Discharge and Sediment Loads at the Kings River Experimental Forest in the Southern Sierra Nevada of California

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The Kings River Experimental Watershed (KREW) is now in its third year of data collection on eight small perennial watersheds. We are collecting meteorology, stream discharge, sediment load, water chemistry, shallow soil water chemistry, vegetation, macro-invertebrate, stream microclimate, and air quality data. This paper primarily examines discharge and sediment data from six watersheds between 1600 m and 2400 m in elevation in the Sierra Nevada, California. The discharge discussion focuses on water year (Wy) 2004, which was relatively dry. The sediment discussion examines bulk mass data from Wy2001 through Wy2004, and presents some detailed analysis of the sediment load beginning with the Wy2003 dataset. Sediment loads in kilograms per hectare were low with the exception of Wy2003. Meteorology data from two stations at the top of the watersheds and two stations at the bottom is presented. Between 2007 and 2009, six of these eight watersheds are planned be harvested, undergo prescribed burns, or both, to quantitatively measure the effects of these USDA Forest Service land management practices.

Keywords: *watershed management, hydrologic processes, sediment yield, fire, thinning, stream ecology, streamflow*

Introduction

Sixty percent of California's water originates from small streams in the Sierra Nevada, yet there is very little information about how these streams are affected by land management activities near the source. Sierra Nevada stream water is considered some of the highest quality water in the state. The quality of aquatic and riparian (near-stream) ecosystems associated with streams is directly related to the condition of adjacent uplands within their watersheds. Past management actions such as timber harvesting, road construction, and fire suppression have altered the vegetation structure of watersheds and have affected headwater streams. Forest Service management believes that prior to European settlement, circa 1850, the western slope of the Sierra Nevada was more open and had predominantly uneven-aged stands. This historic stand structure was extremely resistant to stand-replacing wildfires. Restoration of the Sierra Nevada's forest watersheds to historic or desired conditions requires active management, such as reintroduction of frequent, cool fires and removal of accumulated fuel loads.

The Kings River Experimental Watershed (KREW) is a long-term watershed research study being implemented on the Sierra National Forest to provide much needed information for forest management plans regarding water quantity and quality (Figure 1). This experimental watershed research is designed to: (1) quantify the variability in characteristics of headwater stream ecosystems and their associated watersheds; and (2) evaluate the effect of fire and fuel-reduction treatments on riparian and stream physical, chemical, and biological conditions. This is an integrated ecosystem project at the watershed scale and is part of a larger adaptive management study that began in 1994 as a collaborative effort between the Sierra National Forest, Southern California Edison, and the Pacific Southwest Research Station of the Forest Service. This larger study was designed to evaluate the effects of management actions aimed at recreating an uneven-aged forest that is resistant to wildfires. The KREW staff will evaluate the effects of mechanical thinning, prescribed

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Figure 1. Kings River Experimental Watershed is located on the Kings River, which drains into the San Joaquin River basin. It is part of the Kings River Project, Sierra National Forest, which is a 60,000 ha collaborative study between research and management.

fire, and thinning with fire combination treatment on the watersheds.

Stream monitoring is a well-developed science; however, the majority of work addresses large streams and rivers. Watershed research has been conducted in the United States since the early 1900s, but none of the long-term studies are in ecosystems similar to the Sierra Nevada, and most studies were designed to evaluate severe management actions such as clearcuts and stand-replacing fires. Critical information is lacking because few integrated ecosystem studies exist (Naiman and Bilby 1998). Such studies are essential for understanding stream-watershed ecosystem processes and functions for adaptive management.

The Kings River Experimental Watershed consists of eight watersheds that vary in size from 49 to 228 ha. The Providence Site is composed of four adjacent watersheds (1,500 to 2,000 m in elevation) in mixed-conifer forest – D102, P301, P303, and P304. The four Bull Site watersheds, ranging in elevation from 2,100 to 2,500 m (B201, B203, B204, T003) are in mixed-conifer forest with a large red fir (*Abies magnifica*) component approximately 15 km southeast of the Providence Site. These elevation bands were selected because this is where most Forest Service management activity in the Sierra Nevada has traditionally taken place. The KREW staff is collecting the standard watershed measurements of discharge, sediment load, and a suite of meteorology measurements; the first years of this baseline data are presented in this paper.

