https://doi.org/10.5194/egusphere-2026-4870
Preprint. Discussion started: 31 August 2026

Attributing summer streamflow decline to climate vs. agriculture

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Abstract. Climate warming is reducing the mountain snowpacks that sustain summer streamflow, yet in agricultural and urban catchments this climatic decline is often superimposed on the effects of local water use, and separating the two is difficult. We investigate how much of the continuing dry season-flow decline in a snow-reliant, anthropogenically influenced intermontane catchment with a distinct summer dry season is driven by climate change rather than human water use, and whether the roughly even contributions reported in another study for the last quarter of the 20th century still hold under U.S. Southwest megadrought conditions of the first quarter of the 21st century. Comparing three multi-decadal timeframes across nine catchments in Northern California, we find no significant difference in annual precipitation but a widespread rise in vapor pressure deficit and declining snowpack at lower elevations. Summer flows declined significantly in the catchment affected by human use of groundwater and surface water compared with the near-natural reference catchment. However, unchanged annual total flows indicate seasonal redistribution rather than an overall loss of water. Using a paired-catchment attribution and the mid-20th century record as pre-development and pre-climate change reference, we decompose the late 20th century and early 21st century decline in the managed catchment into climatic and anthropogenic components. The total summer-flow loss nearly doubled between the two climate change periods, from about 21 to 40 $\mathrm{Mm^3}$: During late 20th century, climate change and anthropogenic water use contributed almost equally. But under 21st century megadrought conditions the climatic loss (26 $\mathrm{Mm^3}$) had grown to roughly twice the anthropogenic impact (14 $\mathrm{Mm^3}$), accounting for about two-thirds of the decline. The even contribution no longer holds: climate change now governs the decline. The results suggest that curtailing withdrawals might not sufficiently sustain ecologically relevant late-summer flow and fall pulse flows and additional measures might require managed aquifer recharge, adaptation, and climate mitigation alongside local water management.

1 Introduction

In seasonally snow-covered mountains, the winter snowpack acts as a natural reservoir (Barnett et al., 2005; Mote, 2006). Precipitation accumulates as snow while temperatures stay below freezing, and is released as meltwater once spring warming pushes temperatures past the melting point (Mote, 2006; Kapnick and Hall, 2012). Because melt advances gradually up the elevation gradient, lower altitudes melt earlier than higher ones, staggering the release into a sustained supply of water that either enters streams directly or infiltrates to recharge the underlying groundwater (Godsey et al., 2014). In regions with frequent spring or summer droughts, but particularly in Mediterranean climates, where summers are dry and precipitation is

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limited to winter months, this stored meltwater, sometimes in conjunction with intermediary groundwater storage, becomes the dominant source of warm-season streamflow, sustaining baseflow through the months when little rain falls (Li et al., 2017).

Climate warming undermines this reservoir function. Higher winter temperatures push more precipitation to fall as rain rather than snow, reducing snowpack storage (Trenberth, 2011; Ashfaq et al., 2013; Rhoades et al., 2018) and raising winter discharge in ways that can aggravate floods (Kim and Jain, 2010; Yarnell et al., 2015). Even where snow still accumulates, warming advances snowmelt and triggers rain-on-snow events earlier in the year, shifting the runoff peak toward the start of spring (Gleick and Chalecki, 1999; Stewart et al., 2005; Mote, 2006; Barnhart et al., 2016; Mote et al., 2018; Xiao et al., 2018). Both mechanisms deliver water earlier and leave less to sustain flow through the dry season, so summer baseflow declines (Mote et al., 2005; Ashfaq et al., 2013; Berghuijs et al., 2014; Vano et al., 2015; Asarian and Walker, 2016).

Warming does not act on the snowpack alone. Increased evaporation dries the land surface and intensifies drought (Trenberth, 2011), which propagates from precipitation deficits through soil-moisture deficits to runoff and groundwater deficits over progressively longer timescales (Van Loon et al., 2016; Cook et al., 2018; AghaKouchak et al., 2021). In semi-arid regions, water users respond to these deficits by turning to groundwater for irrigation and urban supplies, since aquifer storage offers a perceived resilience (Thomas et al., 2017). Yet stream and aquifer form a single, connected system rather than separate resources (Famiglietti, 2014): pumping lowers the hydraulic head and draws down the water table, so streamflow either seeps into the aquifer or is intercepted before it reaches the channel, leaving discharge lower than it would otherwise be (Barlow and Leake, 2012; Tijdeman et al., 2018; Jasechko et al., 2021). Agricultural water use thus adds a second driver of summer-flow decline on top of the climatic one.

These drivers rarely act in isolation (Beguería et al., 2003), and separating their contributions to summer-flow decline is difficult—yet the distinction determines whether restoring flow calls for adapting to a changed climate or curbing local water use. The post-2000 megadrought of the U.S. Southwest illustrates this entanglement. It is unprecedented in the instrumental record (Richman and Leslie, 2015) and has been intensified by anthropogenic warming (Diffenbaugh et al., 2015); a 1200-year soil-moisture reconstruction places only one earlier megadrought as more severe and indicates the drought would have been far milder without warming (Williams et al., 2020), with 2000–2021 emerging as the driest 22-year interval in over a millennium (Williams et al., 2022). As reduced snowpack cut surface supply, users turned increasingly to groundwater: in California, aquifers met roughly one-third of demand in wet years but nearly two-thirds in the dry year of 2014 (Harter and Dahlke, 2014). Withdrawals at these rates exceed natural recharge, overdrafting aquifers and lowering water tables (Gleick and Palaniappan, 2010; Famiglietti, 2014).

