Streamflow Response to Climate as Influenced by Geology and Elevation1

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STREAMFLOW RESPONSE TO CLIMATE AS INFLUENCED BY GEOLOGY AND ELEVATION[1]

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ABSTRACT: This study examines the regional streamflow response in 25 predominately unregulated basins to warmer winter temperatures and snowpack reductions over the last half century in the Klamath Basin of California and Oregon. Geologic controls of streamflow in the region result in two general stream types: surface-dominated and groundwater-dominated basins. Surface-dominated basins were further differentiated into rain basins and snowmelt basins on the basis of elevation and timing of winter runoff. Streamflow characteristics and response to climate vary with stream type, as discussed in the study. Warmer winter temperatures and snowpack reductions have caused significantly earlier runoff peaks in both snowmelt and groundwater basins in the region. In the groundwater basins, the streamflow response to changes in snowpack is smoothed and delayed and the effects are extended longer in the summer. Our results indicate that absolute decreases in July-September base flows are significantly greater, by an order of magnitude, in groundwater basins compared to surface-dominated basins. The declines are important because groundwater basins sustain Upper Klamath Lake inflows and mainstem river flows during the typically dry summers of the area. Upper Klamath Lake April-September net inflows have decreased an estimated 16% or 84 thousand acre-feet (103.6 Mm^3) since 1961, with the summer months showing proportionately more decline. These changes will exacerbate water supply problems for agriculture and natural resources in the region.

(KEY TERMS: climate change/variability; rivers/streams; Klamath Basin; groundwater hydrology; surface water/groundwater interactions; base-flow index; Upper Klamath Lake.)

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INTRODUCTION

Snowmelt is the primary source of streamflow in many streams in the western United States (U.S.), comprising 50-80% of the annual flow (Hamlet *et al.*, 2005; Stewart *et al.*, 2005). The spring snowpack represents an accumulated reservoir of water that is released slowly from March through June or later and sustains streams through the typically dry summers of the region (Barnett *et al.*, 2005). Numerous studies have concluded that warmer winter temperatures during the past several decades have resulted in decreased winter snowpack (Cayan *et al.*, 2001; Beebee and Manga, 2004; Knowles *et al.*, 2006; Mote, 2006; Feng and Hu, 2007; Kapnick and Hall, 2010).

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The warming trend may be causing an increase in the fraction of precipitation falling as rain (Knowles *et al.*, 2006; Barnett *et al.*, 2008), or an earlier melting of snow (Kapnick and Hall, 2010), or a combination of the two. The trends are strongest in the Pacific Northwest and northern California, where mountain elevations are relatively low and winter temperatures often hover close to the freezing point (Mote, 2003, 2006; Regonda *et al.*, 2005; Feng and Hu, 2007).

Decreases in snowpack and earlier snowmelt throughout the western U.S. have corresponded with earlier spring runoff and decreases in summer base flow of streams (Aguado *et al.*, 1992; Gleick and Chalecki, 1999; Regonda *et al.*, 2005; Stewart *et al.*, 2005; Van Kirk and Naman, 2008). The decrease in snowpack and associated changes to streamflow have been most pronounced at lower elevations that are on the cusp of rain-snow transitions (Aguado *et al.*, 1992; Knowles and Cayan, 2004; Mote, 2006; Van Kirk and Naman, 2008). Most analyses identify elevation as the primary control of changing stream regimes. But the potential for other factors to influence streamflow response to climate such as groundwater hydrology or the extent of glaciated area is also starting to be recognized (Tague and Grant, 2004; Mote, 2006; Walvoord and Striegl, 2007; Jefferson *et al.*, 2008; Tague *et al.*, 2008; Hodgkins, 2009).

In the Pacific Northwest, groundwater has been shown to attenuate and delay streamflow response to snowmelt by providing additional storage and dampening effects from precipitation (Jefferson *et al.*, 2008). Tague and Grant (2004) compared streamflow regimes in two distinct geologic provinces in the central Oregon Cascades: the High Cascades province, consisting of younger, more permeable volcanics, and the Western Cascades province, consisting of older, more weathered, impermeable volcanics. Streams of the younger High Cascades volcanics are groundwater-dominated and have much more uniform flows with muted winter peaks, slower recession rates, and higher summer base flows relative to runoff-dominated streams draining the older Western Cascades volcanics (Tague and Grant, 2004). The higher late season base flows and slow recession curve of groundwater-dominated streams in the High Cascades province may serve to maintain their sensitivity to climate later in the season, making them more sensitive than runoff-dominated streams to changes in snowmelt amount and timing (Tague and Grant, 2004; Jefferson *et al.*, 2008; Tague *et al.*, 2008).

Chang and Jung (2010) used model projections to examine the future response of streams in the Western Cascades and High Cascades volcanics as well. They reported greater absolute declines but smaller relative declines in groundwater-dominated streams compared to runoff-dominated streams. Their interpretation was that groundwater-dominated streams will be less sensitive to snowmelt change than runoff-dominated streams, at least in the near-term (through the 2040s). The authors suggest that "groundwater basins could buffer the effects of climate-induced changes in streamflow." These findings suggest that the response of groundwater-dominated basins to snowmelt changes has not been completely resolved.

OBJECTIVES

The Klamath Basin region in southern Oregon and northern California offers the opportunity to observe the streamflow response to climate in a region characterized by variable geology and topography. Winter temperature, winter precipitation, and spring snow water equivalent (SWE) data for the Klamath Basin are presented and analyzed briefly in the Supporting Information. The climate trends in the area are similar to what has been described elsewhere for the Pacific Northwest (Mote, 2003, 2006; Beebee and Manga, 2004). Winter temperatures in the Klamath Basin area have increased by about 1°C since 1945 throughout the region, resulting in large decreases in spring snowpack at elevations <1,800 m (average decrease 38%), similar to findings reported for the Pacific Northwest in general (Mote, 2003). Winter precipitation trends since 1945 have been less consistent and more spatially variable than temperature trends in the region. Generally, winter precipitation has decreased in some areas of southern Oregon and increased in some areas of northern California. The relative declines in spring SWE at elevations <1,800 m have been much greater than the relative declines in winter precipitation in the area over the same period.

The overall objective of this study is to examine the streamflow response to these climatic trends, as mediated by two primary landscape controls, geology and elevation. Our hypothesis is that because the streamflow response to snowmelt is smoothed and delayed in groundwater-dominated basins, the effects of snowpack reductions and earlier snowmelt will be extended longer in the season. Summer and fall base flows in groundwater-dominated streams will be more sensitive to snowpack changes compared to surface-dominated streams.

Several researchers have stressed the significance of earlier spring runoff and declining summer base flows in streams throughout the western U.S. and the resulting impacts on agriculture, fishing, hydropower, and other water users (Hayhoe *et al.*, 2004; Barnett *et al.*, 2008; Cayan *et al.*, 2008). We focus on changes to seasonal flows in spring and summer because of their importance to water supply and aquatic resources in the region, particularly in and around Upper Klamath Lake (UKL). Water availability may decrease if runoff is earlier and late-season base flows are reduced. Additionally, increased air temperatures and a longer growing season may increase lake evaporation losses and irrigation demand for water, heightening conflict and competition for limited water supply (NRC, 2007; Barnett *et al.*, 2008; Van Kirk and Naman, 2008; Karl *et al.*, 2009).

