

Chapter 7: Ecoregion 6.2.12 Sierra Nevada: Kings River Experimental Watersheds and Teakettle Experimental Forest, California

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Introduction

This chapter synthesizes watershed research that is relevant to water quality regulatory agencies from the Bull site of the Kings River Experimental Watersheds (KREW) and the adjacent Teakettle Experimental Forest (TEF). The chapter summarizes results of studies and environmental monitoring at these sites on ecological processes and forest management practices affecting water quality, and identifies priority research needs of regulatory agencies that might be met by future work.

Site Description

The KREW and TEF sites are in the Sierra National Forest (SNF), California, on the west side of the Sierra Nevada mountain range (lat. 36° 57' 55" N, long. 119° 3' 20" W) (see fig. 7.1). The KREW and TEF span elevations of 2050 to 2490 m. These forests are dominated at lower elevations by mixed-conifer stands of sugar pine (*Pinus lambertiana* Douglas), white fir (*Abies concolor* Lindl. ex Hildebr.), and ponderosa pine (*P. ponderosa* Lawson & C. Lawson) with an understory of mountain whitethorn (*Ceanothus cordulatus* Kellogg). At higher elevations, red fir (*A. magnifica* A. Murray) and lodgepole pine (*P. contorta* Douglas ex Loudon) dominate, with ponderosa pine and white fir also present. Jeffrey pine (*P. jeffreyi* Balf.), black oak (*Quercus kelloggii* Newberry), live oak (*Q. agrifolia* Née), and manzanita (*Arctostaphylos* sp.) occupy shallower soils. Precipitation is highly variable from year to year, ranging from an annual low of 65 cm to a high of 215 cm. Almost no rain occurs in this Mediterranean climate from July through September. Precipitation is 75 to 90 percent as snow, and the average annual air temperature is 8 °C (Hunsaker et al. 2012). The dominant soil is the Cagwin family, a mixed, frigid Dystric Xeropsamment, and the parent material is unglaciated granite (Johnson et al. 2011a). Study streams are perennial, first- and second-order headwaters (table 7.1) with main channel lengths of 2.1 to 3.2 km and slopes of 1 to 12 percent (Hunsaker and Neary 2012). The study area is in the Kings River drainage basin, which terminates in Tulare Lake, an inland lake in the San Joaquin Valley of California.

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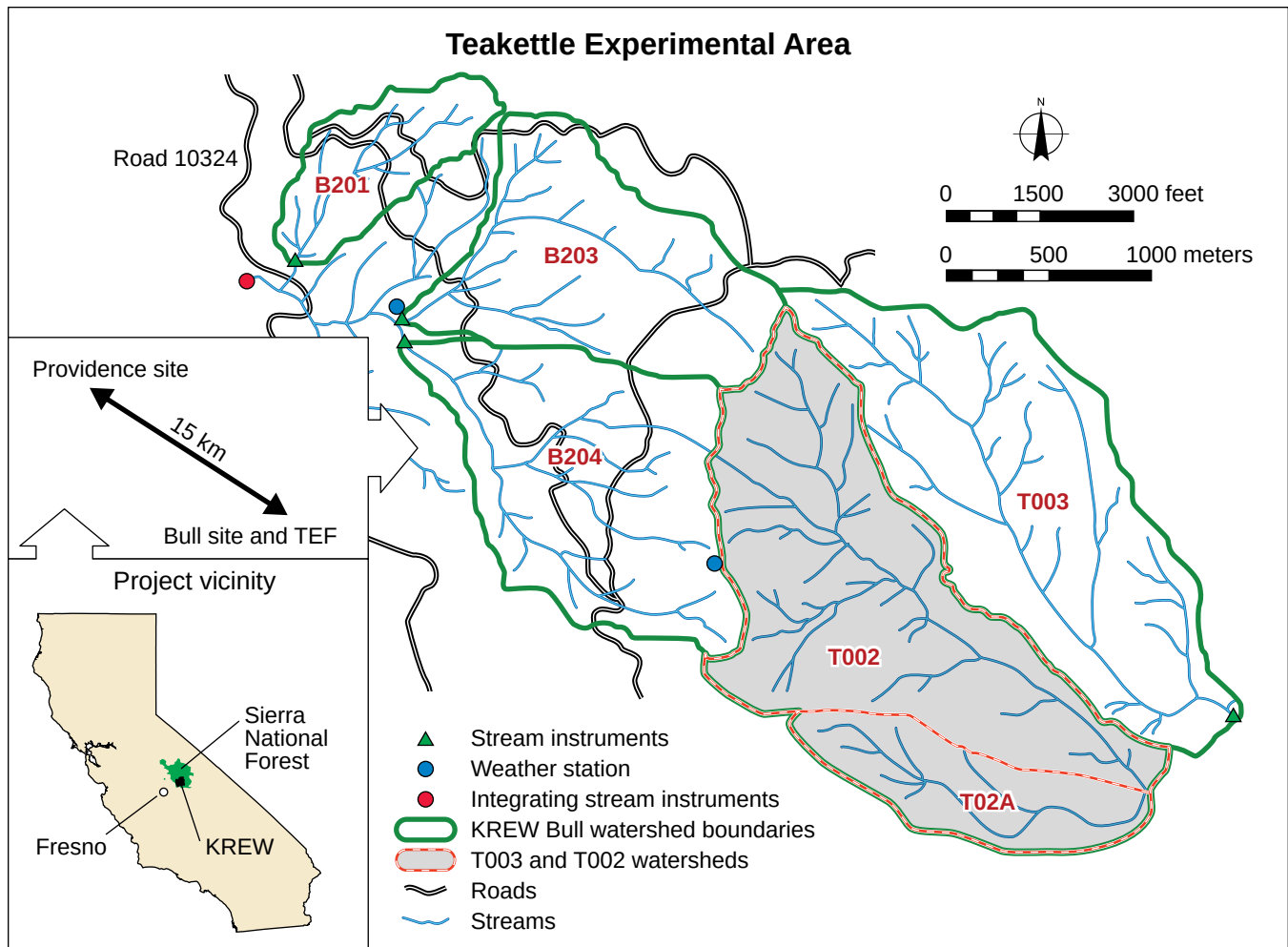


Figure 7.1—Location of the Bull site of the Kings River Experimental Watersheds (KREW) and the adjacent Teakettle Experimental Forest (TEF), including watersheds T003, T002, and T002A, which serve as reference basins with minimal onsite disturbance. Locations of automated instruments for stream measurements and meteorology are shown.

Research History

In 1938, 1300 ha of the SNF surrounding Teakettle Creek were designated as the Teakettle Experimental Area, and several drainages were chosen for study. Stream-gaging stations and sediment basins were built, and geology and soils research began, but studies were halted during World War II. Research resumed in 1957, including regular monitoring of precipitation and stream discharge, and in 1958, the U.S. Forest Service (USFS) officially designated the area as the TEF (North et al. 2002). The initial objective of the TEF was to develop timber harvest techniques that would increase water yield, but shifted to waterflow responses to weather patterns before monitoring was again discontinued in the 1980s. In the 1980s and 1990s, studies of songbirds and snag dynamics began. In 1998, the Teakettle Experiment (North et al. 2002) began studies of alternative methods and combinations of thinning and prescribed burning as strategies to restore the

Table 7.1—Physical and hydrologic characteristics of watersheds T003, B203, and B204

Characteristic	T003	B203	B204
Watershed area (ha)	228	138	167
Mean elevation (m)	2289	2373	2365
Elevation range (m)	2050–2465	2185–2490	2195–2490
Relief (m)	414	303	289
Average slope (%)	24	18	17
Dominant aspect	Southeast	Southwest	Southwest
Drainage density (km/km ²)	5.5	4.6	5.0
Channel length (km)	3.17	2.06	2.16
Dominant soil type (% of area)	Cagwin 94%	Cagwin 80%	Cagwin 98%
Q _{max} (mm/day)	8.46	14.26	11.95
Q _{mean} (mm/day)	1.40	1.80	1.50
Baseflow index (%)	76.1	68.2	68.1
Recession constant (<i>k</i>)	0.027	0.037	0.031
Runoff ratio (%)	33.4	42.9	35.8

Source: Safeeq and Hunsaker 2016.

ecological functions of a natural fire regime using plot-scale treatments that were not located within the gaged TEF watersheds.

In 2000, the USFS Pacific Southwest (PSW) Research Station established the KREW for hydrologic and landscape management research. Objectives of the KREW study included quantifying the variability of important characteristics of Sierra Nevada headwater streams and watersheds (see Hunsaker et al. 2007a) and evaluating effects on streams of forest restoration activities, including tree thinning, commercial timber harvest, and prescribed burning. Restoration goals were to reduce risk of severe wildland fires and to redirect forest structure and composition toward pre-1850 conditions (Hunsaker et al. 2014). The KREW study uses an integrated ecosystem approach that measures an array of physical, chemical, and biological effects of treatments on streams and their watersheds.

