San Francisco Estuary Institute Regional Watershed Program

Human Influences on Nitrogen and Phosphorus Concentrations in Creek and River Waters of the Napa and Sonoma Watersheds, Northern San Francisco Bay, California.

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and
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EXECUTIVE SUMMARY

The Sonoma Creek and the Napa River watersheds are listed as impaired for nitrogen and phosphorus by the State of California in compliance with Section 303(d) of the Clean Water Act administered by the U.S. Environmental Protection Agency. In order to assist the State of California and local stakeholders to address concerns about nutrients, the San Francisco Estuary Institute carried out water sampling to determine the sources or causes of various forms of nutrients in flowing surface waters of the Sonoma Creek and the Napa River watersheds. With the help of stakeholders and oversight from the San Francisco Regional Water Quality Control Board, a sampling plan was devised that provided data to:

1. Determine seasonal nutrient concentrations in locations of human or environmental interest,
2. Interpret the data in the context of water quality guidelines and downstream accumulative impacts associated with the hypothesized stressors, and
3. Demonstrate a methodology that might be successfully applied to help address water quality problems in other parts of the State of California.

The basis of experimental design is encapsulated in the following null-hypothesis:

> $H_{(0)}$ Land use or human population have no influence on nitrogen or phosphorus concentrations in flowing water bodies within Sonoma Creek or Napa River watersheds.

The acceptance of the null-hypothesis would provide evidence that natural processes were the dominant cause of the observations, or in other words, of reasonable doubt that anthropogenic factors strongly influence water quality. Conversely, rejection of the null-hypothesis and development of alternate hypotheses would provide scientific rational for targeting problem areas.

The populations of the Sonoma Creek and Napa River watersheds enjoy a pleasant climate of warm dry summers and cool wet winters. These watersheds have a history of Euro-American agriculturally dominated land use starting during the Mission Era (1823). Despite this long history, land use is still dominated by open space, with agriculture (mainly vineyards) in a close second place. Most of the population lives in the cities of Sonoma, Calistoga, St. Helena, Yountville, and Napa where sewage is managed by collection and treatment facilities. However, many rural and rural-residential areas rely on septic systems for treatment of household wastewater. Soils are well suited for agriculture (evidenced by extensive wine production) but poorly suited for waste disposal using septic systems and filter fields.

During the initial *Characterization Survey*, water samples for analysis of nitrogen and phosphorus and ancillary parameters were collected on October 1-3, 2002, January 6-8, 2003, and July 7-8, 2003 from 39 locations. In addition, a *Hotspot Survey* was carried out on May 5-6, 2004 to better refine the spatial extent of elevated nutrient concentrations in areas of concern identified during the *Characterization Survey*. The Hotspot Survey included re-sampling six locations in Sonoma Creek watershed and adding a further six new sampling locations and re-sampling eight locations in Napa River watershed and adding a further 13 new sampling locations. All water quality data were generated using standard laboratory methods. In addition, GIS data layers were developed using 2000 human census data, ABAG land use, 10m digital elevations models (DEMs) and USGS blue lines.

During the *Characterization Survey*, NOx concentrations ranged from 0-3,162 µg/L, NO_2^- varied from 0-15 µg/L, NH_3 varied from 1-86 µg/L, total dissolved nitrogen varied from 59-4,076 µg/L,

PO_4^{3-} varied from 11-198 μg/L, and total dissolved phosphorus varied from 12-253 μg/L. High concentrations relative to published background concentrations in pristine watersheds of other parts of the world in addition to large spatial variation across the watersheds are primary indicators that $H_{(0)}$ should be rejected. Averaged across the two watersheds, NOx constituted 55% of TDN and PO_4^{3-} was ~60% of TDP and DON made up 45% of TDN and DOP made up only 36% of TDP. In pristine watersheds, 60-90% of nitrogen and >50% of phosphorus is usually locked up in organic matter, another indicator that $H_{(0)}$ should be rejected. Based on EPA guidelines in Level III Eco-Region 6 for TN (500 μg/L) and TP (30 μg/L), across the two watersheds 33 out of 39 locations exceeded the nitrogen guideline and 36 out of 39 locations exceeded the phosphorus guideline. Although exceedance of a guideline does not necessarily coincide with degraded stream health or loss of another beneficial use, these exceedances do help to suggest that in-stream productivity in these watersheds is not nutrient limited. Despite this, only six locations showed signs of increased water column productivity (chlorophyll-a concentration above background). We suggest that periphyton biomass (only observed qualitatively) may be the best indicator of excess nutrients in these watersheds.

NOx concentrations were highest in the winter months and gradually decreased as discharge in the rivers decreased. This pattern is consistent with the notion that non-point source runoff associated winter rainstorms dominate inputs of NOx into the stream networks. Patterns of NH_3 and PO_4^{3-} concentrations were less clear and probably reflect a wider variety of inputs at a lower magnitude and greater instream processing. Downstream trends were evaluated on the mainstems of each watershed. In downstream areas, nutrient concentrations, although elevated with respect of headwater reaches, do not increase systematically but appear instead to vary in response to near channel human population pressures and land uses.

In order to define more clearly the causes of spatial and temporal variation in the Napa River watershed, nutrient-land use relationships were tested using a statistical analysis (Kendall Tau b) and water quality and environmental variables data. Mainstem data were not included in this analysis because each data point is not completely independent from others upstream or downstream. There were too few data points (<4) to carry out this kind of statistical analysis on data from Sonoma Creek watershed. During the late summer/autumn sampling, NOx was negatively correlated with open space variables and did not correlate with urban or human population variables. In contrast, during the winter and early summer sampling periods, NOx correlated significantly with population and urban environmental variables. In addition, during the wet season only, NOx formed positive correlations with agricultural and commercial land use variables. These statistical correlations add support to the hypothesis that NOx mostly associated with urban land use and human populations in non-sewered areas of the watersheds, with additional sources entering the creek mainly during the wet season. NH_3 formed a positive correlation with commercial land use variables adding strength to the hypothesis that commercial land use maybe influencing the NH_3 concentrations in the mainstem of Sonoma Creek. There were no regional correlations found between environmental variables and PO_4^{3-}.

In order to further spatially constrain the occurrence of elevated nutrient concentrations on the mainstem and in some tributaries noted during the *Characterization Survey*, additional sampling locations were added during the *Hotspot Survey* conducted in May 2004. Two areas in Sonoma Creek and six areas in Napa River watersheds were discussed in most detail. Sonoma Creek near Kenwood in Sonoma Creek watershed was focused upon because of a year round source of NOx. The anomaly was isolated to the area downstream from Highway 12 and an unnamed tributary entering Sonoma Creek on the northwest side of town. The hypothesis was strengthened that the NOx is derived from septic waste disposal associated with the community of Kenwood. It was concluded the impact of the community of Kenwood is related to inappropriately sited septic systems, compounded by Kenwood's location in the watershed. However, particularly poor soil characteristics might be responsible for a continued sewage load into the late summer/autumn period – a phenomenon not observed in any other *Hotspot* in the Sonoma or Napa River watersheds. Nathanson Creek, flowing through the eastern side of the City of Sonoma, in the Sonoma Creek watershed was also re-sampled during the *Hotspot Survey*. It was concluded that water quality in Nathanson creek was mostly influenced by NOx, and to a lesser extent NH_3 and PO_4^{3-}, all sourced from dry weather urban runoff that could include exfiltration from sewer lines. There were probably additional inputs from rural areas upstream and downstream from the city during winter storms.

Napa River at Calistoga was selected because of elevated NOx and PO_4^{3-} concentrations during the *Characterization Survey*. Patterns of NOx and PO_4^{3-} were similar indicating a common source. The data support a hypothesis that water quality in this reach of Napa River is influenced by a treated sewage load downstream from Calistoga during the winter and spring in combination with dry weather flows from urban areas in Calistoga and downstream. The *Hotspot* on Bell Canyon Creek was solely identified by high NOx concentrations during the *Characterization Survey*. There is a small sewage treatment facility on the Creek with a zero-discharge permit receiving influent from the St. Helena Hospital. The data collected rejects the hypothesis that seepage from the treatment pond was causing the anomaly and supports a new hypothesis that septic systems are causing elevated NOx concentrations. Unlike the Kenwood situation, the anomaly is not observed during the late summer/ autumn period. The *Hotspot* on the Napa River within and downstream from the City of St. Helena was identified by anomalously high NOx concentration during the January and July 2003 sampling occasions of the *Characterization Survey*. The source of NOx to this reach of the Napa River occurs between Napa River at Pope Street and Napa River at Zinfandel Lane. Available data suggests that a treated sewage discharge is not the cause of the observed anomaly. There are about 1000 people outside of the City of St. Helena that influence that section of the creek. There is presently no explanation offered for the cause of elevated NOx concentrations on this reach of the Napa River but the NOx only anomaly is suggestive of septic system runoff. Salvador Channel draining the northwestern suburbs of the City of Napa showed elevated NOx concentrations during the *Characterization Survey*. The source was determined to be within the City boundary. At this time there is no cause offered but the signature is characteristic of other areas of the Sonoma and Napa River watersheds that are impacted by septic sewage; a NOx only anomaly present only during the winter, spring, and early summer sampling periods. The last *Hotspot* to be discussed was Tulucay Ck./Murphy Ck. characterized by both elevated NOx and PO_4^{3-} concentrations. The NOx anomaly appears to be associated with the urban area. The character of the PO_4^{3-} anomaly differs completely from that of NOx. PO_4^{3-} is found in greater concentrations in the upper watershed and during the dry season. No explanation is presently offered for the cause of the P anomaly in Murphy Creek but geologic sources could play a role. This would account for the clear indication that N and P in this subwatershed have different sources.

First order estimates of average nutrient loads were made for each watershed by combining flow data from the US Geological Survey with maximum nutrient concentrations observed for the gauge location. Background loads of NOx were estimated by combining the discharge data for each watershed with NOx concentrations in the most pristine areas of the watersheds. Total loads of nutrients passing the Napa River gauge were about 3-5 times greater than the loads passing the Sonoma gauge mainly because the gauged area is ~4 times larger and long term average discharge is ~3 times larger. The NOx load in these watersheds is estimated to be about 6 times greater than the historical natural condition.

ACKNOWLEDGEMENTS

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INTRODUCTION

Many watersheds in California are showing signs of degradation due to increased nutrient concentrations associated with agriculture, wastewater, urban runoff, or land development. Presently there are 88 watersheds listed as impaired for at least one form of nitrogen or phosphorus by the State of California in compliance with Section 303(d) of the Clean Water Act (SWRCB, 2002). Each river exhibits a unique combination of stressors in relation to natural and anthropogenic factors and will require system-specific data and interpretation prior to development of management solutions. The Sonoma Creek and the Napa River watersheds are two such listed water bodies. These watersheds were originally listed in 1988 because of the impacts of wastewater discharge on dissolved oxygen, coliform, and eutrophication. Since that time, the Sonoma wastewater treatment facility in the Sonoma Creek watershed and Calistoga, St. Helena, Yountville, and American Canyon wastewater treatment plants in the Napa River watershed have been upgraded to advanced secondary treatment. Despite these treatment advances, there are still many locations in these watersheds showing signs of eutrophication such as excessive algae and aquatic plant growth and concentrations of bio-available nutrients in excess of water quality guidelines. Agriculture, urban runoff, and improperly functioning septic sewage systems have been suggested as potential stressors, however there has been no systematic study to verify or define water quality problems and causes. The objectives of this study were to 1. Determine seasonal concentrations of nutrients in locations of human or environmental interest, 2. Interpret the data in the context of water quality guidelines and downstream accumulative impacts associated with the hypothesized stressors, and 3. Demonstrate a methodology that might be successfully applied to help address water quality problems in other parts of the State of California. The basis of experimental design is encapsulated in the following null-hypothesis:

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The acceptance of the null-hypothesis would provide evidence that natural processes were the dominant cause of the observations, or in other words, of reasonable doubt that anthropogenic factors strongly influence water quality. Conversely, rejection of the null-hypothesis and development of alternate hypotheses would provide scientific rational for targeting problem areas and developing management solutions.

BACKGROUND

Nitrogen and phosphorus are essential for cell structure and process and as such, are referred to as life limiting nutrients (Vollenweider, 1968; Odum, 1971). In near natural systems, the oxidized and most bio-available forms of these nutrients are necessary for maintaining normal ecosystem function and are usually found in relatively low concentrations; nitrate <440 μg N/L, average = 100-120 μg N/L (Meybeck, 1982; Lewis et al., 1999) and phosphate <24 μg P/L, average = 8 μg P/L (Meybeck, 1982). Agriculture and urban land use are the leading disturbance of natural cycles and cause increased release of nutrients into surface drainages. Today, nitrate concentrations in some polluted systems exceed 3,000 µg N/L and phosphate concentrations can exceed 200 µg P/L (Meybeck, 1982). Excess nutrients can cause excessive growth of algae and toxicity associated with some varieties of blue–green algae especially in coastal water bodies and lakes (Vollenweider, 1968; Hopkinson Jr. and Vallino, 1995). Toxic algal blooms are less common in rivers except in very large systems or in reaches where water velocity is slow. In contrast, changes in the number and diversity of phyto-benthos in rivers are commonly discussed in relation to nutrient concentrations and other environmental gradients (Biggs et al., 1990; Leland and Porter, 2000; Biggs, 2000; Leland et al., 2001; Munn et al., 2002; Snyder et al., 2002).

In many watersheds, the extent and intensity of agriculture is known to correlate spatially and temporally with nitrogen and phosphorus concentrations in creeks and rivers (Hagebro et al., 1983; Edwards et al., 1990; Bolstad and Swank, 1997; Spahr and Wynn, 1997; McKee et al., 2001). The process of nutrient release is different for each nutrient, and for differing agricultural land uses in differing physical settings. Phosphorus has a high affinity to soil particles and commonly >50% is transported into streams and rivers in association with particles during rainstorms (Cosser, 1989; Arheimer and Lidén, 2000; McKee et al., 2000). Agricultural practices that exacerbate soil erosion and include the application of fertilizers tend in lead to increased phosphorus concentrations in adjacent and downstream waterways (Daly et al., 2002; Stålnacke et al., 2004). The agricultural nitrogen system is more complex and includes fluxes to and from the atmosphere and losses to subsurface soils and groundwater (Arheimer and Lidén, 2000; McKee and Eyre, 2000). Most nitrogen (>70%) is transported into adjacent waterways in dissolved forms (McKee et al., 2000). Agricultural practices that enhance mineralization of soil nitrogen, nitrogen fixation, erosion of soils rich in organic matter, that produce animal products, or that include fertilizer applications tend in cause increases in nitrogen concentrations in the adjacent waterways (Walling and Foster, 1978; Vagstad et al., 1997).

Disposal of domestic wastewater can be achieved through either centralized treatment facilities and associated sewer systems or the use of a septic tank and filter field on a per dwelling basis. Any impacts of treated wastewater discharge from centralized sewage treatment usually occur when the volume of treated wastewater is proportionally large compared to flow in the receiving waters. Under climatic regimes with a pronounced dry season or during droughts, water quality in the receiving waters may vary greatly between seasons and between years (e.g. Johnson et al., 1976; Muscutt and Withers, 1996; McKee et al., 2001). Wastewater treatment facilities in the Napa River watershed discharge between November and May only. Effluent concentrations in wastewater discharge at the Calistoga and St. Helena treatment facilities range between 3,200-12,200 µg N/L and 500-1,500 µg P/L. The impact of non-centralized domestic wastewater treatment in agricultural areas is often overlooked in studies of land use in relation to water quality perhaps because septic system impacts are thought to be overshadowed by inputs of nutrients from fertilizer use, septic impacts are hard to quantify, and because it is assumed that the septic system technologies work properly. However, in watersheds where agricultural practices use little or no fertilizer augmentation, in urbanized watershed devoid of centralized wastewater treatment or where sandy soils or high groundwater tables lead to failures of septic tank or filter field systems, the nutrient input from domestic wastewater may be proportionally large (Johnson et al., 1976; Pilleboue and Dorioz, 1986; Valiela and Costa 1988). The impacts to surface waters tend to be greater for nitrogen relative to phosphorus because of the ability for soils to adsorb phosphorus (e.g. Hoare, 1984; Gerritise et al., 1995). Reported nitrate concentrations found in ground waters adjacent to the leach field of septic systems are 12,300 µg N/L in sandy soils of Western Australia (Sewell, 1982) and 3,080-11,440 µg N/L nitrate+nitrite under sandy soil conditions in Florida (Lapointe et al., 1990). Concentrations of phosphorus near septic leach fields were 30 µg P/L for Western Australia and 537 and 198 µg P/L for Florida dry and wet seasons. In the sandy soil conditions of Florida, ammonia concentrations are also high 7,030-10,980 µg N/L (Lapointe et al., 1990) but in most other studies that exhibit high nitrate leaching, high concentrations of ammonia are less common (e.g. Hoare, 1984) because nitrification usually occurs in oxygenated shallow ground waters (Lapointe et al., 1990).

Nutrients in urban areas derive from a range of sources including combustion, decomposition of green waste, fertilizer use, food stuffs, cleaning agents, pet manures, leaking sewers, eroding construction sites, abrasion and corrosion, and the atmosphere. Unlike urban wastewater, urban stormwater is difficult to treat at the catchment scale because of flow variability, large volumes during rainstorms, and the diffuse and illusive nature of nitrogen and phosphorus sources. Yet, in some cases, concentrations of phosphorus in urban stormwater can exceed the effluent standards in modern wastewater treatment facilities. For example, Cowen and Lee (1976) observed concentrations of particulate phosphorus ranging from 14-2,850 µg P/L in urban areas of Madison, Wisconsin; the highest concentrations were observed in areas with ongoing construction. Other studies include: urban areas in Auckland and Hamilton, New Zealand (total phosphorus concentrations from 11-1,022 µg P/L and total nitrogen concentrations from 439-5,730 µg N/L), metropolitan Porto Alegre, Brazil (total phosphorus concentrations from 8-2,580 µg P/L and nitrates concentrations from 200-12,610 µg N/L), a suburban town in subtropical Australia (total phosphorus concentrations ranging from 240-1,790 µg P/L and total nitrogen concentrations ranging from 570-2,720 µg N/L) (Williamson, 1986; de Luca et al., 1991; Kerr and Eyre, 1995). Compare these to effluent concentrations in treated wastewater at Calistoga and St. Helena sewage treatment facilities in the Napa River watershed (3,200-12,200 µg N/L and 500-1,500 µg P/L). Thus, non-point source urban runoff can be a significant source of nutrients to rivers especially when point sources have been reduced or eliminated though secondary or tertiary treatment.

METHODS

Location

The Napa River and Sonoma Creek watersheds are located at the northern end of San Francisco Bay and cover a combined area of about 1,500 km^2 (Figure 1). The dry summer sub-tropical climate of these watersheds is typified by warm summers (City of Sonoma July mean daily maximum = 32 ºC; City of Napa July mean daily maximum = 28 ºC) and cool winters (January mean maximum = 14 ºC) (Figure 2). Rainfall is winter dominated and runoff is mostly uncontrolled and follows a similar pattern to rainfall (Figure 2).

