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Effects of Stock Use and Backpackers on Water Quality in Wilderness in Sequoia and Kings Canyon National Parks, USA

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Abstract During 2010–2011, a study was conducted in Sequoia and Kings Canyon National Parks (SEKI) to evaluate the influence of pack animals (stock) and backpackers on water quality in wilderness lakes and streams. The study had three main components: (1) a synoptic survey of water quality in wilderness areas of the parks, (2) paired water quality sampling above and below several areas with differing types and amounts of visitor use, and (3) intensive monitoring at six sites to document temporal variations in water quality. Data from the synoptic water quality survey indicated that wilderness lakes and streams are dilute and have low nutrient and *Escherichia coli* concentrations. The synoptic survey sites were categorized as minimal use, backpacker-use, or mixed use (stock and backpackers), depending on the most prevalent type of use upstream from the sampling locations. Sites with mixed use tended to have higher concentrations of most constituents (including *E. coli*) than those categorized as minimal-use ($P \leq 0.05$); concentrations at backpacker-use sites were intermediate. Data from paired-site sampling indicated that *E. coli*, total coliform, and particulate phosphorus concentrations were greater in streams downstream from mixed-use areas than upstream from those areas ($P \leq 0.05$). Paired-site data also indicated few statistically significant differences in nutrient, *E. coli*, or total coliform concentrations in streams upstream and downstream from backpacker-use areas. The intensive-monitoring data indicated that nutrient and *E. coli* concentrations normally were low, except during storms, when notable increases in concentrations of *E. coli*, nutrients, dissolved organic carbon, and turbidity occurred. In summary, results from this study indicate that water quality in SEKI wilderness generally is good, except during storms; and visitor use appears to have a small, but statistically significant influence on stream water quality.

Keywords Sierra Nevada · *Escherichia coli* · Coliform · Visitor use · Water quality

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Introduction

Wilderness areas in the mountains of the western United States (U.S.) are the headwaters for major rivers that provide high-quality water for drinking, irrigation, and industry across the region. Wilderness areas in the U.S. receive substantial use by day hikers, backpackers, and pack animals (stock), with recreational visitor-use days in U.S. wilderness increasing sixfold from 1965 to 1994, when they approached 17 million/year (Cole 1996). The National Park Service (NPS) and others are concerned that visitor activities in high-use areas of wilderness may be affecting natural resources, including water quality.

Effects of hikers, backpackers, and stock on water quality may be divided into physical, biological, and chemical components. Physical effects may include increased suspended sediment concentrations and turbidity in surface water due to erosion of stream banks, trails, and meadows (Deluca et al. 1998). Such increases may reduce water clarity, light available for primary production, function of delicate gill tissue in fish, and physical habitat for aquatic species (Ryan 1991; Rabeni and Smale 1995).

Biological effects may include introduction of fecal pathogens, such as *Giardia lamblia*, *Cryptosporidium parvum*, or *Escherichia coli* O157:H7 into surface water due to transport from fecal matter deposited on the ground or in water by warm-blooded animals, including stock, humans, and wildlife (Derlet 2008; McClaran and Cole 1993). Because pathogenic bacteria or viruses can pose a health threat to humans, regulations exist for monitoring fecal pollution levels in surface water. Not all strains of fecal bacteria are pathogenic; most *E. coli*, for example, do not cause illness (Myers et al. 2007). However, because quantification of pathogenic strains is costly and time consuming, much simpler analyses of fecal indicator bacteria (FIB) are used as criteria for national primary drinking water regulations and recreational water quality standards established by the U.S. Environmental Protection Agency (EPA 1986, 2012). Most wilderness areas do not have public water supplies or swimming beaches, so EPA water quality standards typically do not apply. Nonetheless, FIB are useful tools for assessing water quality in wilderness areas.

Chemical effects of visitor use may include addition of nutrients, such as nitrogen (N) and phosphorus (P), from stock and backpacker waste. These nutrient additions may cause changes in diatom species assemblages of N- and P-limited alpine lakes and streams, many of which are already receiving elevated levels of nutrients from atmospheric deposition (Sickman et al. 2003b; Nanus et al. 2012; Clow et al. 2003; Saros et al. 2010).

A handful of studies have evaluated potential effects of visitor use on water quality in wilderness areas in the U.S. During 1976–1978, water samples from streams and springs in Great Smoky Mountains National Park were analyzed for fecal coliform, fecal streptococcus, and total coliform bacteria (Silsbee and Larson 1982). Statistical tests documented relations between the bacteria concentrations and elevation, type of water source, and time of year; visitor use was not a major factor (Silsbee and Larson 1982). A study in Yosemite National Park during 2004–2007 related water quality characteristics to basin characteristics and visitor use (Clow et al. 2011). Concentrations of caffeine and personal care products were below the limit of quantification in 98 percent of samples, indicating minimal contamination by humans. Results from the Yosemite study also indicated large inter- and intra-site variability in *E. coli* concentrations, and statistically significant differences in *E. coli* concentrations between some sites, possibly due to visitor use (Clow et al. 2011). A study in Sierra Nevada national forest wilderness areas during 2002–2006 reported significant differences in coliform bacteria concentrations among five visitor-use categories (minimal, day hike, backpacker, stock, and cattle grazing); coliform concentrations in surface water were lowest in minimal-use areas and were highest in cattle-grazing areas (Derlet et al. 2008). One difficulty noted by the authors was that they were unable to meet the recommended holding times (eg., $\leq$24 h) for samples due to the remote nature of their wilderness sites; holding times were up to 7 days (Derlet et al. 2008). In addition, coliform is not a direct indicator of fecal contamination because it exists in soil and vegetation, as well as the gut of warm-blooded animals. One drawback of each of these previous studies is that none of them used the membrane filtration technique for *E. coli* analyses (EPA method 1603), which is the analytical method currently recommended by EPA for comparing FIB data to water quality criteria (U.S. Environmental Protection Agency 1986, 2002, 2012).

There is a clear need for a systematic study of possible effects of visitor use on water quality in wilderness areas using currently accepted methods. During 2010 and 2011, the U.S. Geological Survey (USGS), in cooperation with the NPS, conducted a study to determine the influence of stock and backpackers on water quality in wilderness areas of Sequoia and Kings Canyon National Parks (Fig. 1). The study had three major components: (1) a synoptic survey of water quality in wilderness areas of the parks, (2) paired water quality sampling above and below several areas with differing types and amounts of visitor use, and (3) intensive monitoring at six sites spanning a range of visitor-use types. The synoptic surveys were used to characterize spatial patterns in water quality, and to determine if type and amount of visitor use affects water quality. The purpose of the paired sampling above and below visitor-use zones was to ascertain the impact of various types of use on water quality. Intensive monitoring was used to document changes in stream water chemistry and discharge (stream flow) in response to storm