KREW instrumentation and treatments were repeated at two sites: the Bull site, which is the focus of this chapter, and the Providence site, approximately 15 km northwest of the Bull site and 400 m lower in elevation. Similar treatments and reference watersheds were implemented at both KREW sites (for details see Hunsaker et al. 2007a). Weekly monitoring of atmospheric wet deposition has been conducted at the Providence site (elevation 1981 m) since 2007 as part of the National Atmospheric Deposition Program (NADP) National Trends Network (NADP 2019).

A portion of the original TEF was included within the Bull site of KREW. In 2003, streamflow monitoring was reinitiated on watershed T003 (formerly named TK3) within TEF, which serves as an undisturbed reference watershed for studies

in the adjacent KREW Bull site (fig. 7.1). TEF watersheds TK2 and TK2A also provide additional reference streams for monitored stream invertebrates as biological indicators for the KREW study.

KREW forest restoration treatments were applied to Bull site watersheds B201 (52 ha), which was thinned in 2012; B203 (138 ha), which was burned in 2013; and B204 (167 ha), which was both thinned in 2012 and burned in 2013. Posttreatment effects are being monitored, but results are not available at this writing. This chapter reports results of pretreatment monitoring and studies of the KREW watersheds and adjacent TEF reference watersheds (KREW/TEF).

Availability of publications and data—

Hydrology and sediment transport data from TEF prior to 2002 were published in Dendy and Champion (1973) and Kattelmann (1989). TEF stream discharge data are available online for 1958–1969 and 1977–1989 (USGS 2017). Daily precipitation and stream discharge data for KREW and TEF watersheds, formatted for ready comparison with other experimental forest and ranges and Long Term Ecological Research sites, are available at the ClimDB/HydroDB website (LTER Network 2017). Long-term meteorological and stream discharge data for KREW from 2002 through 2015 are in the Forest Service Research Data Archive (Hunsaker and Safeeq 2017, 2018). “Geology of the Teakettle Creek Watersheds” (LaMotte 1937) is available online. Some unpublished datasets and historical records from the TEF are available at the PSW Research Station Fresno laboratory (USDA FS, n.d.).

The KREW Research Study Plan (Hunsaker et al. 2007a) contains the study design and maps of the research area. The categories of data collected at KREW are in Hunsaker et al. (2007a). Precipitation chemistry data from KREW (NADP site CA2) are available from the NADP (2019). Publications on KREW/TEF are available online (USDA FS 2017).

Biological Responses to Stream Nutrients N and P

Issues of Concern

Beneficial water uses in the region include domestic water supply, agricultural irrigation, freshwater habitat, water contact recreation, and hydropower generation. Approximately 60 percent of California’s surface water originates in the forested lands of the Sierra Nevada (California DWR 2008). Wildland fire and timber harvesting can cause erosion and resulting sedimentation that reduce water quality and cause loss of water storage capacity of reservoirs (Chapel 2014, Minear and Kondolf 2009). Land management practices, such as forest fuels reduction to decrease the severity of fires and restore forests to presettlement conditions, often entail cutting trees, prescribed burns, or both. Such activities have also raised concerns because they can affect water quality and habitat for sensitive wildlife species.

Usually, forest lands are not a major source of excess nutrient loads (Binkley 2004). However, where long-term nitrogen (N) deposition is high from air pollution, it can cause acidification of forest soil and leaching of N into stream water. In the United States and Europe, this process is generically called “acid rain.” The KREW area has high N loadings from air pollution (Hunsaker et al. 2007b). Lichen species are very sensitive to acidifying effects of N deposition, and acidification of surface water by atmospheric deposition of N can harm fish and invertebrate populations. The southern Sierra Nevada soils and the underlying granite confer significant acid-neutralizing capacity that buffers stream water from acidification. Increases in stream water N may contribute to eutrophication of rivers and reservoirs downstream that can decrease the quality of water for contact recreation, such as boating and swimming, and for drinking water sources. Forest management activities may affect streamflow, nutrient and sediment transport, riparian forest composition, and stream temperature, all of which may alter habitat for fish and other aquatic species.

Findings From Studies

Biological responses to stream nutrients have not been directly studied at KREW/TEF. However, surveys and ongoing monitoring of stream biological communities have been conducted in the pretreatment and reference watersheds where ambient stream nutrients and suspended sediments have also been monitored. We present the monitoring findings and studies of stream biological communities first, followed by stream nutrients and their potential sources and sinks within these watersheds.

Stream biological studies and monitoring—

In the KREW study, biological indicators of stream water quality were selected for monitoring because aquatic communities integrate all environmental conditions and might be more informative indicators of water quality effects from management treatments than physical or chemical parameters. Stream benthic macroinvertebrates were chosen as biological indicators and were sampled repeatedly at the same time of year and location, before and after fuel treatments and on reference watersheds. Samples were always taken in the spring (usually June), and in some years, samples were also collected in fall. Benthic algae are also a biological indicator that was sampled twice during pretreatment (Brown et al. 2008), but they have not been resampled posttreatment.

Benthic macroinvertebrates were evaluated in KREW between 2002 and 2015 for their community structure and densities of total, taxonomic, and functional feeding groups (Herbst et al. 2018, 2019). Ten KREW streams plus two additional TEF streams, T002 and T02A, were monitored for invertebrates (fig. 7.1). Three TEF reference streams were monitored to provide a robust measure of biological

condition of “undisturbed” streams. These data have been analyzed at the finer scale of pools versus riffles and the coarser scale of 100-m-long reaches.

Local flow regimes were an important driver of the structure and abundances of invertebrate communities. Community structure differed between riffles and pools. Total invertebrate densities were higher in pools than in riffles, but the opposite relationship was observed for Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies), groups that are called EPT taxa. EPT taxa are sensitive to habitat degradation and poor water quality. Chironomidae, shredding caddis larvae, and sphaeriid clams were more abundant in pools. These findings indicate that riffles were in better condition than pools throughout the monitoring conducted at KREW.

Benthic algal species assemblages and chlorophyll-*a* standing crop, a measure of stream algal biomass, were measured at KREW in 2002 and 2005 by Brown et al. (2008). Benthic algae were previously little studied in the Sierra Nevada, and the findings of Brown et al. (2008) provided a valuable baseline for using algae as a bioindicator of stream condition in the Sierra Nevada. Periphyton are a complex mixture of algae, cyanobacteria (also called Cyanophyta or blue-green algae), heterotrophic microbes, and detritus that respond to many aspects of the stream environment, including nutrients, that might change with land management practices. Hill et al. (2000) and others have suggested monitoring algal assemblages as indicators of biotic integrity. In addition, benthic algae are also the primary producers in small streams and a food resource for many stream organisms, including macroinvertebrates. Chlorophyll-*a* values in KREW streams ranged from 0.2 to 3.2 mg/m² and were similar to values found elsewhere for small, low-nutrient montane streams and for the larger Merced River, which is north of KREW in the Sierra Nevada (Brown and Short 1999). Benthic algal assemblages in KREW streams were dominated by either diatoms (Bacillariophyta) or cyanobacteria with only a few streams having green, red, or yellow-green algae. Diatoms made up 28 to 94 percent of the algal groups, and cyanobacteria comprised 2 to 68 percent. Diatom species richness ranged from 15 to 47 species and was generally comparable to other studies of western montane habitats, including the Merced River. The most abundant diatom species were *Achnanthes minutissimum*, *Cocconeis placentula*, and *Planorbulina lanceolata*. Diatoms are indicators of good water quality because they are generally sensitive to organic pollution and indicative of high dissolved oxygen levels, low specific conductance, and low dissolved chloride levels. Brown et al. (2008) developed a multivariate model of the effect of stream habitat on diatom abundance in KREW streams; it included elevation, water temperature, pH, specific conductance, and stream canopy cover.

Although steelhead trout (*Oncorhynchus mykiss* Walbaum) may have reached elevations higher than 2200 m in the Middle Fork of the Kings River (Moyle et al. 1996), fish were not selected as biological indicators of stream condition because natural barriers prevented native fish species from being present in the headwater streams of KREW before 1850. Nonnative eastern brook trout (*Salvelinus fontinalis* (Mitchill)) were introduced by humans and have been found in the T003, B203, and B204 streams. These exotic fish were unsuitable as biological indicators because they were not indicative of presettlement conditions (Hunsaker et al. 2014).