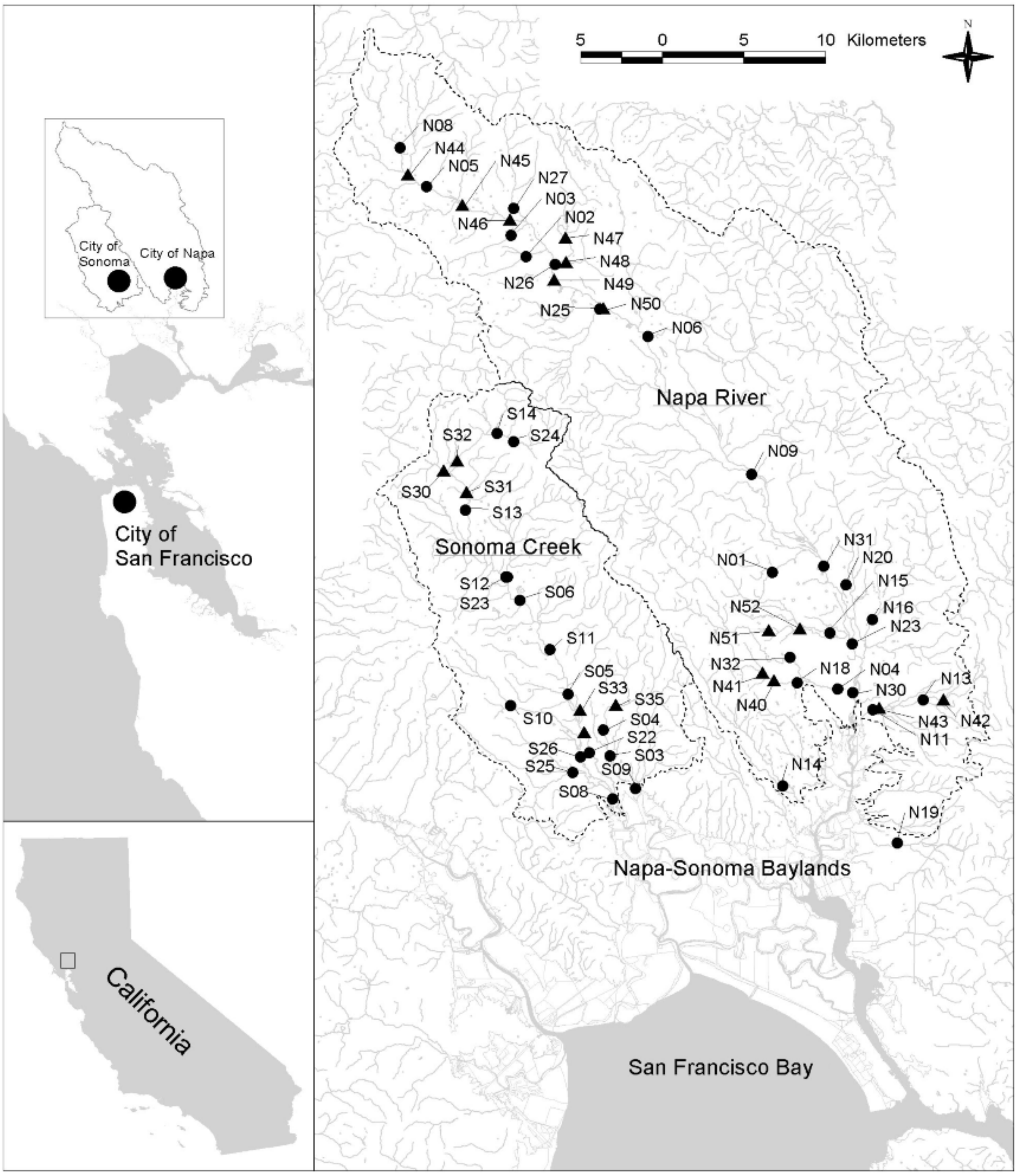


Figure 1. Study area and locations of sample capture. *Characterization Survey* (October 2002, January 2003, and July 2003) (●); *Hotspot Survey* (May 2004) (▲).

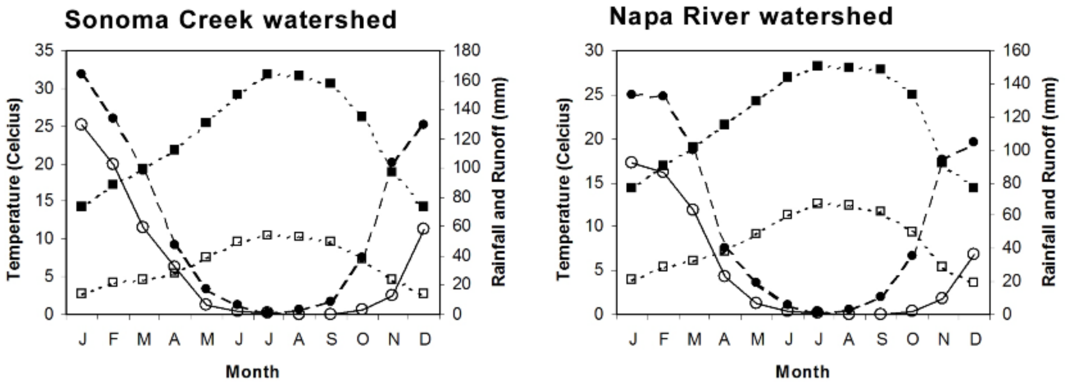


Figure 2. Climate of the study area. Mean monthly temperature maximum (-■-); Mean monthly temperature minimum (-□-); Rainfall in the town of Sonoma or the City of Napa (–●–); Runoff at Sonoma Creek Agua Caliente USGS 11458500 or Napa River Oak Knoll Avenue USGS 11458000 (–○–).

On average, rainfall occurs on just 65 days per year (rainfall is defined as accumulated rainfall on a day ≥0.254 mm/d). Topography, ranges from sea level to 850 m in Sonoma Creek watershed and 1,324 m in Napa River watershed and strongly influences spatial patterns or rainfall and runoff. Annual rainfall in the headwaters of Sonoma Creek and Napa River averages 1,000 and 1,200 mm respectively and extremes likely reach >2000 mm at the highest elevations during very wet years.

The Sonoma Creek watershed is underlain by Sonoma Volcanics (Pliocene inter-bedded flows of locally welded tuff breccias, welded tuff, agglomerate, and andesitic and basaltic flow rocks) and Petaluma Formation (Pliocene brackish water deposits of clay, shale sandstone, nodular limestone, and conglomerate). The geology of the Napa River watershed includes Jurassic-Cretaceous Franciscan complex (a sandstone with smaller amounts of shale, chert, limestone and conglomerate), Great Valley Sequence (Cretaceous forearc basin fill consisting of sandstone, shale and conglomerate), and Sonoma Volcanics. The valley floor or both watersheds consists of older and younger alluvium deposits that include some cemented lenses. Both watersheds are crossed by active faults that fracture bedrock, disrupt aquifers, and contribute to a high incidence of landslides and debris flows during prolonged or high intensity rainfall. In both watersheds, the majority of people reside and agricultural pursuits occur on the valley floors. Soils on the Sonoma Valley floor range from well drained to excessively drained gravelly sandy loams to clay loams in the upper valley to somewhat poorly drained to well drained loams to silty clay loams in the middle and lower valley (USDA, 1972). The valley floor of Napa is characterized by well drained to somewhat poorly drained loams, silt loams, and clay loams (USDA, 1978). Soils on the valley floors of both Napa and Sonoma watersheds have “severe” limitation for development of reliable septic adsorption fields. Soils properties such as permeability, seasonally high water table, thickness, and susceptibility to flooding must be overcome with special design and regular maintenance of septic systems (USDA, 1978).

Land use and population data were compiled and summarized to describe the overall land management pressures in the watersheds (Table 1). Although the Napa River watershed population in areas upstream of the sampling locations is almost twice as numerous as the Sonoma Creek watershed, when area of open space is excluded from the calculations, the population densities are very similar. Both watersheds have similar proportions of their watersheds areas in agriculture, commercial and industrial land uses. These watersheds have a history of Euro-American agriculturally dominated land use starting during the Mission Era (1823) (Grossinger et al., 2004). Despite this long history, land use is still dominated by open space, with agriculture (mainly vineyards) and small areas of dairy (Sonoma Only) and beef grazing in a close second place.

Table 1. Overview of land use in Sonoma Creek and Napa River watersheds. Statistics are based on ABAG 2000 land use data and 2000 census data.

		Sonoma Creek watershed		Napa River watershed	
		Sampled Area (km^2)	Percentage (%)	Sampled Area (km^2)	Percentage (%)
Agriculture		94	33	257	34
Developed	Commercial	13	5	25	3
	Industrial	9	3	20	3
	Urban	74	26	62	8
Open		94	33	400	52
Total		284	100	764	100
Population (individuals)		42,404		82,423	
Population Density (persons / km^2)		152		108	
Population Density (persons / km^2)		223*		226*	

*Population density if the area of open space is excluded from the calculation.

Sampling

Water samples for analysis of nitrogen and phosphorus were collected on three occasions during 2002 and 2003. A total of 39 locations were visited during this, our "Characterization Survey" (16 locations in the Sonoma Creek watershed and 23 locations in the Napa River watershed) (Figure 1). The first set of samples was gathered on October 1st, 2nd, and 3rd 2002 and represented late summer/ autumn very low flow conditions (Figure 2). During that sampling event, sample capture was limited by lack of surface flow at many locations. As such, only 8 out of the potential 16 samples were captured in the Sonoma Creek watershed (Table 2) and only 17 out of the potential 23 samples were captured in the Napa River watershed (Table 3). The second sampling event (with 100% sample capture) occurred on January 6th, 7th, and 8th 2003 about 8-10 days after a winter storm peak and on the eve of a subsequent rainstorm. The objective of this sampling event was to characterize water quality conditions during a winter stable flow period. The 3rd sampling event was completed during July 7th and 8th 2003 and represented mid summer water quality conditions. Sample capture was partially limited

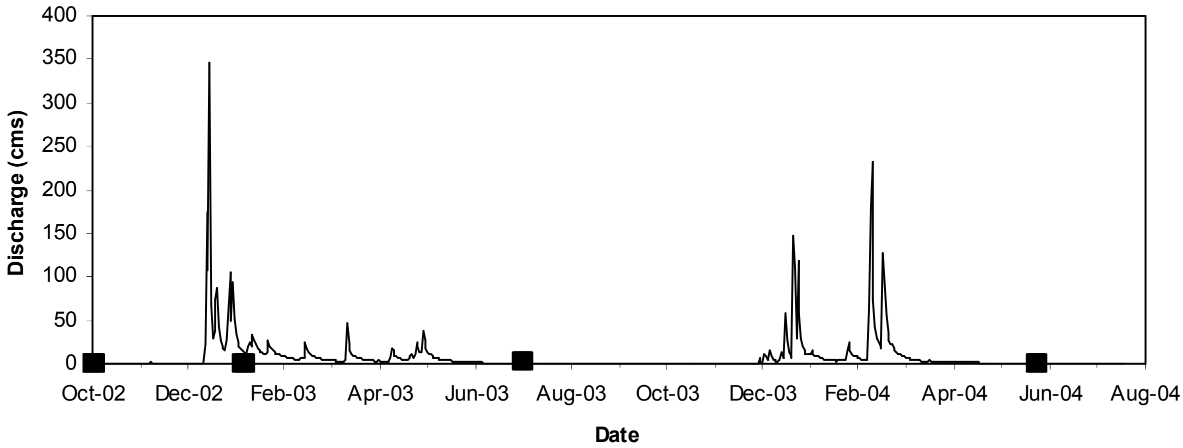


Figure 2. Climatic variation relative to sampling (■) in the Sonoma Creek and the Napa River watersheds during water year 2003 and 2004. Discharge (m^3/s) for Napa River at Oak Knoll Avenue (USGS 11458000 published data) is displayed for illustrative purposes. Broad seasonal variation in hydrology is similar in both watersheds.

Table 2. Sampling locations in Sonoma Creek watershed. X = sample taken.

Station	Description	Oct 2002	Jan 2003	Jul 2003	May 2004	Comments
S-3	Nathanson Ck. @ Watmaugh		X	X	X	Cattle grazing and watering
S-4	Nathanson Ck. @ Nathanson Park		X	X	X	Public park and playground
S-5	Sonoma Ck. @ Maxwell Park	X	X	X	X	Public park and playground, swimming
S-6	Sonoma Ck. near Sonoma Ecology Center	X	X	X		Salmonid habitat, urban
S-8	Sonoma Ck. @ Hwy 121	X	X	X		Flood conveyance
S-9	Schell Ck. @ Hwy 121		X	X		Cattle grazing and watering
S-10	Carriger Ck. @ Marilyn Goode's property	X	X			Perennial flow
S-11	Sonoma Ck. @ Agua Caliente	X	X	X		Salmonid habitat, teenage refuge, graffiti
S-12	Sonoma Ck. @ Glen Ellen	X	X	X		Homeless refuge area
S-13	Sonoma Ck. on Warm Springs Rd.	X	X	X	X	Salmonid habitat
S-14	Sonoma Ck. @ Goodspeed Bridge	X	X	X	X	Perennial flow
S-22	Sonoma Ck. @ Watmaugh		X	X	X	Flood conveyance
S-23	Calabazas Ck. @ Glen Ellen		X	X		Homeless refuge area
S-24	Sonoma Ck. above tent park		X	X		Perennial flow
S-25	Rogers Ck. @ Arnold Drive		X			Rural
S-26	Carriger Ck. @ Watmaugh		X	X		Rural
S-30	Unnamed Tributary @ Lawndale Ave.				X	Mixed land use / Urban fringe
S-31	Sonoma Ck. @ Mound Ave				X	Downstream of the community of Kenwood
S-32	Sonoma Ck. @ Hwy 12				X	Upstream from the community of Kenwood
S-33	Sonoma Ck. @ Andrieux St.				X	Adjacent to the City of Sonoma
S-34	Sonoma Ck. @ Leveroni Rd.				X	Downstream from the City of Sonoma/ Agriculture
S-35	Nathanson Ck. @ 4th St.				X	Urban

Table 3. Sampling locations in Napa River watershed. X = sample taken.

Station	Description	Oct 2002	Jan 2003	Jul 2003	May 2004	Comments
N-1	Dry Ck. @ Railroad Bridge		X	X		Flood conveyance
N-2	Mill Ck. @ the old Bale Mill	X	X	X		State historic park
N-3	Ritchey Ck. nr. Bothe State Park	X	X	X		Camping, horse riding
N-4	Napa Ck. @ Jefferson	X	X	X	X	Flood conveyance, urban
N-5	Napa R. @ Calistoga Community Center	X	X	X	X	Public park and playground, urban
N-6	Napa R. @ Zinfandel Lane	X	X	X	X	Salmonid habitat, swimming
N-8	Napa R. @ Tubbs Lane		X	X		Salmonid habitat
N-9	Napa R. @ Yountville Ecopreserve	X	X	X		Salmonid habitat, swimming, bird watching
N-11	Tulukay Ck. @ Terrace Court		X	X	X	Flood conveyance, kids play area, urban
N-13	Murphy Ck. @ "Stone Bridge" on Coombsville Rd.	X	X	X	X	Salmonid habitat, rural
N-14	Carneros Ck. @ Withers		X	X		Flood conveyance, kids play area
N-15	Salvador channel @ Garfield Park	X	X	X	X	Public park, baseball
N-16	Milliken Ck. @ Hedgeside Avenue	X	X	X		Grazing
N-18	Browns Valley Ck. @ "Little Stone Bridge"	X	X	X	X	Suburban/ rural residential
N-19	Fagan Ck. @ Kelly Rd.	X	X	X		Cattle and horse grazing, golf course
N-20	Soda Ck. @ Silverado Trail		X			Flood conveyance, salmonid fish ladder
N-23	Napa R. @ Trancas St.	X	X	X		Near upper limit of tide
N-25	Sulphur Ck. @ Lower Bridge near Trailer Park	X	X	X		Flood conveyance, trailer park
N-26	Bell Canyon Ck. @ Silverado	X	X	X	X	Adjacent to sewage treatment pond
N-27	Dutch Henry Ck. @ Larkmead Lane Bridge		X			Vineyards
N-30	Napa R. @ 3rd St.	X	X	X		Town riverside park
N-31	Napa R. @ Oak Knoll Ave.	X	X	X		Salmonid habitat
N-32	Redwood Ck. @ Redwood Road		X	X		Homeless refuge
N-40	Browns Valley Ck. @ Buhman Ave.				X	Mixed land use / Urban fringe
N-41	Browns Valley Ck. @ Morningside Dr.				X	Mixed land use / Urban fringe
N-42	Murphy Ck. @ Shady Brook Ln.				X	Agriculture / Open space
N-43	Tulukay Ck. @ Shurtleff Ave.				X	Mixed land use / Urban fringe
N-44	Napa R. @ Heather Oaks Park				X	Upstream from the town of Calistoga
N-45	Napa R. @ Dunaweal Ln.				X	Downstream from Calistoga / adjacent to WWTP
N-46	Napa R. @ Larkmead Ln.				X	Downstream from Calistoga WWTP
N-47	Bell Canyon Ck. @ Crystal Springs Rd.				X	Upstream from Glass Mountain WWTP
N-48	Canon Ck. @322 Glass Mountain Rd.				X	Upstream from Glass Mountain WWTP
N-49	Napa R. @ Lodi Ln.				X	Upstream from the City of St. Helena
N-50	Napa R. @ Pope St. Saint Helena				X	Adjacent to the City of St. Helena
N-51	Salvador Channel @ 2280 Dry Ck. Rd.				X	Mixed land use / Urban fringe
N-52	Salvador Channel @ Hwy 29 near school				X	Urban

by lack of surface water as some locations. As such, only 14 out of the potential 16 samples were captured in the Sonoma Creek watershed and only 21 out of the potential 23 samples were captured in the Napa River watershed. In addition, sampling was carried out on May 5th and 6th 2004 to better refine the spatial extent of elevated nutrient concentrations in selected areas in each watershed identified during the *Characterization*

Survey. This follow up "Hotspot Survey" included re-sampling six locations in Sonoma Creek watershed and adding a further six new sampling locations and re-sampling eight locations in Napa River watershed and adding a further 13 new sampling locations.

At each location, a one-liter water sample was captured by hand dipping a triple sample rinsed sampling bottle into the water column mid-stream and mid-depth. Given low stream turbidity during all sampling events (maximum = 35 NTU, median = 4 NTU), this method was deemed entirely adequate for capturing a representative sample from the water column (e.g., McKee et al., 2001). At two locations (Sonoma Creek at Hwy 121 and Napa River at 3rd Street), water depth was beyond wading depth during all sampling events due to tidal influences. Water samples were captured at these locations by passing a weighted triple rinsed sampling bottle into the water column using a 20 m nylon rope aiming for an even fill throughout the water column. Turbidity was immediately analyzed using a Hach 2100p turbidity meter calibrated on the eve of the sampling event. Immediately following sample capture, the sample was processed in the following manner onsite. All sample receptacles were triple rinsed with either unfiltered or filtered water as appropriate. The one-liter water sample was mixed chaotically each time water was drawn. Using a triple sample rinsed 50 mL syringe, two 45 mL sub-samples were captured for total nitrogen and total phosphorus analyses. Using forceps, a 0.45 micron pre-combusted GF/F filter was then loaded into the filter holder and used to sample rinse and capture sub-samples for nitrate, nitrite, and phosphate and ammonia analyses. All sub-sample receptacles were caped tightly, labeled, bagged for easy sorting at the laboratory and placed on ice in the dark at 4°C. During the October 2002 and January 2003 sampling events, a sub-sample was taken for analysis of chlorophyll-a by loading (using forceps) a non-combusted GF/F filter into a filtering cup and passing 50 mL of whole water through the filter using about 5-10 kpa of vacuum. The filter was then removed from the filtering cup with forceps, folded in half and placed into a 13 mm glass test tube. The tube was labeled and wrapped in aluminum foil, placed on ice and kept in the dark. With the exceptions of the chlorophyll-a sub-samples, at the end of each day, the samples were transferred into a freezer where they were frozen at approximately -20°C. The sub-samples for chlorophyll-a were refrigerated at approximately 4°C.