The Scott River, in the lower Klamath basin of northern California, concentrates these pressures in a single, ecologically critical catchment. It is snow-reliant yet warming. Warmer winters (Mote et al., 2018), reduced snowpack (Mote, 2006), declining summer precipitation, and rising evapotranspiration (Asarian and Walker, 2016; Tang et al., 2009) contribute to decreasing summer streamflow. Concurrently, streamflow is also being drawn on heavily for agricultural irrigation by surface water diversion and — since the 1970s — by groundwater pumping (van Kirk and Naman, 2008) with a delayed stream depletion ranging from days to few months (Foglia et al., 2013). The resulting low flows disconnect tributaries, at times reducing the Scott River to warm, stagnant pools (van Kirk and Naman, 2008) that block anadromous Chinook (*Oncorhynchus tschawytscha*) and

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endangered coho salmon (*Oncorhynchus kisutch*) from reaching spawning and rearing grounds and drive population decline (Coates, 2005). To protect flow, curtailment orders now suspend agricultural withdrawals once discharge falls below monthly thresholds (California State Water Resources Control Board, 2026) —a measure whose justification hinges on how much of the decline is agricultural rather than climatic. Prior work has approached but not resolved this: Drake et al. (2000) tied most of the variance in September discharge to snow water content and precipitation over the preceding year, Asarian and Walker (2016) attributed flow declines to human water use rather than precipitation, and van Kirk and Naman (2008) apportioned the historic-to-modern (1940s–1976 vs. 1977–2005) decline in summer discharge roughly evenly between climate change and agricultural water use. Their attribution, however, ends in 2005; two further decades of warming have since accrued, leaving open whether the decline has continued and whether the climate–agriculture balance still holds.

We therefore ask how much of the continued summer-flow decline in snow-reliant, anthropogenically influenced catchments is attributable to climate change rather than local water use, using the Scott River and its neighboring lower Klamath basins as a case study. Building on the trends and attributions of earlier work, we hypothesize that:

- All known trends in hydro-climatic drivers and controls hold in the tested catchments (April 1 snow water equivalent declining; no changes in annual water-year precipitation; rise in evaporation, with vapor pressure deficit as its proxy).
- Mean summer discharge is trending lower while the low-flow season lengthens.
- Following van Kirk and Naman (2008), streamflow further declined under the additional warming since their analysis, yet the share attributable to agriculture rather than climate has remained unchanged, as higher evaporation raises irrigation demand.

To address these hypotheses, we (1) analyze local trends in precipitation, vapor pressure, snow storage, and streamflow across the lower Klamath catchments and (2) quantify the summer-flow decline in the Scott River catchment attributable to climate change versus agricultural water consumption. We discuss these results against the three preceding studies and review current water and groundwater management practice and its benefits to endangered fish and other groundwater-dependent ecosystems.

2 Methods

2.1 Study Area and Data

The study catchments lie in the mountainous terrain of northern California and southern Oregon, ranging in elevation from roughly 330 to 4300 m. The climate is Mediterranean, with dry summers and wet winters delivering an annual 500 to 2000 mm of precipitation (Asarian and Walker, 2016). Above about 1500 m this precipitation falls almost exclusively as snow, which stores water through the winter season and releases it when melting in spring. The flow regime is correspondingly snow- and rain-driven, with winter peak flows, a spring recession, summer baseflow, and fall pulse flows (Yarnell et al., 2015); Lane et al. (2018) classify the catchments as “Low Snowmelt and Rain” with high winter and spring variability.

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We restricted the analysis to gauged catchments in the lower Klamath basin with records longer than 60 years, the minimum needed to resolve trends across our three periods; the resulting set and its catchment characteristics are listed in Table A1. The catchments differ markedly in human influence. Sacramento and Shasta carry large reservoir storage that alters streamflow, and in the Scott and Shasta valleys shallow alluvial aquifers along the rivers support agriculture and pasture (van Kirk and Naman, 2008). The remaining catchments, among them Salmon, carry neither substantial reservoir or sedimentary aquifer storage nor irrigated agriculture or urban development and are thus effectively unimpaired by direct anthropogenic influence other than a changing climate (Figure 1).

Agriculture in Scott Valley developed after the 1850s Gold Rush around cattle ranching and grain and alfalfa production, with irrigated area expanding from about 29,000 acres in 1959 to 34,000 acres today (Siskiyou County Flood Control and Water District Groundwater Sustainability Agency, 2021). Before the 1960s, crop production was flood-irrigated by diverting Scott River flow, and groundwater pumping was minimal. As sprinkler irrigation spread through the 1960s and 1970s, the pressure it required was supplied by groundwater pumps; this raised total water use and allowed irrigation to continue even when the river ran too low to divert (Siskiyou County Flood Control and Water District Groundwater Sustainability Agency, 2021).

To characterize climatic water supply and atmospheric demand, we obtained precipitation and maximum vapor pressure deficit (VPD) from the PRISM dataset, which combines station observations with an expert algorithm that extrapolates them across a grid according to elevation effects (Daly and Bryant, 2013; Asarian and Walker, 2016). Monthly means were available as a 4 km raster covering the continental United States; we cropped and averaged these to each catchment and converted them to water-year means.

NRCS snow-course data, retrieved with the *RNRCS* package (Lee and Roberti, 2018) were used to quantify snow storage. Snow courses are fixed sites where SWE and snow depth are measured manually each month from January to June, and SWE serves as a proxy for the water content of the snowpack. We evaluated April 1 SWE at all snow courses within the catchments (Table B1), spanning elevations from 1200 to 2100 m.

To characterize summer low flow, we obtained daily mean discharge for all catchments from USGS with the *dataRetrieval* package (de Cicco et al., 2018). Rather than analyzing a fixed set of calendar days as van Kirk and Naman (2008) did, we defined the summer low-flow season by a discharge threshold: the 15th percentile of Historic-period flows, which ranged from 1.1 m^3/s in Shasta River to 16.0 m^3/s in the large Trinity catchment. The season was taken to begin and end when flow fell below and later exceeded this threshold for seven consecutive days. For this "summer-flow" period we computed the following metrics: mean and minimum discharge (m^3/s), start and end day of the year, total duration as well as mean discharge from the end of the low-flow season to year-end (m^3/s).