Stream water N and P—

Stream water nutrient concentrations from pretreatment monitoring (2004–2011) are compared in table 7.2 for T003 in TEF and two adjacent Bull watersheds, B203 and B204 (fig. 7.1). For the three watersheds, average stream water concentrations in biweekly grab samples for ammonium (NH_4^+) were very similar among watersheds (1.6 to 1.8 $\mu\text{mol}_\text{c}/\text{L}$), but the average concentration for nitrate (NO_3^-) varied almost fivefold from 0.4 $\mu\text{mol}_\text{c}/\text{L}$ in T003 to 2.4 $\mu\text{mol}_\text{c}/\text{L}$ in B204. Average orthophosphate (PO_4^{3-}) concentrations in grab samples were the same for all three watersheds (0.8 $\mu\text{mol}_\text{c}/\text{L}$). Nutrient concentrations in individual, biweekly grab samples were often below detection limits of 0.1 mg/L for NH_4^+ -N and 0.01 mg/L for NO_3^- -N and PO_4^{3-} -P. Grab samples, collected every other week, were biased toward baseflow conditions, and event samples were collected during high flows by automated Teledyne ISCO™ pumping samplers.

Table 7.2—Average stream water chemical concentrations ($\mu\text{mol}_\text{c}/\text{L}$) of biweekly grab samples compared to high-flow event samples taken from T003, B203, and B204 streams with an automated ISCO™ sampler^a

	T003			B203			B204		
	Grab	ISCO	P	Grab	ISCO	P	Grab	ISCO	P
pH	6.93±0.03	7.01±0.04	0.03	6.69±0.03	6.51±0.04	<0.01	6.68±0.03	6.64±0.03	0.18
EC	29±1	24±1	<0.01	15±1	18±1	0.08	19±1	20±1	0.25
Ca ²⁺	174±2	154±5	<0.01	69±1	72±3	0.27	108±3	98±3	0.01
Mg ²⁺	36±0	33±1	<0.01	20±0	22±1	0.11	24±1	23±1	0.11
K ⁺	18±1	32±4	<0.01	11±1	21±3	<0.01	18±3	24±2	<0.01
Na ⁺	82±1	67±2	<0.01	48±1	43±2	<0.01	60±1	50±2	0.08
Cl	11±1	16±2	0.01	10±1	22±4	0.01	12±1	18±3	0.03
NH ₄ ⁺	1.68±0.27	3.00±0.65	0.03	1.85±0.32	3.33±0.42	<0.01	1.63±0.19	2.48±0.26	0.01
NO ₃ ⁻	0.45±0.03	0.57±0.08	0.08	0.93±0.39	5.04±1.46	<0.01	2.44±0.29	7.22±1.36	<0.01
Ortho-P	0.83±0.01	1.43±0.21	<0.01	0.84±0.02	0.87±0.03	0.21	0.84±0.02	0.99±0.08	0.03
SO ₄ ²⁻	7.88±0.51	8.23±0.48	0.32	5.57±0.13	7.05±0.50	<0.01	7.70±0.25	9.41±0.70	0.01

pH = measure of acidity, EC = electrical conductivity (a measure of dissolved solids; used as a generic indicator of pollution), Ca = calcium, Mg = magnesium, K = potassium, Na = sodium, NH₄ = ammonium, NO₃ = nitrate, Ortho-P = ortho-phosphate, SO₄ = sulfate.

^a The probabilities of significant differences between the two sample types are given with significant differences in bold (Student's t-test, P < 0.05).

Comparing results of the two sampling methods showed that NH_4^+ , NO_3^- , and PO_4^{3-} stream water concentrations were all significantly higher during high-flow events (table 7.2), indicating that high flows enhanced nutrient concentrations, rather than diluted them. Ammonium concentrations at high flows were about double the average concentration of grab samples, and the differences were statistically significant at all three sites (table 7.2). Although high-flow concentrations of NO_3^- were higher than biweekly grab samples for all three watersheds, the ratio of biweekly to high-flow NO_3^- concentrations varied considerably among watersheds, ranging from 0.2 for B203 to 0.8 for T003. The ratio of biweekly to high-flow PO_4^{3-} concentrations also varied among watersheds, ranging from 0.6 on T003 to 1.0 on B203.

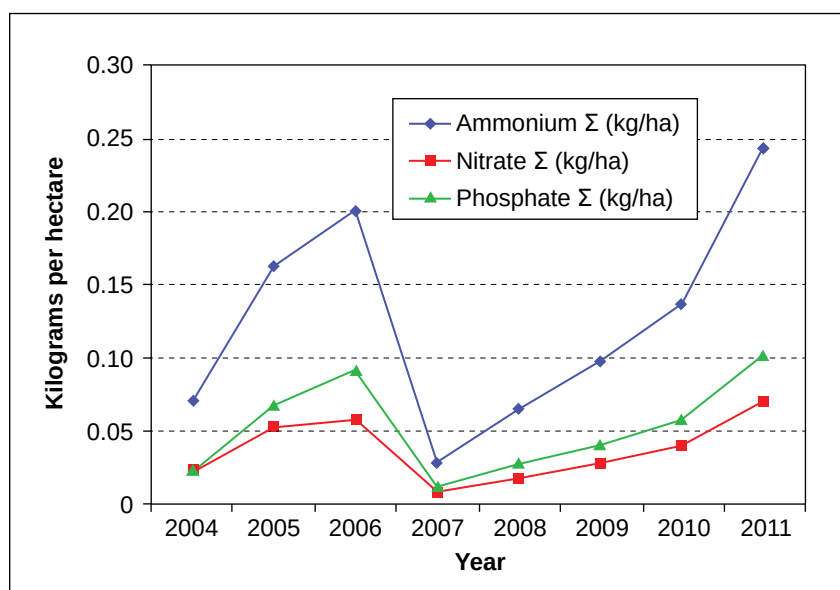


Figure 7.2—Annual flux in stream water of ammonium-nitrogen, nitrate-nitrogen, and phosphate from 2004 to 2011 for reference watershed T003.

Annual stream water fluxes of nutrients from watershed T003 were calculated for water years (WYs) 2004 through 2011 (fig. 7.2). A water year is from October 1 through September 30 of the following year. The fluxes of both N and phosphorus (P) were strongly driven by streamflow, with greatest fluxes in high discharge WYs 2005, 2006, 2010, and 2011; we found that these ions were enriched rather than diluted during high flows. Nitrate-N and PO_4^{3-} -P loads were lower than 0.1 kg/ha/yr in all years. The annual flux of NH_4^+ -N ranged from <0.05 to 0.25 kg/ha/yr and was greater than NO_3^- -N flux in all years.

Sources of N and P from watershed soils and atmospheric deposition—

Watershed soil and atmospheric inputs are sources of nutrients to KREW streams.

Soil physical and chemical characteristics were quantitatively sampled using 87 spatially distributed, 1-m-deep soil pits (Johnson et al. 2011a). The orthophosphate pools in the soil ranged from 75 to 150 kg P/ha, with B204 being the largest.

Nitrate-N and NH_4^+ -N pools in soil were highest in watershed B203 at 23 and 325 kg/ha, respectively, while soil pools in T003 and B204 were similar to each other at 15 kg NO_3^- -N/ha and 200 kg NH_4^+ -N/ha, respectively (fig. 7.3). Rock outcrops lack

