Changes to Whitewater Recreation in California's Sierra Nevada from Regional Climate Warming

By

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ABSTRACT

Whitewater recreation is an aesthetic ecosystem service potentially affected by climate warming alterations to runoff. In California's Sierra Nevada, climate change is likely to reduce water availability with warmer air temperatures and potentially decreasing precipitation. The corresponding changes in the timing and magnitude of streamflow will affect whitewater boating opportunities. In this study 128 whitewater runs were identified on the west-slope of the Sierra Nevada within a 13 basin study area that ranged from serene float trips to remote, difficult, kayak expeditions. A spatially explicit one-dimensional rainfall-runoff model was used to estimate the unregulated hydrology at specific locations within flow thresholds amenable to whitewater recreation. Climate warming scenarios were simulated by increasing air temperature by 2°, 4°, and 6° C and assuming no change in other climate variables such as precipitation.

Mild warming increases the average number of boatable weeks per year, but more extreme warming decreases the average boatable weeks per year across the Sierra Nevada. Runs in low elevation drainages, such as the Cosumnes and the Tule River Basins, are most vulnerable to changes in boatable weeks. Yet high elevation watersheds, such as the Kern River, also have a large reduction in boatable weeks. Watersheds in the central Sierra Nevada show an increase in boatable weeks due to its many gorge type runs at middle elevations. Overall, elevation, run-type, and volume of snowmelt was the best predictor of resiliency for Sierra Nevada whitewater runs.

Recreation is important for river management, yet it is difficult to quantify and to plan for. This research provides a sensitivity analysis of climate warming for the Sierra Nevada and presents a method that can be applied to other regions and whitewater rivers. Climate warming is forcing managers to make decisions with uncertainty in water availability, making allocation decisions difficult among often conflicting uses (e.g., ecology, hydropower generation and recreation). Reduction in whitewater recreation opportunities in unregulated rivers due to climate warming and continued increases in population will likely increase the importance of whitewater boating on regulated rivers, and thus the reliance on reservoir operations for meeting multiple demands.

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INTRODUCTION

Global climate warming can alter hydrological cycles on local, regional, and global scales (IPCC 2008). Studies of California and the western United States agree that regional climate warming is expected to decrease mean annual flow, reduce snowpack, and lead to earlier spring snowmelt runoff (Dettinger et al. 2004; Tanaka et al. 2006; Vicuna et al. 2007; Young et al. 2009). The change in the hydrologic regime will change beneficial uses such as recreation, hydropower, agricultural and urban supply, in addition to potential harm to aquatic and terrestrial ecosystems. Although widely acknowledged as an important emerging issue, studies have only recently begun to address how hydrologic regimes at the watershed scale might respond with a warmer climate, and how those responses vary among neighboring watersheds. Null et al. (2010) examined how impacts to existing water resource demands such as water storage capacity, hydropower generation, and other ecosystem services may differ across individual watersheds of the western Sierra Nevada under regional climate warming scenarios. This study concluded that watershed latitude, drainage area, and elevation were correlated with anticipated hydrologic changes at the basin scale (Null et al. 2010). However, understanding potential impacts to specific uses requires hydrologic models to be resolved at finer spatial scales.

Whitewater recreation is potentially affected by hydrologic changes caused by regional climate warming. Here, whitewater recreation includes canoeing, kayaking, and rafting in rivers with moving water. Whitewater recreation is a global sport and an important commercial enterprise for many rural communities in western North America. Many popular whitewater rivers are regulated by dams, commonly with negotiated "boatable" instream flow releases during the summer when recreation demand is highest. However, increasingly demand for whitewater recreation flows conflict with many other ecosystem services supplied by rivers, including water delivery, ecosystem support, fishing and other recreation, flood control and hydropower (McGurk and Paulson 2000). Hydrologic changes from a warmer climate are likely to increase these conflicts.

Whitewater boating contributes to society via non-market values, such as environmental aesthetics, social, and recreational as well as quantifiable market values (Bricker and Kerstetter 2002). Recreational flows enjoyed by whitewater boaters are now more often discussed under the broader context of ecosystem services (e.g., Costanza et al. 1997; Loomis et al. 2000). The economic value of boating flows are generally not directly quantifiable by studying market transactions, although many quantifiable transactions for goods and services depend on boating flows, such as commercial rafting enterprises, recreation equipment manufacturing and sales, and supporting goods and services (e.g., fuel, food, and lodging) (DBW 2009). Potential changes in boating flows due to climate change could affect local river boating-derived economies. Such changes to recreational opportunities will likely affect policy makers, resource manager and other stakeholder decisions in supporting whitewater boating activities. Although economic benefits of recreation flows vary from river to river, those benefits are likely to change under different management regimes and, perhaps more importantly, with different hydrologic regimes and climates.

The Sierra Nevada region has a Mediterranean-montane climate with a dry season from June to October and a wet season from November to June. The snowline is about 1,000 m during the wet season below which precipitation falls as rain. Precipitation averages about 100 cm/yr for the region, but it varies greatly with latitude, elevation, and local weather patterns. Precipitation is greatest in the northern watersheds of the Feather, Yuba and American. In the highest elevation watersheds in the southern Sierra Nevada such as the Kern and the Kings basins, heavy snowpack persists into late summer.

Whitewater recreation in California is concentrated on the rivers of the west-slope of the Sierra Nevada, where the flow regime is largely predictable and rivers are accessible and navigable. The primary boating season in the western Sierra Nevada is during the vernal snowmelt (April – June), but rain can provide boatable flows during winter, and reservoir releases on regulated rivers can purposefully provide boatable flows in the summer and fall. In this paper, "regulated" rivers are controlled by upstream dams, whereas "unregulated" rivers have a natural flow regime not regulated by upstream impoundments. "Runs" are stretches of rivers boatable, by raft, kayak, or canoe. Most whitewater recreation in the Sierra Nevada is on regulated rivers such as the American, Tuolumne, and Kern Rivers. These rivers are popular recreationally and are served by several commercial outfitters that provide rafts and trained guides. Commercial success often relies on dependable, summer-long regulated flows from upstream dam operations. Most rivers in the Sierra Nevada are regulated for hydropower and water storage, though some dams are operated partly for recreational flows. Flows released for hydropower or recreation often differ from natural flow regimes with respect to the timing, magnitude, duration, and rate of change. These flow alterations often harm downstream riverine and riparian ecosystems (Richter and Thomas 2007). Whitewater runs on unregulated flows account for more runs in the Sierra Nevada, but these runs have fewer users because they are typically more difficult to access and have distinct challenges from their variable and unpredictable timing and magnitude of flows.

This paper examines how anticipated changes in runoff volume and timing from climate warming could affect whitewater recreation in west-slope rivers of California's Sierra Nevada mountains. Potential impacts were evaluated by simulating change in the unregulated hydrology of all boatable rivers and streams in the Sierra Nevada and assess how this would affect the number of weeks of whitewater recreation. While the general consensus of climate studies shows a reduction in water resources in the Sierra Nevada, which for many whitewater recreational sites would shorten the boating season, for some sites the result is a longer boating season due to the timing of runoff and slower melting rates. This study evaluates the hydrologic response (i.e., sensitivity) to climate warming of a broad suite of whitewater runs across a large mountain range, and assesses if specific types of whitewater runs might be disproportionately affected. The results of this study can in turn be used to help develop future river management schemes and serve as a baseline investigation of potential changes to other Mediterranean-montane river systems with climate warming, such as Chile, South Africa, and parts of Europe.

METHODS

An established rainfall-runoff model of unregulated hydrology was used to assess potential changes to whitewater recreation opportunities in the Sierra Nevada with climate warming. This sensitivity analysis required the identification and mapping of all whitewater runs in the Sierra Nevada, and then categorizing each run by recreational difficulty and geomorphic type, establish upper and lower flow thresholds for boatable access, and attribute as regulated or unregulated. While many identified whitewater runs have regulated flows – not presently modeled – the objective was to better understand hydrologic response to climate warming and potential impacts to whitewater recreation. Thus regulated flows may be able to mitigate any warming induced reduction in whitewater recreation through changes to water management operations.

IDENTIFICATION OF WHITEWATER RUNS

The study area consisted of 13 major river basins on the western slope of California's Sierra Nevada, with a total area of 47,657 km^2. The area modeled stretches 650 km north to south, from the Feather River in the north to the Kern River in the south, and 250 km east to west (Figure 1), rising eastward from the Central Valley to a peak elevation of 4421 m. The run types used in the analysis ranged from serene trips along low gradient rivers to remote, difficult, kayak expeditions. The selection of runs included all runs published in reliable bibliographic sources (Holbeck and Stanley 1998; McQoid 2010; Whitewater 2010) and unpublished runs known from personal experience. Though other runs may exist in the region, the inventory was exhaustive given the best available information.