2.2 Trend analysis and attribution

Each time series was divided into three periods to separate the influence of climate change from that of agricultural water use. The *Historic* period runs from 1940, or the start of the record where data acquisition began later, to 1976, a period in which almost no groundwater pumping occurred in Scott Valley. The *Intermediate* period spans 1977 to 1999; it opens with

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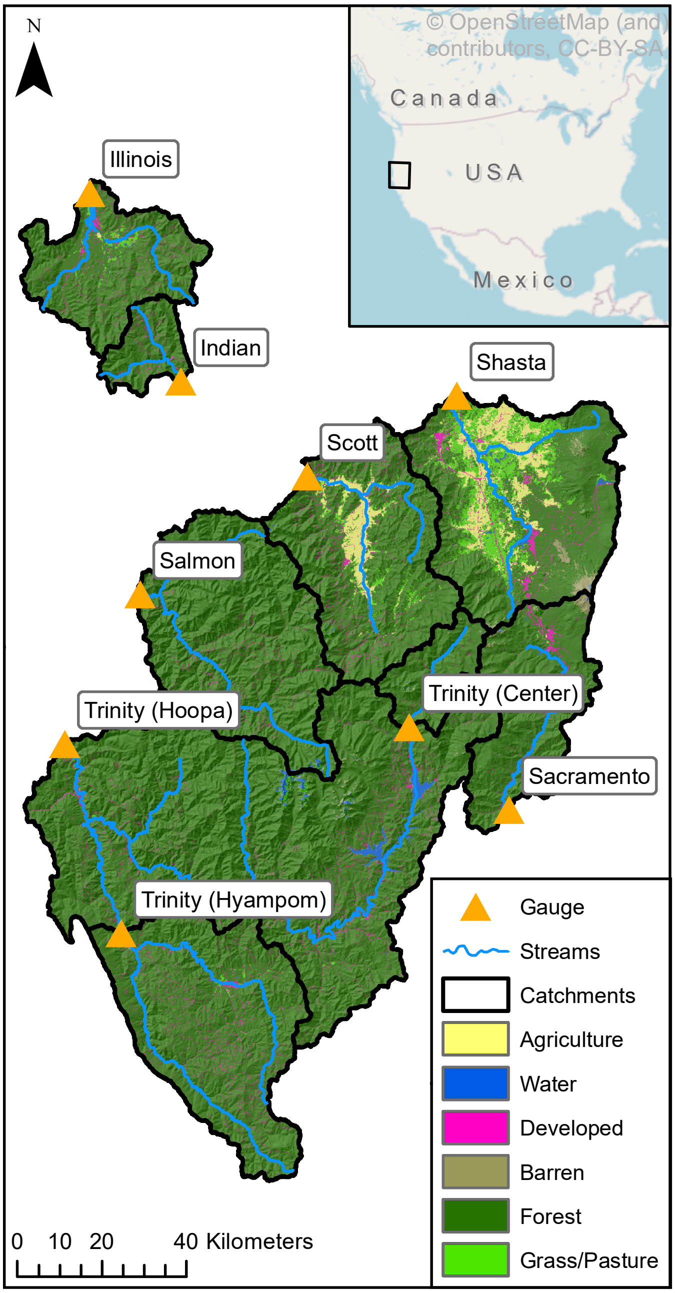

Figure 1. The nine study catchments in the lower Klamath basin, spanning northern California and southern Oregon. Triangles mark the USGS gauges at each catchment outlet, and land cover is shown by color. Landcover data by Dewitz (2024)

the Pacific Decadal Oscillation shift from a cold to a warm phase (Mann and Gleick, 2015) and coincides with the transition in Scott Valley from surface-water only to groundwater-augmented irrigation. The *Modern* period begins in 2000 with the

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onset of the severe U.S. Southwest drought (Williams et al., 2020, 2022) and ends in 2025. Across these periods we analyzed streamflow, snow water equivalent (SWE), precipitation and maximum vapor pressure deficit.

To test whether precipitation, vapor pressure deficit, April 1 SWE, and the summer-flow metrics differ among the three periods, we applied the non-parametric Kruskal-Wallis test, which evaluates whether the era groups are drawn from the same population without assuming a particular distribution (Helsel and Hirsch, 2002). Where the test indicated a significant difference ($\alpha = 0.05$), we applied a Dunn post-hoc test with Bonferroni correction to identify which pairs of periods differed (Helsel and Hirsch, 2002).

To quantify how much of the Scott River summer-flow decline is driven by climate change rather than agricultural water use, we applied a paired-catchment approach (van Kirk and Naman, 2008; Van Loon et al., 2019). The approach relies on a reference catchment without reservoir storage and agricultural irrigation. Long-term changes in discharge would be driven by climate, not by water management or irrigation. We ranked all candidate catchments by how closely their Historic summer regime (day of year 150–300) matched that of the Scott River and selected the closest match; the Salmon River, adjacent to the Scott and used as the reference by van Kirk and Naman (2008), ranked first.

The attribution rests on three assumptions: that Salmon River discharge responds to climate alone, that Scott River discharge responds to both climate and agriculture, and that both catchments experience climate change after the Historic 1940-1976 era to a comparable degree, so that the climate-driven fractional decline is equal in both. Any further decline in Scott River flow relative to Salmon River flow beyond their Historic relationship is therefore attributable to agriculture.