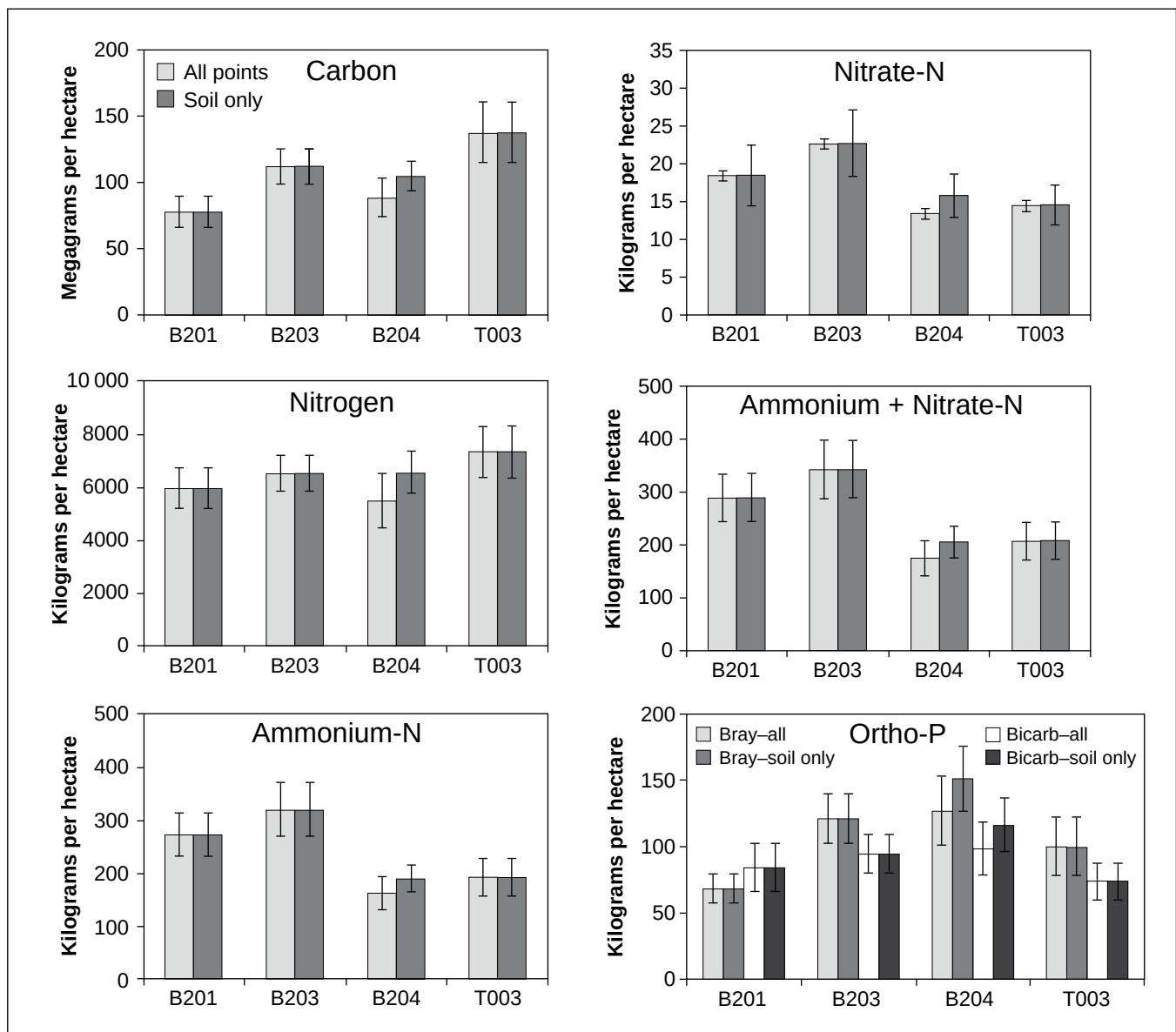


Figure 7.3—Carbon and nutrient pools in the top 1 m of soil for the T003 watershed and the three adjacent Bull watersheds (Johnson et al. 2011a). The data labeled “all” included sample points on bedrock outcrops with no soil. The data labeled “soil only” excluded points on outcrops.

surface soil and are common in these watersheds. Including the effect of outcrops on soil pool sizes, called “all points” in figure 7.3, soil nutrient pool sizes were significantly smaller on B204 than if the effects of outcrops were excluded (called “soil only”), but made no significant difference for T003 and B203. Total N in soil at T003 was highest at ~8000 kg N/ha, while B201 and B204 both had ~6000 kg N/ha. Compared to values reported for other forest locations in the Sierra Nevada, the measured pools of NH_4^+ -N, and mineral N were both high, but the carbon (C):N ratio (22.1 ± 1.6) was similar. Pool sizes of N in watershed soils were consistent with stream water fluxes in that NH_4^+ -N substantially exceeds NO_3^- -N in both. However, soil chemistry alone probably does not explain all aspects of N concentrations in stream water, indicating that other factors, such as hydrology, biological processes, and atmospheric deposition probably also influence stream N levels.

To assess whether deposition of air pollutants is negatively affecting forests, soils, and streams, Fenn et al. (2008, 2011) estimated critical loads of atmospheric deposition for the mixed-conifer forests of the Sierra Nevada. Critical loads are levels of atmospheric deposition below which sensitive components of the forest ecosystem experience no undesirable effects. Sensitive components for Sierra Nevada forests are lichen species that do not tolerate elevated N deposition and streams that could be acidified by increased N deposition. They estimated that critical loads for sensitive lichens were 3 to 5 kg N/ha/yr and for streams were 17 kg N/ha/yr. They further estimated that a background level of atmospheric deposition of N in the southern Sierras, in the absence of anthropogenic air pollution, would be 1 to 2 kg N/ha/yr. Using NADP protocols at KREW, wet atmospheric deposition of total inorganic N, for the WYs 2008 to 2012, measured in an open area that was not under forest canopy, averaged 4.40 ± 1.47 (standard error) kg N/ha/yr. Thus, current levels of N in atmospheric wet deposition alone are considered harmful to sensitive lichen species. The highest annual wet deposition, 10 kg N/ha/yr, measured at KREW in 2008, was below the estimated critical load for damage to streams. However, there is concern that dry deposition of N might cause total N deposition to approach the critical load for streams at times. Dry deposition of N is the net flux from the atmosphere to the watershed in gases, such as nitrogen oxides and ammonia, and particulates, neither of which are efficiently captured by conventional wet precipitation collectors. In forests, dry deposition occurs primarily on the foliar canopy.

A study of internal fluxes of N within the KREW watersheds, using the methods described by Susfalk and Johnson (2002), provided some evidence of the magnitude of the total atmospheric deposition of N and its potential effects on streams. N fluxes in throughfall were measured, as well as the flux of N in soil water leaving the forest floor and entering the underlying mineral soil using ion exchange resin

collectors at points on a uniform 150-m grid across the Bull site (figs. 7.4 and 7.5). Throughfall is precipitation collected under the forest canopy, and it contains the sum of wet plus dry deposition washed from the canopy. Throughfall provides an estimate of total atmospheric deposition, if net leaching of N from foliage is assumed to be negligible. At the majority of sampling points, annual throughfall loads of N were above 2 kg N/ha/yr, which is the background deposition that would be expected in the absence of air pollution (fig. 7.4). At some sampling points, and sometimes for more than 1 year, local extremes of the throughfall N flux were greater than 17 kg N/ha/yr, the critical load of N that would negatively affect stream water, if the average of deposition at all points in the watershed exceeded this value (fig. 7.4). However, the observed annual loads of mineral N in streams were very low (<0.4 kg N/ha/yr) indicating that the limited number of local extreme fluxes of N had only a minor effect on streams. Thus, detailed measurements showed that throughfall N flux is highly variable and that, while locally extreme fluxes can

