SEPARATING EFECTS OF WATER-USE AND CLIMATIC CHANGES ON BASE FLOW IN THE LOWER KLAMATH BASIN

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ABSTRACT: Since the 1940s, snow water equivalent (SWE) has decreased throughout the Pacific Northwest due to climatic factors, while water use has increased. To address late-summer water shortages, managers need to know the proportion of streamflow decline due to climate versus that due to water use. We analyzed 5 streams and 16 snow courses to identify causes of decreased base flow in the Scott River, an important coho salmon rearing tributary in the Klamath Basin. April 1 SWE decreased significantly at most snow courses lower than 1800 m in elevation and increased slightly at higher elevations. Correspondingly, base flow decreased significantly in the two streams with the lowest latitude-adjusted elevation and increased slightly in two higher-elevation streams. Base-flow decline in the Scott River was larger than that in all other streams and larger than predicted by elevation and latitude. Irrigation withdrawal in the Scott watershed has doubled since the 1950s, and the amount of ground water withdrawn has increased from 1 to 50 Mm^3/yr. Water use changes have been minimal in the other watersheds. We estimate that half of the observed 10 Mm^3 (8000 acre-feet) decline in July 1-22 October discharge in the Scott River is due to changes in irrigation use. Returning to pre-1970 irrigation patterns in the Scott Valley could potentially increase streamflow by an average of 0.5 m^3/s (17 cfs) over the July 1-October 22 period.

(KEY TERMS: surface water hydrology; climate variability/change; rivers/streams; Klamath River; salmon; permutation tests)

INTRODUCTION

Snowmelt is an important contributor to discharge in nearly all major rivers of the western United States. Although climate models diverge with respect to trends in precipitation over this region, there is widespread agreement that the effect of current and predicted future climate warming is to decrease the percentage of precipitation falling as snow and accelerate snowpack melt, resulting in earlier peak runoff and lower base flows (Leung and Wigmosta, 1999; McCabe and Wolock, 1999; Miller *et al*., 2003; Snyder *et al*., 2004; Barnett *et al*., 2005; Mote *et al*., 2005; Regonda *et al*., 2005; Zhu *et al*., 2005; Vicuna *et al*., 2007). These trends may have begun nearly a century ago but are well-documented to have occurred over the past 60 years (Hamlet *et al*., 2005; Mote, 2006). Over this same time period, water use in the Pacific Northwest has increased substantially. Total water withdrawal in California, Idaho, Oregon and Washington increased 82% between 1950 and 2000, with irrigation accounting for nearly half of this increase (MacKichan, 1951; Hutson *et al*., 2004). Accordingly, declines in streamflow over the past half century could be due to a combination of climatic factors and increases in water use rather than to climate change alone. Availability of water resources under future climate scenarios is expected to be most limited during the late summer (Gleick and Chalecki, 1999; Miles *et al*., 2000). Development of appropriate water management strategies to deal with these shortages will require distinction between the component of late-summer flow decreases due to climate change, which cannot be immediately addressed by local and regional management, and that due to changes in water use, which can.

The lower Klamath Basin in northern California (Figure 1) provides an important example of the need to separate the effects of climate change on base flow from those of water use changes. The Klamath River and its tributaries support populations of anadromous fish species with economic, ecological, and cultural importance. Of these, coho salmon (*Oncorhynchus kisutch*, Southern Oregon/Northern California Coasts Evolutionarily Significant Unit) are listed as threatened under the U.S. Endangered Species Act (Good *et al*., 2005). In addition, steelhead trout (*O. mykiss*) and Chinook salmon (*O. tshawytscha*) in the lower Klamath Basin are of special concern or are at risk of extinction (Nehlson *et al*., 1991). Habitat degradation, over-exploitation, and reductions in water quality and quantity have been implicated in declines of these species (Nehlson *et al*., 1991; Brown et al., 1994; Good *et al*., 2005). In particular, low late-summer and early-fall streamflow in several tributaries is a major factor limiting survival of juvenile coho salmon (NRC, 2003; CDFG, 2004). Increasing late-summer tributary flow is a major objective of coho salmon recovery efforts, particularly in the Scott River (Figure 1), the most important coho salmon spawning and rearing stream in the basin (Brown et al., 1994; NRC, 2003; CDFG, 2004). If reduction in Scott River base flow has been due solely to climate change, as has been proposed by Drake *et al*. (2000), then flow objectives for coho salmon recovery may not be attainable through local management, and the success of other recovery objectives (e.g., habitat restoration) may be limited by continued low base flows. On the other hand, if reduction in base flow is due in substantial part to changes in amount, timing and source of water withdrawal, then at least that particular component of flow reduction due to water-use factors could be mitigated through local management actions.

The goal of this study is to separate the effects of climate from those of water use on trends in late-summer and early-fall flows in lower Klamath tributaries, with particular emphasis on the

Scott River. We aim to provide water and fisheries managers with information they need to design realistic and attainable base flow objectives for fisheries recovery. Although applied here to a specific basin, our methodology has wide applicability to any river system in which there are at least a few gaged streams unregulated by storage reservoirs. We provide sufficient detail in statistical methods so that they can easily be adopted by researchers in other basins.

STUDY AREA

We define the lower Klamath Basin as the drainage of Klamath River downstream of the Oregon-California state line (Figure 1). This coincides approximately with the location of Irongate Dam, which blocks upstream migration of anadromous fish, as well as the point at which the river exits the low-relief, volcanic geology of the Cascade Mountains and enters the high-relief, geologically complex Klamath Mountain and Coast Range provinces. This point is also roughly at the transition between the ocean-influenced climate to the west and the arid, intermountain climate to the east.

Elevations in the study area range from sea level to 2500 m. Annual precipitation ranges from 50 cm in the eastern-most valleys to over 200 cm at higher elevations. Nearly all precipitation falls from October through April. Precipitation occurs almost exclusively as rain at elevations below 500 m and almost exclusively as snow above 2000 m. Snowpack generally accumulates throughout the mid- to late-winter at elevations exceeding 1500 m. High relief and impermeable bedrock geology contribute to rapid runoff of both rainfall and snowmelt from upland areas, and ground water storage is generally limited to relatively small alluvial aquifers immediately adjacent to major streams. Correspondingly, stream hydrographs in the study area are of the rain/snow type (Poff, 1996), characterized by rapidly increasing discharge at the onset of the rainy season, a broad peak lasting most of the winter and spring, and recession beginning in June, once maximum snowmelt has occurred (Figure 2). Base flow, which is generally 1.5 orders of magnitude lower than peak flow, occurs during late summer and early fall. Variability in this pattern across catchments is driven by the relative contribution of rain and snowmelt to runoff, which, in turn, is determined primarily by elevation and latitude, and to a lesser degree by distance from the coast and local topographic features.

In order to focus on changes in streamflow related to climate change, we limited our analysis to streams that have a continuous record of discharge dating back at least 40 years from the present and are unaffected by storage reservoirs. Only five streams in the lower Klamath Basin met these criteria: the Scott, Salmon, Trinity (upstream of reservoirs), and South Fork Trinity rivers and Indian Creek (Figure 1 and Table 1).

All five of the study watersheds are sparsely populated, although population is increasing in some locales, particularly in the South Fork Trinity watershed. Uplands are mountainous areas managed by the U.S. Forest Service. Substantial timber harvest has occurred in all five watersheds, although it has been more limited in the Salmon and Trinity watersheds because of large amounts of federally designated wilderness. Rugged terrain and a preponderance of federal land limit most human activities to narrow river corridors in the Indian, Salmon, and Trinity watersheds. Additionally, topography prevents substantial agricultural development. The South Fork Trinity watershed supports small-scale agriculture, primarily fruit and vegetable farms, vineyards, and cattle grazing operations. Because agricultural development in the South Fork Trinity watershed is relatively small in scale, few, if any data on irrigation withdrawals are available. Only the Scott watershed contains large areas of private, non-mountainous land that support large-scale agriculture; about 35,000 acres of pasture, grain, and alfalfa are irrigated in the Scott watershed. A typical western system of water rights governs withdrawal and delivery of surface water for irrigation in the Scott Valley (California Superior Court, 1950, 1958, 1980), and the California Department of Water Resources (CDWR) collects some data on irrigation use. However, CDWR does not provide watermaster service to account for distribution of decreed surface rights in all areas of the Scott watershed, and ground-water withdrawal is not regulated.

METHODS

We assumed that temporal trends in climate, streamflow and water use have not necessarily been continuous over the past half-century, and so rather than using regression or other time-series trend methods, we applied statistical models in which the study period is divided into distinct "historic" and "modern" time periods. We then analyzed differences in snow water equivalent (SWE) and streamflow between these two time periods. We used permutation tests (Ramsey and Schafer, 2002; Good, 2005) to perform all statistical hypothesis tests. Because these types of tests have not been widely applied to water resources data, we provide a brief description of permutation testing of hypotheses in the Appendix. We performed all hypothesis tests at the a = 0.05 significance level.