Other watershed and stream characteristics are being studied because KREW is an integrated watershed study. Stream water, soil water, and snowmelt are analyzed for various anions and cations every two weeks, and more often during peak spring runoff and storms. Air quality is monitored for ozone, ammonia, and nitric acid. Riparian and upland vegetation and stream macroinvertebrates are surveyed annually. Fuel loading and channel morphology will be measured prior to treatment implementation and periodically once the treatments are completed.

METHODS

Discharge Methods

Stream discharge is measured with Parshall-Montana flumes (Figure 2). The KREW streams have approximately a 500-fold difference between lowest and highest flow over a 20-year time span, but Parshall-Montana flumes can capture accurately only a 50-fold difference; therefore two flumes, one large and one small, are on each stream. The two-flume design permits precise flow measurements (from standard tables) from 0.75 L/s (0.03 cfs) to 900 L/s (32 cfs). Less precise, but still acceptable, measurements over the range from 0.3 L/s (0.01 cfs) to 1,400 L/s (49 cfs) will be used. All of theWy2004 data from the four Providence streams and most of the data from the two Bull streams are from the small flumes, with 7.6 and 15.2 cm throats respectively. All discharge, meteorology, and sediment data are reported based on the water year which begins on 1 October of the previous year and ends on September 30 of the stated year (Wy2004 runs from 1 October 2003 to 30 September 2004).

Isco®[1] 730 bubblers were chosen to measure stage on the small flumes because freezing does not destroy the instrument. The bubbler relays data to an Isco 6712 sampler, which also takes water samples for chemical analyses. The Isco sampler and bubbler receive electricity from a 12V DC system powered by a 50W solar panel. The stage data is relayed via radio telemetry back to the Fresno office. The backup device on the Providence small flumes is a Telog® WLS-31 pressure transducer. The KREW staff measure stage in the large flumes (61 to 122 cm throat width) using Aquarods that sit in stilling wells. Both the Telogs and the Aquarods are downloaded to a laptop on a monthly basis. Visual stage readings are recorded every

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Figure 2. The two-flume design on the B201 stream allows KREW staff to precisely measure a wide range of flows. The 3-inch Parshall Montana flume (foreground) measures most flows, and the 2-foot Parshall Montana flume (background) measures large rain events.

two weeks except during spring runoff when the sites are visited weekly. All data is stored and managed in the Isco Flowlink® program.

All of KREW's eight watersheds are located within the rain to snow transition zone where many precipitation events drop a combination of rain and snow. In order to better understand the factors that control stream discharge, this paper uses meteorology and discharge data to examine aspects of the water cycle. For this analysis the discharge from the Wy2004 hydrograph was divided into the following four categories: baseflow, rain event flow, snowmelt flow, and soil water. Baseflow was determined by looking at the discharge for the lowest flow period of Wy2004, 1 September to 15 September. Baseflow for the year is derived by multiplying this daily average by 366 (2004 was a leap year. The authors expect this water has been in the ground for at least six months and originates in perennial springs.

Rain event flow (quickflow) is all runoff above baseflow that occurred from the start of each rain event until the flow drops back to where it started, or 24 hours after the rain stops, whichever comes first. Rain events that did not increase the hydrograph by at least 20 percent were ignored. Using the above criteria, six rain events occurred in most of the KREW watersheds. In the Wy2004 hydrograph, these six events and their associated tails had a combined duration of approximately 300 hours. Snowmelt flow is runoff above baseflow that occurs between the start of spring runoff (7 March 2004) and two weeks past the date on which the snow depth sensor at the closest meteorology station indicates zero. The D102 watershed had two distinct snowmelt periods and was handled slightly differently. The authors believe that the snowmelt flow water resides briefly in the shallow soil as it moves to the stream. Soil water was determined by taking total discharge for Wy2004 in each watershed and subtracting baseflow, snowmelt flow, and rain event flow as defined above. We expect that this water is stored in the soil between two weeks and six months.

Meteorology Methods

KREW has four meteorology stations; a station is located at the bottom and the top of each group of four watersheds (Figure 3). Seven parameters are measured at 15-minute intervals: temperature, relative humidity, solar radiation, wind speed, wind direction, snow depth, and precipitation. In Wy2004 there was one functioning snow pillow that measured snow water equivalence. Meteorological data are logged and processed by Campbell Scientific, CR10X data loggers and relayed back to Fresno via radio telemetry. The KREW staff visit each meteorological station once each month and record manual measurements to ground truth the sensors.

