

**RELATIVE EFFECTS OF CLIMATE AND WATER USE ON
BASE-FLOW TRENDS IN THE LOWER KLAMATH BASIN¹***Robert W. Van Kirk and Seth W. Naman²*

ABSTRACT: Since the 1940s, snow water equivalent (SWE) has decreased throughout the Pacific Northwest, while water use has increased. Climate has been proposed as the primary cause of base-flow decline in the Scott River, an important coho salmon rearing tributary in the Klamath Basin. We took a comparative-basin approach to estimating the relative contributions of climatic and non-climatic factors to this decline. We used permutation tests to compare discharge in 5 streams and 16 snow courses between “historic” (1942-1976) and “modern” (1977-2005) time periods, defined by cool and warm phases, respectively, of the Pacific Decadal Oscillation. April 1 SWE decreased significantly at most snow courses lower than 1,800 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, the only study stream heavily utilized for irrigation, was larger than that in all other streams and larger than predicted by elevation. Based on comparison with a neighboring stream draining wilderness, we estimate that 39% of the observed 10 Mm³ decline in July 1-October 22 discharge in the Scott River is explained by regional-scale climatic factors. The remainder of the decline is attributable to local factors, which include an increase in irrigation withdrawal from 48 to 103 Mm³/year since the 1950s.

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

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INTRODUCTION

Snowmelt is an important contributor to discharge in nearly all major rivers of the western United States (U.S.). Analyses of hydrometeorological data from this region show that climate warming has decreased the percentage of precipitation falling as snow and accelerated snowpack melt, resulting in

earlier peak runoff and lower base flows (Hamlet *et al.*, 2005; Mote *et al.*, 2005; Regonda *et al.*, 2005; Stewart *et al.*, 2005; Mote, 2006). 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). Climate patterns in the Pacific Northwest over this time period have been affected both by long-term, systematic warming and by decadal-scale oscillations (Hamlet *et al.*, 2005;

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Regonda *et al.*, 2005; Stewart *et al.*, 2005). In particular, the Pacific Decadal Oscillation (PDO) cycled through a cool phase (increased snowpack and streamflow) from the mid-1940s to 1976 and through a warm phase (decreased snowpack and streamflow) from 1977 through at least the late 1990s (Minobe, 1997; Mote, 2006). Regardless of the degree to which climatic trends since the 1940s reflect short-term *vs.* long-term processes, base flow in Pacific Northwest rain-snow systems is strongly dependent on timing and amount of snowmelt, which is reflected by April 1 snow water equivalent (SWE) (Gleick and Chalecki, 1999; Leung and Wigmosta, 1999; McCabe and Wolock, 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).

Concurrent with the observed declines in April 1 SWE over the past 60 years, 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 caused by a combination of continental-scale climatic factors and watershed-scale increases in water use rather than by climatic factors alone. Although climate models diverge with respect

to future trends in precipitation over this region, there is widespread agreement that the trend toward lower SWE and earlier snowmelt will continue (Leung and Wigmosta, 1999; McCabe and Wolock, 1999; Miller *et al.*, 2003a; Snyder *et al.*, 2004; Barnett *et al.*, 2005; Zhu *et al.*, 2005; Vicuna *et al.*, 2007). Thus, 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 and implementation of appropriate water management strategies to deal with these shortages will require distinction between the component of late-summer flow decrease attributable to large-scale climatic factors and that attributable to local-scale changes in water use. Management actions implemented at the watershed or basin scale have the potential to reverse declines in streamflow that have been caused by increased water use but will not reverse those caused by continental-scale climatic factors.

The lower Klamath Basin in northern California (Figure 1) provides an important example of the need to distinguish the effects of climate on observed declines in base flow from those of water use. 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,

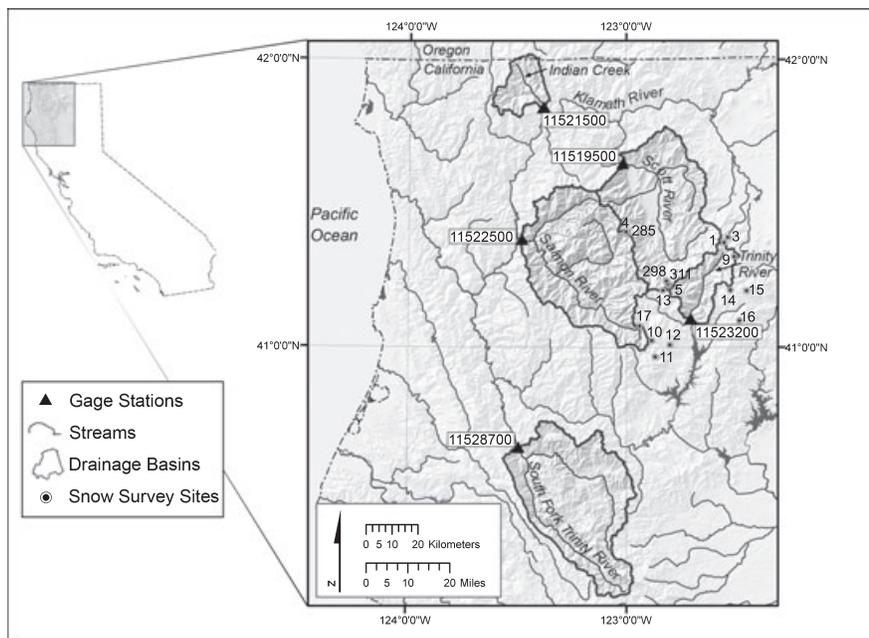


FIGURE 1. Map of Lower Klamath Basin, California, Showing Study Watersheds, Stream Gages, and Snow Courses Used in This Study. Snow course and stream gage numbers correspond to those listed in Tables 1 and 2.

steelhead trout (*Oncorhynchus mykiss*) and Chinook salmon (*Oncorhynchus tshawytscha*) in the lower Klamath Basin are of special concern or are at risk of extinction (Nehlsen *et al.*, 1991). Habitat degradation, over-exploitation, and reductions in water quality and quantity have been implicated in declines of these species (Nehlsen *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 caused primarily by climatic factors, 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 caused by water-use factors could be mitigated through local management actions.