All of the hypothesis tests involved comparing values of a particular precipitation or discharge variable between two groups of consecutive years. In all cases, we corrected the data for dependence due to first-order serial autocorrelation using the correction

$$x_t = u_t - r u_{t-1}, \tag{1}$$

where x_t is the corrected value of the variable for year t, u_t is the uncorrected value for year t, and r is the correlation coefficient between year-t and year-(t – 1) values (Neter *et al*., 1989; Ramsey and Schafer, 2002). We then calculated the test statistic

$$T = \frac{\bar{x}_{late} - \bar{x}_{early}}{\text{standard error}}, \tag{2}$$

where $\bar{x}_{late}$ is the mean of the corrected daily discharge values over the later of the two time periods, $\bar{x}_{early}$ is the mean over the earlier period, and

$$\text{standard error} = s\sqrt{\frac{1}{n_{early}} + \frac{1}{n_{late}}}, \tag{3}$$

where s is the pooled standard deviation, n_{early} is the number of years in the early period, and n_{late} is the number of years in the late period. Although (2) is the test statistic of the standard two-sample t-test, we use it instead in permutation tests and also as the response variable in permutation regressions. Thus, we refer to at as a generic "*T*"-statistic, because in our applications, it may not necessarily have a *t*-distribution.

To define what we will refer to as the "historic" and "modern" time periods, we analyzed daily discharge at the Scott River gage (Figure 1 and Table 1) from the earliest water year of record, 1942, through 2005. For each calendar day except February 29, which was omitted from all analyses, we first $\log_{10}$-transformed the daily discharge data to prevent rare but extreme daily flow events from exerting excessive influence over time-period means. We then divided the 1942-2005 period into an "early" period, defined as calendar years 1942 through $N - 1$, and a "late" period, defined as calendar years N through 2005, where N took on all calendar year designations from 1952 through 1996. This iteration on N divided the 1942-2005 set of years into all possible complementary pairs of subsets of at least 10 years in duration. For each calendar day, we compared discharge between early and late time periods with a permutation test on the *T*-statistic (see Appendix). We performed these tests with a two-sided alternative. The historic and modern periods were then defined to be the early and late periods, respectively, that resulted in the greatest number of consecutive days over which there was a significant difference in discharge. The period of consecutive days with significantly different discharge was defined to be the "late summer" period. For comparison, we performed this same analysis on the other four study streams.

We tested for differences in late-summer discharge between historic and modern periods at all five stream gages. Because of the smoothing inherent in averaging daily discharge over the 65-day late-summer period, we did not transform the raw discharge data. These tests were performed with the one-sided alternative that late-summer discharge during the modern period was less than that during the historic period, in accordance with what would be expected based on climate change. We also performed this analysis on annual water-year discharge, using a one-sided alternative for consistency with the late-summer analysis.

To compare discharge trends among the five study streams, we used a before-after-control-impact-pairs analysis (Stewart-Oaten *et al*., 1986). For each of the ten possible pair-wise combinations of the five study streams, we analyzed the discharge ratio $\frac{Q_a}{Q_b}$, where Q_a is the discharge in the stream with the smaller discharge values and Q_b is the discharge in the larger values. We computed the ratio in this manner in order to prevent small values in the denominator from producing extremely large values of the ratio. We performed these tests for both late-summer discharge and water-year discharge. We used two-sided alternatives here because the purpose of the paired-basin tests was to assess differences in streamflow response among the study streams, and if factors other than climate change affected this response, we would not know *a priori* which stream in a given pair should have the lower relative streamflow during the modern period.

To quantify dependence of change in SWE and streamflow on elevation, we performed permutation regression analysis (see Appendix) of the *T*-statistic (2) as a function of elevation. In this case, the *T*-statistic (2) serves as a dimensionless measure of change in SWE or streamflow between historic and modern periods and thus allows direct comparison of the regression line for streamflow to that for SWE. To incorporate the effect of latitude, we used

Mote's (2006) estimate that winter isotherms along the Pacific Coast of North American increase southward at a rate of 137 m in elevation per degree of latitude. We referenced latitude to that of Indian Creek, the northern-most study watershed, and defined latitude-adjusted elevation of a given snow course or study watershed to be

$$E_{adjusted} = E - 137(L_{Indian} - L) \tag{4}$$

where E is the actual elevation of the snow course or watershed (mean over the watershed), $E_{adjusted}$ is the adjusted elevation, L_{Indian} is the watershed-centroid latitude of the Indian Creek watershed, and L is the latitude of the snow course or watershed-centroid. For the SWE analysis, we used April 1 SWE data for all 16 snow survey courses in the study area for which at least 40 years of data were available (Figure 1, Table 2), and regressed dimensionless change in April 1 SWE against latitude-adjusted snow course elevation. We performed an analogous regression for change in late-summer discharge against latitude-adjusted mean watershed elevation for the five study streams.

Lastly, we estimated the component of base-flow decrease in the Scott River due solely to climate by comparing daily flow in the Scott River with that of a reference stream. Based on geographic proximity and lack of substantial changes in anthropogenic effects on water resources over the past half-century, either the Salmon or Trinity could serve as the reference stream for this estimate. Although the Trinity River watershed is closer in elevation to that of the Scott, we chose the lower-elevation Salmon as the reference watershed in order to overestimate the effects of climate change on the Scott River and hence provide a conservative estimate of the component due to non-climatic factors. We used standard regression analysis to determine the power-law dependence of daily Scott River discharge on daily Salmon River discharge. Because the regression was used for prediction and not for hypothesis testing, we did not correct daily values for serial autocorrelation. In this analysis we used all daily flow values from July 1 through October 22 during each of the calendar years in the historic period. This period of days was chosen because it was the time period over which the relationship between historic and modern discharge in the Scott River differed most from that same relationship in the Salmon River (Figure 2). We applied this power-law function to modern-period Salmon River daily discharge values to estimate what discharge would have been in the Scott River during the modern period if response of flows in the Scott River to regional climate change had been the same as that of flows in the Salmon River. The difference between this estimated modern-period discharge and the observed modern-period discharge was our estimate of the component of Scott River summer discharge decrease due factors other than climate. For comparison, we also determined the power-law dependence of Scott River discharge on Salmon River discharge over the modern period.

RESULTS

The longest period of consecutive days over which Scott River discharge differed significantly between early and late periods occurred when the late period began in 1977 (Figure 3). This period was August 2 through October 5. Only a few days of significant difference occurred outside of the late-summer days shown in Figure 3, and these were all in mid-November and all for divisions in which the late period began in years 1985 through 1989. None of the other four streams had any individual days for which discharge was significantly different between early and late periods.

Mean daily hydrographs showed relatively small differences between historic and modern periods, with the exception of substantially lower modern-period discharge during late summer and early fall in the Scott River (Figure 2). Mean annual discharge in all five study streams was lower during the modern period, but none of the differences were significant (Table 1). Mean late-summer discharge was lower during the modern period in the Scott, Indian, and South Fork Trinity watersheds, and these differences were significant for the Scott and South Fork Trinity and marginally significant for Indian Creek (Table 1). The Scott River showed by far the greatest decrease in late summer discharge between the two time periods (40.3%, $P = 0.00999$). Late-summer discharge in the Salmon and Trinity rivers increased slightly between historic and modern periods, but the increase was not significant. The paired-basin tests revealed that basin-relative change in late-summer flows between the two time periods followed a well-defined order given by: Scott < South Fork Trinity < Indian < Salmon < Trinity. All pair-wise differences in ratio were significant except that between the Indian and Salmon (Table 3). The decreases in late-summer discharge in the Scott River relative to the other four basins were the strongest trends observed in the pair-wise analysis. No significant differences were observed in any of the pair-wise tests for difference in ratio of annual discharge.

Mean April 1 SWE was lower in the modern period at all seven snow courses below 1800 m, and these differences were significant at four of these courses and marginally significant at a fifth (Table 2). Mean April 1 SWE was higher in the modern period at five of the nine courses with elevations above 1800 m, but none of these differences were significant. Change in April 1 SWE between historic and modern periods showed a significant, positive dependence on adjusted snow-course elevation (Figure 4). There was no significant dependence of change in late summer streamflow on adjusted drainage-basin elevation among the five study watersheds, but this dependence was significant when the Scott River was removed from the analysis (Figure 4). The slopes of the SWE and the significant (i.e., Scott River not included) flow regression lines were similar (0.00427/m for change in SWE, and 0.00539/m for change in late summer flow). Under the null hypothesis that the SWE and significant flow regressions are independent of each other, permutation analysis showed that the probability of obtaining a linear relationship between change in SWE and elevation as significant as that observed and a relative difference between the slope of the two lines this small is $P = 0.00203$ (see Appendix). This provides strong evidence that the similarity in slopes of these two regression lines cannot be due to chance alone, i.e., that the dependence of change in streamflow on elevation is linked with that of change in SWE, as expected based on the underlying hydrologic processes.