We related Scott to Salmon summer discharge with a line-of-organic-correlation (LOC), or reduced major axis, regression fitted on the Historic period (Khalil and Adamowski, 2012; Helsel and Hirsch, 2002). Applying the Historic LOC relationship to the Salmon's Intermediate and Modern discharge yields the Scott River flow expected under climate change alone, absent any change in agricultural use and specifically absent the onset of groundwater pumping at the beginning of the Intermediate era. Differencing this prediction against observations decomposes the decline, integrated across the summer window as volumes (Mm^3): the climate contribution is the difference between Historic and predicted flow, the agricultural contribution the difference between predicted and observed flow, and the two sum to the total decline relative to the Historic period.

We quantified uncertainty in the attribution from the line-of-organic-correlation fit itself. The 95% confidence intervals on the Historic slope and intercept, propagated through the prediction, define upper and lower bounds on the predicted Scott River flow, and hence on the attributed climate and agricultural volumes; the same interval is shown on both the predicted hydrograph and the attributed-volume totals.

3 Results

3.1 Trends in regional hydro-climatic drivers

Across the nine catchments, annual precipitation showed no significant difference between the timeframes while atmospheric moisture demand rose. Table 1 summarizes the direction and significance of all between-period trends, and shows that the climate signals appear across catchments rather than in isolated catchments.

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Table 1. Direction and significance of between-period trends across the nine study catchments. Arrows give the trend sign; stars give Kruskal–Wallis/Dunn significance for the Historic–Modern change ($^{*}\,p < 0.05$; $^{**}\,p < 0.01$; $^{***}\,p < 0.001$). A dagger (†) marks changes already significant by the Intermediate period (Historic–Intermediate, $p < 0.05$); marks without a dagger became significant only in the Modern period. No Intermediate–Modern comparison was significant. –, not significant; n/a, no snow course. April 1 SWE is the most significant snow course per catchment (always its lowest). Annual Q is total water-year discharge volume.

	Climate				Summer streamflow			
Catchment	Precip.	VPD	SWE	Annual Q	Mean	Min	Dur.	Start
Sacramento	–	$\uparrow^{***}$	–	–	–	–	–	–
Shasta	–	$\uparrow^{***}$	$\downarrow^{**}$	$\downarrow^{*}$	–	–	–	–
Scott	–	$\uparrow^{**}$	$\downarrow^{***\dagger}$	–	$\downarrow^{***\dagger}$	$\downarrow^{***\dagger}$	$\uparrow^{***\dagger}$	$\downarrow^{***\dagger}$
Indian	–	–	n/a	–	–	–	–	–
Salmon	–	–	n/a	–	–	–	–	–
Trinity Center	–	$\uparrow^{***}$	–	–	$\downarrow^{**}$	$\downarrow^{**}$	–	–
Trinity Hyampom	–	$\uparrow^{**}$	n/a	–	–	–	–	–
Trinity Hoopa	–	$\uparrow^{*}$	$\downarrow^{*}$	–	$\downarrow^{*}$	$\downarrow^{**}$	$\uparrow^{*}$	$\downarrow^{**}$
Illinois	–	$\uparrow^{**}$	n/a	–	–	–	–	–

Annual water-year precipitation did not change significantly in any catchment (Table 1; all $p > 0.19$). Mean precipitation was somewhat higher and more variable in the Intermediate period and lower in the Modern one, but these differences reached significance in none of the catchments, and the Mediterranean seasonal regime—wet winters and dry summers—persisted throughout.

Atmospheric moisture demand, by contrast, changed between timeframes. Maximum vapor pressure deficit (VPD) increased significantly in seven of the nine catchments, the exceptions being the near-natural Salmon ($p = 0.055$) and Indian ($p = 0.15$) catchments (Table 1; Figure 2). In every catchment the increase was confined to the Modern period: Intermediate VPD did not differ from Historic VPD in any of the catchments (Bonferroni-adjusted $p = 1$ in all Historic–Intermediate comparisons). In contrast, Modern VPD was significantly higher in all but two catchments. The largest increases occurred in the Trinity Center ($p = 1 \times 10^{-5}$) and Shasta ($p = 5 \times 10^{-5}$) catchments.

April 1 snow water equivalent (SWE) trended downward at most snow courses, but the decline reached significance at only four of the courses analyzed: SWJ and ETN in the Scott catchment, LSH in the Shasta, and BFT in the Trinity (Table B1). All four lie below about 2000 m; no higher-elevation course showed a significant change. However, not all snow courses at those lower elevations showed significant difference between timeframes.

The clearest change was in the Scott catchment with the two significantly declining courses, SWJ and ETN. At both, mean April 1 SWE fell from roughly 35 mm through 25 mm to 20 mm across the Historic, Intermediate and Modern periods, and both declines were already significant between the Historic and Intermediate periods (Table B1). The Scott's remaining courses (DYM, MB3, MBL) showed no significant change.