Laboratory Analysis

Samples were analyzed at the Romberg Tiburon Centers for Environmental Studies, San Francisco State University. With the exception of ammonia, all analyses for forms of nitrogen and phosphorus were performed using a Bran and Luebbe AutoAnalyzer II. Analyses for nitrate + nitrite (NOx-N) were achieved using field-filtered samples and colormetric methods (copper-cadmium reductor column + sulfanilamide +NED, colorimeter with 540 nanometer interference filters) (Bran and Luebbe Method G-172-96). Nitrite (NO_2^--N) was determined in the same manner without copper-cadmium reduction. Phosphate (PO_4^{3-}P) analyses were performed on field-filtered samples using standard colormetric methods (molybdate ion and antimony ion + ascorbic acid under acidic conditions (pH<1), colorimeter with 880 nanometer interference filters (Bran and Luebbe Method G-175-96). Total dissolved nitrogen (TDN-N) and total nitrogen (TN-N) were analyzed using a modification of the method described by Solórzano and Sharp

(1980a). Field filtered water samples (0.45 micron) (TDN-N) and raw water samples (TN-N) were oxidized using a persulphate and sodium hydroxide solution and an autoclave. After oxidation, hydrochloric acid and an NH_4Cl/ NH_4OH buffer were used to prepare the samples for colormetric analysis following the method outlined above for NOx-N. Total dissolved phosphorus (TDP-P) and total phosphorus (TP-P) were analyzed using a modification of the method described by Solórzano and Sharp (1980b). Field filtered water samples (0.45 micron) (TDP-P) and raw water samples (TP-P) were treated using magnesium sulphate and high temperature to decompose organic phosphorus compounds. After decomposition, the residue is then treated with HCL hydrolyze polyphosphates and prepare the samples for colormetric analysis following the method outlined above for phosphate. Analysis for ammonia + ammonium (designated NH_3-N in the report hereafter) was carried out using a field-filtered sample using calorimetric methods (alkaline citrate medium + sodium hypochlorite and phenol + sodium nitroprusside) (Solórzano, 1969; Strickland and Parsons, 1972). The samples were allowed to sit in the dark for a minimum of 3 hours while a colormetric reaction took place and then read on a single diode-array spectrophotometer at a wavelength of 640 nm. Dissolved organic nitrogen (DON-N) and dissolved organic phosphorus (DOP-P) were determined by subtraction. Analysis of chlorophyll-a followed the methods of Smith, et al. (1981). Briefly, 8 milliliters of 90% spectra-analyzed acetone were added to each cuvette containing a filter. Samples were then vortexed for 10 seconds and frozen for 24 hours. After 24 hours, samples were allowed to come to room temperature, and processed on a Turner Designs 10-AU bench-top fluorometer, which had been calibrated with Sigma chlorophyll standard.

GIS and Statistical Analysis

A Geographic Information System (GIS) was utilized to develop data on environmental variables that might explain patterns of nutrient concentrations in the watersheds. Three different methods where used to model the "footprint" that could influence the water quality at each sampling location. The first footprint was defined as the entire subwatershed that drains to a sample location. The second footprint was defined as the watershed that drains to the stream within 5 km upstream from the sample location. This was chosen because it is known that nutrients can undergo instream transformations (such as assimilation). The watershed literature also describes a 3^{rd} scenario in which land use within the near stream environment is more connected and therefore influences water quality more profoundly (e.g. Johnes and Heathwaite, 1997). Therefore, the third footprint was created that captured everything within 50 meters of all of the streams that drain to a sample location.

The sampling locations were positioned in the field using a Garmin III GPS with an accuracy of ± 20 m. Watersheds / footprints were generated using these GPS locations as pour points along with the USGS' 10 meter resolution Digital Elevation Model (DEM) for the San Francisco Bay Area. USGS 24K Digital Line Graphs (DLG) where used for the base stream coverage and to select all streams contributing to the sample location. Environmental variables were developed for each sample location watershed / footprint using land use data developed by the Association of Bay Area Governments' (ABAG)

2000 Land use data (ABAG, 2000), and population statistics from the U.S. Census Bureau's 2000 Census (U.S. Census Bureau, 2000) (Table 4).

To evaluate the potential covariance of environmental variables with nutrient concentrations and other water quality parameters, Kendall Tau b correlation coefficients were calculated (SAS. 2002, V.5.) on the ranks of data collected in tributaries of Napa River during three sampling events. Correlation coefficients were greater than zero when ranks of both variables increased. Conversely, coefficients were less than zero when ranks varied in opposite directions (an inverse correlation). Correlations between two variables were considered significant with p-values less than 0.05.

RESULTS AND DISCUSSION

Quality Assurance

Concentrations below the detection limits were reported as zero. During the study, blanks were taken using Milli-Q^{TM} water. One field blank was taken during each of the four sampling events. Laboratory blanks were run specifically to distinguish between potential contamination prior to analysis and during analysis. In all instances, field and laboratory blanks were <1.5x the detection limits indicating no adverse contamination of any samples. One field duplicate sample was taken during each of the four field-sampling events. Mean and standard error were calculated on each occasion and on all occasions precision was within acceptable limits. All duplicate analyses were < ±30%; 65% of the duplicate analysis < ±10%). The standard errors averaged 6 µg/L for NOx, 14 µg/L for NO_2^-, 9 µg/L for NH_3, 4 µg/L for PO_4^{3-}, 5 µg/L for TDN and 11 µg/L for TDP. This level of precision is typical of nutrient concentration analyses in natural waters.

Spatial Variation and Water Quality Guidelines

Detectable concentrations of NH_3, and PO_4^{3-} were measured in both watersheds at all locations on at least one sampling occasion during the *Characterization Survey* (Table 5). NOx was below the detection limit (0.5 µg/L) at locations S-8 and N-9 (Oct-02), and N-14 (Jul-03), and NO_2^- was below detectable concentrations in 26% of the samples in Sonoma Creek watershed and 32% of the samples in Napa River watershed. Even at locations characterized by >75% open space land use (S-14, N-1, N-2, N-3, and N-8), NOx concentrations range from 3-614 µg/L, NH_3 concentrations range from 2-7 µg/L and PO_4^{3-} concentrations range from 9-81 µg/L. The spatial variation of NOx, NH_3, and PO_4^{3-} concentrations was slightly greater in Napa River watershed relative to Sonoma Creek watershed. Overall, concentrations of NOx and PO_4^{3-} are well in excess of published data on pristine watersheds in other parts of the world (Meybeck, 1982; Lewis et al., 1999).

Spatial nutrient concentration variation in Sonoma Creek and Napa River watersheds indicate varying human influences. On average, NOx constituted 52% and 56% of TDN in Napa River and Sonoma Creek watersheds respectively. On average, PO_4^{3-} was 68% and 59% of TDP in Sonoma and Napa respectively. TN and TP were

Table 4. Environmental variables generated from the GIS analysis.

Short Name	Description of the Environmental Variable
Total_AREA	Total subwatershed area upstream from the sampling location
Total_POP	Total human population upstream from the sampling location
Total_AGRI	Area in agriculture upstream from the sampling location
Total_COMM	Area in commercial land use upstream from the sampling location
Total_INDU	Area in industrial land use upstream from the sampling location
Total_OPEN	Open space area upstream from the sampling location
Total_URBA	Urbanized area upstream from the sampling location
Total POPden	Human population density in the subwatershed upstream from the sampling location
Total_AGRI%	Percentage of land in agriculture upstream from the sampling location
Total_COMM%	Percentage of land in commercial land use upstream from the sampling location
Total_INDU%	Percentage of land in industrial land use upstream from the sampling location
Total_OPEN%	Percentage of open space land upstream from the sampling location
Total_URBA%	Percentage of land in urban land use upstream from the sampling location
5km_AREA	Subwatershed area that drains to the stream within 5 km upstream from the sampling location
5km_POP	Human population within the subwatershed area that drains to the stream within 5 km upstream from the sampling location
5km_AGRI	Area of agriculture within the subwatershed area within 5 km upstream from the sampling location
5km_COMM	Area of commercial land use within the subwatershed area within 5 km upstream from the sampling location
5km_INDU	Area of industrial land use within the subwatershed area within 5 km upstream from the sampling location
5km_OPEN	Open space area within the subwatershed area within 5 km upstream from the sampling location
5km_URBA	Urban land use area within the subwatershed area within 5 km upstream from the sampling location
5km_POPden	Human population density within the subwatershed area that drains to the stream within 5 km upstream from the sampling location
5km_AGRI%	Percentage of land in agriculture within the subwatershed area within 5 km upstream from the sampling location
5km_COMM%	Percentage of land in commercial land use within the subwatershed area within 5 km upstream from the sampling location
5km_INDU%	Area of industrial land use within the subwatershed area within 5 km upstream from the sampling location
5km_OPEN%	Percentage of open space area within the subwatershed area within 5 km upstream from the sampling location
5km_URBA%	Percentage of urban land use area within the subwatershed area within 5 km upstream from the sampling location
50m_buffer_AREA	Subwatershed area that drains to the stream from a 50 m buffer in each bank of the total channel length upstream from the sampling location
50m_buffer_POP	Human population living within 50 m of the channel upstream from the sampling location
50m_buffer_AGRI	Area of agriculture within 50 m of the channel upstream from the sampling location
50m_buffer_COMM	Area of commercial land use within 50 m of the channel upstream from the sampling location
50m_buffer_INDU	Area of industrial land use within 50 m of the channel upstream from the sampling location
50m_buffer_OPEN	Area of open space within 50 m of the channel upstream from the sampling location
50m_buffer_URBA	Area of urban land use within 50 m of the channel upstream from the sampling location
50m_buffer_POPden	Human population density within 50 m of the left and right bank of the channel upstream from the sampling location
50m_buffer_AGRI%	Percentage of land in agriculture within 50 m of the channel upstream from the sampling location
50m_buffer_COMM%	Percentage of land in commercial land use within 50 m of the channel upstream from the sampling location
50m_buffer_INDU%	Percentage of land in industrial land use within 50 m of the channel upstream from the sampling location
50m_buffer_OPEN%	Percentage of land area in open space within 50 m of the channel upstream from the sampling location
50m_buffer_URBA%	Percentage of land area in urban land use within 50 m of the channel upstream from the sampling location

Table 5. Summary of nutrient concentrations (µg/L) in Sonoma Creek and Napa River watersheds observed during the Oct-02, Jan-03, and Jul-03 sampling events.

	NOx	NO_2^-	PO_4^{-3}	NH_3	TDN	TDP
Sonoma						
Minimum	0	0	11	1	125	30
Maximum	2,163	15	180	64	4,076	253
Mean	660	2	61	13	962	93
5-percentile	2	0	28	3	154	46
95-percentile	1,619	9	131	40	2,504	206
Napa						
Minimum	0	0	7	2	59	12
Maximum	3,162	13	198	86	3,273	174
Mean	619	3	44	15	836	64
5-percentile	3	0	10	2	128	23
95-percentile	2,090	9	88	49	2,147	130

usually indistinguishable from TDN and TDP, respectively, indicating that the concentrations of particulate nitrogen and particulate phosphorus were near zero in these watersheds under the stable flow conditions sampled. This also suggests that there was only a very small mass of organic matter/algae in the water column corroborated by the fact that few samples had chlorophyll-a concentrations >1µg/L. TN and TP will not be discussed any further. The ratio of NOx : DON has been used as an indicator of anthropogenic nutrient loads in watersheds (e.g. Edwards et al., 2000). In pristine watersheds, most nitrogen (60-90%) and phosphorus (>50%) is locked up in organic matter (Meybeck, 1982). On average, DON made up 45% of TDN and DOP made up only 36% of TDP in our study watersheds, a further indication of anthropogenic impact outside of natural processes. The spatial variation and forms of nutrients indicate human influences on water quality in both watersheds.

Water quality guidelines have been developed by a number of agencies usually in support of regulatory framework to protect water from the impacts of development of urban, commercial, industrial, or agricultural land uses. The San Francisco Bay Basin (Region 2) Water Quality Control Plan (RWQCB 2007) provides a threshold criterion guideline for agricultural supply for NOx of 5,000 µg/L. All samples collected during stable flow conditions in Sonoma Creek ad Napa River watersheds were below this guideline. A body of literature indicates that nitrate (NO_3^-) may also be chronically toxic to aquatic life, especially fish and amphibian eggs, at concentrations as low as 1,100 µg/L (Kincheloe et al., 1979; Crunkilton, 2000). In the Sonoma Creek watershed during the *Characterization Survey*, 33% of all samples and 72% of the locations exceeded this concentration at least once (Figure 3). In the case of the Napa River watershed, 20% of all samples and 43% of the locations exceeded this concentration at least once.

The San Francisco Bay Basin (Region 2) Water Quality Control Plan does not provide objectives for total ammonia, however the EPA Office of Water provided an update on guidelines for ammonia in 1998 (EPA, 1998) that describe numeric objectives for water bodies where salmonid species are present and absent. The Criterion Maximum

Concentration or CMC, which applies to short (acute) exposure, and the Criterion Continuous Concentration or CCC, which applies to longer (chronic) exposure, varies primarily with pH and the type of fishery involved. In waters with lower pH, total ammonia nitrogen concentrations can be greater without proven detriment (trauma) to coldwater fish species (salmonids for example). The CMCs for waters with salmonid present range from 885 µg/L at pH=9.0 to 32,600 µg/L at pH=6.5. The CCC (presence or absence of salmonids not specified) ranges from 254 µg/L at pH=9.0 to 3,480 µg/L at pH=6.5. pH in these watersheds ranged from 7.5-9.7 and maximum NH_3 concentrations (64 and 86 µg/L) found in the Sonoma Creek and the Napa River watersheds respectively during this study were well below these guidelines.

The San Francisco Bay Basin (Region 2) Water Quality Control Plan does not provide guidelines for phosphate, PO_4^{3-}, TDP, TP, TDN or TN. Establishing nutrient criteria in streams is made very challenging given a variety of reasons (e.g. protection of human health or protection of biological resources (Dodds and Welch, 2000). In addition, confounding factors such as temperature, turbidity, grazing, depth and velocity make it very difficult to predict water quality in response to nutrient concentrations. The US EPA has developed nutrient criteria for TN and TP for a range of “Eco-Regions” throughout the contiguous continental United States. The majority of California, including the Sonoma Creek and the Napa River watersheds, are within Eco-Region III (the Xeric West) (EPA, 2000). The EPA subdivided Eco-Region III into 12 sub-regions called Level III Eco-Regions based on climatic, physical and biological differences. Greater California including the Sonoma Creek and the Napa River watersheds are within Level III Eco-Region 6. The criteria for TN and TP in the Level III Eco-Region 6 are 500 µg/L and 30 µg/L respectively (EPA, 2000). In Sonoma Creek watershed, 13 out of 16 locations exceeded the guidelines for nitrogen and 16 out of 16 locations exceeded the guidelines for phosphorus (Figure 3). In the Napa River watershed 20 out of 23 locations exceeded the guidelines for nitrogen and 21 out of 23 locations exceeded the guidelines for phosphorus (Figure 3).

Exceedance of a guideline does not necessarily coincide with degraded stream health or loss of a beneficial use (e.g. ANZECC, 2000; Dodds and Welch, 2000). Waters may not meet certain environmental or human needs, and management action could be triggered to either more accurately determine whether the beneficial use is supported or to remedy the problem. In addition, the exceedances of the available guidelines in Sonoma Creek and Napa River watersheds indicate that in-stream productivity is not likely to be limited by nutrients in most locations. Phosphorus concentrations exceeded guidelines even at the most pristine sites, suggesting that P is not likely limiting anywhere in the watershed, while in pristine headwaters it appears that N concentrations are limiting and that overall the watersheds may in fact be naturally N-limited. Some reaches in the Sonoma and Napa River watersheds may be more vulnerable to both excessive phytoplankton or benthic algal growth, including any reaches devoid of riparian vegetation where light and temperature conditions might favor greater productivity. Reaches in the middle and lower mainstem of the Napa River characterized by large dry season pools often isolated from each other by bed interflow, and tidal reaches of both watersheds may also be vulnerable.

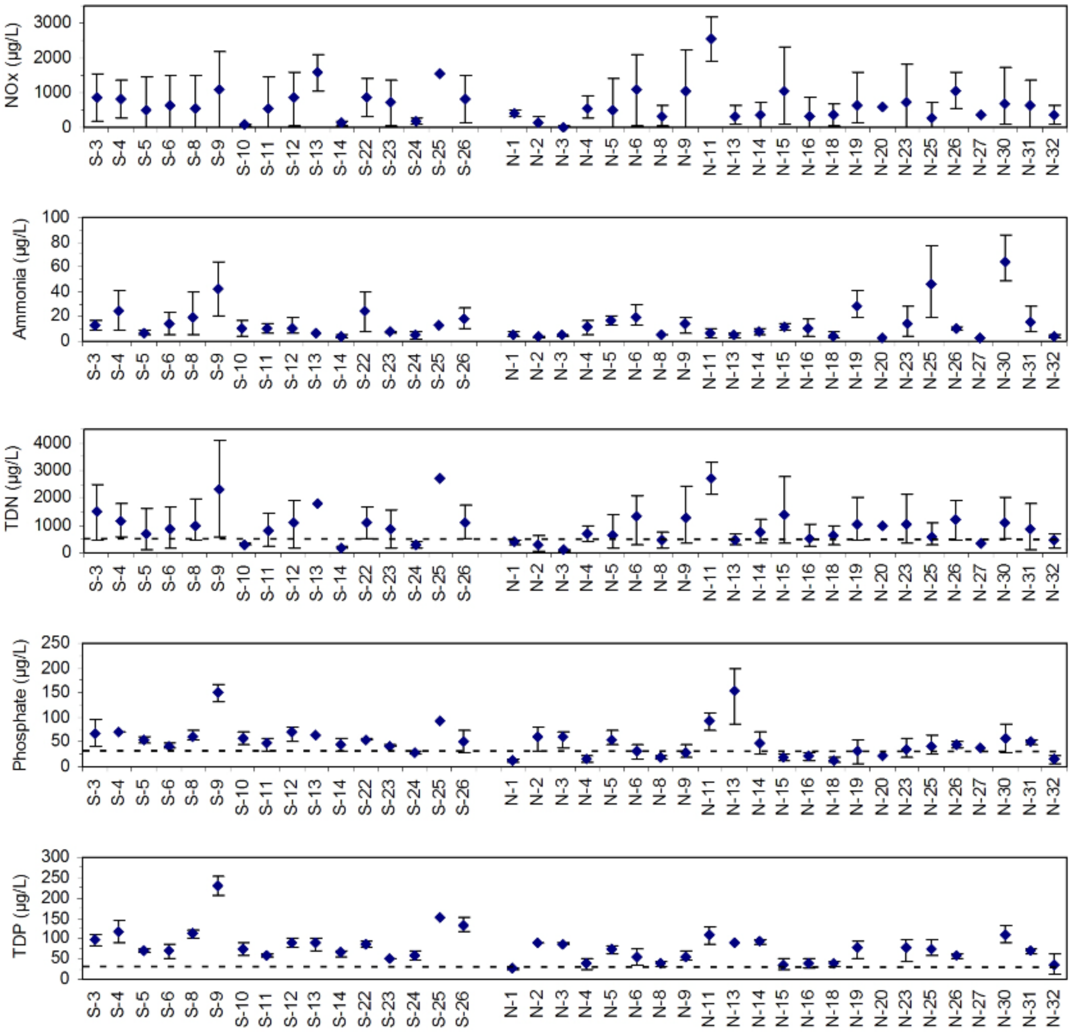


Figure 3. Spatial variation of nutrient concentrations (Mean, minimum and maximum). Dashed lined are water quality guidelines: NOx 1,129 µg/L (RWQCB, 1995); TDN 500 µg/L, PO_4^{3-} and TDP 30 µg/L (EPA, 2000).