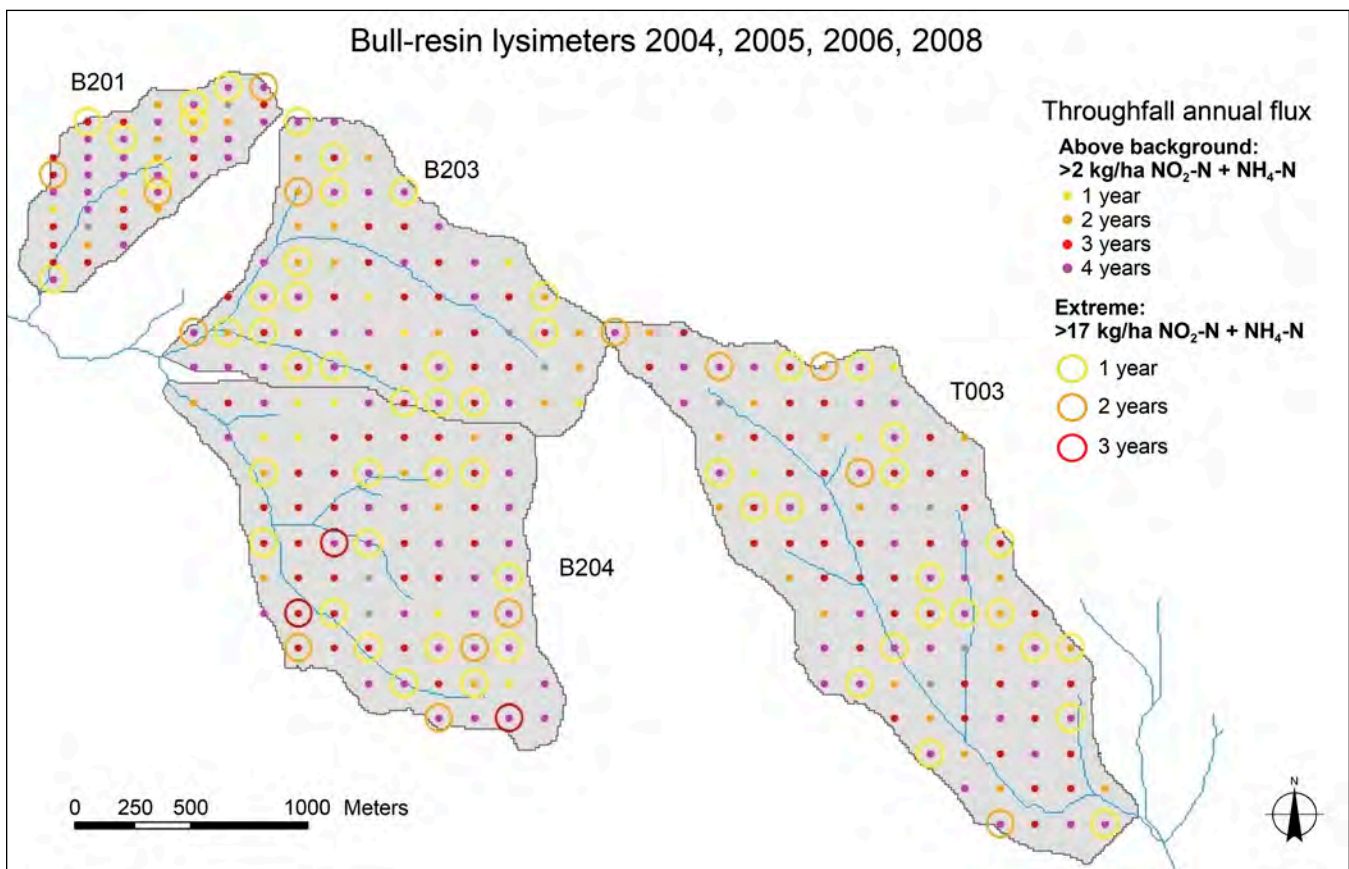


Figure 7.4—The spatial pattern of annual nitrogen flux (nitrate nitrogen plus ammonium nitrogen [$\text{NO}_2\text{-N} + \text{NH}_4^+\text{-N}$]) in throughfall, for 2004, 2005, 2006, and 2008, measured on the Kings River Experimental Watersheds' sampling grid by aboveground ion exchange resin collectors. The estimated atmospheric deposition flux in the absence of anthropogenic air pollution, 2 kg N/ha/yr, was defined as background, and the flux that would negatively affect streams, 17 kg N/ha/yr, was defined as extreme.

exceed the critical load to streams at some points within the watershed, the low N flux measured in stream water indicates that, at the scale of the whole watershed, critical loads of N for streams are probably not being exceeded.

Fluxes of N in soil water provide evidence that N cycling is not spatially uniform within the study watersheds. After entering the forest floor layer as throughfall, soil water is altered by additions of N from sources such as decomposition of organic matter, and N is depleted by sinks such as uptake by soil microbes and tree roots. Resin samplers in the shallow mineral soil (depth 13 cm) found N fluxes elevated above throughfall at the majority of points (fig. 7.5). Locally high (>10 kg N/ha/yr) and extreme (>20 kg N/ha/yr) soil fluxes were found entering shallow mineral soil at some sampling points for 1 or more years. Soil water that drains from the forest floor eventually flows to streams via interflow or groundwater where it may be further altered as a result of N-cycling processes along the way. While N concentrations in stream water have been observed to increase during

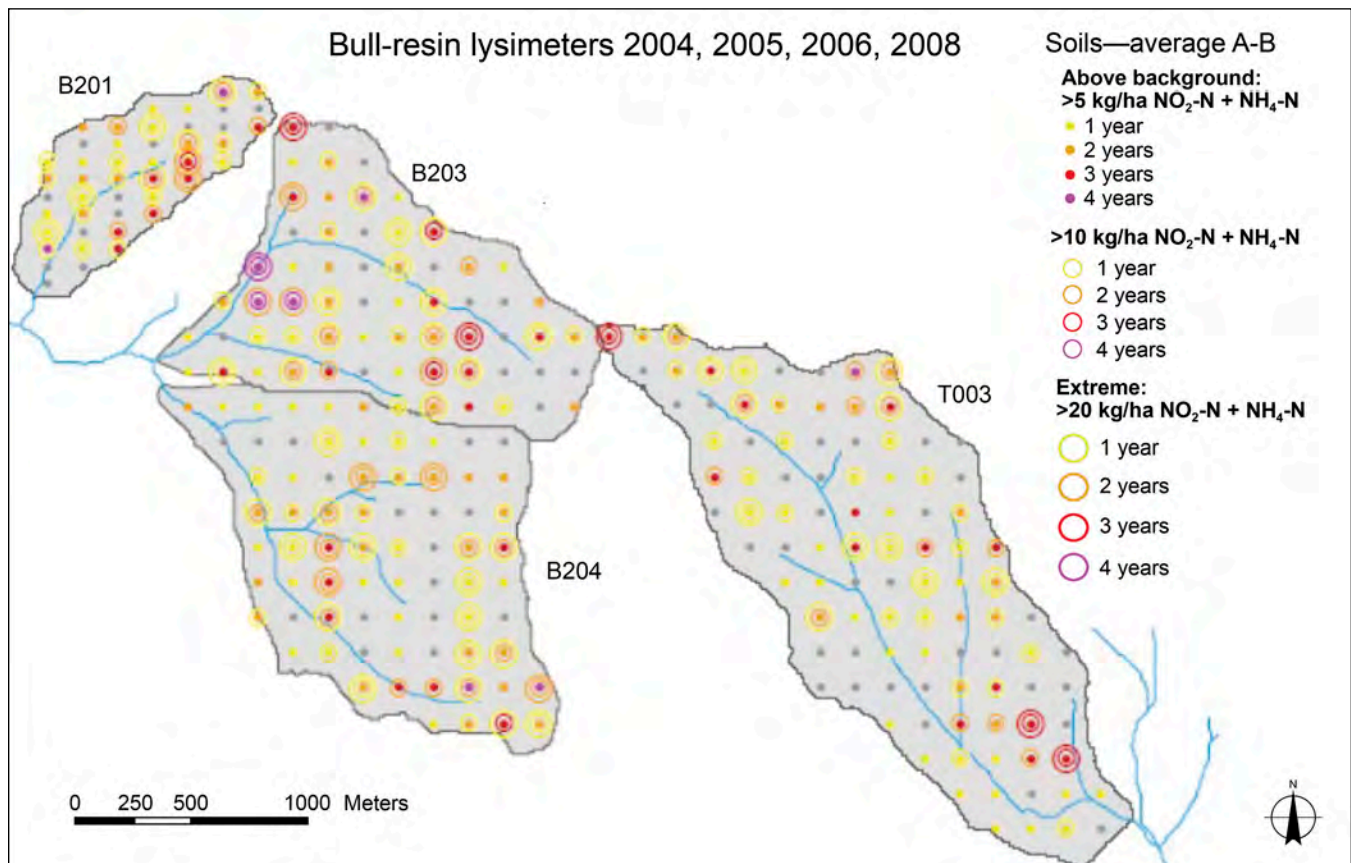


Figure 7.5—The spatial pattern of annual nitrogen flux (nitrate nitrogen plus ammonium nitrogen [$\text{NO}_2\text{-N} + \text{NH}_4^+\text{-N}$]) into shallow soil, for 2004, 2005, 2006, and 2008, at the Bull site. These values are measured on the King River Experimental Watersheds' sampling grid by ion-exchange resin lysimeters 13 cm depth in the mineral soil. Background (unenriched) level was defined at 5 kg N/ha/yr and extreme level as 20 kg N/ha/yr.

high precipitation events and snowmelt, the increases in stream water N are small compared to the high levels observed in soil water. These locally high values of soil water N may be indicators of “hotspots” of N cycling within the watersheds. The increase in stream N concentrations, at higher flows, suggests that hotspots might be more hydrologically connected to streams during wetter, high-flow conditions. Under dryer conditions, hotspots may be less connected to streams, and vegetation and microbial uptake may effectively retain N produced at hotspots. Consistent with these observations was evidence described by Johnson et al. (2011b) and Woodward et al. (2013) of soil N hotspots in forests at the Providence site. Thus, the flux of N entering the soil surface in throughfall is altered by sources and sinks of N in the forest floor, some of which may produce local hot spots where soil fluxes within small areas exceed levels that would be detrimental to streams, if N loading, on average, was this high over the whole watershed. During wet conditions, increased hydrologic connectivity between hot spots and streams might explain increased N levels observed in streams at high flows. However, the detailed mechanisms of N cycling that ultimately process atmospherically deposited N as it passes through watershed soils and enters stream water are currently not fully understood.

Other Factors Relevant to Biological Responses to N and P

Following an ecosystem approach, scientists at KREW have monitored many environment factors that affect stream N and P and biological responses to them within these watersheds.

Streamflow generation processes—

Processes controlling streamflow generation were analyzed using geochemical tracers and end-member mixing analysis for WYs 2004–2007 on the eight KREW watersheds (Liu et al. 2012). Streamflow in these headwaters was dominated by subsurface flow (about 60 percent of discharge), while snowmelt runoff contributed less than 40 percent and fall storm runoff (overland flow) less than 7 percent. Snowmelt runoff is water that flows overland and has little contact with the soil, while subsurface flow follows the soil-bedrock interface or moves through the soil along preferential pathways and combines water from both rain and snowmelt that has infiltrated into the soil.

Hydrology and watershed characteristics—

Despite the dominance of subsurface flow on an annual basis, precipitation magnitudes and patterns also play important roles in stream hydrology and chemistry fluxes. Hunsaker et al. (2012) and Safeeq and Hunsaker (2016) analyzed KREW meteorology and stream discharge data for WYs 2004 through 2014. Our analysis

of the variability of annual precipitation at KREW/TEF, based on long-term (1981–2010) precipitation data, and using a statistical model (Daly et al. 1994), found that from 2004 to 2014, only 2 years had normal precipitation (125 to 175 cm), while 4 years were above normal (175 to 225 cm), and 5 were below normal (50 to 75 cm).

