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LINKING ON-FARM DAIRY MANAGEMENT PRACTICES TO STORM-FLOW FECAL COLIFORM LOADING FOR CALIFORNIA COASTAL WATERSHEDS

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Abstract. How and where to improve water quality within an agricultural watershed requires data at a spatial scale that corresponds with individual management decision units on an agricultural operation. This is particularly true in the context of water quality regulations, such as Total Maximum Daily Loads (TMDLs), that identify agriculture as one source of non-point source pollution through larger tributary watershed scale and above and below water quality investigations. We have conducted a systems approach study of 10 coastal dairies and ranches to document fecal coliform concentration and loading to surface waters at the management decision unit scale. Water quality samples were collected on a storm event basis from loading units that included: manure management systems; gutters; storm drains; pastures; and corrals and lots. In addition, in-stream samples were collected above and below the dairy facilities and from a control watershed, managed for light grazing and without a dairy facility or human residence and corresponding septic system. Samples were analyzed for fecal coliform concentration by membrane filtration. Instantaneous discharge was measured for each collected sample. Storm runoff was also calculated using the curve number method (SCS, 1985). Results for a representative dairy as well as the entire 10 dairy data set are presented. Fecal coliform concentrations demonstrate high variability both within and between loading units. Fecal coliform concentrations for pastures range from 206 to 2,288,888 cfu/100 ml and for lots from 1,933 to 166,105,000 cfu/100 ml. Mean concentrations for pastures and lots are 121,298 (SE = 62,222) and 3,155,584 (SE = 1,902,713) cfu/100 ml, respectively. Fecal coliform load from units of concentrated animals and manure are significantly more than units such as pastures while storm flow amounts were significantly less. Compared with results from earlier tributary scale studies in the watershed, this systems approach has generated water quality data that is beneficial for management decisions because of its scale and representation of current management activities. These results are facilitating on-farm changes through the cooperative efforts of dairy managers, regulatory agency staff, and sources of technical and financial assistance.

Keywords: fecal coliform, systems approach, spatial scale, water quality assessment

1. Introduction

Community and regulatory efforts aimed at reducing non-point source pollution often lack water quality data at a spatial scale that is linked to both site specific land use practices and landowner management decisions. Water quality samples are often collected from locations that represent drainage areas of one square kilometer or larger, resulting in a sample that integrates contributions from multiple land uses under different management strategies from multiple landowners (O'Connell *et al.*, 2000; Halloway and Dahlgren, 1999; Fischer *et al.*, 1996). This level of spatial integration makes site-specific recommendations for improving water quality difficult. A common monitoring strategy is sampling above and below a suspected pollution source within a given watershed (Ong *et al.*, 1996; Sischo *et al.*, 2000; CRWQCB, 2003). The primary outcome is to assign the difference between the below and above pollutant load to all the land use practices being carried out by the land owner, but such data has little ability to assign priorities to potential remediation efforts within the land parcel itself or to differentiate between components of the land use that may be discharging differing pollutant amounts. For example, monitoring a creek for phosphorous above and below an adjacent golf course will not differentiate phosphorous loads coming from the fairways, the club house, the parking lot, or the road leading to the golf course.

In the case of microbial pollution, a third monitoring strategy is to utilize a spatially-diverse network of monitoring sites within a watershed and then rely upon microbial source tracking techniques to assign percentages of the estimated total microbial load to different vertebrate or environmental sources present in the watershed (Hagedorn *et al.*, 1999; Cole *et al.*, 2003). This method can identify vertebrate species that are contributing to the overall microbial load in the watershed. Nevertheless, having data, for example, that assigns 30% of the *Escherichia coli* isolated from a stream to dogs and 70% to cattle provides little guidance as to where an owner should focus remediation efforts within the land parcel. For example, assuming a dairy owner is presented with such data (30:70 dog:cow), should the owner construct a new barn, repair the manure storage lagoon, fence riparian corridors, reduce herd size, sell the farm's two dogs, or some combination of these in order to effectively meet water quality objectives.

This mismatch between the spatial scale of water quality monitoring data and the spatial scale at which land owners design infrastructure and make land use management decisions is particularly common for microbial pollutants associated with fecal contamination, such as fecal coliform or *E. coli.* The combination of high concentrations of bacterial indicators such as *E. coli* in fecal material, the patchy distribution of fecal material on our urban and rural landscapes (Tate *et al.*, 2003; Kullas *et al.*, 2002), and the wide differences in the infiltration rate of surfaces ranging from asphalt to pasture (SCS, 1986) collectively result in wide differences in the loading rate of microbial pollutants into surface water from the different components within a singe land use. We have observed this phenomena on dairy farms where the flux of fecal coliforms during storm-flow conditions is highly variable across the dairy depending on the site's characteristics, such as animal density, grazing and manure management, and other such factors (Lewis *et al.*, 2001). This variation in loading is important because dairy operators in California and elsewhere are being required through such directives as the U.S. Clean Water Act to minimize the transport of pollutants from their properties. We need to generate monitoring data that can appropriately focus these water quality protection efforts on those parts of the dairy that are causing the highest pollutant loading rates, otherwise, inadvertent amounts of guesswork enters into the remediation effort often with mixed results as to improved water quality.

In the Northern California coastal watershed of Tomales Bay, referred to as the “Bay,” entities such as the San Francisco Bay Regional Water Quality Control Board (CRWQCB, 2004) and the National Shellfish Sanitation Program Model Ordinance (USDHHS, 1999) are requiring dairy farms to minimize their discharges of fecal coliforms into tributaries and ephemeral streams draining into the Bay. Each dairy property is unique and comprised of a complex set of management units such as pastures, milking barns, loafing areas, dry lots, and manure storage facilities. The dairy manager’s water quality data needs are generally at a scale that matches these units, which is smaller than that provided by tributary scale, above-and-below, and microbial source tracking monitoring methods. In order to assist these dairy owners in developing a targeted remediation plan, we developed a novel on-farm monitoring method that matches water quality data to the spatial scale of these on-farm management units. Our objective was that an appropriately scaled monitoring method would generate water quality data that would guide land owners as to which specific land use practices are contributing the greatest pollutant loads on their property and thereby help prioritize which management practices would need to be modified to help meet the water quality objectives for the Bay.