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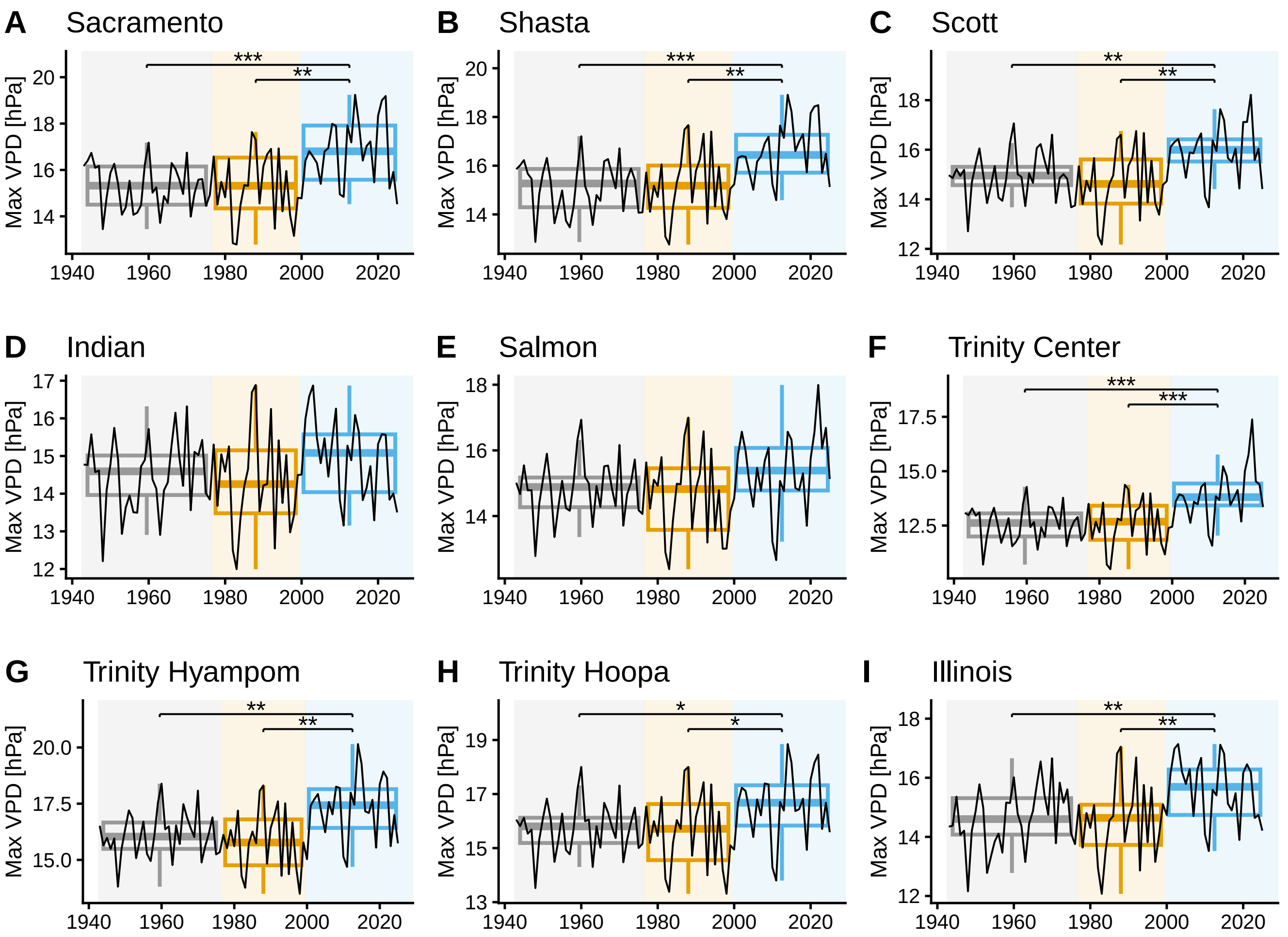

Figure 2. Maximum vapor pressure deficit for the nine catchments, across the three periods: Historic (1940–1976, Grey), Intermediate (1977–1999, Orange) and Modern (2000–2025, Blue). Each panel shows the annual values over the record together with boxplots summarizing each period, with the era backgrounds shaded. Brackets between period boxplots denote Dunn post-hoc significance (Bonferroni-adjusted) following a Kruskal–Wallis test: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$; non-significant pairs are unmarked.

3.2 Summer streamflow trends

The same catchment that led the snowpack decline also stands out in the flow it feeds: significant declines in summer streamflow were observed in the Scott and two Trinity catchments. Of the nine catchments, only Scott and Trinity Hoopa showed significant change across all four low-flow metrics—mean, minimum, duration and start of the low-flow season—while the near-natural Salmon, Indian and Illinois catchments, and the higher Sacramento catchment, showed no significant change in any summer (low flow period) metric (Table 1). In annual water-year discharge, by contrast, no significant difference was detected in every

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catchment but the Shasta ($p = 0.04$; Table 1), indicating that the summer decline, where it occurred, was a redistribution within the year rather than a loss of total annual water.

In the Scott, mean summer discharge fell from about 1.5 to 0.75 m^3/s and minimum discharge approached zero, while the low-flow season began roughly 30 days earlier and lengthened by about 50 days across the record (Figure 3). Mean, minimum, duration and start of the season all significantly changed early, between the Historic and Intermediate periods (Table 1). No metric differed significantly between the Intermediate and Modern periods. The end of the low-flow season shifted only marginally later ($p = 0.04$), and mean discharge after the season showed no change.