Figure 3. Sensors on a 6-meter tower at the upper Providence meteorology station measure temperature, relative humidity, solar radiation, wind speed, wind direction and snow depth (left). The 3-meter high Belford® gauge measures total precipitation (right).

Rainfall amounts reported here are typically an average value of the four precipitation gauges. For the six large events the totals generally vary by 10-15 percent between meteorology stations. The small events (< 25 mm) were more difficult to present in a comprehensive manner, as different sites recorded, and most likely received, very different amounts of precipitation. For small events, the data from the Upper Providence station, which is at a middle elevation for KREW, is presented instead of an average of all stations. Brief showers (< 5 mm) were excluded from the precipitation dataset because they generally did not occur at all four meteorology sites and several load-cell sensors do not exhibit sufficient precision to measure minute changes.

Sediment Methods

Sediment catchment basins exist on all eight streams, but only five of these had been constructed and were being analyzed in Wy2003 and Wy2004 (Figure 4). The basins vary in size from 25 m^2 to 200 m^2 and are slightly more than one meter deep at their deepest point. They are all lined with pond liner to make sure each year's sediment is clearly defined. These ponds are dug out by hand each September. After a total wet weight is measured, a representative sample is dried and used to determine the dry mass for each basin.

Starting in Wy2003 the organic and mineral fractions were determined. The organic fraction is made up of three components: large organic matter such as sticks that are removed by hand, coarse organic matter such as twigs that are floated off of an oven-dried sample, and fine organic matter that is burned off for 24 hours at 500°C. The dry weights of the three components are added together to arrive at a total organic fraction.

Figure 4. The B204 sediment catchment basin, lined with commercial pond liner, traps sediment behind a 1.2-meter-high log structure. Sediment is removed each fall, weighed wet and subsampled. A dried subsample is analyzed to determine organic and mineral fractions and particle size distribution.

A representative sample of the mineral fraction is dried at 110°C until the sample loses less than one percent weight between hourly weighings (usually after 12 hours). A standard sieve analysis is then performed to determine a particle size breakdown using 2, 1, 0.5, 0.25, 0.125, and 0.065 mm sieves.

RESULTS AND DISCUSSION

Discharge and Meteorology Results

The 2004 water year had two large storms (>125 mm of precipitation); storms of this magnitude may produce bankfull flows and move sediment. The 25 December 2004 storm came primarily as rain at all elevations and moved minor amounts of sediment, while the 26 February 2005 storm delivered snow (Figure 5). The timing, magnitude, and duration of these events was statistically normal. Four other storms each provided about 50 mm of precipitation. Whether these smaller precipitation events deliver rain or snow, the soil can usually absorb the majority of the moisture, and surface runoff is limited to rock outcrops and human-compacted areas such as roads. While there was a normal distribution of these events from November through February, a typical year would have seen about three more equivalent events in March and April.

The 80 mm of rain in November recharged the shallow soil moisture but did not produce discharge peaks associated with surface flow. The smaller December events also had little effect on the hydrograph. The hydrograph response to fall storms varies very little by watershed elevation or size, so the water from the distal portions of the watershed (> 50 m from the stream) is not rapidly arriving at the stream.

The large 25 December 2004 event produced between 5,000 and 7,000 cubic meters of water in each of the four analyzed watersheds (Figure 5); this converts to about 5 mm of depth spread over each watershed. Only 5 mm of the total 130 mm that fell as precipitation was measured as discharge in the streams. The next three precipitation events were snow. The last major precipitation event on 25 February 2005 fell as snow in all except the lowest elevation areas (D102 watershed).

Water that drained out of the watersheds as a direct result of rainstorms was on average only about 7 percent of the total yearly discharge (Figure 6). This value is strongly correlated with watershed elevation, with the lower elevation watersheds having the highest percentage of their discharge derived from rainstorms. Water that originated in melting snowpack accounts for an average

Figure 5. For water year 2004, the hydrographs of four watersheds are very similar in the fall and early winter, but differ in the spring. The precipitation record (lowest graph) shows only two large storms (>125 mm) and four mid-sized events (>50 mm).