The tidal portion of Sonoma Creek was sampled at Highway 121 (location S-8) and was the only location sampled in Sonoma Creek that had detectible chlorophyll-a concentrations (12 µg/L in October 2002). Tidal portions of the Napa River were sampled at Trancas Street (N-23 and 3rd Street (N-30). These locations had maximum dry season chlorophyll-a concentrations of 18 µg/L and 9 µg/L respectively. The middle reaches of the Napa mainstem represented by sampling locations N-6 and N-9 did display measurable dry season concentrations of 1-2 µg/L and the flood control channel in St. Helena near the confluence with the Napa River also had measurable dry season chlorophyll-a concentrations (3 µg/L).

Given an excess supply of nutrients, why are water column chlorophyll-a concentrations not greater and why are toxic algae species not dominating occasionally or periodically in vulnerable reaches? Excessive benthic algal biomass was observed in many locations. These mostly consist of filamentous green algae (e.g., Cladophora) and diatoms – blue-green varieties were less common (Krottje unpublished observations). Preliminary data indicate benthic chlorophyll concentrations exceed 100 mg/m^2 at many locations (Krottje unpublished data). There is an evolving consensus that 100-200 mg/m^2 may be the maximum "acceptable" benthic chlorophyll density for temperate streams (Dodds et al., 1997; Dodds et al., 1998; Biggs, 2000; Dodds and Welch, 2000) but it is not clear if this is true for other climatic regimes. Overall, the large spatial variation in nutrient concentrations, the ratio of nutrient forms to one another, and the exceedance of water quality guidelines, and the related isolated incidences of greater chlorophyll-a concentrations and the observation of generally elevated benthic algal biomass are all evidence in support of the rejection of $H_{(0)}$. The exceedances of water quality guidelines may provide a good benchmark to measure change against, should the same locations be visited in the future.

Seasonal Variation

Nutrient concentrations varied with season in each watershed (Figure 4). A total of six locations in Sonoma Creek watershed and eight locations in the Napa River watershed were revisited during each sampling event; the exception was October 2002 when two were missed in each watershed due to no surface flow. The locations in each watershed are representative of a wide range of stream types and land uses; upper watershed, mid and lower watershed mainstems and several tributaries. Mean NOx in particular showed a clear trend in both watersheds; NOx concentrations were highest in the winter months and gradually decreased as discharge in the rivers decreased. This pattern is consistent with the notion that non-point source runoff associated winter rainstorms dominate inputs of NOx into the stream networks of both watersheds. The pattern however, is less clear for Sonoma Creek watershed when the range of concentrations is considered. The Sonoma analysis included data from locations S-3 and S-13. As discussed in the next section, the processes leading to inputs of NOx at these locations appear to differ from other locations in the watershed. Seasonal patterns of NH_3 and PO_4^{3-} were less clear and probably reflect a wider variety of inputs at a lower magnitude with greater instream processing. NH_3 concentrations show a similar pattern in both watersheds; greater concentrations in the spring, summer and late summer months and lower concentrations during the wet season. NH_3 appears to show a delayed response to peaks in NOx. One possible explanation is that NOx is taken up by biota in the spring as temperatures and light conditions become more favorable and then released back into the water column via the breakdown of dissolved organic matter during cycles of phytoplankton and periphyton growth and mortality over the spring and summer. Patterns similar to these have been observed in other rivers (Cooper and Cooke, 1984; Cooper and Thomsen, 1988). Other explanations will be offered in later sections. PO_4^{3-} concentrations vary less between seasons than do NOx and NH_3. Generally, concentrations seem to be higher in the winter and decreased though the spring and summer before increasing slightly again in the late summer/ autumn. Although the variations are subtle, this pattern maybe associated with surface runoff from non-point sources during the winter and dry weather

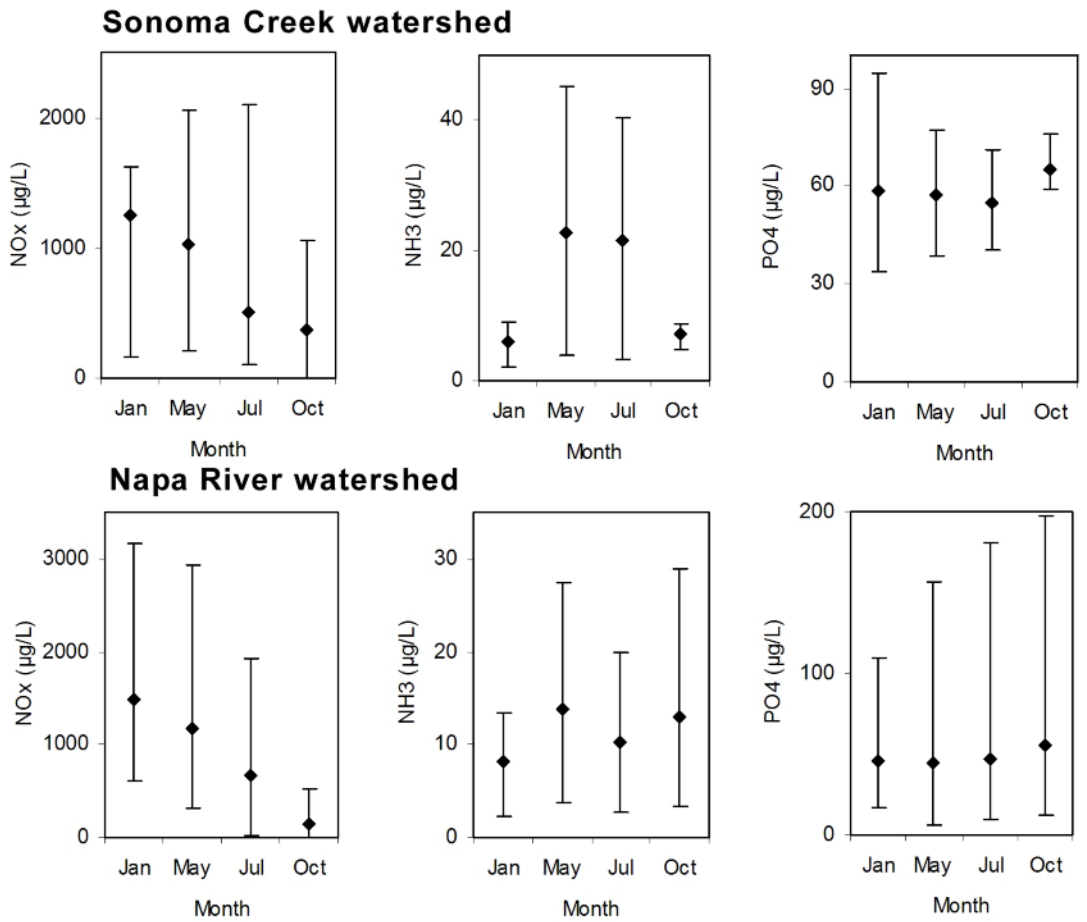


Figure 4. Variation of nutrient concentrations with season in the Sonoma Creek and Napa River watersheds. Diamonds are the mean concentration and whiskers are the maximum and minimum concentrations encountered.

flows containing phosphorus during the late summer/ autumn; a pattern observed in other watersheds (e.g. McKee et al., 2001). Analysis of seasonal variations in nutrient concentrations has helped to build some preliminary hypotheses about the input processes of each type of nutrient. NOx shows a clearer trend than do NH_3 and PO_4^{3-} perhaps because NOx is supplied to the creek at a higher loading rate dominantly via a single pathway.

Downstream Accumulative Impacts

The change in concentrations of each nutrient form from the headwaters to sea level was systematically studied on the mainstem of each watershed (Figure 5 and 6). In both watersheds, the lowest nutrient concentrations were observed in the mountainous headwater areas where human impacts are lesser. This characteristic has been noted in watersheds in other areas of the world where the lowland valleys are developed for agriculture and urban land uses and the upland areas remain relatively undeveloped (e.g.

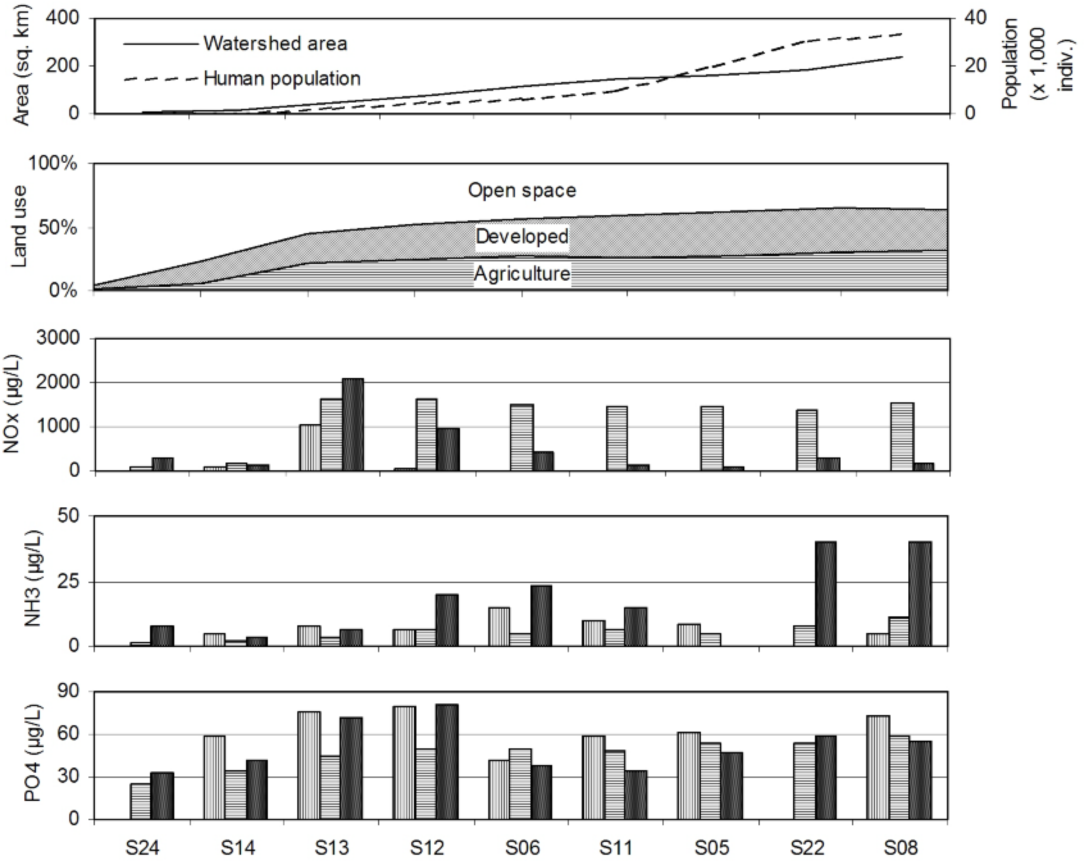


Figure 5. Nutrient concentrations on the mainstem of Sonoma Creek from the headwaters to tidal influence in response to changes in watershed area, population, and land use. The category "developed" is inclusive of urban, commercial and industrial land uses. Samples collected in October 2002 (▥), January 2003 (▤), and July 2003 (▦).

Balstad and Swank, 1997). Mineral nutrients in the stream ecosystems of the upper Sonoma Creek and Napa River are likely supplied through natural processes such as mineralization of organic matter in soils, on watersheds surfaces, and riparian organic debris. Phosphorus can be derived from geological weathering, and nitrogen can be supplied from the atmosphere through rainout or dry deposition and nitrogen fixation (McKee and Eyre, 2000). Atmospheric nitrogen deposition (kg/ha/yr) has been measured and estimated locally (Weiss, 1999 and references therein). Nitrogen deposition is influenced by proximity to urban pollution sources, prevailing winds, and annual rainfall. About 68% of the total deposition in the Bay Area was oxidized nitrogen. In areas that, like the Napa and Sonoma valleys, lie upwind of major urban areas, a total N deposition of 4-6 kg/ha/yr was proposed (Weiss, 1999). Assuming 1,000 mm of annual rainfall and a NOx deposition of 2.7 – 4.1 kg/ha/yr (68% of 4-6), an equivalent concentration in rainfall of 270-410 µg/L is calculated. Headwater tributaries in the Sonoma Creek watershed with

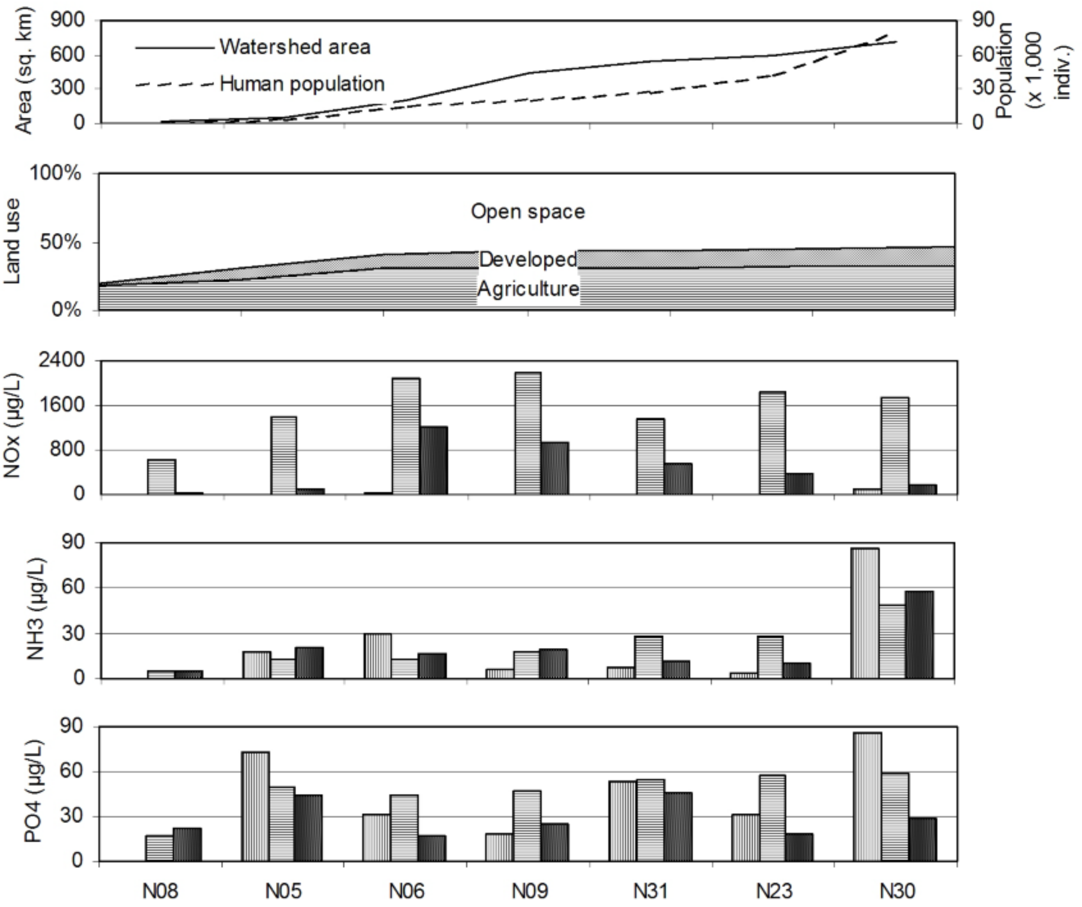


Figure 6. Nutrient concentrations on the mainstem of Napa River from the headwaters to tidal influence in response to changes in watershed area, population, and land use. The category "developed" is inclusive of urban, commercial and industrial land uses. Samples collected in October 2002 (▥), January 2003 (▤), and July 2003 (▦).

in excess of 90% open space showed NOx concentrations ranging from 67-288 µg/L and headwater tributaries of the Napa River watershed (>90% open space) showed concentrations between 3-300 µg/L. Thus, it appears nitrogen concentrations in headwater areas can be completely accounted for by N-deposition. The other processes of natural nutrient supply have not been defined in Bay Area creeks and represent a potential area for future research.

With the exception the upper watershed locations, each watershed showed a unique pattern of concentration of each nutrient form in response to differing downstream effects of human pressures. During the wet season, (January 2003 sampling), NOx concentrations sharply increased between location S-14 and S-13 on Sonoma Creek and remained elevated downstream. The same increase in NOx concentration was evident in both October 2002 and July 2003 and appears to be associated with urbanization in the vicinity (likely the community of Kenwood). The community of Kenwood relies on septic systems for the treatment of wastewater. Given that there is not a similar increase in NH_3 and PO_4^{3-}, loads from septic systems are proposed at the likely cause of the NOx anomaly. During the dry seasons, NOx concentrations decreased by at least half within 5 km downstream (location S-12). There are at least three hypotheses for this decrease: 1. dilution from tributary input (Graham Creek), 2. groundwater input, and 3. instream assimilation. Although none of these causes can be completely ruled out, dilution from Graham Creek or groundwater input seem less likely given that the same trend was not observed during the wet season. During the October 2002 sampling we observed an unremarkable increase in chlorophyll-a concentration from <DL at S-13 to 1 µg/L at S-12. This suggests that water column productivity is not the main assimilative mechanism. We qualitatively observed phyto-benthos throughout the study area including attached and semi-attached green filamentous algae. Phyto-benthos has been related to land use and nutrient concentrations in other California streams (Leyland et al., 2001) and northwestern USA (Leland and Porter, 2000; Munn et al., 2002; Snyder et al., 2002) and might play an important role in the assimilation of NOx in Sonoma Creek. Although the processes operating in the creek remain unclear, it is almost certain that NOx load associated with the community of Kenwood is impacting water quality in the Creek downstream at location S-13.

Concentrations of ammonia remained relatively constant from the headwaters to the tidal areas in Sonoma Creek during the wet season. During the dry season (July 2003 sampling) NH_3 concentrations were greatest in the middle watershed between location S-12 and S-11 and at S-22 and S-8 in the lower watershed. The middle watershed concentrations are not that remarkable (<25 µg/L) and may be a result of decay of organic matter associated with the NOx input in the vicinity of Kenwood. Coupled NOx assimilation / ammonia production in has been noted before in freshwater environments (Cooper and Cooke, 1984; Cooper and Thomsen, 1988). An alternative hypothesis is found by reviewing the land use statistics for locations S-13, S-12, and S-6. The occurrence and intensity of commercial land use in both the entire watershed upstream from a sampling location as well as within 50 m of each bank of the creek increases progressively from S-13 to S-12 to S-6. The increase in ammonia at location S-22 is associated with an increase in both NOx and PO_4^{3-} and appears to result from a combination of commercial, urban, and agricultural runoff influences indicated by increases in all three environmental statistics in this area of the watershed. The sampling location on Nathanson Creek (S-04) in the City of Sonoma shows a similar NOx-NH_3-PO_4^{3-} signature and therefore urban runoff and commercial land use are advanced as the most likely combination but animal manures associated with dairying and beef production downstream from the City of Sonoma cannot be ruled out. Although NH_3 concentrations are not excessive compared with any guidelines, there appears to be localized variation associated with either instream processes or land use in the vicinity of the Creek.