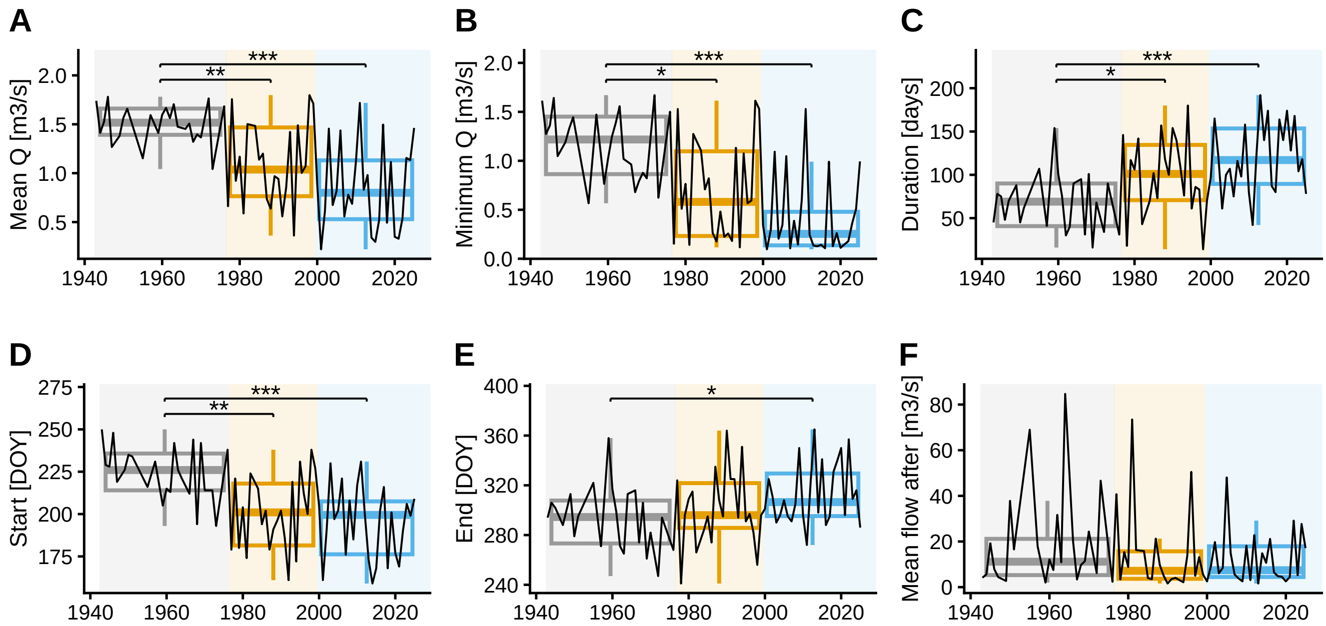

Figure 3. Summer low-flow metrics for the Scott River (USGS 11519500) across the three periods: Historic (1940–1976, grey), Intermediate (1977–1999, orange) and Modern (2000–2025, blue). Each panel shows the annual values over the record together with boxplots summarizing each period, with the era backgrounds shaded. Panels: (A) mean discharge of the low-flow season; (B) minimum discharge of the low-flow season; (C) duration of the low-flow season; (D) start day of the low-flow season; (E) end day of the low-flow season; and (F) mean discharge from the end of the low-flow season to the end of the water year. Brackets between period boxplots denote Dunn post-hoc significance (Bonferroni-adjusted) following a Kruskal–Wallis test: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$; non-significant pairs are unmarked.

The Trinity Center and Hoopa catchments also showed significant declines in mean and minimum summer discharge, and the Hoopa additionally in duration and start of the season (Table 1). Unlike the Scott, however, these changes reached significance only between the Historic and Modern periods. The Trinity is heavily regulated by upstream storage and inter-catchment diversion, so its declines cannot be read as a natural-flow signal. The Shasta catchment showed a significant decline only in post-season discharge.

3.3 Attribution of the summer-flow decline

Applying the paired-catchment model (Figure B1) to the Scott River decomposed its summer-flow decline into a climatic and an agricultural component, both of which grew over the record: The standardized hydrographs of the two catchments, near-identical in the Historic period, gradually diverged from the Historic period and from each other in the Intermediate and Modern period. (Figure 4).

Carrying the Historic relationship forward, the Scott flow predicted from the Salmon exceeded the observed Scott flow in both later periods, and the gap widened over time, indicating the agricultural impact (Figure 5 A). The total difference between observed Intermediate or Modern period Scott flows and those observed during the Historic period, however, are much larger: Relative to the Historic summer volume of 97.0 Mm^3, the total decline grew from 20.6 Mm^3 (21 %) in the Intermediate period to 39.7 Mm^3 (41 %) in the Modern, nearly doubling between the two periods (Figure 5 B). In the Intermediate period this decline was split roughly evenly between agriculture (10.9 Mm^3) and climate (9.7 Mm^3). During that period, the confidence intervals of the two components overlapped. By the Modern period the climatic component had risen to 25.9 Mm^3 while the agricultural component reached 13.8 Mm^3; climate thus accounted for 85% of the flow decline between the Intermediate and Modern period. By the Modern period, climate change constitutes roughly two-thirds of the flow decline since the Historic period and its confidence interval lay entirely above that of the agricultural component (agriculture 12.3–15.3 Mm^3, climate 24.4–27.4 Mm^3). Between the Intermediate and Modern periods the agricultural loss grew by about a quarter, the climatic loss by more than two and a half times.

The two drivers acted at different times within the year (Figure 5 A): The agricultural flow decline component was concentrated in the early and middle low-flow season, when irrigation demand is highest, and persisted as a smaller signal past the fall pulse flows into the following months. The climatic component dominated the late-summer flow decline.

4 Discussion

We set out to separate the climatic and anthropogenic contributions to the continued summer-flow decline of a snow-reliant, agriculturally influenced catchment, and to ask whether the roughly even contribution found by van Kirk and Naman (2008) through 2005 still holds. It does not. Both drivers have reduced Scott River flow, but not in step with one another: the total summer-flow loss has nearly doubled since the late twentieth century, and by the most recent period the climatic contribution has grown to roughly twice the agricultural one. Local water use continues to matter, but climate change now governs the decline.

The growth of the climatic component follows from a warming signal that is coherent across all nine study catchments rather than local to the Scott. Annual precipitation showed no significant difference in any catchment, so the decline cannot be attributed to a drying of the region; warming has instead altered how that unchanged precipitation is stored and released, consistent with projections of shifts in precipitation timing rather than amount (Trenberth, 2011; Rhoades et al., 2018; Pathak et al., 2018; Allen et al., 2020). Rising maximum vapor pressure deficit, significant in seven of the nine catchments, reflects the higher atmospheric moisture demand that accompanies warmer temperatures and draws additional water from soils and streams