Research Approach and Objectives

The goal of this study is to distinguish the relative effects of regional-scale climatic factors from those of local-scale factors 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 develop realistic and attainable base-flow objectives for fisheries recovery. Ideally, such a study would analyze water-use data, including location and timing of withdrawals, source of water withdrawn (ground *vs.* surface), and rate of consumptive use. Furthermore, in agricultural settings, it is desirable to analyze the type of crops irrigated, method of irrigation application, amount of return flow, and pathways (ground *vs.* surface) by which return flow enters stream channels. Unfortunately, almost no data of these types are available for the watersheds of the lower Klamath Basin, including that of the Scott River, where a large amount of irrigated agriculture occurs. Thus, as an expeditious, first-order attempt to distinguish between effects of climate *vs.* water use on base flow declines, we use statistical analysis of existing SWE and streamflow data from across the basin. Results of this study can then be used to

prioritize future data collection and modeling efforts focused more specifically on mechanisms that could explain the observed statistical trends and on the predicted effects of possible management strategies.

We begin with the operating hypothesis that declines in base flow that have been observed in the Scott River are caused primarily by climate trends, as expected based on the large body of climate literature cited above and on the results of Drake *et al.* (2000), the only published study we could find that has addressed this problem. According to this hypothesis, trends in base flow observed in the Scott River should be consistent with those observed in other streams in the lower Klamath Basin, across which climate is relatively uniform. Further, we expect to observe differences in base-flow trends among these streams because of variation in elevation and latitude, which directly influence SWE. Secondary differences in streamflow trends among streams in the basin can then be attributed to local, watershed-scale factors such as land and water use. Although applied here to a specific basin, our methodology has applicability to any river system in which there are at least a few gaged streams unregulated by storage reservoirs. We use permutation tests for our statistical hypothesis tests, but this is not a methodological study intended to compare the results and applicability of these types of tests to those of other types of statistical tests. However, because permutation tests are not widely applied in water resources research, we provide sufficient detail in statistical methods so that they can be adopted by researchers in other basins.

The objectives of this paper are to (1) quantify basin-scale trends in streamflow and SWE in the lower Klamath Basin, (2) analyze the dependence of base flow and SWE trends on elevation and latitude, (3) compare relative change in base flow among different streams in the basin using a paired-basin approach, and (4) use paired-basin correlation analysis to estimate the component of decline in Scott River base-flow that is attributable to regional-scale climatic factors. The difference between this component and the total decline in base flow is attributable to local-scale factors, which we discuss. We also compare our results with those of Drake *et al.* (2000) and discuss implications for fisheries management.

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 2,500 m. Annual precipitation ranges from 50 cm in the eastern 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 2,000 m. Snowpack generally accumulates throughout the mid-winter to late-winter at elevations exceeding 1,500 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.

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, 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,

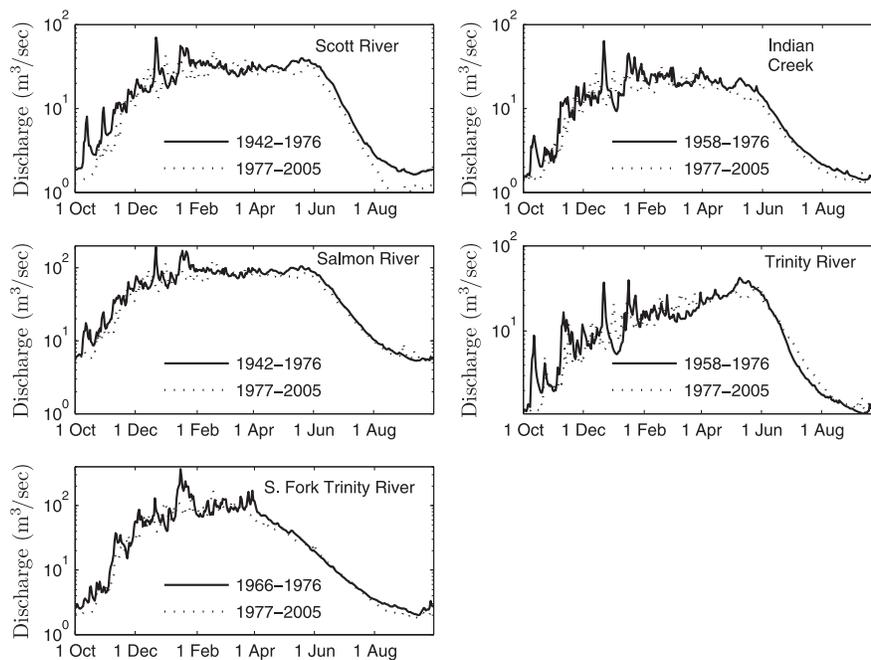


FIGURE 2. Mean Historic-Period and Modern-Period Hydrographs for the Five Study Streams. All streams display a rain-snow hydrologic regime with base flow period during late summer. Discharge is shown on a logarithmic scale to facilitate visual comparison of modern and historic periods at low discharge values. However, statistical comparison of annual and late-summer discharge between periods was performed on untransformed data.

TABLE 1. Study Basin Descriptions and Flow Statistics.