While many studies have reported observed (Redmond and Koch, 1991; Cayan *et al.*, 1999; Regonda *et al.*, 2005; Stewart *et al.*, 2005) or projected (Leung and Wigmosta, 1999; Barnett *et al.*, 2005; Cayan *et al.*, 2008) changes in snowpack and streamflow, they often consider time horizons or geographical areas beyond the scale of most planning exercises or regulatory actions. There is a need to improve understanding of climate change impacts related to water resources at smaller temporal and spatial scales that are more relevant to decision making (Stewart *et al.*, 2005; Bates *et al.*, 2008). In this study, we consider a relatively small geographic extent, the Klamath Basin area, focusing on observed changes rather than modeled or projected changes. We hope that our focus on a smaller geographic extent will be useful for local land and resource managers and will broaden our understanding of streamflow response to climate variability and climate change within this region. If streamflow response to regional warming differs throughout the area, multiple strategies and management activities may be required. We also hope that our focus on observed rather than projected streamflow responses will heighten the urgency for developing climate change adaptation strategies and incorporating observed trends and changes into current forecasting and modeling exercises.

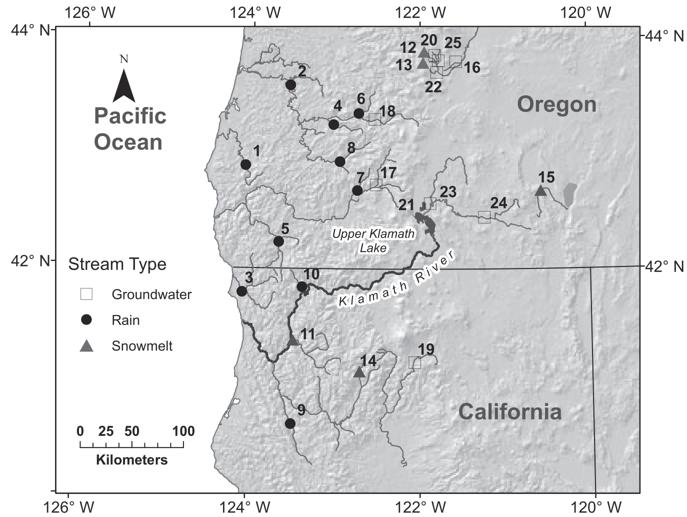


FIGURE 1. Map Showing the Location and Basin Type of the 25 Streamflow Gages Used in the Study. The numbers are associated with streamflow gages in Table 1.

STUDY AREA

The study area includes northern California and southern Oregon and extends south to north from 40.5° to 44.0°N and east to west from 120°W to the coast of the Pacific Ocean (Figure 1). It includes the Klamath River, the largest basin in this area, and several other streams outside of the Klamath Basin but believed to be responding to the same long-term warming trend (Figure 1). The area is almost entirely mountainous terrain and generally ranges in elevation from sea level to 2,500 m, although the volcanic peak of Mt. Shasta in California extends above 4,300 m. The Cascade Mountain Range bisects the study area into nearly equal western and eastern portions. Steep slopes and impermeable bedrock characterize much of the western side of the study area while the eastern side is lower gradient, lower relief, and consists of more permeable volcanic geology.

The western side of the study area is wetter, with a marine-influenced climate, while the eastern side is more intermountain and semiarid. Average annual precipitation is much greater on the west side compared to the east side due to the rain shadow effect of the Cascades. Almost all the annual precipitation falls in the winter months throughout the region. Precipitation occurs as snow and rain from about 400 to 1,500 m, with snowpack generally accumulating above this elevation range from mid to late winter (Tague and Grant, 2004; Van Kirk and Naman, 2008). In general, river basins on the wetter, western slopes are warmer and lower in elevation while river basins on the rain-shadowed eastern slopes drain cooler temperature, higher elevation areas.

METHODS

To examine long-term streamflow responses to the climate trends, we obtained daily, monthly, and annual streamflow data from the U.S. Geological Survey (USGS) and the Oregon Water Resources Department (OWRD) for 25 sites (Figure 1) having at least 40 years of record. Seventeen of these streamflow sites are included in the USGS Hydro-Climatic Data Network, a set of stream gaging sites identified as being relatively unaffected by anthropogenic influences, land-use changes, and measurement changes or errors (Slack *et al.*, 1993). The remaining eight streamflow sites in the study area are generally free of any major diversions or dams and are therefore suitable for the study of climate impacts on long-term streamflow trends as well. The flows at the Williamson River below Sprague near Chiloquin, Oregon (USGS gage number 11502500) were modified by subtracting the Sprague River near Chiloquin (USGS gage number 11501000) to focus solely on the Williamson River contribution to this site (Will R no Spr; Table 2), similar to Gannett *et al.* (2007). We subsequently subtracted the Williamson River near Klamath Agency, Oregon (USGS gage number 11493500) from the modified Williamson flows to focus on groundwater accretions between Klamath Marsh and the mouth of the Williamson River (Will R. GW; Table 2), as in Gannett *et al.* (2007).

We also obtained UKL monthly net inflow data for the available period of record from 1961 to 2009 (Bureau of Reclamation [BOR], Klamath Falls, Oregon, 2009, unpublished data). These data were recently revised by BOR and USGS to include estimates of PacifiCorp diversions for the period 1984-2007. This is not a streamflow site but is an indirect measure of inflow and unregulated losses, mainly evaporation, in UKL. It is calculated from the sum of the volume of monthly flow diversions/releases and the changes in lake storage volume. Net inflow represents the volume of water available to BOR for irrigation, lake storage, and downstream river flows.

For each streamflow site, we obtained basin area, mean basin elevation, and mean annual precipitation above the gage from OWRD (Jonathan LaMarche, OWRD, 2009, unpublished data). We computed several streamflow statistics based on the period of record to characterize individual stream hydrology: the average mean daily discharge for each day of the water year; the mean annual flow, coefficient of variation, and mean annual runoff (mean annual flow divided by the basin area); the base-flow index, defined as the average annual ratio of the lowest daily flow over the mean daily flow and expressed as a percentage (Poff, 1996); the centroid of streamflow (Stewart *et al.*, 2005) for the water year; the month of maximum and minimum monthly flows; and the one-year autocorrelation coefficients for annual flows.

One of the strongest landscape controls of streamflow in the study area is geology. The change from impermeable bedrock geology on the western side of the study area to permeable volcanic geology on the eastern side results in a transition from surface-dominated basins to groundwater-dominated basins. We used the base-flow index (Poff, 1996) to distinguish between these two major stream types. The base-flow index is expressed as a percentage, with higher values meaning higher base flows and more groundwater influence. In our study streams, the base-flow index ranged from 1 to 89%. We considered streams with base-flow indices >20% to be groundwater-dominated basins and <20% to be surface-dominated basins, but the exact percentage was not critical. The maximum base-flow index for any surface-dominated stream in the study area was 16% and the minimum base-flow index for any groundwater-dominated stream was 30% (Table 2), indicating a natural break in the data. Poff (1996) did not report a threshold but reported an average base-flow index of 28-30% for unregulated groundwater streams.

In the cooler, higher elevation watersheds, the major runoff is delayed by up to several months, relative to winter precipitation. We further separated the surface-dominated basins into rain basins and snowmelt basins on the basis of basin elevation and the date of the streamflow centroid. Rain basins are at lower elevation, <1,200 m, where winter precipitation is expressed as streamflow almost immediately and the date of the stream centroid occurs in or before early March. Snowmelt basins are at higher elevations, >1,200 m, where winter precipitation is accumulated as snowpack and observed as streamflow later in the spring, during snowmelt. In these systems, the date of the stream centroid occurs in or after mid-March. There is a transition from rain basins to snowmelt basins as elevation increases. The 1,200-m elevation corresponds to the lower end of the range of snowcourse site elevations and snow accumulation in the study area. All of the groundwater-dominated basins in the study area occur at elevations >1,200 m where winter precipitation accumulates as snow, so there was no need to separate these basins by elevation.