2. Methods

2.1. Study Location

The Tomales Bay Watershed is located approximately 64 kilometers north of San Francisco, California (Figure 1). It encompasses approximately 559 square kilometers divided among three main tributaries: Lagunitas, Olema, and Walker Creeks (Fischer *et al.*, 1996). The Bay itself is approximately 19 kilometers long and less than 1.6 kilometers wide. Average bay depth is 3.7 meters with a maximum depth of 18.6 meters. The bay and its tributary streams are habitat for the endangered coho salmon, threatened steelhead, as well as multiple species of birds and plants. In 1979, the Bay and its watershed were recognized as a “Special Resource Area” by the Regional Coastal Commission, and qualify as a wetland of regional importance under the Western Hemisphere Shorebird Reserve.

Agricultural production began in the region in approximately 1850 and included dairying, livestock ranching, and row crop production such as potatoes. Row crop production declined in the early 1900s to less than 200 hundred hectares of specialty vegetables today. Dairy production and livestock ranching have continued since

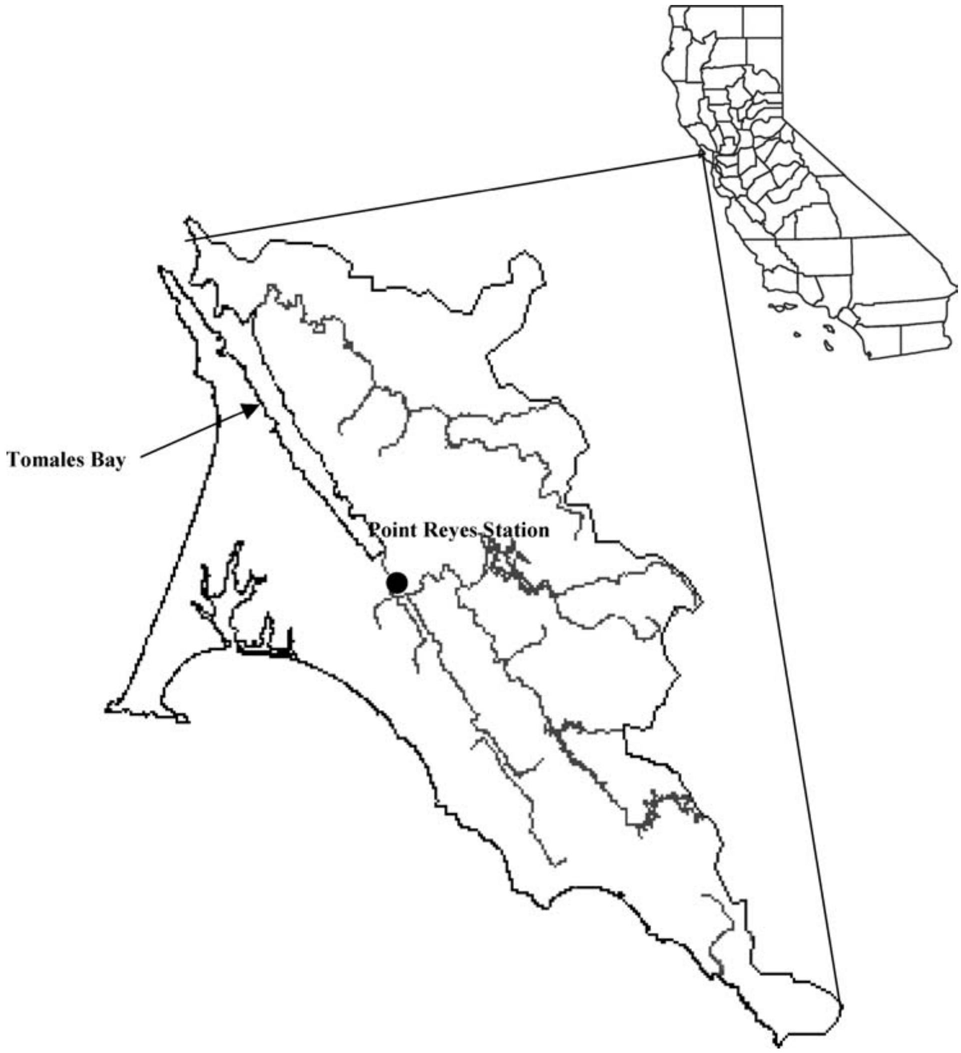

Figure 1. Tomales Bay and watershed located in Marin County, north of San Francisco Bay, California.

the 1850s. There are records of a native oyster fishery from 1890, although earlier use of the resource by native Americans has been documented. Currently, native oysters are limited with over-harvesting and sedimentation of habitat in the early 1900s sited as the primary causes throughout the region (Postel, 1988). Commercial production of oysters began in 1918 and is ongoing now with approximately 280 hectares of leased bay tidal lands in active production. It is the need for water of sufficient quality to produce shellfish and the cultural and economic value of dairy and livestock agriculture in the Bay watershed that has generated the impetus for the implementation of water quality regulations as well as the research presented here.