There was a strong power-law relationship dependence of daily Scott River discharge on daily Salmon River discharge over the period July 1 through October 22 for both historic and modern time periods (Figure 5). However, Scott River discharge was much lower relative to Salmon River discharge during the modern period than during the historic period. Furthermore, whereas the magnitudes of daily discharge in the Salmon River showed little difference between the historic and modern periods, daily discharge in the Scott River showed a large decrease in mean (from 3.23 m^3/s to 2.15 m^3/s). During the historic period, discharge in the Scott River was less than 1 m^3/s on 4.26% of all days from July 1 through October 22, whereas during the modern period, flows were less than 1 m^3/s on 46.2% of these days. Applying the historic-period power-law relationship to modern-period Salmon River daily discharge produced an estimate of Scott River daily flow under the influence of climate change alone (Figure 6). The estimated mean hydrograph differed very little from the observed historic-period hydrograph except during October, when estimated modern-period discharge was lower. Observed July 1 through October 22 discharge in the Scott River averaged 31.8 Mm^3/yr during the historic period and 21.3 Mm^3/yr during the modern period. Our estimate of July 1 through October 22 discharge under the influence of climate change alone is 26.5 Mm^3/yr during the modern period. Thus, the component of decrease in Scott River discharge due to factors other than climate is conservatively estimated at 5.2 Mm^3/yr, 50% of the observed decrease.

DISCUSSION

Climate patterns in the Pacific Northwest since the mid-20th century have been affected by both long-term, systematic warming and by decadal-scale oscillations (Hamlet *et al*., 2005; Regonda *et al*., 2005; Stewart *et al*., 2005). We found that the greatest number of days of significantly lower discharge in the Scott River occurred when the late period began in 1977, exactly when the Pacific Decadal Oscillation (PDO) entered a warm, dry phase. This period was generally associated with lower snowpack and streamflow throughout the Pacific Northwest, especially when compared with those of the cool, wet 1945-1976 period (Mote, 2006). As we included an increasing portion of this phase in the early period, the difference between early and late periods decreased to zero (Figure 3). Furthermore, all of our study streams showed small to moderate decreases in total annual discharge during the modern period, independent of SWE or base flow trends. Thus, much of the climate-based difference between our historic and modern periods is probably due to dominance of the historic period by a cool phase in the PDO and dominance of the modern period by a warm phase. Barthalow (2005) observed a warming trend of 0.5 °C/decade in Klamath River water temperatures over this same time period, which was thought to be related to the PDO.

Regardless of the degree to which our two time periods reflect short- versus long-term climate patterns, base flow in Pacific Northwest rain-snow systems is strongly dependent on timing and amount of snowmelt, which is reflected by April 1 SWE (McCabe and Wolock, 1999; Leung and Wigmosta, 1999; Gleick and Chalecki, 1999). Trends in April 1 SWE appear to be driven primarily by temperature, which, along the Pacific Coast, is a function of elevation and latitude (Knowles and Cayan, 2004; Mote, 2006), and secondarily by precipitation (Hamlet *et al*., 2005; Mote *et al*., 2005; Stewart *et al*., 2005). Models indicate that global warming may increase precipitation over the Pacific Northwest (McCabe and Wolock, 1999; Leung and Wignmosta, 1999; Salathé, 2006) so that at the highest elevations, April 1 SWE may actually increase as a result of climate change due to increased winter-time precipitation, despite the trend toward higher temperatures. In the lower Klamath Basin, SWE has declined significantly at many lower-elevation snow courses but has increased slightly at several higher-elevation courses (Table 2). Thus, our results are consistent with regional-scale analyses and reflect trends in both temperature and precipitation.

The patterns of base flow change between the historic and modern periods in the South Fork Trinity, Indian, Salmon and Trinity watersheds are exactly as predicted by SWE-elevation-latitude relationships. The within-basin analysis (Table 1), the paired-basin analysis (Table 3), and the regression analysis (Figure 4) all show that absolute and relative base flow in the modern period in these streams are ordered as predicted by latitude-corrected elevation: South Fork Trinity < Indian < Salmon < Trinity. The lowest of these show significant decreases in base flow, as predicted by significant decreases in SWE at lower elevations. The higher two basins show moderate, but statistically insignificant increases in base flow, as predicted by small increases in SWE at higher elevations. Increases in late-summer flow have occurred in the Salmon and Trinity watersheds despite moderate decreases in total annual flow in these streams, suggesting effects from finer-scale patterns in temperature and precipitation that we did not analyze.

Base-flow trends in the Scott River clearly do not follow those of the other four streams. The latitude-corrected elevation of the Scott River watershed is only 31.5 m less than that of the Trinity River watershed (Figure 4), but base flows in the Scott River showed by far a greater decrease between historic and modern periods than those in any of the other four watersheds. The paired-basin analyses (Table 3), regression relationships (Figure 4), and Salmon River comparison (Figure 5) provide strong evidence that base flow in the Scott River has responded to climate in a much different way than the other four streams and/or that factors other than climate have contributed to changes observed in Scott River base flow since the late 1970s.

Certainly, some of the trends in Scott River base flow are due to the same climatic factors that have affected the other study streams. Differences in Scott River base flow between early and late periods were greatest when the late period began with the first year of the warm-phase PDO (Figure 3), suggesting a strong link between Scott River base flow and climatic variability. Decreases in mean annual discharge between historic and modern periods were 6.2% in the Trinity River, 13.0% in the Salmon River, 14.3% in Indian Creek, 15.1% in the Scott River, and 17.0% for the South Fork Trinity River (Table 1). *P*-values for the significance of these declines were remarkably similar for all but the Trinity River (Table 1). Furthermore, the paired-basin analysis showed no significant trends in total annual discharge among the study streams. Thus, at the annual scale, response of the Scott River to climatic differences between the two time periods was indistinguishable from those of the other study streams. Differences in response of the Scott River relative to the other streams appear to be limited only to base flow trends.

Geographic factors may be partially responsible for the large apparent difference in base flow response between the Scott River and the other study streams. Although not the furthest east of the study basins, the Scott watershed does lie partially within a precipitation shadow formed by the large region of high-elevation terrain to the west of the watershed, contributing to a drier, more continental climate than that of the other four study watersheds. The Scott watershed has by far the smallest basin yield (discharge per unit watershed area, Table 1), an indication of both lower precipitation and higher evapotranspiration, the latter of which includes a large amount of irrigation not present in the other watersheds. The elevation dependence exhibited by base flow change in the other streams predicts an increase in base flow in the Scott River between historic and modern periods (Figure 4). However, the comparison with the Salmon River predicts a decrease, albeit one only half as great as that observed. The two snow courses with the largest decreases in April 1 SWE were courses 4 and 285, located on the western side of the Scott watershed (Table 2, Figure 1, Figure 4). Although these are two of the lower-elevation snow courses in the study area, their decline is disproportionate with their elevation (Figure 4). The large decreases in April 1 SWE at these courses could be due to local geography (e.g., the precipitation shadow), but a snow survey technician who has conducted measurements at these courses noted that forest vegetation has encroached on the courses, reducing accumulation of snowpack on the courses themselves (Power, 2001). Furthermore, none of the other courses in the Scott basin (numbers 5, 298 and 311) show patterns inconsistent with the rest of the courses, and SWE has increased slightly at courses 5 and 311 (Table 2).

Additional data support the conclusion that part of the observed decrease in Scott River base flow since the 1970s is due to an increase in withdrawal of water for irrigation in the Scott Valley. Although data on water use in the Scott Valley are sparse and difficult to obtain, those that we were able to find show that irrigation withdrawals in the Scott Valley more than doubled between the 1950s and the late 1980s (Figure 7). We were unable to locate data from the 1960s and 1970s to determine when the majority of the increase occurred, but across the western U.S. as a whole, the largest increase in irrigation withdrawal between 1950 and 2000 occurred in the 1970s (Hutson *et al*., 2004).

Perhaps more importantly, ground water replaced surface water as the dominant source of irrigation water in the Scott Valley between 1990 and 2000 (Figure 7), reflecting trends observed across the western U.S. (Hutson *et al*., 2004). Mack (1958) estimated that during water year 1953, recharge to the alluvial aquifers in the Scott Valley was provided by precipitation (about 25 Mm^3), irrigation seepage (about 21 Mm^3), and tributary inflow (unspecified amount). Because conveyance for sprinkler irrigation now occurs in a pipe network, groundwater recharge related to the former flood irrigation practices has been eliminated, as has been observed in other locations around the western U.S. (Johnson *et al*., 1999; Venn *et al*., 2004). Total withdrawal of ground water for irrigation averaged 50 Mm^3 per year from 1998 to 2001. Even if recharge due to precipitation and tributary inflow have remained unchanged, then change in irrigation application method and increased pumping of ground water in the Scott Valley could have resulted in decline of aquifer water levels. These alluvial aquifers discharge to the Scott River and its tributaries (Mack 1958), and thus decline in aquifer levels could result in lowered base flows in the Scott River, potentially impacting salmonid rearing and migration, and the aquatic community as a whole. Because of lag times inherent in ground water responses, even if pumping occurs during the middle of the irrigation season, effects on base flow could persist into the late summer and early fall. Furthermore, because ground-water pumping in the Scott Valley is unregulated, effects on base flow could be far greater than would be indicated by reported annual withdrawal amounts alone.

