by the RWQCB.

Data Handling and Analysis

All data were entered into NPStoret (housed at PORE), which is the database created and provided by the NPS Water Resources Division. These data are periodically uploaded to the EPA STORET database that allows for public access. Sites with fewer than four results were considered to have a dataset too small for analysis and are not included in this report's figures (U.S. EPA 1998).

Water quality data contains many values that can not be quantified, but are known to be above or below a certain threshold (reporting detection limit [RDL]); these data are considered censored during statistical analysis (Helsel 2005). The SFAN nutrient results are often reported as 'ND' (non-detect), meaning that the value is not defined as zero, but is only known to be less than the RDL of that particular method. The SFAN bacteria results can be censored on either end (producing results above or below the detectable and quantifiable range), which further complicates data analysis. Because of these differences, separate statistical methods and programs had to be used to analyze the nutrient and bacteria data, resulting in figures with slightly different formatting and appearance.

A study by the USGS (Antweiler and Taylor 2008) evaluated the main classes of statistical treatment of censored environmental data, and found that the nonparametric Kaplan-Meier method was an effective technique for overall determination of summary statistics for datasets with less than 70% censoring, while the regression on order statistics (ROS) method was determined to be an adequate alternative. Due to high numbers of censored results, the robust ROS method developed by Helsel and Cohn (1988) was used to create summary statistics and figures for all SFAN nutrient results; this was accomplished by using Dennis Helsel's macros with Minitab (v.15) Statistical Software (Helsel 2005). The Helsel-Cohn Robust ROS method is ideal for data that is 50-80% censored; it assumes a distribution for censored data (only) by calculating regression on a probability plot in order to compute summary statistics. Conversely, the Kaplan-Meier statistical method was used (through the NPStoret database) to create summary statistics and figures for all SFAN turbidity and bacteria data. This method was selected because no single site had more than 50% censoring (threshold of Kaplan-Meier method in NPStoret) and it is considered to be a better statistical method for these types of data (Antweiler and Taylor 2008).

Quality Control

Field equipment was calibrated at the beginning of each sampling day: a three-point calibration was performed for all pH meters, a one-point calibration was performed for specific conductance, and dissolved oxygen was calibrated with the water-saturated air method (one-point). Calibration checks were performed immediately following each calibration, and again at

the end of the field day, in order to monitor for fouling and drift, and to ensure that the instruments stayed within the calibration acceptance criteria of each parameter.

In order to assess precision, core parameters and grab samples were both collected in duplicate once per sampling day (or 10% of all samples) and samples were submitted to the professional laboratories for testing. Additionally, trip blanks (distilled water) were collected and submitted for laboratory analysis, in order to detect and locate possible sources of contamination. Laboratory quality control (QC) measures included matrix spikes, method blanks, laboratory control spikes and use of a variety of calibration standards. All data that were entered into NPStoret were verified by an alternate staff person.

Measurement Quality Objectives

The SFAN has established measurement quality objectives (MQOs) for all monitored parameters. There are MQOs for calibration acceptance, precision, and systematic error (percent recovery). Measurement of systematic error (reported as percent recovery) is a measurement of the accuracy of the laboratory procedures and equipment, which is determined by conducting matrix spikes or laboratory control spikes, to test a known value of a particular analyte. The MQO for systematic error (percent recovery) varies for each parameter, as follows: 70-130% for TKN and ammonia (as N), 75-125% for nitrate (as N), and 90-110% for turbidity. The professional laboratory contracted by the SFAN did not report any QC results that were outside these acceptable ranges.

The MQOs for precision are defined in the SFAN Freshwater Quality Monitoring Protocol as the acceptable thresholds of relative percent difference (RPD), calculated from the duplicated QC sample sets. The precision MQO for nitrate (as N), TKN, and ammonia (as N) is +/- 30% RPD, while the MQO for total coliform and fecal coliform is +/- 60% RPD; an MQO was not established for *E. coli*, but it can be assumed to be 60% as well.

A total of 307 duplicate QC samples were collected during WYs 2009-2010; 36% of these (109:307) included a censored result which prevented calculation of RPD/precision. Because of this limitation, Table 10 contains the mean RPD values (for each parameter) calculated only from those QC tests that had quantifiable RPD (did not include a censored result). The only parameter that did not produce any precision MQO failures was nitrate (as N); no nitrate duplicate had an RPD above 30%, and the mean RPD of all QC tests was only 3.89% (Table 10). The TKN results also had a low mean RPD (17.06%), well below the precision MQO. The mean RPD values for the total coliform and *E. coli* QC tests were much higher (30.70% and 37.36%, respectively), but still well below their specific MQO of +/- 60%. The fecal coliform QC tests (all run by a professional, external laboratory) produced the poorest results: the highest ratio of MQO failures and a mean RPD beyond the acceptable threshold of 60% (although only 0.37% over).

Table 10. Precision of SFAN nutrient and bacteria samples during water years 2009-2010.

	Nitrate as N (mg/L)	TKN (mg/L)	Total Coliform (MPN/100mL)	<i>E. coli</i> (MPN/100mL)	Fecal Coliform (MPN/100mL)
Total Number of QC Duplicates (Dups)	69	70	69	70	29
Number of QC Dups with Measurable RPD¹	14	34	63	61	26
Number that Failed to Meet MQO for RPD¹	0	5	6	16	11
Mean RPD¹ (Precision)	3.89%	17.06%	30.70%	37.36%	60.37%
SFAN MQO for RPD (Precision)	+/- 30%	+/- 30%	+/- 60%	+/- 60%	+/- 60%

¹ Many duplicate QC measurements (36% of 307) did not have measurable RPD because of a censored result; therefore, the calculated mean RPD values and number of failures do not include all duplicate QC measurements collected during WYs 2009-2010.

Results and Discussion

This report includes results collected from October 1, 2008 through Sept 30, 2010 (WYs 2009-2010), the third and fourth years of protocol implementation. Due to the two-year rotating basin design of this protocol, the WY 2009 and 2010 data represent the first two years of monitoring this specific rotation (11 sites in the Redwood Creek watershed, 9 in the Lagunitas Creek watershed, and 5 in the San Francisquito Creek watershed). While it is not yet possible to observe long-term trends, the data can be viewed in the context of established water quality objectives, ecological objectives, and regional reference values established by the EPA.

Routine monitoring visits took place monthly, and storm sampling was conducted at least once per water year at each site. One storm event was captured at the Redwood Creek watershed sites during each water year, while the Lagunitas Creek watershed sites received additional storm sampling during each water year; two events were captured during WY 2009, and four storm sampling events were captured during WY 2010. Although the protocol does not require storm sampling of the San Francisquito Creek watershed, one storm event was captured at these sites during WY 2009 as well as during WY 2010.

Some SFAN sites exhibited intermittent seasonal flow patterns, and were recorded as ‘dry’ or ‘no flow’ on routine monthly visits during WYs 2009-2010. Five sites in the Redwood Creek watershed (CDC2, KC1, GGD, GG1, and GG2) and two sites in the San Francisquito watershed (WU2 and WU3) were too low for sampling during the dry seasons, so the summary statistics are computed from smaller datasets. The six Olema Creek watershed sites (within the Lagunitas Creek watershed) have the largest datasets, due to the additional monitoring required by the San Francisco Bay RWQCB’s Tomales Bay Pathogen TMDL Program.

Summary statistics for WYs 2009-2010 are presented in the following sections, organized by parameter and watershed group. Sites with less than four results were not included in the figures. All calculations, results, and statistics discussed in this report are from these two water years as a whole, not individually. All means and standard deviations presented in tables are rounded to one more decimal place than the least precise value (least number of decimal places) of each corresponding dataset (Sullivan 2011).

Core Parameters

Water temperature, dissolved oxygen, pH, and specific conductance are defined as core parameters in the SFAN Freshwater Quality Monitoring Protocol; these all interrelated, and describe the most basic level of water chemistry. Thorough knowledge of these parameters is needed in order to better understand the nutrient and bacteria data collected. Core parameters are measured in-situ during every site visit, alongside each grab sample collection.

Summary statistics of all core parameter results from WYs 2009-2010 are displayed in detail in Tables 11, 12, and 13; however, box and whiskers plots of these data are displayed separately (sorted by parameter) for simplified viewing. Turbidity and stream discharge data are included at the end of this section, although not defined as core parameters in the SFAN Protocol.

Sites with fewer than four results are included in the summary tables, but are excluded from the figures since their datasets are too small for analysis (U.S. EPA 1998). All summary statistics are

based on instantaneous measurements routinely collected at approximately the same time of day on each visit; therefore, the data in the tables and figures presented do not reflect the true minimum and maximum values of diurnal variation.

Table 11. Core parameter results from the Redwood Creek watershed (water years 2009-2010). (Std. dev. = standard deviation. N of obs. = number of observations.) All means and standard deviations are rounded to one more decimal place than the least precise value (least number of decimal places) of each corresponding dataset.

Parameter	Statistic	BJC1	FC2	FC1	CDC2	RDW1	KC1	RDW2	GGD	GG2	GG1	RDW3
Water temperature (°C)	Mean	11.54	10.86	10.72	9.21	11.24	10.74	11.62	-	9.81	10.67	11.36
	Median	10.6	10.9	10.9	9.1	11.1	10.7	11.7	-	9.9	10.4	11.7
	Minimum	8.4	7.9	7.7	6.7	8.0	8.4	8.6	9.6	8.5	9.3	7.7
	Maximum	16.5	14.0	13.6	11.4	14.5	13.1	15.2	10.3	11.6	13.3	14.7
	Std. dev.	2.65	1.95	1.97	1.31	2.06	1.37	2.05	-	0.97	1.39	1.93
	N of obs.	25	25	25	8	25	12	25	2	9	15	25
Dissolved oxygen (mg/L)	Mean	9.416	10.350	10.020	10.940	9.720	9.439	8.550	-	9.994	8.231	7.741
	Median	9.47	10.21	10.16	10.96	9.86	9.63	9.05	-	10.26	8.73	8.37
	Minimum	7.57	8.98	8.59	10.44	7.59	7.04	2.73	9.30	7.21	2.65	1.08
	Maximum	11.52	11.39	11.59	11.38	11.32	11.18	10.59	10.36	11.12	11.33	11.03
	Std. dev.	1.119	0.600	0.842	0.326	1.111	1.308	1.923	-	1.256	2.157	2.624
	N of obs.	25	25	25	8	25	12	25	2	9	15	25
pH (pH units)	Mean	7.910	7.858	7.534	7.509	7.499	7.230	7.398	-	7.448	7.292	7.374
	Median	8.08	8.01	7.66	7.84	7.64	7.33	7.48	-	7.59	7.26	7.44
	Minimum	6.86	6.57	6.55	6.85	6.92	6.77	6.80	6.47	6.76	6.87	6.87
	Maximum	8.34	8.25	8.14	7.91	7.92	7.67	8.02	6.87	8.02	7.72	7.87
	Std. dev.	0.441	0.419	0.413	0.494	0.293	0.293	0.348	-	0.418	0.300	0.329
	N of obs.	25	25	25	7	23	11	23	2	9	14	22
Specific conductance (µS/cm)	Mean	232.10	152.80	161.10	206.90	212.60	287.40	233.10	-	256.00	348.40	253.10
	Median	234.8	155.4	166.7	206.2	223.6	272.2	235.8	-	227.2	362.0	242.5
	Minimum	137.6	94.5	120.0	160.0	155.0	210.7	175.3	212.5	178.9	239.9	193.1
	Maximum	326.2	200.3	196.3	236.1	257.1	421.5	293.0	354.0	356.5	503.0	379.6
	Std. dev.	39.84	30.58	23.48	24.30	30.29	64.12	32.19	-	66.52	77.90	48.80
	N of obs.	25	25	25	8	25	12	25	2	9	15	25
Turbidity (NTU)	Mean	3.41	1.519	1.302	-	1.074	-	1.770	-	-	2.067	1.706
	Median	1.13	1.31	0.83	-	0.83	-	1.51	-	-	1.79	1.65
	Minimum	0.67	0.29	0.23	15.2	0.16	1.03	0.38	-	2.37	0.82	0.63
	Maximum	11.6	3.47	3.19	246	3.26	1.77	3.52	-	5.53	3.59	2.71
	Std. dev.	4.31	1.107	1.164	-	1.008	-	1.217	-	-	1.406	0.746
	N of obs.	8	7	8	2	8	2	8	-	2	3	8

Table 12. Core parameter results from the Lagunitas Creek watershed (water years 2009-2010). (Std. dev. = standard deviation. N of obs. = number of observations.) All means and standard deviations are rounded to one more decimal place than the least precise value (least number of decimal places) of each corresponding dataset.

Parameter	Statistic	OLM18	OLM1	OLM14	OLM6A	OLM11	OLM10B	LAG1	LAG2	LAG3
Water temperature (°C)	Mean	10.64	11.29	10.97	10.73	11.87	11.55	12.30	11.65	11.50
	Median	10.9	11.5	11.0	11.0	11.8	11.8	12.4	11.1	11.3
	Minimum	5.8	6.5	5.2	5.1	4.7	4.6	10.2	5.3	5.3
	Maximum	13.7	14.4	15.2	13.5	16.8	15.3	14.2	16.0	15.9
	Std. dev.	2.16	2.19	2.66	2.10	3.15	2.98	1.16	3.07	2.68
	N of obs.	39	39	38	39	40	40	27	27	27
Dissolved oxygen (mg/L)	Mean	7.336	8.557	9.642	10.590	9.564	8.569	9.514	9.064	10.540
	Median	7.80	9.02	10.02	10.51	9.46	9.01	9.54	9.58	10.54
	Minimum	0.01	2.14	4.60	8.93	6.39	0.73	7.30	2.96	8.69
	Maximum	11.47	10.89	11.66	12.02	12.79	11.22	11.20	11.91	12.80
	Std. dev.	2.453	2.107	1.363	0.690	1.353	2.127	0.745	2.183	0.893
	N of obs.	39	39	39	39	39	40	26	27	27
pH (pH units)	Mean	6.599	6.986	7.526	8.022	7.556	7.427	7.544	7.762	8.073
	Median	6.65	7.09	7.64	8.09	7.65	7.55	7.61	7.81	8.22
	Minimum	5.58	6.04	6.29	7.12	6.65	6.52	6.95	6.83	6.98
	Maximum	7.27	7.39	7.94	8.34	7.96	8.02	7.91	8.21	8.49
	Std. dev.	0.398	0.335	0.367	0.252	0.297	0.363	0.256	0.346	0.367
	N of obs.	39	39	40	39	40	39	26	26	26
Specific conductance (µS/cm)	Mean	133.70	150.90	206.00	275.10	235.30	246.80	292.10	292.50	290.50
	Median	125.5	146.4	196.1	270.0	244.7	263.2	299.6	325.8	314.6
	Minimum	57.6	70.8	83.2	163.6	78.3	73.9	193.0	96.5	108.8
	Maximum	318.1	249.8	344.4	345.6	351.1	367.7	346.0	400.2	371.4
	Std. dev.	48.09	44.18	70.38	50.36	82.60	73.64	39.69	90.25	74.04
	N of obs.	39	39	39	39	40	40	27	27	27
Turbidity (NTU)	Mean	12.87	16.7	51.3	12.64	58.8	30.5	16.56	38.9	38.8
	Median	4.17	1.96	2.45	2.81	2.06	2.48	1.29	1.02	1.23
	Minimum	1.09	0.29	0.26	0.80	0.54	0.79	0.29	0.31	0.18
	Maximum	70.5	131	352	94.4	378	209	94.2	242	216
	Std. dev.	18.63	36.5	105.5	24.38	116.8	64.2	32.22	83.9	73.8
	N of obs.	17	16	17	17	17	17	11	10	11

Table 13. Core parameter results from the San Francisquito Creek watershed (water years 2009-2010). (Std. dev. = standard deviation. N of obs. = number of observations.) All means and standard deviations are rounded to one more decimal place than the least precise value (least number of decimal places) of each corresponding dataset.

Parameter	Statistic	WU4	WU3	WU2	WU1	MGG1
Water temperature (°C)	Mean	11.66	10.26	9.90	11.48	12.02
	Median	10.8	10.0	10.1	11.4	12.3
	Minimum	8.9	9.0	8.8	8.0	8.2
	Maximum	16.0	13.0	10.5	14.9	15.3
	Std. dev.	2.13	1.30	0.58	2.15	2.31
	N of obs.	18	7	7	21	21
Dissolved oxygen (mg/L)	Mean	8.257	9.581	9.857	6.169	7.023
	Median	9.08	9.62	9.57	7.08	8.04
	Minimum	0.92	7.84	8.88	1.15	1.29
	Maximum	11.03	10.80	10.64	10.99	10.61
	Std. dev.	2.840	0.903	0.722	3.747	2.966
	N of obs.	18	7	7	21	21
pH (pH units)	Mean	7.797	7.374	7.456	7.207	7.380
	Median	8.03	7.30	7.54	7.17	7.34
	Minimum	6.55	7.03	6.97	6.62	6.58
	Maximum	8.71	7.94	7.98	7.84	8.03
	Std. dev.	0.553	0.333	0.367	0.299	0.358
	N of obs.	18	7	7	21	21
Specific conductance (µS/cm)	Mean	472.10	372.40	404.00	451.40	538.50
	Median	482.3	338.7	437.9	454.2	542.0
	Minimum	272.6	234.4	174.1	175.1	156.4
	Maximum	644.0	538.0	587.0	707.0	905.0
	Std. dev.	101.60	111.50	144.60	112.80	206.90
	N of obs.	18	7	7	21	21
Turbidity (NTU)	Mean	2.24	2.282	2.125	2.10	1.754
	Median	0.85	0.60	1.97	0.71	0.82
	Minimum	0.36	0.47	0.60	0.39	0.31
	Maximum	11.6	5.00	3.97	11.1	7.42
	Std. dev.	3.38	2.378	1.621	3.32	2.318
	N of obs.	11	5	4	11	11

Water Temperature

There is not an established water quality objective for water temperature in SFAN streams, so criteria for salmonids are often considered as ecological objectives. The water temperature range for optimal growth of juvenile coho salmon is 10 to 15.6°C (Armour 1991); although salmonids have differing temperature requirements during different life history stages and seasons, this range is used as a guideline when reviewing the SFAN water temperature results. During WYs 2009-2010, mean water temperatures were within the optimal range at each SFAN site, with the exception of three GOGA sites (CDC2, GG2, and WU2) which had mean values slightly below 10°C. The minimum water temperature recorded at each Redwood Creek watershed site fell below the optimal range (Figure 6); nearly all of these minimums were recorded during February, March, or April of 2009. Program-wide, the Lagunitas Creek watershed sites exhibited the widest range of results, with summer temperatures often tripling those recorded in the winter (Figure 7). Meanwhile, the San Francisco watershed sites exhibited the narrowest range in results, particularly at sites WU2 and WU3, the tributaries of West Union Creek (Figure 8).