	Scott River	Indian Creek	Salmon River	South Fork Trinity River	Trinity River
USGS stream gage	11519500	11521500	1522500	11528700	11523200
Drainage area (km ²)	1,691	311	1,945	1,979	386
Mean basin elevation (m)	1,688	1,220	1,386	1,378	1,734
Latitude of basin centroid (°N)	41.479	41.904	41.293	40.468	41.228
Earliest year analyzed	1942	1958	1942	1966	1958
Mean annual historic-period discharge (Mm ³)	605.7	403.1	1,744	1,420	385
Mean annual modern-period discharge (Mm ³)	514	345.3	1,517	1,175	361.1
<i>p</i> -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
<i>p</i> -value: historic and modern late summer discharges equal	<0.001	0.055	0.629	0.049	0.799

Notes: Flow data are from the USGS National Water Information System, <http://www.waterdata.usgs.gov/nwis>, accessed December 2006. Historic period ends in 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.

topography prevents substantial agricultural development. The South Fork Trinity watershed supports some 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 120 km² of pasture, grain, and alfalfa are irrigated in the Scott watershed. A typical western-U.S. system of water rights based on the doctrine of prior appropriation governs withdrawal and delivery of surface water for irrigation in the Scott Valley (California Superior Court, 1950, 1958, 1980). Under this type of water rights system, surface water diverted from streams is delivered to water users in order of decreed water right priority date (date on which the claim to put the water to beneficial use was first made; these are typically dates in the mid to late 19th Century in California). Early in the irrigation season, when streamflows are high, all users receive their full allocation of water. As streamflow declines throughout the irrigation season, those users with junior (i.e., more recent) priority dates must cease diversion to leave the available water to users with more senior rights. By the end of a typical irrigation season, only users with the most senior rights continue to divert surface water. The California Department of Water Resources (CDWR) collects some data on irrigation use in the Scott Valley. However, CDWR does not provide watermaster service to account for distribution of decreed surface rights in all areas of the Scott watershed, and withdrawal and distribution of ground water is unregulated.

METHODS

Streamflow and SWE data were available in our study area from the mid-1940s to the present. Given our working hypothesis regarding climate effects and the natural division of this time period into two distinct phases of the PDO (cool from mid-1940s to 1976, warm from 1977 on), we used a two-step comparison approach to analysis of temporal trends (Helsel and Hirsch, 1992). Because streamflow data for the Scott River were first collected in water year 1942, we defined the “historic” period as 1942-1976 and the “modern” period as 1977-2005. We then analyzed differences in SWE and streamflow between these two time periods. We used permutation tests (Ramsey and Schafer, 2002; Good, 2005; see Appendix A) to perform all statistical hypothesis tests. We performed these tests at the $\alpha = 0.05$ significance level.

All of the hypothesis tests involved comparing values of a particular SWE or discharge variable between the historic and modern periods. Although use of permutation tests does not require the data to meet any distributional assumptions, it does require independence of observations (Good, 2005). Thus, we first corrected the data for dependence caused by first-order serial autocorrelation using the correction as

$$x_t = u_t - ru_{t-1}, \quad (1)$$

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 first-order serial autocorrelation coefficient (i.e., the Pearson correlation coefficient between u_t and u_{t-1} (Neter *et al.*, 1989; Ramsey and Schafer, 2002). We then calculated the test statistic as

$$T = \frac{\bar{x}_1 - \bar{x}_2}{SE}, \quad (2)$$

where \bar{x}_1 is the mean of the corrected daily discharge values over Group 1, \bar{x}_2 is the mean over Group 2, and

$$SE = s\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}, \quad (3)$$

where s is the pooled standard deviation, n_1 is the number of years in Group 1 and n_2 is the number of years in Group 2. Groups 1 and 2 refer to the complementary subsets into which the data are divided according to a given permutation (see Appendix A). To calculate the value of the test statistic obtained from the data as they occurred in the observed permutation, Group 1 is taken to be the collection of data observed over the modern period of years, and Group 2 is that observed over the historic period, that is,

$$T_{\text{observed}} = \frac{\bar{x}_{\text{modern}} - \bar{x}_{\text{historic}}}{SE} \quad (4)$$

Although (Equation 4) is the test statistic of the standard two-sample t -test, we use it instead in permutation tests and as the response variable in regressions. Thus, we refer to it as a generic “ T ”-statistic.

As we wanted to focus our analysis on the period of days during the base flow period over which declines in discharge in the Scott River have been most apparent, we defined the “late summer” period of base flow based on analysis of the Scott River data at the daily scale instead of defining this period based on visual examination of hydrographs or on a convenient calendar designation (e.g., August and September). We first \log_{10} -transformed daily discharge for each individual day between June 1 and November 30. The transformation was performed not to meet the assumptions of the hypothesis test but rather to prevent rare but extreme daily flow events from exerting excessive influence over group mean. We then compared the mean of the transformed discharge between historic and modern periods of years with a permutation test on the T -statistic (see Appendix A). We performed these tests with a two-sided alternative. This analysis showed that the mean of \log_{10} -transformed daily discharge (equivalently, the geometric mean) differed significantly between the historic and modern periods on every day of the period August 2 through October 5. We thus defined “late summer” to be this period of consecutive days.

Streamflow and SWE Trends

We tested for differences in total late-summer discharge between historic and modern periods at all five stream gages. For streams on which gaging began after 1942, we defined the historic period to begin with the first year in the period of record (Table 1). 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 at each stream gage and on April 1 SWE at all 16 snow courses in the study area for which at least 40 years of data were available (Figure 1, Table 2). For these tests, we also used a one-sided alternative, for consistency with the late-summer for analysis.

Dependence of Base Flow and SWE Trends on Elevation and Latitude

To quantify dependence of change in SWE and streamflow on elevation, we performed permutation regression analysis (see Appendix A) of the observed T -statistic (Equation 4) as a function of elevation. In this case, T_{observed} 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 America increase southward at a rate of 137 m in elevation per degree of latitude. We referenced latitude to that of Indian Creek, the furthest north of the study watersheds, and defined latitude-adjusted elevation of a given snow course or study watershed to be

$$E_{\text{adjusted}} = E - 137(L_{\text{Indian}} - L), \quad (5)$$

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. Centroids and mean elevations of the drainage basins were computed in a Geographic Information System from Digital Elevation Models. For the SWE analysis, we regressed dimensionless change in April 1 SWE

TABLE 2. Snow Course Descriptions and April 1 Snow Water Equivalent (SWE) Statistics.