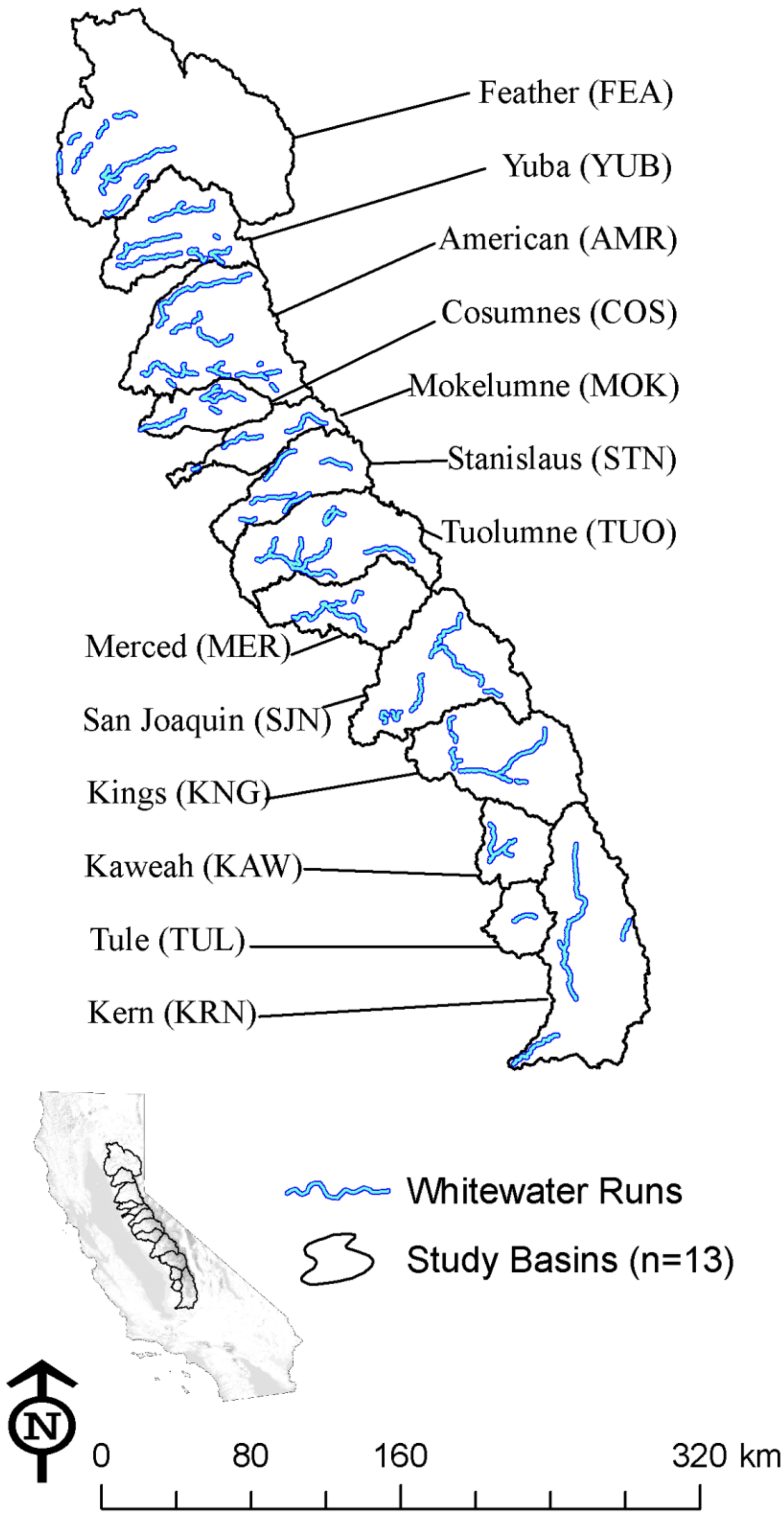

Figure 1. Map of study area basins with whitewater runs and take-outs shown.

All runs were designated within the inventory by level of difficulty and run type, which was used here to help describe their potential recreational use and general physical characteristics of the run. The difficulty of each run ranges from Class I to Class V, with I being flat water and V being at the limits of safety for experts. Each run was further classified with a "run type" to describe its geophysical setting using one of the following: steep creek, creek, gorge and river. Run type can vary within runs. For example, longer runs such as the Middle Fork of the Kings River, which starts as a small, steep creek, progresses to creek, then gorge, and ends as a river over the course of its 56 km. We assigned a single run type for each run based on the average topography, gradient and flow regime. A steep creek was defined as having an average gradient greater than 25 m/km. Steep creeks are usually found near the top of a watershed, but sometimes are found lower in the watershed as a tributary into a deep canyon. A creek had a high flow threshold less than 1500 cfs and an average gradient of less than 25 m/km. Gorge runs were defined as having lower flow thresholds and greater difficulty than runs upstream and downstream. Many Sierra Nevada rivers contain gorges about midway in the watershed where the river constricts between granite walls and becomes steeper. A river run type has a high flow threshold, greater than 1500 cfs. River run types are usually less steep, found at lower elevations and class I and II. See Figure 2 a,b,c,d for photographic examples. Discharge is presented in cubic feet per second (cfs), as per common usage in the study area.

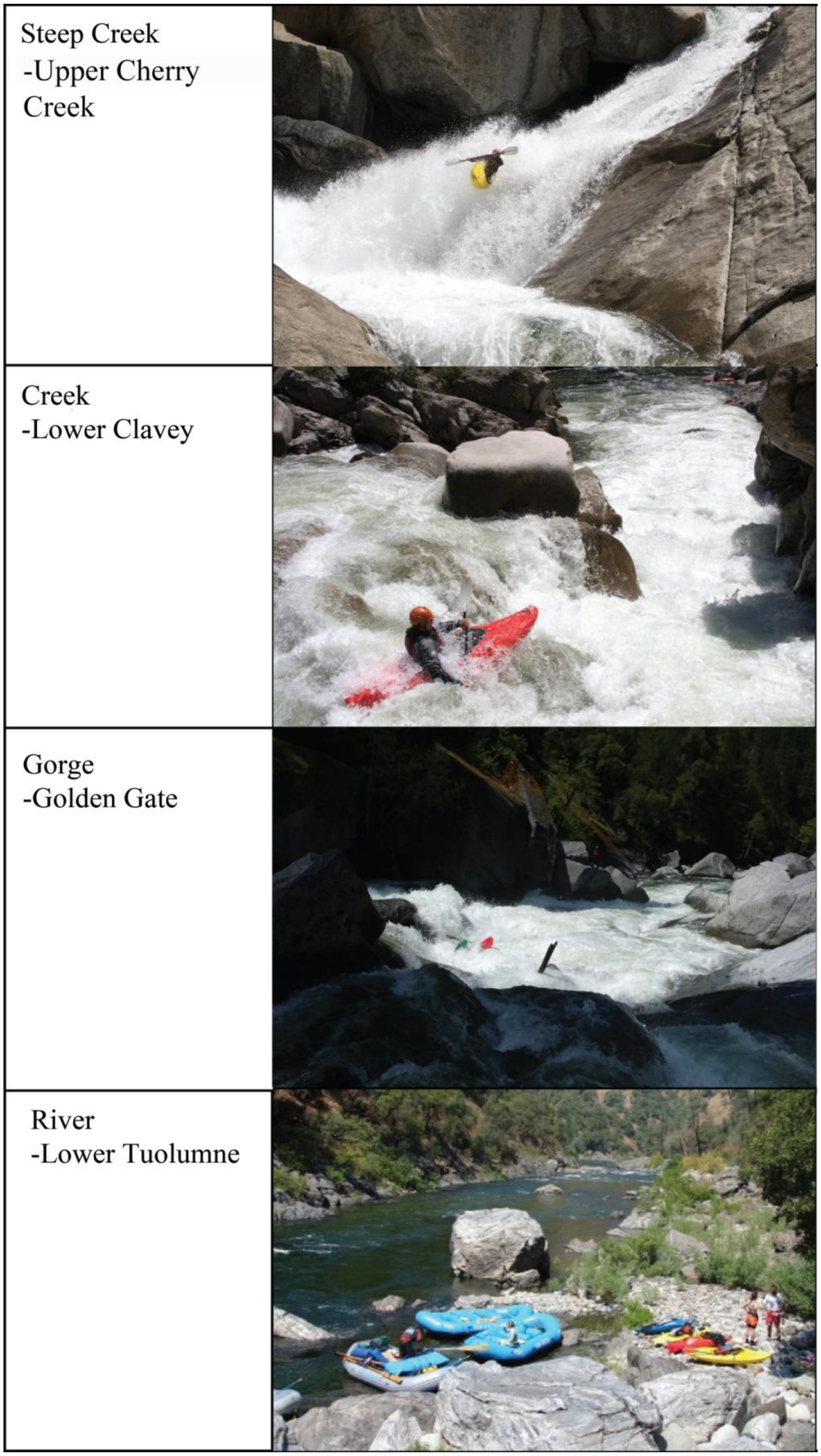

Figure 2. Examples of whitewater run types used to classify inventory

UNREGULATED FLOW SIMULATION WITH WEAP

The Water Evaluation and Planning System (WEAP21), a spatially explicit, one-dimensional rainfall-runoff model, was used to estimate the physical hydrology of the study area. As described in Yates et al. (2005) and Young et al. (2009), the WEAP21 application for the western Sierra Nevada simulates unregulated stream flows by explicitly accounting for overland flow and runoff, snow accumulation and melt, soil moisture storage, and evapotranspiration losses. Using weekly time steps, Young et al. (2009) modeled twenty one water years (1980-2001) using DAYMET climate data for historical precipitation, air temperature, and vapor pressure deficits. High spatial resolution DAYMET surface weather data is generated by interpolating observations and topography by the Numerical Terradynamic Simulation Group at University of Montana. Basins were characterized using USGS 10 m digital elevation models (DEM), soil surveys from the Natural Resource Conservation Service (NRCS), and land cover from the USGS National Land Use Classification Database (NLCD). Yates et al. (2005) and Young et al. (2009) describe model assumptions, governing equations, and performance. Simulated flows were calibrated at unregulated stream flow locations using data from United States Geological Survey (USGS) stream gage stations, and at some regulated sites using estimates of unregulated hydrology from the California Department of Water Resources (DWR). The period of record (1980-2001) captures a wide range of recent historical climatic and discharge conditions typical of the region, including an extended drought (1987-1992), the wettest year on record (1983), and the flood year of record (1997). For this study, unregulated flows were simulated for each of the 13 major river basins. Each basin was subdivided into 252 subwatershed nodes, where observed flows were used to evaluate model performance. Each subwatershed was intersected with 250 m contours to create 1234 catchments that were modeled individually. Because WEAP21 does not route flows from one catchment to another, but instead aggregates all flows at subwatersheds, a flow allocation procedure, described below, was needed to disaggregate flows for locations within subwatersheds.