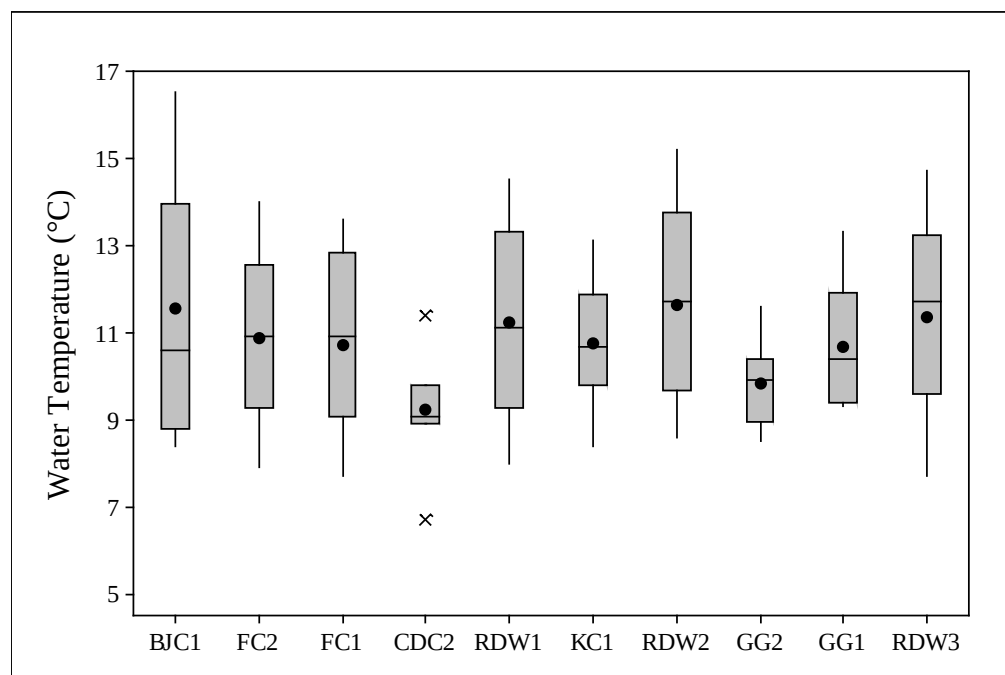


Figure 6. Water temperature results from the Redwood Creek watershed (water years 2009-2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

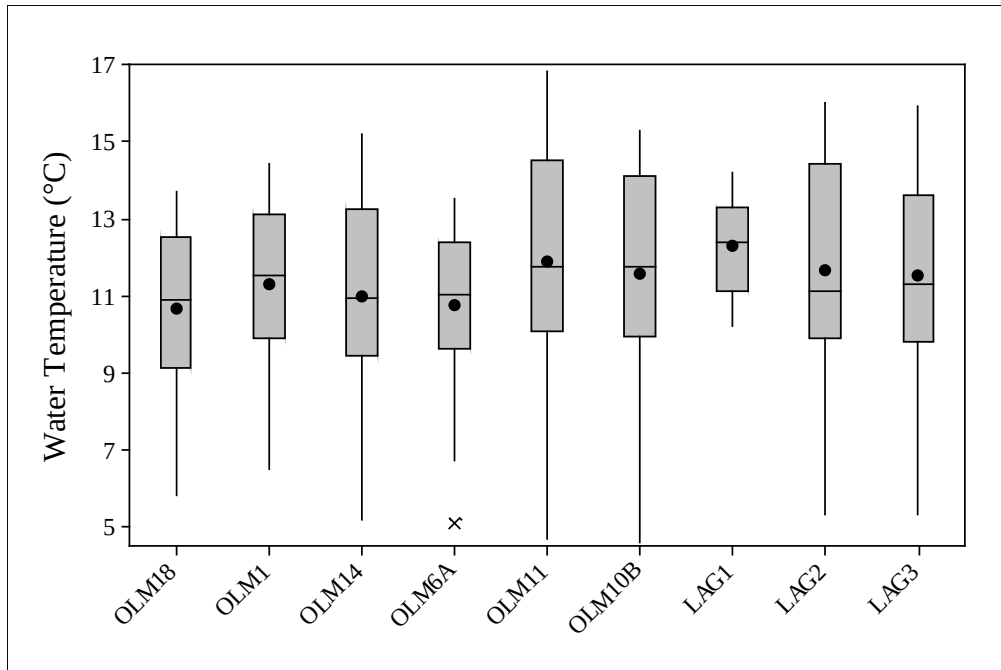


Figure 7. Water temperature results from the Lagunitas Creek watershed (water years 2009-2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

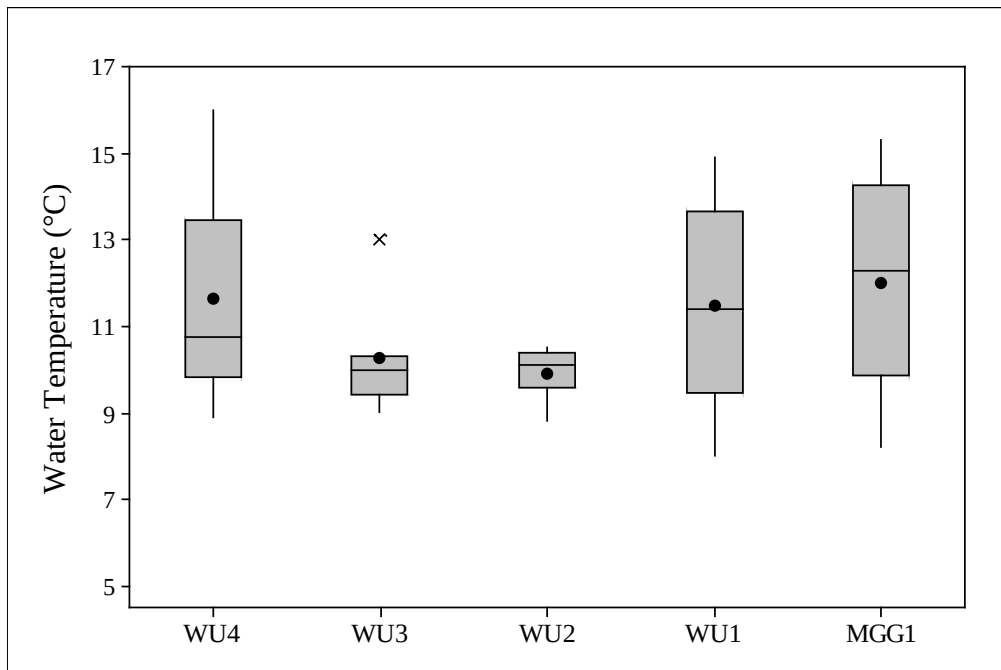


Figure 8. Water temperature results from the San Francisquito Creek watershed (water years 2009-2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

During WYs 2009-2010, only 1.5% (9:586) of all results were above the upper end of the optimal range ($> 15.6^{\circ}\text{C}$), and at least one exceedance was recorded in each watershed. None of these exceedances were near 25°C , a temperature known to be lethal to juvenile coho salmon (Moyle 2002). The highest water temperature recorded at any site was a value of 16.8°C during August 2010 in Olema Creek. Of the 50 lowest temperatures recorded program-wide, almost all were from the Lagunitas Creek watershed sites, particularly the Olema Creek sites. Although these sites routinely exhibited the lowest minimum temperatures (below the optimal range of 10 to 15.6°C [Armour 1991]) they were less likely to have caused stress on salmonids because they were mostly recorded during December and January, which is not during the peak rearing season.

Dissolved Oxygen

The San Francisco Bay RWQCB established a dissolved oxygen minimum of 7 mg/L, which applies to all SFAN sites monitored during WYs 2009-2010. This threshold is particularly important to the Lagunitas and Redwood Creek watershed sites, because they still support salmonid populations. Twelve percent (70:585) of all dissolved oxygen measurements collected from the SFAN sites during WYs 2009-2010, failed to meet the objective of 7 mg/L. The Redwood Creek watershed sites had the lowest rate of objective failures; the mean oxygen concentration of each site was above the objective, and only six percent (12:196) of the watersheds' individual results fell below this level (Figure 9). The dissolved oxygen means of all Lagunitas watershed sites were also above 7 mg/L; however, 11% (34:315) of the results from this watershed failed to meet the objective (Figure 10). The San Francisquito Creek watershed sites had the highest rate of failure; 32% (24:74) of this watershed's samples failed to meet the objective, and one West Union Creek site (WU1) produced a mean of 6.169 mg/L, the lowest of any SFAN site (Figure 11).

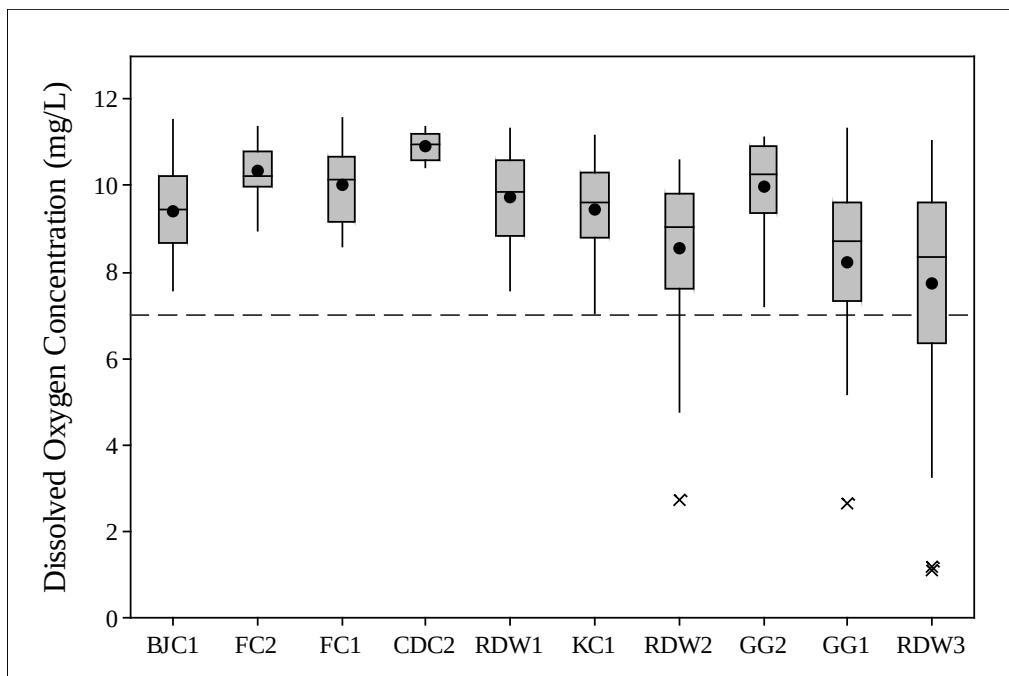


Figure 9. Dissolved oxygen results from the Redwood Creek watershed (water years 2009-2010). The dashed line represents the minimum water quality objective of 7 mg/L (CA RWQCB 2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

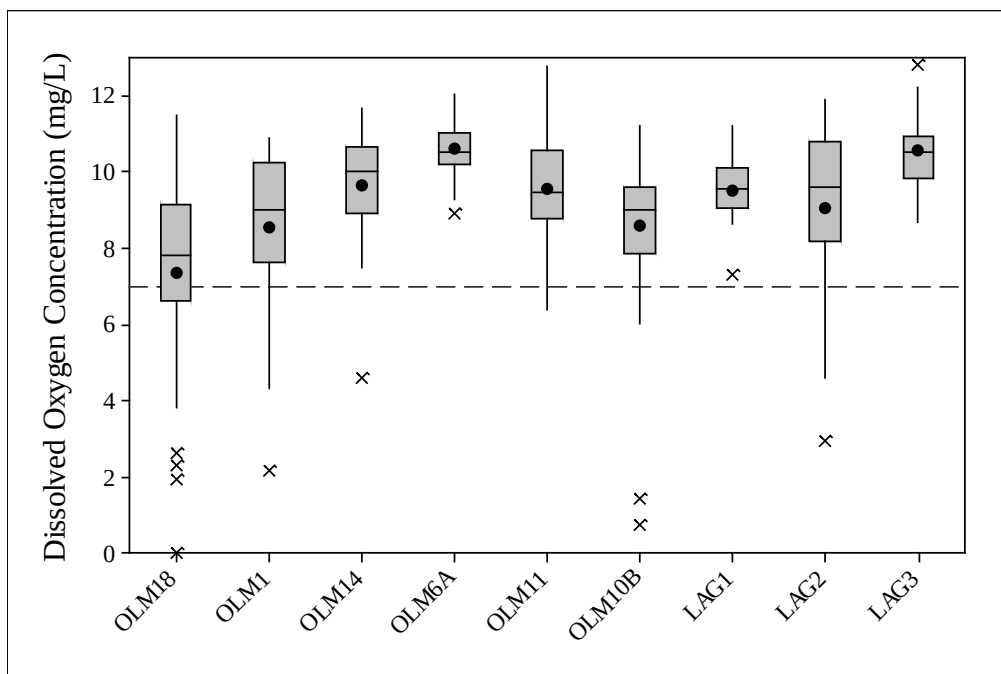


Figure 10. Dissolved oxygen results from the Lagunitas Creek watershed (water years 2009-2010). The dashed line represents the minimum water quality objective of 7 mg/L (CA RWQCB 2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

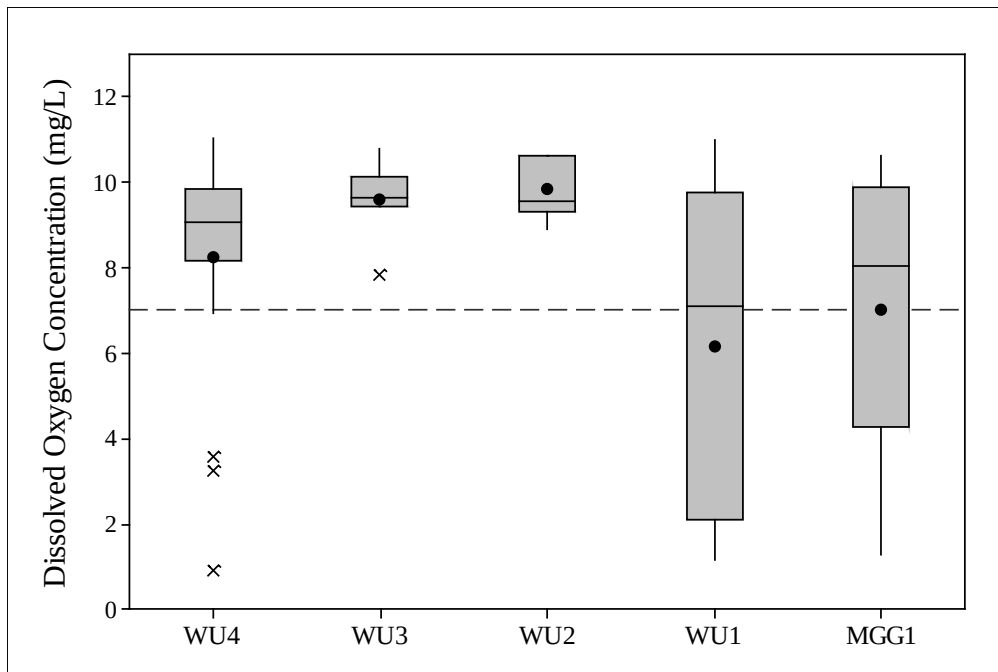


Figure 11. Dissolved oxygen results from the San Francisquito Creek watershed (water years 2009-2010). The dashed line represents the minimum water quality objective of 7 mg/L (CA RWQCB 2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

The majority of dissolved oxygen objective-failures at all SFAN sites were associated with 'low' or 'no-flow' conditions during late summer or early fall. As temperatures rose and flow volumes decreased, the dissolved oxygen levels in most SFAN streams diminished, until revived by the first winter storms.

pH

The water quality objective for pH results (applicable to all SFAN water quality sites) is an optimal range of 6.5 to 8.5 pH units, based on the conditions necessary to support aquatic life (CA RWQCB 2010). Only one result (out of 186) from the Redwood Creek watershed failed to meet this objective (a value of 6.47 pH units at site GGD) (Figure 12). The two upper Redwood watershed sites seemed to exhibit slightly wider ranges in pH during WYs 2009-2010, and they produced two of the highest means in the SFAN. The majority of all objective failures, program-wide, were recorded within the Lagunitas watershed. Fifteen results (out of 314 from the Lagunitas watershed) were detected below the objective minimum of 6.5 pH units; each of these failures was found at one of the three farthest upstream Olema Creek sites (OLM18, 1, or 14) which consistently produced some of the lowest pH results in the watershed (Figure 13). On each Lagunitas sampling day, the highest pH values were consistently found at OLM6A and LAG3; both of these sites are tributaries that feed into mainstem Olema and Lagunitas Creeks, respectively. Nearly all results from the San Francisquito Creek watershed were within the objective range, and just one result (out of 74) was above the objective maximum, with a value of 8.71 at WU4 (Figure 14).