The downstream variation of the concentrations of PO_4^{3-} is not as remarkable as NOx variation and range between 25-81µg/L. There is a peak in concentration in the vicinity of location S-13 and S-12 that appears to coincide with increases in developed land and agriculture and perhaps the community of Kenwood and the town of Glen Ellen. It is unlikely that leaky septic systems are the cause given that phosphorus is usually bound in soils within a short distance from septic filter fields (Hoare, 1984; Gerritise et al., 1995). In the lower watershed there is a slight increase in concentration around S-22. The fact that PO_4^{3-} concentrations near the community of Kenwood and town of Glen Ellen and at S-22 downstream of the City of Sonoma are greater in the dry season sampling relative to the wet season sampling suggests that the sources are point in nature. The process of instream release provides another possibility for the observations; however, studies in other watersheds have usually found net retention of PO_4^{3-} during low flow periods and release in the form of resuspended inorganic particulate phosphorus (mostly high flow) or dissolved and particulate organic phosphorus (high and low flow) (e.g. Svendsen et al., 1995; Dorioz et al., 1998). Instream release of PO_4^{3-} is not likely a dominant process. PO_4^{3-} concentrations are lowest in the upper watershed locations and remain relatively constant along the valley floor mainstem expect for small fluctuations associated with either instream generation or more likely localized inputs.

NOx concentrations in the Napa River from the headwaters to tidal influence were greater during the wet season sampling (January 2003) than during either dry season sampling (October 2002 and July 2003) suggesting that non-point sources dominated the inputs to the mainstem. During the wet season, NOx concentrations increased steadily from location N-08 downstream to N-09 in response to increased agricultural and developed land use. During the July 2003 sampling event, a large increase in NOx concentration occurred between location N-05 and N-06; downstream from N-06, concentrations gradually decreased. The pattern in not replicated for NH_3 or PO_4^{3-} suggesting a point source for NOx only. The town of St. Helena is upstream from N-06 and three wastewater treatment facilities operate between location N-05 and N-06 (Calistoga, St. Helena, and Glass Mountain). Calistoga and St. Helena wastewater treatment facilities only discharge during the wet season and Glass Mountain is a zero-discharge facility discounting wastewater discharge. Alternate possible hypotheses for the increases in NOx between location N-05 and N-06 include input of urban runoff, contaminated groundwater input (perhaps leaky septic systems) or groundwater leachate from the treatment facilities. The slight increase in NOx concentration between location N-31 and N-23 appears to be associated with the Salvador Channel tributary (40% developed and 34% agriculture) that also displayed an elevated NOx (location N-15: 2,312 µg/L) during the wet season. Overall, NOx concentrations were least in the upper mainstem and increased downstream in a manner dependent upon season and localized inputs.

Ammonia concentrations generally increase from a low in the headwaters (N-08) downstream to location N-06 but were unremarkable (<30 µg/L) throughout the watershed. The only exception was within the City of Napa at location N-30 (49-86 µg/L); the only sampling location in the Napa River watershed influenced by tidal action. Locations N-05, N-06, and N-30 displayed greater NH_3 concentration in the dry season suggesting point sources, rather than surface runoff, however this might also include urban dry weather flows from activities such as garden watering (and runoff of garden fertilizers), and car washing. A resident population of water foul in the vicinity of N-30 may also contribute to elevated ammonia and PO_4^{-3} concentrations.

Phosphate concentrations in the Napa River watershed were lowest in the upper watershed in a similar manner to Sonoma Creek. There appears to be local sources between locations N-08 and N-05, between locations N-09 and N-31 and in the vicinity of N-30. The increase in concentration upstream of N-05 appears to be associated with the urban area of Calistoga. The increase in concentration between N-09 and N-31 may be associated with urban runoff from the town of Yountville, treated wastewater discharge from the Yountville wastewater treatment facility or input from Dry Creek. Water in Dry Creek (location N-01) was sampled in January and July 2003 and concentrations were 17 and 9 µg/L respectively, thus Dry Creek is ruled out as a source. The increase in PO_4^{3-} concentrations during all seasons between N-23 and N-30 may to be associated with the urban area of the City of Napa however, the influence of resident water foul and resuspension and release from bottom sediments in the tidal river cannot be ruled out. Neither of the sampled tributaries that enter the Napa River between locations N-23 and N-30 showed elevated PO_4^{3-} concentrations.

Evaluation of dissolved nutrient concentrations spatially in the watersheds, the ratios of different forms to one another, comparisons to water quality guidelines, and evaluation of downstream trends on the mainstems of Sonoma Creek and Napa River provide evidence for human impacts. These kinds of patterns have been observed in other watersheds in response to treated wastewater inputs (Muscutt and Withers, 1996), urbanization (Spahr and Wynn, 1997), and agriculture (Edwards et al., 1990). It has also been demonstrated that land use in the near channel zone has a disproportional influence on water quality relative to other watershed areas (Bolstad and Swank 1997; Johnes and Heathwaite, 1997; Sliva and Williams, 2001). In most cases, it is not yet clear what combination of these kinds of processes operate throughout the Sonoma Creek and Napa River watersheds. However, it is clear that $H_{(0)}$ is rejected for both watersheds:

> $H_{(1)}$ *Land use and human populations influence nitrogen and phosphorus concentrations in flowing water bodies within Sonoma Creek or Napa River watersheds.*

Some preliminary hypotheses have been put forward and will be built upon in the sections to follow.

Nutrient-Land Use Relationships

In order to define more clearly the causes of spatial and temporal variation in the Napa River watershed, a statistical analysis (Kendall Tau b) was performed on the tributary water quality and environmental variables data sets. Mainstem data were not included in this analysis because each data point is not completely independent from others upstream or downstream. There were too few data points (<4) to carry out this kind of statistical analysis on data from Sonoma Creek watershed. The selection of sampling locations in Sonoma Creek watershed at the beginning of the study was influenced by a lack of perennial flow. Please note that we did do the statistical analysis for phosphorus but there where no statistically significant relationships found.

In the Napa River watershed, during the late summer/ autumn season, NOx did not correlate positively with any environmental variables (Table 6). Subwatersheds with a greater proportion of area in open space showed lower concentrations of NOx, an observation further supported by significant ($p<0.01$) negative correlations between NOx and *Total OPEN%* and *50m_buffer_OPEN%*. In contrast, during the wet season, NOx correlated significantly with population and urban environmental variables (Table 7). In addition, NOx correlated significantly with commercial and agricultural land use variables in both the 5 km footprint and the 50 m buffer footprint. This supports a hypothesis that NOx was entering tributary streams from a variety of sources during the wet season, however the lack of any statistical correlations between environmental variables and phosphorus tends to call into question the premise that commercial land use and agriculture were a large source. Typically, pollution related to commercial and agricultural activities would show both an N and P signature. In addition, the commercial and agricultural environmental variables that correlated with NOx (Table 7) also co-correlated with the various population and urban statistics. In July 2003, when the watershed had returned to much drier conditions, NOx concentrations in tributary streams was significantly correlated with urban and population variables only. By weight of evidence, we suggest NOx concentrations during stable flow in the Napa River are mostly influenced by human population and urban (including suburban and rural residential) land use and likely derived from the leach fields and runoff from septic systems.

Table 6. Correlations between environmental variables and water quality parameters in the Napa River watershed for late summer / autumn dry season samples (October 2002). Note, only those variables and parameters that showed significant correlations with p-values < 0.05 are tabulated. Number of sample locations = 10. A dot (.) indicates $p>0.05$; * $p<0.05$; ** $p<0.01$; *** $p<0.001$.

	NOx	NO_2^-	NH_3	Chl-a
Total_OPEN%	-0.561**	.	.	.
5km_POP	.	.	.	0.574**
5km_COMM	.	0.686**	0.577**	.
5km_POPden	.	.	.	0.557**
5km_COMM%	.	0.700**	0.559**	.
5km_URBA%	.	.	.	0.574**
50m_buffer_OPEN%	-0.561**	.	.	.

Table 7. Correlations between environmental variables and water quality parameters in the Napa River watershed for wet season samples (January 2003). Note, only those variables and parameters that showed significant correlations with p-values < 0.05 are tabulated. Number of sample locations = 16. A dot (.) indicates p>0.05; * p<0.05; ** p<0.01; *** p<0.001.

	NOx	NO_2^-	NH_3	Turb
Total_POP	0.483**	.	0.397*	.
Total_COMM	.	0.435*	0.629***	.
Total_URBA	0.434*	.	.	.
Total POPden	0.444*	.	.	.
Total_OPEN%	-0.533***	.	.	.
Total_URBA%	0.367*	.	.	.
5km_AREA	0.509**	.	.	.
5km_POP	0.561***	.	0.399*	.
5km_AGRI	0.570***	.	.	.
5km_COMM	0.535**	0.546**	0.667***	.
5km_URBA	0.505**	.	.	.
5km_POPden	0.420*	.	.	.
5km_COMM%	0.552**	.	0.474*	0.454*
5km_INDU%	.	.	0.417*	0.446*
5km_URBA%	0.393*	.	.	.
50m_buffer_POP	0.500**	.	0.397*	.
50m_buffer_AGRI	0.380*	.	.	.
50m_buffer_URBA	0.412*	.	.	.
50m_buffer_POPden	0.444*	.	.	.
50m_buffer_COMM%	0.431*	.	.	.
50m_buffer_OPEN%	-0.483**	.	.	.

The occurrence of higher NO_2^- concentrations appears to relate most commonly to commercial environmental variables (Table 6, 7, and 8). In addition, NO_2^- correlated to population variables during the mid summer sampling (Table 8). It is not known what kind of commercial activities might enhance nitrite concentrations but given the correlation between commercial land use and population environmental variables, it is possible that the nitrite is sourced from septic system leach fields in the similar manner to nitrate. This premise is corroborated by the occurrences of high nitrite concentrations at locations S-13 and S-12 downstream from the community of Kenwood in the Sonoma Valley. The occurrence of higher NH_3 concentrations and turbidity appears to be associated with commercial land use environmental variables indicated by a number of significant correlations across all seasons (Table 6, 7, and 8). In addition, NH_3 correlated with a number of population variables as well as *5km_INDU%* and *5km_AGRI* during the wet season (Table 7). The positive correlation between NH_3 and commercial land use adds strength to the hypothesis that commercial land use influenced the NH_3 concentrations in the mainstem of Sonoma Creek. Ammonia is used as a cleaning agent

Table 8. Correlations between environmental variables and water quality parameters in the Napa River watershed for wet season samples (July 2003). Note, only those variables and parameters that showed significant correlations with p-values < 0.05 are tabulated. Number of sample locations = 14. A dot (.) indicates p>0.05; * p<0.05; ** p<0.01; *** p<0.001.

	NOx	NO_2^-	NH_3	Turb
Total_COMM	.	.	0.628**	0.606**
Total POPden	0.456*	.	.	.
Total_OPEN%	-0.398*	.	.	.
Total_URBA%	0.553**	.	.	.
5km_AREA	.	.	0.529**	.
5km_POP	.	0.447*	.	.
5km_AGRI	.	.	0.442*	.
5km_COMM	.	0.492*	0.693***	0.550*
5km_POPden	.	0.511*	.	.
5km_AGRI%	.	.	.	.
5km_COMM%	.	0.618**	0.668***	.
5km_URBA%	.	0.544**	.	.
50m_buffer_COMM	.	.	0.562**	.
50m_buffer_URBA	0.451*	.	.	.
50m_buffer_POPden	0.500**	0.423*	.	.
50m_buffer_COMM%	.	0.466*	.	.
50m_buffer_OPEN%	.	.	.	.
50m_buffer_URBA%	0.464*	.	.	.

in many commercial enterprises. Disposal of grey water containing residues of ammonium based cleaning agents in the vicinity of drainage ways in these watersheds may be influencing water quality, however it should be emphasized that the changes are subtle and concentrations of NH_3 noted in the Sonoma Creek and Napa River watersheds during this study were well below guidelines recommended by the US EPA.

Overall, the use of statistical methods has added further support for conclusions about broad patterns in nutrient concentrations observed in the streams of the Sonoma Creek and Napa River watersheds during the study: 1. there were seasonal concentration patterns that are related to nutrient sources, 2. NOx (nitrate and to a less extent, nitrite) was supplied to different reaches from a number of sources including diffuse runoff from agriculture and urbanization but most dominantly from runoff associated with septic systems in non-sewered areas, 3. ammonia may be partly associated with regeneration from the breakdown of organic matter within the creeks in response to upstream NOx loads, but the largest signal appeared to be associated with commercial land use activities, and 4. phosphate was found in moderate concentrations and, with few exceptions, was not strongly related to human activities.

The following sections describe locations in each of the watersheds where nutrient concentrations appeared to be anomalous during the *Characterization Survey* and warranted focused study.

NOx Hotspots

In order to further spatially constrain the occurrence of elevated nutrient concentrations on the mainstem and in some tributaries noted during the *Characterization Survey*, additional sampling locations were added during the *Hotspot Survey* conducted in May 2004. There were three areas identified for further investigation in Sonoma Creek watershed and six areas identified in Napa River watershed (Table 9).

Table 9. Areas of the Sonoma Creek and Napa River watersheds identified for further investigation and determination of the likely sources and causes of elevated nutrient concentrations.

Hot spot (HS)	**Sampling locations (*Characterization Survey*)**	**Description**	**Additional sampling locations (*Hotspot Survey*)**	**Anomaly indicating a need for further investigation**		
				NO_x	**NH_3**	**PO_4^{3-}**
	Sonoma Creek watershed					
HS-1	S-14, S-13	Upper Sonoma Ck. in the vicinity of the community of Kenwood	S-30, S-31, S-32	X		X
HS-2	S-5, S-22	Sonoma Ck. adjacent to and downstream from the City of Sonoma	S-33, S-34	X	X	X
HS-3	S-4, S-3	Nathanson Ck. within and downstream of the City of Sonoma	S-35	X	X	X
	Napa River watershed					
HS-4	N-5	Napa River within and upstream from the City of Calistoga	N-44, N-45, N-46	X		X
HS-5	N-26	Bell Canyon Ck.	N-47, N-48	X		
HS-6	N-6	Napa River within and upstream from the City of St. Helena	N-49, N-50	X		
HS-7	N-15	Salvador Channel northwest City of Napa	N51, N-52	X		
HS-8	N-4, N-18	Napa Ck. / Browns Valley Ck. on the western side of the City of Napa	N-40, N-41	X		
HS-9	N-11, N-13	Tulucay Ck. / Murphy Ck.	N42, N43	X		X

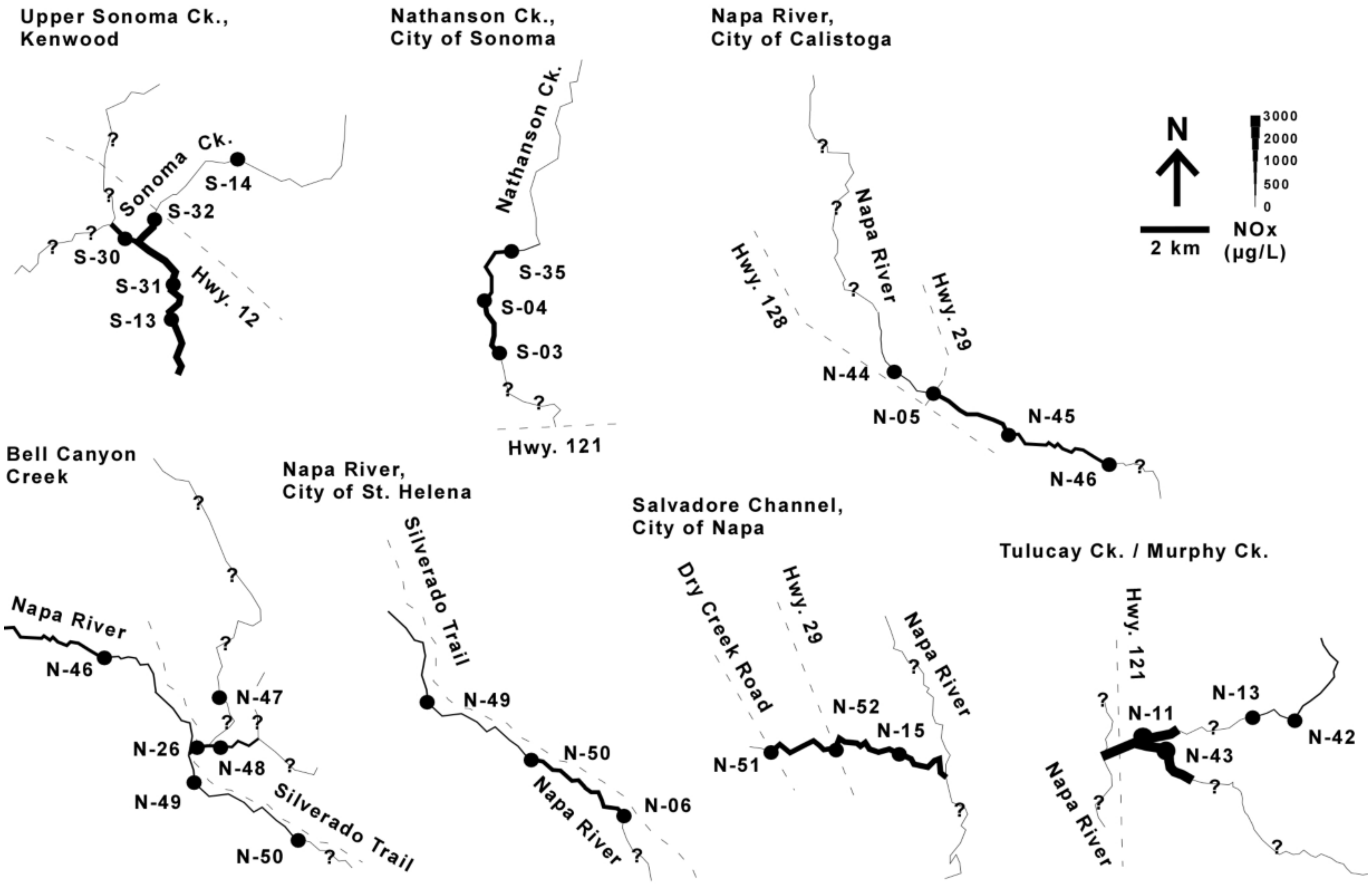
After analysis of the data from the May survey, two *Hotspots* identified during the *Characterization Survey* were determined to be off less importance than the other sites. Sonoma Creek adjacent to and downstream of the City of Sonoma (HS-3) showed reasonably constant concentrations of NOx, NO_2^-, NH_3, and PO_4^{3-} during May 2004 throughout the reach. The main reason for including this reach in the *Hotspot Survey* was the observation of a large increase in NH_3 and a slight increase in PO_4^{3-} concentrations during July 2003. The NH_3/PO_4^{3-} anomaly appears to be a late summer phenomenon only. The possible causes include regeneration within the stream or dry weather inflows associated with commercial and perhaps industrial land use along that reach. Agricultural and urban runoff seems less likely given the lack of a NOx signal.

The other *Hotspot* of less importance based on nutrient concentrations was the Napa Ck. / Browns Valley Ck. reach (HS-8) on the western side of the City of Napa. This reach was focused upon because of the occurrence of high pathogen counts (RWQCB, 2006). With the exception of NH_3, nutrient concentrations were not anomalous during the May survey. NH_3 concentrations ranged between 6 µg/L at Morningside Drive on Browns Valley Creek (N-41) to 22 µg/L at Jefferson Street on Napa Creek (N-4) in the downstream portion of the reach. These concentrations are not remarkable, however there was a systematic increase in concentrations from N-41 to N-40 to N-18 to N-4, indicating a source. There is a general increase in urbanization, population and commercial land use in a downstream direction along this reach. Given that there is no systematic increase in NOx or PO_4^{3-}, the NH_3 increase seems less likely to be associated with commercial land use.