REGIONAL CLIMATE WARMING SCENARIOS WITH WEAP

To date, downscaled regional climate models consistently indicate that California will be warmer (+2-6 ° C) by 2100, though these same analyses disagree as to whether precipitation will increase or decrease during this period (Dettinger 2005). This lack of consensus regarding precipitation reinforces the notion of extremes inherent to the Mediterranean-montane climate of the Sierra Nevada. As detailed by Null et al. (2010), the hydrologic sensitivity to climate warming is simulated for unregulated flows for four climate scenarios on a weekly time step over a period of 20 years. A historical baseline condition, from the calibrated rainfall-runoff model described above, is used to evaluate departures from baseline with 2° C incremental increases to atmospheric temperature. All other climate factors are held constant over the model period. This approach retains the stochasticity of the time period, but allows evaluation of relative hydrologic changes from potential +2° C, +4° C, and +6° C warmer conditions consistent with the range of projected temperatures for this region. Climate warming scenarios in WEAP have more rain driven events and less snowmelt runoff which greatly alters annual hydrographs. No changes are made to potential ecosystem responses to atmospheric warming, such as changes in vegetative cover, fire regime, and land uses.

Flow Allocation method

Because flows from the unregulated hydrology model (Young et al., 2009) were simulated for specific points that generally do not coincide with whitewater run locations, a flow allocation method was used to estimate flows for specific runs. Flows for locations of interest were determined by allocating the flow from each contributing WEAP21 catchment in proportion to the contributing catchment area. Using ArcGIS (v 9.3, ESRI, Redlands, CA), upstream drainage basins were defined, termed “rec-basin” here, for each whitewater run endpoint (i.e., “take-out”) based on the flow direction of a 10 m USGS DEM. Each rec-basin was intersected with the WEAP21 catchments and calculated the proportional area (p) of the rec-basin in each catchment. The proportioned simulated flows (Q) from each catchment (i) reflect the proportional area flowing to each endpoint for a given week (t). Total flow at each take-out (Q_T) was calculated by summing all contributing proportional flows from each catchment (Equation 1).

$$Q_T(t) = \sum_{i=1}^{n} p_i[Q_i(t)] \quad (1)$$

This technique of proportioning WEAP catchments assumes homogeneity in soil conductivity, vegetation, precipitation, and snow accumulation per WEAP catchment, so a proportion of the area equals the same proportion in flow. This assumption is made in the WEAP model as well (Young et al. 2009). The effects of non-homogeneity are minimized by the high spatial resolution of the WEAP catchments.

The “take-out” or endpoint of each run was selected as the representative point for analyzing flows for each run. The take-out position was selected as the best location for flow estimation because flows exceeding boatable flow thresholds were more likely to be reflected by downstream conditions. If a significant tributary increased the flow near the take-out of a run the flow point was moved upstream of the tributary to better represent flow in the stretch of interest.

Identification of flow thresholds

Flow thresholds were selected for each whitewater run by identifying low flow and high flow thresholds to produce a range of boatable conditions. The low flow threshold represents flow conditions below which too many obstacles for safe and uninterrupted navigation, whereas the high flow threshold represents the upper limit of stream power that is safe to navigate. Flow thresholds were identified using information for each run from published sources (e.g., (Holbeck and Stanley 1998; McQoid 2010; Whitewater 2010) and personal observation.

Identification of boatable weeks

Weeks having flows within the thresholds were considered boatable weeks. Boatable weeks do not represent actual recreational user days on the river; rather they represent flow conditions suitable for whitewater recreation. Because of the resolution of the rainfall-runoff model, the weekly time step has some limitations for the analysis. For example, rainfall events that create boatable flows for only a few hours (a scenario that is not uncommon) are not captured here. An hourly or finer resolution time step would be necessary to capture these types of events. However, the weekly time step does capture snow melt and longer rain events, including rates of change, which constitute the most boatable flows for most runs.

To better reflect actual boating patterns in the Sierra Nevada only spring boatable weeks were counted. For the base case, April 1st roughly describes the start of the boating season under historical conditions. With warming, to compensate for earlier runoff, the change in hydrograph centroid timing was rounded to the nearest whole week and subtracted from April 1st. The centroid timing is the time in the year when half of the mean annual runoff has occurred. The change in centroid timing was calculated for each major watershed for 2, 4, and 6 degree Celsius warming.

Results

Inventory of whitewater runs

128 recreational whitewater runs were identified on the west slope of the Sierra Nevada (Table A1). Geographically, the runs span the entire Sierra Nevada from the East Branch of the North Fork Feather River to the South Fork Kern River. The Feather, Yuba and American river basins have 55 runs, nearly half of the inventory. Greater precipitation in the northern Sierra Nevada and easier access to its rivers likely accounts for the uneven distribution in whitewater runs. Runs with regulated flows are 43% of all runs identified and are usually at lower elevations than the unregulated runs. The elevations of take-outs range from 55 m above sea level on the Cosumnes River to over 2200 m on the upper San Joaquin River. The average take-out elevation is 725 m. The contributing watershed drainage area to each take-out ranged from 31 km^2 for one run on the upper Yuba River (*Upper Canyon Creek*) to nearly 6000 km^2 on the lower Kern River, and the average drainage area is approximately 1000 km^2. The distribution of the difficulty of whitewater runs is heavily imbalanced, with the majority being Class V runs (73), and the fewest number of runs are Class II (5). Steep creek, creek and river run types are relatively evenly distributed (~30%) with 40, 30, and 44 runs of each type, respectively. Gorge runs represent only 11% of the runs identified in the study area (14).

The base case represents the unregulated runoff under historical atmospheric conditions for 21 years of atmospheric data. However, because the run inventory includes both regulated and unregulated reaches, first any fundamental bias was determined between the two by testing the mean and variance of simulated unregulated runoff. There was no difference in base case boatable weeks, as determined by estimates of unregulated flows, between regulated and unregulated runs for gorges (F=0.27, p=0.60), rivers (F=0.94, p=0.33), and steep creeks (F = 1.71, p = 0.19). However, a significant difference exists between creek run types currently under flow regulation and those that are not (F=53.9, p<0.01). While the unregulated flows for creeks differ in boatable weeks, there are also significant differences in stream gradient (p=0.02) between regulated and unregulated runs, suggesting that exogenous factors may affect their recreational potential. Based on this evidence, pooling all runs, regardless of flow regulation status, is acceptable for the analytical purposes in that it provides a more robust assessment of potential changes to recreational opportunities in the Sierra Nevada and elsewhere.

The average number of boatable weeks per run was calculated considering the upper and lower flow thresholds. The Feather and Kern Rivers both have the largest mean boatable weeks, and the Tule and Cosumnes Rivers, which have relatively small drainage areas, have the fewest mean boatable weeks. The runs with the largest number of boatable weeks were typically at low elevations with large drainage areas. Runs with fewer boatable weeks were the steep creeks that were typically class V.

UNREGULATED FLOWS UNDER REGIONAL CLIMATE WARMING

The annual average total number of boatable weeks in the Sierra Nevada increased when air temperature was increased by 2^{o} C, with 4^{o} C the annual average total boatable weeks was nearly the same as the base case and under 6^{o} C warming the annual average total number of boatable weeks decreased. Runs in the northern Sierra Nevada watersheds such as the Feather, American and Cosumnes Rivers and the southern Sierra Nevada runs in the Kern, Kaweah and Tule River watersheds all showed relative decreases in boatable weeks with 2, 4, and 6°C warming. The largest decrease was 30% in the lower elevation drainages of the Cosumnes and the Tule with a 6°C warming scenario. The watersheds in the central Sierra such as the Stanislaus, Merced and Kings show an increase in average boatable weeks under all three warming scenarios. The Mokelumne, Stanislaus, Tuolumne, Merced and San Joaquin Rivers show a greater relative increase in boatable weeks with an increase of 2 and 4 °C than with 6 °C (Figure 3) over the entire year.