Course Number	Elevation (m)	Latitude (°N)	Earliest Year of Record	Mean Historic-Period April 1 SWE (cm)	Mean Modern-Period April 1 SWE (cm)	<i>p</i> -Value: Historic and Modern April 1 SWE Equal
17	1,554	41.077	1946	40.3	30.2	0.021
14	1,646	41.150	1947	84.7	90.2	0.666
285	1,676	41.397	1951	104.2	68.2	0.001
15	1,722	41.197	1947	66.2	52.0	0.022
298	1,737	41.233	1956	49.4	44.5	0.224
3	1,783	41.382	1942	37.0	30.0	0.059
4	1,798	41.400	1951	95.0	52.1	<0.001
16	1,838	41.093	1942	55.5	51.5	0.261
13	1,875	41.200	1949	91.1	91.1	0.482
311	1,890	41.225	1949	71.1	72.5	0.568
12	1,951	41.008	1947	127.8	126.7	0.434
11	1,981	40.967	1947	95.2	101.2	0.704
5	2,012	41.217	1946	80.8	81.4	0.524
1	2,042	41.367	1942	95.3	88.4	0.218
10	2,042	41.023	1946	111.7	112.7	0.542
9	2,195	41.318	1946	84.2	86.9	0.634

Notes: Table is sorted by elevation for ease of interpretation. Data are from the California Department of Water Resources snow course database, <http://www.cdwr.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.

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.

Comparison of Relative Base-Flow Decline Among Study Streams

To compare base-flow trends among the five study streams, we used a before after control-impact-pairs analysis (Stewart-Oaten *et al.*, 1986). For each of the 10 (${}^5C_2 = \frac{5!}{2!3!} = 10$) unique pairwise combinations (*a,b*) of the five study streams and for each year in the intersection of the periods-of-record of the two streams, we computed the ratio $\frac{Q_a}{Q_b}$, where Q_a is the total late-summer discharge in stream *a* for the given year and Q_b is the total late-summer discharge in stream *b*. To prevent small values in the denominator from producing extremely large values of the ratio, we chose stream *b* to be the stream in each pair with the larger mean late-summer discharge during the modern period. We then compared the mean of these annual ratios $\frac{Q_a}{Q_b}$ between modern and historic periods using the permutation method. We used two-sided alternatives 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.

Component of Scott River Base-Flow Decline Attributable to Climate

We estimated the component of base-flow decrease in the Scott River due 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 watershed is closer in elevation to that of the Scott, we chose the Salmon as the reference watershed because it is much closer in size to that of the Scott (Table 1) and because the hydrograph of the Salmon River is more similar to that of the Scott than to any of the other study streams (Figures 2 and 3). Furthermore, because the latitude-adjusted elevation of the Salmon River watershed is lower than that of the Scott River, comparison with the Salmon River provides an overestimate of the effect of climate and hence an underestimate of the effect of local-scale factors on Scott River base-flow. We used the line of organic correlation (Helsel and Hirsch, 1992) to determine the linear relationship between daily Scott River discharge and daily Salmon River discharge. Because the relationship was used for prediction and not for hypothesis

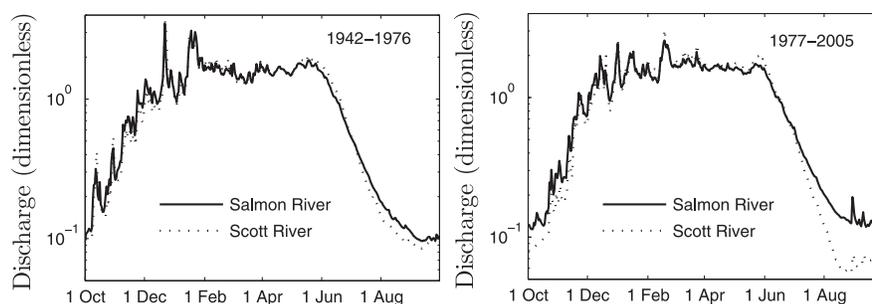


FIGURE 3. Period-of-Record Mean Dimensionless Hydrographs for the Salmon and Scott Rivers, Historic and Modern Periods. Dimensionless discharge is daily discharge divided by mean period-of-record discharge. Note that the hydrographs were nearly identical during the historic period but that during the modern period, Scott River discharge was much lower than Salmon River discharge from early July through late October.

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 Scott and Salmon river hydrographs differed most between the historic and modern periods (Figure 3). We applied the organic linear relationship 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. Because the line had a negative intercept, predicted discharge on a small percentage of days was slightly negative, and discharge on these days was set to zero. 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 line of organic correlation relating Scott and Salmon river discharge over the modern period.

RESULTS

Streamflow and SWE Trends

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). The Scott River showed by far the greatest

decrease in late summer discharge between the two time periods (40.3% decrease, $p < 0.001$), followed by the South Fork Trinity (18.2% decrease, $p = 0.049$) and Indian Creek (10.0% decrease, $p = 0.055$). Late-summer discharge increased slightly in the Salmon (1.2% increase, $p = 0.629$) and Trinity (10.3% increase, $p = 0.799$) rivers between historic and modern periods.

Mean April 1 SWE was lower in the modern period at all seven snow courses below 1,800 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 1,800 m, but none of these differences were significant.

Dependence of Base Flow and SWE Trends on Elevation and Latitude

Change in April 1 SWE between historic and modern periods showed a significant, positive dependence on latitude-adjusted snow-course elevation (Figure 4). There was no significant dependence of change in late summer streamflow on latitude-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 A). This provides strong evidence that the similarity in slopes of these two