Although total precipitation during a year determines annual stream discharge, individual stream responses to incoming precipitation are partly governed by the physical attributes of each watershed. For many years, especially during wet WYs 2005 and 2006, B203 had the highest total discharge per unit area, and B204 had the second highest at the Bull site. These rankings also applied to the mean and maximum flows (table 7.1). The ratio of long-term average discharge to long-term average precipitation, called runoff ratio, for B203 was 43 percent, while for T003 it was 33 percent. The runoff ratio is also an indication of the separation of incoming water between discharge and evapotranspiration, assuming no net change in storage and seepage as deep groundwater. Thus, according to this metric, T003 has a greater fraction of incoming water leaving via evapotranspiration than do B203 or B204.

There are several similarities among the adjacent T003, B203, and B204 watersheds, but also substantial differences in hydrologic functioning. Cagwin soils dominate (>90 percent) of all three of these watersheds. The mean elevation of B203 and B204 is about 100 m higher than that of T003. Watershed T003 is larger than B203 and B204 and has a longer channel, a higher drainage density, and a higher average slope. The ratio of base flow to total flow, called the base flow index, was almost 10 percent higher on T003 than for B203 and B204, implying that T003 has a greater groundwater influence and longer flow path than the two Bull watersheds, consistent with its slower base flow recession (Safieq et al. 2013) (table 7.1).

Sediment—

The amount of sediment carried by a stream can be affected by forest management activities. The pool behind the T003 weir and settling ponds below the flumes on the Bull watersheds, have served as sediment collection basins. Hunsaker and Neary (2012) analyzed the KREW watershed bedload data for pretreatment years, assuming that collected sediment was primarily bedload in these granitic watersheds. Because the Bull and Teakettle watersheds receive 75 to 90 percent of their precipitation as snow, soil erosion tended to be lower than for the more rain-dominated KREW Providence watersheds. Variability among streams and years was high because the annual sediment load was related to the annual precipitation, which varied widely, and because large individual flow events contributed substantial fractions of annual loads. Average annual sediment loads from WY 2003 through WY 2009 ranged from a low of 8 ± 11 kg/ha at B204 to a high of 16 ± 21 kg/ha at T003. When we compare the current sediment loads measured at T003 to historical

measurements (Dendy and Champion 1973), we find similar average annual loads with high variability. The 4 years measured between 1940 and 1951 show an annual average load of 18 kg/ha, and the 4 years measured between 1958 and 1962 show a similar annual average load of 20 kg/ha with a range of 1 to 35 kg/ha.

Historical data from TEF and recent data from KREW will allow for an updated sediment budget for the headwaters of the Kings River and will improve assessments of the effects of contemporary forest management practices on sediment and nutrient loads. Reid and Dunne (1996) produced a sediment budget for the North Fork Kings River basin showing that bank erosion was causing half of current total sediment delivery, which they estimated at 16 Mg/km²/yr. Road surface erosion was the only disturbance category they considered, and they estimated that it contributed less than one-quarter of the total sediment yield. Work in KREW and other Sierra watersheds has found similarly that bank erosion is a major component of sediment budgets and that in-channel sources dominate sediment supply (Bales et al. 2015, Kwan and Swanson 2014, Martin 2009, Nolan and Hill 1991).

Stream temperature—

Stream temperature is an important habitat factor for aquatic organisms and has been a concern when riparian vegetation has been removed or trees thinned close to streams. Forests in the southern Sierra Nevada are open and naturally patchy, thus streams receive considerable sunlight. Stream temperature is continuously monitored at the outlet of KREW watersheds. The effects of precipitation and snowpack accumulation on stream temperature were apparent for T003 in WYs 2009 and 2013. In both years, low water temperatures (≤ 2 °C) started in late October, but during 2013, with little snowpack, water temperatures started to increase in mid-February, while in 2009, with a normal snowpack, water temperature increase did not begin until mid-April (Hunsaker and Safeeq 2017, 2018; USDA FS, n.d.).

Dose-Response Studies

Dose-response studies for stream nutrients have not been conducted at TEF or KREW.

Reference Watersheds

The T003 (228 ha), TK2 (220 ha), and TK2A (70 ha) watersheds have been managed for minimal onsite human disturbance since TEF was established in 1938, permitting no management activities such as roads, timber harvest, or mineral exploration (fig. 7.1). No wildland fires larger than 0.1 ha have been recorded since 1910, although there were fires before that time, as was common in the southern Sierra Nevada. The boundaries of the TEF are not fenced. Cattle from adjacent

lands occasionally enter the reference watersheds, but usually exert minimal grazing pressure. The research and monitoring findings from T003, presented in this chapter, are indicative of reference stream conditions, including streamflow, stream nutrient concentrations and fluxes, sediment loads, and stream biological communities, including macroinvertebrates and benthic algae. Only macroinvertebrate data are available for watersheds TK2 and TK2A.

Watershed T003 serves as a reference watershed for the Bull site of KREW and could also represent conditions for undisturbed forested watersheds at this elevation in the southern Sierra Nevada. It is valuable as a site for scientific studies of water quality and the structure and function of forest and stream ecosystems in an undisturbed mixed-conifer forest. The exclusion of confounding onsite human disturbance, for example, makes this a potentially useful site for studying effects of regional and global atmospheric effects on forests and stream water quality. Air pollution, originating from transportation, urban and agricultural sources in central California, does reach this area (Hunsaker et al. 2007b), and analyses of long-term climate records from this region have found signs of long-term warming of air temperature (Cayan et al. 2008).

Cross-Site and Regional Studies

Precipitation chemistry data from KREW (NADP site CA28) have been used in regularly produced regional and national analyses of atmospheric deposition patterns and trends (NADP 2019). The USFS's Sierra Nevada Adaptive Management Study used KREW data in water yield modeling, since the period of record was considerably longer at KREW than for most other headwaters in the region (Bales et al. 2015). Jepsen et al. (2015) calibrated a model with KREW data to investigate how hydrogeology might mediate long-term responses of mountain streamflow to reduced snowfall in a warming climate.

KREW has participated in other regional-scale studies. Goulden et al. (2012) used KREW streamflow data to validate a water balance model that characterized evapotranspiration along an elevation gradient in the Sierra Nevada. The U.S. Geological Survey's Southwest Climate Science Center sponsored a study that used vegetation data from KREW and other forests in the southern Sierra Nevada to evaluate the effect of forest management on forest resistance to drought. The KREW has also participated in the National Science Foundation-sponsored Southern Sierra Critical Zone Observatory (SSCZO 2017) and the National Ecological Observatory Network (NSF and Battelle 2017), both of which collect standardized environmental data from a network of study sites for use in cross-site, regional- and continental-scale geoscience and ecological investigations.

Responses to Management and Natural Disturbances

Korte and MacDonald (2007) and Stafford (2011) measured road and hillslope erosion over three winters during the calibration period of KREW. High variability in sediment production rates was found among years, among different types of road surfaces, and among individual road plots. Native- and mixed-surface roads produced three times the sediment of gravel-surfaced roads. The estimated sediment delivery from roads was compared to the measured sediment yields in three of the lower elevation Providence watersheds. In two of these watersheds, forest roads contributed less than 10 percent of total sediment yield. In the third basin, roads were estimated to contribute 25 to 50 percent of the total sediment yield, and nearly all of the road-related sediment came from a single mixed-surface road that crossed the stream a short distance above the weir pond (Korte and MacDonald 2007).

These results were consistent with earlier work in the central Sierra Nevada (Coe 2006, MacDonald et al. 2004), indicating that native-surface roads are usually the primary anthropogenic source of sediment in this region. Coe (2006) and Stafford (2011) suggested that sediment delivery from forest roads could be reduced by (1) reducing the length of roads draining to stream crossings and covering them with crushed rock, (2) minimizing the number of stream crossings, (3) minimizing road grading, and (4) improving placement and design of road drainage structures. These guidelines have been used in road-related training courses for California state agency personnel and registered professional foresters.

In the past, natural disturbances for landscapes such as KREW/TEF consisted primarily of wildland fires and extreme climate events. Wildland fires have been effectively excluded by fire suppression activities since the 1930s. The prolonged drought from WYs 2012 through 2015, with drastically low snow amounts, provided recent opportunities to observe hydrologic and ecologic responses to this climate extreme, but analyses have not yet been published.