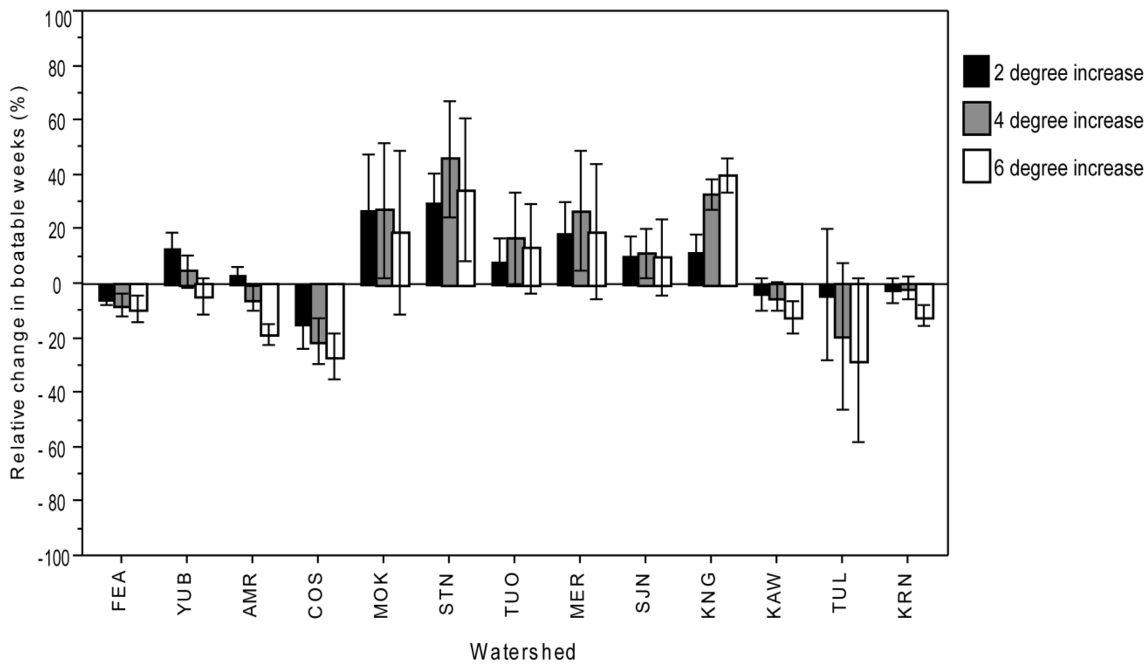

Figure 3. Annual percent change in boatable weeks by study basin for 2, 4, 6°C climate warming. Watersheds are sorted from north to south (left to right) with standard errors across runs are shown.

Although all flows within the flow thresholds are potentially boatable throughout the water year, most boating on Sierra Nevada rivers occurs in the spring because air temperatures are warmer, spring snowmelt flows are easier to predict, and the roads used to access the rivers are clear of snow. Thus, to more accurately represent potential impacts to river use, the analysis was refined for the period during the vernal snowmelt by removing weeks when flows may be within designated thresholds, but when few people participate in whitewater recreation. The average weekly change in centroid timing for each watershed was used to represent the change in timing that boaters start accessing rivers in the spring under warming scenarios. The change in centroid timing shifted the threshold date from April 1st to as early as mid February for the runs in the San Joaquin, Stanislaus, Mokelumne and Kings under 6 degree warming (Table 1).

Table 1. Change in weekly average centroid timing by watershed (Null et al. 2010).

Watershed	2 ^{o}C warming	4 ^{o}C warming	6 ^{o}C warming
Feather	2	3	3
Yuba	2	3	4
American	2	3	4
Cosumnes	1	1	2
Mokelumne	2	4	6
Stanislaus	2	5	6
Tuolumne	2	4	5
Merced	2	4	5
San Joaquin	2	4	6
Kings	2	4	6
Kaweah	2	3	5
Tule	1	2	3
Kern	1	2	3

When only vernal snowmelt months were considered, the observed trends show a similar general increase in boatable weeks under 2^{o}C warming, and a decrease under 6^{o}C warming (Figure 4).

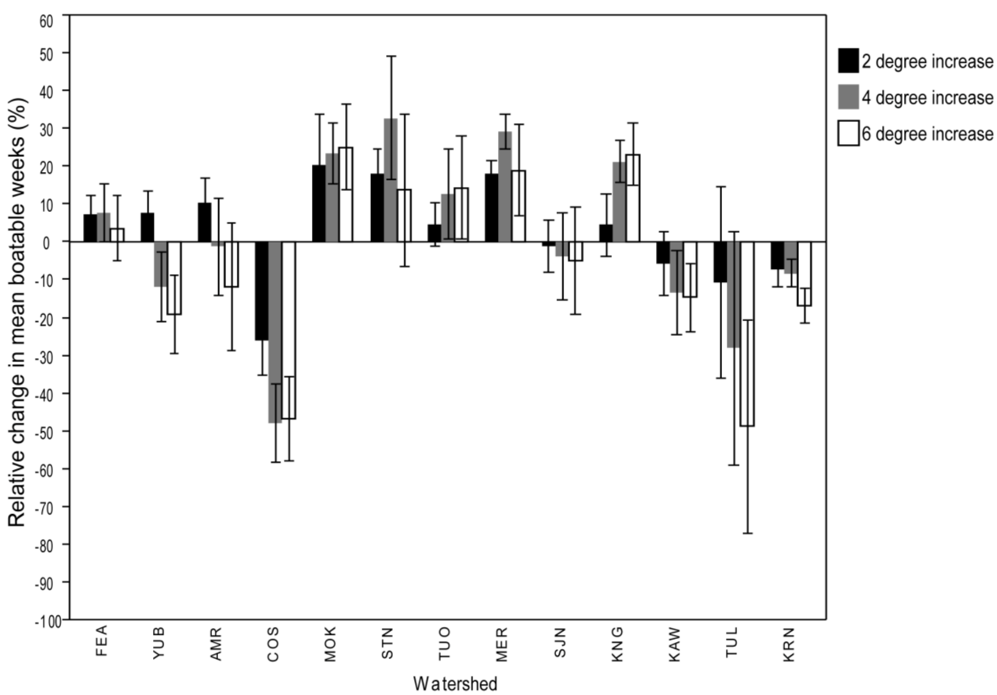

Figure 4. Percent change in boatable springtime weeks by watershed for 2, 4, 6°C climate warming. Basins are sorted from north to south (left to right).

Overall, run-type was a good predictor of sensitivity to climate change for whitewater runs. The average number of boatable weeks increased on gorge type runs, the average boatable weeks on steep creeks remained nearly constant and the average boatable weeks on creek and river type runs decreased with warming (Figure 5). The largest increase in average boatable weeks was about 23% for gorge type runs under 4°C warming and the largest decrease in average boatable weeks was 17% in creek run types with 6°C warming. The river run types showed less variability than the other three run types.

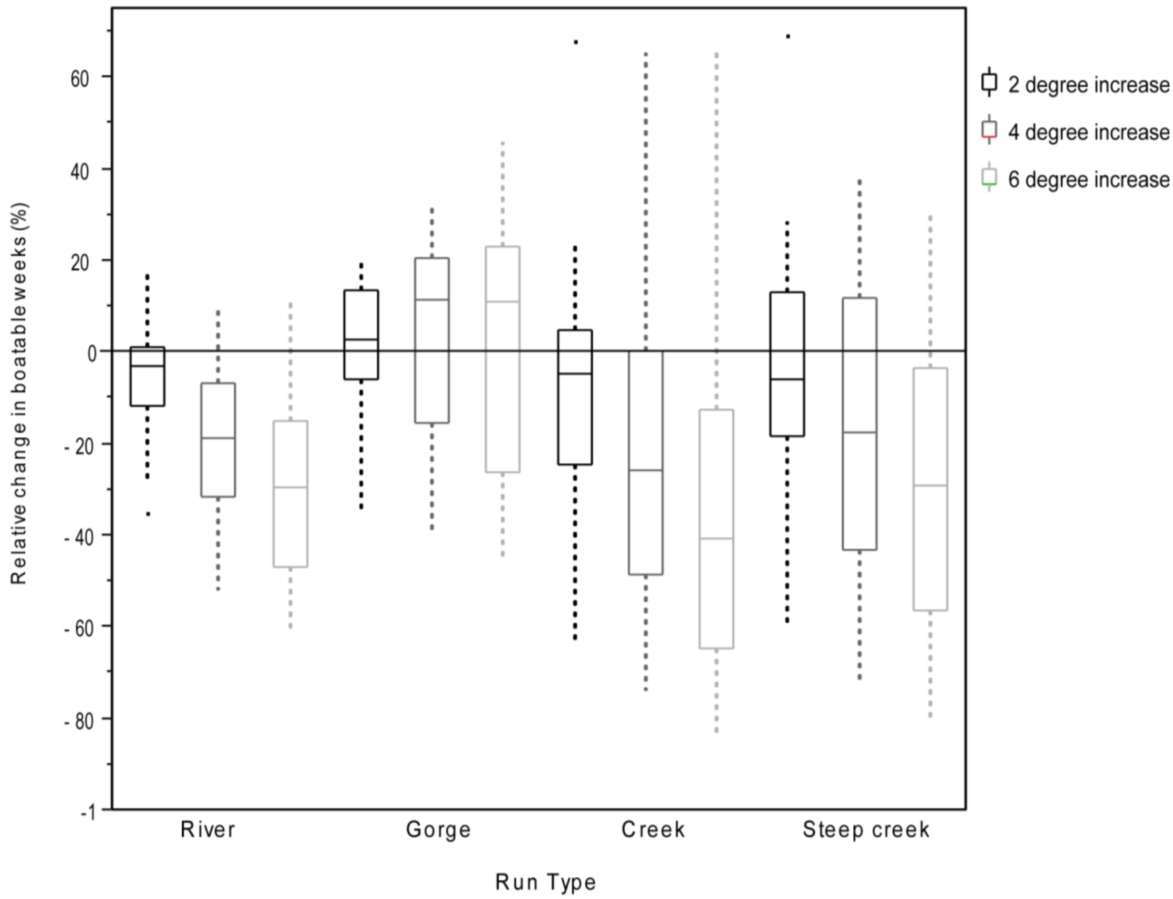

Figure 5. Percent change in boatable weeks by temperature scenario and run type. The River run type has the least variability and the Gorge type shows the only average increase in boatable weeks under each of the warming scenarios.