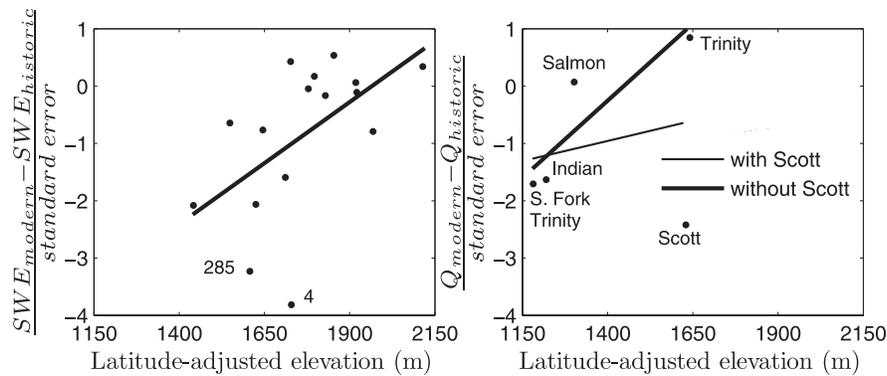


FIGURE 4. Change in April 1 Snow Water Equivalent (SWE; left) and Late-Summer Flow (right) Between the Historic and Modern Periods as a Function of Latitude-Adjusted Elevation. Decrease in both parameters is measured by the dimensionless *T*-statistic (Equation 4). Snow course Numbers 4 and 285 are identified in the left panel. Change in April 1 SWE showed a significant dependence on elevation ($y = 0.00427x - 8.39, p = 0.028$). Change in late-summer flow showed no significant dependence on elevation with all data included ($y = 0.00141x - 2.39, p = 0.700$) but showed significant dependence on elevation when the Scott River was removed from the analysis ($y = 0.00539x - 7.80, p = 0.042$).

regression lines cannot be caused by chance alone, that is, 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.

Comparison of Relative Base-Flow Decline Among Study Streams

Late-summer flow in the Scott River declined between historic and modern periods relative to all four of the other study streams, and all of the differences in discharge ratio involving the Scott River were significant (Table 3). Decline in base flow in the Scott River was greatest relative to the Trinity River, followed by that relative to the Salmon River, Indian Creek, and the South Fork Trinity River, respectively. Late-summer flow in the South Fork Trinity declined

relative to all study streams except the Scott, and these differences were all significant. Late-summer flow in Indian Creek declined relative to the Trinity and Salmon rivers, but only the decline relative to the Trinity was significant. As mentioned above, late-summer discharge in the Salmon and Trinity rivers increased slightly between the historic and modern periods, and the paired-basin test showed that the increase observed in the Trinity River was significantly greater relative to that in the Salmon River.

Component of Scott River Base-Flow Decline Attributable to Climate

Scott River daily discharge from July 1 to October 22 was much lower relative to Salmon River discharge during the modern period than during the

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.

Pair	Mean Ratio of Late-Summer Discharge (historic)	Mean Ratio of Late-Summer Discharge (modern)	Stream With Lower Relative Late Summer Discharge in Modern Period	<i>p</i> -Value: Historic and Modern Ratios Equal
Scott/Trinity	1.65	0.602	Scott	<0.001
Scott/Salmon	0.136	0.063	Scott	0.001
Scott/Indian	0.961	0.589	Scott	0.003
Scott/South Fork Trinity	0.599	0.400	Scott	0.010
Trinity/South Fork Trinity	0.397	0.590	South Fork Trinity	0.007
South Fork Trinity/Salmon	0.334	0.272	South Fork Trinity	0.035
Indian/ South Fork Trinity	0.590	0.747	South Fork Trinity	0.018
Trinity/Indian	0.803	0.973	Indian	0.001
Indian/Salmon	0.237	0.223	Indian	0.174
Trinity/Salmon	0.172	0.193	Salmon	0.045

Notes: Mean ratios of late-summer discharge are shown here; means of late summer discharge for each basin are given in Table 1; *p*-values are reported for the two-sided alternative hypothesis.

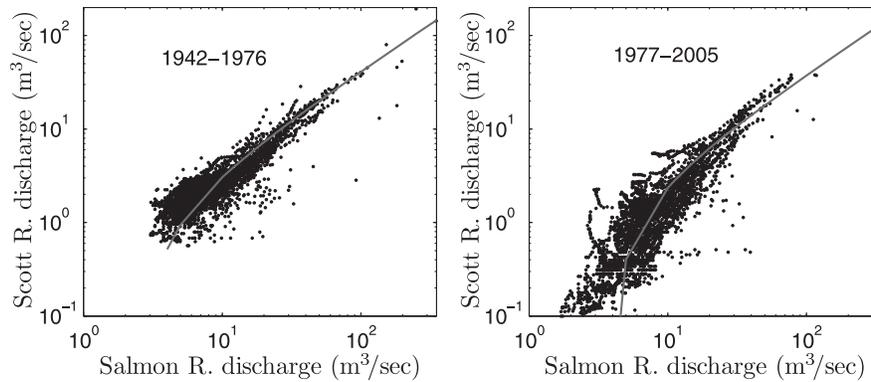


Figure 5. Scatterplots and Lines of Organic Correlation Relating Scott River Daily Discharge (y) and Salmon River Daily Discharge (x) for July 1 Through October 22, Historic and Modern Periods. Lines of organic correlation are $y = 0.422x - 1.17$ for the historic period and $y = 0.398x - 1.62$ for the modern period. Discharge is plotted on logarithmic scales to show detail at low discharge values; however, the lines of organic correlation and all analyses were performed on the untransformed data. Note that daily discharge in the Scott River never fell below $0.566 \text{ m}^3/\text{s}$ during the historic period but fell below this value on 28.6% of all days between July 1 and October 22 during the modern period.

historic period (Figures 3 and 5). 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 to $2.15 \text{ m}^3/\text{s}$). During the historic period, discharge in the Scott River was less than $1 \text{ m}^3/\text{s}$ on 4.3% of all days from July 1 through October 22, whereas during the modern period, flows were less than $1 \text{ m}^3/\text{s}$ on 46.2% of these days. Applying the historic-period organic linear relationship to modern-period Salmon River daily discharge produced an estimate of Scott River daily flow under the influence of regional-scale climate trends alone (Figure 6). The estimated mean hydrograph differed very little from the observed his-

toric-period hydrograph from July 1 through early August, but estimated modern-period discharge was lower over most of August, September, and October. Observed July 1 through October 22 discharge in the Scott River averaged $31.8 \text{ Mm}^3/\text{year}$ over the historic period and $21.3 \text{ Mm}^3/\text{year}$ over the modern period. Our estimate of July 1 through October 22 discharge under the influence of regional-scale climate trends alone averaged $27.8 \text{ Mm}^3/\text{year}$ over the modern period. Thus, the component of decrease in Scott River discharge caused by factors other than regional-scale climate is estimated at $6.5 \text{ Mm}^3/\text{year}$, 61% of the observed decrease.