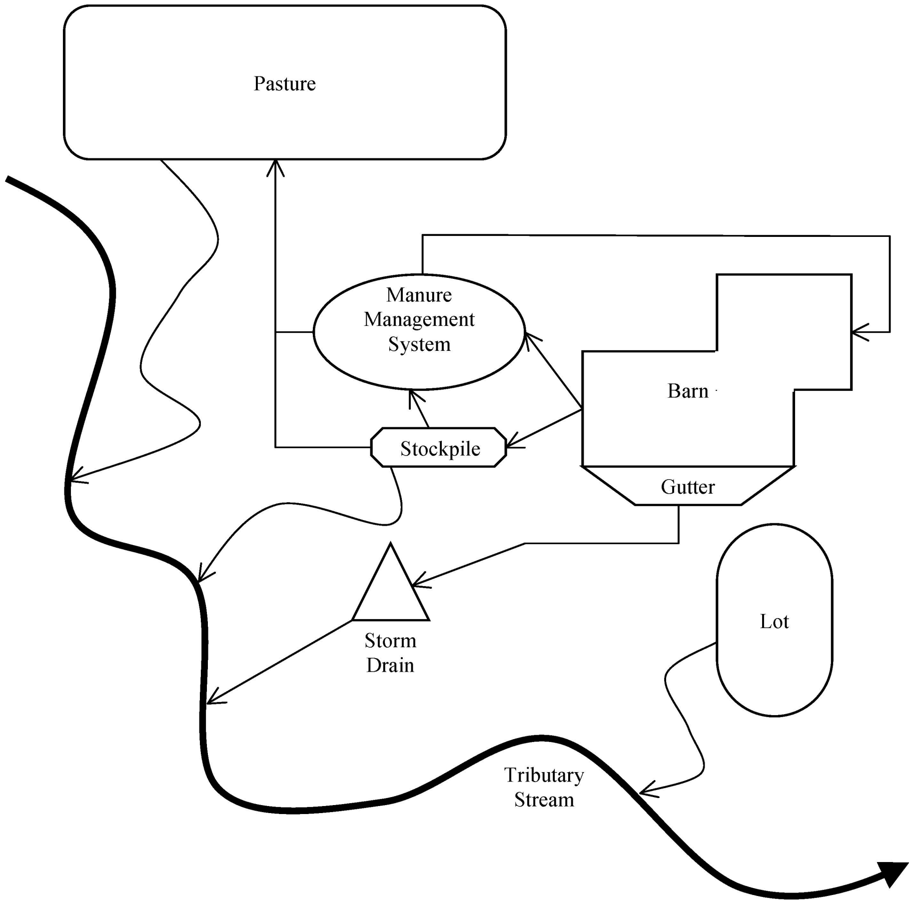

Figure 2. Loading unit schematic representing dairy barn and corresponding units. Bold line depicts tributary stream channel. Thin lines and arrows indicate general flow paths for barn wash water, manure, and sources of fecal coliform to the tributary stream.

2.2. Systems approach monitoring strategy

Dairy farms are comprised of different management areas that likely discharge differing loads of fecal coliform due to different fecal loading and/or rainfall to runoff ratios. Hence, we designed our monitoring strategy at the spatial scale of these fecal coliform loading units illustrated in Figure 2 and described below:

Manure management system (MMS): Retention lagoons and flush systems that capture and store barn manure. These systems are critical to dairy production systems as the primary management measure to prevent the direct release of pollutants to surface waters. Materials from these systems were sampled to provide a context of manure generated and managed within the studied facilities. They represent nascent materials, with little or no dilution from precipitation in contrast to the other loading units.

Pasture: These units range in size from tens to hundreds of hectares on to which calves and adult animals are released to graze annual grasses. In some cases, these units are disked and seeded for the production of feed silage. Manure from the manure management systems is spread and irrigated on to these units during the spring, summer, and fall, for irrigation and fertilization of grasses and feed crops.

Lot: Typically positioned next to barns, these units range from several hectares to less than a hectare in size. These units are used to provide daily exercise to milking cows which are milked two or three times a day and do not move away from the barn and milking facilities. In general, these areas hold high densities of dairy cattle during the summer, are scraped of manure in the fall, and not used in the winter.

Manure stockpile: Areas where solid manure is stored and composted. For example, manure scraped from lot units is stored at these stockpile locations. Stockpiled manure is spread and distributed to pastures during the spring, summer, and fall for fertilization.

Gutter: Drainage structures installed on dairy homes and barns to capture roof runoff before entering subsurface drains. The purpose of these gutters is to capture and separate water that has not been impacted by manure from other surface runoff that has, and then provide for its direct release to surface waters.

Drain: These drains are a continuation of the stormwater system from the gutter units. Water that is separated by gutters is routed through these drains to streams.

Runoff: Surface runoff along driveways and parking areas in and around dairy homes and barns.

In addition to sampling the different fecal coliform loading units described above, tributary-scale and above-and-below sampling were conducted to establish additional metrics of water quality. These sampling units included:

Control: Watersheds with little to no intensive animal agriculture facilities, substantial human development, and minimal rangeland usage by cattle.

Upstream: Represents tributary streams before entering areas of dairy facility infrastructure. These sample locations receive runoff from a variety of land uses including pastures, grasslands, and woodlands.

Downstream: Encompasses tributaries at various locations below dairy facilities including streams on the Eastern Shore, and in the Nicasio, Olema, and Chileno Creek watersheds.

2.3. Storm Event Sampling

It was determined previously that excessive fecal coliform loading to the Bay was rainfall dependent (O'Connell *et al.*, 2000). California Department of Health

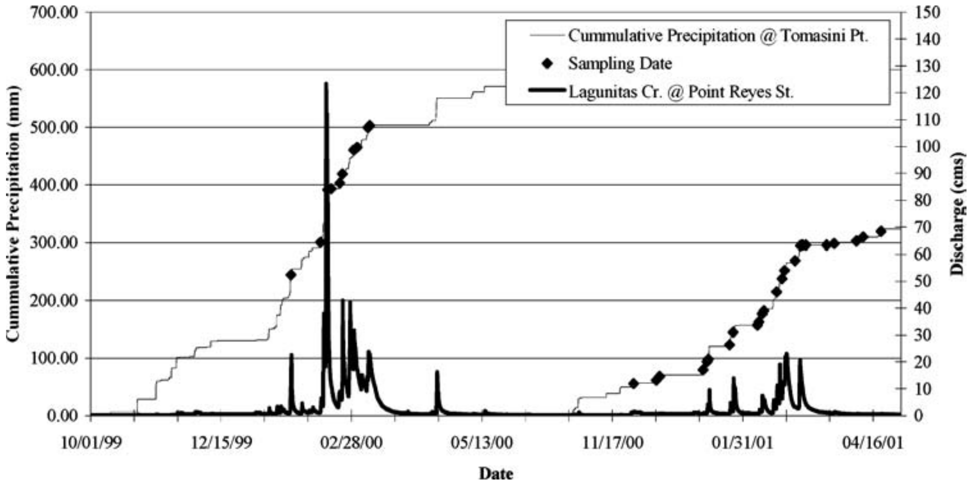

Figure 3. Daily discharge (thick line) in Lagunitas Creek and cumulative precipitation (thin line) at Tomasini Point. Sampling dates are designated by diamonds. (Data sources included: USGS stream gauge # 11460600 for discharge and California Data Exchange Center gauge code TMP for precipitation.)