We used several approaches to illustrate the differences in streamflow response to climate among these stream types. First, hydrographs and streamflow statistics were analyzed to characterize differences in the variability and seasonal distribution of flow for the stream types. Next, the percentile rank of the water year flow in 1977 was calculated for each site to examine the streamflow response to an extremely dry year for various stream types. 1977 was the driest year from 1925 to 2007, based on the record of annual average precipitation from the 20 U.S. Historical Climatology Network (USHCN) (Menne *et al.*, 2009) stations in the study area. Finally, stepwise multiple linear regression was used to correlate annual flows from several sites with one or more years of winter precipitation at local USHCN climate stations.

To illustrate the seasonal importance of groundwater-dominated basins in the study area, we calculated the average monthly contribution of flow from upstream groundwater-dominated basins as a percentage of downstream mainstem flows in three major river systems in the study area. The systems and streamflow sites were (1) the USGS Klamath River above Iron Gate Dam, California (upstream) and the USGS Klamath River near Klamath, California (downstream) on the Klamath River; (2) the USGS N Umpqua above Copeland Creek near Toketee Falls, Oregon (upstream) and the USGS Umpqua River near Elkton, Oregon (downstream) on the Umpqua River; and (3) the USGS Rogue River below Prospect, Oregon (upstream) and the USGS Rogue River near Agness, Oregon (downstream) on the Rogue River. The complete periods of record were used for the Klamath River (1963-2007) and the Umpqua River (1950-2007). For the Rogue River, we used the period 1969-1976, which represents the period of measurements prior to the construction of Lost Creek Lake in 1977, located between the upstream and downstream Rogue River sites. The use of different periods for the three sites does not affect this particular analysis because we are evaluating flows within basins rather than between basins.

Finally, trends in monthly and annual streamflow were compared among the stream types. For the Williamson River, we only examined trends at the two sites with modified flows, described above, and excluded the Williamson River below Sprague near Chiloquin (USGS gage number 11502500), since this would have been redundant. Streamflow trends were calculated in both relative terms, as a percentage decrease or increase over time, and absolute terms, as a unit of flow increase or decrease over time. We focused on trends in absolute terms primarily because while relative changes may be important locally, absolute changes are most important for assessing cumulative downstream impacts.

A Mann-Kendall trend test, a nonparametric test for a monotonic trend (Helsel and Hirsch, 2002), was used to calculate trends for each month at each site based on the period of record, beginning in 1945 or from the earliest year data were available after 1945. In the Pacific Northwest, the Pacific Decadal Oscillation (PDO) is positively correlated with temperature and somewhat negatively correlated with precipitation (Beebee and Manga, 2004; Mote, 2006). The PDO was in a predominately negative or cool phase from 1945 to 1976 and a predominately positive or warm phase from 1977 to 1995. It has oscillated between negative and positive values since about 1995. The trend tests were started in 1945 to correspond with the PDO cycles and the beginning of many snowpack records in the study area. To facilitate comparison of trends among sites, all streamflow trends were normalized to a 50-year period and expressed on a per unit area basis.

A multiple-stage Kruskal-Wallis test, a nonparametric test for differences in the groups based on rank (Helsel and Hirsch, 2002), was used to test for group differences in the monthly and water year trends by stream type. This procedure involves using the Kruskal-Wallis test to examine for differences among the groups or stream types for each month or water year. When statistically significant differences occur, the Dun's multiple comparison test is used to identify which specific groups or stream type(s) differ.

For six groundwater-dominated basins near or tributary to UKL, we also computed mean daily discharge for each day of the water year for two separate periods corresponding to two major PDO phases: 1945-1976 and 1977-2007. If a particular streamflow record began after 1945, we computed mean daily discharges beginning with the first year data were available. The mean daily flow hydrographs for the two periods were compared graphically.

To focus on changes in the seasonal timing and volume of UKL net inflows, April-September, April-June, and July-September net inflows were calculated for the available period of record 1961-2009. The April-September period is the standard measure of water supply used by BOR for the irrigation season. Approximately 75% of the total April-September net inflow occurs during the first three months, April-June, which corresponds to the snowmelt season. Net inflows for the remaining months, July-September, are of interest because they reflect base flows from tributary groundwater-dominated basins and direct subsurface seepage into the lake, as well as evaporative losses from the lake. We trend tested net inflow volumes for each month, for the water year, and for the April-September, April-June, and July-September periods. The net inflow volumes are presented in units of thousand acre-feet (taf), as well as SI units (Mm^3), because these units are most familiar to basin interests. Trends in UKL net inflow are expressed as total volumes or percent changes for the 1961-2007 period and have not been normalized to basin area because the contributing basin is not known exactly.

Serial correlation and long-term persistence can confound hypothesis testing in statistical trend tests (Helsel and Hirsch, 2002; Cohn and Lins, 2005). Many of the groundwater-dominated streams in the study area exhibited strong serial correlation and hydroclimate data, in general, may be characterized by long-term persistence (Cohn and Lins, 2005). The magnitude of differences or trends is not affected by these characteristics but the assumption of independent data, necessary for testing statistical significance, is violated. We report statistical significance while acknowledging these issues.

RESULTS AND DISCUSSION

Streamflow Characteristics

The distribution of stream types and the location of individual stream gages are shown in Figure 1. Table 1 presents the streamflow gage name and number, period of record, and several basin attributes for the areas above the gage, by basin type. Hydrographs for representative streams from the three stream types in the study area are presented in Figure 2. All three rivers in Figure 2 are located on the west side of the study area and are comparable in terms of mean annual precipitation and mean annual runoff. But the seasonal distribution of streamflow varies considerably due to differences in elevation and geology.

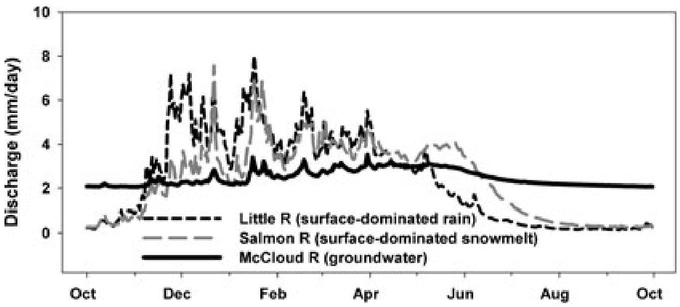
The two surface-dominated hydrographs are similar (Figure 2). Both are characterized by rapidly rising discharge in the fall, broad peaks throughout the winter, a recession beginning between March and June, and low base flows in summer and early fall. The main difference between the rain basin and the snowmelt basin is the timing of the winter precipitation response, which occurs later in the spring in the snowmelt basin. In the groundwater-dominated basin, the winter recharge response is delayed and attenuated due to the large component of subsurface flow, resulting in a very different hydrograph from the surface-dominated basins. In general, groundwater hydrographs are characterized by slowly increasing discharge in winter, more muted snowmelt peaks, and high base flows in summer and fall, producing a relatively uniform hydrograph in comparison to the surface-dominated basins (Figure 2).

Streamflow statistics and the seasonal distribution of flow are quite different for surface-dominated basins and groundwater-dominated basins (Table 2). The winter recharge signal in groundwater-dominated

TABLE 1. Site Information for Streamflow Gages Used in This Study.