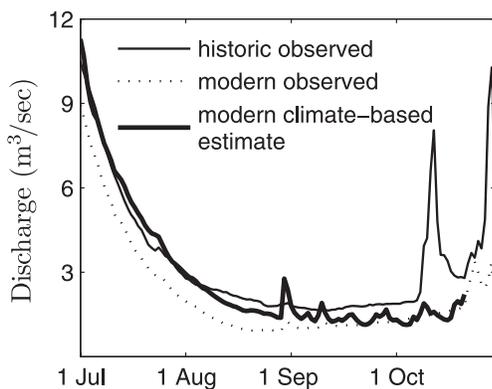


FIGURE 6. Mean July Through October Hydrographs for the Scott River, Showing Observed Historic-Period and Modern-Period Discharge and Estimated Modern-Period Discharge Based on Correlation With the Salmon River (climate-based estimate). Estimated modern-period flows show little deviation from historic-period flows during July and early August but are lower than historic-period flows from mid-August through late October.

DISCUSSION

Streamflow and SWE Trends and Dependence on Elevation and Latitude

Base flow and April 1 SWE in the lower Klamath Basin follow general trends toward lower April 1 SWE and lower base flows observed throughout the Pacific Northwest over the past 60 years (Hamlet *et al.*, 2005; Mote *et al.*, 2005; Regonda *et al.*, 2005; Stewart *et al.*, 2005; Mote, 2006). Models indicate that global warming may increase precipitation over the Pacific Northwest (Leung and Wigmosta, 1999; McCabe and Wolock, 1999; Salathé, 2006) so that at the highest elevations, April 1 SWE may actually increase because of increased winter-time precipitation, despite the trend toward higher temperatures. In the lower Klamath Basin, SWE has decreased significantly at 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 showed that when compared with that of the historic period, late-summer discharge in the modern period in each stream, both independently and relative to the other streams, followed the order predicted by latitude-corrected elevation and by the SWE patterns. Base flow decreased in the two watersheds with the lowest latitude-adjusted elevation (South Fork Trinity River and Indian Creek), and the decrease was greatest in the South Fork Trinity, which has the lowest latitude-adjusted elevation of any of the study streams. Base flow increased in the Trinity and Salmon rivers, and the increase was greatest in the Trinity River, which has the highest latitude-adjusted elevation of any of the study streams. The increases in late-summer flow observed in the Salmon and Trinity watersheds have occurred 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 Decline in the Scott River Relative to the Other Streams

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 (Figures 3 and 5) provide strong evidence that base flow in the Scott River has responded to regional-scale 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 caused by the same climatic factors that have affected the other study streams. 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% in the South Fork Trinity River (Table 1). The *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. Differences in response of the Scott River relative to the other streams appear to be limited only to base flow trends because 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.

Factors Affecting Scott River Base-Flow

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 about 40% as large 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, Figures 1 and 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 caused by 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; J. Power, personal communication). 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 provide evidence that part of the observed decrease in Scott River base-flow since the

1970s is likely caused by 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 acquire show that irrigation withdrawals in the Scott Valley increased by 115% between 1953 and the period over which modern data are available (1988-2001; 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). This increase in irrigation withdrawal accompanied an 89% increase in irrigated land area (Figure 7). In 1953, 77 cm of irrigation was applied over the growing season, and Mack (1958) reported that application rates in the 1940s averaged about 76 cm per year. Average application rate over the period 1988-2001 was 88 cm per year, a 15% increase over historic values. The limited data available show no change in crop types since the 1950s; irrigation has been applied primarily to alfalfa, grain, and pasture through both the historic and modern periods. Climatic factors could have influenced the increase in irrigation application rate; a warmer climate could result in a longer growing season and in higher evapotranspiration rates. However, the 15% increase in application rate is small compared the observed increases of 89% in irrigated land area and

115% in irrigation withdrawal between the historic and modern periods.

A second important trend in irrigation practices in the Scott Valley is that most irrigation in the Scott Valley is currently applied with sprinklers, and conveyance occurs in a pipe network. Recharge of ground water resulting from former flood irrigation practices has been largely eliminated, as has been observed in other locations around the western U.S. (Johnson *et al.*, 1999; Venn *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 Mm³), tributary inflow (unspecified amount), and irrigation seepage (about 21 Mm³). Thus, in 1953, of the 48 Mm³ withdrawn for irrigation, only about 27 Mm³ (56%) was used consumptively. This efficiency is typical of flood irrigation systems with ditch conveyance (Battikhi and Abu-Hammad, 1994; Venn *et al.*, 2004). Conversion from flood to sprinkler irrigation has been reported to increase efficiencies to about 70% (Venn *et al.*, 2004), implying that while withdrawal of irrigation water in the Scott Valley has increased 115% since the 1950s, consumptive use may have increased by as much as 167%. Venn *et al.* (2004) reported that after conversion from flood to sprinkler irrigation in an alluvial valley in Wyoming, streamflow decreased significantly in the late summer and early fall because of decreased recharge of ground water, and this same mechanism could be acting in the Scott Valley as well.

A third important change is that ground water replaced surface water as the dominant source of irrigation water between 1990 and 2000 (Figure 7), reflecting trends observed across the western U.S. (Hutson *et al.*, 2004). Even if recharge from precipitation and tributary inflow have remained unchanged since the 1950s, change in irrigation conveyance and application methods 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. In the upper Snake River basin of Idaho, where ground water-surface water interactions in an irrigation system have been extensively studied, conversion from flood to sprinkler irrigation and increase in pumping of ground water have resulted in significant declines discharge from the aquifer into the Snake River (Johnson *et al.*, 1999; Miller *et al.*, 2003b). Because of lag times inherent in ground water responses, withdrawal of ground water in the middle of the irrigation season can affect stream base-flow into the late summer and early fall. Furthermore, ground water provides a source of irrigation water late in the season