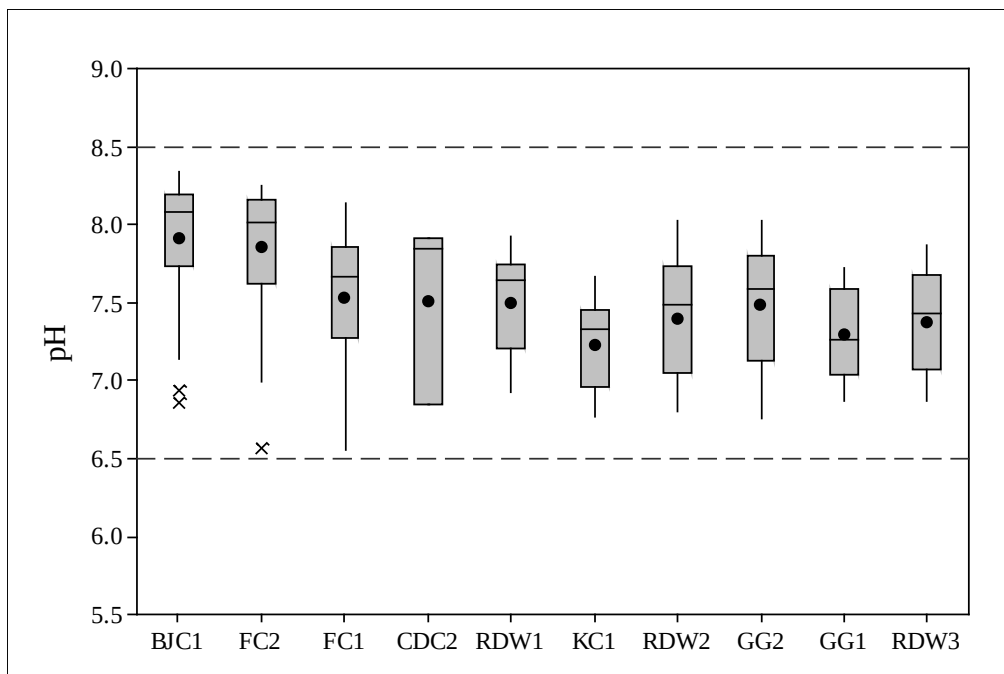


Figure 12. pH results from the Redwood Creek watershed (water years 2009-2010). The dashed lines represent the water quality objective range of 6.5 - 8.5 pH units (CA RWQCB 2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

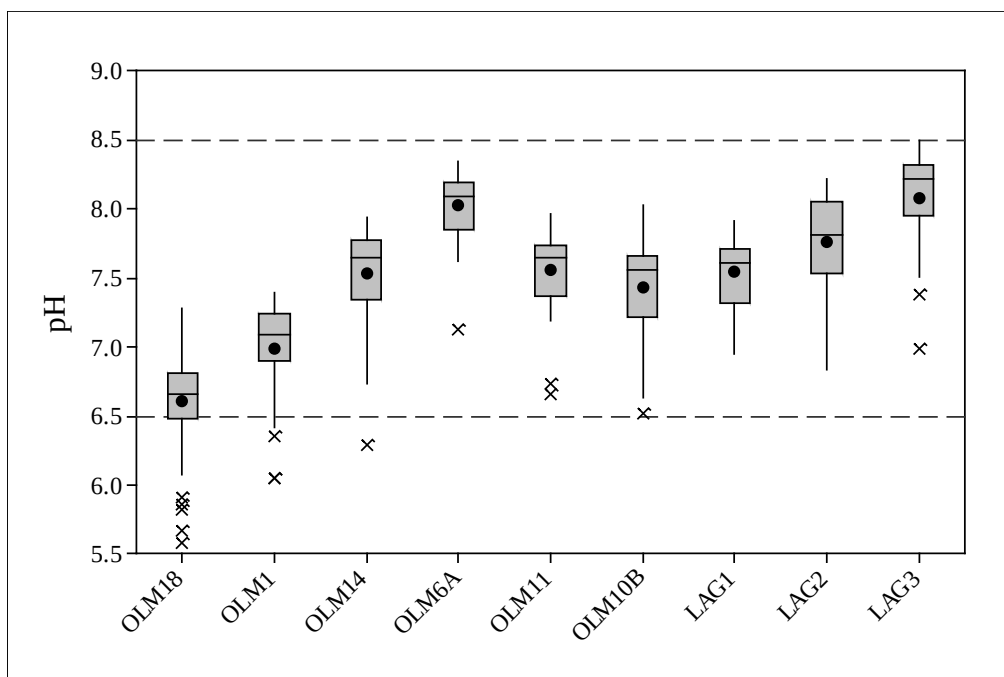


Figure 13. pH results from the Lagunitas Creek watershed (water years 2009-2010). The dashed lines represent the water quality objective range of 6.5 - 8.5 pH units (CA RWQCB 2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

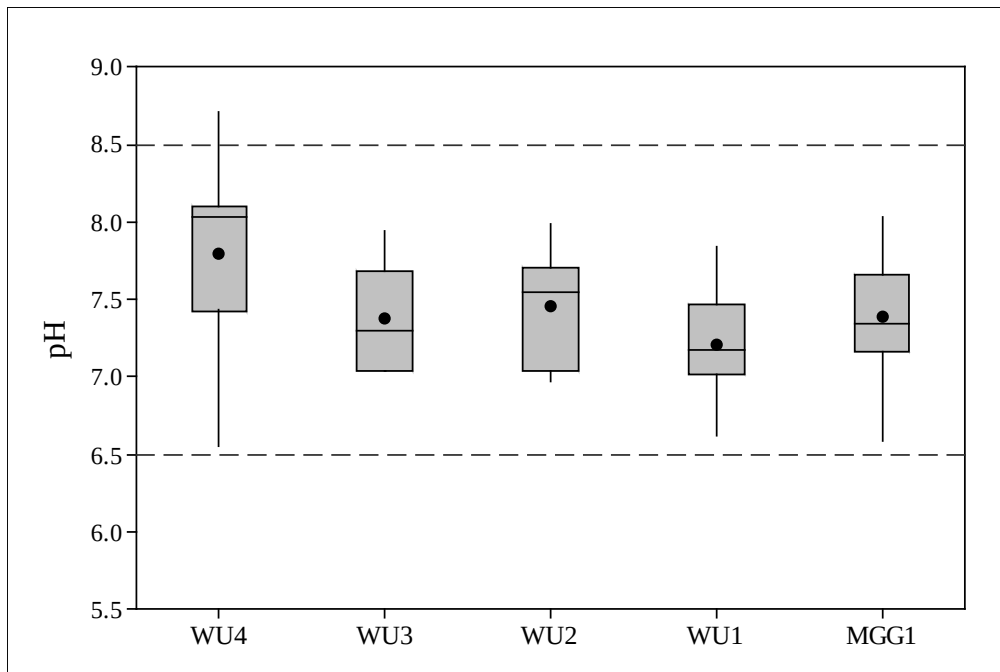


Figure 14. pH results from the San Francisquito Creek watershed (water years 2009-2010). The dashed lines represent the water quality objective range of 6.5 - 8.5 pH units (CA RWQCB 2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

During WYs 2009-2010, 97% (558:574) of all SFAN water quality samples tested for pH were within the objective range of 6.5 to 8.5 pH units. The Lagunitas Creek watershed sites exhibited the widest range of pH means, but the differences between individual sites were consistently observed and could be due to inherent differences in geology or flow regimes. The highest pH means were found at LAG3 (located in Devil's Gulch in Samuel P. Taylor State Park) and OLM6A (a tributary to Olema Creek). OLM6A is the only Lagunitas watershed site that flows from the east side of the San Andreas Fault, and the significantly different geology could explain the higher pH and specific conductance values often found at this site (Coopridge 2004). Program-wide, all WY 2009-2010 pH results were highly variable, and each watershed exhibited similar means. No seasonal patterns were determined during either water year of monthly monitoring.

Specific Conductance

Conductivity (the ability of a solution to conduct an electrical current) is an indicator of the presence of dissolved solids, and is influenced by local geology as well as urban runoff and other anthropogenic inputs. Since conductivity fluctuates with temperature, a value of 'specific conductance' is calculated in-situ using the simultaneously-measured water temperature value, in order to yield a conductivity value corrected to 25°C. The Basin Plan does not include an objective for specific conductance, however, freshwater streams are expected to have conductivity levels between 150 and 500 $\mu\text{S}/\text{cm}$ in order to support diverse aquatic life; this ecological objective is displayed with dashed lines in Figures 15, 16, and 17 (Behar 1997).

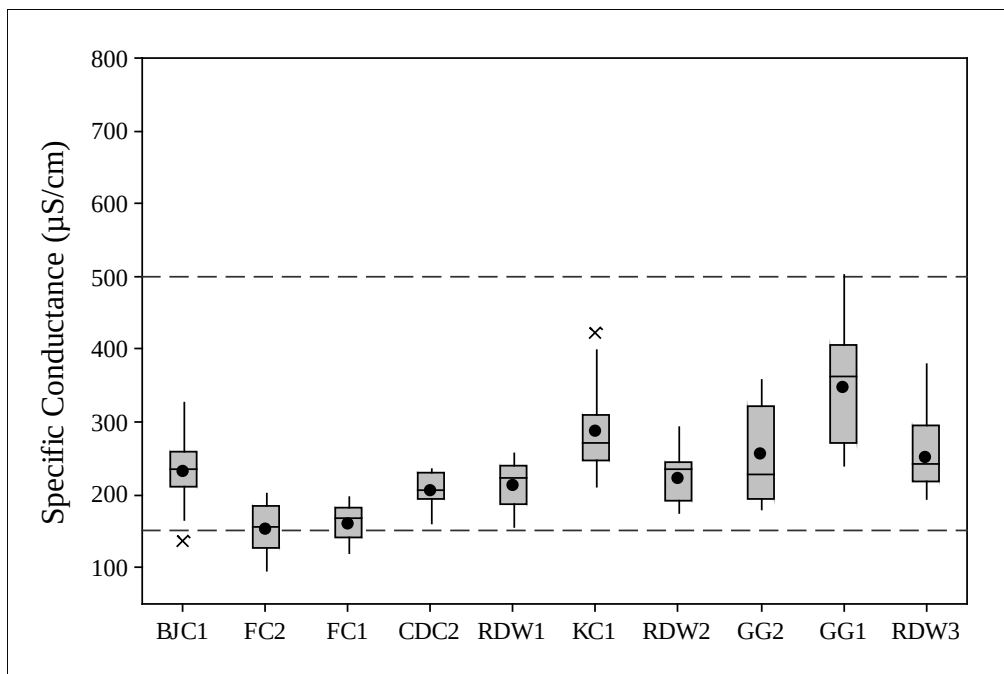


Figure 15. Specific conductance results from the Redwood Creek watershed (water years 2009-2010). The dashed lines represent the ecological objective range of 150-500 $\mu\text{S}/\text{cm}$ (Behar 1997). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

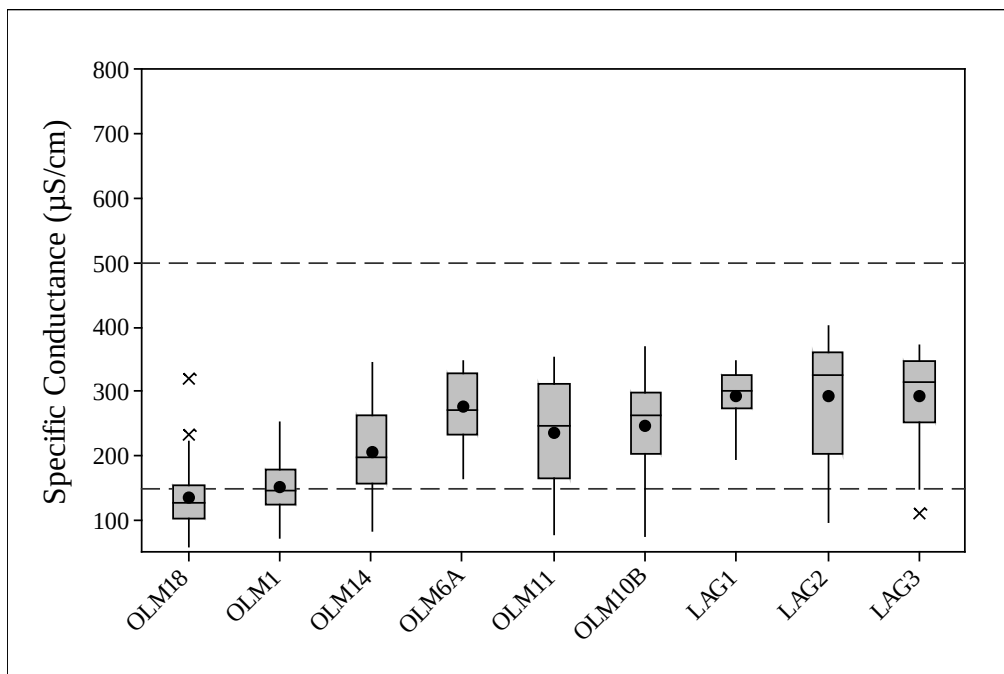


Figure 16. Specific conductance results from the Lagunitas Creek watershed (water years 2009-2010). The dashed lines represent the ecological objective range of 150-500 $\mu\text{S}/\text{cm}$ (Behar 1997). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

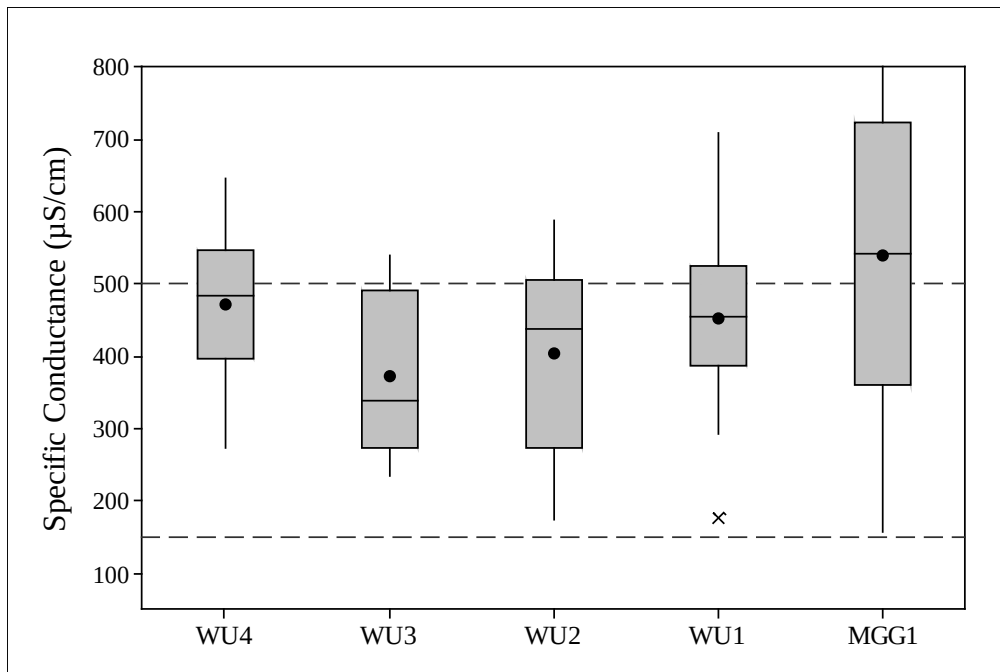


Figure 17. Specific conductance results from the San Francisquito Creek watershed (water years 2009-2010). The dashed lines represent the ecological objective range of 150-500 $\mu\text{S}/\text{cm}$ (Behar 1997). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

The Redwood and Lagunitas Creek watershed sites produced much lower (and less variable) specific conductance results, compared to the San Francisquito sites. The data from the Redwood Creek watershed sites were most consistently within this ecological objective of 150-500 $\mu\text{S}/\text{cm}$ (Figure 15). Only 11% (22:196) of the Redwood results were outside of this range, with just one result (out of 196) that exceeded the objective; this value was 503 $\mu\text{S}/\text{cm}$ (barely beyond the upper threshold). Seventy-six percent of the results from the Lagunitas Creek watershed were within this ecological objective range, 24% (76:317) fell below the range, and no results were above 500 $\mu\text{S}/\text{cm}$ (Figure 16). The farthest upstream site in Olema Creek, OLM18, produced the lowest mean specific conductance value of any SFAN water quality site (133.7 $\mu\text{S}/\text{cm}$). The San Francisquito Creek watershed sites consistently had the highest specific conductance results, producing the five highest means in the SFAN, and 39% (29:74) of results from this watershed exceeded the ecological objective maximum of 500 $\mu\text{S}/\text{cm}$ (Figure 17).

Overall, the highest specific conductance results (of each individual site) were often found during periods of low flow in the late summer and early fall. The lowest specific conductance results of each individual site were found during January, February, or March sampling events (at 24 out of 25 sites), when streamflow levels were at their highest.

Turbidity

Turbidity is the capacity of suspended sediment (including clay, silt, fine organic and inorganic matter, and microscopic organisms) in water to scatter light (American Public Health Association et al. 1998). Inputs of such solids occur because of erosion from stream banks, runoff from various source areas within a watershed, and re-suspension from the streambed during storm events. While erosion and sedimentation are natural processes, agriculture and land development can accelerate these means and result in an imbalance in the amount of sediment in a stream system (Coopridge and Carson 2006). The San Francisco Bay RWQCB has identified both Lagunitas Creek and San Francisquito Creek as ‘impaired’ by sediment. Turbidity was monitored (during WY 2010 only) at all SFAN water quality sites. Although Redwood Creek is not specifically listed as impaired by the RWQCB, it is especially important to monitor turbidity at the SFAN Redwood Creek sites as well, because this watershed provides critical habitat for salmonids.

Turbidity is often measured in nephelometric turbidity units (NTU). A level of turbidity greater than 5 NTU is considered visible turbidity, and turbidity levels above 25 NTU have been shown to cause reductions in salmonid growth (Sigler et al. 1984). There is not an established objective for turbidity levels in SFAN streams, but the ecological objective maximum of 25 NTU is kept in mind when looking at these results. Additionally, the NPS Water Resource Division uses a “screening criteria” of 50 NTU to determine water quality exceedances in its Baseline Water Quality Inventory and Analysis Reports (NPS 2003). Although these objectives are important to keep in mind, it is often not the peak levels that determine negative ecological consequences, but the persistence of high levels after storm events; longer durations of high turbidity levels are more likely to cause damage to fish and other aquatic organisms (Newcombe and MacDonald 1991). This program captures single turbidity samples during site visits, and does not conduct continuous monitoring or turbidity threshold sampling.

No turbidity samples were collected during WY 2009. A total of 231 samples were collected during WY 2010; 12% of these exceeded the ecological objective maximum of 25 NTU and nearly all of these failures were from the Lagunitas Creek watershed. The four lowest mean turbidity values of all SFAN sites were found within the Redwood Creek watershed (Figure 18). Out of 56 samples collected from the Redwood watershed sites during WY 2010, there was only one result that exceeded the ecological objective: 246 NTU at CDC2 during a rain event in December 2009 (site not included in Figure 18 due to small sample size). Conversely, the mean turbidity levels from the 11 Lagunitas Creek watershed sites were the 11 highest means program-wide, and 20% (27:133) of all results from this watershed exceeded the ecological objective maximum of 25 NTU (Figure 19). Turbidity levels mimicked the rise and fall of stream discharge levels in Olema Creek, fluctuating together during storms, so most of these exceedances were observed during storm sampling events. The San Francisquito Creek watershed sites exhibited low turbidity results year-round, even during storm sampling, and no single result exceeded 25 NTU (Figure 20).