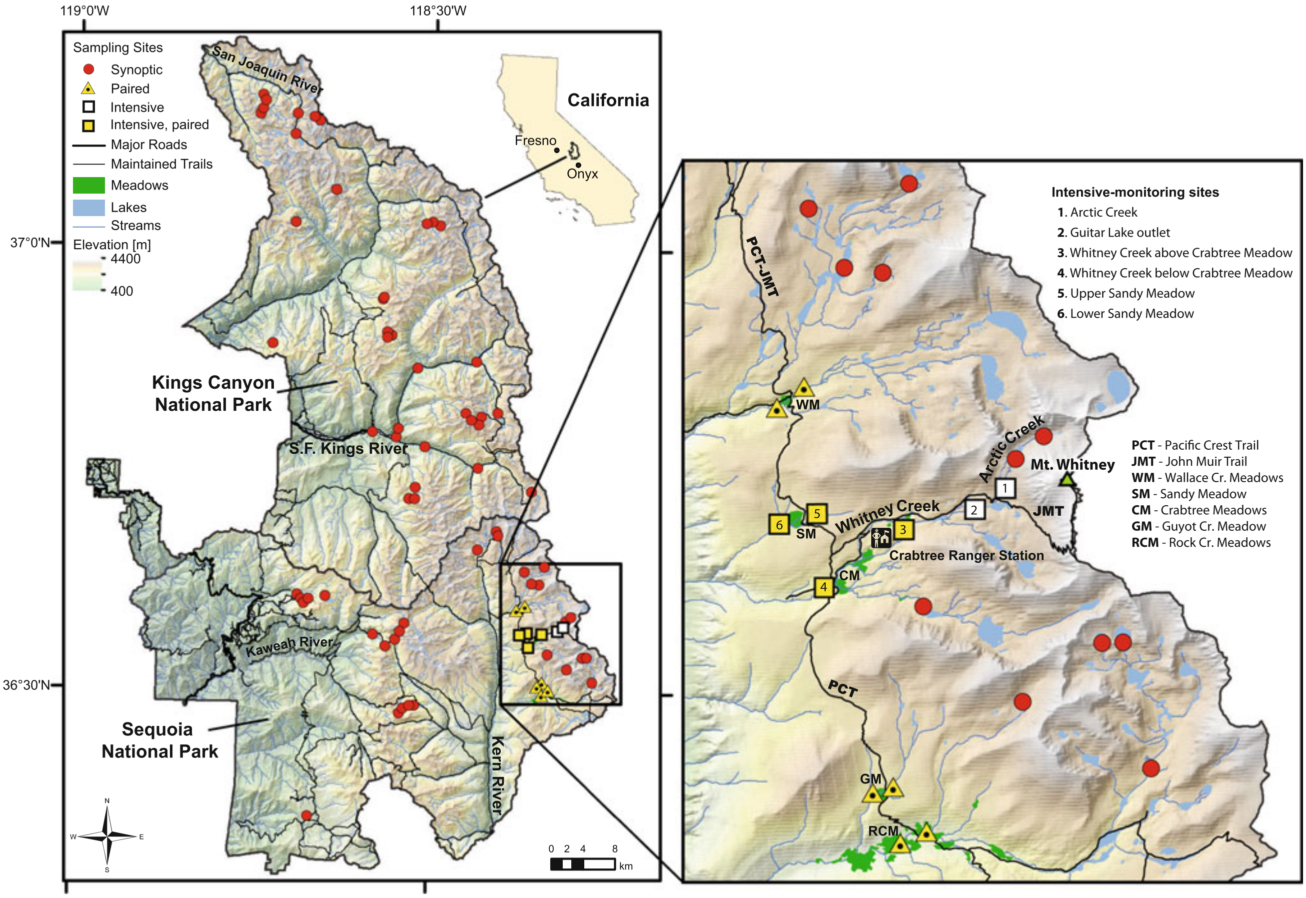


Fig. 1 Location of sampling sites in Sequoia and Kings Canyon National Parks

events, and to characterize seasonal variations in water quality as a function of visitor use and basin characteristics. All samples were analyzed for major dissolved constituents, particulate and dissolved nutrients, *E. coli*, and total coliform bacteria using approved USGS and EPA methods.

Methods

Regional Setting

Sequoia and Kings Canyon National Parks (SEKI) are located in the southern Sierra Nevada, approximately 100 km east of Fresno, California (Fig. 1). The parks are contiguous, jointly administrated, and have a combined area of 3,504 km^2 (http://www.nps.gov/seki/index.htm; accessed 11/19/2012). Elevation ranges from 418 m (1,370 ft) in the Sierran foothills to 4,417 m (14,494 ft) at Mount Whitney, on the north-south trending Sierran Crest. Major vegetation communities include oak woodlands and chaparral in the foothills, mixed conifer forest at low- and mid-elevations, red fir and lodgepole pine in the upper montane, and sparse grasses and forbs in the alpine zone (Vizgirdas and Rey-Vizgirdas 2009).

Glacial landforms dominate the parks' high country, with vast expanses of exposed bedrock and talus above tree line, and deep, u-shaped glacial valleys at mid-elevations. Abundant lakes and streams drain the alpine and subalpine zones, which are the headwaters for the Kaweah, Kings, Kern, and San Joaquin Rivers. Hydroclimate in the high country is characterized by accumulation of deep seasonal snow packs during winter, followed by a large snowmelt pulse in the spring. Summers are warm and dry, with infrequent, but often intense, thunderstorms. Annual precipitation at Crabtree Meadow, 5 km west of Mount Whitney, was 81 cm during 2010 and 101 cm during 2011, with approximately 75–85 % of annual precipitation falling as snow (http://cdec.water.ca.gov/cdecapp/snowapp/sweq.action; accessed 11/19/2012). High-elevation trails usually are covered by snow from November through May or June. Streamflow has a strong seasonal pattern, with low flow through the winter, a snowmelt peak in June, and a gradual decline to base-flow conditions through the summer and fall.

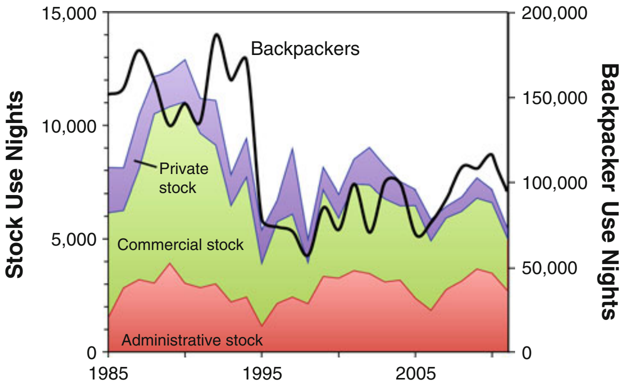


Fig. 2 Annual stock-use (*shading*) and backpacker-use (*line*) nights in SEKI wilderness, 1985–2011. Backpacker-use nights do not include those hiking the John Muir Trail in SEKI and originating north of Sierra National Forest or south of Sequoia National Forest; those two groups can account for up to 2,200 people and 17,000 backpacker-use nights; Gregg Fauth, SEKI, written communication)

More than 96 % of SEKI is designated or managed as wilderness, which is accessible to visitors only on foot and horseback via a network of over 1,300 km of trails (http://www.nps.gov/seki/index.htm; accessed 11/19/2012). Overnight stays in wilderness require permits, enabling the NPS to track and manage wilderness backpacker use in the parks. Backpacker use was relatively high during 1985–1995, averaging approximately 150,000 nights/year; it dropped substantially in 1995 due to an abnormally deep snowpack (over 200 % of normal), which limited access to the backcountry (Fig. 2; SEKI Wilderness Office, written communication). Wilderness backpacker-use nights averaged 89,752 ± 15,756 (average ±1 SD) per year during the decade preceding this study (2000–2009; Fig. 2; SEKI Wilderness Office, written communication).

Stock use is tracked by the NPS through its stock-use permit system and is documented in annual NPS administrative reports; those data indicated that stock use has varied widely since 1985; stock use nights (one overnight stay by a stock animal) averaged 7,420 ± 967/year during 2000–2009 (Fig. 2; Frenzel and Haultain 2012; Haultain and Frenzel 2011). Stock use was nearly evenly split between commercial (45 %) and NPS administrative (42 %) use, with private users accounting for the remainder (13 %). Horses and mules accounted for over 95 % of stock use, with burros and llamas accounting for less than 5 % (Frenzel and Haultain 2012; Haultain and Frenzel 2011).