Services uses the 24-hour cumulative precipitation from a local precipitation station, Tomasini Point, to direct winter shellfish growing closures for the Bay. As such, we conducted our water quality monitoring on a storm event basis in order to identify on-farm loading units that generated large fluxes of fecal coliforms during these storm events. We used the same precipitation station for our rainfall data. Annual cumulative precipitation at Tomasini Point, daily stream discharge in Lagunitas Creek, and sampling dates in response to rainfall during the 1999–2000 and 2000–2001 winters are illustrated in Figure 3.

At each site where a water sample was taken, instantaneous flow was measured using a Global Waters flow meter (Global Waters Inc., Gold River, California, USA) or alternatively, the time to fill a container of known volume or area-velocity method (velocity × channel width × channel depth) (Mosley and McKercher, 1993).

2.4. Fecal coliform enumeration

Duplicate water samples were collected into sterile 50 ml conical tubes and shipped overnight at 4 to 10 °C to the Veterinary Medicine Training and Research Center, University of California in Tulare, California. Three to five 10 or 100-fold serial dilutions were constructed from each sample. For each dilution, approximately 50 ml was filtered through a 47 mm, 0.45 μm pore sterile filter (Millipore, Billerica, MA), incubated on mFC agar (Difco agar by Becton Dixon Company, Sparks, MD) at 44.5 °C, and enumerated for fecal coliforms after 24 hours (APHA, 1995). A negative control was included with each shipment. These negative controls were previously collected field samples that had been autoclaved so that the color and texture of the negative control mimicked actual field samples.

2.5. Load calculation

Using the measured fecal coliform concentration and instantaneous flow for each storm-based sampling event, we calculated instantaneous load of fecal coliforms for each loading unit, defined as:

$$\text{instantaneous load (cfu/sec/hectare)} = \frac{(\text{cfu}/100\ \text{ml})(10^6\ \text{ml}/\text{m}^3)(\text{m}^3/\text{sec})}{(\text{total surface area of loading unit in hectares})}$$

where (cfu/100 ml) is the concentration of fecal coliforms in the water sample and (m^3/s) is the measurement of instantaneous flow of surface runoff or stream flow. This calculation is necessary in order to compare how different loading units function to discharge their loads of fecal coliforms on a standardized basis of per unit time and per unit area. In addition, we estimated the total load of fecal coliforms that would discharge off of a loading unit during the storm's duration, calculated as:

$$\text{storm load (cfu/storm/hectare)} = \frac{(\text{cfu}/100\ \text{ml})(10^6\ \text{ml}/\text{m}^3)\,(\text{total volume of runoff as m}^3)}{(\text{total surface area of loading unit in hectares})}$$

where (cfu/100 ml) is defined above and the estimated total volume of runoff per storm being a function of the loading unit's infiltration capacity, slope, surface area, 5-day and 24-hour antecedent rainfall integrated in the Curve Number method (SCS, 1985).

2.6. Analysis and statistics

Statistical analysis was conducted to identify patterns in fecal coliform concentration and load from the respective loading units in order to facilitate water quality management decisions. Results are presented for both a representative dairy and the overall data set, including above-and-below and tributary-scale sampling. Mean differences were determined by fitting a linear mixed effects model to each of these five response variables (Pinheiro and Bates, 2000): fecal coliform concentration; instantaneous runoff; storm runoff; instantaneous fecal coliform load; and storm fecal coliform load. In the linear fixed effects models, loading or other such unit (pasture, stockpile, etc.) was modeled as the fixed effect, sample location was modeled as a group effect to account for repeated measurement at each site (168 sites sampled 1 to 35 times), and the dependent variable was one of the five response variables mentioned above that had been transformed via taking the natural logarithm of the value. Coefficients and standard errors were estimated using restricted maximum likelihood, with significant differences between loading units determined by a Wald's test (P-value <0.05).

3. Results and Discussion

3.1. Precipitation and streamflow

Total annual precipitation at the Tomasini Point rain gauge was 64.5 cm for 1999–2000 and 36.3 cm for 2000–2001. The hydrograph (Figure 3) demonstrates the flow of a typical Bay tributary, Lagunitas Creek, as a function of cumulative precipitation. The amount of precipitation required to prime the watershed such that Lagunitas Creek exhibited storm-flow conditions was to 12.7 cm of cumulative precipitation during the two years of study.

3.2. A single representative dairy

As a means to summarize and illustrate the data collected across 10 facilities, we employed the concept of a representative dairy. Representative dairy watershed results for three storm events are variable between and within loading units (Table I). The minimum fecal coliform concentration, instantaneous load, and storm load values were measured from upstream loading units. By comparison, the maximum concentration, instantaneous load, and storm load were measured from lot loading units. Within the representative dairy data set, higher concentrations were consistently measured for the majority of the loading units on January 10, 2001. This event deposited approximately 6.35 cm of rain in 24 hours and was the first stream flow generating storm to occur during the 2000–2001 water year. Samples collected from loading units during subsequent storms had generally lower concentrations.

Results from the downstream loading unit are analogous to results that would be generated from a tributary scale watershed monitoring program. The concentration and load values from the representative dairy are as much as three orders of magnitude greater than those from a control tributary. For example on February 22, 2001, the single sample fecal coliform concentration, instantaneous load and storm load in the control stream was 954 cfu/100 ml, 7,038 cfu/hectare/second, and 43,629,177 cfu/hectare/storm. In a similar fashion, results from the upstream and downstream loading units represent the type of data generated from above and below monitoring programs. In comparing these two loading units, concentrations and loads at the downstream unit are two, three, and in some cases four orders of magnitude greater than at the upstream unit. In either case, tributary scale and above and below monitoring, the results indicate that loading is taking place but do not provide direction on where that loading can be targeted and reduced.