The number of boatable weeks was compared by water year type under historical atmospheric conditions as designated by the California Department of Water Resources. Water years are classified by annual unregulated runoff separately for the Sacramento and San Joaquin River basins (DWR 2009). The water year types include: wet, above normal, below normal, dry and critically dry. The number of boatable weeks with respect to water year type generally decreased in spring from a wet year to a critically dry year (Figure 6). There were no below normal water years in our 21-year time series. The Feather River, because of a high base flow, showed an increasing trend from wet to critically dry which differs from the other watersheds (Figures 6,7).

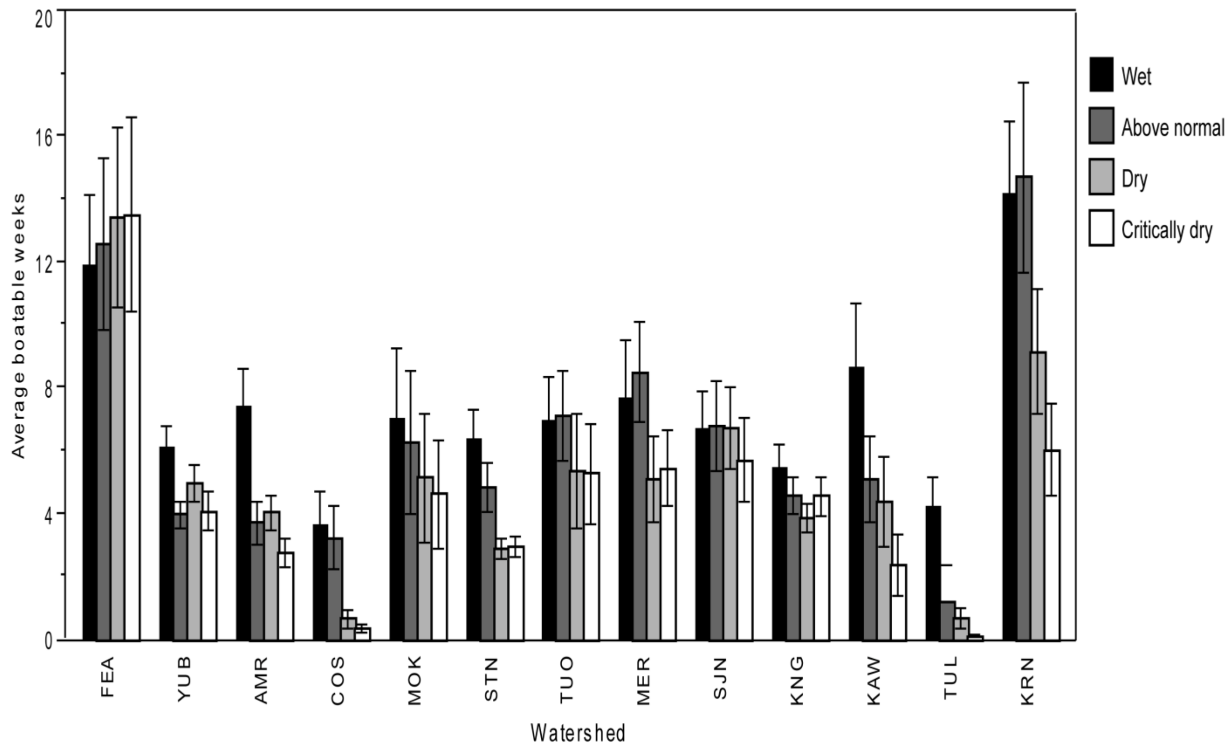

Figure 6. Average number of boatable springtime weeks by water year type with historical flows. The Feather River (FEA) does not follow the trend of decreased boatable weeks with drier water year types observed in the other watersheds.

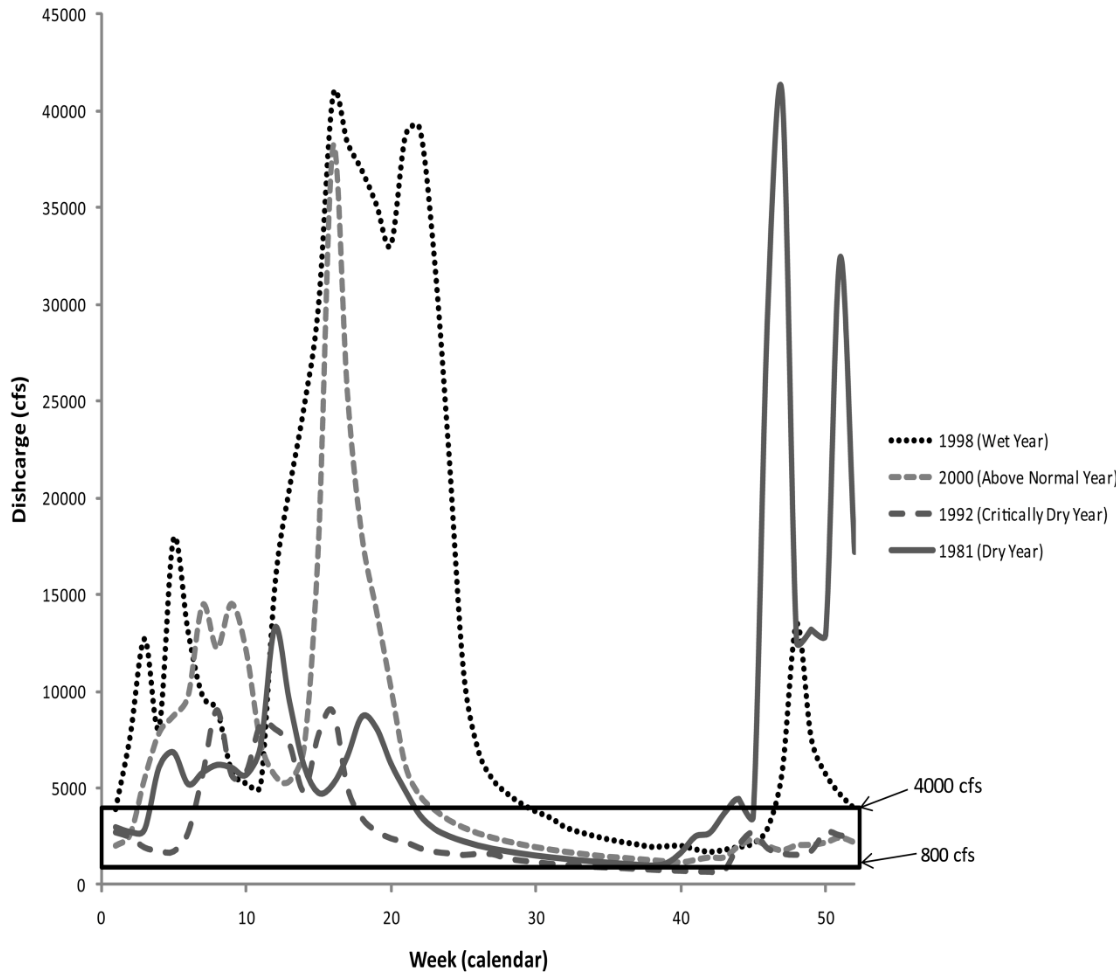

Figure 7. Hydrograph of the Cresta run in the Feather River study basin (FEA) showing range of simulated unregulated flows during different water year types. Boatable flow thresholds are 800 cfs minimum discharge and 4000 cfs maximum discharge.

A critically dry water year type with 6° C warming is the worst-case for boating in the Sierra Nevada. Under such conditions, almost no boatable flows occur in the spring on low elevation watersheds such as the Cosumnes and Tule (Figure 8). Every watershed except the Kings, San Joaquin and Feather shows more than 50% reduction in boatable weeks for these conditions.