	Map No.	Gage No.	Period of Record (WY)	Basin Elev. (m)	Basin Area (km^2)	Annual pcp. (cm)
Surface-dominated rain basins						
S. Fk. Coquille R. at Powers, Oregon[1]	1	14325000	1925-2007	655	441	256
Umpqua R. nr Elkton, Oregon[1]	2	14321000	1925-2007	749	9,399	129
Smith R. nr Crescent City, California[1]	3	11532500	1932-2007	770	1,583	282
Little R. at Peel, Oregon[1,2]	4	14318000	1955-2007	861	458	156
Illinois R. nr Kirby, Oregon[1]	5	14377100	1962-2007	881	941	173
Steamboat C. nr Glide, Oregon[1]	6	14316700	1957-2007	945	715	155
Elk C. nr Trail, Oregon[1]	7	14338000	1946-2007	950	335	115
South Umpqua R. at Tiller, Oregon[1]	8	14308000	1940-2007	979	1,162	126
S. Fk. Trinity blw Hyampom, California[1]	9	11528700	1966-2007	1,122	1,971	148
Indian C. nr Happy Camp, California[1]	10	11521500	1957-2007	1,129	308	168
Surface-dominated snowmelt basins						
Salmon R. at Somes Bar, California[1]	11	11522500	1928-2007	1,299	1,936	140
Cultus C. abv Crane Prairie Res. nr La Pine, Oregon	12	14051000	1938-2006	1,596	86	166
Deer C. abv Crane Prairie Res. nr La Pine, Oregon	13	14052000	1938-2006	1,619	37	150
Trinity R. abv Coffee C. nr Trinity Ctr., California[1]	14	11523200	1958-2007	1,630	382	110
Chewaucan R. nr Paisley, Oregon[1]	15	10384000	1925-2007	1,842	689	67
Groundwater-dominated basins						
Fall R. nr La Pine, Oregon	16	14057500	1939-2007	1,390	103	60
Rogue R. blw Prospect, Oregon[1]	17	14330000	1969-2007	1,425	1,159	133
N. Umpqua abv Copeland C. nr Toketee Falls, Oregon	18	14316500	1950-2007	1,474	1,218	136
McCloud R. nr McCloud, California[1]	19	11367500	1931-2007	1,496	940	143
Cultus R. abv Cultus C. nr La Pine, Oregon	20	14050500	1938-2006	1,572	43	162
Williamson R. blw Sprague R nr Chiloquin, Oregon	21	11502500	1925-2007	1,576	7,719	63
Brown C. nr La Pine, Oregon	22	14054500	1939-2005	1,582	113	144
Sprague R. nr Chiloquin, Oregon[1]	23	11501000	1925-2007	1,599	4,110	58
Sprague R. nr Beatty, Oregon[1]	24	11497500	1954-2007	1,643	1,357	58
Deschutes R. blw Snow C. nr La Pine, Oregon	25	14050000	1937-2007	1,756	298	179

Notes: Basin elevations, areas, and precipitation are computed for the areas above the gage. Sites are grouped by stream type and sorted by elevation within each type. Map numbers refer to Figure 1.
[1]Streamflow site is included in the USGS HydroClimatic Data Network (HCDN).
[2]Little R. at Peel, Oregon has missing data from October 1989 to June 1999. We do not believe that this affects the trend analysis at this site.



River	USGS Gage No	Elev (m)	Mean Annual Pcp (cm/yr)	Mean Annual Discharge (cm/yr)
Little R, OR	(14318000)	860	156	89
Salmon R, CA	(11522500)	1300	141	83
McCloud R, CA	(11367500)	1500	143	87

FIGURE 2. Mean Daily Discharge, Normalized to Basin Area, for Three Streams Representative of the Three Stream Types in the Study Area: Surface-Dominated Rain Basins, Surface-Dominated Snowmelt Basins, and Groundwater-Dominated Basins. The period of record used for all three sites in this figure is 1951-1980.

basins is smoothed and delayed at daily, seasonal, and annual time scales, relative to the surface-dominated basins. Daily flows in the groundwater-dominated basins are much less variable than in the surface-dominated basins, as indicated by the coefficient of variation (Table 2). In the surface-dominated basins, maximum monthly flows occur December-February for the lower elevation rain basins and May-June for the higher elevation snowmelt basins, whereas minimum flows typically occur August-October. In the groundwater-dominated basins, maximum monthly flows occur April-May in some systems but are as late as July or even September in others. Minimum monthly flows occur August-October in some systems but are as late as January-March in others.

Groundwater-dominated basins have a much higher fraction of their total flow in summer and early fall compared to the surface-dominated basins (Table 2). Absolute flows are higher in summer in groundwater-dominated basins as well. On average, mean July runoff is about four times greater and mean August or September runoff is about seven times greater in groundwater-dominated basins than in surface-dominated basins.

Annual flows in many of the groundwater-dominated basins are significantly autocorrelated at one-year lags, suggesting that there is inter-annual memory in these systems (Table 2). Figure 3 shows the response of all the streams, by stream type, to the dry year, 1977, as a function of the annual autocorrelation coefficient. The 1977 water year flow for the streams with low autocorrelation ranks in the lowest percentile, meaning these streams were extremely dry that year. In general, streams with low annual autocorrelation are very responsive to a single wet or dry year. Figure 3 shows that as the annual autocorrelation increases, indicated by increasing autocorrelation coefficients, the percentile rank of the 1977 water year flows becomes more moderate. The long-term memory in these systems means that they are less responsive to a single wet or dry year and more responsive to wet and dry multiyear cycles. Risley *et al.* (2005) recognized that these characteristics might be useful in predicting flows in the Upper Klamath Basin and explored the use of an autoregressive model for such purposes.

Another illustration of the responsiveness of groundwater-dominated basins to wet and dry year cycles is through multiple linear regression with winter precipitation. Figure 4 shows observed flows compared to predicted flows, based on one or more years of winter precipitation, at two groundwater stream sites. The Williamson River below Sprague near Chiloquin is responsive to two precipitation sites, Crater Lake, Oregon and Paisley, Oregon, which represent precipitation on the western and eastern side, respectively, of the watershed area at this site. Five variables explain 87% of the total variance in water year flows from 1961 to 2007: winter precipitation in the current and previous three years at Crater Lake and the winter precipitation for the current year at Paisley (Figure 4). The flow at the Williamson below Sprague near Chiloquin is a combination of the Sprague River and the Williamson River. Both of these basins are similar in terms of mean annual runoff, but the Sprague River is less groundwater-dominated relative to the Williamson River (see Table 2). Sprague River flows are primarily responsive to winter precipitation for the current year at Crater Lake and Paisley. Williamson River flows without the Sprague (Will R no Spr) are responsive to several years of winter precipitation, with the two-year lag of Crater Lake winter precipitation being the first variable selected in stepwise regression.

Upper Klamath Lake net inflows reflect the combined sum of these tributary inflow sources and the different climate responses of those sources. Five variables explain 88% of the total variance in UKL water year net inflow: the current year and two-year lag of October-March precipitation at Paisley and the current year, one-year lag, and three-year lag of October-March precipitation at Crater Lake (Figure 4). Several other groundwater-dominated basins in the study area behave similarly. These characteristics show the responsiveness of these systems to wet and dry year cycles. They may also be useful in predicting flows.

Stream Types, Streamflow Trends, and Climate Response

Stream type is important when assessing the streamflow response to climate for two reasons.

TABLE 2. Streamflow Statistics for Streamflow Sites and Modified Flow Sites in the Study Area.