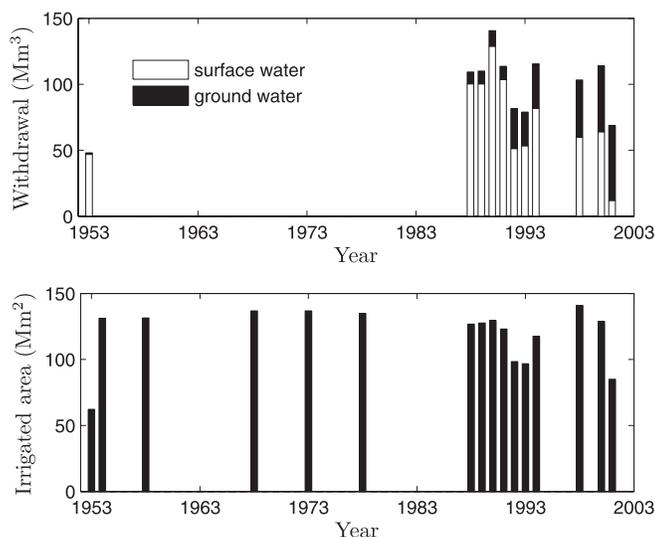


FIGURE 7. Annual Irrigation Withdrawal (top) and Irrigated Land Area (bottom) in the Scott River Basin From 1953 to 2001. Note that ground water made up less than 3% of total withdrawals in 1953 and more than 80% in 2001. Total annual withdrawal increased from 48 Mm³ in 1953 to an average of 103 Mm³ over the period 1988-2001, in close proportion to increase in irrigated area (62 Mm² in 1953, average of 117 Mm² over 1988-2001). Data for 1953 are from Mack (1958). All other data were provided by the California Department of Water Resources upon request.

when streamflow is low and availability of surface water is limited. Thus, transition from an irrigation system based primarily on diversion of surface water from streams to one with a large capacity to pump ground water allows more water to be used late in the irrigation season. Finally, because ground-water pumping in the Scott Valley is unregulated, actual withdrawal amounts could differ from those reported on an annual basis by CDWR, and there is a general lack of data that is sufficient in spatial and temporal extent to perform the mechanistic modeling of interactions between ground and surface water that would be necessary to quantify the effect that changes in irrigation practices have had on streamflow in the Scott River.

Comparison With Drake et al. (2000)

Our estimate that 39% of the decrease in Scott River base-flow is due to climatic factors is contrary to that of Drake *et al.* (2000), who concluded that 78% of the decrease is due to decline in April 1 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, they did not use any variables related to water use, which clearly show substantial changes over the same time period during which base flows have decreased (Figure 7). Finally, 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 decrease in a multiple regression equation explaining September discharge in the Scott River. Their regression equation was

$$\begin{aligned}
 Q = & (2.5 + 1.18 \times \text{annualprecip.} + 8.6 \\
 & \times \text{Augustprecip.} - 6.7 \times \text{Julyprecip.} + 0.48 \\
 & \times \text{Course 285 SWE} + 0.25 \\
 & \times \text{Course 5 SWE})^2, \quad (5)
 \end{aligned}$$

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. Because SWE at Snow Courses 4 and 285 were highly correlated, Snow Course 285 was chosen to represent these courses in the regression equation. Snow Course 5 was used to represent SWE at Courses 5 and 298, two highly correlated courses at which April SWE exhibited little temporal trend. The regression analysis did not include SWE at the other

snow course in the Scott River watershed (Course 311) nor at courses near the Scott River drainage basin divide in adjacent watersheds (Courses 1 and 13; Figure 1). April 1 SWE at these courses showed no significant decrease between historic and modern periods (Table 2). The estimate that 78% of the decline in Scott River base-flow is due to climate was based on the r^2 -value of 0.78 for the regression Equation (5).

Based on mean values for the explanatory variables in the regression equation, the annual precipitation term is six times greater in magnitude than the August precipitation term and over 10 times greater in magnitude than the July precipitation term. Thus, July and August precipitation contribute relatively little to September discharge. The annual precipitation term is about 1.5 times greater than the Snow Course 285 term and about three times greater than the Snow Course 5 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 the regression equation.

Implications for Fisheries

Based on our estimate of the component of Scott River base-flow decrease attributable to changes in water use, returning irrigation to historic-period patterns in the Scott River would, in theory, increase July 1-October 22 discharge by an average of $0.65 \text{ m}^3/\text{s}$. This estimate includes continued irrigation withdrawal at the pre-1970s rate of about 50 Mm^3 , albeit with as much as 21 Mm^3 of this returning to the aquifer and streams via canal seepage. It also accounts for decrease in streamflow caused by regional-scale climate trends. Under current conditions, streamflow in the Scott River can drop below $0.283 \text{ m}^3/\text{s}$ 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 $0.65 \text{ m}^3/\text{s}$ 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; Sandercocock, 1991; Stanford and Ward, 1992). Bartholow (2005) observed a warming trend of 0.5°C/decade in Klamath River water temperatures over the same period of years we have analyzed, suggesting that provision of cold-water refugia for aquatic life will become even more critical as climate warming continues. 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 provide evidence that observed declines in base flow have not been caused by climate trends 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 ground-water withdrawals and their effects on surface water, and water-use data that are easily obtainable. A major research need in the Scott Valley relevant to water management and aquatic species conservation is a comprehensive study of interactions between ground water and surface water that includes mechanistic modeling of effects of ground-water withdrawal on streamflow throughout the valley.