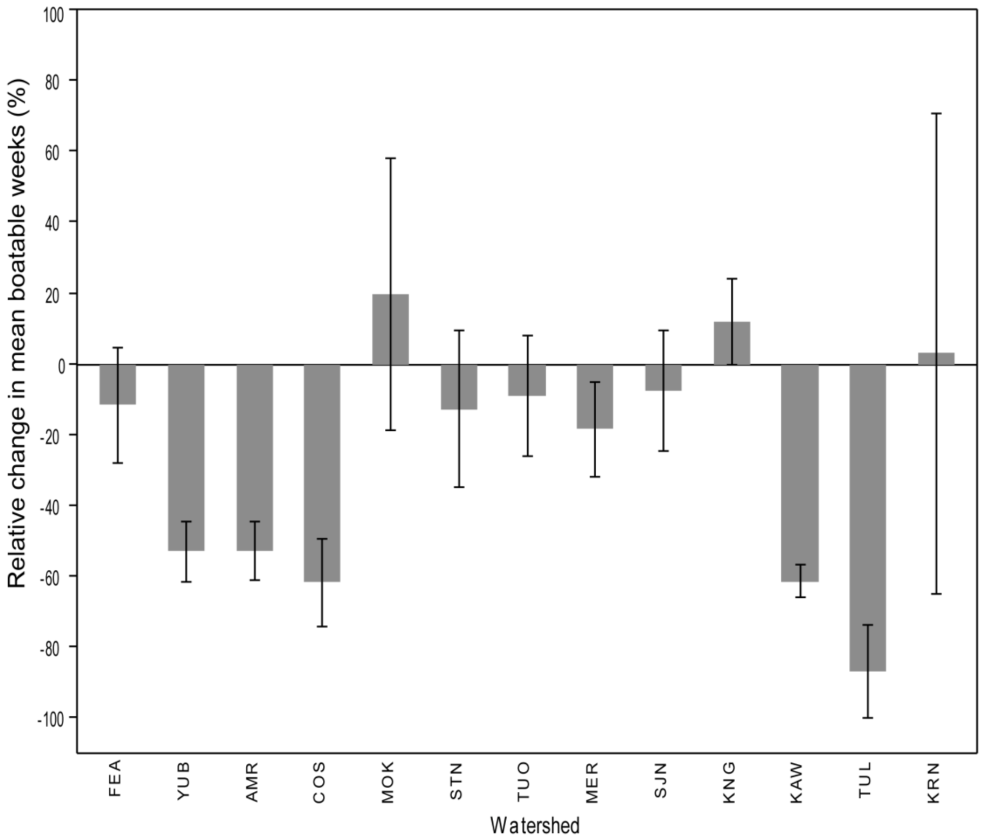

Figure 8. Relative percent change in boatable weeks during critical dry years with 6°C climate warming for unregulated runs represents the "worst case" scenario for whitewater boating on rivers in the Sierra Nevada.

DISCUSSION

Overall, climate warming will reduce opportunities for whitewater recreation on some Sierra Nevada rivers and increase opportunities on other rivers. Results from past studies suggest that reductions in mean annual flow, earlier runoff, longer periods of low flow conditions and reductions in snowmelt volume are non-uniformly distributed throughout the Sierra Nevada (Young et al. 2009; Null et al. 2010). The largest reduction in snowmelt volume was in the 1,750-2,750 m elevation range (Young et al. 2009). Watersheds in the northern Sierra Nevada are most vulnerable to decreased mean annual flow because of the large snow storage below 3000 m. Rivers in the central Sierra such as the Mokelumne, Stanislaus, San Joaquin are most affected by longer periods with low flow conditions and southern-central Sierra rivers such as the Kaweah and Kern are most susceptible to runoff timing changes (Null et al. 2010). However, when focusing on whitewater recreation, while the low elevation drainages, such as the Cosumnes and the Tule, were most vulnerable to changes in boatable weeks, high elevation watersheds, such as the Kern, also had large reductions in boatable weeks. The watersheds with the least reduction in spring boatable weeks were in the central Sierra Nevada with more gorge type runs at middle elevations.

In the base case the Feather and Kern watersheds had the most average boatable weeks because most runs are in the lower part of the watershed. The Kern and Feather rivers have many long, constant gradient runs with large contributing areas which support a large boatable flow range. An example is the Cresta run on North Fork Feather which is classified as a river type run with a flow range of 3200 cfs (Figure 7). In some years flows may be within the boatable thresholds for nearly 3 months. Watersheds in the central Sierra Nevada have shorter, steeper, more difficult runs with smaller flow windows and therefore have fewer runnable weeks under base case conditions.

Rivers in the central Sierra Nevada, such as the Mokelumne, Stanislaus, Tuolumne and Merced showed more boatable spring weeks with warming. This increase is due to the large number of runs where the peak runoff from snowmelt is much higher than the boatable high flow threshold. These runs are usually very steep creeks and gorges, among the most difficult Class V runs. The relative increase in boatable weeks due to climate warming observed in these runs is from the reduction in spring snowmelt runoff. Peak snowmelt runoff for these runs under historical conditions is larger than the high flow threshold and therefore the only boatable time is during the snowmelt recession. Discharge for some years drops below the boatable range of flows rapidly, such as the flow regime for Fantasy Falls on the North Fork Mokelumne (Figure 9), which has on average of 1.4 boatable weeks under the basecase scenario of snowmelt recession. In the 4°C warming scenario, however, the spring runoff peak discharge is about 700 cfs and within the boatable range of flows. When the peak discharge is lower, the slope of the recession limb is more gradual, which then increases the number of weeks within the boatable flow range.

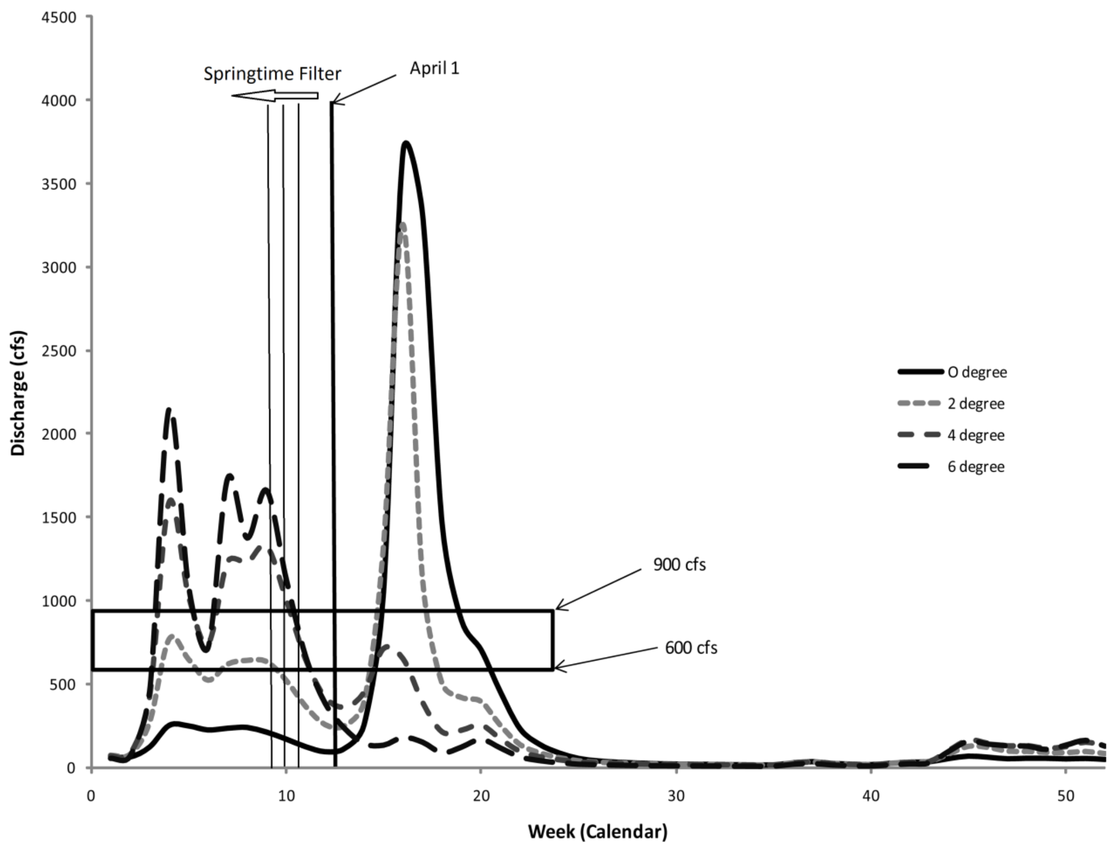

Figure 9. Hydrograph of the Fantasy Falls run in the upper Mokelumne River study basin (MOK) showing boatable flow range and increase in boatable weeks with a 4 °C increase in air temperature for the WEAP21 simulation in year 2000. Boatable flow thresholds are 600 cfs minimum discharge and 900 cfs maximum discharge. The change in springtime threshold date for the Mokelumne watershed using the centroid timing shifts the start of springtime boating earlier.

Changes in spring boatable weeks by run type show a non-uniform change as a result of warming (Figure 5). All run types show fewer boatable weeks except for the gorge type runs. The river runs have large upstream drainage areas and large flow windows, so they have many average boatable weeks per year historically with the lowest variability. As air temperatures increase, the variability increases and boatable weeks decrease. Creeks show the largest variation in boatable weeks because the large variation in physical characteristics of the run type. Creeks range from having a maximum high flow threshold of 1500 cfs to a minimum low flow threshold of 300 cfs, and have the largest range of elevations and gradients. Gorge runs show increasing boatable weeks because the peak of the annual hydrograph is much higher than the upper boatable flow threshold and therefore when the snowmelt peak is reduced, the recession limb is less steep in the flow range of interest which increases boatable weeks. Steep creeks occur in high elevation headwaters as well as steep lower elevation side canyon tributaries to gorge type runs.

Unregulated runs account for 57% of the whitewater runs identified on the west slope of the Sierra Nevada. In these natural systems, runoff produces boatable flows within the natural flow regime and whitewater recreation does not conflict with ecological uses. Popular commercial rafting runs such as the Lower Kaweah, Chamberlain Falls, Goodyears Bar, and El Portal to

Briceburg are on unregulated rivers. All of these runs, except for the El Portal to Briceburg, have fewer boatable weeks with 4^{o}C and 6^{o}C warming, some as much as 44% less (Chamberlain Falls). Some watersheds, where boatable weeks have more resiliency to climate warming such as the San Joaquin are almost fully regulated for hydropower. The unregulated runs showed the same trend as the runs of the entire Sierra, with the largest variability in the creek and steep creek runs and an increase in boatable weeks for gorge runs (Figure 5). However, the smaller, steep creek runs are less developed for hydropower (only 18% are regulated), presumably because of low volumes of discharge. Most gorge runs (79%) are regulated for hydropower, however, indicating that river managers may be able to mitigate anticipated changes to flow regimes with climate warming to both enhance ecological benefits of the snowmelt recession (*sensu* Yarnell et al. 2010) and extend whitewater recreational opportunities.