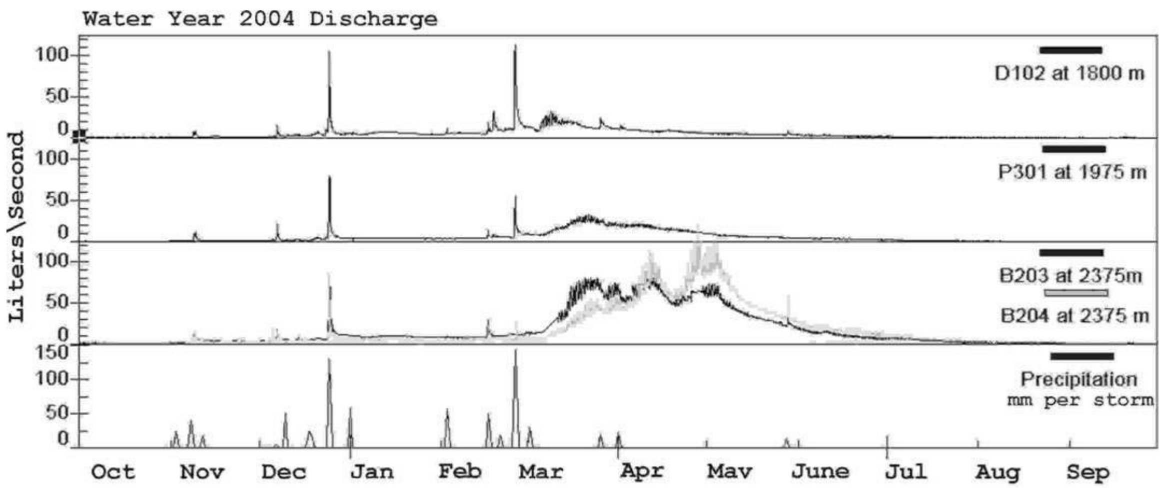
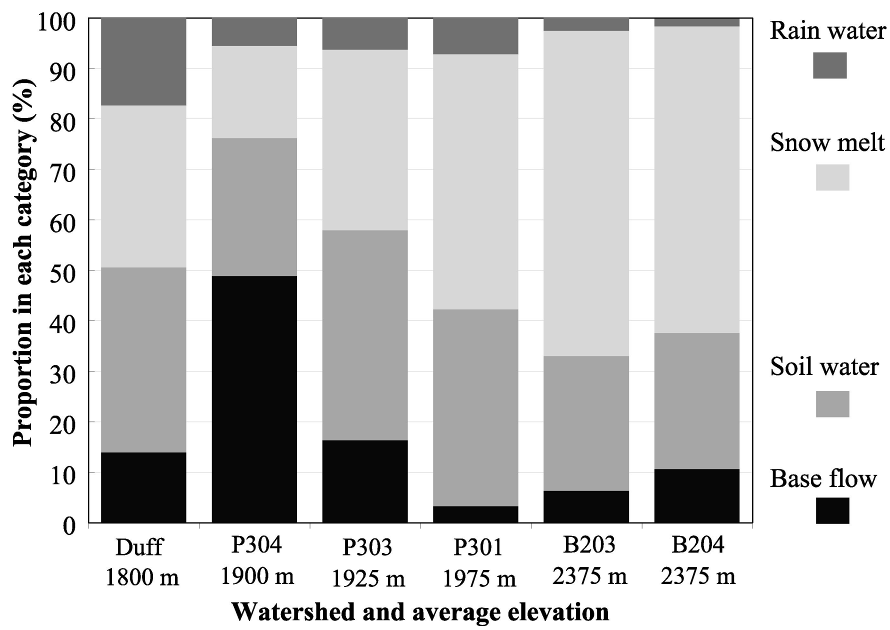


Figure 6. The annual discharge from six watersheds is divided into source components. The percentage of water from snow melt correlates with increasing elevation. Rainwater is a relatively small percentage at all elevations.



of 37 percent of the total discharge from the four lower watersheds, and was also strongly correlated with elevation, but in a reverse direction from rainfall water. Because the two highest watersheds (B203 and B204) produce twice the annual discharge of the lower watersheds, and because 68 percent of their discharge is generated by melting snowpack, 57 percent of the total water from the six analyzed watersheds came from snowmelt.