Reliability and Limitations of Findings

Research results and monitoring datasets from KREW/TEF are most applicable to central and southern Sierra Nevada forests. They also might be relevant for other mountain forest areas with similar climate, steep topography, and granitic soils, such as the Rocky Mountains. TEF findings are useful because they are from watersheds with little human disturbance. The other KREW watersheds have experienced commonly used forest management practices such as timber harvests, tree plantations, hazard tree removal, and road networks. Clearcut harvesting was not extensively used here, although clearing of a few acres of trees sometimes took

place after insect outbreaks produced tree mortality. If environmental factors such as soils or land use are substantially dissimilar, or a high degree of accuracy is needed, we suggest considering validation monitoring or experiments to test how well results from KREW/TEF predict local conditions elsewhere.

Research Needs

The highest priority research need of the regulatory community related to N and P that might be filled at KREW/TEF is monitoring of long-term effects of forest fuels treatments on water quality, including biological indicators, and stream loading and export of N, P, and suspended sediments. These science needs include effects on stream water quality over the first two to three decades following fuels treatments, and ultimately understanding the long-term effects on the stream and watershed ecosystem of regularly repeating these treatments every 25 to 30 years. Such data could then be compared to nutrient and sediment export documented from high-severity wildfires in the Sierra Nevada (e.g., Murphy et al. 2006, Oliver et al. 2011), providing a much needed comparison between prescribed fire and wildfire effects. Regulatory agencies could use these data to assess the effectiveness of current practices and to develop science-based standards and best management practices for future fuels treatments that are sustainable and protect water quality in the Sierra Nevada.

The KREW fuel reduction treatments provide opportunities to study post-treatment effects on water quality that can be compared to both pretreatment data and conditions on the nearby undisturbed reference watershed. Limited data on short-term treatment effects are available for the Lake Tahoe Basin (Stephens et al. 2004) and Sequoia National Forest (Engle et al. 2008). Water quality monitoring at KREW/TEF, including nutrients, sediments, and macroinvertebrate biological indicators, is currently supported by PSW Research Station, and some past support was provided by the California Bay Delta Program, but continuation depends on the year-to-year availability of funding and personnel. Assuring long-term monitoring of water quality effects of the KREW treatments will require resources dedicated for that purpose. Posttreatment monitoring of benthic algae as a biological indicator is not currently supported and would require additional resources. Long-term effects on water quality of regularly repeating fuels treatments in the future might be assessed by developing a model that could be improved with results from the KREW experiment. However, such modeling is not planned as part of the KREW experiment and would require additional resources.

Some other interesting research questions that might be answered at KREW/TEF, but that are of lower priority for the regulatory community, include the following:

- How do the effects of riparian restoration using mechanical thinning and prescribed fire in riparian areas vary within different vegetation types and stream sizes (Van de Water and North 2011)?
- Would updating the KREW sediment budget produced by Reid and Dunne (1996), using geochemical tracers that identify sources of sediment (Belmont 2013), improve assessments of the effects of contemporary management practices on sediment and nutrient loads?
- How do prescribed fire and wildland fire affect the quality of public drinking water sources, especially dissolved organic matter (DOM) and DOM precursors of halogenated disinfection byproducts (Kuhn et al. 2014, Wang et al. 2015)?
- How does atmospheric deposition of N from air pollution affect stream water quality, and how might deposition be affected by climate change?
- What threshold levels of N and P enrichment will produce undesirable biological responses in Sierra Nevada headwater streams?

Potential Utility to Water Quality Regulatory Agencies

The results from the studies conducted to date in the KREW/TEF research watersheds have been used several ways by California's regulatory agencies. For example, these agencies have used the KREW research findings documenting the effects of forest roads on water quality (Stafford 2011) for road design and maintenance training for agency personnel and registered professional foresters, and for developing improved forest practice regulations related to roads.

Stream biotic communities, including algae and macroinvertebrates, have been surveyed in KREW/TEF reference stream, where detailed ambient stream nutrient chemistry has also been systematically monitored. Such data might be useful to regulatory agencies as scientific evidence of undisturbed reference stream conditions for use in developing water quality criteria or standards for Sierra Nevada headwater streams.

KREW/TEF monitoring results can be used to help evaluate the potential effects from proposed land management activities, including timber harvesting, in the central and southern Sierra Nevada. Sediment and turbidity data from the KREW watersheds with fuel reduction treatments and reference streams might be compared to data being collected from intensively managed industrial timberlands in the Sierra Nevada to assess the effects of contemporary timber harvest operations on water quality. For a regional comparison, KREW fuel treatment effects on water quality might be compared to those reported by Bales et al. (2015) for central

and southern Sierra Nevada watersheds. These findings and others from KREW have been used by agencies, including the State Water Resources Control Board, California Department of Forestry and Fire Protection, California Board of Forestry and Fire Protection, California Department of Water Resources, Sierra Nevada Conservancy, and the Bay Delta Program.

The TEF watersheds have some of the longest flow records for small headwater Sierra Nevada streams. Streamflow data from Teakettle Creek watersheds (McGurk 2001, USGS 2017) have been used for flood flow frequency analyses used to validate flow estimation methods for proper design of watercourse crossings (Cafferata et al. 2017). Streamflow data from these watersheds also have potential to be valuable for predicting the effects of large rain-on-snow events in the Sierra Nevada.

Findings from KREW/TEF are potentially useful for predicting how forest management will affect water yield and other aspects of stream ecosystems. The Southern Sierra Integrated Regional Water Management Plan (2014) for the Sierra Nevada south of the San Joaquin River discussed the importance of KREW to the region and noted that it was the only long-term research study in the planning area. An approved plan is required for state funding of water projects including new infrastructure, as well as fuel reduction work and forest restoration. Results from KREW have also been used to inform project planning by local and regional groups such as the Sustainable Forests and Communities Collaborative and the Dinkey Collaborative Forest Landscape Restoration.

Key points:

- Although stream water N is currently low in southern Sierra Nevada headwater streams, increased N might cause undesirable eutrophication and stream acidification. Sources of stream N include atmospheric deposition and forest disturbance by forest management or wildland fire.
- Long-term monitoring has measured baseline levels of N and P and biological communities in streams draining KREW watersheds before and after they were treated with typical fuel-reduction practices and in a reference stream that will remain untreated.
- Ecosystem inputs of N and P in atmospheric deposition have been monitored at KREW, and ecosystem pools of these nutrients have been quantified in soils.
- During high flows, N concentrations in the streams increase rather than become diluted.
- Discharge variability is high both within and between years for headwater streams in this Mediterranean climate, and hydrologic processes can differ even for small, adjacent watersheds within similar landscapes.

- The highest priority science need of water quality regulatory agencies that might be filled at KREW would be a better understanding of long-term ecosystem effects of forest management treatments to reduce wildland fire hazards, especially regarding impacts on water quality, stream biological communities, and riparian zone functions.
- Regulatory agencies might use existing long-term, high-quality data on the physical, chemical, and biological components of the undisturbed reference watershed to develop ecosystem models to better understand processes and predict stream responses to changing environmental conditions, such as warming climate and increased deposition of air pollution.
- Effects of forest management on watershed processes, such as sediment yield from roads measured at KREW, have been used in the design and refinement of forest management regulations. Studies of effects of typical forest practices on streams are currently underway at KREW and are also expected to be useful for regulatory purposes.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

Nutrients other than N and P are not generally a source of area-wide concern in forested areas of the Sierra Nevada. However, in some local basins, drainage from active or abandoned mines or spoil disposal sites may degrade water quality by introducing high levels of sediment, acidity, sulfate (SO_4^{2-}), iron (Fe), manganese (Mn), and other toxic metals to surface water. KREW and TEF do not have a history of substantial mining, and so may serve as a baseline for stream conditions in the absence of mining disturbance.

Although carbon (C) is not a nutrient for the purposes of this report, C interacts strongly with nutrients, and storage and emissions of C in forests are a growing concern in California and globally because they affect climate warming. Sierra Nevada forests are regionally important for C storage and their effects on the carbon budget. Processes that play roles in forest C storage include wildland fire, prescribed fire, tree thinning, commercial timber harvest, and tree mortality caused by insect outbreaks. Storage of C is likely to be an important factor in future regulation of California forest management practices.

Findings From Studies

The KREW/TEF research has measured potassium (K^+), SO_4^{2-} , magnesium (Mg^{2+}), and calcium (Ca^{2+}) in stream water and soil. There are stream-to-stream variations

among these nutrients. Concentrations of several of these nutrients were often higher in the undisturbed reference watershed, T003, than for the companion KREW streams during the pretreatment period (table 7.2). For all watersheds, the average stream water concentrations of K^+ and SO_4^{2-} increased during high flows, similar to the flow response of stream N and P, whereas Ca^{2+} and Mg^{2+} did not. These responses to flow were consistent with findings of Godsey et al. (2009), who reported nearly chemostatic behavior for rock weathering products such as Ca, Mg, and increased concentrations with flow for more biologically active ions such as K^+ and NO_3^- in a study of 59 geochemically diverse and undisturbed U.S. watersheds. Thus solute concentrations in KREW streams are not explained by a conceptual model in which a fixed flux of solutes is diluted by a variable flux of water.