Study Sites

Component 1 of the study

A total of 72 surface water sites (Fig. 1) were sampled during the synoptic survey of water quality, which was conducted during a 1-week period under low-flow conditions in September 2010 via helicopter and on foot; each site was sampled once (site information is provided in ESM Table 1). The synoptic survey included 20 high-elevation lakes that were sampled during the U.S. Environmental Protection Agency's 1985 Western Lake Survey (WLS). Sites in the WLS were selected to represent lakes thought to be sensitive to atmospheric deposition of pollutants due to their occurrence in high-elevation basins with short growing seasons, sparse vegetation, thin soils, and slow-weathering bedrock (Landers et al. 1987); these lakes also are likely to be sensitive to visitor-use activities. In the 2010 synoptic survey, the WLS lakes were augmented with nearby lakes and streams to increase sampling density and provide additional data on wilderness water quality. The additional sampling sites were typically in basins adjacent to and within 2 hours hiking distance from the WLS lakes; these criteria were based on the need to meet nutrient and *E. coli* holding time requirements, which precluded longer hiking distances between sampling sites.

Synoptic survey data from lakes and streams were combined into one data set because most lakes in SEKI are small and well- mixed, and to a large extent, behave like "wide spots in the stream." This is supported by data from a 1999 synoptic survey of high-elevation lakes and streams in national parks in the western U.S. (including the WLS lakes sampled in SEKI), which indicated no statistically significant differences in the chemistry of lakes and streams (Clow et al. 2002; 2003). This is not expected to be the case for all environments, but appears to be true for the high-elevation water bodies that were sampled in the 1999 study, which the SEKI WLS lakes were part of.

All synoptic survey sites were categorized according to the dominant type of visitor use upstream from the sampling point based on inspection of topographic maps and overnight camping zone maps, NPS information on stock grazing zones, and consultation with NPS wilderness managers. Sites with no campgrounds, grazing zones, or mapped trails upstream from the sampling sites were classified as "minimal use" ($n = 42$). Sites that were downstream from areas used primarily by backpackers and with little or no overnight stock use were classified as "backpacker-use" ($n = 9$), and sites that were below areas with overnight stock and backpacker use were classified as "mixed-use" ($n = 21$).

Component 2

Paired sampling was conducted during the summers of 2010 and 2011 upstream and downstream from three mixed-use zones and two backpacker-use zones, all of which were accessible by trail (Fig. 1). The mixed-use zones included Crabtree and Rock Creek Meadows, which

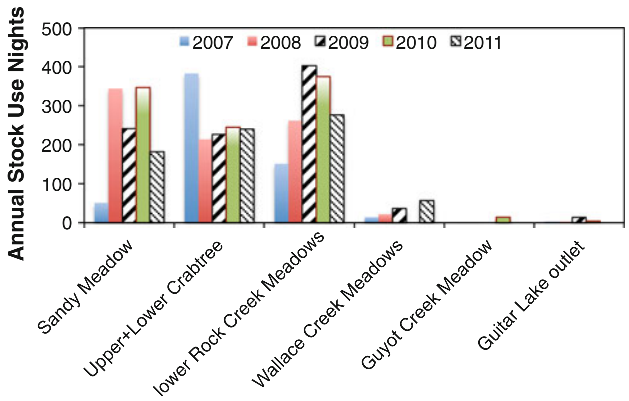


Fig. 3 Annual stock use nights at paired-sampling sites classified as mixed use (Sandy Meadow, upper + lower Crabtree Meadows, and lower Rock Creek Meadows) and backpacker use (Wallace Creek Meadows, Guyot Creek Meadow). Guitar Lake outlet is included for reference. Stock use nights include nights when stock are allowed to graze and when they are picketed and fed supplemental feed

were used by both stock and backpackers, and Sandy Meadow, which was used primarily by stock (Figs. 1, 3). Backpacker-use zones included Guyot and Wallace Creek Meadows; these areas had backpacker campsites and little or no documented overnight stock use between upstream and downstream sampling sites (Figs. 1, 3). Twenty-one pairs of upstream/downstream samples were collected at mixed-use sites, and eight pairs of upstream/downstream samples were collected at backpacker-use sites (58 samples total).

Component 3

Intensive monitoring was conducted in the Whitney Creek basin and Sandy Meadow, 2 km to the north. Six sites were instrumented with dataloggers and in-stream sensors for continuous monitoring of streamflow, temperature, and turbidity; these sites were sampled approximately biweekly during August–September 2010, and July–September 2011. Four of the sites were located along an elevation gradient in the Whitney Creek basin; the highest site was on Arctic Creek (site 1; a tributary to Whitney Creek), followed downstream by Guitar Lake outlet (2) in the backpacker-use zone, and Whitney Creek above Crabtree Meadows (3) and Whitney Creek below Crabtree Meadows (4) in the mixed-use zone (Fig. 1). The Whitney Creek basin receives extensive overnight use by stock in the lower section (at upper and lower Crabtree Meadows), by backpackers in the lower, middle, and upper section, and minimal use in the Arctic Creek sub-basin. Although stock are allowed in the middle and upper sections of Whitney Creek basin, NPS stock-use reports indicated that overnight use was substantially less in these areas than in the lower section (Fig. 3; Frenzel and Haultain 2012; Haultain and Frenzel 2011). Two of the intensive-monitoring sites were installed at Sandy Meadow; one set of the aforementioned equipment was installed above the meadow (5) and another set was installed below the meadow (6). In addition, automated water samplers were installed at the two Sandy Meadow sites to collect water samples during storm events, when most transport of suspended sediment, nutrient, and fecal bacteria typically occurs (Peters 1994; Tsihrintzis and Hamid 1997; Wetzel 2003; Davies-Colley et al. 2008; McKergow and Davies-Colley 2010). The autosamplers were programmed to trigger during storms by a rise (and subsequent fall) in stage over a 10-min period exceeding specified criteria (e.g., 0.02 ft).

Basin characteristics were calculated for all sampling sites in the study (synoptic-survey, paired-sampling, and intensive-monitoring sites) using the USGS StreamStats software program (http://water.usgs.gov/osw/streamstats/california.html; accessed 11/19/2012). The StreamStats program can provide information on up to 508 basin characteristics, including many that have been shown to be useful for predicting nutrient and alkalinity concentrations in high-elevation parks in the western U.S. (e.g., area, elevation, average slope, mean annual precipitation, percent of basin covered by forest; Clow and Sueker 2000; Clow et al. 2010; Sickman and Melack 2002).

Rationale for Microbial and Chemical Analyses

Each of the main groups of analyses (microbial, chemical) provides unique and useful information; when combined, they can provide a more complete understanding of flow paths and processes influencing water quality than when used alone.

Traditionally, the microbial quality of freshwaters has been measured using members of the coliform bacterial group. Total coliform counts provide an indication of overall sanitary conditions. Coliform is a relatively diverse group of Gram-negative bacteria, many of which are of fecal origin, but can also be associated with soil and vegetation. Recently, *E. coli* (a type of coliform) has been used to provide more direct evidence of fecal contamination by warm-blooded animals, such as mammals and birds, because it preferentially inhabits the gut and intestine, and normally is able to survive outside the body for a limited amount of time. As such, it is a useful indicator of the possible presence of fecal-origin pathogens that pose human health risks; however, as noted previously, only a small fraction of *E. coli* strains are pathogenic (Myers et al. 2007). Recent advances in analytical techniques have made it possible to analyze water samples for *E. coli* and total coliform fairly easily even in wilderness areas, given proper equipment, clean techniques, and quality assurance procedures.

Chemical analyses provide basic information on the chemical characteristics of water, which can be used to gain insight into the sources of solutes in water, the degree of interaction between soil and water, and flow paths of water through terrestrial and aquatic landscapes. This information can aid interpretation of microbiological data, which are affected by many of the same processes that influence water chemistry (e.g., flow paths through soil, and degree of interaction between soil and water).

Sample Collection and Analyses

All water samples were collected from the outlets of lakes or along well-mixed reaches of streams using standard USGS grab-sampling techniques (http://water.usgs.gov/owq/FieldManual/; accessed 11/19/2012). Samples were processed within 24 h of collection and were kept cool and in the dark during transport by placing them in insulated containers in the cargo hold of the helicopter, or in the internal compartment of field packs if transport was on foot.