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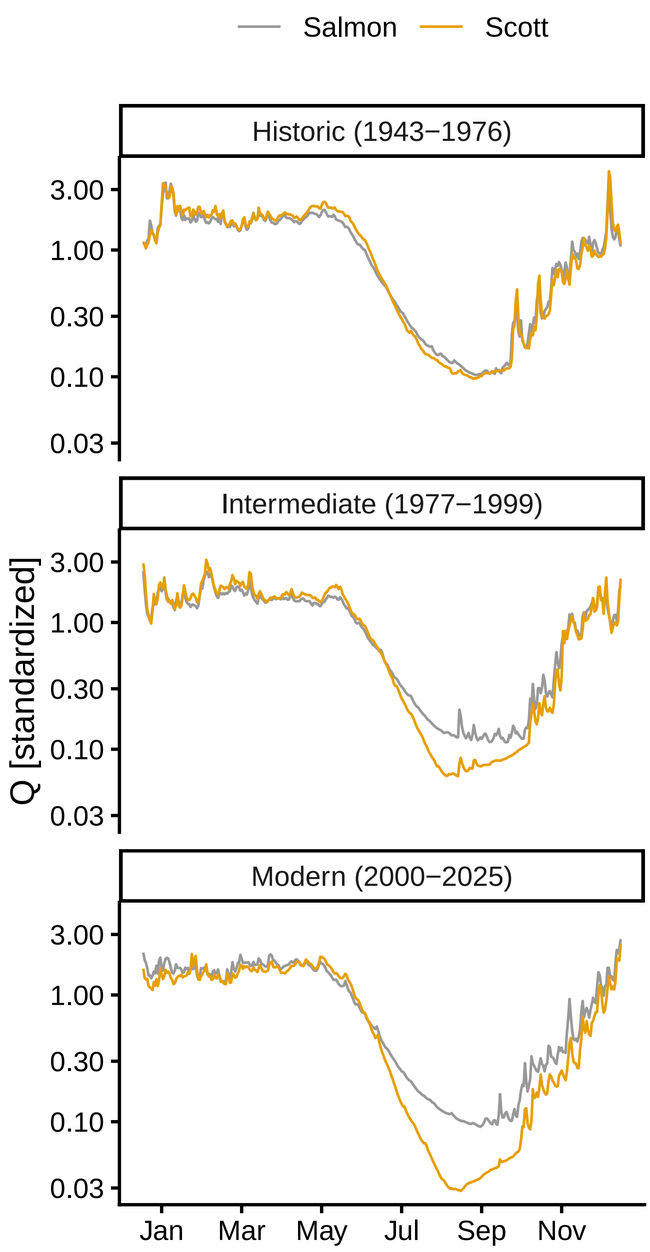

Figure 4. Standardized mean daily hydrographs of the Scott (agriculturally influenced) and Salmon (near-natural reference) catchments, by period. Each catchment's discharge is divided by its own summer flow mean ($Q_{standardized} = Q/mean(Q_{summer})$).

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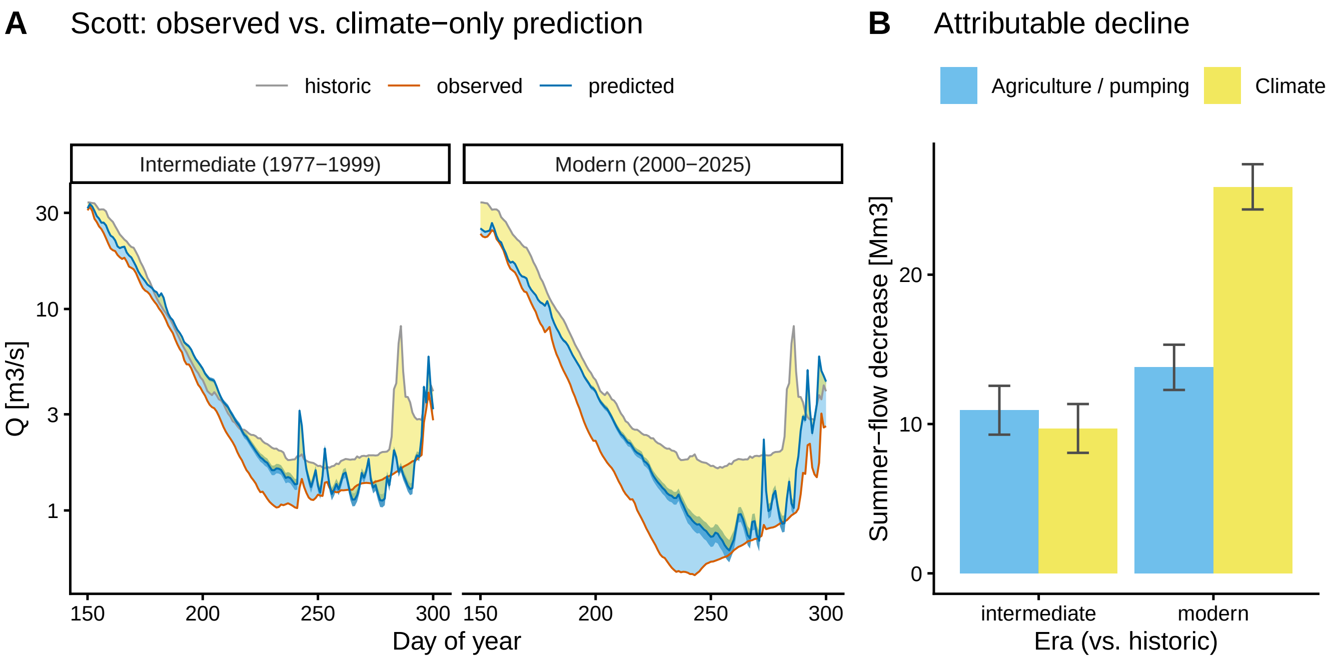

Figure 5. Decline of Scott River late-summer flow (day of year 150–300) attributed to climate versus agriculture, using Salmon River as a near-natural reference. **A** Mean daily discharge in the Intermediate (1977–1999) and Modern (2000–2025) eras: observed Scott (orange), flow predicted from Salmon under the historic (1943–1976) LOC relationship (blue, with 95 % confidence interval), and mean historic Scott flow (grey). The area between observed and predicted is attributed to agriculture, that between predicted and historic to climate. **B** Summer-flow decrease (Mm^3) per era, separated into climate and agriculture; error bars give the 95 % LOC-parameter confidence interval.

through the dry season (Cook et al., 2018; Zhang et al., 2016). At the same time, April 1 snow water equivalent declined at the lower-elevation courses, consistent with a shift from snowfall toward rain and an earlier, faster loss of the snowpack that once sustained late-summer flow (Ashfaq et al., 2013; Kapnick and Hall, 2012; Mote et al., 2018; Li et al., 2017).