The regulated rivers in the Sierra Nevada are developed primarily for hydropower production which greatly affect whitewater recreation. Hydropower production in the region usually consist of a dam which diverts water into a tunnel or canal to a powerhouse downstream. The downstream river sections consist of a bypassed reach between the dam and the powerhouse and a peaking reach below the powerhouse. Most regulated whitewater runs in the Sierra Nevada occur in bypassed reaches. Therefore, boatable flows on these runs only occur during spill events or explicit releases for recreation. Regional climate warming studies have shown that spill events may increase with warmer air temperatures (Madani and Lund 2010) which could increase the number of boatable weeks on these runs. However, the same studies show decreased storage later in the summer which may decrease late releases for recreation. Climate warming may shift the timing of boatable conditions on regulated runs from summer releases to late winter-early spring spills.

IMPLICATIONS FOR RIVER MANAGEMENT

In the western Sierra Nevada, regulated flows used for whitewater recreation are often under license from the Federal Power Act and issued by the Federal Energy Regulatory Commission (FERC). Many FERC licenses are now being reissued under different operating rules – usually to improve downstream ecological conditions – so flow regimes are increasingly scrutinized for their impacts to river recreation. As flow release schedules shift toward the natural flow regime (Poff et al. 1997), and especially toward mimicking the vernal snowmelt recession limb of the hydrograph (Yarnell et al. 2010), fewer boatable days in late summer may result. Although higher flow conditions in late summer are unnatural in Mediterranean-montane riverine ecosystems, such as Sierra Nevada rivers, many whitewater enthusiasts and commercial operators depend on stable, boatable flows in regulated systems.

Mediterranean-montane river regions of the world such as the Chilean Andes, Mediterranean Basin, Southern Australia and South Africa are also popular regions for whitewater boating. If these regions respond similarly to climate warming (Klausmeyer and Shaw 2009), the California results suggest that rivers may also have a non-uniform reduction in boatable weeks with climate warming. Whitewater runs in these regions will likely see a reduction in boatable weeks similar to that in the Sierra Nevada where narrow gorge runs in the European Alps may be less vulnerable than river runs in Chile or Southern Australia, for example. In a changing climate many adjustments in management will be needed to minimize the effects of climate change on water resources such as whitewater recreation.

This study does not include regulated flows which constitute the largest current use. However, this study does provide a range of conditions to assess the nature of the problem. Recreation is an important use of rivers, yet it is difficult to quantify and to plan for. This research provides a sensitivity analysis on climate change.

CONCLUSION

The number of weeks with boatable flows on Sierra Nevada's 128 whitewater recreational runs is expected to change non-uniformly with climate warming. The reduction in springtime boatable weeks is neither geographically uniform across the mountain range nor linear in response to incremental increases in annual average air temperature. However, for runs in which the historical volume of snowmelt is much larger, the simulated flows show the smallest change with climate warming. Runs in low elevation watersheds such as the Tule and the Cosumnes show the largest change in boatable weeks. Within each watershed, run type also influenced change in boatable weeks, with gorge runs having a longer season, and river runs lower in elevation having a shorter season. Overall, elevation, run-type, and volume of snowmelt are the best predictors of resiliency for Sierra Nevada whitewater runs.

Future managers will be faced with reduced water resources, making allocation decisions difficult among often conflicting uses (e.g., ecology, hydropower generation and recreation). The physical characteristics in a stretch of river that boaters find desirable for whitewater also make ideal locations for hydropower projects. The observed reduction in whitewater recreation opportunities in unregulated rivers due to climate warming and continued increases in population will likely increase the importance on boating on regulated rivers, and thus the reliance on operations for meeting multiple demands. While managing rivers for such multiple and conflicting demands with climate warming will be challenging, especially in areas heavily used for recreation such as the Sierra Nevada, the findings underscore the importance of crafting solutions to support ecosystem services and beneficial uses.

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APPENDIX

Table A1. Attributes of runs used in analysis

Run Name	Elevation (m)	Longitude (°)	Latitude (°)	Area (km^2)	Watershed	Low Flow (cfs)	High Flow (cfs)	Regulation	Difficulty	Run Type
Devils Canyon	490	-121.2715	39.7101	2627.8	Feather	800	3000	unimp	IV	River
Rock Creek	514	-121.3277	39.9115	4844.9	Feather	800	4000	reg	IV	Creek
Cresta	425	-121.4271	39.8152	5088.4	Feather	800	4000	reg	IV	River
S. Feather below diversion	294	-121.2780	39.5488	272.0	Feather	250	450	reg	V	Gorge
Ben & Jerrys	276	-121.5613	39.7371	305.3	Feather	250	600	reg	V	Gorge
Bald Rock	277	-121.2848	39.6384	2869.2	Feather	500	1500	unimp	V	Gorge
Poe	285	-121.4736	39.7404	5158.6	Feather	800	1800	reg	V	Gorge
S. Feather above diversion	1170	-121.0857	39.6752	87.9	Feather	200	400	reg	V	Steep creek
Upper W. Branch	426	-121.5622	39.7928	287.9	Feather	300	1500	unimp	IV	Creek
E. Branch N. Feather	692	-121.2253	40.0137	2649.8	Feather	600	3000	unimp	IV	River
Big Kimshew	756	-121.5073	39.8796	70.1	Feather	250	500	unimp	V	Steep creek
S. Branch	485	-121.2698	39.7058	84.7	Feather	250	500	unimp	V	Steep creek
Little N. Fork Middle Feather	501	-121.2727	39.7100	119.9	Feather	250	600	unimp	V	Steep creek
Plumbago to Ourhouse	642	-120.9723	39.4189	353.0	Yuba	600	2000	reg	IV	River
Sierra to Downieville	896	-120.8142	39.5579	363.5	Yuba	500	2500	unimp	IV	River
Our house	439	-121.0834	39.3947	418.3	Yuba	600	2000	reg	IV	River
Rossasco Canyon	802	-120.8874	39.5386	575.4	Yuba	700	1700	unimp	IV	River
Goodyears Bar	691	-120.9970	39.5190	671.2	Yuba	700	3000	unimp	IV	River
Washington to Edwards	595	-120.9821	39.3304	711.0	Yuba	700	2000	reg	III	River
Edwards to Purdons	499	-121.0504	39.3247	749.8	Yuba	800	3000	reg	IV	River
49 to Bridgeport	165	-121.1928	39.2927	895.7	Yuba	500	2000	reg	V	River
Yuba Gap	865	-120.7499	39.3609	384.7	Yuba	300	450	reg	V	Gorge
Purdons to 49	339	-121.0955	39.2952	804.5	Yuba	600	1000	reg	V	Gorge
49 to Colgate	167	-121.1892	39.3305	1855.2	Yuba	600	1000	reg	V	Gorge
Colgate	167	-121.1892	39.3305	1855.2	Yuba	500	1500	reg	V	Gorge
Lower Pauley	894	-120.8221	39.5696	65.9	Yuba	300	600	unimp	IV	Steep creek
Lavezzola	896	-120.8223	39.5698	120.7	Yuba	300	600	unimp	IV	Creek
Lower Canyon Creek	866	-120.7501	39.3611	130.4	Yuba	400	900	reg	IV	Steep creek
Indian to Spalding	1528	-120.6155	39.3461	156.8	Yuba	400	900	unimp	V	Creek
Upper Canyon Creek	1791	-120.5912	39.4412	31.2	Yuba	100	250	reg	V	Steep creek
Fordyce	1530	-120.6182	39.3519	137.1	Yuba	300	600	reg	V	Steep creek
East meets West	1658	-120.5695	39.3271	141.4	Yuba	400	800	unimp	V	Creek
Loves Falls	1303	-120.6156	39.5683	145.4	Yuba	200	400	unimp	V	Steep creek
Rock Creek	399	-120.7754	38.7941	189.5	American	300	800	reg	V	River
Generation Gap	569	-120.7687	39.1824	506.5	American	800	2500	unimp	IV	River
Giant Gap	339	-120.9248	39.0988	606.1	American	700	2000	unimp	IV	River
Chamberlain Falls	278	-120.9023	39.0416	653.2	American	600	5000	unimp	IV	River
Ponderosa	241	-120.9398	39.0001	850.4	American	800	2500	unimp	II	River
Tunnel Chute	252	-120.8542	38.9714	1412.4	American	900	2000	reg	IV	River
Slab Creek Run	303	-120.7932	38.7686	1537.8	American	700	2500	reg	IV	River
Chilli Bar	216	-120.9039	38.8049	1646.3	American	900	5000	reg	III	River
Coloma to Greenwood	197	-120.9449	38.8243	1675.6	American	900	10000	reg	II	River
South Fork Gorge	143	-121.0352	38.7721	2081.3	American	900	8000	reg	III	River
Golden Gate	568	-120.6257	38.7938	1164.7	American	700	1500	unimp	V	Gorge
Lovers Leap	1317	-120.2705	38.7757	182.0	American	500	1500	unimp	V	Creek
Lower Silver Creek	627	-120.5904	38.7895	457.4	American	600	800	reg	IV	Creek
Kyburz	978	-120.4485	38.7710	630.7	American	700	3000	unimp	IV	River
Lower Rubicon	424	-120.6870	38.9899	678.6	American	800	2000	reg	V	River
South Silver	1660	-120.3159	38.8195	55.5	American	100	250	unimp	V	Steep creek
Weber Creek	353	-120.8734	38.7393	129.7	American	350	600	unimp	V	Steep creek
Shirttail Creek	278	-120.9021	39.0410	141.3	American	150	350	unimp	V	Steep creek
North Middle American	391	-120.7208	39.0240	230.0	American	600	800	unimp	V	Steep creek
Upper Silverfork	1515	-120.2372	38.7243	231.8	American	500	700	unimp	V	Steep creek
Royal Gorge	872	-120.5685	39.2148	270.6	American	700	1400	unimp	V	Steep creek
Lower Silverfork	1199	-120.3151	38.7675	288.5	American	350	600	unimp	V	Steep creek