Samples were analyzed for chemistry using methods developed for low ionic strength waters in an approved USGS laboratory (Fishman et al. 1994; Clesceri et al. 1999). Analytes and methods included alkalinity by Gran titration; calcium (Ca), magnesium (Mg), silica (Si), sodium (Na), and potassium (K) by inductively coupled plasma (ICP-AES); chloride (Cl), sulfate (SO_4), and nitrate (NO_3) by ion chromatography; dissolved organic carbon (DOC) by ultra-violet promoted persulfate oxidation with infrared detection, pH using a low-ionic-strength electrode, specific conductance (SC) by Wheatstone bridge, particulate carbon (PC) and particulate nitrogen (PN) by high temperature combustion in an elemental analyzer, and particulate phosphorus (PP) by NaOH/persulfate digestion followed by colorimetric analysis of phosphate. Blanks and replicates constituted 5 % of the sample total; solute concentrations in the blanks were less than the detection limit for all constituents, and reproducibility of chemical analyses was better than 1 μmol l^{-1} or 1.5 % for all constituents.

For each component of the study, samples for *E. coli* and total coliform analyses were collected in sterile 100-ml bottles and processed within 24 h of collection using the m-ColiBlue24 membrane filter technique (EPA method 10029). Synoptic water quality survey samples were processed in the NPS water quality laboratory near park headquarters; samples from the paired-site sampling and intensive-monitoring components of the study were processed at a solar-powered field laboratory set up for the study near Crabtree ranger station. The m-ColiBlue24 method involves filtering a water sample through a sterile 0.45-μm membrane filter, then placing the filter in a sterile petri dish on Hach m-ColiBlue24 agar and incubating at 35 °C for 24 h (http://nepis.epa.gov/Adobe/PDF/P1008S3U.pdf, accessed 11/18/2012; http://www.hach.com/epa, accessed 11/18/2012). *E. coli* and total coliforms were enumerated by counting cultures using a low-power (5–15×) binocular microscope; results are expressed as colony forming units per 100 ml (CFU 100 ml^{-1}). When the total number of colonies exceeded 200 per membrane, results were reported as ">200" as directed in method guidance documentation (www.hach.com/asset-get.download-en.jsa?id=7639984023; accessed 12/09/12). Equipment was maintained in sterile condition by flame sterilization (Myers et al. 2007). Holding time tests confirmed previous studies that indicated minimal changes in *E. coli* and total coliform concentrations within 24 h of collection if samples are held unfrozen below 10 °C (Myers et al. 2007; Bordner and Winter 1978; Pope et al. 2003).

For *E. coli* and total coliforms, blanks comprised 10 % of the sample total; all blanks had 0 CFU 100 ml^{-1} for *E. coli* and total coliforms, except one sample that had 1 CFU 100 ml^{-1} for total coliforms. Negative controls (*P.aeruginosa*) and positive controls (*E. coli* and total coliforms) were analyzed approximately monthly; all negative controls had 0 CFU 100 ml^{-1} for *E. coli* and total coliforms and all positive controls had >200 CFU 100 ml^{-1} *E. coli* and total coliforms. Replicates were analyzed on 50 % of the *E. coli* and total coliforms samples; median differences between the environmental samples and replicates were 1 CFU 100 ml^{-1} for *E. coli* and 17 CFU 100 ml^{-1} for total coliforms.

Statistical Tests

Differences in concentration distributions among visitor-use categories (minimal-use, backpacker-use, and mixed-use categories) in the synoptic water quality survey data were evaluated using the nonparametric rank-sum test (Helsel and Hirsch 1992). Correlations between synoptic survey sample concentrations and basin characteristics were evaluated for significance using the Pearson product–moment correlation test (Helsel and Hirsch 1992); some data required a log transformation to obtain a normal distribution prior to use in the correlation analyses. Tests for normality were performed using Shapiro-Wilk test (1965). All tests for statistical significance were evaluated at a significance level of 0.05.

To evaluate the relative importance of basin characteristics and visitor-use in determining *E. coli* concentrations at the synoptic survey sites, a stepwise Generalized Linear Modeling (GLM) approach was used, similar to Clow et al. (2010). This approach identifies and selects the most powerful explanatory variables using an iterative procedure, yielding an equation in which the sign of the variable coefficients indicates whether a given parameter has a positive or negative influence on the independent variable (e.g., *E. coli* concentration), and the magnitude of scaled coefficients indicates the parameter's relative importance in terms of predictive power. In the GLM for *E. coli*, basin characteristics were entered as continuous variables and visitor-use category was entered as a categorical variable.

Data from the paired-sampling sites were tested for differences between concentrations at sites upstream and downstream from mixed-use and backpacker-use zones using the Wilcoxon signed-rank test (Helsel and Hirsch 1992).

To aid interpretation of spatial and temporal variations in water quality and FIB at the intensive-monitoring sites, a principal components analysis (PCA) was performed on the intensive monitoring data set. PCA tests for interrelations between variables in complex data sets. Statistically significant interrelations among variables are represented by components, which may be interpreted in terms of processes or sources of solutes (Clow et al. 1996; Puckett and Bricker 1992).

Results and Discussion

Hydroclimate

Heavy winter snowfall and cool, wet spring weather in the southern Sierra resulted in late snowmelt and deep May 1 snow packs, which contained 142 and 177 % of normal water content for that date in 2010 and 2011, respectively (http://cdec.water.ca.gov/cdecapp/snowapp/sweq.action; accessed 12/6/2012). At the nearest long-term stream gage, South Fork of the Kern River near Onyx, California (USGS site ID 11189500), runoff was 106 % of normal in 2010, and 237 % of normal in 2011 (http://waterdata.usgs.gov/ca/nwis/uv?site_no=11189500; accessed 7/26/13).

Rainfall at Crabtree Meadow during summer 2010 was 8.1 cm, or 10 % of total annual precipitation, and there were two storm events greater than 1 cm (1.7 cm on July 10–13 and 1.4 cm on August 23–26). During summer 2011, rainfall was 15.3 cm, or 15 % of total annual precipitation; the data indicate one large rain event during July 27–August 2 (6.1 cm), and several smaller events during July 5–7 and September 13–18 (1.0 cm each) (http://cdec.water.ca.gov/cdecapp/snowapp/sweq.action; accessed 11/19/2012). Field observations indicated that rainfall during thunderstorms exhibited high spatial variability; thus, the rain gage at Crabtree ranger station (Fig. 1) did not always reflect rain falling in other parts of the study area.

Visitor Use

Wilderness use by backpackers in SEKI during 2010 and 2011 was approximately 128 and 104 % of the 2000–2009 average, respectively (Fig. 2). Stock use was 97 % of average in 2010, and 73 % of average during 2011 (Fig. 2). The lower backpacker- and stock-use numbers for 2011 were attributable to the late persistence of snow cover, which made access over passes difficult and delayed the opening of meadows to grazing due to wet conditions (the opening and closing dates of meadows is controlled by the NPS to limit impacts during wet conditions and to avoid overgrazing; Frenzel and Haultain 2012; Haultain and Frenzel 2011).

Wilderness permits issued for the Crabtree wilderness zone, which includes the Whitney Creek basin and adjacent areas, indicated 4,502 backpacker use nights during 2010 and 4,530 use nights during 2011 (SEKI Wilderness Office, written communication).

Stock use was much greater at the paired-sampling sites that were classified as mixed use than those classified as backpacker use (Fig. 3; Frenzel and Haultain 2012; Haultain and Frenzel 2011). Figure 3 shows stock-use nights (one animal for one night) during 2007–2011; these data include both grazing nights and nights when stock are picketed near the meadows and fed supplemental feed, as is done when meadows are closed to grazing. During 2010 and 2011, the meadows did not open for grazing until late summer because of the late snowmelt during both of those years. Thus, the meadows probably were less affected by erosion and deposition of fecal matter during early summer than normal, although transport of sediment and fecal contaminants from the picketing areas near the meadows to streams might still have occurred.