Our conclusion that the decrease in Scott River base flow is due in part to an increase in irrigation use is contrary to the conclusion of Drake *et al*. (2000), who concluded that the decrease is due solely to decline in SWE. The disparity in these conclusions is easily explained by analysis methods. First, Drake *et al.* (2000) analyzed hydrologic data from the Scott River watershed alone, whereas our study employed a comparative approach using other watersheds in the basin. Secondly, Drake *et al*. (2000) based their conclusion on decrease in April 1 SWE at snow courses 4 and 285 and a single term representing this SWE in a multiple regression equation explaining September discharge in the Scott River. Their regression equation was

$$Q = (2.5 + 1.18 \times \text{annual precip.} + 8.6 \times \text{August precip.} - 6.7 \times \text{July precip.} + 0.48 \times \text{course 285 SWE} + 0.25 \times \text{course 5 SWE})^2, \tag{5}$$

where Q is September discharge, annual and monthly precipitation are as recorded on the Scott Valley floor, and April 1 values were used for the SWE terms. Based on mean values for the explanatory variables in this regression equation, the annual precipitation term is six times greater in magnitude than the August precipitation term and over ten times greater in magnitude than the July precipitation term. Thus, the August and July precipitation terms contribute relatively little to September discharge. At best, their appearance in the regression equation is correlative and not causative; almost all precipitation that falls during the summer is lost to evapotranspiration and has little or no effect on streamflow. The annual precipitation term is about 1.5 times greater than the snow course 285 term and about 3 times greater than the snow course 4 term. Mean annual precipitation at the Ft. Jones weather station, located near the Scott River gage, was 55.9 cm during the historic period and 54.8 cm during the modern period. April 1 SWE at course 5 averaged 80.8 cm during the historic period and 81.4 cm during the modern period. These two variables show almost no change between historic and modern periods, and the sum of their respective terms in the regression equation is over twice as large as the snow course 285 term. Therefore, the conclusion of Drake *et al*. (2000) is based on a single term that accounts for less than one-third of the total magnitude of the variable terms in their regression equation.

Based on our estimate of the component of Scott River base-flow decrease due to changes in water use, returning irrigation to pre-1977 patterns in the Scott River would, in theory, increase July 1-October 22 discharge by an average of 0.512 m^3/s. This estimate includes continued irrigation withdrawal at the pre-1970s rate of about 50 Mm^3 and accounts for the decrease in streamflow due to climate change. Under current conditions, streamflow in the Scott River can drop below 0.283 m^3/s in the late summer and early fall of dry years. At this discharge, some reaches of the river become a series of stagnant and disconnected pools that are inhospitable to many aquatic species. An additional 0.512 m^3/s could create a viable corridor for movement of aquatic species, decrease fluctuations in water temperature (particularly daily maxima), and maintain the functionality of cold water seeps and tributary mouths upon which salmonids rely (Cederholm et al. 1988; Sandercock 1991; Stanford and Ward 1992). Although it is not likely that irrigation sources, withdrawal amounts, and application methods in the Scott River watershed will revert back to those of the 1960s, our results at least show that observed declines in base flow have not been due to climate change alone and hence could be reversed to the benefit of salmon and other aquatic life through changes in water management. However, management of water resources in the Scott Valley to meet the needs of both agriculture and fish will require consistent and accurate watermaster service for the entire valley, quantification of groundwater withdrawals and their effects on surface water, and water-use data that are easily obtainable.

CONCLUSIONS

Since the 1940s, April 1 SWE has decreased significantly at low-elevation snow courses in the lower Klamath Basin in response to climate variability and change. No significant trends were apparent at higher elevations. Correspondingly, base flow has decreased significantly in the two study streams with the lowest latitude-adjusted elevation and increased slightly in two of the other study streams. With the Scott River excluded from the analysis, the dependence of base-flow change on adjusted elevation follows the same trend as that of SWE. Despite a latitude-adjusted elevation only 1.8% lower than the highest-elevation watershed in the study, the Scott River has experienced a much larger reduction in base flow than the other study streams. Geographic differences may account for some of the discrepancy in base flow trends between the Scott River and the other four watersheds. However, irrigation withdrawal in the Scott watershed has increased from about 48 Mm^3 per year to over 100 Mm^3 since the 1950s, and the amount of ground water withdrawn for irrigation has increased from about 1 Mm^3 per year to about 50 Mm^3. We conservatively estimate that half of the observed 10 Mm^3 decline in July 1-October 22 discharge in the Scott River is due to changes in irrigation use. Returning water use to pre-1977 patterns in the Scott River watershed would benefit salmon and other aquatic biota by increasing July 1-October 22 streamflow by an average of 0.512 m^3/s while still allowing irrigation withdrawal at a rate of about 50 Mm^3 per year.

If our study watersheds are representative of others in the lower Klamath Basin, climate- induced decreases in late-summer streamflow in low-elevation watersheds will, at best, complicate the recovery of anadromous salmonids and may, at worst, hinder their persistence. Sound water management and recovery efforts such as habitat and watershed restoration will be required to help offset the effects of climate change on river ecology, particularly because both decreased base flows and increased water temperatures occur simultaneously during warm periods. Because rivers and streams at lower elevations are particularly susceptible to changes in climate, they are more sensitive to local, human-induced changes associated with water and land use. The South Fork Trinity River is of particular concern. It harbors one of the few remaining stocks of wild spring chinook salmon in the entire Klamath Basin, and the latitude and elevation of the drainage put it at particular risk of climate-induced changes that adversely affect chinook salmon and other species. Furthermore, development and largely unquantified water use on the South Fork Trinity River and important fish bearing tributaries such as Hayfork Creek exacerbate the problem. We recommend additional gaging on streams that are susceptible to the effects of human use, such as Hayfork Creek, and on streams that drain wilderness areas, such as Wooley Creek in the Salmon River watershed, in order to monitor future trends in water use and climate in the lower Klamath Basin.

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TABLE 1. Study basin descriptions and discharge statistics. Historic period ends with water year 1976; modern period is 1977 through 2005. *P*-values are reported for the one-sided alternative hypothesis that modern-period discharge is less than historic-period discharge.

	Scott River	Indian Creek	Salmon River	South Fork Trinity River	Trinity River
USGS stream gage	11519500	11521500	1522500	11528700	11523200
Drainage area (km^2)	1691	311	1945	1979	386
Mean basin elevation (m)	1688	1220	1386	1378	1734
Latitude of basin centroid (°N)	41.479	41.904	41.293	40.468	41.228
Earliest year analyzed	1942	1958	1942	1958	1966
Mean annual historic-period discharge (Mm^3)	605.7	403.1	1744	1420	385.0
Mean annual modern-period discharge (Mm^3)	514.0	345.3	1517	1175	361.1
P-value: historic and modern annual discharges equal	0.127	0.116	0.113	0.163	0.294
Mean late summer historic-period discharge (Mm^3)	10.96	9.193	37.04	14.77	7.273
Mean late summer modern-period discharge (Mm^3)	6.541	8.274	37.47	12.08	8.024
P-value: historic and modern late summer discharges equal	0.00999	0.0547	0.629	0.0486	0.799

TABLE 2. Snow course descriptions and April 1 snow water equivalent (SWE) statistics. Table is sorted by elevation for ease of interpretation. Data are from the California Department of Water Resources snow course database, http://cdec.water.ca.gov/misc/SnowCourses.html, *accessed* May, 2007. Historic period is earliest year of record through 1976; modern period is 1977 through 2005. *P*-values are reported for the one-sided alternative hypothesis that modern-period SWE is less than historic-period SWE.

Course No.	Elevation (m)	Latitude (°N)	Earliest year of record	Mean historic-period April 1 SWE (cm)	Mean modern-period April 1 SWE (cm)	*P*: historic and modern April 1 SWE equal
17	1554	41.077	1946	40.3	30.2	.0213
14	1646	41.150	1947	84.7	90.2	0.666
285	1676	41.397	1951	104.2	68.2	0.00109
15	1722	41.197	1947	66.2	52.0	0.0218
298	1737	41.233	1956	49.4	44.5	0.224
3	1783	41.382	1942	37.0	30.0	0.0588
4	1798	41.400	1951	95.0	52.1	0.000208
16	1838	41.093	1942	55.5	51.5	0.261
13	1875	41.200	1949	91.1	91.1	0.482
311	1890	41.225	1949	71.1	72.5	0.568
12	1951	41.008	1947	127.8	126.7	0.434
11	1981	40.967	1947	95.2	101.2	0.704
5	2012	41.217	1946	80.8	81.4	0.524
1	2042	41.367	1942	95.3	88.4	0.218
10	2042	41.023	1946	111.7	112.7	0.542
9	2195	41.318	1946	84.2	86.9	0.634

TABLE 3. Paired-basin tests of the null hypothesis that the ratio of late summer (August 2 through October 5) discharge is equal between modern and historic periods. *P*-values are reported for the two-sided alternative hypothesis.