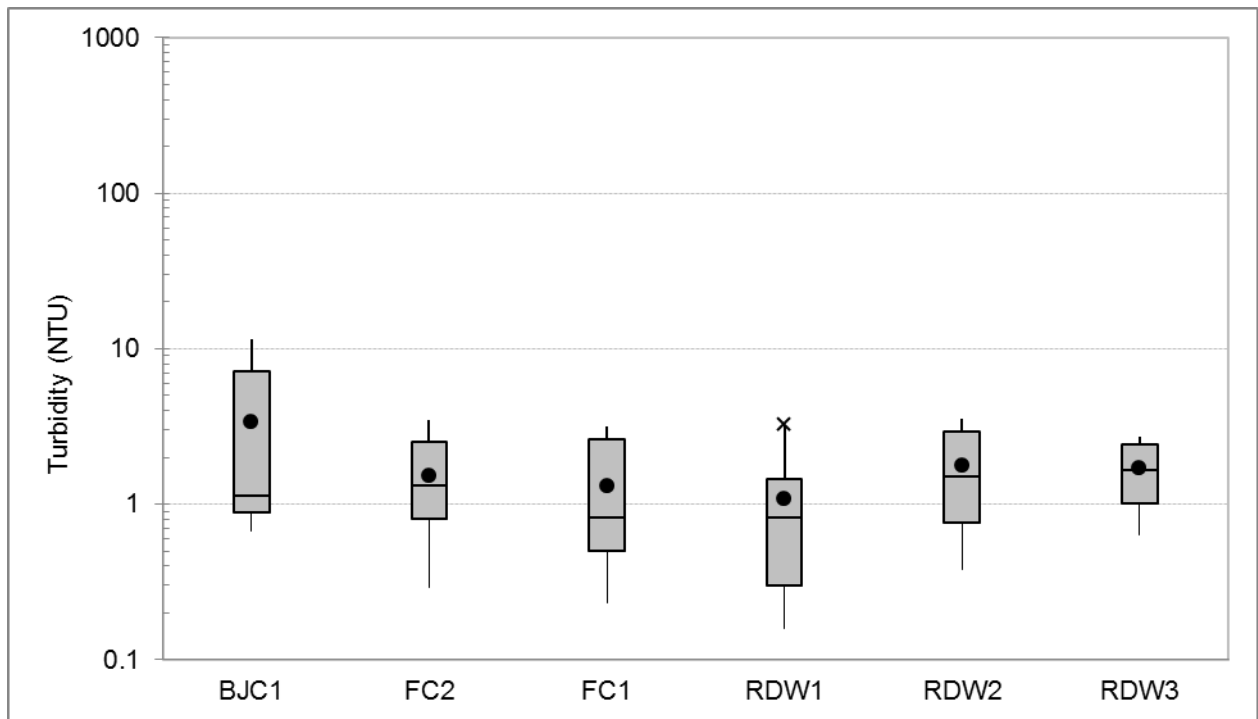


Figure 18. Turbidity results from the Redwood Creek watershed (water years 2009-2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

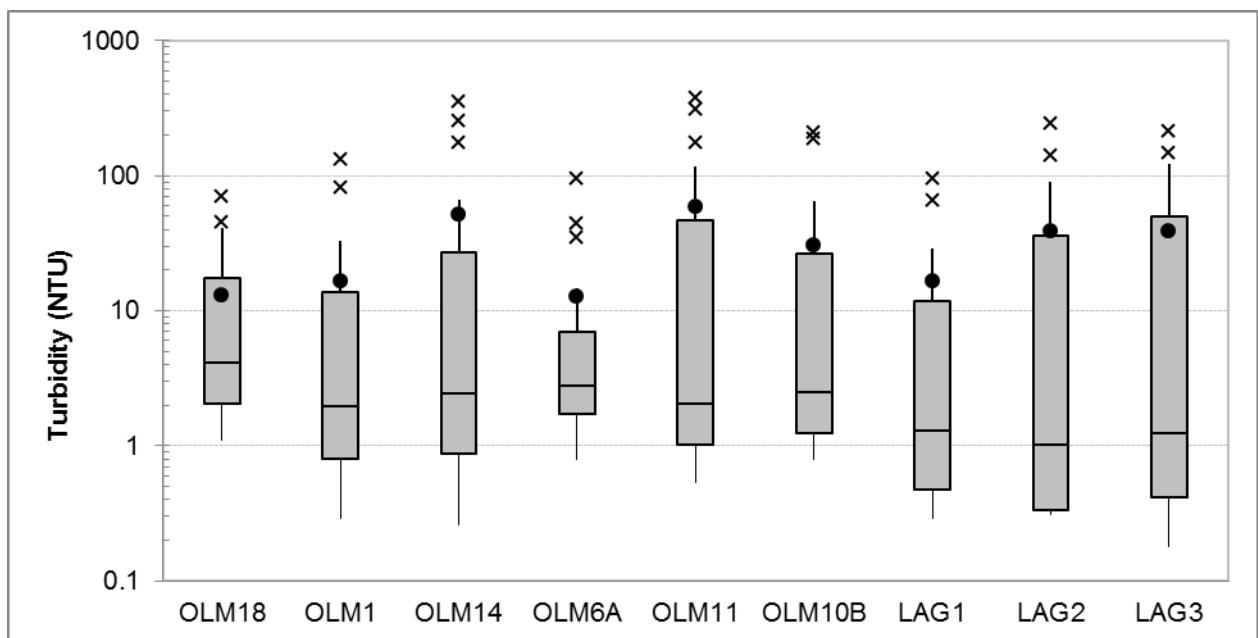


Figure 19. Turbidity results from the Lagunitas Creek watershed (water years 2009-2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

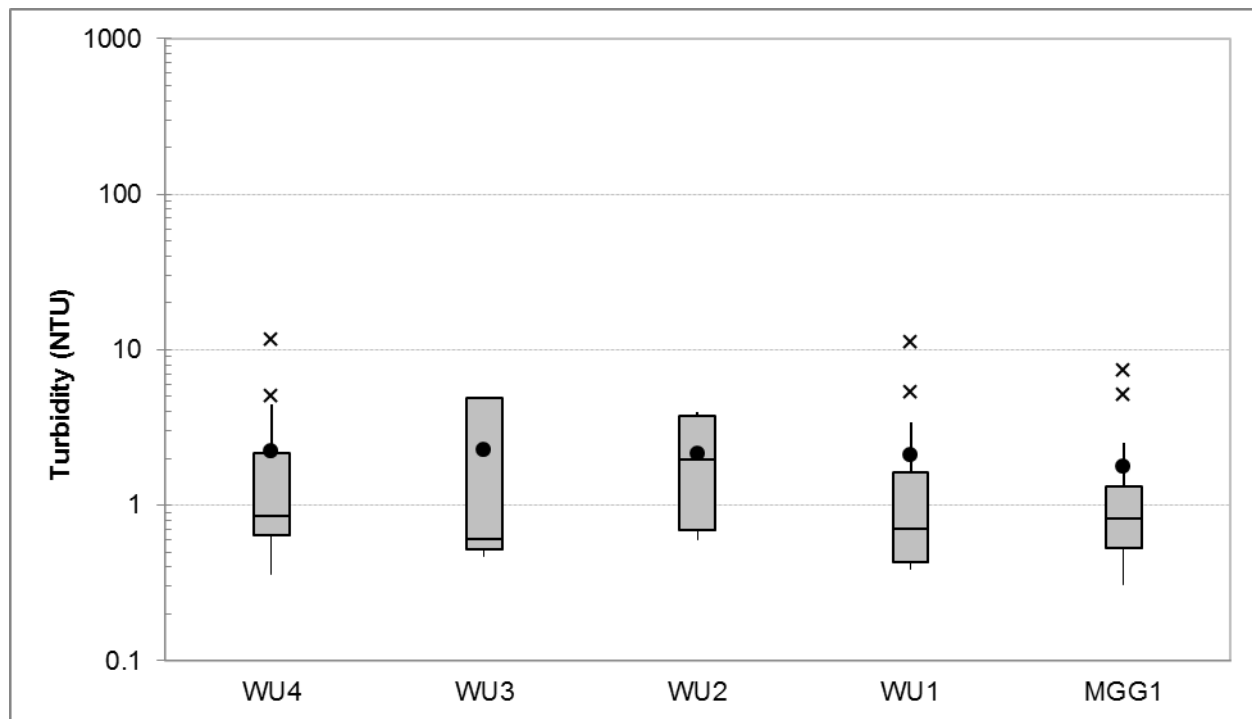


Figure 20. Turbidity results from the San Francisquito Creek watershed (water years 2009-2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

Discharge

Discharge monitoring takes place at SFAN stream gaging stations, year-round, following the standard operating procedures of the peer-reviewed SFAN Streamflow Monitoring Protocol (Fong et al. 2011). Of the 25 water quality sites monitored during WYs 2009-2010, two sites overlap with SFAN stream gaging stations: OLM11 in Olema Creek under the Bear Valley Road Bridge, and RDW2 on Redwood Creek under the Hwy 1 bridge. Pressure transducers are installed at each gage, which record water level data every 15 minutes, year-round. These data are post-processed in order to create stage-discharge rating curves for each gaging station. Figures 21 and 22 display the mean daily discharge results from the Redwood and Olema Creek gaging stations, collected continuously during WYs 2009-2010. Both Redwood and Olema Creek (and their tributaries) experience low flow conditions during the summer months, and are highly responsive to winter storm events. The individual discharge measurement results (collected during WYs 2009-2010) ranged from 0.13 – 196.95 cfs at the Redwood Creek gage, and 0.28 – 555.52 cfs at the Olema Creek gage. These maximums only represent the highest values recorded during on-site discharge measurements, and are not the highest values collected by the gages; they are not shown in the figures below because they are not daily means, and they were not recorded during water quality monitoring site visits. In addition to the 15-minute water level data, individual stream discharge measurements are collected at each gaging station on a monthly basis, as well as during high flow monitoring in the winter. During WYs 2009-2010, a total of 31 discharge measurements were collected at the Redwood gage, including 18 that occurred during water quality visits. A total of 34 discharge measurements were collected at the Olema gage, including 27 that occurred during water quality visits. The individual discharge measurements that took place during water quality visits are plotted in Figures 23 and 24. Figure 23 displays the 18 discharge measurements collected at the Redwood gage during water quality sampling events, plotted along with their corresponding dissolved oxygen results. Figure 24 displays the 27 discharge measurements collected at the Olema gage during water quality sampling events, plotted along with their corresponding turbidity (WY 2010 only) and dissolved oxygen results.

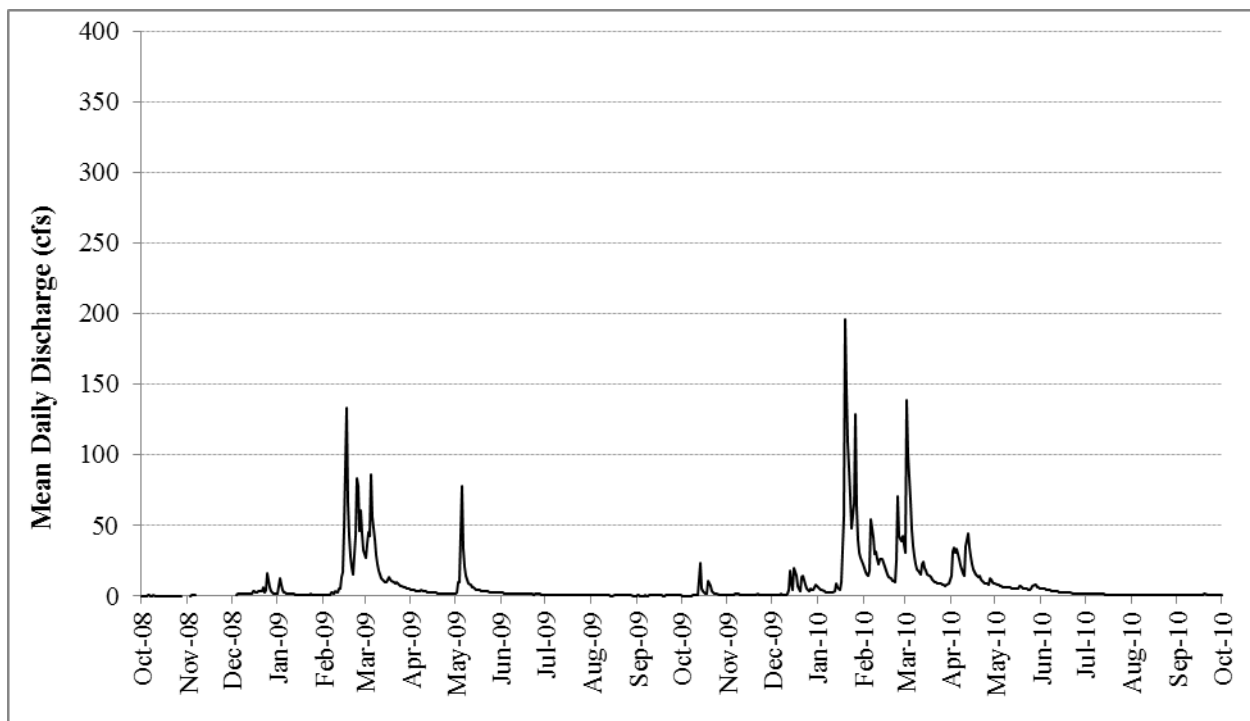


Figure 21. Mean daily discharge results from the Redwood Creek gaging station (water years 2009-2010).

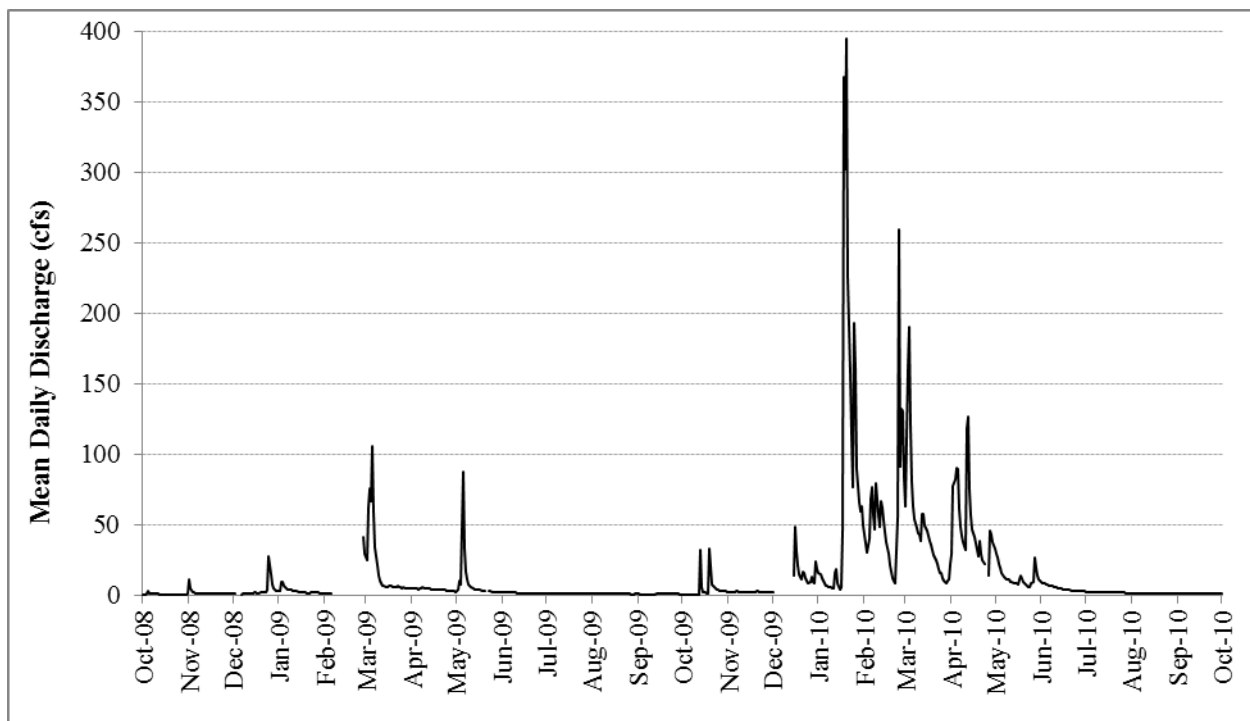


Figure 22. Mean daily discharge results from the Olema Creek gaging station (water years 2009-2010).

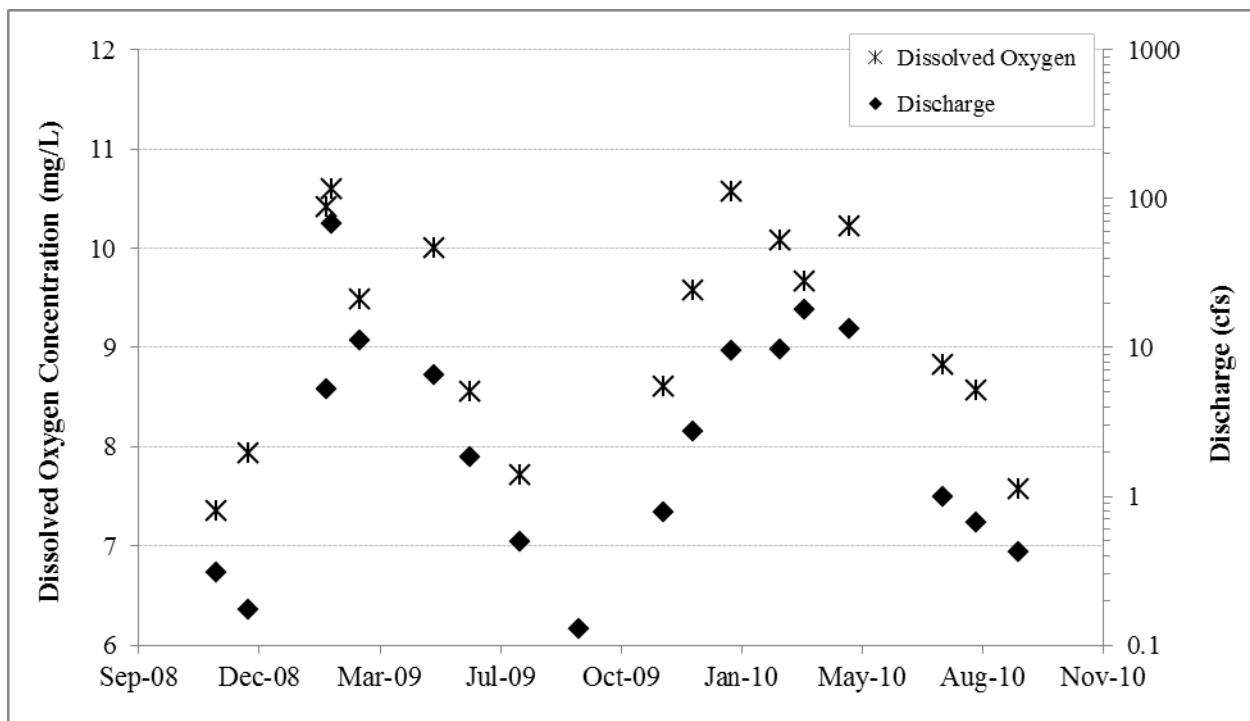


Figure 23. Discharge and dissolved oxygen results from site RDW2 in the Redwood Creek watershed (water years 2009-2010).