The average baseflow contribution to the annual discharge is 17 percent, but this value was skewed by P304, where baseflow accounts for 56 percent of discharge. If P304 is excluded, baseflow contributes an average of 11 percent of the annual discharge in the other five watersheds. Small perennial watersheds may have a larger baseflow component, because without good groundwater sources they would not be perennial during the late summer in the Mediterranean climate that characterizes the southern Sierra Nevada. The lower elevation watersheds rely almost entirely on baseflow from 1 July through 1 October. While these baseflows are important to stream biology, macroinvertebrates, and riparian plants in the lower elevation watersheds (P303 and D102), the last three months of the water year produced less water than the three days around the 25 December storm.

Water derived from the soil is difficult to estimate. The soil percentages (Figure 6) do not show a clear pattern, but the amount of water contributed per hectare from soil is similar for all watersheds. During Wy2004, soil water estimates for Providence watersheds varied from 462 m^3/ha in D102 to 711 m^3/ha in P304. For B203 and B204, shallow soil water contributed 1,085 m^3/ha and 984 m^3/ha respectively. The soil profile stored and then released approximately 6 cm of moisture at 1,900 m of elevation and approximately 10 cm of moisture at 2,375 m. While we have not yet developed a full water budget, it can be concluded that very little of the moisture that entered the soil's lower profiles was released back to the streams.

In watershed P303, monthly total discharge never exceeded precipitation (Figure 7). Of the total precipitation during Wy2004, only 13 percent contributed to streamflow. At higher elevations at B203, 40 percent of the total precipitation flowed down the stream (Figure 7). From a regional viewpoint, the watersheds at 1,900 m can not be expected to contribute significantly to storage in California reservoirs during dry years. At 2,375 m, slightly more precipitation falls, but a much larger percentage of that water will flow into the reservoirs.

We acknowledge that this data is a snapshot of one dry year which had only 70 percent of the average annual precipitation. It was not an extremely anomalous meteorological year, as there are 14 drier years during the 90-year period of record at Huntington Lake precipitation gauge, approximately 25 km north of KREW and at a similar elevation. Three-week-long dry periods, such as the one that occurred in January, are not unusual in the southern Sierra Nevada.

Sediment Results

Sediment loss rates per hectare vary by three orders of magnitude among the five watersheds over the four-year dataset (Figure 8). Within a single watershed the rates vary by a factor of 100 during the four years. Between neighboring watersheds, but in the same water year, rates also vary by a factor of 100.

Figure 7. Watersheds vary in the amount of precipitation that becomes discharge. In watershed P303 at 1,925 m elevation, only 13 percent of the incoming precipitation results in discharge (top graph), whereas in watershed B203 at 2,375 m 40 percent of precipitation contributes to discharge. (bottom graph). Precipitation greatly exceeds discharge until March when spring snow melt begins.