The other areas sampled during the *Hotspot Survey* show patterns similar to those of the *Characterization Survey* and are deemed of high importance. As discussed in previous sections, there is a large year round source of NOx along the reach of Sonoma Creek near Kenwood (HS-1). An additional two sampling locations during the *Hotspot Survey* helped to isolate the extent of the source area to the area downstream from Highway 12 (Figure 7) and data from these helped to strengthen the hypothesis that the NOx source is septic system sewage disposal associated with the town. There are rural residential housing lots almost continuously up Sonoma Creek between Highway 12 (S-32) and the Sugarloaf Ridge State Park (S-14) with a 2000 census population of 72. The Soil Survey for Sonoma County (USDA, 1972) describes the limitation for septic filter field usage in each soil type. The soils along the reach of Sonoma Creek between S-14 and S-32 are gravelly clay loams with severe limitation for septic use associated with moderately slow permeability. Septic systems associated with these dwellings are either isolated from the creek or more likely creek flow dilutes sewage loads sufficiently and dampens the signal.

Location S-30 on the largest (unnamed) tributary creek entering mainstem Sonoma Creek within the community of Kenwood showed elevated NOx (1,536 µg/L) slightly less that location S-31 on Sonoma Creek on the downstream outskirts of town (2,230 µg/L). Land use in the unnamed tributary is mainly open space (73%) with a small amount of agriculture (15%). The remaining area (12%) supports a human population of ~1,100 people (2000 census). About 900 people live on the reach of mainstem Sonoma Creek between S-32 and S-31. On the sampling day in May 2004, flow was greater in the unnamed tributary than on the mainstem by approximately 2x (authors field estimate – there is no official gauge record). Thus, despite a lower concentration in the tributary, the load and impact of the mainstem was greater, a premise consistent with the population

Figure 7. NOx concentrations in selected areas of the Sonoma Creek and Napa River watersheds. The line thickness is proportional to the concentration. A “?” indicates that concentrations are speculative or on known.



statistics. The drainage characteristics of the clay loams and gravelly clay loam soils in the community of Kenwood adjacent to the mainstem of Sonoma Creek are rated as severe for septic waste disposal use due to moderately slow permeability. The drainage characteristics of the loam and clay soils in the unnamed tributary for septic filter fields are more severe due to slow to very slow permeability and a hard pan at 1 m depth in addition to a shallow water table 1-1.5 m depth from the surface) (USDA, 1972**)**. The NOx concentrations and loads issuing from this tributary and section of town appear consistent with the soil characteristics.

During the *Hotspot Survey* and the *Characterization Survey*, concentrations gradually diminished downstream from the community of Kenwood. The human population between S-31 and S-13 was 342 persons and the population between S-13 and S-12 (Sonoma Creek at Glen Allen) was 2,137 persons. So why did concentrations decrease on all sampling occasions between Kenwood and Glen Ellen despite population upstream from and in the town of Glen Ellen? The answer is found in the relationship between population and watershed size and water yield. The total population density sharply rises from 11 persons / km^2 at location S-32 to 56 persons /km^2 at location S-31 associated with the community of Kenwood. Between S-31 and S-12 and all the way downstream to S-05, the population density remains relatively constant – fluctuating between 54-67 persons / km^2. Although there is no official gauge record for each sampling location, qualitative observations during fieldwork support a general positive relationship between increasing watershed area and increasing flow in Sonoma Creek. Thus it is concluded that the impact of the community of Kenwood on NOx concentrations in the Creek is a function of its location in the watershed rather than a function of poor septic system maintenance or particularly poor soil characteristics relative to other parts of the Sonoma Valley – in fact the drainage characteristics of the soils for septic waste disposal are severe throughout most of the Valley (USDA, 1972). However, particularly poor soil characteristics might be responsible for a continued sewage load into the late summer/autumn period – a phenomenon not observed in any other Hotspot in the Sonoma or Napa River watersheds.

Nathanson Creek flowing through the eastern side of the City of Sonoma was re-sampled during the *Hotspot Survey* (HS-2). One additional sampling location was added to help constrain the location of the source. The NOx concentration at location S-35 on the northeastern side of Sonoma was 297 µg/L. Concentrations increased by ~4x between S-35 and S-04 and by 1.4x between S-04 and S-03 (Figure 7). It appears that most of the NOx source is associated with the residential areas adjacent to the Creek and to a lesser extent the agricultural area downstream from the City/rural boundary. NH_3 concentrations on Nathanson Creek were higher during the July 2003 and May 2004 samplings than during the January 2003 wet season sampling and were greater at location S-04 (urban) than at S-03 (urban and agricultural influence). PO_4^{3-} concentrations were between 62-95 µg/L during all sampling occasions and slightly elevated during the wet season at S-03. The *Hotspot Survey* data further support the conclusion that water quality in Nathanson creek was mostly influenced by NOx, and to a lesser extent NH_3 and PO_4^{3-}, all sourced from dry weather urban runoff. There were probably additional inputs from rural areas upstream and downstream from the city during winter storms.

Napa River at Calistoga (HS-4) was selected because of elevated NOx and PO_4^{3-} concentrations during the *Characterization Survey* (Table 9). This reach was resurveyed during May 2004 with an additional three sampling locations added upstream and downstream of the City of Calistoga. NOx concentrations increased slightly from 256 µg/L to 324 µg/L between locations N-44 and N-05. Between locations N-05 and N-45 NOx concentrations increased by 4x and then decreased back to 1,003 µg/L further downstream at location N-46 (Figure 7). The same pattern was observed for PO_4^{3-} indicating a common source. NO_2^- and NH_3 remained relatively constant throughout this reach. The City of Calistoga discharges treated sewage just upstream of N-45 for 6 months of the year (November to May). Discharge from the plant was about 40-50 m^3/day on 5/5, 5/6, and 5/7, respectively. Measured river discharge was 1,050 m^3/day on those days, giving dilution ratios of 25. Effluent nitrate concentration reported for May [only one sample analyzed] was 18 mg/L; ammonia was 0.2 mg/L, and TP was 3.3 mg/L. There is also a wastewater storage pond adjacent to the river that was renovated with a new liner installed as part of a treatment plant upgrade completed in October 2003. It is possible that leaching from the holding pond may have influenced nutrient concentrations during October 2002 and July 2003.

The *Hotspot* on Bell Canyon Creek (HS-5) was solely identified by high NOx concentrations during the *Characterization Survey* (Table 9). Adjacent to Bell Canyon Creek between location N-26 and N-48, there is a small sewage treatment facility with a zero-discharge permit receiving influent from the St. Helena Hospital. Sampling locations N-47 and N-48 were added during the *Hotspot Survey* to help determine if leakage from the treatment pond was the cause of the anomaly. The NOx concentration downstream from Bell Canyon Reservoir (location N-47) was 41 µg/L during the May 2004 sampling. The NOx concentration was 775 µg/L at N-48 and 973 µg/L at location N-26 (Figure 7). These observations suggest that the cause it not pond leakage. About 400 people live upstream from location N-48 and ~300 people live between the three sampling locations. The soils in the area are gravelly loams characterized by severe properties for septic sewage disposal (either because of low permeability or limited soil depth). The NOx anomaly is likely associated with runoff from septic tanks in the area.

The *Hotspot* on the Napa River within and upstream from the City of St. Helena (HS-6) was identified by anomalously high NOx concentration during the January and July 2003 sampling occasions of the *Characterization Survey* (Table 9). During the *Hotspot Survey* in May 2004 two additional sampling locations were added to try to isolate the source. The source of NOx to this reach of the Napa River occurs between location N-50 (Napa River at Pope Street) and N-06 (Napa River at Zinfandel Lane (Figure 7). The land use and population statistics do not provide and explanation for source. The City of St. Helena operates a sewage treatment facility on the west bank of the Napa River about halfway between location N-50 and N-06. During 2003 this facility only discharged to the River in January and concentrations of nitrate in effluent measured by the facility were <200 µg/L. There are about 1000 people living between N-50 and N-06. A small-unnamed tributary enters the Napa River just upstream of N-06 from the east side of the Valley that may receive runoff from housing on Howell Mountain Road. Presently there is no explanation offered for the cause of elevated NOx concentrations on this reach of the Napa River – but a sample taken from that tributary may provide enlightenment.

Salvador Channel draining the northwestern suburbs of the City of Napa showed elevated NOx concentrations during the *Characterization Survey*. In order to determine the spatial extent of the NOx source, a further two sampling locations were added during the *Hotspot Survey* in May 2004 (Table 9). The NOx concentration at location N-51 upstream from the City boundary in May 2004 was just 8 µg/L (Figure 7). Between this location and N-52 (Salvador Channel at Highway 29), the NOx concentration increased to 1,565 µg/L. There was a further increase in concentration from Highway 29 downstream to N-15 (Garfield Park) to 1,737 µg/L. Neither PO_4^{3-} nor NH_3 were anomalous or showed any systematic trends. At this time there is no cause offered but the signature is characteristic of other areas of the Sonoma and Napa River watersheds that are impacted by septic sewage; a NOx only anomaly present only during the winter, spring, and early summer sampling periods.

The last *Hotspot* to be discussed is HS-9 (Tulucay Ck. / Murphy Ck.) characterized by both elevated NOx and PO_4^{3-} in January and July of 2003 (Note no sample was taken during October 2002 due to lack of flow). During the *Hotspot Survey* an additional three sampling locations were added to help identify the spatial extent and causes of this anomaly (Table 9). NOx concentrations were 2,943 µg/L and 2,958 µg/L at locations N-11 and N-43 respectively and <500 µg/L at locations N-13 and N-42 (Figure 7). The NOx anomaly appears to be associated with the urban area that supported a population of 2,166 persons upstream from N-11 and 1,731 persons upstream from N-43 (2000 census data). These observations and those on Salvador Channel inspire the question: After an urban area is upgraded to a centralized sewer system, how long does it take for water quality in adjacent creeks to respond? The character of the PO_4^{3-} anomaly differs completely from that of NOx. Concentrations of PO_4^{3-} were 196 µg/L at the upstream location (N-42) and systematically decreased downstream to 156 µg/L at N-13 and 72 µg/L at N-11. Location N-13 showed the highest concentrations of PO_4^{3-} of any locations across both watersheds. Concentrations in January 2003 were 85 µg/L, in May 2004 were 156 µg/L, in July 2003 were 181 µg/L and in October 2002 were 198 µg/L. The Tulucay / Murphy Creek subwatershed is underlain by tertiary volcanic flow rocks and tertiary pyroclastic and mudflow deposits. No description of the mineralogy of these lithologies has been found but it is likely that they contain apatite, a phosphatic mineral that is common in basaltic rocks. Dissolution and leaching via ground water pathways might be the dominant supply of PO_4^{3-} to surface drainages in this and other subwatersheds in the Sonoma Creek and Napa River watersheds where volcanic geology dominates and where other sources of phosphorus are minimal.

Nutrient Loads

First order estimates of average nutrient loads were made for each watershed by combining flow data from the US Geological Survey with maximum nutrient concentrations observed for the gauge location. Load estimates made in this manner are crude at best and likely under estimate the real loads given concentrations during large floods are likely greater than were measured during stable flow conditions. Never the less, load estimate provide some measure of the nutrient load contribution of these watersheds to the downstream receiving waters of San Pablo Bay and provide a useful comparison for estimates of per capita sewage load for the populations of each watershed. Discharge data are available for one location in Sonoma Creek watershed (Sonoma Creek at Agua Caliente; USGS station number 11458500). Nutrient data were collected at this location (S-11) during the present study. Discharge data are available for Napa River watershed near Napa on Oak Knoll Avenue (USGS station number 11458000). Nutrient data were collected at the USGS gauge during our study (location N-31). Annual average discharge for Sonoma Creek at Agua Caliente is ~62 Mm^3 (n=28 years) and for Napa River at Oak Knoll Avenue is ~182 Mm^3 (n=46 years). Dry season loads were calculated by combining the average concentrations for the October and July sampling periods with an estimate of the long-term annual average dry season discharge (May to October = 2% of the mean annual runoff) (McKee et al., 2003). Background loads of NOx were estimated by combining the discharge data for each watershed with NOx concentrations in the most pristine areas of the watersheds. There was no reason to suspect that natural nutrient concentrations would differ between watersheds so the NOx concentrations for sampling locations with the greatest proportion of land use in open space were averaged and used in the calculation (Sonoma Creek and Goodspeed bridge: location S-14 and Mill Ck. at the old Bale Mill: location N-02). The estimated anthropogenic load of NOx was then calculated by difference. Total loads of nutrients passing the Napa River gauge were about 3-5 times greater than the loads passing the Sonoma gauge mainly because the gauged area is ~4 times larger and long term average discharge is ~3 times larger (Table 10). The NOx load in these watersheds is estimated to be about 6 times greater than the historical natural condition. Dry season loads accounted for <2% of the total annual loads.

Throughout this analysis we have presented hypotheses on sources of nutrients in various reaches of these watersheds. At this time, based on our sampling design and data in-hand, it is difficult to determine with certainty the mass of nutrients associated with each source. We have discussed sources of nutrients associated with septic systems (mainly nitrogen), wastewater treatment (nitrogen and phosphorus), atmospheric deposition (mainly nitrogen but some phosphorus), urban runoff (nitrogen and phosphorus), and natural weathering (phosphorus). However, there are other major sources of nutrients that have not been discussed in detail and these often dominate nitrogen and phosphorus inputs to agricultural watersheds (nitrogen fixation and the applications of nitrogenous and phosphatic inorganic and organic fertilizers (McKee and Eyre 2000)). It is possible to estimate nitrogen fixation in these watersheds but it would take some effort. In the case of fertilizers, there are data available. There was 6,300 metric t of nitrogenous fertilizers and 3,900 metric t of phosphatic fertilizers applied to agriculture in the counties of Sonoma and Napa during calendar year 2003 (CDFA, 2003, 2004). The nitrogen content (as N) of fertilizers typically ranges between 4 and 46% (average 25%) and the phosphorous content (as P) can range between 2 and 22% (average 12%). Thus, approximately 1,600 metric t N and 470 metric t P were applied in one year in these counties.

Although Sonoma Creek and Napa River are not the only systems draining these counties, it is still interesting to compare the estimated fluvial nutrient loads to the fertilizer application rates. This would be best achieved through the construction of nutrient budgets. A nutrient budget is a simple model that quantifies the input, output, and storage of nutrients in a define system. Although simple to construct, nutrient budgets are often difficult to close because some of the inputs and outputs are usually not locally quantified. That said, these can be estimated from the large quantity of literature published on agricultural systems. The development of nitrogen and phosphorus budgets for Sonoma Creek and Napa River watersheds would be a valuable tool for comparing nutrient masses associated with septic systems, treated sewage, and urban runoff with the less easily controlled masses associated with nitrogen fixation, fertilizers, atmospheric deposition, and natural weathering. Management decisions could then focus on certain inputs with a sound knowledge of anticipated benefits in the context of the other less controllable sources.

Table 10. First order estimates of loads of nutrients (kg/year) at each watershed gauging station during WY 2003. Sonoma Creek at Agua Caliente (11458500); Napa River near Napa (Oak Knoll Avenue) (11458500).

	Gauged Area (km^2)	Discharge (Mm^3)	NOx (kg)	NH_3 (kg)	TDN (kg)	PO_4^{-3} (kg)	TDP (kg)
Sonoma Creek							
Natural			14,459				
Anthropogenic			75,005				
Dry Season		1.2	89	15	331	57	72
Dry Season (%)		2	0.1	1.6	0.4	1.9	1.9
Total	151	62	89,464	930	90,960	2,996	3,879
Napa River							
Natural			42,445				
Anthropogenic			202,242				
Dry Season		3.6	1,009	36	1,593	180	248
Dry Season (%)		2	0.4	0.7	0.5	1.8	1.8
Total	565	182	244,687	5,080	323,525	9,978	13,529
Total entering downstream water bodies		244	334,151	6,010	414,485	12,974	17,408

SUMMARY AND CONCLUSIONS

Data on nutrient concentrations and other water quality parameters with the addition of environmental variables developed using GIS were generated at a total of 58 locations throughout the mainstems and tributaries of the Sonoma Creek and Napa River watersheds. NOx concentrations ranged from the detection limit to 3,162 µg/L, NO_2^- varied from 0-15 µg/L, NH_3 varied from 1-86 µg/L, total dissolved nitrogen varied from 59-4,076 µg/L, PO_4^{3-} varied from 11-198 µg/L, and total dissolved phosphorus varied from 12-253 µg/L. It appears that in-stream productivity in these watersheds is not nutrient limited. Only 6 locations showed signs of increase water column productivity (chlorophyll-a concentrations above background). Excessive benthic algal biomass was observed in many locations and preliminary data indicate benthic chlorophyll concentrations exceed 100 mg/m^2 (the suggested level for concern in temperate systems). Overall, the large spatial variation in nutrient concentrations, the ratio of nutrient forms to one another, the exceedance of water quality guidelines, the related isolated incidences of greater chlorophyll-a concentrations, and the observation of generally elevated benthic algal biomass are all evidence in support of the rejection of $H_{(0)}$. Preliminary data suggests that NOx concentrations were highest in the winter months and gradually decreased as discharge in the rivers decreased and contrasted with patterns of NH_3 and PO_4^{3-} concentrations were less clear and probably reflect a wider variety of inputs at a lower magnitude and greater instream processing. In downstream areas, nutrient concentrations, although elevated with respect of headwater reaches, do not increase systematically but appear instead to vary in response to near channel human population pressures and land uses. NOx correlated significantly with population and urban environmental variables. In addition, during the wet season only, NOx formed positive correlations with agricultural and commercial land use variables. NH_3 formed a positive correlation with commercial land use variables adding strength to the hypothesis that commercial land use maybe influencing the NH_3 concentrations in the mainstem of Sonoma Creek. There were no regional correlations found between environmental variables and PO_4^{3-}. A number of locations were re-sampled during a *Hotspot Survey* designed to better identify the spatial extent of anomalous high nutrient concentrations and to help strengthen hypotheses about the causes. First order estimates of average nutrient loads were made for each watershed. The NOx load in these watersheds is estimated to be about 6 times greater than the historical natural condition.

Interpretation of the data provided a number of reasons for rejecting $H_{(0)}$:

- Except in headwater reaches, concentrations of NOx, NH_3 and PO_4^{3-} were high relative to expected concentrations in pristine watersheds.

- Concentrations of NOx varied greatly between sampling locations and increased in a downstream direction in relation to anthropogenic factors.

- Total dissolved nitrogen was dominated by NOx and total dissolved phosphorus was dominated by PO_4^{3-}.

- Approximately 85% of the sampling locations exceeded EPA guidelines in Level III Eco-Region 6 for TN (500 µg/L) and ~92% of the sampling locations exceeded EPA guidelines in Level III Eco-Region 6 for TP (30 µg/L).

- NOx concentrations were highest during the winter months indicating considerable seasonal variation greater than would be expected in natural watersheds.

- NOx correlated significantly with population and urban environmental variables during the winter, spring and early summer and during the wet season only with agricultural and commercial land use variables.

- NH_3 formed a positive correlation with commercial land use variables.

- When certain areas were focused upon during the Hotspot Survey, the extent of a concentration anomaly could usually be pinpointed to a change in land use.