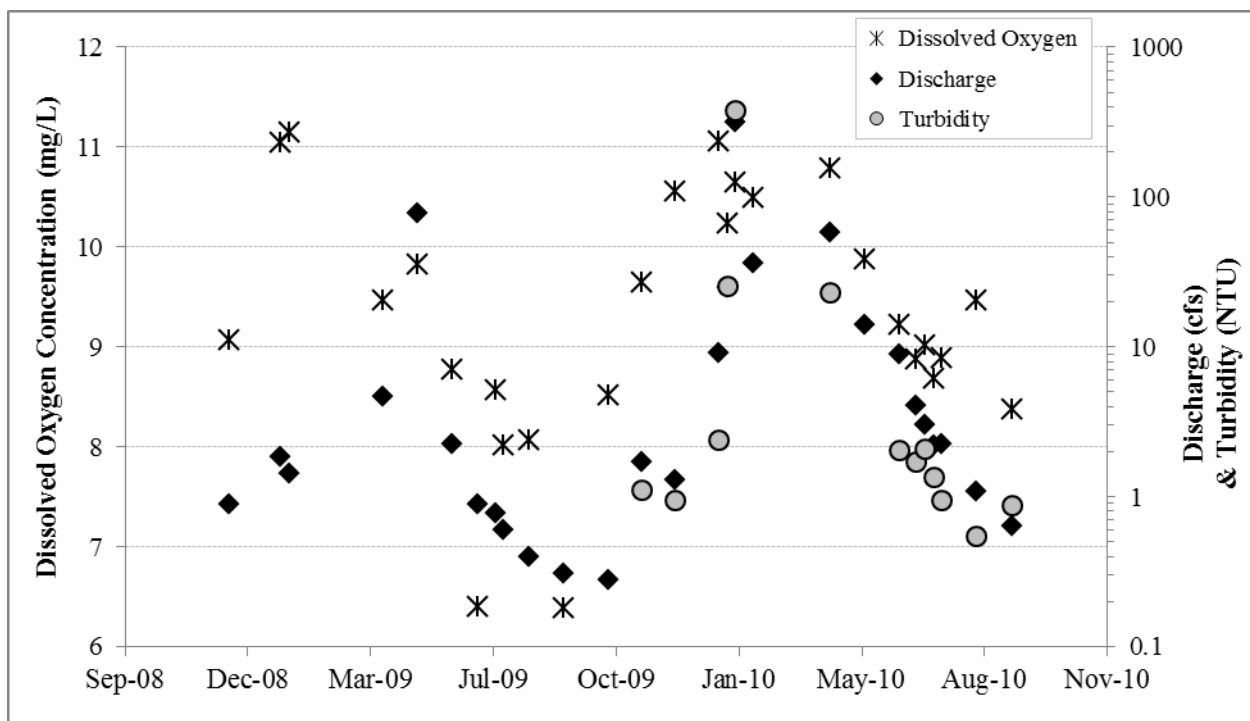


Figure 24. Discharge, dissolved oxygen, and turbidity results from site OLM11 in the Lagunitas Creek watershed (water years 2009-2010). Turbidity was not monitored during WY 2009.

Nutrient Parameters

All nutrient samples were collected in sterile, laboratory-issued bottles during each site visit, and stored immediately on ice until transferred to a professional laboratory for processing. During WYs 2009-2010, nitrate (as N) and TKN were the only nutrient parameters sampled on a monthly basis (and during storms) at all primary SFAN water quality sites. Ammonia (as N) was monitored quarterly, instead of monthly, and additional ammonia samples were collected during storm sampling of the Lagunitas and Redwood Creek watersheds during February 2009. Out of the 25 SFAN sites monitored during WYs 2009-2010, five of these were established as secondary sites in the SFAN Protocol which excludes collection of nutrient samples. Nutrient sampling did not take place at WU2, WU3, and WU4 (in the San Francisquito Creek watershed) or FC2 and GG2 (in the Redwood Creek watershed).

Summary statistics of all nutrient data collected during WYs 2009-2010 are displayed in detail in Tables 14, 15, and 16; however, box and whiskers plots of these data are displayed separately (sorted by parameter) for simplified viewing. Sites with fewer than four results are included in the summary tables, but are excluded from the figures since their datasets are too small for analysis (U.S. EPA 1998). Due to relatively low nutrient levels in the SFAN streams, many results were reported as non-detect, which means that the analyte was not detected at or above the laboratory's reporting detection limit (RDL). These results were considered censored and required the use of the robust ROS method developed by Helsel and Cohn (1988) in order to create summary statistics and figures for all SFAN nutrient results (see Data Handling and Analysis in the Methods section for a description). All summary statistics are based on instantaneous measurements routinely collected at approximately the same time of day on each visit; therefore, the data in the tables and figures presented do not reflect the true minimum and maximum values of diurnal variation.

Table 14. Nutrient results from the Redwood Creek watershed (water years 2009-2010). (Std. dev. = standard deviation. N of obs. = number of observations.) All means and standard deviations are rounded to one more decimal place than the least precise value (least number of decimal places) of each corresponding dataset.

Parameter	Statistic	BJC1	FC1	CDC2	RDW1	KC1	RDW2	GGD	GG1	RDW3
Nitrate as nitrogen (mg/L)	Mean	0.163	-	0.80	-	-	-	-	0.225	-
	Median	0.16	-	0.71	-	-	-	-	0.16	-
	Minimum	< 0.15	< 0.15	0.26	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15
	Maximum	0.26	< 0.15	1.8	0.19	0.33	0.28	0.23	0.74	0.31
	Std. dev.	0.047	-	0.58	-	-	-	-	0.188	-
	# NDs/ # Results ¹	14/25	24/24	0/8	22/25	11/12	24/25	1/2	6/15	23/25
Total Kjeldahl nitrogen (mg/L)	Mean	0.256	0.184	0.66	0.183	0.333	0.21	-	0.49	0.282
	Median	0.19	0.14	0.64	0.11	0.26	0.11	-	0.42	0.26
	Minimum	< 0.25	< 0.25	< 0.25	< 0.25	< 0.25	< 0.25	0.36	0.27	< 0.25
	Maximum	0.81	0.63	1.4	0.74	0.96	1.0	0.62	1.1	0.95
	Std. dev.	0.196	0.136	0.44	0.191	0.268	0.26	-	0.24	0.207
	# NDs/ # Results ¹	14/25	19/25	1/8	18/25	4/12	18/25	0/2	0/15	11/25

¹The number of results that were reported as 'ND' (not detected at or above the reporting detection limit) are shown above, as a ratio over the total number of results from that site.

Table 15. Nutrient results from the Lagunitas Creek watershed (water years 2009-2010). (Std. dev. = standard deviation. N of obs. = number of observations.) All means and standard deviations are rounded to one more decimal place than the least precise value (least number of decimal places) of each corresponding dataset.

Parameter	Statistic	OLM18	OLM1	OLM14	OLM6A	OLM11	OLM10B	LAG1	LAG2	LAG3
Nitrate as nitrogen (mg/L)	Mean	-	0.23	0.25	0.289	0.210	0.173	0.50	0.077	0.189
	Median	-	0.11	0.18	0.23	0.15	0.13	0.44	0.05	0.17
	Minimum	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15
	Maximum	0.38	1.2	1.9	0.96	0.57	0.66	1.2	0.36	0.38
	Std. dev.	-	0.31	0.36	0.227	0.154	0.138	0.20	0.079	0.084
	# NDs/ # Results ¹	23/26	14/26	10/26	7/26	12/26	15/26	1/26	21/26	8/26
Total Kjeldahl nitrogen (mg/L)	Mean	0.55	0.37	0.43	0.42	0.53	0.52	0.41	0.45	0.35
	Median	0.35	0.28	0.30	0.33	0.36	0.42	0.30	0.33	0.26
	Minimum	< 0.25	< 0.25	< 0.25	< 0.25	< 0.25	0.26	< 0.25	< 0.25	< 0.25
	Maximum	2.6	1.2	1.6	1.3	1.8	1.4	1.7	1.4	1.4
	Std. dev.	0.50	0.28	0.39	0.33	0.47	0.32	0.36	0.33	0.30
	# NDs/ # Results ¹	1/26	11/26	6/26	6/26	4/26	0/26	5/26	3/26	9/26

¹The number of results that were reported as 'ND' (not detected at or above the reporting detection limit) are shown above, as a ratio over the total number of results from that site.

Table 16. Nutrient results from the San Francisquito Creek watershed (water years 2009-2010). (Std. dev. = standard deviation. N of obs. = number of observations.) All means and standard deviations are rounded to one more decimal place than the least precise value (least number of decimal places) of each corresponding dataset.

Parameter	Statistic	WU1	MGG1
Nitrate as nitrogen (mg/L)	Mean	-	-
	Median	-	-
	Minimum	< 0.15	< 0.15
	Maximum	< 0.15	< 0.15
	Std. dev.	-	-
	# NDs/ # Results ¹	21/21	21/21
Total Kjeldahl nitrogen (mg/L)	Mean	0.284	0.269
	Median	0.28	0.25
	Minimum	< 0.25	< 0.25
	Maximum	0.45	0.52
	Std. dev.	0.084	0.106
	# NDs/ # Results ¹	8/21	10/21

¹The number of results that were reported as 'ND' (not detected at or above the reporting detection limit) are shown above, as a ratio over the total number of results from that site.

Nitrate (as Nitrogen)

Neither the state of California nor the San Francisco Bay RWQCB has set objectives for nitrates, however, there is a national drinking water objective of 10 mg/L nitrate (as N) established by the EPA, as well as a regional reference value of 0.16 mg/L (NO₃-N + NO₂-N) (U.S. EPA 2000). Additionally, a study by R. Crunkilton (2000) found that a level of 1.1 mg/L nitrate (as N) can be toxic to aquatic life, especially fish and amphibian eggs. For this report, SFAN nitrate results are compared to the ecological threshold of 1.1 mg/L nitrate (as N), which is shown as a dashed line in the following figures (Crunkilton 2000). The RDL for all nitrate (as N) samples processed during WYs 2009-2010, was 0.15 mg/L (using EPA Method 300).

During WYs 2009-2010, 437 nitrate (as N) samples were collected from the 20 SFAN primary sites; the majority of these (64%) had undetectable levels of nitrate (below the laboratory's RDL of 0.15 mg/L NO₃-N). Most of the detections (77%) were from the Lagunitas Creek watershed. Out of 161 samples from the Redwood Creek watershed, 22% contained detectable levels of nitrate. Of these detections, the three highest results (and the only two results that exceeded the ecological objective) were all from the same site, CDC2, a tributary of Redwood Creek just downstream of MUWO (Figure 25). CDC2 produced the highest mean nitrate (as N) level of any SFAN water quality site. Five Redwood watershed sites were excluded from Figure 25 because the majority of their results were non-detect; these include the three mainstem Redwood sites (RDW1, RDW2, and RDW3), the Kent Creek site (KC1), and the lower Fern Creek site (FC1) in MUWO which had 100% non-detect results. Within the Redwood Creek watershed, the highest nitrate levels (of each individual site) were usually recorded during storm sampling events.

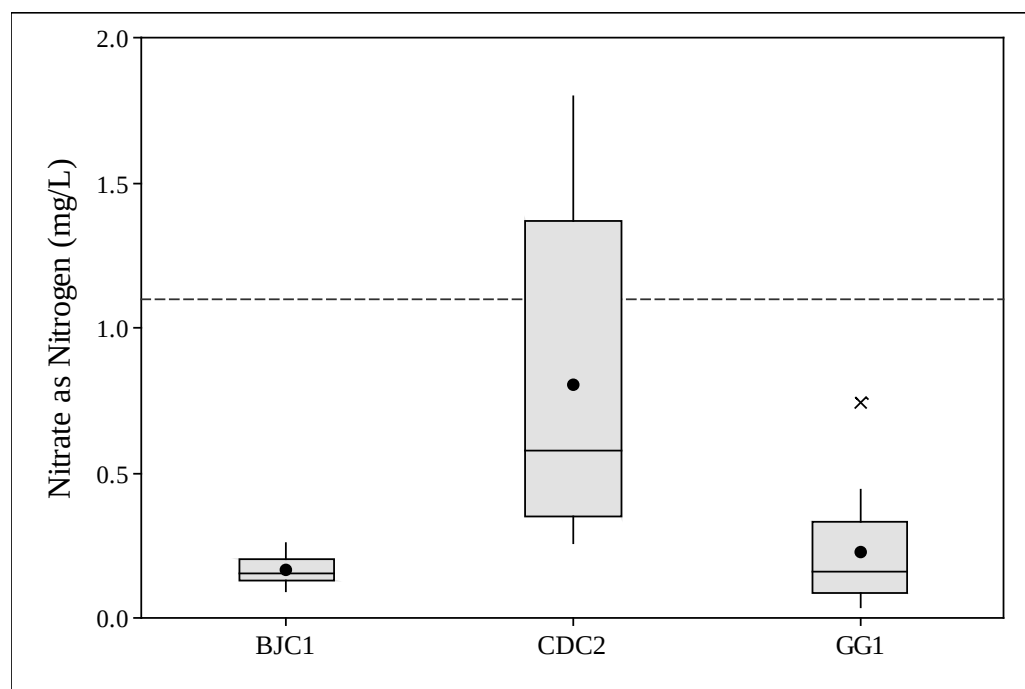


Figure 25. Nitrate (as N) results from the Redwood Creek watershed (water years 2009-2010). The ecological threshold of 1.1 mg/L is displayed as a dashed line for reference. Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

A total of 234 nitrate (as N) samples were collected from the Lagunitas Creek watershed. Although 53% of these (123:234) contained detectable nitrate levels, only four individual results exceeded the ecological objective of 1.1 mg/L nitrate (as N) (Figure 26). The Bear Valley Creek site (LAG1) revealed the highest mean in the watershed (0.50 mg/L) as well as the highest number of detections during WYs 2009-2010 (25:26). Conversely, the Cheda Creek site (LAG2) had the lowest mean in the watershed and only 19% detections, and the farthest upstream Olema Creek site (OLM18) had the lowest number of detections in the watershed (3:26 results). In the San Francisquito Creek watershed, a total of 42 samples were collected during WYs 2009-2010 (from the only two primary sites: WU1 and MGG1) and every result was reported as non-detect.

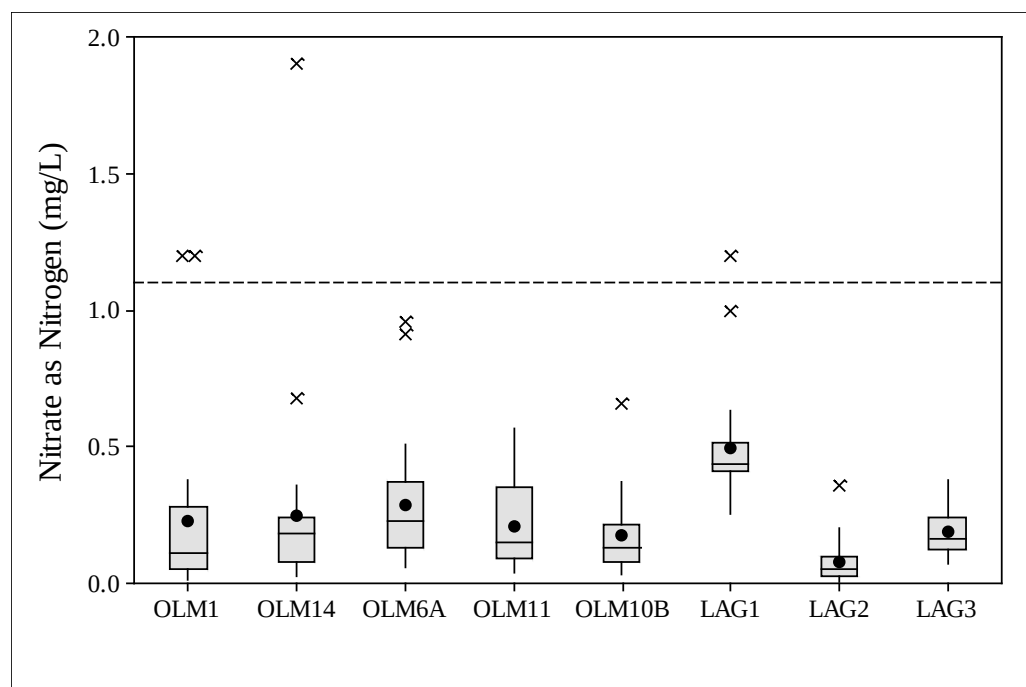


Figure 26. Nitrate (as N) results from the Lagunitas Creek watershed (water years 2009-2010). The ecological threshold of 1.1 mg/L is displayed as a dashed line for reference. Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

Total Kjeldahl Nitrogen (TKN)

Combined ammonia-nitrogen and organic nitrogen are referred to as TKN. Different forms of nitrogen can exist in streams as a result of both natural and anthropogenic sources. Monitoring TKN, in addition to nitrate and ammonia, can create a clearer understanding of what forms of nitrogen (organic or inorganic) are available at different times of the year. The San Francisco Bay RWQCB's Basin Plan does not currently have an established criterion for TKN; however, the EPA encouraged the establishment of regulatory objectives for nutrients by conducting a large scale survey to provide states with regional reference values. The regional reference value for SFAN streams is 0.36 mg/L TKN (U.S. EPA 2000).