	Mean Annual Flow (m^3/s)	Coeff. of Var. (%)	Mean Annual Runoff (mm/day)	Base-Flow Index (%)	Mean Date of Streamflow Centroid	Mean August Flow/WY Flow (%)	Month of Max. Flow	Month of Min. Flow	Autocorrelation Coefficient
Surface-dominated rain basins									
SF Coquille R.	22.2	190	4.4	2	02/07	5	January	August	−0.02
Umpqua R.	206.5	150	1.9	14	02/24	17	January	August	0.05
Smith R.	106.3	180	5.8	6	02/14	10	January	September	0.01
Little R.	12.8	170	2.4	4	02/17	7	December	August	−0.12
Illinois R.	35.7	190	3.3	2	02/13	4	January	August	0.09
Steamboat C.	20.5	170	2.5	5	02/17	9	January	August	−0.01
Elk C.	6.2	200	1.6	1	02/17	3	January	August	0.05
S. Umpqua R.	29.1	160	2.2	5	02/22	8	January	September	0.05
SF Trinity R.	39.8	200	1.7	4	02/26	7	January	September	0.14
Indian C.	11.9	170	3.3	10	03/07	16	February	September	0.08
Surface-dominated snowmelt basins									
Salmon R.	50.5	140	2.3	9	03/18	15	May	September	0.10
Cultus C.	0.6	140	0.6	1	04/27	6	June	October	0.15
Deer C.	0.2	160	0.5	1	04/16	5	May	September	0.13
Trinity R.	11.9	160	2.7	8	03/30	14	May	September	−0.05
Chewaucan R.	4.2	150	0.5	16	04/15	23	May	August/September	0.14
Groundwater-dominated basins									
Fall R.	4.0	20	3.3	89	04/04	102	May	January/February	**0.82**
Rogue R.	41.2	50	3.1	53	03/29	68	May	September	0.31
N. Umpqua	41.2	60	2.9	66	03/25	77	May	September	0.22
McCloud R.	26.0	39	2.4	79	04/03	88	April/May	January	**0.50**
Will R. GW	8.9	20	3.6	69	03/28	94	March	October	**0.68**
Will R. no Spr.	13.0	50	0.3	56	03/25	71	April	September	**0.75**
Cultus R.	1.8	30	3.5	71	04/11	117	July	March	**0.62**
Will R.	29.6	79	0.3	48	03/26	50	April	August	**0.30**
Brown C.	1.0	30	0.8	80	04/04	110	September	February	**0.68**
Spr. R. Chilo	16.5	110	0.3	30	03/27	34	April	November	0.16
Spr. R. Beatty	8.7	110	0.6	32	03/31	56	May	December	0.22
Deschutes R.	4.0	50	1.2	64	04/14	142	August	March	**0.58**

Note: Bold numbers indicate statistical significance ($p < 0.10$) for autocorrelation coefficients.

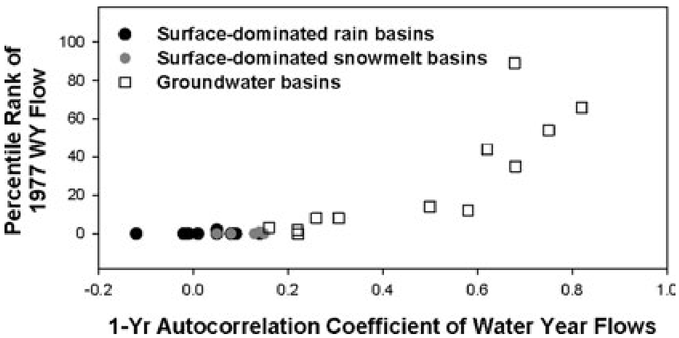


FIGURE 3. Percentile Rank of 1977 Water Year Streamflow for the Period of Record as a Function of the One-Year Autocorrelation Coefficient of Water Year Flow.

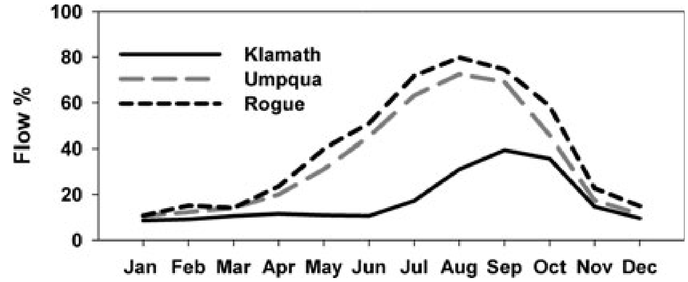


FIGURE 5. Average Monthly Flow Upstream as a Percent of Downstream Flow for the Klamath River, the Umpqua River, and the Rogue River. The streamflow sites and periods of record used are described in the Methods section.

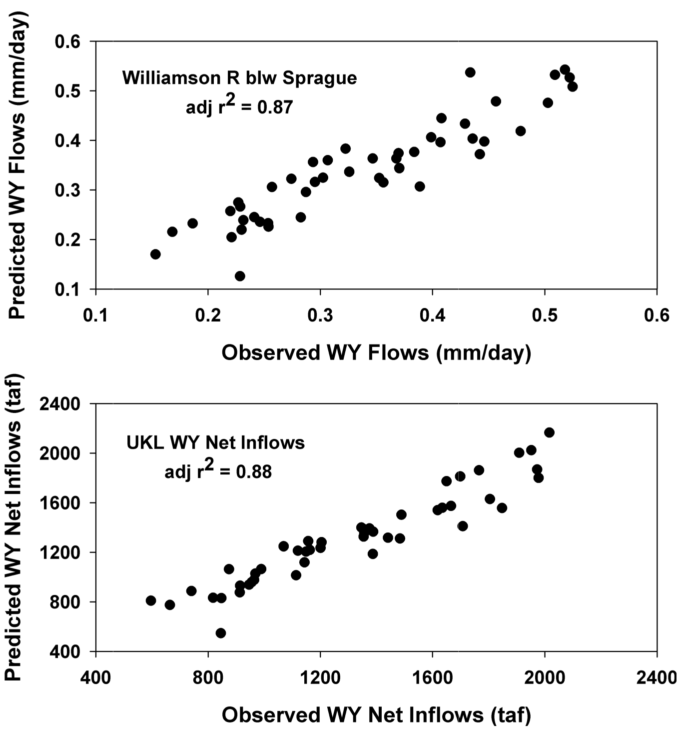


FIGURE 4. Predicted *vs.* Observed Water Year Flows for Williamson River Below Sprague Near Chiloquin, Oregon (mm/day) and Upper Klamath Lake (UKL) Net Inflow 1961-2007 (thousand acre-feet/year). Predicted values are based on stepwise linear regression of multiple years of October-March winter precipitation (cm) from USHCN station data at Crater Lake, Oregon (CL) and Paisley, Oregon (P). Equation for the top plot: Will R avg WY flow = $0.00196CLpcp + 0.0058Ppcp + 0.00056CLpcp_{lag1yr} + 0.00053CLpcp_{lag2yr} + 0.00052CLpcp_{lag3yr} - 0.20924$. Equation for the bottom plot: UKL avg WY net inflow = $8.37CLpcp + 2.38CLpcp_{lag1yr} + 1.93CLpcp_{lag3yr} + 13.9Ppcp + 10.2Ppcp_{lag2yr} - 693$.

First, groundwater-dominated basins are seasonally very important to mainstem flows during the typically dry summers of the region. Figure 5 shows the average monthly contribution of flow at an upstream site as a percentage of average monthly flow at a downstream site for three major river systems in the study area. In all three systems, the upstream sites represent groundwater-dominated basins, or are primarily supported by flows from groundwater-dominated basins, while the downstream sites represent surface-dominated basins. The transition from groundwater stream types to surface-dominated stream types with distance downstream is common in Cascade river systems (Tague and Grant, 2004).

Flows in the upstream groundwater-dominated basins are only a minor component of the downstream flows in the winter and spring but become much more important during summer and fall, especially July-October (Figure 5). This is due to a combination of higher fractions of summer flow in the groundwater-dominated basins at the upstream sites as well as the low summer flows in the surface-dominated basins downstream. In the Rogue and Umpqua River systems, as much as 60-80% of the downstream summer flows originate at the upstream sites, even though these groundwater-dominated basins are located 200-225 km upstream and comprise only 10-15% of the total watershed area at the downstream sites.

In a dry year, such as 1977, the upstream contributions from groundwater-dominated basins become much more important to downstream flows during all months of the year, not just summer months. On the Klamath River, the annual contribution of the upstream site averaged 26% for all water years but was 51% during water year 1977. On the Umpqua River, the annual contribution upstream averaged 20% for all water years but was 39% during 1977. For the Rogue River, the average contribution upstream averaged 29% for all water years but was 65% during 1977. The important point is that contributions from groundwater streams become an increasingly important component of flow in these systems during the driest part of the year and during the driest years.