Pair	Stream with lower relative late summer discharge in modern period	*P*-value: historic and modern late-summer discharge ratios equal
Scott/Trinity	Scott	0.000458
Scott/Salmon	Scott	0.00111
Scott/South Fork Trinity	Scott	0.0100
Scott/Indian	Scott	0.00322
South Fork Trinity/Trinity	South Fork Trinity	0.00719
South Fork Trinity/Salmon	South Fork Trinity	0.0348
South Fork Trinity/Indian	South Fork Trinity	0.0183
Indian/Trinity	Indian	0.00142
Indian/Salmon	Indian	0.174
Salmon/Trinity	Salmon	0.0447

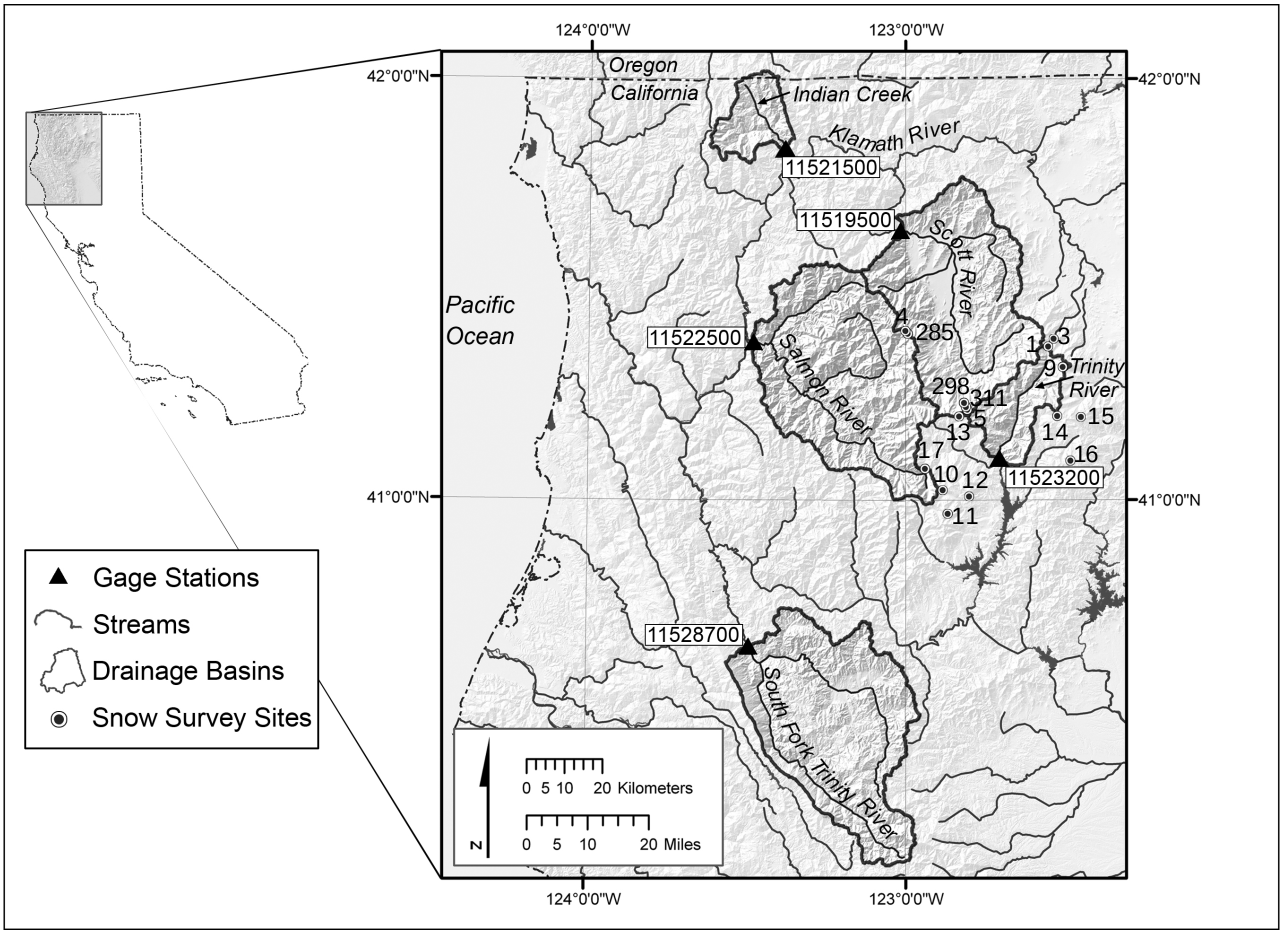
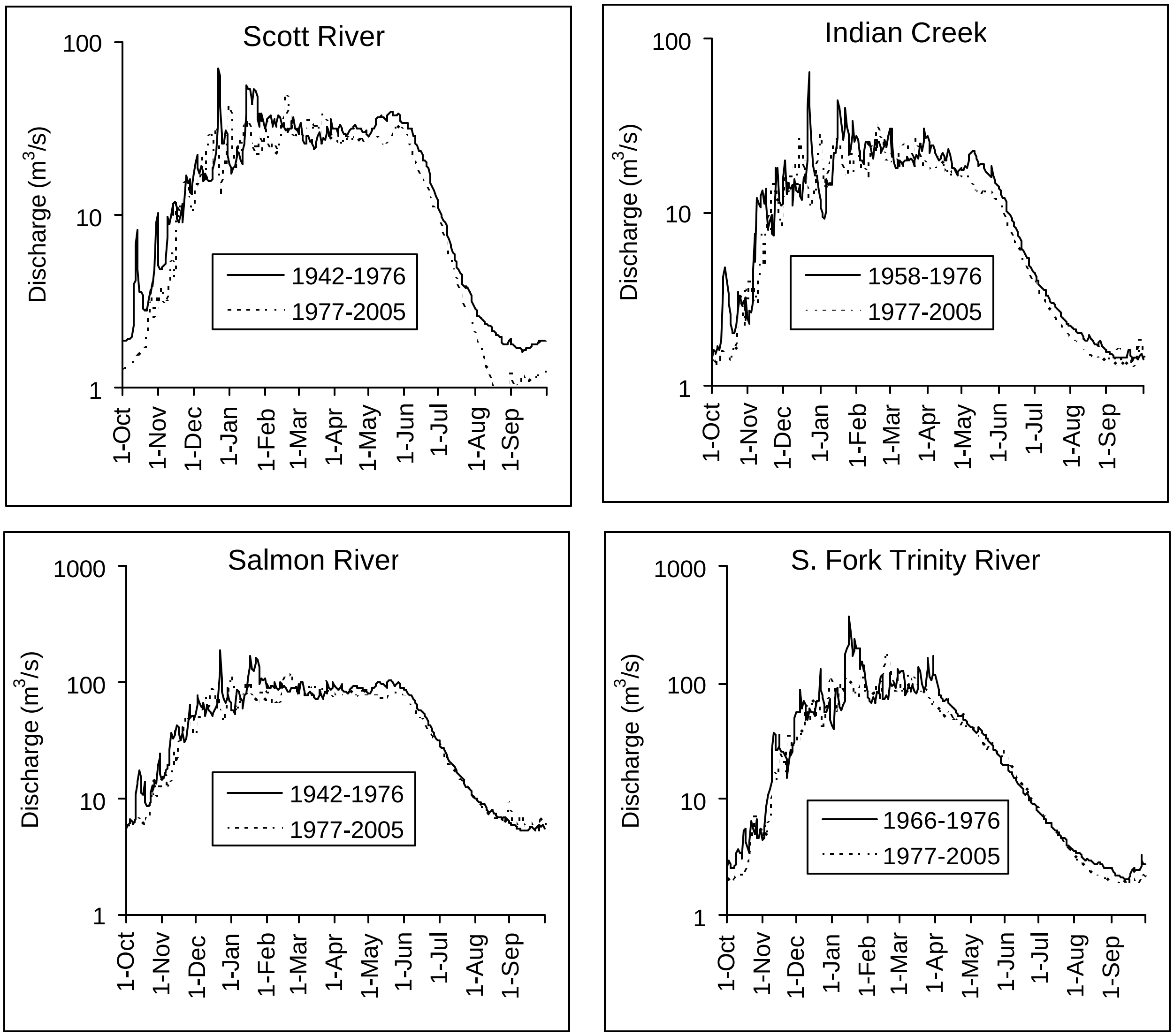


FIGURE 1. Map of lower Klamath Basin, California, showing study watersheds, stream gages, and snow courses used in this study. Snow course and stream gage numbers correspond to those listed in Tables 1 and 2.