Synoptic Survey of Water Quality

Concentrations of inorganic solutes and nutrients measured during the synoptic water quality survey were low, consistent with results from previous synoptic surveys of water quality in the park (Table 1; Clow et al. 2002; Landers et al. 1987). Concentrations of most inorganic solutes (e.g., alkalinity, Ca, Si) were lower at minimal- and backpacker-use sites than at mixed-use sites ($P \leq 0.05$, Table 1), probably reflecting greater interactions between water, soil, and vegetation at mixed-use sites than at the other two types of sites. In contrast, there were no significant differences in concentrations of any of the nutrient (NO_3, TDN, PN, TDP, PP) or carbon (DOC, PC) analytes among the visitor-use categories (Table 1). The lack of differences in concentrations of nutrients and carbon among visitor-use categories may reflect complex internal cycling of these

Table 1 Mean concentrations and basin characteristics for synoptic sites categorized by main type of visitor use

	Main type of visitor use[a]		
	Minimal	Backpackers	Mixed
Alkalinity (μeq l^{-1})	72.7*	68.7*	139.4#
Specific conductance (μS cm^{-1})	10.6*	10.5*	28.0#
pH	6.7*	6.7*	7.0#
Ca (μeq l^{-1})	64.7*	62.1*	147.4#
Mg (μeq l^{-1})	5.6*	5.4*	12.9#
Na (μeq l^{-1})	22.0*	22.8*	82.0#
K (μeq l^{-1})	3.9*	4.7*#	6.7#
Si (μmol l^{-1})	43.4*	36.9*#	77.3#
Cl (μeq l^{-1})	2.3*	2.7*#	27.9#
SO_4 (μeq l^{-1})	12.4*	11.6*#	64.4#
NO_3 (μmol l^{-1})	1.9*	3.9*	1.7*
TDN (μmol l^{-1})	7.0*	8.6*	6.2*
PN (μmol l^{-1})	1.6*	1.2*	1.7*
DOC (mg l^{-1})	1.0*	0.7*	0.8*
PC (mg l^{-1})	0.3*	0.3*	0.4*
TDP (μmol l^{-1})	0.03*	0.02*	0.04*
PP (μmol l^{-1})	0.10*	0.08*	0.09*
E. coli (CFU 100 ml^{-1})	0.3*	1.1*#	2.8#
Total coliforms (CFU 100 ml^{-1})	79*	162*#	214#
Basin area (km^2)	2.5*	2.6*	82.2#
Mean annual precipitation (cm)	104.7*	101.0*	100.1*
Average maximum January temperature (°C)	-0.5*	0.2*	0.5*
Site elevation (m)	3,362*	3,177*#	2,786#
Average basin elevation (m)	3,531*	3,424#	3,358#
Relief (m)	559*	661*#	1,851#
Mean basin slope (°)	25.9*	28.5*	24.1*
% forest	2.2 %*	2.4 %*	6.4 %*
% lakes and ponds	4.3 %*	3.1 %*	3.7 %*
Basin perimeter (km)	7.3*	7.9*	40.0#
Longest flow path (m)	2,268*	2,527*	11,683#

For each constituent, values followed by *different symbols* indicate concentration distributions are significantly different at $p \leq 0.05$

[a] Sites with minimal use are far from any upstream trails, camp sites, or stock grazing areas ($n = 42$); backpacker sites are in areas frequented by backpackers but not stock ($n = 9$); mixed-use sites are in areas frequented by backpackers and stock ($n = 21$)

parameters within watersheds, including uptake by algae in lakes and streams (Wetzel 2001).

Concentrations of *E. coli* and total coliforms were low at most of the synoptic sites, averaging 1 and 135 CFU 100 ml^{-1} among all the sites, indicating minimal contamination by fecal matter and other bacterial sources (Table 1; Fig. 4). Although concentrations were low, several clusters of slightly higher than average *E. coli* concentrations occurred in the Whitney Creek basin and the two main tributaries to the South Fork of the Kings River (Fig. 4). These areas receive high visitor use, but variations in wildlife populations might play a role as well (it was not possible to evaluate this hypothesis due to lack of site-specific data on wildlife populations).

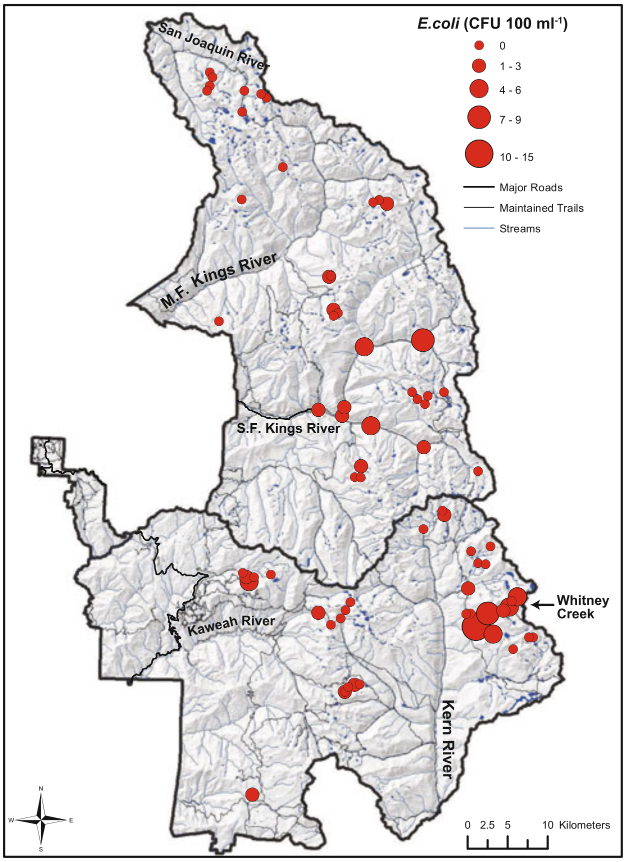


Fig. 4 Concentrations of *E. coli* in surface water samples collected in SEKI during fall 2010

When categorized by visitor-use type, mean *E. coli* concentrations during the synoptic survey at minimal-, backpacker-, and mixed-use sites were 0.3, 1.1, and 2.8 CFU 100 ml^{-1}, respectively (Table 1). Mean total coliform concentrations at minimal-, backpacker-, and mixed-use sites were 79, 162, and 214 CFU 100 ml^{-1}, respectively. For both *E. coli* and total coliforms, concentrations were lower at minimal-use sites than at mixed-use sites ($P \leq 0.05$), and concentrations at backpacker-use sites were intermediate (Table 1).

The *E. coli* concentrations measured in this study during the synoptic survey were similar in magnitude to those measured in Yosemite National Park during 2004–2007 by Clow et al. (2011). In contrast, Derlet and Carlson (2006) reported *E. coli* concentrations for 15 "stock-use" sites in Sierra Nevada wilderness that averaged 280 CFU 100 ml^{-1}, 100 times higher than the average at mixed-use sites in this study (the two categories are