These relationships have implications for El Niño years too. There is evidence that increasing trends in winter precipitation and snowpack in northern California are linked to an increase in the frequency of El Niño events since the 1970s (Howatt *et al.*, 2007). Climate data in the study area indicate that northern California is often wetter than southern Oregon during El Niño years. This suggests that during an El Niño year, wet conditions in the lower Klamath Basin in northern California will compensate for drier conditions in the Upper Basin. But the streams in the lower Basin are mostly surface-dominated basins with low summer and fall base flows, as described earlier. Therefore, lower Klamath tributaries will not augment late season mainstem flows during an El Niño event, especially if that event occurs during a dry year cycle when flows in the upper Klamath groundwater-dominated basins are low.

The second reason that stream type is important is because the three stream types respond differently to climate trends, as shown in Table 3 and Figure 6. In the 10 surface-dominated rain basins, most of the changes in monthly streamflow are observed in the winter in response to monthly trends in precipitation. December shows an increase and January, February, and March show large declines in flow. These same monthly trends are generally observed in the monthly precipitation data at the 20 USHCN stations in the study area. Summer flow declines, although large in relative terms, are very small in absolute terms (Table 3). October flows have declined moderately and November flows show large declines. The large November declines in the rain basins are interesting because there are no corresponding declines in November monthly precipitation at any of the USHCN stations in the area. It may be that warmer summer temperatures are resulting in increased evapotranspiration and decreased soil moisture, causing these systems to take longer to recharge and start flowing again in the fall. Declining flows in November could have biological implications for migrating fall salmon runs by delaying their return to smaller tributaries until later in the season.

Unlike the rain basins, there has been little change in flows in the five snowmelt basins during the winter months (Table 3 and Figure 6). These basins store much winter precipitation as snow throughout the season, making them less sensitive to fluctuations in monthly precipitation during the winter months. The most notable change has been in the spring season. Monthly flows show a large increase in March, little change in April, and large decreases in May and June. Differences in trends are statistically significant between March and May ($p = 0.012$), March and June ($p = 0.012$), April and May ($p = 0.037$), and April and June ($p = 0.060$). The

TABLE 3. Absolute and Relative Trends in Monthly and Water Year Flows for Three Streamflow Types and for UKL Net Inflow.

	October	November	December	January	February	March	April	May	June	July	August	September	WY
Median of trends in surface-dominated rain basins													
mm/day	−0.22	−0.60	+0.41	−0.37	−1.12	−0.71	−0.19	−0.30	−0.08	−0.03	−0.02	−0.03	−0.36
% change	−46	−33	+9	−8	−22	−17	−6	−14	−17	−14	−12	−17	−14
Median of trends in surface-dominated snowmelt basins													
mm/day	−0.02	−0.06	−0.03	+0.02	−0.05	+0.19	+0.05	−0.81	−0.44	−0.05	−0.01	−0.01	−0.16
% change	−21	−33	−14	+9	−14	+9	+7	−20	−31	−23	−21	−12	−10
Median of trends in groundwater-dominated basins													
mm/day	−0.27	−0.36	−0.28	−0.23	−0.21	−0.08	−0.18	−0.37	−0.53	−0.50	−0.33	−0.30	−0.44
% change	−19	−22	−24	−20	−24	−17	−19	−26	−31	−24	−24	−22	−21
Kruskal-Wallis test (*p*-value no group differences)													
p-Value	0.010	0.016	0.000	0.122	0.055	0.031	0.176	0.286	0.006	0.006	0.000	0.000	0.062
Dun's multiple comparison test (*p*-value no paired differences)													
Rain *vs.* snowmelt	0.003	0.005	0.083	–[1]	0.026	0.010	–[1]	–[1]	0.013	0.472	0.526	0.196	0.025
Rain *vs.* groundwater	0.571	0.102	0.000	–[1]	0.076	0.126	–[1]	–[1]	0.004	0.002	0.001	0.003	0.781
Snow *vs.* groundwater	0.002	0.118	0.087	–[1]	0.415	0.164	–[1]	–[1]	0.864	0.069	0.001	0.000	0.040
Trends in UKL net inflow 1961-2007													
Change in taf	−26	−36	−33	−17	−36	−2	−22	+2	−20	−11	−18	−19	−263
% Change	−29	−30	−24	−12	−25	−2	−13	+2	−29	−32	−46	−32	−18

Notes: taf, thousand acre-feet. Streamflow trends are normalized to a 50-year period and Upper Klamath Lake (UKL) net inflow trends are for 1961-2007. Statistical test results are for the test of group differences, as described in the text.

[1]The Dun's multiple comparison test was not run for these particular months because the Kruskal-Wallis test results showed no significant differences ($p < 0.10$) in the trends among stream types.

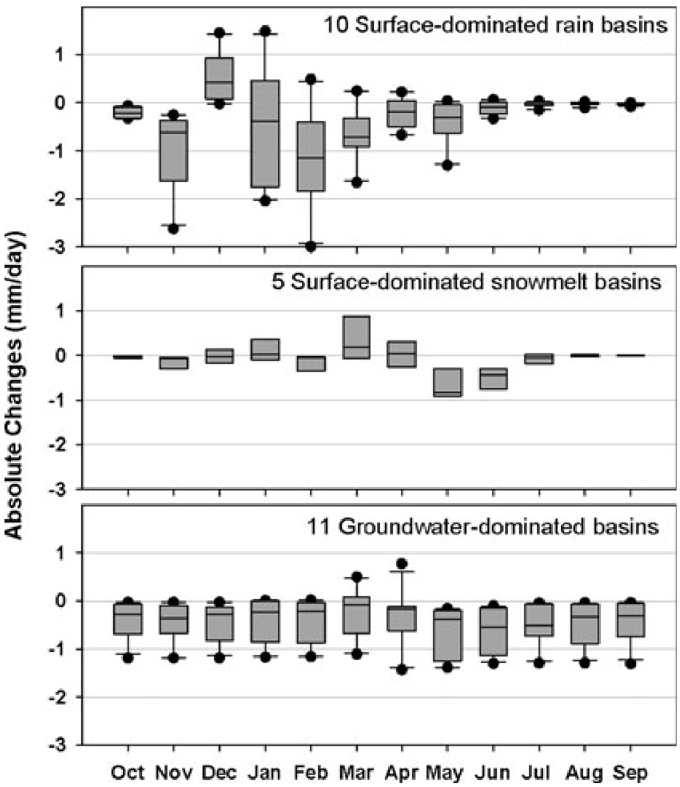


FIGURE 6. Boxplots of the Linear Trends in Monthly Flows, Normalized to a 50-Year Period and Expressed in Absolute Terms, for All the Streams in Each Basin Type in the Study Area. In a boxplot, the line inside the box represents the median 50-year trend, the box itself represents the interquartile range (25th-75th percentile range) of the trends, and the whiskers are the 10th and 90th percentiles of the trends. The number of data points represented by each box corresponds to the number of stream sites for each stream type. Because there are only 5 streamflow sites and data points for the snowmelt basins, the 10th and 90th percentiles are not calculated and the boxes do not have whiskers.

increasing trend in March flows (+0.19 mm/day) contrasts with the large decline in March flows (−0.71 mm/day) in the rain basins in the study area (Table 3). The increase in March flows and the large declines in May and June flows in the snowmelt basins are probably in response to decreasing snowpack and earlier snowmelt in the study area. This is indicative of earlier onset of spring snowmelt, a phenomena well documented in the western U.S. (Cayan *et al.*, 2001; Stewart *et al.*, 2004). Like the rain basins, the snowmelt basins show large relative change but very small absolute change in the summer months (Table 3).