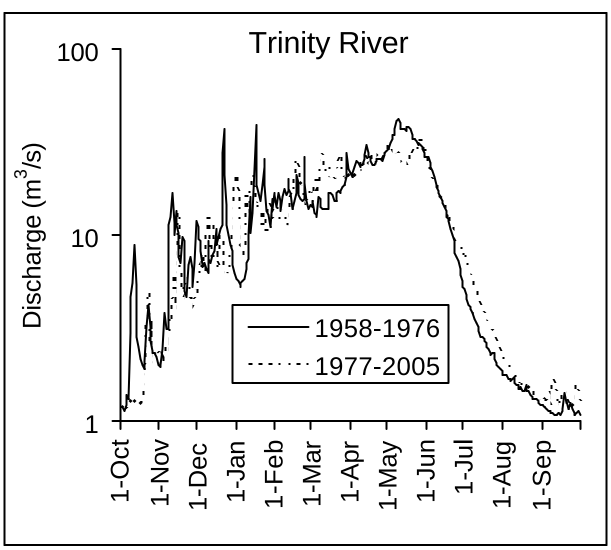


FIGURE 2. Mean historic- and modern-period hydrographs for the five study streams. All streams display a rain-snow hydrologic regime with base flow period during late summer.

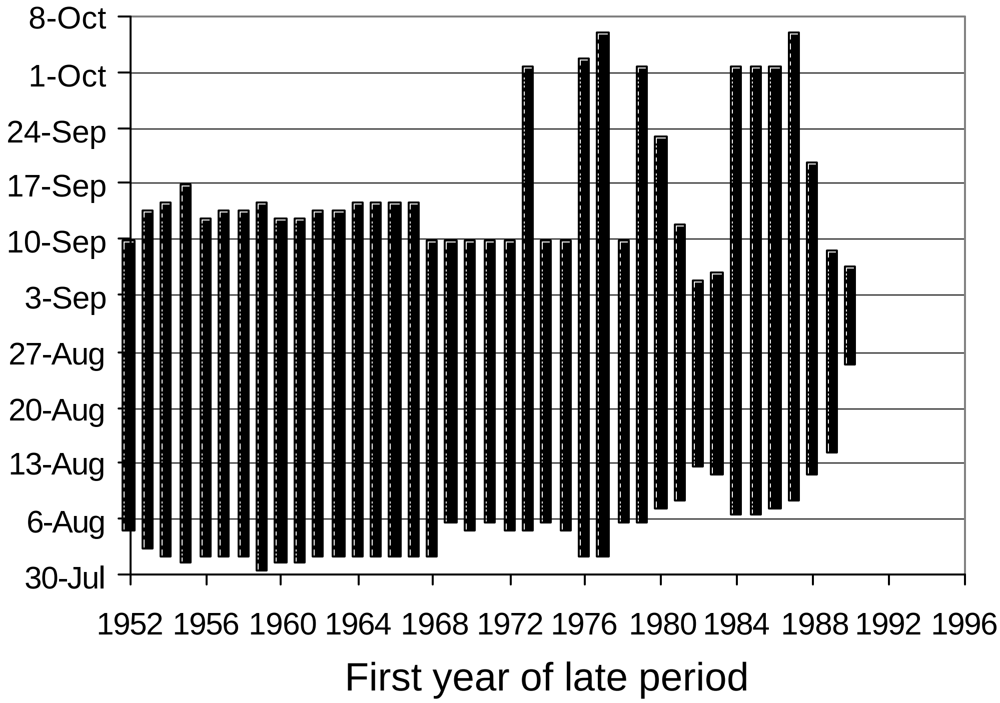


FIGURE 3. Consecutive days during which late-period discharge is significantly less than early-period discharge (at a = 0.05) in the Scott River as a function of the year in which the late period begins. Early period begins in 1942; late period begins in the year indicated on the horizontal axis and ends in 2005.

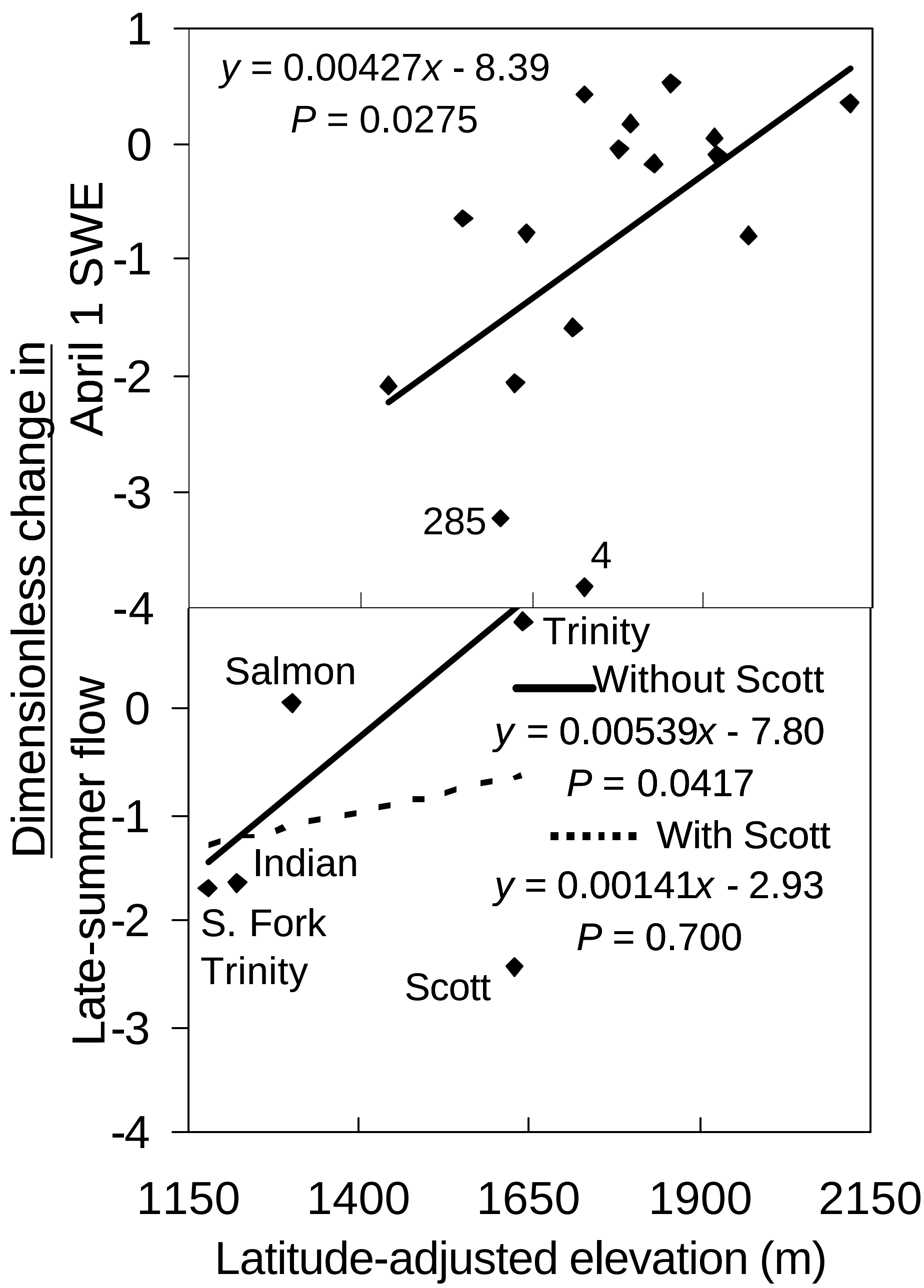


FIGURE 4. Change in April 1 snow water equivalent (SWE, top) and late-summer flow (bottom) between the historic and modern periods as a function of latitude-adjusted elevation. Decrease in both parameters is measured by the dimensionless *T*-statistic (2).

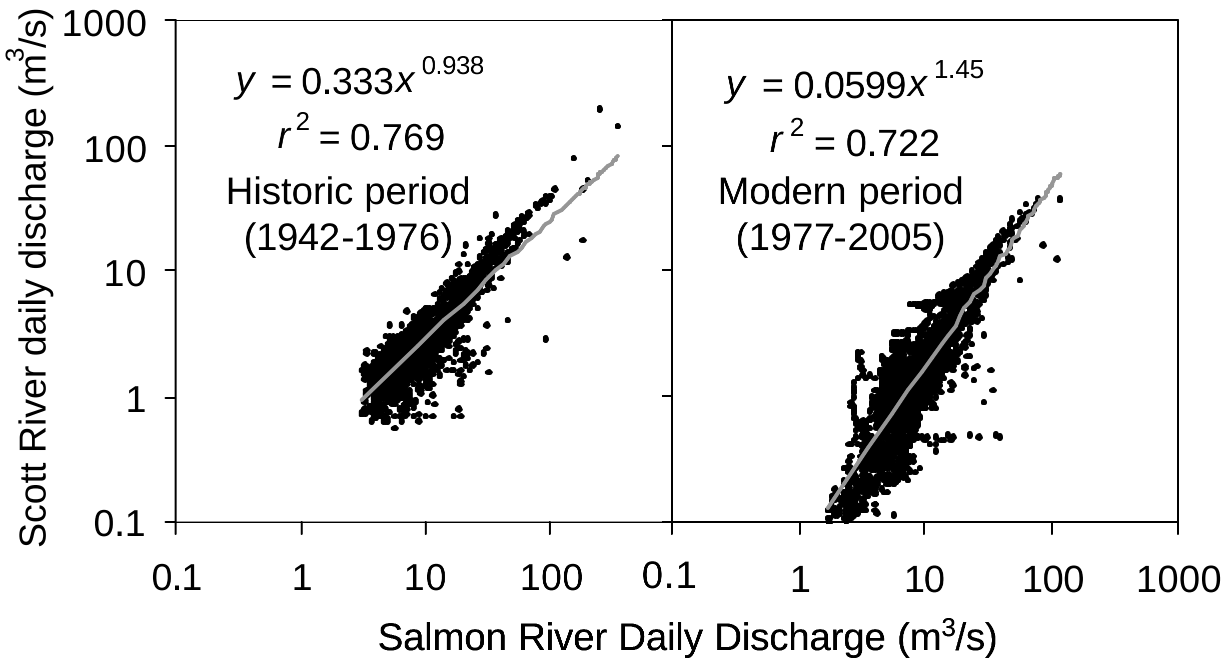


FIGURE 5. Scott River daily discharge as a function of Salmon River daily discharge for July 1 through October 22, historic and modern periods.