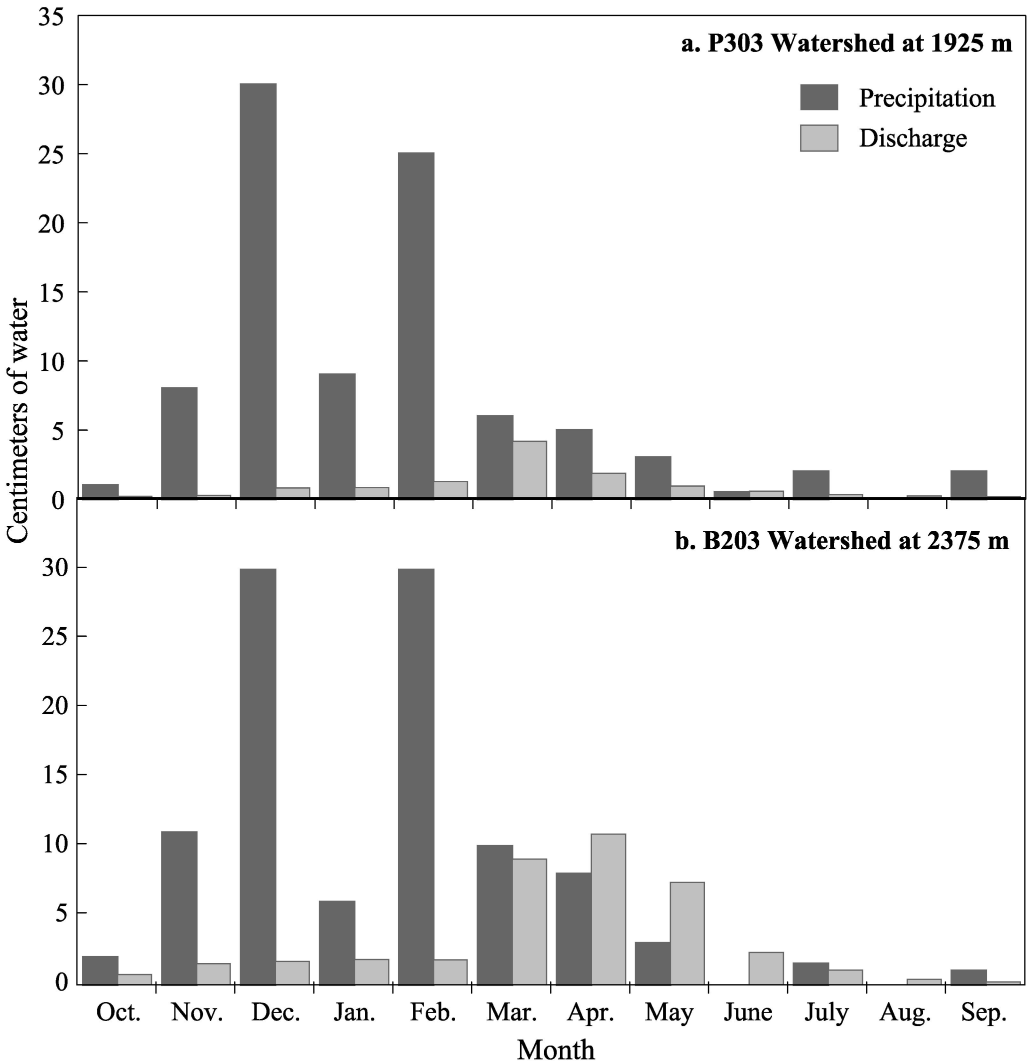
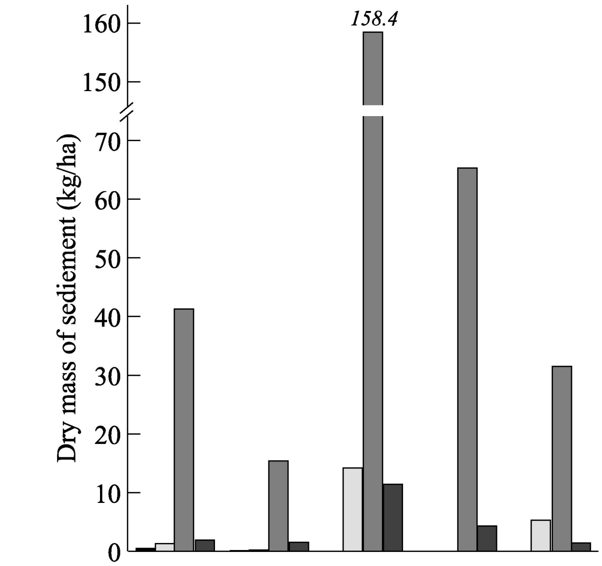


Figure 8. The dry mass of sediment captured in each basin varies by orders of magnitude between years and between adjacent watersheds.



Watershed *Water year*	P301	P303	P304	D102	B201
2001	0.5	0.1	-	-	-
2002	1.3	0.2	14.2	-	5.3
2003	41.3	15.4	158.4	65.3	31.5
2004	1.9	1.5	11.4	4.3	1.4

These data indicate only 0.002 mm loss of soil depth each year (average of all basin data and an average soil density of 1.2 g/cm^3). Based on this four-year period, one might conclude that it would take 500 years to loose a millimeter of soil depth. This conclusion is misleading because erosion can be almost non-existent and then greatly increase during infrequent but intense rainfall events.

On average the basins captured 17 times more sediment in Wy2003 than in Wy2004. The total rainfall was similar (a 300 mm difference); however, the magnitude and intensity of the single largest event was very different. In Wy2003, 290 mm of rain fell in 30 hours during the 7 November storm. For a steady rainfall, that amount averages to 9.7 mm per hour, but 27 mm actually fell during the most intense hour of this storm. In Wy2004, 142 mm fell in 60 hours during the 24-25 December storm. This amount represents an average of 2.3 mm per hour, but only 11 mm fell during the most intense storm hour (Table 1). With hard rain falling (> 5 mm per hour), we observed no overland flow in undisturbed areas of the watersheds under the forest canopy. The overland flow and sediment movement seen in Wy2004 probably came predominantly from roads, unstable stream banks, or erosion just below large rock outcrops. The percentage of precipitation that falls as rain versus snow also affects soil loss.