Run Name	Elevation (m)	Longitude (°)	Latitude (°)	Area (km^2)	Watershed	Low Flow (cfs)	High Flow (cfs)	Regulation	Difficulty	Run Type
Upper Main Cosumnes	110	-120.9540	38.5208	1285.9	Cosumnes	500	3000	unimp	II	River
Lower Main Cosumnes	55	-121.0433	38.5012	1383.6	Cosumnes	800	2000	unimp	II	River
Lower North Cosumnes	547	-120.6661	38.6554	213.7	Cosumnes	300	500	unimp	V	Creek
Lower Middle Cosumnes	242	-120.8464	38.5541	1285.9	Cosumnes	600	1200	unimp	IV	Creek
Upper North Cosumnes	978	-120.5342	38.6702	101.6	Cosumnes	200	400	unimp	V	Steep creek
Lower Camp Creek	547	-120.6660	38.6556	162.6	Cosumnes	400	600	unimp	V	Creek
Sly Park Creek	547	-120.6660	38.6556	162.6	Cosumnes	250	500	reg	V	Steep creek
Upper MiddleCosumnes	577	-120.6087	38.6085	229.3	Cosumnes	350	700	unimp	V	Steep creek
Bear to Tiger	714	-120.4911	38.4464	861.8	Mokelumne	700	4000	reg	IV	River
Below Tiger Dam	631	-120.5301	38.4191	931.2	Mokelumne	600	3000	reg	IV	River
Electra	187	-120.7204	38.3126	1409.1	Mokelumne	500	3500	reg	III	River
Panther Creek	840	-120.4167	38.4739	48.5	Mokelumne	150	300	unimp	V	Steep creek
Fantasy Falls	1206	-120.1429	38.4974	400.0	Mokelumne	600	900	unimp	V	Steep creek
Mt Knight	374	-120.3575	38.1541	911.1	Stanislaus	1200	3000	reg	V	River
S. Stan Strawberry	1287	-120.1575	38.1111	161.9	Stanislaus	400	1200	reg	V	Creek
Dardanelles	1647	-119.8768	38.3615	302.9	Stanislaus	400	700	unimp	V	Creek
Boards Crossing	1105	-120.2735	38.2655	422.0	Stanislaus	500	1500	reg	IV	Creek
Donnells	1509	-119.9293	38.3473	516.5	Stanislaus	400	800	unimp	V	Steep creek
Sand Bar Flat	831	-120.1582	38.1833	851.5	Stanislaus	800	1500	reg	IV	Creek
Italian Bar	332	-120.4251	38.0740	276.6	Stanislaus	400	1200	reg	IV	Steep creek
Hells Kitchen	1176	-120.2336	38.3064	395.5	Stanislaus	300	600	reg	V	Steep creek
Cherry Creek	437	-120.0476	37.8406	1989.0	Tuolumne	600	2000	reg	V	River
Lower Tuolumne	249	-120.3262	37.8805	3312.7	Tuolumne	600	8000	reg	IV	River
Middle Cherry	682	-119.9681	37.8962	582.5	Tuolumne	300	800	reg	V	Gorge
Rainbow Pool	1086	-119.9281	37.8118	170.5	Tuolumne	400	800	unimp	IV	Creek
N. Tuolumne	259	-120.2540	37.8968	258.3	Tuolumne	400	1000	unimp	V	Steep creek
Upper Clavey	700	-120.0775	37.8947	380.0	Tuolumne	500	1000	unimp	V	Creek
Lower Clavey	356	-120.1166	37.8639	411.4	Tuolumne	600	1200	unimp	V	Creek
West Cherry	1563	-119.9031	38.0527	101.0	Tuolumne	200	600	unimp	V	Steep creek
Upper Cherry	1560	-119.9029	38.0526	153.7	Tuolumne	150	500	unimp	V	Steep creek
Lower S. Tuolumne	436	-120.0484	37.8402	400.1	Tuolumne	250	400	unimp	V	Steep creek
El Portal to Briceburg	347	-119.9663	37.6057	1814.3	Merced	1000	5000	unimp	IV	River
Briceburg to Bagby	251	-120.1031	37.6029	2333.0	Merced	800	2500	unimp	III	River
Merced Gorge	830	-119.7341	37.6802	931.5	Merced	800	1600	unimp	V	Gorge
South Merced	425	-119.8882	37.6538	623.4	Merced	500	1500	unimp	V	Creek
Grand Canyon of T	1159	-119.6602	37.9163	774.7	Merced	500	1200	unimp	V	Steep creek
Horseshoe Bend	300	-119.5042	37.1478	3738.0	San Joaquin	1000	8000	reg	IV	River
Patterson Bend	199	-119.5495	37.0940	3827.7	San Joaquin	1500	5000	reg	V	River
Lower S. San Joaquin	1130	-119.2436	37.4367	1200.2	San Joaquin	400	600	reg	V	Gorge
Chawanakee Gorge	428	-119.3888	37.1495	3231.0	San Joaquin	500	800	reg	V	Gorge
Paiute Cr. to Florence	2244	-118.9438	37.2429	391.7	San Joaquin	800	2500	reg	IV	River
Florence to Mono Hot Springs	2001	-119.0128	37.3265	654.5	San Joaquin	500	1500	reg	IV	Creek
Tied for first	678	-119.3345	37.2163	2751.9	San Joaquin	600	1500	reg	IV	Creek
Devils Postpile	1051	-119.2668	37.4092	2073.6	San Joaquin	400	650	unimp	V	Steep creek
Kings Canyon	324	-119.0956	36.8578	2321.6	Kings	800	2500	unimp	V	River
Upper Dinkey	1404	-119.1204	37.0010	188.0	Kings	200	600	unimp	V	Steep creek
North Kings above Dinkey	380	-119.1222	36.9027	650.0	Kings	200	400	reg	IV	Steep creek
Balch Camp to Kings Confluence	299	-119.1345	36.8699	1001.9	Kings	400	1000	reg	V	Creek
Kings Park Boundary	1233	-118.7563	36.8097	1059.0	Kings	500	1000	unimp	V	Creek
Kings Horseshoe Bend	688	-118.8748	36.8380	1231.2	Kings	800	1000	unimp	V	Creek
Super Dink	1722	-119.1558	37.0648	104.5	Kings	200	500	unimp	V	Steep creek
Dinkey Waterfalls	381	-119.1225	36.9029	341.2	Kings	200	400	unimp	V	Steep creek
Middle Kings	689	-118.8747	36.8383	824.0	Kings	700	1500	unimp	V	Steep creek
Lower Kaweah	217	-118.9267	36.4180	1332.5	Kaweah	500	4000	unimp	IV	River
Lower North Kaweah	249	-118.9019	36.4478	358.9	Kaweah	800	1500	unimp	IV	Creek
Potwisha	479	-118.8222	36.4909	414.2	Kaweah	400	800	unimp	V	Creek
Kaweah Park Boundary	392	-118.8385	36.4793	433.3	Kaweah	500	1300	unimp	IV	Creek
Upper North Kaweah	525	-118.8964	36.5453	231.5	Kaweah	200	800	unimp	IV	Steep creek
Lower East Kaweah	391	-118.8384	36.4790	247.0	Kaweah	200	400	unimp	V	Steep creek

Run Name	Elevation (m)	Longitude (°)	Latitude (°)	Area (km^2)	Watershed	Low Flow (cfs)	High Flow (cfs)	Regulation	Difficulty	Run Type
Limestone	1109	-118.4772	35.9461	2181.0	Kern	500	3000	unimp	III	River
Fairview to Gold Ledge	1005	-118.4641	35.8910	2336.0	Kern	600	3000	reg	IV	River
Gold Ledge	830	-118.4452	35.7825	2509.9	Kern	500	3000	reg	IV	River
Kernville	800	-118.4210	35.7494	2616.9	Kern	500	2000	reg	II	River
Miracle to Democrat	587	-118.6562	35.5321	5829.5	Kern	600	3000	reg	IV	River
Cataracts of the Kern	210	-118.7966	35.4402	5960.1	Kern	600	2500	reg	V	Gorge
Upper South Kern	1837	-118.1343	36.0350	530.1	Kern	300	500	unimp	V	Steep creek
Brush Creek	1140	-118.4797	35.9658	79.9	Kern	100	250	unimp	IV	Steep creek
Dry Meadow	1193	-118.4828	35.9932	93.6	Kern	75	200	unimp	V	Steep creek
Headwaters of the Kern	1515	-118.3724	36.1769	1166.3	Kern	500	2500	unimp	V	Creek