During WYs 2009-2010, the laboratory's RDL for all TKN tests (Standard Method 4500-Norg C) was 0.25 mg/L, and 66% of all SFAN samples (290:438) were reported to be above this level. The Redwood Creek watershed sites had the lowest detection rate; 48% of samples (77:162) had detectable levels of TKN, and half of these detections exceeded the regional reference value of 0.36 mg/L TKN. The highest mean TKN value of any SFAN site was found at the Camino del Canyon site, CDC2 (which also had the highest nitrate (as N) mean). The two lowest program-wide TKN means were also observed in the Redwood watershed, at sites FC1 and RDW1 (Figure 27). These two sites (FC1 and RDW1), along with RDW2, had the lowest percentages of detectable TKN results out of all the SFAN primary sites.

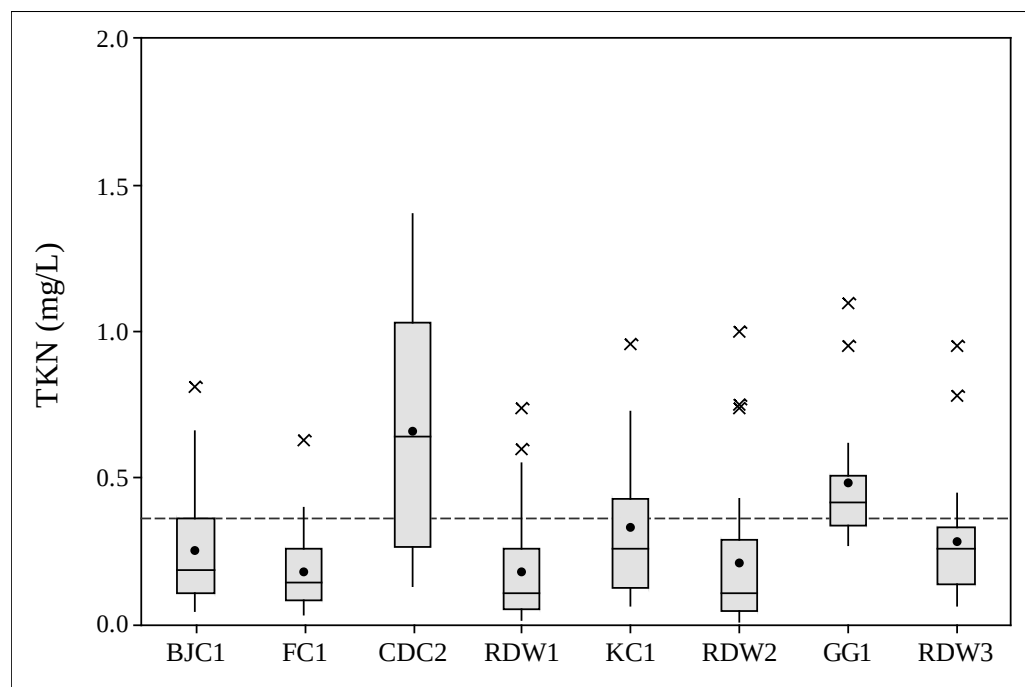


Figure 27. Total Kjeldahl nitrogen (TKN) results from the Redwood Creek watershed (water years 2009-2010). The regional reference value of 0.36 mg/L is displayed as a dashed line. Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

The Lagunitas Creek watershed had the highest rate of TKN detections; 81% (189:234) of samples had detectable levels of TKN (above the 0.25 mg/L RDL) and over half of these were above the regional reference value of 0.36 mg/L. Two mainstem Olema Creek sites, OLM18 and OLM11, had the highest means within the watershed, although all Olema Creek sites had fairly similar means (Figure 28). The farthest upstream Olema Creek site, OLM18, also produced the highest single TKN result (program-wide) during WYs 2009-2010; this outlier (2.6 mg/L recorded on 10/7/2008) is excluded from Figure 28. Fifty-seven percent of samples from the San Francisquito Creek watershed contained detectable levels of TKN, and 38% of these were above the regional reference value of 0.36 mg/L (Figure 29).

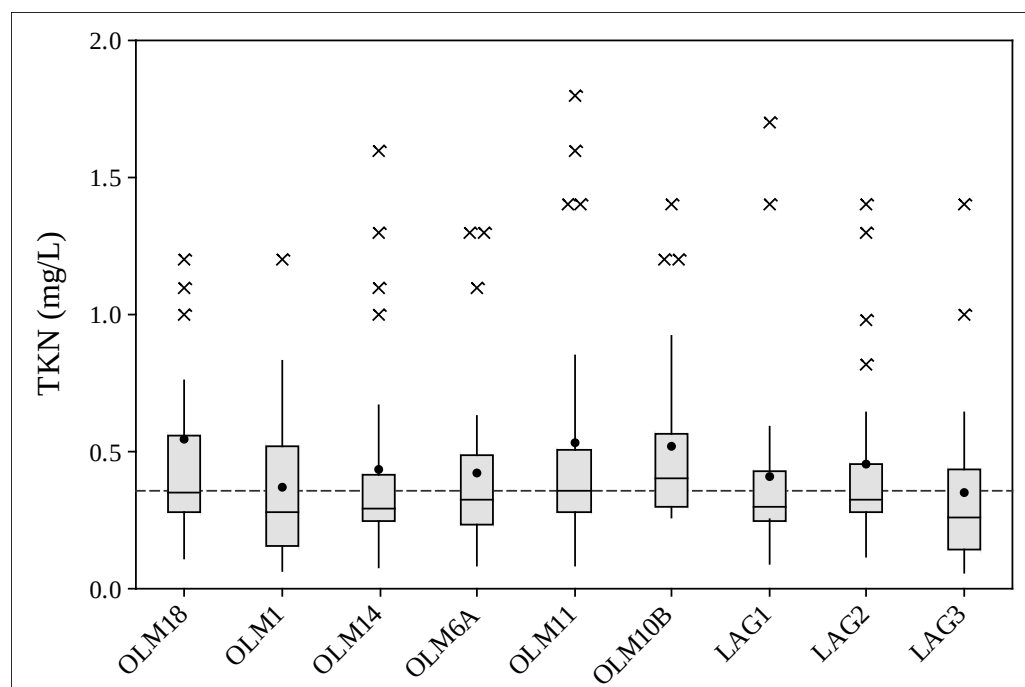


Figure 28. Total Kjeldahl nitrogen (TKN) results from the Lagunitas Creek watershed (water years 2009-2010). The regional reference value of 0.36 mg/L is displayed as a dashed line. Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.' (This figure excludes one outlier: a result of 2.6 mg/L at site OLM18)

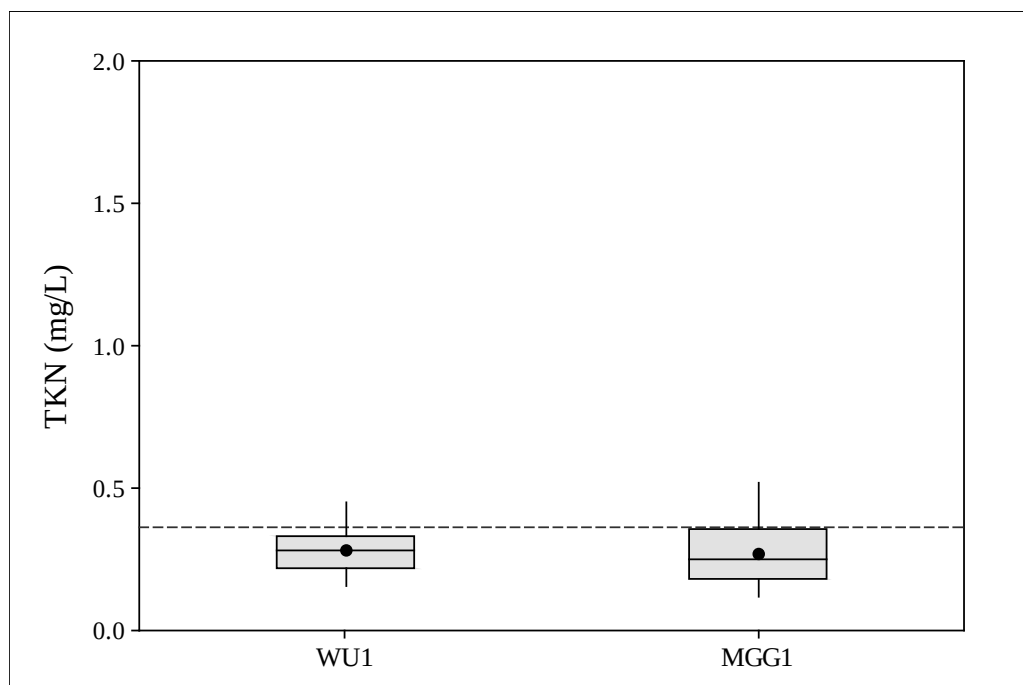


Figure 29. Total Kjeldahl nitrogen (TKN) results from the San Francisquito Creek watershed (water years 2009-2010). The regional reference value of 0.36 mg/L is displayed as a dashed line. Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

Ammonia (as Nitrogen)

The San Francisco Bay RWQCB's Basin Plan established a water quality objective of 0.025 mg/L un-ionized ammonia (as an annual median maximum), a level which can be highly toxic to aquatic life (CA RWQCB 2010). The professional laboratory contracted by the SFAN processes the ammonia samples using Standard Method 4500-NH₃ and reports all results as 'ammonia (as N)' with a RDL of 0.10 mg/L. In order to compare these lab results to the established water quality objective, un-ionized ammonia must be calculated utilizing conversion factors for the water temperature, pH, and electrical conductance values that were recorded at the time of sample collection.

During WYs 2009-2010, ammonia samples were collected at all SFAN primary sites on each quarterly visit, and additional samples were collected once from the Redwood and Lagunitas watersheds during storm sampling each water year. The total number of ammonia samples collected during WYs 2009-2010 (quarterly and storm) was 154, and only one of these had detectable levels of ammonia (as N) above the RDL of 0.10 mg/L. This result was collected during the dry season (in July 2010) at the farthest upstream tributary of Lagunitas Creek that is monitored by the SFAN (LAG3 at Devil's Gulch); the reported result was 0.12 mg/L, only 0.02 mg/L above the RDL. The core parameters recorded simultaneously with this sample collection were as follows: 13.6°C water temperature, 8.23 pH units, and 261.5 µS/cm conductivity. The corresponding conversion factors applied to the raw reported result of 0.12 mg/L ammonia (as N) produced a result of 0.0045 mg/L un-ionized ammonia (as N); this single result is well below the water quality objective of 0.025 mg/L.

Pathogenic Indicator Bacteria

Total coliform, *E. coli*, and fecal coliform bacteria are indicators of pathogens that can be detrimental to human health. Each of these three parameters is monitored year-round as part of the SFAN Freshwater Quality Monitoring Program. The results are reported with the units ‘MPN/100mL’ which stands for ‘most probable number of colony-forming units per 100 mL of sample volume.’ These results do not quantify the amount of bacteria in a body of water, but are used to estimate concentrations of bacteria that may indicate the presence of pathogens. Currently the EPA uses *E. coli* as an indicator of risk to human health, and it is the recommended parameter for fresh water. Total coliform bacteria results are automatically reported along with *E. coli*, and although these results may be used to view long-term trends in the future, total coliform is not commonly used as a pathogenic indicator for human health concerns. Since human contact with surface water is uncommon at the SFAN monitoring sites, the established objectives may seem irrelevant; however, the water from these sites may influence a variety of recreational sites downstream. The objectives also help to provide some context when examining the magnitude and frequency of recorded exceedances.

All bacteria samples were collected in sterile, factory-sealed bottles and stored immediately on ice. Fecal coliform samples were transported to a professional laboratory for processing, while total coliform and *E. coli* (TC/EC) samples were processed at the in-house laboratory at PORE. In this laboratory, TC/EC results are produced together from a single test. Due to the cost savings of processing these samples in-house, TC/EC samples were able to be collected at nearly every SFAN site visit (at both primary and secondary sites) during WYs 2009-2010. Fecal coliform samples were only collected at the six Olema Creek sites (within the Lagunitas watershed); this sampling is organized by the San Francisco Bay RWQCB, mandated by the Tomales Bay Pathogen TMDL Program. Fecal coliform samples were required to be processed by RWQCB’s contracted laboratory, to ensure consistency and data comparability between all samples reported to the TMDL program, regardless of the partner organization collecting the samples.

Unlike the nutrient data that are often censored at the lower end (from non-detect results), the TC/EC data can be censored on either end due to the laboratory method used; this makes data analysis more challenging, and requires the use of the Kaplan-Meier statistical method (through the NPStoret database) to create summary statistics and figures (see Data Handling and Analysis section under Methods). In addition to the complication of censoring on both ends, the TC/EC data also have varying lower and upper quantification limits that differ between sites and seasons. Samples processed at the standard 10x dilution factor have a quantification range of 10 – 24,190 MPN/100 mL. During WYs 2009-2010, samples were also processed at 1x and 100x dilution factors, which resulted in quantification ranges of 1 – 2,419 MPN/100mL and 100 – 241,900 MPN/100 mL, respectively.

Summary statistics of all bacteria data collected during WYs 2009-2010 are displayed in detail in Tables 17, 18, and 19; however, box and whiskers plots of these data are displayed separately (sorted by parameter) for simplified viewing. Just one site out of the 25 SFAN sites monitored (GGD in the Redwood watershed) had fewer than four results; these data are included in the summary tables, but are excluded from the figures since the dataset is too small for analysis (U.S. EPA 1998). All summary statistics are based on instantaneous measurements routinely collected at approximately the same time of day on each visit; therefore, the data in the tables and figures presented do not reflect the true minimum and maximum values of diurnal variation.

Table 17. Pathogenic indicator bacteria results from the Redwood Creek watershed (water years 2009-2010). All means and standard deviations are rounded to one more decimal place than the least precise value (least number of decimal places) of each corresponding dataset.

Parameter	Statistic	BJC1	FC2	FC1	CDC2	RDW1	KC1	RDW2	GGD	GG2	GG1	RDW3
Total coliform (MPN/100 mL)	Mean	597.0	280.0	160.0	4872.0	723.0	1068.0	983.6	-	1398.0	1733.0	2403.0
	Median	340	220	120	2100	450	530	770	-	920	910	890
	Minimum	41	10	20	730	85	140	160	1000	270	200	98
	Maximum	>2419	920	500	24000	3400	4600	>2419	1300	4600	9200	14000
	Std. dev.	663.1	221.4	122.9	7973.0	740.2	1355.0	707.5	-	1289.0	2366.0	5213.0
	# censored/ # results ¹	1/25	0/24	0/25	0/8	0/25	0/12	1/25	0/2	0/9	0/15	3/24
E. coli (MPN/100 mL)	Mean	31.0	24.0	27.0	633.0	64.0	122.0	82.0	-	45.0	306.0	565.0
	Median	4	7	4	210	31	85	52	-	20	43	98
	Minimum	<1	<1	<1	29	<10	<10	<10	<10	4	10	<10
	Maximum	200	290	310	3100	310	310	520	200	260	1200	11000
	Std. dev.	62.4	61.0	65.8	1067.0	74.0	120.7	105.0	-	82.1	446.8	2225.0
	# censored/ # results ²	11/25	7/24	12/25	0/8	1/25	1/12	4/25	1/2	1/9	0/15	3/24

¹ These censored results are '> QL' (above the quantification limit) & are shown as a ratio over the total number of results.

² These censored results are '< QL' (below the quantification limit) & are shown as a ratio over the total number of results.

Table 18. Pathogenic indicator bacteria results from the Lagunitas Creek watershed (water years 2009-2010). All means and standard deviations are rounded to one more decimal place than the least precise value (least number of decimal places) of each corresponding dataset.

Parameter	Statistic	OLM18	OLM1	OLM14	OLM6A	OLM11	OLM10B	LAG1	LAG2	LAG3
Total coliform (MPN/100 mL)	Mean	5378.0	3247.0	4097.0	2146.0	5876.0	6767.0	2778.0	2242.0	2573.0
	Median	1200	980	1100	1200	2500	3200	1100	690	1000
	Minimum	80	210	280	180	400	51	200	47	230
	Maximum	>24190	>24190	>24190	>24190	>24190	>24190	>24190	>24190	>24190
	Std. dev.	8192.0	6118.0	6673.0	4943.0	7923.0	9774.0	5370.0	4825.0	5360.0
	# censored/ # results ¹	3/35	3/35	3/35	2/35	7/35	9/35	2/26	1/26	2/26
E. coli (MPN/100 mL)	Mean	319.0	1027.0	705.0	173.0	1099.0	1064.0	213.0	1085.0	-
	Median	52	63	96	31	150	170	100	23	-
	Minimum	<10	1	<10	<10	52	<1	10	1	<10
	Maximum	2600	>24190	12000	3400	16000	14000	2200	24000	>24190
	Std. dev.	569.0	4081.0	2158.0	575.0	2921.0	2624.0	442.2	4686.0	-
	# censored/ # results ²	2/35	1/35 *	1/35	2/35	0/35	2/35	1/26	0/26	2/26 *
Fecal coliform (MPN/100 mL)	Mean	228.0	232.0	264.0	110.0	361.0	348.0	-	-	-
	Median	81	46	81	81	180	140	-	-	-
	Minimum	8	7	20	8	46	14	-	-	-
	Maximum	>1600	>1200	>1600	1200	>1600	>1200	-	-	-
	Std. dev.	411.0	361.5	408.3	219.3	424.9	377.9	-	-	-
	# censored/ # results ¹	1/30	1/30	1/30	0/30	2/32	2/30	-	-	-

¹ These censored results are '> QL' (above the quantification limit) & are shown as a ratio over the total number of results.

² These censored results are '< QL' (below the quantification limit) & are shown as a ratio over the total number of results.

* OLM1 and LAG3 each produced one censored *E. coli* result of '> QL'; the LAG3 *E. coli* dataset is censored on both ends.