The datasets from the P301, P303, D102, and B201 sediment basins show similar patterns in their organic fraction and mineral fraction particle size (Table 1). The organic component was between 20 and 30 percent in both years, with the total average mass of organics contributed per hectare small: 5 - 10 kg/ha in Wy2003 and 0.5 kg/ha in Wy2004. Since the magnitude of the largest rain event in Wy2004 was small, we suggest that the organic matter was primarily leaves and sticks falling off the trees directly above the stream rather than material being transported by overland flow.

In the future KREW staff will present data from all eight watersheds and track changes in the size distribution of the mineral fraction. Seventy sediment fences were constructed in 2003 and 2004 to quantify erosion from graveled roads, natural surface roads, and undisturbed hillslopes. Fourteen headcuts were surveyed in 2003 and will be resurveyed in the future. The combination of these efforts will give us a better understanding of where sediment originates and how it moves through the watershed.

CONCLUSIONS

The KREW project has the instruments in place to continue with baseline data collection at eight streams and watersheds, four meteorological sites, and 70 sediment fence locations. At the Bull Site, spring snow melt supplies the majority of the discharge. At the Providence Site, baseflow is a significant contributor to the P304 hydrograph and rain water is important to the D102 hydrograph. Such knowledge allows us to adjust our sampling for other attributes such as stream chemistry and efficiently plan field visits based on response characteristics. Spring snow melt began several weeks earlier than usual in Wy2004 at all elevations; this is a trend that has been observed during the last 50 years in the southern Sierras and has been predicted to continue with climate change (Brown and Binkley 1994). The five sediment catchment basins constructed prior to Wy2004 showed that rates of soil loss vary greatly between watersheds but are all correlated to the peak discharge. We will have sediment data for the additional three streams starting with Wy2005.

Burning and thinning treatments are scheduled to occur between 2007 and 2009 with the Providence Site starting in 2007 and the Bull Site starting in 2008. By that time, KREW will have baseline datasets of sufficient duration and precision to discern whether there are measurable changes that result from these low-severity treatments. This watershed experiment is designed to improve our knowledge of how headwater ecosystems function, and to

Table 1. The mass of mineral and organic fractions in annual stream sediment loads and the median particle size are reported with respect to peak discharge and storm intensity. During pretreatment years, organic matter is consistently between 20 and 30 percent of the total dry weight in the KREW sediment basins.

Water Year 2003	**P301**	**P303**	**P304**	**D102**	**B201**
Mineral mass / area (kg/ha)	28.0	12.0	113.8	49.3	26.5
Organic mass / area (kg/ha)	13.3	3.4	24.6	16.0	5.0
Median particle size (mm)	0.500	0.500	0.125	0.250	0.250
Peak discharge (L/s)	110	–	120	170	100
Water Year 2004	**P301**	**P303**	**P304**	**D102**	**B201**
Mineral mass / area (kg/ha)	1.7	1.4	6.7	3.8	1.2
Organic mass / area (kg/ha)	0.6	0.4	7.5	1.6	0.5
Median particle size (mm)	0.500	0.500	0.125	0.250	0.125
Peak discharge (L/s)	80	85	44	113	22

Averages for all Measured Watersheds	**Bulk Mass *(kg/ha)***	**Peak Discharge *(L/s)***	**Largest Storm Event *(mm/hr)***	**Most Intense Hour *(mm)***
WY 2002	0.3	33.0	–	–
WY 2003	58.4	125.0	9.7 for 30 hours	27.0
WY 2004	5.1	68.8	2.3 for 60 hours	11.0

support extensive modeling exercises for the watersheds both before and after treatments. Modeling will include soil erosion, stream discharge, nutrient fluxes, and air pollution and climate change effects. Eventually comparisons between treatments and responses can be made for KREW and other long-term, forest watershed experiments in the western United States. Such comparisons are important to identify differences and similarities among stream and watershed responses for different ecoregions, to increase our understanding of ecosystem processes and thus facilitate the customization of standards and guidelines for adaptive management.

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