TABLE I
Fecal coliform concentration, instantaneous load, and storm load from a representative dairy watershed

Loading unit	Storm date	Concentration (cfu/100 ml)	Fecal coliform instantaneous load[a] (cfu/hec/second)	Storm load[b] (cfu/hec/storm)
Upstream	2/22/00	600	524	45,731,299
	2/22/00	1,911	2,508	10,227,222
	1/10/01	3,374	106	425,559,280
	1/10/01	1,422	27	491,482,488
	2/22/01	200	591	48,060,896
	2/22/01	2,908	8,641	328,437,398
Downstream	2/22/00	18,666	36,667	3,413,473,043
	2/22/00	54,888	56,625	10,037,236,211
	1/10/01	3,052,750	6,517,102	100,909,373,020
	1/10/01	1,840,629	283,162	60,842,445,981
	2/22/01	30,961	1,147,678	11,264,423,727
	2/22/01	34,573	35,395	12,570,443,871
Gutter	1/10/01	1,489	14,838	2,522,362,925
	1/23/01	69	3,857	81,878,137
Storm Drains	2/22/00	3,111	278,667	16,650,465
	1/10/01	1,054,995	136,968,462	364,614,873,307
	1/23/01	22,664	593,808	2,559,602,706
	1/23/01	19,331	343,145	22,953,795,757
	2/22/01	80,596	120,320	55,428,800,558
Runoff	2/22/01	26,664	626,077	15,393,009,228
Pastures	2/10/00	20,666	373,316	5,538,863,131
	2/10/00	82,222	2,557,245	23,806,106,280
	2/10/00	52,888	11,196	15,312,979,194
	2/22/00	25,333	39,781	1,466,086,191
	1/11/01	926,657	11,120,088	13,544,497,190
	2/11/01	41,996	91,257	16,454,370,668
	2/11/01	488	2,476	307,011,686
	2/11/01	18,665	532,140	11,732,824,938
	2/11/01	5,350	10,072	3,363,173,458
	2/19/01	1,818,183	12,324,419	49,732,622,121
	2/22/01	15,998	298,665	3,439,675,957
	2/22/01	371	45,637	41,864,984
	2/22/01	2,531	346,852	285,815,752
	2/22/01	1,798	9,029	203,079,614

(*Continued on next page*)

TABLE I
(*Continued*)

Loading unit	Storm date	Concentration (cfu/100 ml)	Fecal coliform instantaneous load[a] (cfu/hec/second)	Storm load[b] (cfu/hec/storm)
Lots	2/22/00	1,400,000	65,546,519	1,039,885,894,005
	2/22/00	40,666	420,542	34,685,993,230
	2/22/00	733,33	29,867,459	1,465,016,069,239
	2/22/00	1,244,444	40,547,336	2,486,087,875,070
	2/22/00	333,333	15,483,291	247,591,879,526
	2/22/00	88,889	318,114	37,233,774,820
	1/10/01	3,209,877	8,824,309	374,585,606,242
	1/10/01	359,147	13,229,825	64,530,769,345
	1/10/01	166,105,499	338,429,321	281,430,003,821
	1/10/01	3,120,090	147,758,941	364,107,681,963
	1/10/01	3,950,617	16,522,749	21,915,441,900
	1/23/01	89,787	1,882,556	106,714,704,442
	2/22/01	202,020	13,872,285	165,021,617,825
	2/22/01	606,061	10,704,355	539,204,986,797
	2/22/01	63,085	2,953,159	51,530,990,944
	2/22/01	112,234	150,622	64,791,902,987

[a]Instantaneous load (cfu/acre/second) is the product of fecal coliform concentration (cfu/100 ml) and instantaneous flow (cfs) divided by the area of the loading unit in acres.
[b]Storm load (cfu/acre/storm) is the product of fecal coliform concentration (cfu/100 ml) and storm runoff (acre-feet) divided by the area of the loading unit in acres.

By generating water quality results from the various loading units within the representative dairy, the manager is provided with information useful to the management of manure and stormwater sources. In general, the concentrations and load values from pastures and lots indicate that they are consistently the greatest potential source of fecal coliform loading with the representative dairy. This observation can help to prioritize and focus the manager's attention to these loading units. Results from the gutter unit confirm the importance of separating roof runoff from any manure as it moves into the area waterways. Following the gutter results, concentrations and loads in the drains indicate that attention is needed to prevent manured and relatively clean stormwater from mixing.

3.3. Across ten dairies

Results for the entire data set more robustly demonstrated variability within and between loading units that was indicated by the representative dairy results (Table II).

TABLE II
Mean fecal coliform, flow, and load values for each of the different loading units with standard error in parenthesis

Loading unit (sample size)	F. coliform concentration (cfu/100 m)	Instantaneous flow (cms)	Storm runoff (cm)	Instantaneous load (cfu/acre/sec)	Storm load (cfu/hec/storm)
Tributary Units					
CONTROL	1,405[1,2a]	0.0458[1,2]	4,691.7[1,4]	6,973[1]	481,982,738[1,2]
($n = 76$)	(431)	(0.0068)	(477.17)	(2,350)	(215,308,371)
UPSTREAM	5,450[1]	0.0286[1,3]	2,888.9[2]	16,553[1]	841,855,615[1,2]
($n = 45$)	(1,916)	(0.0103)	(781.7)	(6,911)	(199,659,123)
DOWNSTREAM	152,983[3]	0.1129[2]	9471.9[2,3]	361,789[2,3]	14,579,661,068[1,2,4]
($n = 175$)	(59,252)	(0.0188)	(1034.5)	(188,779)	(427,9416,176)
Facility Units					
PASTURES	121,298[3]	0.0081[3,4]	303.3[2,3]	2,557,628[2]	6,104,069,293[2,4]
($n = 48$)	(62,222)	(0.0019)	(97.4)	(1,986,820)	(1,753,802,875)
GUTTERS	298[2]	0.0001[6]	9.9[4]	6,983[1]	769,383,268[1]
($n = 17$)	(155)	(0.0001)	(3.6)	(3,758)	(521,562,583)
DRAINS	262,826[3,4]	0.0007[5]	30.8[4,5]	12,557,370[3,4]	282,736,762,000[3]
($n = 19$)	(114,078)	(0.0002)	(11.1)	(7,486,937)	(132,073,986,310)
RUNOFF	195,124[4,5]	0.0012[5]	16.0[1,2,3]	9,794,315[4,5]	98,169,497,044[3,4]
($n = 16$)	(71,113)	(0.0004)	(7.4)	(5,560,808)	(63,192,697,473)
STOCKPILES	7,259,497[6]	0.00035	19.7[1,5]	104,231,183[6]	2,063,340,364,734[5]
($n = 18$)	(3,172,665)	(0.0001)	(8.6)	(36,587,652)	(627,431,847,787)
LOTS	3,155,584[5]	0.0014[5]	48.1[1,3,4]	27,500,500[5]	3,416,841,967,000[3]
($n = 91$)	(1,902,713)	(0.0003)	(16.0)	(7,909,735)	(3,090,613,134,000)
MMS	18,996,165[6]	0.0066[3,4]	115.9[1,4]	2,759,316,280[6]	27,025,994,170,000[5]
($n = 44$)	(7,678,048)	(0.0015)	(22.2)	(1,491,201,551)	(12,380,201,729,000)

[a]Different numbers for the different loading units within the same outcome variable are significantly different ($P < 0.05$), as determined by the Wald test. This multiple comparison test was conducted by iteratively refitting the linear mixed-effects regression model with each loading unit set as the referent category.