$H_{(0)}$ is rejected for both watersheds:

> *$H_{(1)}$ Land use and human populations influence nitrogen and phosphorus concentrations in flowing water bodies within Sonoma Creek or Napa River watersheds.*

NEW HYPOTHESES THAT COULD BE FURTHER TESTED THOUGH ADDITIONAL WORK

Regional

- During the winter, NOx is supplied to the drainage ways from a variety of sources including runoff from agriculture, septic systems, treated sewage discharge, and urban runoff.

- During the spring and summer, NOx is supplied to the drainage ways dominantly from septic systems with some additional runoff from dry weather flows in urban areas.

- NH_3 is sourced from commercial land use and regeneration within the drainage ways.

- Neither watershed is nutrient limited. There are mineral nutrients loads in excess of that which can be assimilated into organic forms within the riparian zone during stable flow conditions. It appears that portions of the watersheds that are not impacted by human activity are nitrogen limited.

- Phytoplankton does not play a dominant role in any assimilation that occurs.

Localized

- Reaches devoid of riparian shading, the middle and lower fluvial reaches of the Napa River where large pools isolated by bed interflow form during the summer and autumn, and tidal reaches of both watersheds are vulnerable reaches that are more susceptible to excessive nutrient load and therefore good indicators of impairment of beneficial uses and suitable for long term monitoring.

- NOx concentrations on Sonoma Creek at Kenwood and the unnamed tributary on the northwest side of Kenwood are influenced by runoff from septic systems. The unique late summer signature is associated with particularly poor soil conditions for septic water disposal.

- NOx, NH_3, and PO_4^{3-} concentrations on Nathanson Creek, City of Sonoma, are influenced by urban and agricultural runoff during the wet season and urban dry weather flows during the summer and autumn.

- Water quality in the reach downstream from Calistoga is influenced by treated sewage input during winter stable flow conditions and urban dry weather flows during the summer and autumn.

- NOx concentrations in Bell Canyon Creek are influenced by septic system runoff during winter stable flow conditions, spring, and early summer.

- The NOx anomaly in the reach downstream from St. Helena is associated with runoff from non-sewered population living in areas that drain to the reach between St Helena and Zinfandel Lane.

- The NOx anomaly in Salvador channel is associated with runoff from discontinued septic systems or sewer line exfiltration, or perhaps runoff from a dog walking park.

- The NOx anomaly in Tulucay / Murphy Creeks is associated with runoff from discontinued septic systems or sewer line exfiltration.

- The PO_4^{3-} anomaly in Tulucay / Murphy Creeks is associated with ground water leaching from the tertiary volcanic flow rocks, pyroclastics and volcanic mudflows that dominate the geology of the subwatershed.

UNANSWERED QUESTIONS

Septic System Waste Disposal

Q1. By what mechanism (saturation from above, saturation from below, location specific) and pathway (groundwater, surface water, combination) does NOx derived from septic systems / leach field enter the drainage ways?

Q2. What is the public opinion of septic waste disposal as a problem and what can their sense of smell tell us about the mechanisms and pathways?

Q3. After a town or urban area is upgraded to a centralized sewer system, how long does it take for water quality in adjacent creeks to respond?

Q4. What influence does the tourist population have on the proper functioning of septic sewage disposal?

Sources of Phosphorus

Q5. What is the source of phosphorus in the headwaters of the Tulucay / Murphy Creek subwatershed?

Urban Runoff

Q6. What are the wet weather and dry weather concentrations and loads of nutrients derived from runoff of urban areas in these watersheds?

Unknown Causes of Hotspots

Q7. What is the cause of the NOx anomaly downstream from the city of St. Helena?

Receiving Water Impacts

Q8. What are the concentrations and loads of nutrients during flood flow?

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Appendix A. Water quality at the study locations organized by sampling event.

Station	Description	Lat	Long	Date	Time	NOx	NO_2^-	PO_4^{-3}	NH_3	TN	TP	Chl-a	pH	Turb
.	.	.	.	.	.	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	.	NTU
S-5	Sonoma Ck. @ Maxwell Park	38.29840	-122.48120	10/1/02	12:15	2	0	61	9	125	67	0	8.5	1
S-6	Sonoma Ck. near Sonoma Ecology Center	38.35070	-122.51627	10/1/02	15:40	18	0	42	14	166	52	0	8.6	<1
S-8	Sonoma Ck. @ Hwy 121	38.24047	-122.45130	10/1/02	10:00	0	1	73	5	552	100	12	7.5	9
S-10	Carriger Ck. @ Marilyn Goode's property	38.29211	-122.52320	10/1/02	14:15	56	0	70	16	260	88	0	8.4	<1
S-11	Sonoma Ck. @ Agua Caliente	38.32318	-122.49470	10/1/02	15:00	15	0	59	10	203	63	0	8.9	<1
S-12	Sonoma Ck. @ Glen Allen	38.36003	-122.52603	10/1/02	16:15	29	0	79	6	201	93	0	8.5	<1
S-13	Sonoma Ck. @ 986 Warm Springs Rd.	38.40492	-122.55097	10/1/02	17:21	1059	1	76	8	803	98	1	8.8	-
S-14	Sonoma Ck. @ Goodspeed Bridge	38.44295	-122.53110	10/1/02	18:00	67	0	59	5	148	68	0	8.6	<1
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
S-3	Nathanson Ck. @ Watmaugh	38.26457	-122.45307	1/6/2003	11:02	1534	3	95	9	2504	111	0	9.5	6
S-4	Nathanson Ck. @ Nathanson Park	38.27860	-122.45748	1/6/2003	11:50	1376	1	72	8	1761	90	0	8.7	6
S-5	Sonoma Ck. @ Maxwell Park	38.29840	-122.48120	1/6/2003	12:40	1455	1	54	5	1619	68	0	9.1	7
S-6	Sonoma Ck. near Sonoma Ecology Center	38.35070	-122.51627	1/6/2003	14:08	1496	1	49	5	1694	71	0	9.6	6
S-8	Sonoma Ck. @ Hwy 121	38.24047	-122.45130	1/6/2003	9:58	1522	1	59	11	1976	113	0	9.3	6
S-9	Schell Ck. @ Hwy 121	38.24625	-122.43508	1/6/2003	10:30	2163	9	168	64	4076	206	0	9.1	9
S-10	Carriger Ck. @ Marilyn Goode's property	38.29211	-122.52320	1/6/2003	13:12	93	0	44	4	288	60	0	9.2	6
S-11	Sonoma Ck. @ Agua Caliente	38.32318	-122.49470	1/6/2003	13:40	1443	1	48	6	1467	63	0	9.4	7
S-12	Sonoma Ck. @ Glen Allen	38.36003	-122.52603	1/6/2003	14:46	1613	1	50	6	1897	76	0	9.4	6
S-13	Sonoma Ck. @ 986 Warm Springs Rd.	38.40492	-122.55097	1/6/2003	15:48	1619	4	45	3	1780	72	0	9.3	4
S-14	Sonoma Ck. @ Goodspeed Bridge	38.44295	-122.53110	1/6/2003	16:51	166	0	33	2	251	56	0	9.5	4
S-22	Sonoma Ck. @ Watmaugh	38.26580	-122.46783	1/6/2003	11:20	1389	1	53	8	1693	76	0	9.3	6
S-23	Calabazas Ck. @ Glen Allen	38.36003	-122.52603	1/6/2003	15:07	1382	1	42	6	1558	50	0	9.2	9
S-24	Sonoma Ck. above tent park near white barn	38.43438	-122.50810	1/6/2003	16:25	79	0	25	1	154	46	0	9.5	2
S-25	Rogers Ck. @ Arnold Drive	38.25515	-122.48002	1/6/2003	18:05	1550	4	94	12	2711	152	0	9.4	7
S-26	Carriger Ck. @ Watmaugh	38.26358	-122.47450	1/7/2003	8:50	1500	2	75	10	1729	117	0	9.6	2
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
S-3	Nathanson Ck. @ Watmaugh	38.26457	-122.45307	7/7/2003	10:35	172	4	41	17	477	81	-	8.9	4

Appendix A. Water quality at the study locations organized by sampling event (Continued).

Station	Description	Lat	Long	Date	Time	NOx	NO_2^-	PO_4^{-3}	NH_3	TN	TP	Chl-a	pH	Turb
.	.	.	.	.	.	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	.	NTU
S-4	Nathanson Ck. @ Nathanson Park	38.27860	-122.45748	7/7/2003	11:00	266	5	71	40	578	146	-	8.7	4
S-5	Sonoma Ck. @ Maxwell Park	38.29840	-122.48120	7/7/2003	12:35	102	2	47	-	306	75	-	9.5	2
S-6	Sonoma Ck. near Sonoma Ecology Center	38.35070	-122.51627	7/7/2003	14:05	437	9	38	24	731	86	-	9.1	4
S-8	Sonoma Ck. @ Hwy 121	38.24047	-122.45130	7/7/2003	9:45	174	5	55	40	470	121	1	8.4	4
S-9	Schell Ck. @ Hwy 122	38.24625	-122.43508	7/7/2003	10:10	8	1	133	20	590	253	-	8.9	3
S-11	Sonoma Ck. @ Agua Caliente	38.32318	-122.49470	7/7/2003	13:35	129	3	33	15	331	53	-	9.2	2
S-12	Sonoma Ck. @ Glen Allen	38.36003	-122.52603	7/7/2003	14:30	960	15	81	19	1214	103	-	9.7	2
S-13	Sonoma Ck. @ 986 Warm Springs Rd.	38.40492	-122.55097	7/7/2003	15:15	2092	3	71	6	1253	100	-	8.8	1
S-14*	Sonoma Ck. @ Goodspeed Bridge	38.44295	-122.53110	7/7/2003	15:45	115	0	42	3	190	72	-	8.6	1
S-22	Sonoma Ck. @ Watmaugh	38.26580	-122.46783	7/7/2003	11:15	301	5	59	40	539	93	-	8.7	3
S-23	Calabazas Ck. @ Glen Allen	38.36003	-122.52603	7/7/2003	14:40	45	0	44	8	165	51	-	9.0	2
S-24	Sonoma Ck. above tent park near white barn	38.43438	-122.50810	7/7/2003	16:35	288	1	33	8	386	68	-	8.9	5
S-26	Carriger Ck. @ Watmaugh	38.26358	-122.47450	7/7/2003	11:35	126	6	28	26	500	151	-	9.0	8
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
S-3	Nathanson Ck. @ Watmaugh	38.26457	-122.45307	5/5/2004	14:40	1568	6	77	25	1792	95	-	-	-
S-4	Nathanson Ck. @ Nathanson Park	38.27860	-122.45748	5/5/2004	13:39	1124	19	62	41	1399	94	-	-	-
S-5	Sonoma Ck. @ Maxwell Park	38.29840	-122.48120	5/5/2004	11:40	597	8	56	45	885	66	-	-	-
S-13	Sonoma Ck. @ 986 Warm Springs Rd.	38.40492	-122.55097	5/5/2004	9:35	2052	4	66	13	2305	85	-	-	-
S-14	Sonoma Ck. @ Goodspeed Bridge	38.44295	-122.53110	5/5/2004	10:40	203	0	43	4	272	55	-	-	-
S-22	Sonoma Ck. @ Watmaugh	38.26580	-122.46783	5/5/2004	14:19	595	9	38	9	836	151	-	-	-
S-30	Unnamed Ck. @ Lawndale Ave.	38.42220	-122.56925	5/5/2004	10:05	1536	5	15	20	1593	15	-	-	-
S-31	Sonoma Ck. @ Mound Ave	38.41010	-122.55352	5/5/2004	11:02	2230	3	59	10	2326	66	-	-	-
S-32	Sonoma Ck. @ Hwy 12	38.42703	-122.55968	5/5/2004	10:18	72	0	26	6	152	35	-	-	-
S-33	Sonoma Ck. @ Andrieux St.	38.28970	-122.47463	5/5/2004	12:20	545	9	41	34	790	73	-	-	-
S-34	Sonoma Ck. @ Leveroni Rd.	38.27732	-122.47178	5/5/2004	14:00	705	9	53	32	986	64	-	-	-
S-35	Nathanson Ck. @ 4th St.	38.29248	-122.44993	5/5/2004	13:12	297	11	69	14	861	98	-	-	-
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
N-2	Mill Ck. @ the old Bale Mill	38.53992	-122.51067	10/3/02	12:00	3	0	81	4	65	89	0	8.2	-

Appendix A. Water quality at the study locations organized by sampling event (Continued).

Station	Description	Lat	Long	Date	Time	NOx	NO_2^-	PO_4^{-3}	NH_3	TN	TP	Chl-a	pH	Turb
.	.	.	.	.	.	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	.	NTU
N-3	Ritchey Ck. nr. Ranger station (Bothe State Park)	38.55175	-122.52124	10/3/02	11:37	5	0	68	5	129	88	0	8.1	-
N-4	Napa Ck. @ Jefferson	38.30383	-122.29339	10/2/02	11:50	254	5	19	17	424	49	1	8.4	2
N-5	Napa R. @ Calistoga community Center	38.57876	-122.58044	10/3/02	10:55	8	0	73	18	180	75	1	7.7	-
N-6	Napa R. @ Zinfandel Lane	38.49549	-122.42560	10/2/02	16:50	28	1	31	29	286	73	2	8.4	-
N-9	Napa R. @ Yountville Ecopreserve	38.41890	-122.35326	10/2/02	16:00	0	0	18	7	323	46	2	8.7	-
N-13	Murphy Ck. @ "Stone Bridge" on Coombsville Road	38.29389	-122.23418	10/2/02	10:20	104	0	198	7	300	174	0	8.5	1
N-15*	Salvador channel @ Garfield Park	38.33119	-122.29916	10/2/02	13:50	97	0	14	8	333	26	1	8.5	-
N-16	Milliken Ck. @ Hedgeside Avenue	38.33827	-122.26945	10/3/02	12:30	18	0	22	4	249	33	0	7.9	-
N-18	Brown Valley Ck. @ little stone Bridge	38.30389	-122.32224	10/2/02	13:15	29	0	12	3	280	44	9	8.3	10
N-19	Fagan Ck. @ on Kelly Rd.	38.21495	-122.63692	10/2/02	8:50	156	5	55	40	604	93	0	8.1	2
N-23	Napa R. @ Trancas St.	38.32508	-122.63875	????	????	8	0	31	4	332	97	18	8	-
N-25	Sulphur Ck. @ Lower Bridge near Trailer Park	38.51083	-122.45929	10/2/02	17:30	2	1	65	43	303	99	3	8.3	-
N-26	Bell Canyon Ck. @ Silverado	38.53617	-122.64227	10/3/02	9:55	524	1	41	9	449	50	0	8.5	-
N-30	Napa R. @ 3rd St.	38.29818	-122.63830	10/2/02	11:20	103	7	87	86	730	104	7	7.6	-
N-31	Napa R. @ Oak Knoll Ave	38.36823	-122.63947	10/2/02	18:25	15	0	53	8	110	63	0	8.2	-
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
N-1	Dry Ck. @ Railroad Bridge	38.36500	-122.63942	1/7/2003	16:30	500	2	17	4	307	24	0	9.1	6
N-2	Mill Ck. @ the old Bale Mill	38.53992	-122.51067	1/8/2003	10:30	300	0	31	4	629	22	0	9.2	6
N-3	Ritchey Ck. nr. Ranger station (Bothe State Park)	38.55175	-122.52124	1/8/2003	10:53	23	0	40	4	59	38	0	9.2	8
N-4	Napa Ck. @ Jefferson	38.30383	-122.29339	1/7/2003	12:22	921	0	22	5	1008	45	0	9.3	8
N-5	Napa R. @ Calistoga Community Center	38.57876	-122.58044	1/8/2003	11:13	1387	9	50	13	1406	61	0	9.0	8
N-6	Napa R. @ Zinfandel Lane	38.49549	-122.42560	1/8/2003	8:54	2084	13	45	13	2098	59	0	9.2	7
N-8	Napa R. @ Tubbs Lane	38.60040	-122.59892	1/8/2003	11:35	614	4	17	6	751	42	1	9.0	22
N-9	Napa R. @ Yountville Ecopreserve	38.41890	-122.35326	1/8/2003	12:50	2208	9	46	18	2414	71	0	8.9	7
N-11	Tulukay Ck. @ Terrace Court	38.28852	-122.26935	1/7/2003	11:27	3162	3	110	10	3273	130	0	9.0	4
N-13	Murphy Ck. @ "Stone Bridge" on Coombsville Road	38.29389	-122.23418	1/7/2003	10:48	616	7	85	4	720	90	0	9.0	4
N-14	Carneros Ck. @ Withers	38.24648	-122.63744	1/7/2003	9:47	706	0	70	5	1195	97	0	9.3	9
N-15	Salvador channel @ Garfield Park	38.33119	-122.29916	1/7/2003	13:39	2312	4	27	11	2767	50	0	9.2	8

Appendix A. Water quality at the study locations organized by sampling event (Continued).