Table 19. Pathogenic indicator bacteria results from the Redwood Creek watershed (water years 2009-2010). All means and standard deviations are rounded to one more decimal place than the least precise value (least number of decimal places) of each corresponding dataset.

Parameter	Statistic	WU4	WU3	WU2	WU1	MGG1
Total coliform (MPN/100 mL)	Mean	443.0	291.0	408.0	1896.0	597.0
	Median	340	190	240	440	300
	Minimum	<10	120	75	31	68
	Maximum	1300	870	1200	8700	>2419
	Std. dev.	384.3	263.3	396.1	3013.0	674.0
	# censored/ # results ¹	1/18 *	0/7	0/7	2/20	1/20
<i>E. coli</i> (MPN/100 mL)	Mean	55.0	18.0	28.0	35.0	44.0
	Median	10	8	10	20	30
	Minimum	<10	<1	<1	<10	<1
	Maximum	410	97	120	150	200
	Std. dev.	100.7	36.4	44.9	41.0	52.8
	# censored/ # results ²	3/18	3/7	2/7	3/20	3/20

¹These censored results are '> QL' (above the quantification limit) & are shown as a ratio over the total number of results.

* WU4 is the only exception – this single censored result is '<QL' (below the quantification limit).

²These censored results are '< QL' (below the quantification limit) & are shown as a ratio over the total number of results.

Total Coliform

The contact recreation maximum for total coliform, established by the San Francisco Bay RWQCB's Basin Plan, is 10,000 MPN/100mL for a single sample. During WYs 2009-2010, a total of 554 total coliform samples were collected from the SFAN water quality sites; 5% of all results (27:554) exceeded the contact recreation maximum, and nearly all of these exceedances (25:27) were from the Lagunitas Creek watershed. Twenty-seven additional results were above their quantification limit (2,419 MPN/100mL), and although of unknown value, these could potentially have been exceedances as well. The Redwood Creek watershed had the two lowest mean total coliform results in the SFAN (sites FC1 and FC2), while the Lagunitas watershed produced the three highest means in the SFAN (Figures 30 and 31). The San Francisquito Creek watershed produced the only non-detect result program-wide, and only had three results above the quantification limit of 2,419 MPN/100mL (Figure 32). No seasonal patterns were observed in the SFAN total coliform results.

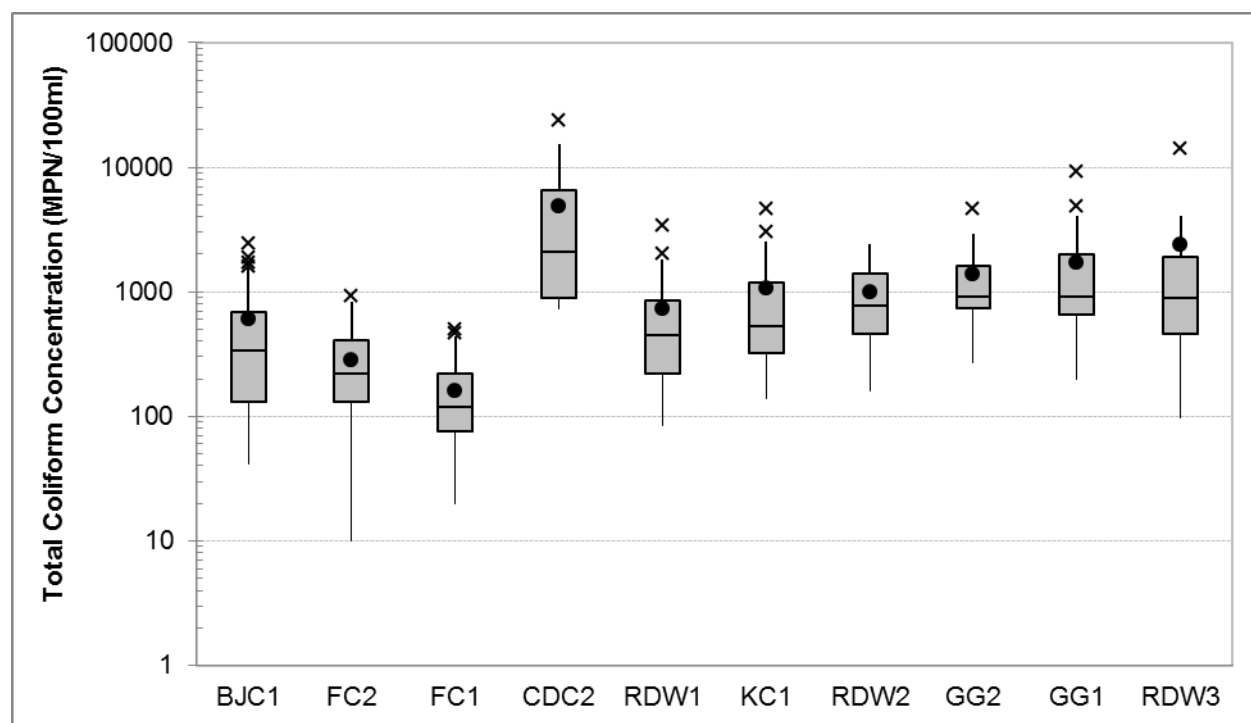


Figure 30. Total coliform results from the Redwood Creek watershed (water years 2009-2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

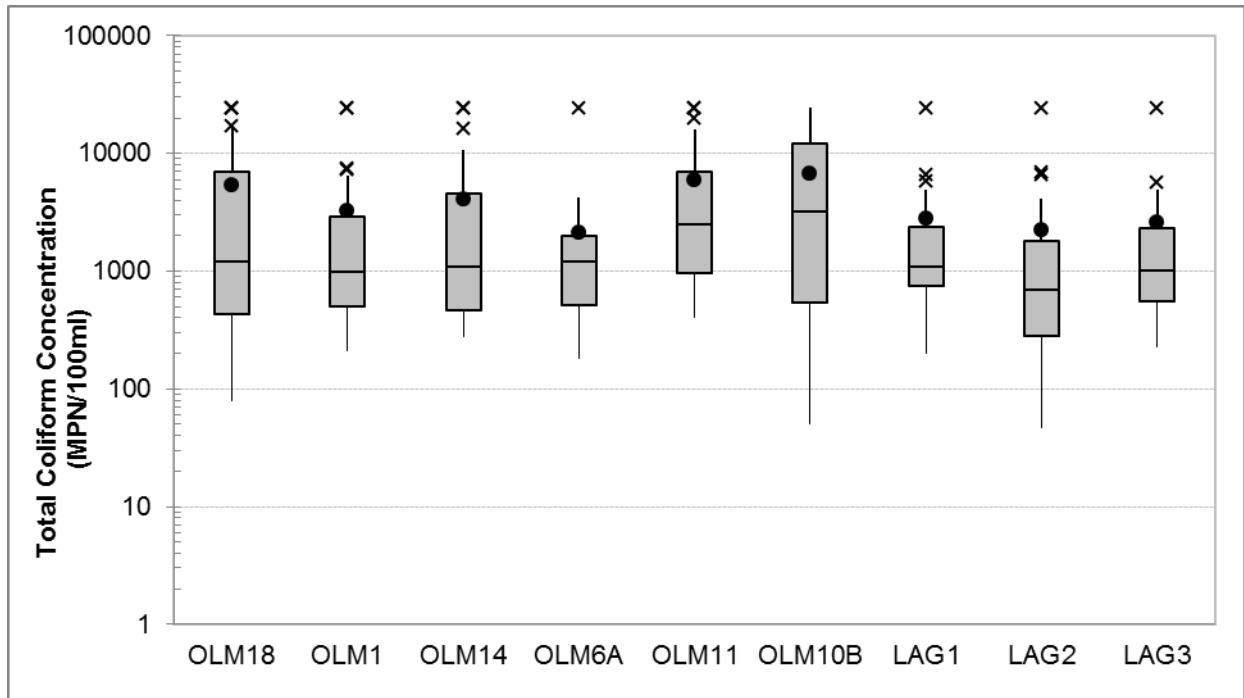


Figure 31. Total coliform results from the Lagunitas Creek watershed (water years 2009-2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

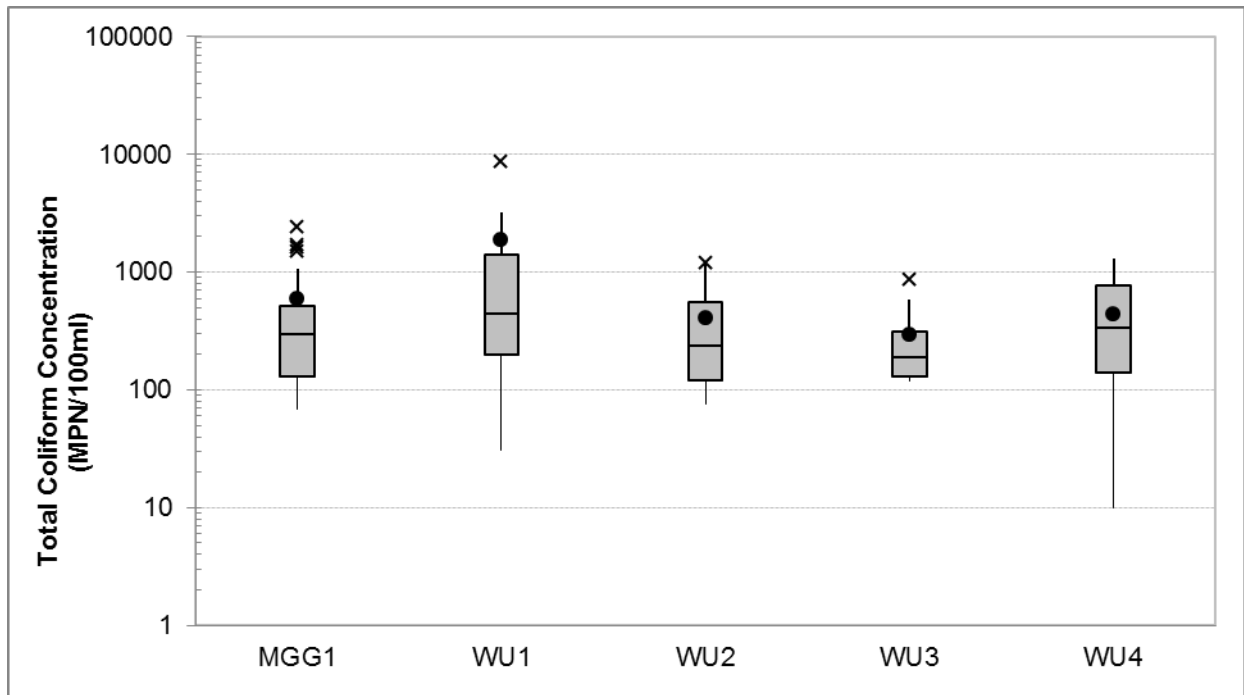


Figure 32. Total coliform results from the San Francisquito Creek watershed (water years 2009-2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

***Escherichia coli* (*E. coli*)**

The contact recreation maximum for *E. coli*, established by the San Francisco Bay RWQCB's Basin Plan, is 235 MPN/100mL for a single sample. During WYs 2009-2010, a total of 554 *E. coli* samples were collected from all SFAN water quality sites; 15% of these results exceeded the contact recreation maximum, and the majority of these exceedances (64 of 83) were from the Lagunitas Creek watershed. Twelve percent of all samples, program-wide, were reported as non-detect (below the quantification limit of 1, 10, or 100 MPN/100mL, depending on the dilution used); the majority (64%) of these non-detect results were from the Redwood Creek watershed. Nine percent of all samples from the Redwood Creek watershed exceeded the contact recreation maximum of 235 MPN/100mL (Figure 33). One quarter of these exceedances were observed during storm sampling events. The highest single result from the Redwood Creek watershed was found at the farthest downstream site during July of 2009 (a result of 11,000 MPN/100mL at RDW3).

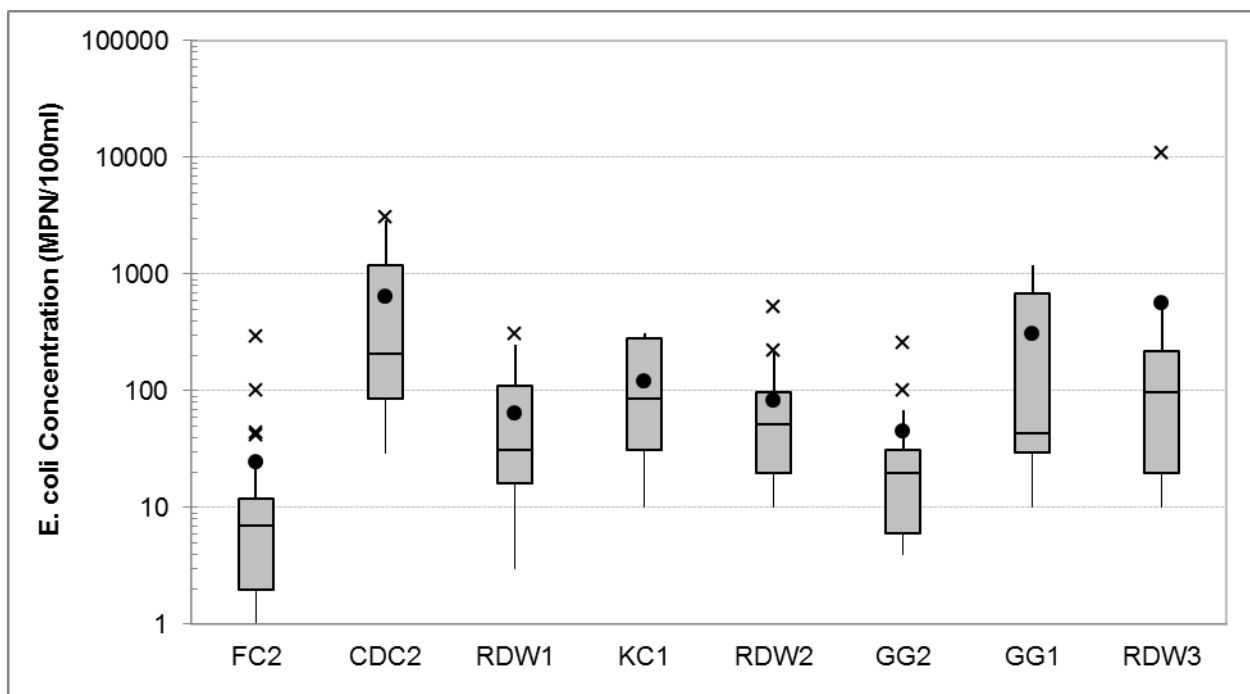


Figure 33. *Escherichia coli* results from the Redwood Creek watershed (water years 2009-2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

Two results from the 554 *E. coli* samples collected program-wide during WYs 2009-2010 were reported to be above the quantification limit of 24,190 MPN/100mL; both of these results were from the October 2009 storm sampling event in the Lagunitas watershed (sites OLM1 & LAG3). Since LAG3 also produced one non-detect result (November 2009), the dataset is said to be 'censored on both ends.' Summary statistics (and a box & whiskers plot) were not computed for site LAG3 because the Kaplan-Meier method does not tolerate censoring on both ends.

The Lagunitas Creek watershed had the highest exceedance rate in the SFAN (Figure 34). Twenty-two percent (64:288) of all Lagunitas watershed samples exceeded the contact recreation maximum, and 58% of these exceedances were from storm sampling events, which also produced the 19 highest results in the program (above 2,000 MPN/100mL). The farthest downstream Olema Creek water quality sites (OLM11 and OLM10B) produced the two highest *E. coli* means during WYs 2009-2010, while site OLM6A produced the lowest *E. coli* mean in the Lagunitas watershed. This site is considered a reference site because it is a tributary of Olema Creek that flows out of an area with minimal human or agricultural impact.

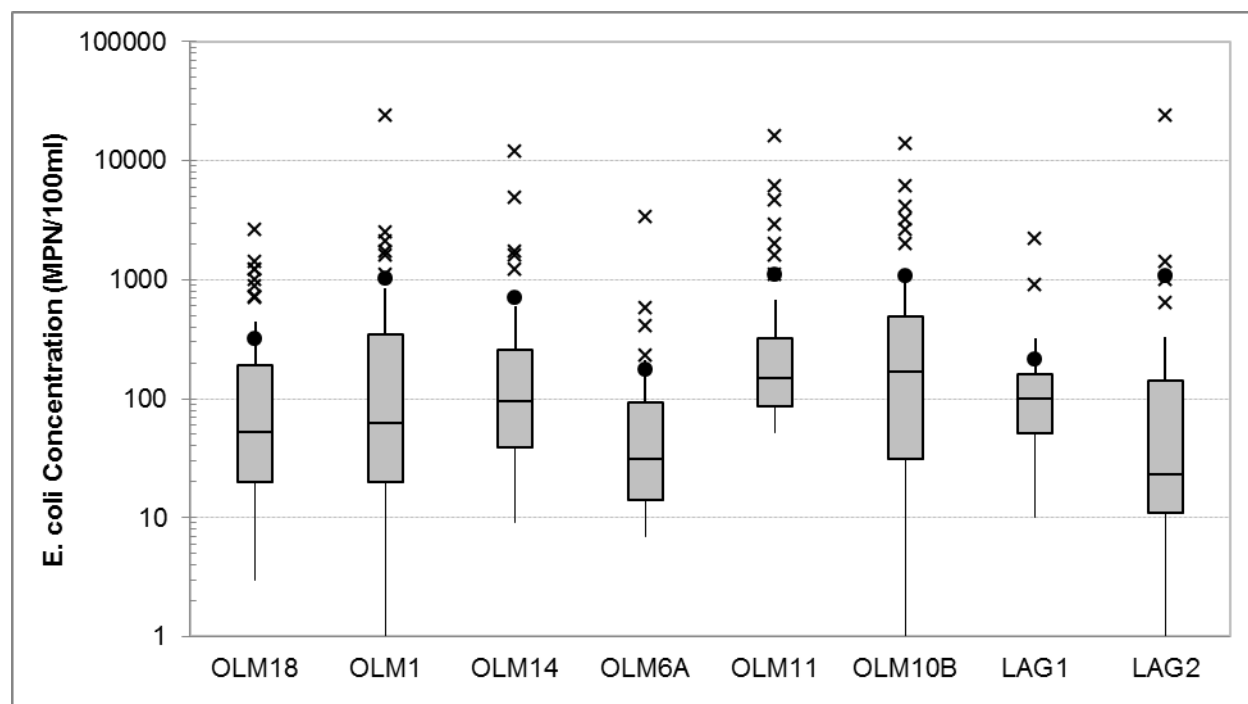


Figure 34. *Escherichia coli* results from the Lagunitas Creek watershed (water years 2009-2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

A total of 72 *E. coli* samples were collected from the San Francisquito Creek watershed; 19% of these were reported as non-detect and only one result exceeded the contact recreation maximum of 235 MPN/100mL (Figure 35). This exceedance was a result of 410 MPN/100mL at site WU4 during the August 2010 sampling. Overall, the San Francisquito Creek watershed produced some of the lowest *E. coli* means in the program. Although these sites are located near horseback riding and hiking trails, the use is minimal, and there are not major sewer systems or agricultural *E. coli* sources near by.