CONCLUSIONS

We statistically analyzed streamflow in five lower Klamath Basin streams that are unregulated by storage reservoirs as well as April 1 SWE at all 16 snow courses in the basin with long periods of record. We compared streamflow and April 1 SWE between historic (1942-1976) and modern (1977-2005) periods, which were defined based on two distinct phases of the PDO. The historic period was a cold phase, which has been associated with high snowpack and high streamflows throughout the Pacific Northwest, and the modern period was a warm phase, which has been associated with lower snowpacks and streamflows region-wide. April 1 SWE decreased significantly between historic and modern periods at low-elevation snow courses in the lower Klamath Basin. No significant trends were apparent at higher elevations. Correspondingly, base flow decreased significantly in the two study streams with the lowest latitude-adjusted elevation and increased slightly in two of the higher-elevation study streams. With the Scott River excluded from the analysis, the depen-

dence 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 Mm³ per year to over 100 Mm³ since the 1950s, and the amount of ground water withdrawn for irrigation has increased from about 1 Mm³ per year to about 50 Mm³. We estimate that 39% of the observed 10 Mm³ decline in July 1-October 22 discharge in the Scott River has been caused by regional-scale climatic factors and that the remaining 61% is attributable to local factors, which include increases in irrigation withdrawal and consumptive use. Even after accounting for climatic factors, returning water use to pre-1970s patterns of withdrawal sources and quantities, conveyance mechanisms, and application methods in the Scott River watershed could benefit salmon and other aquatic biota by increasing July 1-October 22 streamflow by an average of 0.65 m³/s.

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 warming on river ecology, particularly because both decreased base flows and increased water temperatures occur simultaneously during periods of warm climate. Because streams at lower elevations are more susceptible to decreases in base flow caused by decreases in April 1 SWE, local-scale human-induced changes associated with water and land use could have a greater affect on streamflow and water temperature in these streams than in higher-elevation streams experiencing the same continental-scale warming. 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 “control” streams that drain wilderness areas, such as Wooley Creek in the Salmon River watershed and the North Fork Trinity River, to monitor future trends in water use and climate in the lower Klamath Basin.

APPENDIX A: 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). Most of these tests, whether parametric or non-parametric, are based on the assumption that the data were obtained through random sampling of infinite populations. However, this assumption is generally not met by data sets 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. For example, if we analyze 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 infinite population to which inference can be drawn. Permutation tests, often called randomization tests in experimental contexts, are 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 paper.

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. Once the time-series data are corrected for serial autocorrelation, the observations constitute independent, annual values for each of the 64 years between 1942 and 2005, inclusive, and hence satisfy the assumptions of permutation tests. We then measure the magnitude of difference in the mean for each of the two time periods 1942-1976 and 1997-2005, relative to variability, using the test statistic (Equation 4). This division of 64 years into the historic and modern period is only one of the $\frac{64!}{35!29!} \approx 1.39 \times 10^{18}$ distinct ways in which this set of 64 annual values can be divided into two groups of size

35 and 29. Each of these distinct ways is called a permutation, and each has associated with it a particular value of the test statistic (Equation 2). The distribution of these test statistics is called the permutation distribution. The p -value of the permutation test is the probability that we could have selected a permutation at random for which the value of the test statistic was at least as extreme (using either one or two tails, as appropriate to the alternative hypothesis) as that of the observed grouping (i.e., division of the time period into 1942-1976 and 1977-2005 time periods).

In practice, when the number of permutations is on the order of 10^4 or less, one computes the test statistic for every possible permutation and obtains the exact p -value of the test. This procedure is inherently non-parametric and requires no assumptions about the distribution of the original data or the number of observations, even if one uses a test statistic such as (Equation 2) that can be used in the context of a parametric test. 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 (see Supplementary Material). 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 (Equation 2) is in fact a 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 mean 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* mean at least as extreme as that observed in a randomly selected division 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* mean 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. 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

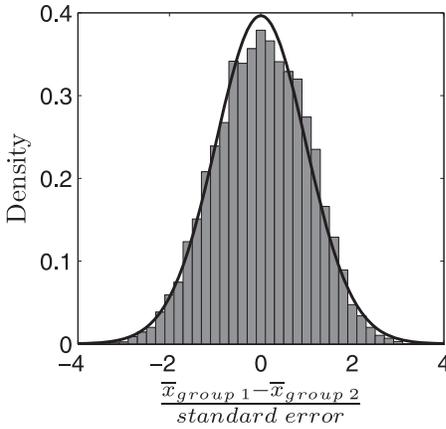


FIGURE A1. Permutation Distribution of the T -Statistic (Equation 1) for the Difference Between Historic-Period and Modern-Period Late Summer Discharge in the Scott River (Table 1). The histogram shows T -statistics from 10,000 randomly selected permutations (from among the 1.39×10^{18} possible), and the curve is the Student's t -distribution that would be used for the analogous t -test based on random samples from populations with unequal variances. The t -distribution has 39 degrees of freedom, as calculated using Satterthwaite's approximation (Ramsey and Schafer, 2002). In this case, the permutation and sampling distributions of the test statistic are identical.

inappropriate because our data do not constitute 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. We perform the permutation test on 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 $16! \approx 2.09 \times 10^{13}$, 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. In the regression with the Scott River removed ($n = 4$), the value of the test statistic obtained from the observed pairing of dependent and independent variables was 7.58, the largest among the 24 permutations. Thus, the p -value for this test is $1/24 = 0.0417$ (Table A1). Regression analysis of these same four data points based on random

Table A1. Cumulative Distribution of the Test Statistic $\frac{MSR}{MSE}$ for the Regression of Change in Streamflow *vs.* Adjusted Basin Elevation With Scott River Removed (Figure 4).

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

Note: 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. The F -distribution underestimates probabilities for small values of the test statistic and overestimates them for the larger values.

sampling produces a p -value of 0.110 (Table A1). If the four study streams had been randomly selected from a large number of streams (on the order of 40 streams or more), 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 large population from this set of four. Using permutation testing, 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 .

To compare the slopes of the SWE and streamflow regressions (Figure 4), we first computed slopes m_1 for each of the possible 24 permutations of the

streamflow data and slopes m_j for each permutation in a random sample of 1,000 permutations from among the 16! possible for the SWE data (see Supplementary Material). We then calculated the symmetric relative difference between the slopes given by

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

for all possible combinations i, j as i ranged over the 24 streamflow permutations and j ranged over the 1,000 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 pairs 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* randomly selecting a permutation of the SWE data showing as strong a linear relationship as that observed is the product of the two individual 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.

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SUPPLEMENTARY MATERIAL

Supplementary materials mentioned in the text (computer code to conduct permutation tests) are available as part of the online paper from: <http://www.blackwell-synergy.com>.

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