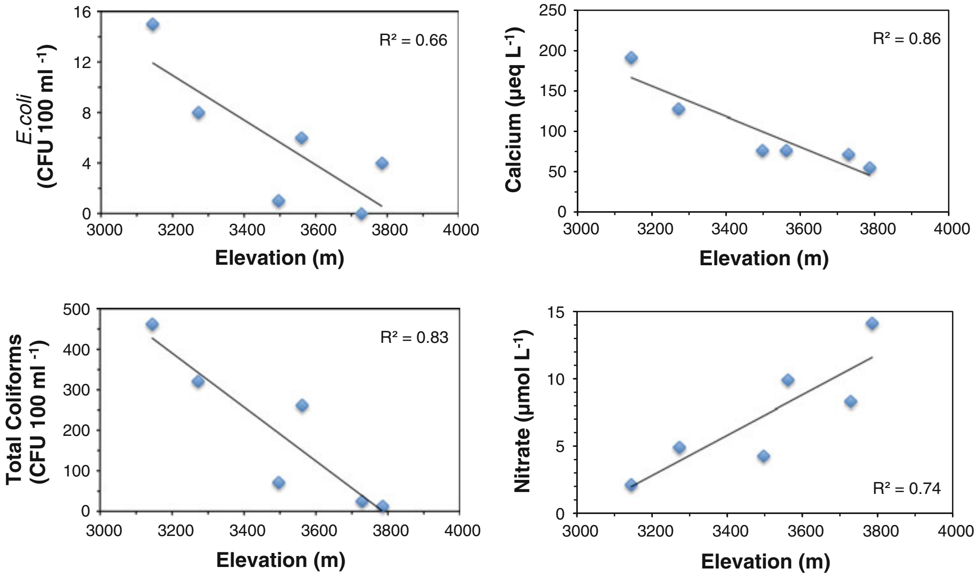


Fig. 5 Concentrations of *E. coli*, total coliforms, calcium, and nitrate in stream water versus elevation along a transect in Whitney Creek basin during synoptic survey in fall 2010

roughly equivalent). It should be noted that Derlet and Carlson (2006) did not report holding times, and their method had limited precision (100 CFU 100 ml^{-1}, compared to 1 CFU 100 ml^{-1} in the current study). It also should be noted that Derlet and Carlson (2006) stated that all coliforms in their study were identified as *E. coli*, and they based their estimates of *E. coli* concentrations on measurements of coliforms and the assumption that all coliform were *E. coli*. These results conflict with those from the present study, which indicate that *E. coli* comprised only a small fraction of total coliforms in the synoptic survey water samples (Table 1). By assuming that all coliforms were *E. coli*, it is possible that Derlet and Carlson (2006) might have overestimated *E. coli* concentrations in their study.

In the current study, variations in basin characteristics might help explain some of the differences in observed concentrations of *E. coli* and total coliforms in the synoptic survey samples. For example, elevation was highest at minimal-use sites, intermediate at backpacker-use sites, and lowest at mixed-use sites (Table 1). The elevation dependence of visitor use type reflects differences in accessibility and suitability for overnight use; the highest elevation sites are inaccessible to stock due to lack of trails and the rough terrain, and are difficult to access even by backpackers. Sites favored by backpackers and those that tend to have minimal overnight stock use often occur near treeline, where soil often is thin and patchy, and grazing opportunities are limited. Mixed-use sites tend to occur in forest and meadow areas below treeline, which are more sheltered during inclement weather and tend to have better grazing. Elevation is unlikely to be a primary control on FIB concentrations; however, it can serve as a surrogate for other basin characteristics that may co-vary with elevation, such as water residence time and the degree of interaction between water, soil, and vegetation, which may affect FIB concentrations more directly.

A plot of selected analytes for samples collected from six sites along an elevation transect in the Whitney Creek basin during the synoptic water quality survey illustrates how water quality varied as a function of elevation. Concentrations of *E. coli*, total coliforms, and weathering products (as exemplified by Ca) were negatively correlated with elevation (Fig. 5), and positively correlated to basin size and stream order (not shown); nitrate showed the opposite pattern (Fig. 5). These results are consistent with previous research on coliform bacteria in Great Smoky Mountains National Park (GRSM; Silsbee and Larson 1982), and of mineral weathering and N cycling in the Rocky Mountains and Sierra Nevada (Sickman and Melack 2002; Sickman et al. 2003a; Clow et al. 2010; Clow and Sueker 2000; Berg et al. 2005). Silsbee and Larson (1982) attributed the downstream increase in fecal- and total coliform concentrations in GRSM to increasing contact with soil and leaf litter, where bacteria reside, as water flows downstream. Similarly, for weathering products, the earlier studies invoked increasing biogeochemical interactions between water, soil, and vegetation as basin size and stream order increased and elevation decreased along a stream transect (Clow et al. 2010; Berg et al. 2005). The downstream decline in NO_3 probably reflects uptake of atmospherically deposited N by aquatic biota as water flows downstream, as well as higher N assimilation rates at lower elevations where soil and vegetation are more abundant (Clow et al. 2010; Sickman and Melack 2002; Sickman et al. 2001).

The relative importance of basin characteristics and visitor use were explored using a stepwise GLM approach (see "Methods" section for more detail). The "best" model included length of the longest flow path (negative effect) and basin relief (positive effect), which together explained 33 % of the variance in log *E. coli* concentrations. The negative effect of flow path length might reflect the limited survival time for *E. coli* outside the gut. The positive relation between relief and log *E. coli* concentration is more puzzling, and can only be speculated on at this time. Adding visitor-use category (minimal-, backpacker-, mixed-use) to the GLM increased the variance explained to 44 %; the coefficients for minimal-, backpacker-, and mixed-use categories were −0.26, −0.01, and 0.27, respectively, indicating the relative influence of the different visitor-use categories on modeled *E. coli* concentrations (negative for minimal use, and positive for mixed use). Although the amount of unexplained variance was large, it appears that both basin characteristics and visitor use play small, but statistically significant roles in influencing wilderness water quality. We hypothesize that much of the unexplained variance was due to differences in hydrologic conditions and wildlife populations at the synoptic sampling sites, which we were unable to account for.

Table 2 *P* values for Wilcoxon signed ranked test on paired samples collected upstream and downstream from mixed-use and backpacker-use sites

	Mixed use		Backpacker use	
	Down>Up	Up>Down	Down>Up	Up>Down
E. coli	**<0.0001**	1.000	0.815	0.188
Total coliform	**<0.0001**	1.000	0.063	0.938
Temperature	**0.002**	0.998	0.563	0.438
SC	**<0.0001**	1.000	0.207	0.793
Alkalinity	**<0.0001**	1.000	0.328	0.672
Ca	**<0.0001**	1.000	**0.004**	0.996
SO_4	**<0.0001**	1.000	0.809	0.191
DOC	**0.001**	0.999	0.500	0.500
PP	**0.001**	0.999	0.500	0.500
Cl	**0.023**	0.977	**0.023**	0.977
PC	0.054	0.946	0.453	0.547
Na	0.074	0.926	**0.047**	0.953
Si	0.418	0.582	0.055	0.945
Mg	0.337	0.664	0.500	0.500
K	0.728	0.272	0.313	0.688
PN	0.359	0.641	0.500	0.500
NO_3	1.000	**<0.0001**	0.473	0.527

Differences were considered significant where $P \leq 0.05$, which are indicated in bold. There were 21 pairs of samples at mixed-use sites, and eight pairs of samples at backpacker-use sites

Water Quality Above and Below Mixed-Use and Backpacker-Use Areas

At the upstream/downstream paired-sampling sites, concentrations of *E. coli* and total coliforms were significantly higher downstream from mixed-use sites than upstream from them ($P < 0.05$; Table 2; Fig. 6). The increase in *E. coli* concentrations indicate that fecal contamination of stream water was occurring at the mixed-use sites, while the increase in total coliform concentrations indicates a general increase in bacterial levels as water passed through the meadows. Possible sources of fecal contamination at the mixed-use sites include stock, humans, and wildlife; however, the relative importance of these sources of contamination cannot be quantified with available data.