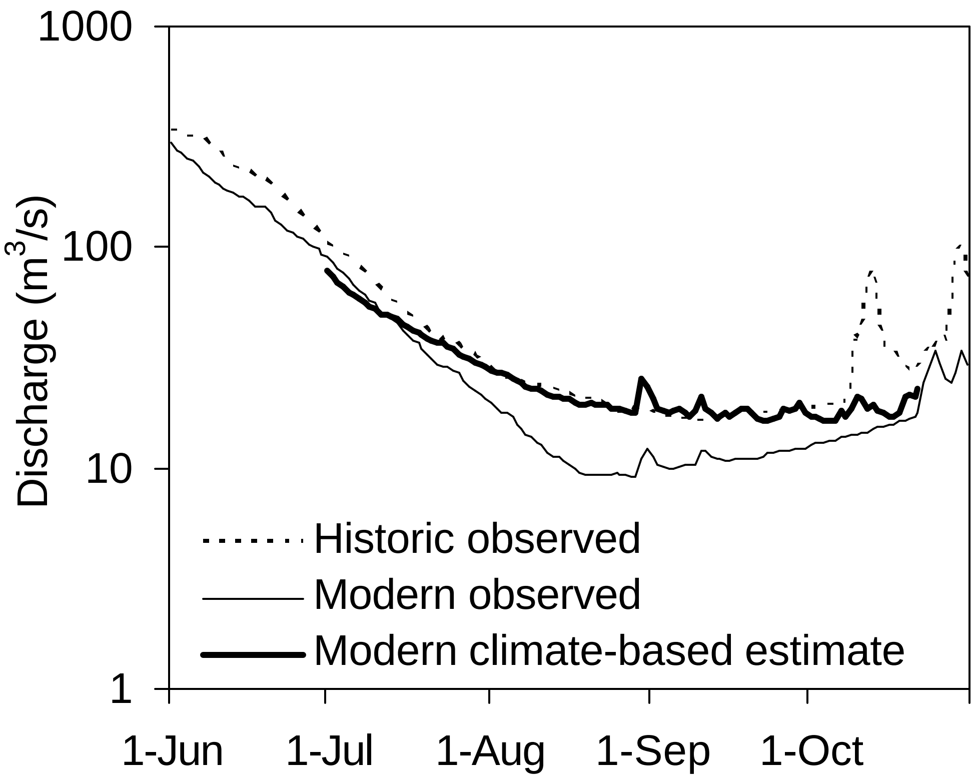


FIGURE 6. Mean summer and early-fall hydrographs for the Scott River, showing observed historic- and modern-period discharge and estimated modern-period discharge based on climatic effects alone.

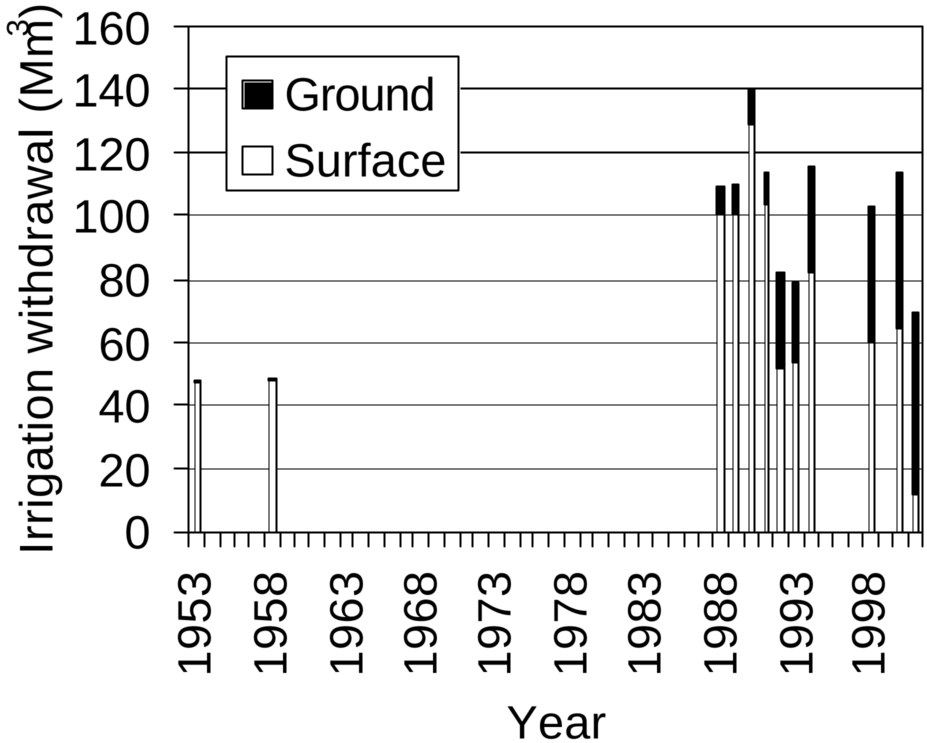


FIGURE 7. Annual irrigation withdrawal in the Scott River basin from 1953 to 2001. Data for 1953 are from Mack (1958). Data for 1958 were provided by Bill Bennet (retired), California Department of Water Resources. All other data were provided by the California Department of Water Resources upon request.

APPENDIX: PERMUTATION TESTS

Standard statistical hypothesis tests are commonly used to analyze time-series data collected at precipitation and streamflow gages (e.g., Helsel and Hirsch, 1992; McCuen, 2003). Almost all of these tests, whether parametric or nonparametric, are based on the assumption that the data were obtained through random sampling of infinite populations. The result of analyzing a test statistic based on the sample(s) is an inference that is made on the population(s). However, this hypothesis testing framework is almost never appropriate for application to data collected at precipitation and stream gages. First, these types of data are not randomly selected. The locations of stream and precipitation gages are almost never randomly chosen, and the recording of data at regular intervals such as days, months or years does not constitute random selection. Second, the data rarely constitute a sample but rather comprise the entire population. As a result of this second observation, there is no appropriate population to which inference can be made. For example, if we are analyzing the difference in annual discharge between two time periods and have discharge values for every year in both time periods, then we have the entire population at hand. There is no sampling, and hence no population to which inference can be drawn. Permutation tests (also called randomization tests in experimental contexts) are the appropriate statistical tests to use for analysis of these and other types of non-sampled data (Ramsey and Schafer, 2002). We refer the reader to the comprehensive texts by Edgington (1995) and Good (2005) for a full treatment of theory and methodology and here present only a brief treatment of the two permutation tests used in this article.

The basic concept behind permutation tests is best illustrated by the example of testing for differences in mean between two groups. Consider the comparison of late-summer discharge in the Scott River between the two time periods. The data constitute annual values for each of the 64 years between 1942 and 2005, inclusive. The particular means we report in Table 1 are based on division of this 64-year period into one 35-year period (historic, 1942-1976) and one 29-year period (1977-2005). We measure the magnitude of their difference, relative to their variability, using the standard test statistic (2). This division of 64 years into groups of size 35 and 29 is one of the $\frac{64!}{35!29!} = 1.39 \times 10^{18}$ distinct ways in which this population of 64 annual values can be divided into two complementary groups. Each of these distinct ways is called a permutation, and each has associated with it a particular value of the test statistic. The distribution of these test statistics is called the permutation distribution. The *P*-value of the permutation test is the probability, based on the permutation distribution, of having obtained a value of the test statistic as extreme or more extreme (using either one or two tails, as appropriate to the alternative hypothesis) than the one obtained from the observed grouping (i.e., division of the time period into 1942-1976 and 1977-2005 time periods). That is, the *P*-value is the probability that we could have selected a permutation at random that had a difference in means as great as that in the observed permutation.

In practice, when the number of permutations is relatively small, on the order of 10^4 or less, it is easy to simply compute the test statistic for every possible permutation and obtain the exact *P*-value of the test. This procedure is inherently nonparametric, even if we use a test statistic such as (2) that is usually used in the context of a parametric test. We simply compare the observed test statistic with all the others and determine exactly how many permutations out of the total result in test statistic value as extreme or more extreme than the one observed. This requires no assumptions about the distribution of the original data and in fact will result in the same *P*-value with use of any number of different test statistics. For example, in the two-group comparison case, it can be shown that one obtains the same *P*-value when the simple difference in means is used instead of the *T*-statistic (Edgington, 1995).