At the larger watershed scale fecal coliform concentrations ranged from 1 to 30,885 cfu/100 mL for control watershed, 11 to 84,443 cfu/100 mL for upstream, and 44 to 9,248,040 cfu/100 mL for downstream loading units (Figure 4). Concentrations from within manure management systems were consistently the highest, which is anticipated given the nature of the material managed within these systems. Only the concentrations from lots and stockpiles approached similarly high values. Control watershed concentrations were consistently the lowest of the loading units. Concentrations in upstream and gutter samples were not different than control watershed sample concentrations ($p < 0.05$).

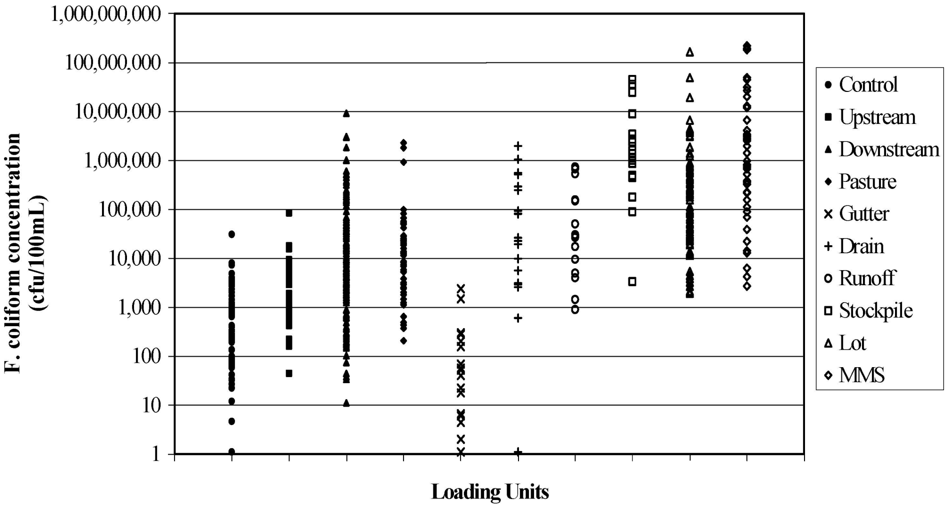

Figure 4. Fecal coliform concentrations in water samples from respective loading units.

Fecal coliform concentrations ranged for pastures between 206 and 2,288,888 cfu/100 mL; gutters between 0 and 2,378 cfu/100 mL; drains between 1.5 and 1,975,309 cfu/100 mL; facility runoff from 898 to 740,741 cfu/100 mL; stockpiles between 3,333 and 44,893,400 cfu/100 mL; lots between 1,933 and 166,105,000 cfu/100 mL; and manure management systems from 2,708 to 219,978,000 cfu/100 mL (Figure 4). Gutters had significantly lower mean fecal coliform concentration than all other loading units except control. On the other end of the scale, runoff from stockpiles had similar mean fecal coliform concentrations to manure management systems and both were significantly greater than all other loading units. Mean fecal coliform concentration from lots was significantly greater than pastures and drains while neither were significantly different than facility runoff.

The measured instantaneous flow from the respective units was directly related to the unit area. The control, downstream, and upstream had the greatest mean instantaneous flow in that order (Table II and Figure 5). These units represent the scale of flow that would be documented through tributary or above and below monitoring programs. Comparatively, measured flow for pastures ranged from 0.00 to 0.06 cms; gutters from 0.00 to 0.0005 cms; drains from 0.00 to 0.0042 cms; runoff from 0.0008 to 0.0057 cms; stockpiles from 0.00 to 0.0008 cms; lots from 0.00 to 0.0244 cms; and manure management systems from 0 to 0.0374 cms. These are the flow quantities that the dairy producer would experience in making management decisions within an operation. For these units, mean instantaneous flow was significantly greater from pastures than lots, drains, gutters, runoff, and stockpiles (Table II and Figure 5). Flow from manure management systems was a function of pump size, horsepower and pipe diameter.

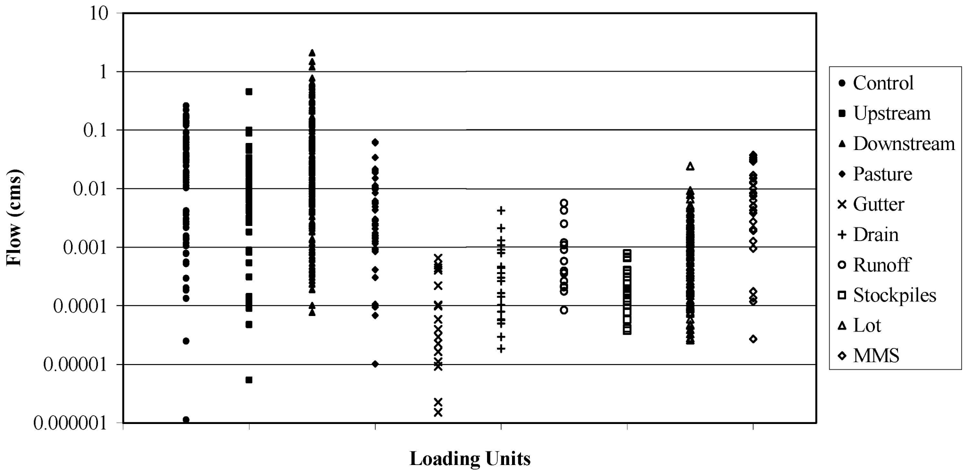

Figure 5. Instantaneous discharge measured at respective loading units during collection of surface water samples.