The 11 groundwater-dominated basins show much more uniform trends for all months, reflecting the more uniform flows in general in these systems (Table 3 and Figure 6). Generally, the declines in March and April are less than the declines in other months, although only differences between March and May trends ($p = 0.020$) and March and June trends ($p = 0.028$) are statistically significant. As in the snowmelt basins, the comparatively smaller declines in March are likely a response to reduced snowpack and earlier snowmelt. But in the groundwater basins, the streamflow response to changes in snowpack is attenuated and delayed and the declines are extended throughout the summer. The March trends are intermediate between the large negative March trends in the rain basins and the positive March trends in the snowmelt basins. There are strong absolute reductions in flow throughout the summer months, in contrast to the surface-dominated basins (Table 3). As explained above, because many of the larger river systems depend on flows from these basins during these months, these declines will be important downstream.

The statistical differences in trends among the stream types for each month and for the water year are summarized in Table 3. A low p-value for the Kruskal-Wallis test indicates that the trends from at least one group of streams are significantly different from the trends of the other stream types. A low p-value for the Dun's multiple comparison test means that the trends from the paired stream types indicated in the table are significantly different. Focusing on the spring and summer results, the positive March trends in the snowmelt basins are significantly different from the negative March trends in the rain basins but not the groundwater basins. This difference reflects the change in runoff timing with a shift toward earlier flow, as described above. By June, the rain basins are showing slightly negative, absolute trends that are significantly higher than the June trends in the other two basin types. In summer, absolute trends are slightly negative in the rain and snowmelt basins but are strongly negative in the groundwater basins. The July-September declining trends in the groundwater basins are an order of magnitude greater and are significantly different from both the rain basins and the snowmelt basins.

There are some latitudinal differences in the trends as well. Climate data from the study area show that winter precipitation and snowpack have been increasing in some areas of northern California since 1945 (Supporting Information) (Howatt *et al.*, 2007). Streamflow trends reflect these differences, with some streams in northern California showing less of a decrease, or an increase, in flows. The Trinity River above Coffee, a snowmelt basin in northern California, is the second highest elevation basin in our study area. It is the only stream in the study area that has an increasing trend in water year flows (+0.12 mm/day or +5%) over the period of record. The McCloud River near McCloud, a groundwater basin in northern California, has a negligible change in

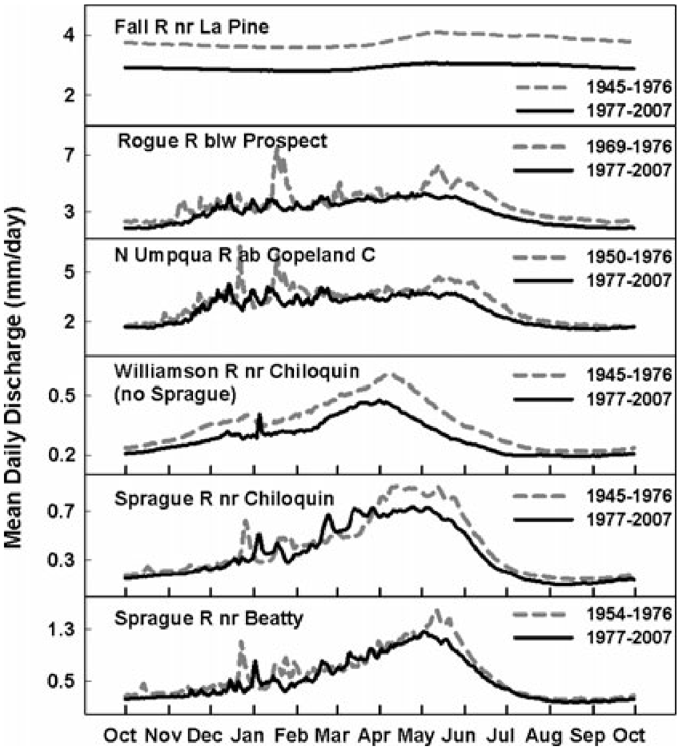


FIGURE 7. Mean Daily Discharge for Two Periods, Pre-1976 and Post-1977, for Six Groundwater-Dominated Basins in Oregon Near or Tributary to Upper Klamath Lake. The period of record used to compute the averages for each basin is shown in the legend.

water year flows (−0.05 mm/day or −1%) over the period of record, although there are some indications that the snowmelt peak is arriving earlier in the spring. These differences emphasize the importance of site-specific information to the interpretation of climate trends and streamflow response.

We plotted average mean daily flows in six groundwater-dominated basins tributary to or near UKL in southern Oregon for two periods, corresponding to major changes in the PDO (Figure 7). Most of the basins have an obvious snowmelt peak, with the exception of the Fall River (Figure 7). In all six basins, there is less flow overall on an annual basis in the more recent period, reflecting a decrease in precipitation over the last several decades. The timing of flow has changed in the more recent period as well. The snowmelt response appears to have shifted earlier and become more muted as a result of warmer winter temperatures (Hamlet *et al.*, 2005; Mote, 2006). March flows show little change or, in some cases, an increase, more recently. The recession of the annual hydrographs begins earlier and the base flows are lower in the more recent period. These are the kinds of changes described for groundwater-dominated basins in Table 3 and Figure 6.

Upper Klamath Lake Net Inflow Trends

Upper Klamath Lake serves as the main water supply for the Klamath Irrigation Project as well as the headwaters of the Klamath River. The inflow and volume in the lake are extremely important for maintaining lake levels, downstream river flows, and irrigation of agricultural lands and national wildlife refuges. Three native species of fish listed on the U.S. Endangered Species Act, Coho salmon (*Oncorhynchus kisutch*), shortnose sucker (*Chasmistes brevirostris*), and Lost River sucker (*Deltistes luxatus*), require specific lake levels and river flows in order to meet basic life-history requirements like spawning and rearing. Because of limited storage and carryover in UKL, annual net inflow into the lake determines the amount of water available for management of lake level elevations; releases to help meet downstream Klamath River flows; and irrigation deliveries to agricultural lands and national wildlife refuges. The Williamson and Sprague Rivers (Table 1), two groundwater basins discussed above, are major tributaries to the lake.

For the water year, UKL net inflow has declined 18% or 263 taf (324.4 Mm^3) over the 1961-2007 period of record. The April-September UKL net inflow volume, the standard measure of water availability in the basin, shows a similar relative decline of 16% or 84 taf (103.6 Mm^3) for the period (Figure 8). This represents a substantial decrease in water availability during the April-September irrigation season. Considering the spring and summer periods of the April-September irrigation season separately, the declines have been greater during July-September (Figure 8). Declines in net inflows are 12% or 44 taf (54.3 Mm^3) during the April-June period and 38% or 53 taf (65.4 Mm^3) during the July-September period. The difference between these two periods is much greater in relative terms than in volumetric terms because most of the April-September net inflow comes during the spring period, April-June.

The trends in the spring and summer periods indicate a shift in timing of April-September net inflow, with a greater proportion of the net inflow arriving earlier in the spring. The percentage of total April-September net inflow occurring in the April-June period has increased from about 70% of the total in 1961 to 80% of the total in 2009 (Figure 9). Correspondingly, there has been a decrease in the July-September percentage of April-September net inflow from about 30% of the total in 1961 to 20% of the total in 2009. Similar to the streamflow sites in the study area, this earlier timing is likely in response to reduced winter snowpack and earlier snowmelt. If winter temperatures continue to increase as predicted (Mote and Salathe, 2010), the trend toward earlier net inflow will continue.