Consistent with patterns observed in stream water concentrations, Ca^{2+} pools in soils were significantly higher, and SO_4^{2-} -S pools were significantly lower on watershed T003 than in soils of adjacent watersheds B203 and B204 (Johnson et al. 2011a). Mechanisms that cause the differences among soil nutrient pools in these adjacent watersheds are not well understood.

Monitoring of wet deposition at the KREW NADP site (CA28) has included K^+ , SO_4^{2-} , Mg^{2+} , and Ca^{2+} . Rates of deposition of these elements are similar to other monitoring sites in the southern Sierra (Yosemite as well as Sequoia and Kings Canyon National Parks), but higher than values measured in the northern Sierra that are less affected by air pollution.

Other Factors Relevant to Stream Nutrients Other Than N and P

As was mentioned earlier in this chapter, numerous environmental factors that may influence biological responses to nutrients other than N and P have been measured at KREW/TEF, including streamflow, sediment transport, and temperature. In addition, soil carbon storage at KREW/TEF was found to vary among these watersheds. Soil carbon storage in T003 was significantly higher at 140 Mg C/ha, than in watersheds B203 and B204, which both had C storage of 120 Mg C/ha (Johnson et al. 2011a). A possible explanation for this difference in soil C storage may be that B203 and B204 were disturbed by previous onsite management activities, while T003 was not.

Dose-Response Studies

Dose-response studies of stream nutrients have not been conducted at KREW/TEF.

Reference Watersheds

Monitoring of the stream draining reference watershed T003 has measured stream water concentrations of Ca^{2+} , K^+ , Mg^{2+} , and SO_4^{2-} and their responses to streamflow. Other work quantified the soil pools of Ca^{+2} , SO_4^{2-} , and C in this undisturbed watershed (Johnson et al. 2011a).

Responses to Management and Natural Disturbances

Fuel reduction treatments, including prescribed fire and mechanical thinning, have been estimated to increase forest carbon storage in the long term by shifting growing space from many small trees to fewer large, old trees while reducing loss of stored C from high-intensity wildland fires (Gonzalez et al. 2015). However, effects of these practices on C storage have not been thoroughly tested. Based on a carbon balance for the first 10 years after thinning and burning of plot treatments at TEF, Wiechmann et al. (2015) estimated that understory thinning and prescribed burning can help stabilize forest carbon and restore ecosystem resilience. Stacy et al. (2015) measured pretreatment erosion-induced stream export of soil carbon in the eight KREW streams. Because these forests had low soil erosion rates, they concluded that erosion in these forest ecosystems is not likely to be a significant C sink. Measured C concentrations in sediment from WYs 2009 through 2011 ranged from 16 to 120 g/kg, with T003 having the highest concentrations. Although 30 to 50 percent of the annual sediment load consists of organic matter (Hunsaker and Neary 2012), it is not known over the long term how much of this organic matter is stabilized and thus contributes to the erosion-induced C sink in benthic sediments. Stacy et al. (2015) concluded that croplands and grasslands are larger contributors to the erosion-induced C sink than forests such as those at KREW/TEF. Effects of natural disturbances, such as severe wildland fire and insect-induced tree mortality, on C storage and nutrients other than N and P have not been studied at KREW/TEF.

Reliability and Limitations of Findings

Research results and monitoring datasets from KREW/TEF that are related to nutrients other than N and P, are probably applicable to other central and southern Sierra Nevada forest areas. They also could be relevant for other forest mountain areas with similar climate, steep topography, and granitic soils, for example, in the Rocky Mountains. If environmental factors such as soils or land use are dissimilar to KREW/TEF, or a high degree of accuracy is needed, we suggest considering validation monitoring or experiments to test how well results from KREW/TEF predict local conditions.

Research Needs

The highest priority research need of the regulatory community that is not directly related to N and P that could be filled at KREW/TEF is an improved scientific understanding of the effects of fuels management treatments and forest restoration on carbon cycling and export, especially for soil carbon for forests in the southern Sierra Nevada. Filling this science gap would be important for regulatory agencies because research results from KREW/TEF might be used

to produce more accurate estimates of the effects of fuels reduction treatments on carbon budgets for Sierra Nevada forests. Such information could be used to develop regulatory strategies to sequester carbon and reduce greenhouse gas emissions in California (Battles et al. 2014). Future work at KREW/TEF that might help fill this need includes (1) investigations of changes in C storage in soils and standing and downed biomass as a result of fuels reduction treatments; (2) studies of effects of treatments, compared to reference watersheds, on export by erosion and stream transport of dissolved and particulate C that follows up on work by Stacy et al. (2015); and (3) measurements of emissions from streams and soils of greenhouse gasses such as carbon dioxide, methane, and nitrogen oxide. Although the recent KREW fuels treatments might offer opportunities to fill these needs, such studies are not currently planned. Implementing them would require additional resources.

Potential Utility to Water Quality Regulatory Agencies

A number of existing research results and monitoring datasets from KREW/TEF related to nutrients other than N and P may be of immediate practical use to water quality regulatory agencies. Stream water chemistry and biological indicator monitoring data from reference watershed T003 might serve as a baseline undisturbed headwater stream for assessing impacts of mine drainage in basins disturbed by mining in the southern Sierra Nevada. Trends in atmospheric deposition and stream water concentrations and fluxes of nutrients, such as SO_4^{2-} that have been measured at KREW/TEF, might be used by regulatory agencies as early indicators of how regional levels of air pollution may affect water quality in the southern Sierra Nevada. Results from previous studies of C storage in soils at KREW/TEF might be useful to regulatory agencies for developing or improving models of C storage and fluxes in Sierra forests and how they might be affected by fuel treatments. Quantitative measurements of C storage in the undisturbed T003 basin (Johnson et al. 2011a) and stream flux (Stacy et al. 2015), along with published studies on effects of forest fuels treatments on C storage (Wiechmann et al. 2015), might be useful for developing such models.

Key points:

- Nutrients other than N and P are not currently associated with water quality issues in most of this region, but sequestration and emission of C from forests are a significant concern because of their effects on climate warming.
- Several nutrients other than N and P have been monitored at KREW in stream water and atmospheric deposition, and pools of them have been measured quantitatively in watershed soils.

- Understory thinning and prescribed burning may increase C sequestration in Sierra Nevada forests under some silvicultural approaches, but additional data collected over longer time periods are needed to increase confidence in this outcome.
- The highest priority regulatory research need that might be filled at KREW/TEF that is unrelated to N and P would be a better scientific understanding of the short- and long-term effects of forest fuels treatments on forest C storage and exports. Although KREW management treatments offer opportunities to fill this need, such studies are not planned and would require additional resources.

Overview and Synthesis

The research at KREW/TEF has great potential as a source of useful science for water quality regulatory agencies. Because the Sierra Nevada provides about 60 percent of California's water for agriculture and urban uses (California DWR 2008), findings are useful for both human and ecosystem needs. This project is studying important questions about how land management treatments that are being used in this region are affecting water quality and quantity. Specifically being looked at is whether these treatments reduce the risk of severe wildland fires and restore ecological integrity and resilience. Because the confounding influences of land use have been controlled at this site, it also presents opportunities to monitor and study the effects of warming climate and regional air pollution on water quality in these mountain streams and forests. The value of this study is enhanced because much of it has been initiated since 2003, using scientific and technical approaches that are up-to-date and of high quality. KREW, for example, is the only watershed study in the southern Sierra Nevada that has taken an integrated ecosystem approach that investigates a broad suite of biological, physical, and chemical environmental processes. This whole-system perspective makes it possible to study underlying mechanisms and cause-and-effect relationships that provide scientific bases for modeling stream responses to land management. In addition, environmental measurements at KREW/TEF have used state-of-the-art instrumentation and analytical methods, which produce environmental data with high-frequency and resolution. Examples include quantitative measurements of soil carbon pools, spatially distributed throughfall and soil solution nutrient concentrations, and high-frequency monitoring of stream water nutrients during runoff events. The watershed-scale management experiments underway at KREW/TEF provide opportunities to help answer important, practical questions, such as how fuels management treatments in the Sierras may affect water quality, and C emissions and, at the same time, more basic ecological questions, such as how Sierra Nevada stream ecosystems respond to changing environmental conditions such as drought and wildland fire.

Key points:

- The KREW/TEF watersheds are the only study area that takes an integrated ecosystem approach in the southern Sierra Nevada, which is an important source of water supply for the state of California.
- Studies address important practical questions about how water quality is affected by land management practices used in the region to reduce the severity of wildland fires and to restore forest structure and composition toward conditions that are resilient to natural disturbances and to potential anthropogenic stresses, such as climate change and air pollution.
- Scientific and technical approaches at KREW/TEF are up-to-date and have strong potential to produce useful results for water quality regulatory agencies.

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