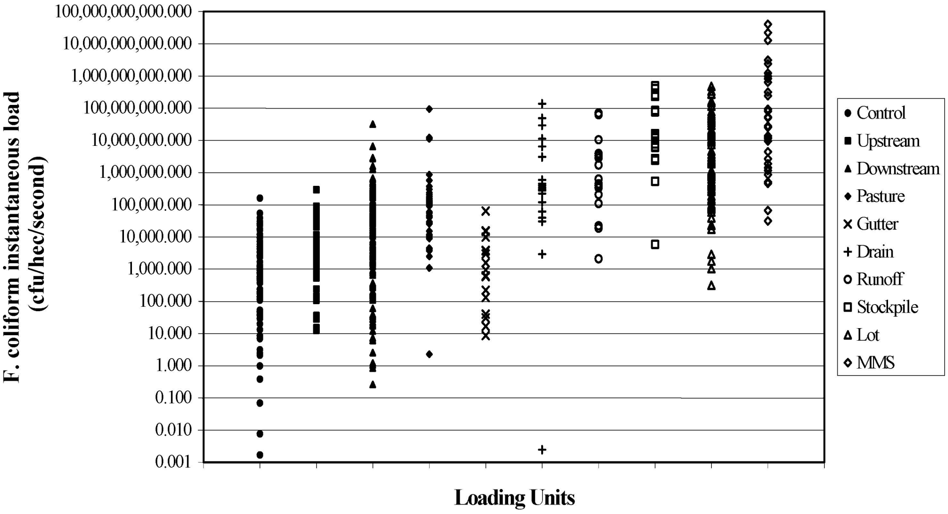

Figure 6. Fecal coliform instantaneous load from individual loading units, calculated as the product of fecal coliform concentration and measured instantaneous discharge.

Values for both instantaneous (Table II and Figure 6) and storm (Table II and Figure 7) loads from the control unit are lower than the downstream unit although only instantaneous load is significantly lower. Similarly, the downstream unit has greater loads than the upstream unit. Indications as to where that loading is taking place between the upstream and downstream are provided by the results from the other units. The greatest loads or potential load values were measured from the manure management system. Ostensibly, these materials are managed and stored to prevent their release to the stream and these results affirm the purpose for that

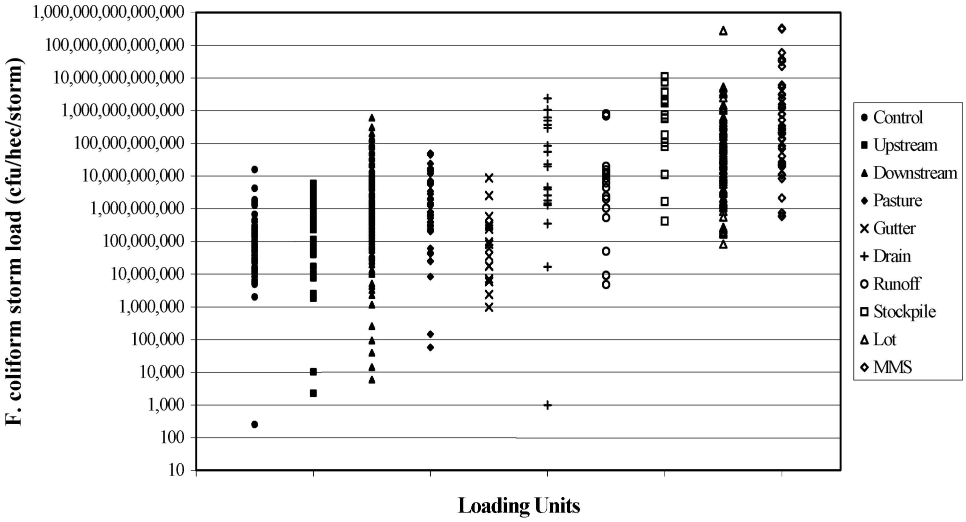

Figure 7. Fecal coliform storm load from respective loading units, calculated as the product of fecal coliform concentration and estimated storm runoff using the curve number method (SCS, 1985).

management and the absolute need to insure that these storage systems are functioning. Outside of those systems, loads from lots and stockpiles are greater relative to the other loading units within the dairies. The loads from gutters are generally the lowest followed by those from pastures.

3.4. Concentration, flow, and load to inform management decisions

Concentration data is useful information to manage water quality particularly when concentrations are used to regulate water quality for an established standard. Concentration is also a useful measure to guide water quality management decisions. Flow volumes are indicative of transport potential, a loading unit's manageability, and an important characteristic for prioritizing water quality concerns. For example, a specific loading unit of concern delivering greater flow than another unit would be a higher management concern because of the greater potential load downstream. However, more flow often represents a larger area requiring greater mitigation effort, while the unit with less flow is generally smaller and easier to manage. With flow and concentration measurements, loads can be calculated and used for prioritization of remediation. Land use managers will want to focus on units with the greatest loading when they are allocating time and money to reduce fecal coliform loading into receiving bodies of water, such as Tomales Bay. These can include point source (lots and stockpiles) and non-point source areas (upstream areas and pastures).

Mean concentration in fecal coliform from point sources is higher ($p < 0.001$) than for non-point source loading units (Figure 8a) while point source mean