Station	Description	Lat	Long	Date	Time	NOx	NO_2^-	PO_4^{-3}	NH_3	TN	TP	Chl-a	pH	Turb
.	.	.	.	.	.	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	.	NTU
N-16	Milliken Ck. @ Hedgeside Avenue	38.33827	-122.26945	1/7/2003	14:59	846	2	13	10	1011	28	0	9.1	35
N-18	Brown Valley Ck. @ "Little Stone Bridge"	38.30389	-122.32224	1/7/2003	12:49	674	0	19	2	1002	41	0	9.2	6
N-19	Fagan Ck. @ Kelly Rd.	38.21495	-122.63692	1/7/2003	17:08	1602	7	37	20	2025	92	0	8.6	11
N-20	Soda Ck. @ Silverado Trail	38.35792	-122.63930	1/7/2003	15:26	603	4	23	2	973	22	0	9.2	2
N-23	Napa R. @ Trancas St.	38.32508	-122.63875	1/7/2003	14:20	1841	6	58	28	2129	92	0	9.0	15
N-25	Sulphur Ck. @ Lower Bridge near Trailer Park	38.51083	-122.45929	1/8/2003	9:55	711	5	35	76	1080	58	0	9.1	18
N-26	Bell Canyon Ck. @ Silverado	38.53617	-122.64227	1/8/2003	12:20	1588	2	40	9	1882	37	0	8.7	6
N-27	Dutch Henry Ck. @ Larkmead Lane Bridge	38.56665	-122.51919	1/8/2003	11:59	376	1	37	2	351	32	0	8.7	3
N-30	Napa R. @ 3rd Street	38.29818	-122.63830	1/7/2003	10:25	1723	3	59	49	1992	89	0	9.4	13
N-31*	Napa R. @ Oak Knoll Avenue	38.36823	-122.63947	1/7/2003	15:50	1344	4	55	28	1778	74	0	9.4	13
N-32	Redwood Ck. @ Redwood Road	38.31785	-122.63863	1/7/2003	13:12	649	0	22	2	686	61	0	8.9	8
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
N-1	Dry Ck. @ Railroad Bridge	38.36500	-122.33813	7/8/2003	14:26	333	1	9	7	484	28	-	8.5	1
N-2	Mill Ck. @ the old Bale Mill	38.54087	-122.50852	7/8/2003	19:50	71	0	74	3	138	88	-	9.0	2
N-3	Ritchey Ck. nr. Ranger station (Bothe State Park)	38.55158	-123.52113	7/8/2003	19:30	16	0	72	5	136	84	-	9.0	2
N-4	Napa Ck. @ Jefferson	38.30125	-122.29237	7/8/2003	13:08	436	4	10	12	641	25	-	8.0	5
N-5	Napa R. @ Calistoga Community Center	38.57840	-123.58070	7/8/2003	19:00	93	1	44	20	305	81	-	8.6	3
N-6	Napa R. @ Zinfandel Lane	38.49520	-122.42650	7/8/2003	17:00	1215	9	17	16	1578	35	-	8.6	1
N-8	Napa R. @ Tubbs Lane	38.60065	-123.59853	7/8/2003	18:35	25	0	23	5	193	33	-	8.9	3
N-9	Napa R. @ Yountville Ecopreserve	38.41947	-122.35370	7/8/2003	20:45	941	5	24	19	1125	46	-	8.9	2
N-11	Tulokay Ck. @ Terrace Court	38.28860	-122.26947	7/8/2003	11:10	1921	1	75	3	2133	86	-	8.8	<1
N-13	Murphy Ck. @ "Stone Bridge" on Coombsville Road	38.29395	-122.23395	7/8/2003	10:42	186	1	181	3	323	164	-	8.1	1
N-14	Carneros Ck. @ Withers	38.24648	-122.33288	7/8/2003	10:00	0	1	26	10	320	87	-	7.9	1
N-15	Salvador channel @ Garfield Park	38.33095	-122.29938	7/8/2003	14:14	785	4	14	14	1072	25	-	8.7	4
N-16	Milliken Ck. @ Hedgeside Avenue	38.33833	-122.26958	7/8/2003	15:30	93	2	29	17	339	51	-	8.9	2
N-18	Brown Valley Ck. @ "Little Stone Bridge"	38.30388	-122.32238	7/8/2003	13:24	349	2	10	7	586	30	-	8.9	1
N-19	Fagan Ck. @ Kelly Rd.	38.21495	-122.25325	7/8/2003	9:10	166	3	7	26	488	51	-	8.4	3
N-23	Napa R. @ Trancas St.	38.32508	-122.28435	7/8/2003	15:00	399	6	19	10	608	42	-	8.9	2

Appendix A. Water quality at the study locations organized by sampling event (Continued).														
Station	**Description**	**Lat**	**Long**	**Date**	**Time**	**NOx**	**NO_2^-**	**PO_4^{-3}**	**NH_3**	**TN**	**TP**	**Chl-a**	**pH**	**Turb**
.	.	.	.	.	.	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	.	NTU
N-25	Sulphur Ck. @ Lower Bridge near Trailer Park	38.51087	-122.49258	7/8/2003	17:31	137	5	26	19	327	62	-	8.3	1
N-26	Bell Canyon Ck. @ Silverado	38.50283	-122.48703	7/8/2003	17:56	981	2	52	12	1226	64	-	8.5	2
N-30	Napa R. @ 3rd Street	38.29818	-122.28370	7/8/2003	11:48	190	4	28	58	538	131	9	9.4	34
N-31	Napa R. @ Oak Knoll Avenue	38.36823	-122.30347	7/8/2003	16:01	540	4	46	12	765	73	-	9.0	2
N-32	Redwood Ck. @ Redwood Road	38.31785	-122.32750	7/8/2003	13:47	98	3	7	5	192	12	-	8.6	1
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
N-4	Napa Ck. @ Jefferson	38.30125	-122.29237	5/5/2004	15:39	895	8	24	22	1055	33	-	-	-
N-5	Napa R. @ Calistoga Community Center	38.57840	-123.58070	5/6/2004	10:05	324	1	38	13	485	38	-	-	-
N-6	Napa R. @ Zinfandel Ln.	38.49520	-122.42650	5/6/2004	13:40	1249	3	27	11	2379	41	-	-	-
N-11	Tulukay Ck. @ Terrace Ct.	38.28860	-122.26947	5/5/2004	18:50	2943	43	72	4	3362	81	-	-	-
N-13	Murphy Ck. @ "Stone Bridge" on Coombsville Rd.	38.29395	-122.23395	5/5/2004	18:05	348	0	156	7	481	-	-	-	-
N-15	Salvador Channel @ Garfield Park	38.33095	-122.29938	5/6/2004	14:48	1737	6	6	28	2519	14	-	-	-
N-18	Browns Valley Ck. @ "Little Stone Bridge"	38.30388	-122.32238	5/5/2004	16:02	850	3	17	14	1083	37	-	-	-
N-26	Bell Canyon Ck. @ Silverado Trail	38.50283	-122.48703	5/6/2004	11:05	973	3	46	13	1115	-	-	-	-
N-40	Browns Valley Ck. @ Buhman Ave.	38.30528	-122.33877	5/5/2004	16:17	458	2	20	11	574	26	-	-	-
N-41*	Browns Valley Ck. @ Morningside Dr.	38.30957	-122.44670	5/5/2004	16:45	858	1	15	6	938	22	-	-	-
N-42	Murphy Ck. @ Shady Brook Ln.	38.29388	-122.52320	5/5/2004	17:45	490	1	196	4	592	-	-	-	-
N-43	Tulukay Ck. @ Shurtleff Ave.	38.28970	-122.26532	5/5/2004	18:20	2958	0	71	15	3306	97	-	-	-
N-44	Napa R. @ Heather Oaks Park	38.58567	-122.59333	5/6/2004	9:44	256	2	57	10	430	69	-	-	-
N-45	Napa R. @ Dunaweal Ln.	38.56873	-122.55527	5/6/2004	10:17	1304	1	186	13	1399	203	-	-	-
N-46	Napa R. @ Larkmead Ln.	38.56057	-122.52203	5/6/2004	10:43	1003	3	131	16	1183	315	-	-	-
N-47	Bell Canyon Ck. @ Crystal Springs Rd.	38.55053	-122.48308	5/6/2004	11:30	41	1	20	16	338	-	-	-	-
N-48	Canon Ck. @322 Glass Mountain Rd.	38.53702	-122.48267	5/6/2004	11:55	775	1	73	12	1273	156	-	-	-
N-49	Napa R. @ Lodi Ln.	38.52727	-122.49108	5/6/2004	12:12	492	2	56	11	505	71	-	-	-
N-50	Napa R. @ Pope St. Saint Helena	38.51137	-122.45567	5/6/2004	12:30	425	3	47	16	1222	50	-	-	-
N-51	Salvador Channel @ 2280 Dry Ck. Rd.	38.33307	-122.34195	5/6/2004	14:10	8	6	7	14	410	24	-	-	-
N-52	Salvador Channel @ 121 near school	38.33378	-122.32028	5/6/2004	14:30	1565	0	16	40	2499	31	-	-	-

* Average of a duplicate sample.

Appendix B. Environmental variables generated from the Geographic information system (GIS). Area (km^2); Population (persons)											
ID	**Total_AREA**	**5km_AREA**	**50m_buffer_AREA**	**Total_POP**	**5km_POP**	**50m_buffer_POP**	**Total_AGRI**	**Total_COMM**	**Total_INDU**	**Total_OPEN**	**Total_URBA**
N-01	47.51	5.41	7.94	1948	390	331	6.84	0.00	0.40	38.03	2.24
N-02	4.31	0.00	0.40	56	0	5	0.23	0.00	0.01	4.02	0.05
N-03	6.13	4.99	0.75	94	75	12	0.23	0.07	0.14	5.83	0.13
N-04	40.10	6.23	5.58	12670	9811	1468	14.52	0.31	0.04	18.39	6.84
N-05	52.28	18.93	5.96	3730	3530	443	11.52	0.22	0.18	36.14	4.45
N-06	197.93	10.67	23.05	14885	3680	1637	61.52	0.89	3.23	117.70	14.59
N-08	12.49	8.90	1.47	60	43	7	2.24	0.05	0.06	10.24	0.07
N-09	447.83	21.06	61.12	20333	634	2241	136.70	16.50	15.10	251.13	28.40
N-11	22.82	12.46	3.71	2166	1947	363	9.41	0.00	0.02	10.01	3.38
N-13	2.82	0.00	0.66	69	0	24	1.49	0.04	0.04	1.00	0.41
N-14	17.95	3.92	2.96	506	104	80	11.29	0.01	0.08	6.45	0.12
N-15	11.12	9.88	1.90	8654	8577	1308	3.75	0.25	0.02	2.93	4.18
N-16	36.26	11.02	4.90	848	535	157	16.32	0.00	0.02	17.80	2.11
N-18	8.48	7.03	1.32	922	856	163	2.26	0.03	0.00	4.47	1.71
N-19	15.95	10.96	2.71	244	161	40	2.57	6.15	0.01	7.19	0.02
N-20	11.65	5.38	1.69	199	94	28	4.51	0.00	0.01	6.94	0.19
N-23	588.09	15.40	82.86	43217	13392	6217	188.08	17.01	19.26	323.18	40.57
N-25	23.55	4.99	3.87	2509	2272	409	6.16	0.16	0.13	14.97	2.13
N-26	21.72	8.84	3.19	1512	659	171	9.61	0.22	0.08	9.77	2.04
N-27	13.69	8.02	1.39	88	59	9	3.42	0.01	0.01	10.23	0.05
N-30	707.55	16.29	98.61	79507	28833	9284	233.89	18.57	19.94	376.59	58.57
N-31	547.74	16.81	76.90	27118	583	3278	168.11	16.64	19.19	310.66	33.14
N-32	26.40	2.77	3.73	1398	598	180	12.19	0.00	0.03	12.78	1.41
N-40	6.86	0.00	1.05	291	0	43	1.82	0.00	0.00	3.85	1.19
N-41	5.65	0.00	0.59	232	0	20	1.64	0.00	0.00	3.53	0.48
N-42	2.39	0.00	0.52	36	0	11	1.36	0.04	0.04	0.95	0.16
N-43	22.57	13.13	3.68	1731	1534	268	9.34	0.00	0.02	9.96	3.25
N-44	22.17	13.84	2.38	547	507	110	5.02	0.07	0.12	16.18	0.99
N-45	73.61	21.91	8.26	6042	5380	633	16.49	0.44	0.32	50.98	5.66
N-46	80.70	17.06	9.21	6180	2193	652	20.68	0.46	0.56	53.13	6.14
N-47	15.11	9.32	2.33	838	521	79	7.03	0.00	0.04	7.31	0.73
N-48	4.82	0.00	0.57	398	0	46	1.56	0.07	0.03	2.15	1.01
N-49	149.51	19.23	16.42	8374	875	866	42.74	0.79	1.13	95.21	10.23

Appendix B. Environmental variables generated from the Geographic information system (GIS) continued.

ID	Total_AREA	5km_AREA	50m_buffer_AREA	Total_POP	5km_POP	50m_buffer_POP	Total_AGRI	Total_COMM	Total_INDU	Total_OPEN	Total_URBA
N-50	191.60	17.96	22.38	13890	5085	1596	60.02	0.86	1.73	114.85	14.14
N-51	0.45	0.00	0.09	23	0	11	0.38	0.00	0.00	0.07	0.00
N-52	3.70	0.00	0.54	2824	0	679	1.82	0.03	0.00	0.37	1.49
.	.	.	.	.	.	.	.	.	.	.	.
S-03	17.57	7.83	2.10	7503	6225	1039	7.08	1.87	0.25	2.39	6.30
S-04	12.95	6.52	1.34	3322	2756	329	6.32	0.99	0.21	2.29	3.45
S-05	-	-	-	-	-	-	-	-	-	-	-
S-06	117.37	13.33	18.15	6310	1299	1111	31.61	2.97	5.04	52.95	24.79
S-08	235.52	12.35	39.42	33291	1007	6039	75.90	10.50	7.09	88.29	57.64
S-09	25.52	12.93	4.24	1610	811	247	10.64	1.08	1.46	6.00	7.91
S-10	12.60	9.03	1.49	492	357	61	1.29	0.19	0.00	6.81	4.32
S-11	144.53	13.01	22.38	9745	2441	1601	38.56	6.90	5.38	60.95	32.74
S-12	76.59	10.33	11.65	4681	760	810	18.82	0.27	3.21	39.08	15.21
S-13	46.87	16.05	7.19	2544	1912	481	9.92	0.09	2.50	28.14	6.21
S-14	14.47	13.07	1.47	166	149	18	0.86	0.00	0.02	10.99	2.52
S-20	4.38	0.00	0.51	63	0	7	1.63	0.11	0.03	2.05	0.55
S-21	66.43	0.00	10.08	3896	0	667	16.16	0.21	2.84	32.07	14.84
S-22	184.66	8.94	27.40	30537	6241	4791	54.75	9.08	6.01	64.05	49.85
S-24	7.45	0.00	1.18	93	0	15	0.11	0.00	0.00	4.87	2.42
S-25	13.45	8.80	2.15	969	789	147	3.54	0.06	0.08	8.47	1.53
S-26	25.39	9.47	3.35	1367	760	257	8.91	0.29	0.03	9.88	6.29
S-30	8.50	7.55	1.24	1093	1083	209	1.31	0.00	0.00	6.18	1.01
S-31	39.18	14.03	5.84	2202	1759	388	6.21	0.06	1.48	23.22	8.22
S-32	20.94	9.04	2.99	238	101	35	2.10	0.01	0.11	13.93	4.79
S-33	174.29	12.61	26.53	26227	14123	3635	50.01	8.32	6.00	63.19	46.76
S-34	182.48	10.66	28.53	30036	10284	4884	54.12	9.02	6.01	63.78	49.54
.	.	.	.	.	.	.	.	.	.	.	.
ID	**5km_AGRI**	**5km_COMM**	**5km_INDU**	**5km_OPEN**	**5km_URBA**	**50m_buffer_AGRI**	**50m_buffer_COMM**	**50m_buffer_INDU**	**50m_buffer_OPEN**	**50m_buffer_URBA**	**Unused**
N-01	0.89	0.00	0.01	4	0	1	0.00	0.11	6.49	0.40	.
N-02	0.00	0.00	0.00	0	0	0	0.00	0.00	0.38	0.00	.
N-03	0.05	0.00	0.08	5	0	0	0.00	0.00	0.73	0.01	.
N-04	0.61	0.30	0.01	2	4	2	0.06	0.00	2.20	1.19	.
N-05	5.49	0.16	0.09	10	3	1	0.04	0.00	3.73	0.70	.

Appendix B. Environmental variables generated from the Geographic information system (GIS) continued.

ID	5km_AGRI	5km_COMM	5km_INDU	5km_OPEN	5km_URBA	50m_buffer_AGRI	50m_buffer_COMM	50m_buffer_INDU	50m_buffer_OPEN	50m_buffer_URBA	Unused
N-06	2.89	0.20	1.63	4	2	8	0.10	0.26	13.28	1.87	.
N-08	2.09	0.02	0.03	7	0	0	0.01	0.00	1.22	0.00	.
N-09	7.17	0.08	9.14	3	2	17	2.08	2.24	36.38	3.52	.
N-11	6.05	0.00	0.01	3	3	2	0.00	0.00	1.51	0.55	.
N-13	0.00	0.00	0.00	0	0	0	0.00	0.00	0.22	0.19	.
N-14	3.69	0.01	0.01	0	0	2	0.00	0.02	0.75	0.04	.
N-15	3.14	0.25	0.02	2	4	1	0.03	0.01	0.67	0.65	.
N-16	5.50	0.00	0.01	4	2	2	0.00	0.00	2.28	0.25	.
N-18	1.91	0.03	0.00	3	2	0	0.02	0.00	0.66	0.42	.
N-19	2.41	5.01	0.01	4	0	0	1.22	0.00	1.02	0.02	.
N-20	2.58	0.00	0.00	3	0	1	0.00	0.00	0.92	0.07	.
N-23	7.45	0.32	0.04	2	6	25	2.16	2.77	46.72	5.78	.
N-25	2.02	0.16	0.13	1	2	1	0.02	0.04	2.13	0.42	.
N-26	4.02	0.20	0.05	3	1	1	0.02	0.04	1.47	0.23	.
N-27	2.70	0.00	0.00	5	0	0	0.00	0.00	1.04	0.02	.
N-30	2.63	1.51	0.52	3	8	32	2.34	2.94	53.38	8.01	.
N-31	9.29	0.02	0.15	6	1	23	2.11	2.76	44.92	4.30	.
N-32	0.92	0.00	0.01	1	1	2	0.00	0.00	1.51	0.32	.
N-40	0.00	0.00	0.00	0	0	0	0.00	0.00	0.58	0.29	.
N-41	0.00	0.00	0.00	0	0	0	0.00	0.00	0.37	0.10	.
N-42	0.00	0.00	0.00	0	0	0	0.00	0.00	0.21	0.08	.
N-43	6.19	0.00	0.01	4	3	2	0.00	0.00	1.50	0.52	.
N-44	3.76	0.03	0.08	9	1	1	0.01	0.00	1.65	0.20	.
N-45	5.82	0.36	0.13	12	3	2	0.07	0.02	5.19	0.85	.
N-46	7.99	0.22	0.36	7	1	3	0.07	0.06	5.65	0.87	.
N-47	5.27	0.00	0.04	3	1	1	0.00	0.03	1.25	0.02	.
N-48	0.00	0.00	0.00	0	0	0	0.02	0.01	0.15	0.16	.
N-49	6.62	0.22	0.18	11	2	5	0.09	0.10	10.03	1.23	.
N-50	8.37	0.21	0.34	5	4	7	0.10	0.21	12.79	1.84	.
N-51	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	0.00	.
N-52	0.00	0.00	0.00	0	0	0	0.01	0.00	0.06	0.25	.
.	.	.	.	.	.	.	.	.	.	.	.
S-03	1.05	1.62	0.09	0	5	1	0.24	0.03	0.16	0.95	.

Appendix B. Environmental variables generated from the Geographic information system (GIS) continued.

ID	5km_AGRI	5km_COMM	5km_INDU	5km_OPEN	5km_URBA	50m_buffer_AGRI	50m_buffer_COMM	50m_buffer_INDU	50m_buffer_OPEN	50m_buffer_URBA	Unused
S-04	1.75	0.92	0.10	1	3	1	0.08	0.03	0.16	0.42	.
S-05	-	-	-	-	-	-	-	-	-	-	.
S-06	2.92	2.53	0.36	2	5	5	0.53	0.89	7.01	5.16	.
S-08	9.25	0.24	0.12	1	2	15	1.78	1.24	11.59	10.64	.
S-09	6.44	0.62	0.98	1	4	2	0.12	0.24	0.90	1.30	.
S-10	1.28	0.19	0.00	3	4	0	0.03	0.00	0.83	0.53	.
S-11	4.68	2.01	0.08	1	5	6	1.15	0.94	8.31	6.33	.
S-12	3.13	0.05	0.38	2	4	3	0.08	0.69	4.64	3.50	.
S-13	6.88	0.09	2.26	4	3	1	0.02	0.56	3.26	1.90	.
S-14	0.84	0.00	0.02	10	2	0	0.00	0.00	0.83	0.64	.
S-20	0.00	0.00	0.00	0	0	0	0.00	0.00	0.31	0.00	.
S-21	0.00	0.00	0.00	0	0	2	0.06	0.65	4.11	2.92	.
S-22	3.32	1.01	0.02	0	4	8	1.46	0.97	8.84	8.44	
S-24	0.00	0.00	0.00	0	0	0	0.00	0.00	0.57	0.60	.
S-25	3.40	0.06	0.08	4	2	1	0.04	0.06	1.14	0.40	.
S-26	6.31	0.10	0.02	1	2	1	0.05	0.01	1.04	0.84	.
S-30	1.31	0.00	0.00	5	1	0	0.00	0.00	0.82	0.22	.
S-31	4.52	0.06	1.42	5	3	1	0.01	0.27	2.89	1.75	.
S-32	0.92	0.01	0.09	6	2	0	0.01	0.04	1.66	1.11	.
S-33	2.54	1.34	0.13	2	7	7	1.29	1.05	8.84	8.01	.
S-34	3.07	1.52	0.03	0	6	8	1.42	1.05	8.99	8.76	.