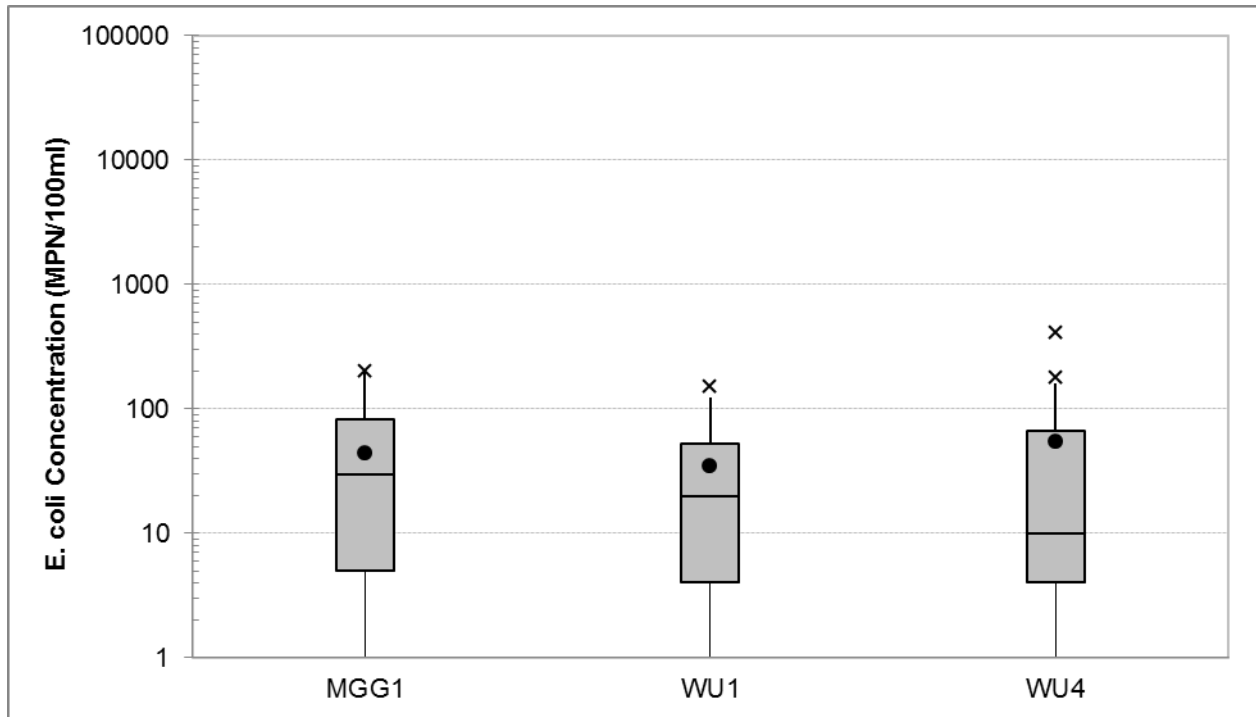


Figure 35. *Escherichia coli* results from the San Francisquito Creek watershed (water years 2009-2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

Although they have large enough datasets, four SFAN water quality sites (BJC1, FC1, WU2, and WU3) were excluded from the box & whiskers plots, because the software encountered the censoring limit before reaching the 25th percentile and could not continue. These sites had high percentages of censored (non-detect) results. Summary statistics for these four sites are displayed in Tables 17 and 19.

Fecal Coliform

The contact recreation maximum for fecal coliform, established by the San Francisco Bay RWQCB's Basin Plan, is 400 MPN/100mL for a single sample. The sampling plan for the Tomales Bay Pathogen TMDL Program includes an intensive fecal coliform sampling period of five consecutive weeks, in the winter and summer, in addition to routine monthly monitoring. During this reporting period, the seasonal weekly sampling took place in January and June of WY 2009 and WY 2010. Fecal coliform was not monitored in November 2008, August–October 2009, or March 2010. During WYs 2009-2010, a total of 182 fecal coliform samples were collected from the Olema Creek sites; 16% of these results (29:182) exceeded the contact recreation maximum, and another 8% were reported to be exactly at the maximum threshold of 400 MPN/100mL. The two highest means were from the farthest downstream sites (OLM11 and OLM10B) while OLM6A had the lowest fecal coliform mean of any site in the watershed (in addition to the lowest *E. coli* mean).

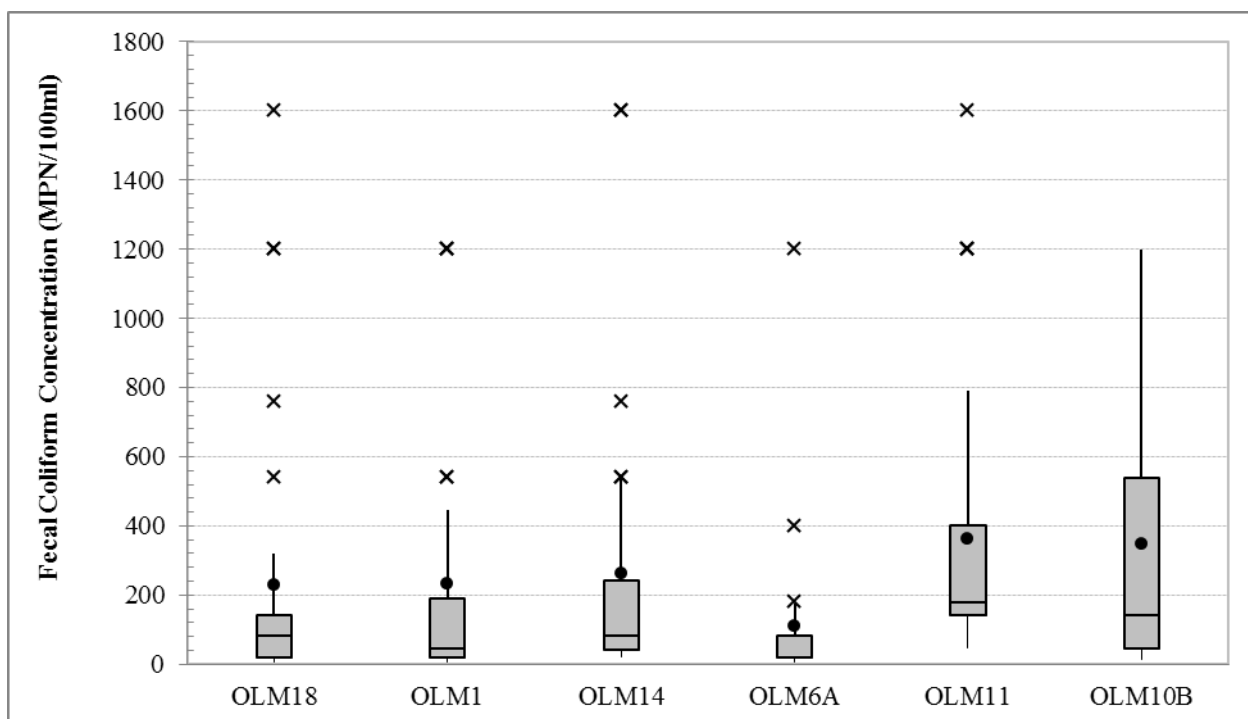


Figure 36. Fecal coliform results from the Lagunitas Creek watershed (water years 2009-2010). Boxplots present the interquartile range between the 75th and 25th percentiles (top and bottom of the boxes), the mean (solid dot), and the median (middle line); whiskers are drawn to 1.5 times the interquartile range; and outliers (beyond whiskers) are displayed with an 'x.'

Conclusion

The data presented in this report summarize the third and fourth years of monitoring under the SFAN Freshwater Quality Monitoring Protocol (Coopridger and Carson 2006). This two-year rotation (WYs 2009-2010) involved routine monitoring of 25 sites in three watersheds within three SFAN park units (GOGA, MUWO, and PORE), and it will be repeated in WYs 2013-2014. WYs 2011-2012 will repeat the sampling routine of the alternate rotation, which includes 32 sites in eight different watersheds within four different SFAN park units (JOMU, PINN, GOGA, and PORE). After WYs 2013-2014 there will be eight years of protocol implementation, but due to the rotating basin design, this will yield just four years of data for each of these SFAN watersheds. After WY 2014, more extensive data analysis will be considered, but it is likely that the first protocol objective (long-term trends analysis) will not be possible until there is a more substantial dataset.

Two other objectives proposed in the SFAN Freshwater Quality Monitoring Protocol are not addressed in this report because they have never become part of the program: diurnal variability has not been measured because of significant needs for additional funding, staff time, and continuous monitoring equipment, and loading has never been calculated by the San Francisco Bay RWQCB's Pathogen TMDL Program (nor is it a requirement of their program). The SFAN water quality monitoring program satisfies the third objective of the SFAN protocol, by determining the extent that the sites meet established federal and state water quality standards, through routine sampling.

This biennial report presents physical, chemical, and biological ranges found at the SFAN water quality sites during WYs 2009-2010 (October 1, 2008 – September 30, 2010); the data from these two years of monitoring commonly met the established water quality objectives. Overall, the parameters that most commonly met the established objectives were total coliform, pH, nitrate (as N), and ammonia (as N), which had failure rates of 5%, 3%, 1%, and 0%, respectively. If divided up by watershed, these four parameters still exhibited some of the lowest failure rates.

The watershed with the highest rates of exceedance for any monitored parameter, was the San Francisquito Creek watershed; 39% of specific conductance results were outside the ecological objective range of 150 and 500 $\mu\text{S}/\text{cm}$ (Behar 1997), and 32% of dissolved oxygen results were below the objective of 7 mg/L (CA RWQCB 2010). Although these two parameters had high failure rates, the San Francisquito Creek watershed results commonly met water quality objectives for all other monitored parameters (Table 20).

Table 20. Percentages of results that failed to meet water quality objectives¹, sorted by watershed group for each parameter. The shaded boxes are those parameters of the greatest concern for that particular watershed (with more than a 10% failure rate).

Parameter	Redwood	Lagunitas	San Francisco
Dissolved oxygen	6%	11%	32%
pH	1%	5%	1%
Specific conductance	11%	24%	39%
Turbidity	2%	20%	0%
Nitrate (as nitrogen)	1%	2%	0%
Ammonia (as nitrogen)	0%	0%	0%
Total coliform	1%	9%	0%
<i>Escherichia coli</i>	9%	22%	1%
Fecal coliform	n/a	16%	n/a

¹Water quality objectives and corresponding references: > 7 mg/L dissolved oxygen (CA RWQCB 2010), 6.5 to 8.5 pH units (CA RWQCB 2010), 150 to 500 µS/cm specific conductance (Behar 1997), < 25 NTU turbidity (Sigler et al. 1984), < 1.1 mg/L nitrate as nitrogen (Crunkilton 2000), < 0.025 mg/L un-ionized ammonia (CA RWQCB 2010), < 10,000 MPN/100mL total coliform (CA RWQCB 2010), < 235 MPN/100mL *E. coli* (CA RWQCB 2010), and < 400 MPN/100mL fecal coliform (CA RWQCB 2010).

One of the watersheds in the study area that supports a viable population of coho salmon and steelhead is Lagunitas. This watershed repeatedly failed to meet certain water quality objectives during WYs 2009-2010: 24% of the specific conductance results were outside of the ecological objective range; 20% of turbidity results exceeded the ecological objective maximum of 25 NTU; 22% of *E. coli* results exceeded the contact recreation maximum objective of 235 MPN/100mL; and the fecal coliform results failed to meet the recreational objective (400 MPN/100mL) at a rate of 16%. High levels of pathogenic indicator bacteria in the Lagunitas Creek watershed have been documented for many years, and monitoring of these levels continues through the San Francisco RWQCB's Tomales Bay Pathogen TMDL Program. The Lagunitas Creek watershed results failed to meet the dissolved oxygen objective of 7 mg/L at a rate of 11%, and all other monitored parameters exhibited low failure rates (Table 20).

The other watershed that supports a viable population of coho salmon and steelhead is Redwood. During WYs 2009-2010, the Redwood Creek watershed had slightly high failure rates for specific conductance, *E. coli*, and dissolved oxygen results, which failed to meet water quality objectives at rates of 11%, 9%, and 6%, respectively (Table 20). All other parameters monitored in the Redwood Creek watershed commonly fell within the water quality objectives.

During water years 2009 and 2010, this water quality program produced a clear snapshot of watershed health in three SFAN watersheds. Continuing with this long-term monitoring program is necessary in order to document seasonal ecological fluctuations, determine trends, guide management decisions, and evaluate the success of restoration projects.

Literature Cited

- 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.
- Antweiler, R.C. and H.E. Taylor. 2008. Evaluation of statistical treatments of left-censored environmental data using coincident uncensored data sets: I. Summary statistics. *Environmental Science and Technology*, 42: 3732–3738.
- Armour, C. L. 1991. Guidance for evaluating and recommending temperature regimes to protect fish. U.S. Fish and Wildlife Service. Fort Collins. Biological Report 90(22).
- Behar, Sharon. 1997. Testing the Waters: Chemical and Physical Vital Signs of a River. River Watch Network, Montpelier, VT. ISBN-0-782-3492-3.
- California Regional Water Quality Control Board (CA RWQCB) - San Francisco Bay Region. 2010. San Francisco Bay Basin (Region 2) Water Quality Control Plan (Basin Plan). California Regional Water Quality Control Board, San Francisco Bay Region, Oakland, California.
- California Regional Water Quality Control Board (CA RWQCB) - San Francisco Bay Region. 2011. Total Maximum Daily Loads (TMDLs) and the 303(d) List of Impaired Water Bodies. Available at: http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/ (Accessed December 2011).
- Coopridge, M.A. and R.G. Carson. 2006. San Francisco Bay Area Network freshwater quality monitoring protocol, version 2.11. NPS/SFAN/NRR – 2006/016. National Park Service, Fort Collins, Colorado.
- Coopridge, M. 2004. San Francisco Bay Area Network preliminary water quality status report. National Park Service, San Francisco Bay Area Network, Sausalito, California.
- Crunkilton, R. 2000. Acute and chronic toxicity of nitrate to brook trout (*Salvelinus fontinalis*) eggs and fry. Wisconsin Cooperative Fisheries Extension Unit Annual Report, 1999-2000.
- Fong, D., D. Press, M. Koenen, and M. DeBlasi. 2011. San Francisco Bay Area Network (SFAN) streamflow monitoring protocol: volume 1: narrative and appendixes – version 2.92. Natural Resources Report NPS/SFAN/NRR—2011/343. National Park Service, Fort Collins, Colorado.
- Freeman, L.A., J.R. Smithson, M.D. Webster, G.L. Pope, and M.F. Friebe. 2003. Water Resources Data-California, Water Year 2002, Volume 2. Pacific Slope Basins from Arroyo Grande to Oregon State Line except Central Valley. USGS-WDR-CA-02-2. U.S. Geological Survey, Water Resources Division. Sacramento, California.

- Helsel, D.R. 2005. Nondetects and Data Analysis: Statistics for Censored Environmental Data. Wiley, New York. 250 pages.
- Helsel, D.R. and T.A. Cohn. 1988. Estimation of Descriptive Statistics for Multiply Censored Water Quality Data. *Water Resources Research*, 24: 1997-2004.
- Lehre, A.K. and C. Wahrhaftig. 1974. The climate and hydrology of the Golden Gate National Recreation Area. Prepared for U.S. Dept of Interior, National Park Service. University of California, Berkeley.
- Moyle, P.B. 2002. Inland Fishes of California, Revised and Expanded. University of California Press, Berkeley, California.
- National Park Service (NPS). 2002. Recommendations for core water quality monitoring parameters and other key elements of the NPS Vital Signs Program water quality monitoring component. Freshwater Workgroup Subcommittee. Fort Collins, Colorado.
- National Park Service (NPS). 2003. Baseline water quality data inventory and analysis, Point Reyes National Seashore. Water Resources Division. Technical Report NPS/NRWRD/NRTR- 2000/280.
- National Park Service (NPS). 2006. Management policies. U.S. Department of Interior, National Park Service, Washington, D.C. ISBN 0-16-076874-8.
- Newcombe, C.P. and D.D. MacDonald. 1991. Effects of suspended sediments on aquatic ecosystems. *North American Journal of Fisheries Management*. 11: 72-82.
- Rantz, S.E. 1982. Measurement of discharge by conventional current-meter method. USGS WSP 2175.
- Serpa, L. 2011. 2011 Survey of California freshwater shrimp, *Syncaris pacifica*, in Lagunitas Creek, Marin County, California. Prepared for the Marin Municipal Water District.
- Sigler, J.W., T.C. Bjornn, and F.H. Everest. 1984. Effects of chronic turbidity on density of steelheads and coho salmon. *Transactions of the American Fisheries Society*, 113: 142-150.
- Skancke, J. S. 2011. Freshwater quality monitoring in the San Francisco Bay Area Network: 2008 annual report. Natural Resource Technical Report NPS/SFAN/NRTR—2011/464. National Park Service, Fort Collins, Colorado.
- Sullivan, Michael. 2011. Fundamentals of Statistics, Third Edition. Page 118. Pearson Prentice Hall, New Jersey.
- U. S. Environmental Protection Agency (U.S. EPA). 1986. Ambient water quality criteria for bacteria. EPA 440/5-84-002.
- U. S. Environmental Protection Agency (U.S. EPA). 1998. Guidance for data quality assessment. EPA/600/R-96/084.

U. S. Environmental Protection Agency (U.S. EPA). 2000. Ambient water quality criteria recommendations information supporting the development of state and tribal nutrient criteria for rivers and streams in nutrient ecoregion III. EPA 822-B-00-016.

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