When the number of permutations is large, there are two choices for conducting the test. One is to randomly select a large number of permutations from among those possible and use this sample to represent the entire set of permutations. The other is to use a standard parametric test statistic (such as the *T*-statistic) from an analogous sample-based hypothesis test. It has been shown that for the permutation versions of most of these basic tests, the permutation distribution approaches the sampling distribution of the test statistic asymptotically as the number of permutations becomes infinite, regardless of the distribution of the original data (Edgington, 1995; Good, 2005). In our example of 1.39×10^{18} permutations, the permutation distribution of (2) is in fact a Student's *t*-distribution (Figure A1). Hence, we can calculate the *P*-value of the test by comparison of the test statistic with the standard *t*-distribution without having to generate any permutations. In this case, the *P*-value of the permutation test for difference in means coincides with that of the two-sample *t*-test but the interpretation is different. In the permutation test, the *P*-value is the probability of having obtained a difference in *population* means at least as extreme as that observed in a randomly selected permutation of the data into two *populations* of sizes 35 and 29. In the two-sample *t*-test, the *P*-value is the probability of having obtained a difference in *sample* means at least extreme as that observed based on random selection of a *sample* of size 35 from one population and a *sample* of size 29 from a second, independent population, under the null hypothesis that *the population* means are the same. Rejection of the permutation null hypothesis allows us to conclude that the population means are significantly different, whereas rejection of the null hypothesis in the two-sample case allows us to infer that the populations from which these samples were selected have different means. Thus, even though we might get the "right answer" in terms of the *P*-value with naïve use of a two-sample *t*-test, our inference would be meaningless because our data do not constitute random samples from infinite populations.

In the permutation version of linear regression, the permutations consist of all possible ways of pairing the observations of the dependent variable, *y*, with those of the independent variable, *x*. There are *n*! such permutations possible with a set of *n* ordered pairs. Among several that could be used, we use the standard regression test statistic given by the ratio of regression mean square to error mean square. The observed statistic is that obtained from the data points as they were reported, and that value is compared against the values obtained from all of the other permutations. When the number of permutations is large, the permutation distribution of this test statistic is an $F_{1,n-2}$-distribution, identical to the sampling distribution of this test statistic. The SWE regressions used data pairs from 16 stations, so the number of permutations is 2.09×10^{13}, and use of the standard *F*-distribution is appropriate for computing the *P*-value of the permutation test. However, the number of permutations in the streamflow regressions was very small, so the standard *F*-distribution is not a good approximation to the permutation distribution (Table A1). In the regression with the Scott River removed ($n = 4$), there are $4! = 24$ permutations. The value of the $\frac{MSR}{MSE}$ test statistic obtained from the observed pairing of dependent and independent variables was 7.58, which was the largest value of the test statistic among the 24 permutations. Thus, the P-value for this test is 1/24 = 0.0417. Regression analysis of these same four data points based on random sampling would produce a P-value of 0.110. If the four study streams had been randomly selected from a very large number of streams (on the order of 40 streams), then the probability is 0.110 of having observed a linear relationship at least this strong in a *sample* of four (x, y) pairs under the null hypothesis that there was no linear relationship between x and y in the whole *population*. However, because these four streams were not selected at random (they were selected because they were streams that happened to have long periods of flow records), it is inappropriate to draw inferences to a population from this set of four. Using the permutation testing framework, the probability is 0.0417 of having observed a linear relationship this strong by chance assignment of the x and y values into (x, y) pairs, and we conclude that among this *population* of four study streams, there is a significant dependence of y on x.

Comparing the slopes of the SWE and streamflow regression (Figure 4) is more tricky, given that there is no such thing as a confidence interval around a parameter estimate in the permutation framework. To compare the slopes, we first computed slopes, m_i, for each of the possible 24 permutations of the streamflow data and computed slopes, m_j, for a random sample of 1000 permutations from among the 16! possible for the SWE data. We then calculated the symmetric relative difference between the slopes given by

$$\frac{|m_i - m_j|}{0.5(|m_i| + |m_j|)} \tag{6}$$

for all possible combinations i,j as i ranged over the 24 streamflow permutations and j ranged over the 1000 randomly selected SWE permutations. The observed relative difference was smaller than 92.61% of these differences. However, we are interested in differences in slopes not for all possible combinations of regression lines but only for those that are statistically significant to begin with. If the dependence of change in streamflow on adjusted elevation is independent of that of SWE on adjusted elevation, then the probability of randomly selecting a regression pair with a difference in slopes as small as the observed difference *and* having randomly selected a permutation of the SWE data showing as strong a linear relationship as that observed is the product of these two probabilities. The probability of the former event is $1 - 0.9261 = 0.0739$, and the probability of the latter is 0.0275. Thus, the desired probability is 0.00203. We conclude that it is extremely unlikely to have observed regression relationships this similar by chance alone if the dependence of change in streamflow on elevation is independent of that of change in SWE on elevation.

TABLE A1. Cumulative distribution of the test statistic $\frac{MSR}{MSE}$ for the regression of change in streamflow versus adjusted basin elevation with Scott River removed (Figure 4). The test statistic values are those from each of the 24 possible permutations. The permutation probability is the probability of observing a test statistic at least as large from the permutation distribution, and the sampling probability is the probability of observing a test statistic at least as large from the sampling distribution, namely an $F_{1,2}$-distribution. Note that the F-distribution underestimates probabilities for small values of the test statistic and overestimates them for the larger values.

Test statistic value	Permutation probability	Sampling probability
7.5800	0.0417	0.1105
7.3102	0.0833	0.1139
2.6847	0.1250	0.2430
2.2445	0.1667	0.2728
2.1459	0.2083	0.2806
2.0749	0.2500	0.2864
1.9534	0.2917	0.2971
1.8136	0.3333	0.3104
1.2981	0.3750	0.3726
1.2497	0.4167	0.3799
1.0196	0.4583	0.4189
0.9162	0.5000	0.4395
0.9001	0.5417	0.4429
0.8407	0.5833	0.4560
0.5477	0.6250	0.5363
0.5388	0.6667	0.5393
0.4449	0.7083	0.5734
0.4289	0.7500	0.5798
0.3393	0.7917	0.6191
0.2621	0.8333	0.6596
0.2047	0.8750	0.6953
0.1894	0.9167	0.7059
0.0677	0.9583	0.8191
0.0622	1.0000	0.8263

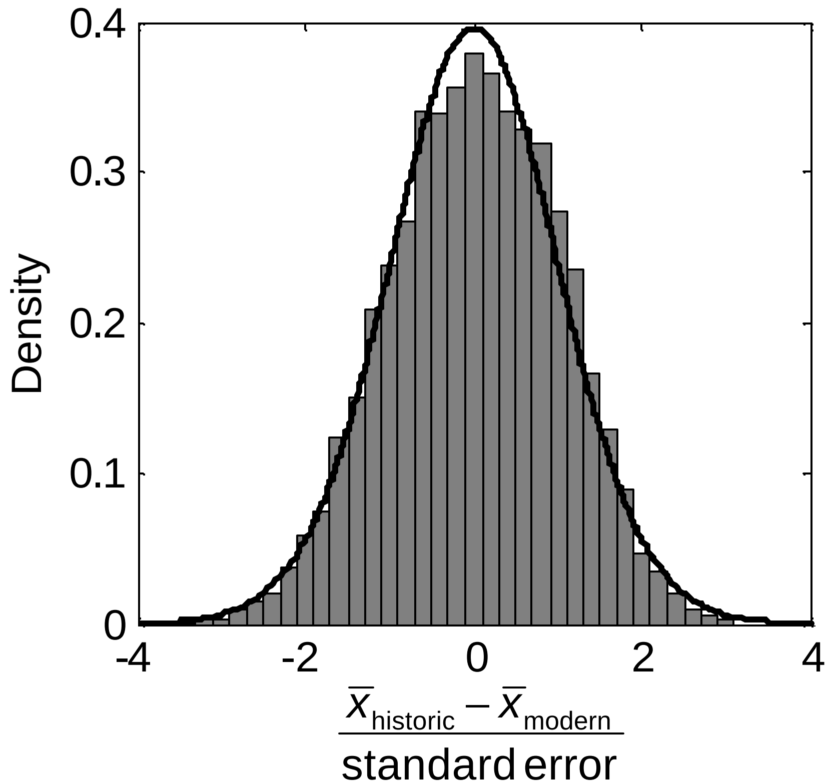


FIGURE A1. Permutation distribution of the *T*-statistic for the difference between historic- and modern-period late summer discharge in the Scott River (Table 1). The histogram shows *T*-statistics from 10,000 randomly selected permutations (from among the 1.39×10^{18} possible), and the curve is the Student's *t*-distribution that would be used for the analogous *t*-test based on random samples.