At backpacker-use sites, there were few statistically significant differences in concentrations between upstream and downstream locations (Table 2; Fig. 6). Notably,

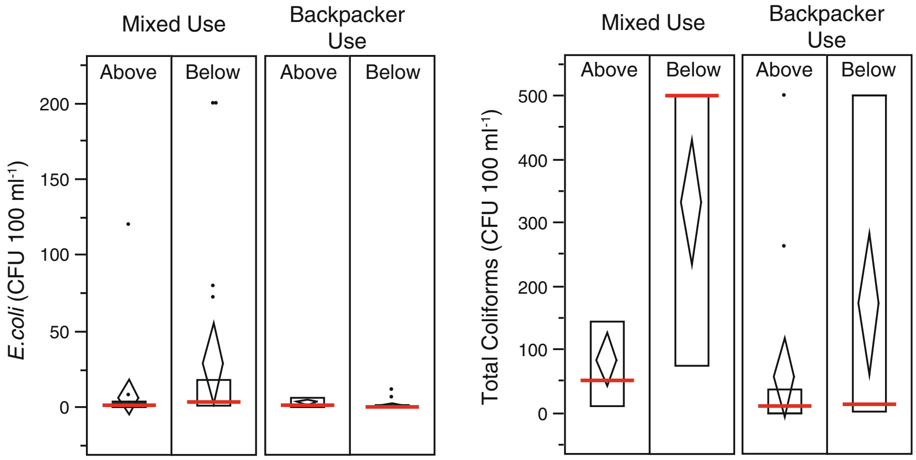
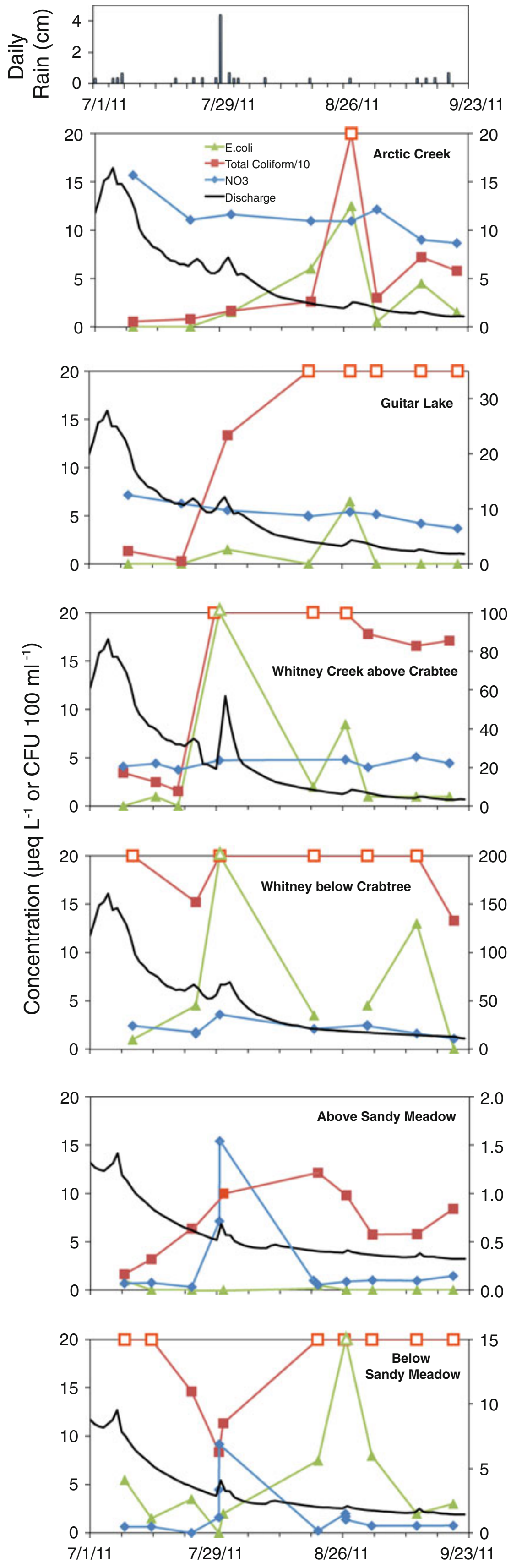


Fig. 6 Statistical distributions of *E. coli* and total coliform concentrations at paired-sampling sites above and below areas with mixed use and backpacker use. Median: *thick red horizontal line*. Interquartile range (IQR): *black rectangle*. Mean and SD: *black diamond*. Samples greater or less than IQR: *black dots*



◀**Fig. 7** Daily rainfall, streamflow, and concentrations of *E. coli*, total coliform/10, and NO_3 at intensive-monitoring sites. *Open symbols* represent *E. coli* or total coliform concentrations >200 CFU 100 ml^{-1}. Rainfall data are from http://cdec.water.ca.gov/cdecapp/snowapp/sweq.action; accessed 11/19/2012

concentrations of *E. coli* and total coliforms were not significantly different at upstream and downstream sites at the backpacker-use sites. The only statistically significant differences at backpacker use sites were for Ca, Na, and Cl, which were slightly higher downstream from the sites than upstream. This might indicate a visitor use effect, but concentrations were too low to be of ecological importance.

Temporal Variability at Intensive-Monitoring Sites

There were substantial differences in streamflow among the intensive-monitoring sites, largely reflecting variations in basin size. Streamflow increased in Whitney Creek from the headwaters to the lowest sampling location below Crabtree Meadows (Fig. 7) due to inputs from snowmelt and tributary streams. Streamflow at the two Sandy Meadow sites was much lower than at the other intensive monitoring sites (Fig. 7), as expected because the Sandy Meadow basin was relatively small. Streamflow gradually decreased through the summer sampling season at all of the intensive-monitoring sites as snowmelt inputs declined.

Along the Whitney Creek transect, *E. coli* and total coliform concentrations usually were greater at the two lowest sites than at the two highest sites (Fig. 7). This might reflect greater visitor use in the lower part of the basin, although contributions from wildlife might be important as well. Nitrate concentrations showed the opposite pattern, with the highest concentrations usually found at the highest elevations in the Whitney Creek basin, where assimilation rates of atmospherically deposited N are expected to be low due to the scarcity of soil and vegetation (Fig. 7). At Sandy Meadow, *E. coli* and total coliform concentrations were very low at the site upstream from the meadow, and while still low, were almost always higher downstream from the meadow, indicating that there was a source of *E. coli* in the meadow. Nitrate concentrations usually were low at both of the Sandy Meadow sites, reflecting high N assimilation rates in the meadow and forest ecosystems surrounding the stream (Fig. 7).

At all of the intensive sampling sites, there was a general seasonal pattern of increasing *E. coli* concentrations through the summer, punctuated by spikes in concentration during and shortly after storm events (Fig. 7). Total coliform concentrations showed a similar temporal pattern at most sites, with concentrations often exceeding

200 CFU 100 ml^{-1} during the latter half of the summer. The seasonal pattern in *E. coli* and total coliforms may reflect decreasing dilution by snowmelt through the summer, and perhaps greater inputs of bacteria later in the season. Nitrate concentrations generally declined through the summer at the Arctic Creek and Guitar Lake sites, where concentrations were highest, and were stable through the summer at the other sites. As with the FIB, pulses of NO_3 occurred during storms.

Summer rainstorms sometimes caused dramatic increases in concentrations of FIB, nutrients, and turbidity at the intensive-monitoring sites, although responses were highly variable (Figs. 6, 7). *E. coli* concentrations increased strongly in response to the large storm event on 29 July 2011 at the two sites in the lower part of Whitney Creek basin, but the other intensive-monitoring sites showed little response (Fig. 7). During 2011, Sandy Meadow was not open to stock until late August (SEKI wilderness office, written communication), so fecal matter inputs from stock prior to that time were probably minimal; this might help explain the lack of response in *E. coli* concentrations at lower Sandy Meadow to the 29 July 2011 storm. In contrast to the lack of response in *E. coli* concentrations, NO_3 and DOC increased at lower Sandy Meadow during the 29 July 2011 storm, indicating flushing of dissolved organic material from meadow soils (Fig. 8). Concentrations of turbidity (Fig. 8), PP, PC, and PN (not shown) increased as well; these increases were much larger than those observed for dissolved constituents, and are indicative of surface transport of particulate material during high-energy precipitation events (ie., thunderstorms). These results are consistent with previous studies of stormwater runoff quality, and indicate that water quality impacts may be greatest during storms (Saraceno et al. 2009; Tsihrintzis and Hamid 1997; Solo-Gabriele et al. 2000; Rasmussen and Ziegler 2003; Davies-Colley et al. 2008; McKergow and Davies-Colley 2010). Interestingly, concentrations of silicate weathering products (Si, Na, alkalinity) decreased in response to storm events (Fig. 8).