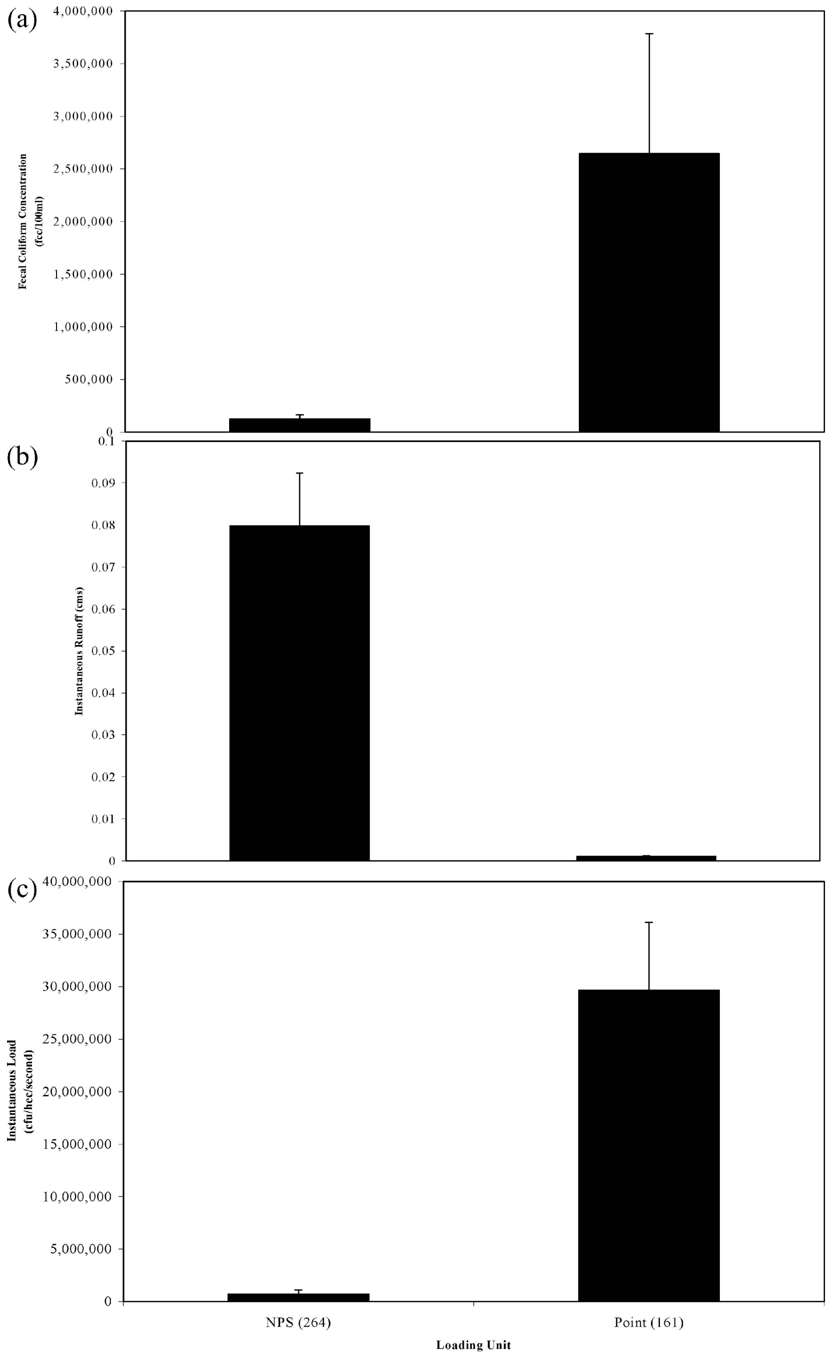

Figure 8. Comparison of point source and nonpoint source loading unit mean fecal coliform concentration (a), instantaneous runoff (b), and instantaneous fecal coliform load (c). Error bars represent the standard error.

instantaneous flow is lower ($p < 0.001$) than non-point source unit flow (Figure 8b). This difference is also true for mean storm runoff between point and non-point source units. Both sources represent areas that merit attention and management to improve water quality because of their respective mean fecal coliform instantaneous loads (Figure 8c) in comparison to control and tributary watershed values (Table II). However, it may be easier in the short term to mitigate point source units that generate the lower runoff volumes.

4. Conclusion

The application of a systems approach sampling and analysis program has generated water quality data at an appropriate scale to inform dairy managers on where to implement management measures to improve water quality. Comparison of results from a control watershed with those from watersheds containing dairies, indicate that there is increased loading from dairy watersheds. This had already been established in Tomales Bay through previous studies (O'Connell *et al.*, 2000). Similarly, comparison of results from upstream and downstream units indicate fecal coliform loading increases in a down gradient direction within the dairy watersheds. Neither of these two findings provides direction to the dairy operator on where to start efforts to reduce that loading.

Results from within the dairy operations, however, do identify patterns of fecal coliform concentration, storm runoff volumes, and potential loading amounts that are useful to prioritize remediation actions. The operator can weigh the options for where and what to implement in partnership with technical and financial assistance, based on the area of a given unit, the runoff that will be generated from it, and the concentration of fecal coliform in that runoff. In addition, the combination of concentration and flow to calculate load provides the land use manager with a standard per unit area per unit time measure to make fair comparisons of different facility areas or units.

The values of concentration, flow, and load associated with these units demonstrates patterns that are equally instructive. The high concentrations and loads for the material within the manure management system emphasized the value and importance of a functioning system to capture and store the material with the greatest potential to load fecal coliform to surface waters. Outside of those systems, dairy managers would get the greatest reduction in fecal coliform loading through reduction of concentrations and runoff generated from lots and stockpiles. Following lots and stockpiles attention should be given to pastures.

Concentration and load values from gutters are similar to those identified in upstream and control units indicating that, if this water can be kept separate from manure sources, it can be directed back into surface waterways. Results from storm drains and surface runoff identify that mixing of stormwater and manure sources may be occurring and that attention to the maintenance of storm drains will help to reduce and prevent this mixing and resulting deliver of bacteria to surface waters.

Any allocation of resources for water quality management should recognize that there are long and short-term priorities. One potential method to select these long and short-term priorities is to separate those areas with high total loads because of large storm runoff volumes from those with high total loads because of high concentrations. For example a 364-hectare pasture or upstream area could have a storm runoff volume of 10,480 cubic meters resulting from 1.9 cm of precipitation, and have a fecal coliform concentration of 8,222 cfu/100 ml. In comparison, a 1.2-hectare lot could have less than 8.6 cubic meters of storm runoff from the same storm with a concentration of 49,333,333 cfu/100 ml. The questions for management prioritization are which unit presents the greatest fecal coliform load and which would be the easiest to mitigate. This is an individual operation and case-by-case decision but with this smaller spatial scale water quality data in hand, the individual producer can make such decisions.

Prior to the availability of this systems approach data, these dairies had been singled out as a source of bacteria pollution to the bay without the information needed to reduce that loading. With this data in hand, these dairy producers are now prioritizing and implementing on-farm efforts to improve water quality. In addition, regulatory agency staff and agencies that provide technical and financial support are now working cooperatively to assist these dairies in their efforts, putting their resources where they will provide the most benefit. Practices being constructed through this partnership include sediment catch basins and vegetative buffers below lots and pastures, as well roof drainage systems to separate storm water from manure sources.

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