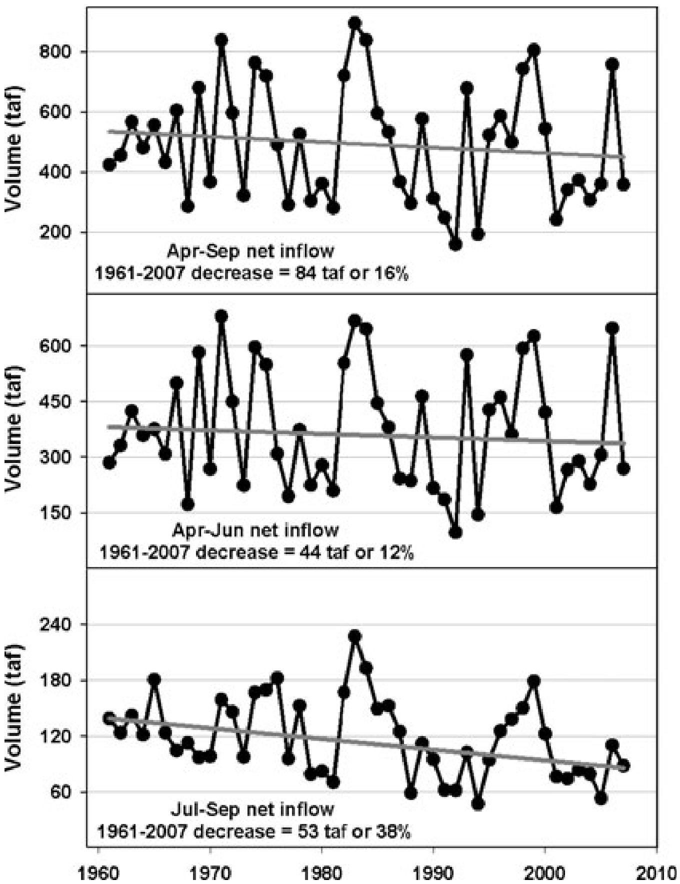


FIGURE 8. Time Series Plots With Kendall's Tau Trend Lines of April-September, April-June, and July-September Upper Klamath Lake Net Inflow Volumes for the Available Period of Record From 1961 to 2007. Volumes are expressed in units of thousand acre-feet (taf) rather than SI units (Mm^3) because of their common usage by water interests in the basin.

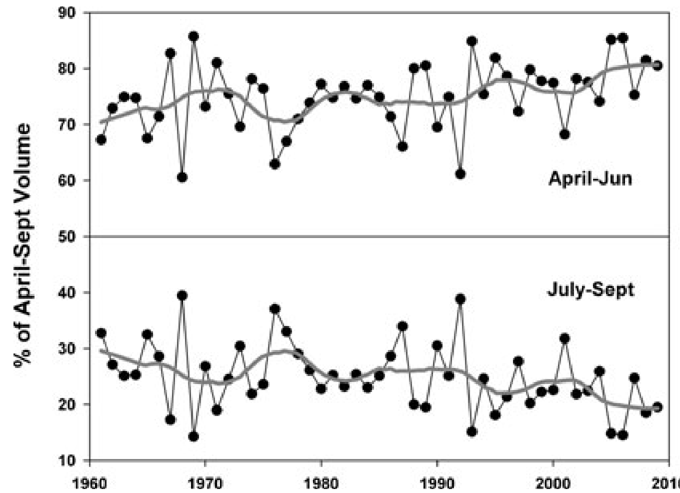


FIGURE 9. April-June and July-September Net Inflow Volumes Expressed as a Percentage of the Total April-September Net Inflow Volume Over the 1961-2009 Period of Record. Gray lines are LOWESS smooths of the data.

A decrease in the total volume and a shift toward earlier timing of UKL net inflow represent challenges for water supply management. Less UKL net inflow overall will mean even more limited water supply to meet the needs of power interests, irrigators, and biological resources in a region that is already experiencing conflict and competition for water (NRC, 2007). A shift toward earlier UKL net inflow will mean more water to meet biologically mandated lake levels and river flows in the spring, but less water for those same needs in the summer. In addition, irrigation demands peak in summer and may increase with warmer temperatures and longer growing seasons (Karl *et al.*, 2009). Exacerbating the water supply situation is the fact that UKL net inflows in fall and early winter have declined as well, meaning the lake is slower to refill now after the end of the season. The 2009 season illustrates the challenges presented by these trends. There was very low net inflow to the lake from the end of summer through early winter, causing the lake elevation to reach a record low in the winter of 2010, and compromising water availability for threatened suckers, coho salmon, agriculture, and wildlife refuges during the 2010 season. The low UKL net inflow was partially a result of the long-term declining trend in base flows coupled with an El Niño event during the 2009-2010 winter that resulted in low winter precipitation in the upper Klamath Basin.

Water supply management should take into account the long-term declines and earlier timing of UKL net inflows, particularly during the summer and fall months. To the extent that the changes are a response to increasing winter temperatures and that winter temperatures continue to increase in the future (Mote and Salathe, 2010), these changes are irreversible in the short term. In this case, historic hydrology will not be representative of future hydrologic conditions. Adjusting lake management and forecasting methods to account for these trends and timing changes will help alleviate future water supply problems. The focus of state and federal water management agencies on April-September UKL net inflows, which are dominated by the snowmelt peak, may have obscured declining trends in summer and fall/winter base flows and the changes in UKL net inflow timing. It may be useful to analyze inflows separately during the runoff-dominated period, April-June, and the base-flow-dominated period, July-September and later in the fall/winter, in part because flows during these two seasons are driven by different hydrological processes and may exhibit different trends and characteristics. The decreased variability and autocorrelation of base flows may be useful for predictions and flow forecasts outside of the irrigation season as well.

CONCLUSIONS

Geology and elevation are both very important in determining streamflow response to climate in this region. Elevation influences temperature and the form and timing of the winter recharge signal whereas geology mediates the transition of the winter recharge signal to streamflow. The groundwater-dominated basins have much less seasonal and annual variation and much greater summer and fall flows compared to rain and snowmelt surface-dominated basins (Table 2). Warmer winter temperatures have reduced snowpack and caused earlier snowmelt throughout the region, resulting in an earlier winter recharge response in snowmelt and groundwater basins (Table 3 and Figure 6). In the groundwater basins, the streamflow response to changes in snowpack is smoothed and delayed and the effects are extended longer in the season. The snowmelt response is arriving earlier in these basins and streamflow has decreased significantly in the summer and fall. Our results indicate that absolute decreases in July-September base flows are significantly greater, by an order of magnitude or more, in groundwater basins compared to surface-dominated basins.

The declines are particularly important because groundwater basins sustain UKL inflows and mainstem river flows during the typically dry summers of the area. Net inflow into UKL has decreased over the 1961-2007 period, especially in the summer, and the timing of net inflow has shifted toward earlier in the spring. These changes represent major challenges for water supply and water management in the Klamath Basin.

This study shows that not all streams respond uniformly to the same climate signal. In this region, it is important to consider geology when evaluating streamflow response to climate change, both past and future. Because stream type may vary spatially at a finer scale than climate parameters like temperature and snowpack, this may necessitate studies at a smaller geographic extent than is common for most climate studies.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Figure S1. Map showing the linear trend in average October-March winter temperature at the 20 USHCN stations in the study area, 1945-2007.

Figure S2. Map showing the percent change in total October-March winter precipitation at the 20 USHCN stations in the study area, 1945-2007. Light gray squares indicate decreases and dark gray circles indicate increases.

Figure S3. Map showing the percent change in annual snow water equivalent at the 47 snowcourse sites in the study area, 1945-2007. Light gray squares indicate decreases and dark gray circles indicate increases. Station numbers are identified by name in Table S2.

Figure S4. Percent change in annual snow water equivalent as a function of site elevation at the 47 snowcourse sites in the study area, 1945-2007.

Table S1. USHCN station names, elevations, trends in winter temperature and winter precipitation, and the *p*-values associated with those statistical trends.

Table S2. Snowcourse site names, numbers, states, agencies, elevations, trends in snow water equivalent, and the *p*-values associated with those statistical trends.

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