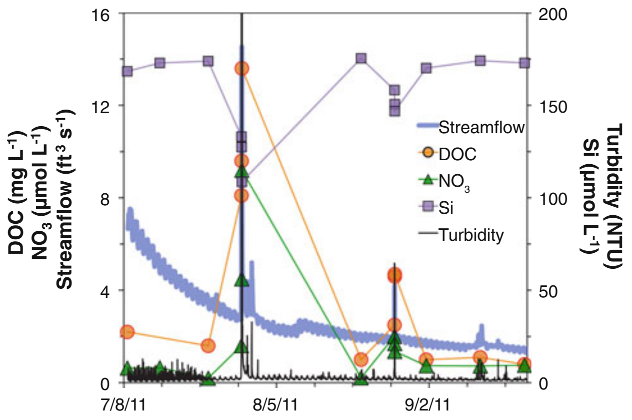


Fig. 8 Streamflow and concentrations of turbidity, Si, DOC, and NO_3 in stream water below Sandy Meadow during summer 2011

The differences in behavior of various solutes, nutrients, and FIB can provide insight into their sources and flow paths of water during storms. One way to analyze and interpret variations in complex chemical and microbial data sets is through PCA (see “Methods” section for more detail). A PCA on data from the intensive-monitoring sites indicated that three components could explain approximately 80 % of the variation in stream water quality at the intensive monitoring sites (Fig. 9). The first component, which loaded heavily on NO_3 (negative), alkalinity, Na, Si, Ca, and Mg (all positive), is interpreted to represent percolation of dilute precipitation (containing N) through soil. When snowmelt or rainfall flushes through the subsurface, it acquires weathering products due to cation exchange and flushing of soil pore water, and loses N through assimilation by vegetation and soil microbes. The second component had strong positive loadings for H, Mg, K, Cl, PP, PN, PC, and DOC; while H is likely derived from precipitation, mobile forms of most of the other parameters occur primarily in shallow, organic-rich soil horizons. Thus, the second component is interpreted to represent flushing of shallow soil horizons by slightly acidic precipitation (snowmelt or rain). The third component had strong positive loadings for *E. coli*, total coliforms, PC, and PN; this is interpreted to represent surface runoff from soil containing coliform bacteria and particulate organic matter. These

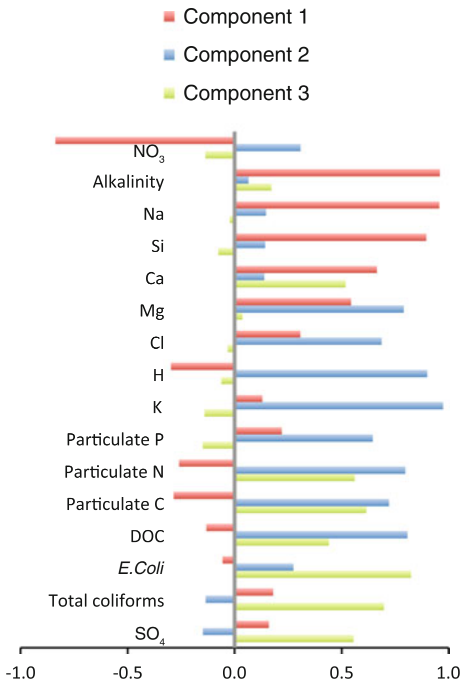


Fig. 9 Principal component loadings for chemical and bacteria concentrations in samples collected at intensive-monitoring sites during 2011

results provide improved understanding of the sources and mechanisms influencing water quality in SEKI wilderness, including why concentrations of FIB, turbidity, and particulate C, N, and P increase during storms.

Identification of Fecal Pollution Sources: Future Directions

One limitation associated with the use of *E. coli* in microbial water quality assessments is its limited value in the identification of fecal pollution sources (Stoeckel et al. 2004; Stoeckel and Harwood 2007). Library-independent molecular methods based on quantitative polymerase chain reaction (qPCR), collectively known as quantitative microbial source tracking (qMST), have recently been developed (Stoeckel et al. 2004; Stoeckel and Harwood 2007; Domingo et al. 2007; Simpson et al. 2004). The qMST methods have been primarily used in urban and agricultural settings to distinguish human and non-human sources of pollution. Fewer studies have been conducted in remote settings, such as wilderness areas, where the primary pollution sources may include wildlife, stock, or humans. While methods are available to distinguish human and ruminant (eg., cattle) fecal sources, markers for wildlife feces are lacking or have not been thoroughly tested in multiple geographic locations. Similarly, although equine markers have been developed (Simpson et al. 2004; Dick et al. 2005; Field et al. 2003; Johnson et al. 2004), additional research is needed to establish their accuracy in geographically diverse areas. The low concentrations of fecal bacteria that may be found in wilderness areas, such as SEKI, make identification of sources problematic; bacteria counts over 100 CFU 100 ml^{-1} generally are needed for reliable identification of fecal sources. Future studies in SEKI and other wilderness areas may wish to focus on collection of qMST samples during storms, when FIB concentrations tend to be much higher than during low-flow conditions.

Summary and Conclusions

This study used a multi-component approach to evaluate the influence of visitor use on water quality in a remote wilderness area in Sequoia and Kings Canyon (SEKI) National Parks in the Sierra Nevada of California, USA. A fall-season synoptic survey of water quality in 72 lakes and streams demonstrated that water quality in park wilderness was good, with low concentrations of nutrients and FIB. Concentrations of FIB were modestly higher at sites categorized as mixed use than at minimal-use sites ($P \leq 0.05$), and concentrations at backpacker-use sites were intermediate. A stepwise General Linear Model (GLM) was developed to examine the relative importance of basin characteristics and visitor use on water quality. The model had only weak predictive power ($r^2 = 0.44$); however, both basin characteristics and visitor-use category were statistically significant explanatory variables. Other variables that might be important, but could not be quantified for the synoptic survey sites, included hydrologic conditions and wildlife populations.

Paired sampling above and below several areas with differing types of visitor use indicated increases in FIB and particulate nutrient concentrations below areas classified as mixed use ($P \leq 0.05$). There were no statistically significant differences in nutrient or FIB concentrations above and below areas of backpacker use.

Intensive monitoring at a subset of sites documented that nutrient, FIB, and particulate concentrations were low, except during storms, when they sometimes increased substantially (although the response was highly variable).

Microbial source tracking (MST) techniques might be useful for identifying specific sources of fecal contamination in SEKI wilderness, but the typically low concentrations of FIB in these areas makes application of MST problematic. Future studies in SEKI and similar areas may wish to focus on collection of MST samples during storms, when FIB concentrations tend to be much higher than during low-flow conditions.

Several key lessons have been learned in this study, which was perhaps the first to quantify FIB concentrations in a remote wilderness setting using currently accepted analytical techniques and quality assurance procedures. First, despite logistical difficulties associated with wilderness, it is possible to conduct such a study; however, special consideration must be given to holding times, and sufficient resources must be allotted to allow meeting those requirements. Second, care must be taken when selecting sites for paired sampling above and below visitor use areas. Ideally, sites would be identified that allow examination of each visitor-use category of interest separately. In reality, it is difficult to find sites that do not represent some mixture of visitor use; even when such sites can be identified, limited resources can make use of those sites challenging because of the difficulty of access. Lastly, although the field of MST has recently made rapid advances, further research and development of these methods is needed before they can be applied in wilderness areas to reliably distinguish equine, human, and wildlife sources of fecal contamination.

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