Together these changes lower summer baseflow without any change in precipitation amount: water that once accumulated as snow and drained slowly through the summer now arrives earlier and evaporates faster, leaving less to sustain the low-flow season (Stewart et al., 2005; Barnhart et al., 2016; Vano et al., 2015).

The agricultural component of the decline is consistent in both timing and mechanism with the history of water use in Scott Valley. It emerged early—the summer-flow decline was already significant between the Historic and Intermediate periods—coinciding with the documented transition from flood irrigation to groundwater-fed sprinklers through the 1960s and 1970s (Siskiyou County Flood Control and Water District Groundwater Sustainability Agency, 2021). Because stream and aquifer form one connected system, pumping for irrigation lowers the water table and intercepts water that would otherwise sustain the river, so the switch to groundwater both raised total demand and shifted its impact directly onto summer baseflow (Barlow and Leake, 2012). The warmer, higher-demand conditions that lengthen the growing season and permit an additional cutting

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of alfalfa raise that demand further (Sorooshian et al., 2014). The persistence of a smaller agricultural signal past the fall pulse flows, into the months after irrigation ends, is consistent with the delayed response of a depleted aquifer slowly re-equilibrating with the stream.

Independent estimates support the magnitude of this component. Our Intermediate agricultural loss of 10.9 Mm^3 is of comparable magnitude to the roughly 10 Mm^3 of agricultural depletion estimated by van Kirk and Naman (2008) for a period spanning the same transition, despite the two approaches differing in method and in exact interval. A detailed groundwater study of Scott Valley likewise inferred increased crop water consumption of a similar order to afford a third cutting of alfalfa through groundwater pumping (Foglia et al., 2018). The direction of our result also matches earlier work attributing late-summer flow declines to human water use rather than to precipitation change (Drake et al., 2000; Asarian and Walker, 2016), so that the agricultural signal we found is corroborated from several independent directions.

The novelty of our result lies not in the presence of either driver, both of which were already known, but in how their balance has changed. van Kirk and Naman (2008) found climate and agriculture to have contributed in roughly equal measure to the summer-flow decline through 2005, and our Intermediate period reproduces that near-even contribution, with agriculture and climate responsible for 10.9 Mm^3 and 9.7 Mm^3 respectively. By the Modern period, however, the two had diverged substantially: the climatic loss had risen to 25.9 Mm^3 while the agricultural loss reached 13.8 Mm^3. Climate in the Modern period accounted for roughly two-thirds of the total decline since the Historic period. The decline itself nearly doubled between the Intermediate and Modern period.

The shift runs counter to our expectation. We had anticipated that the streamflow would decline further but that the relative shares would hold, reasoning that warmer conditions would raise irrigation demand in step with the climatic loss and so preserve the balance. Instead, the climate component in the Modern period grew approximately ten times faster than the agricultural component, accounting for 85% of the streamflow decline between the Intermediate and Modern period. Rising demand did increase the agricultural loss, but at a fraction of the pace of the accelerating climatic impact. The even division that characterized the late twentieth-century decline has, in other words, given way to a decline that is now predominantly climate-driven—a change that matters most for the ecosystems that depend on that river flow.

Since the low-flow season starts earlier, runs longer, and reaches lower minima, tributaries disconnect from the main stream and stretches of the Scott contract into warm, stagnant pools (van Kirk and Naman, 2008). The warmer, slower water raises stream temperature and favors nuisance algae (Power et al., 2015), conditions poorly suited to the cold-water native fish of the catchment (Moyle et al., 2013). For the anadromous Chinook and the endangered coho salmon that must move through the Scott to reach spawning and rearing habitat, and —in the case of young coho—over-summer in Scott River's tributaries, a longer and more severe low-flow season narrows the window in which passage is possible. Because that season is both deepening and, increasingly, climate-driven, the ecological stress is not only worsening but shifting toward a cause that is harder to manage locally by reducing agricultural water use. For example, while the agricultural impacts are focused on the distal tributary and mainstem Scott River flows on the valley floor, climate impacts may reach into the upper watershed and headwaters of these stream systems, above diversion points and the alluvial groundwater aquifer.

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Current management addresses the decline by limiting agricultural withdrawals, curtailing diversions once discharge falls below monthly thresholds (California State Water Resources Control Board, 2026). Our results suggest a structural limit to how much this can achieve for late-summer flow. The late-summer months, when curtailment is applied, are also when the climatic component dominates the decline, so curtailment acts on the smaller share of the problem. Its reach is further weakened: because the impact runs largely through groundwater, suspending pumping relieves the stream only after a lag, as the depleted aquifer re-equilibrates (Tolley et al., 2019; Scantlebury and Harter, 2026). Measures that add water rather than withhold it—managed recharge of the aquifer during the wet season, when water is available to store—may therefore complement curtailment by shifting supply into the season when the river needs it (Foglia et al., 2018; Augustin and Baumann, 2024). None of these local measures, however, addresses the climatic component directly, and the same warming that drives that component also raises irrigation demand, tightening the pressure on flow even where practices are unchanged (Sorooshian et al., 2014). Sustaining summer flow in the Scott thus depends not only on how its water is managed locally but on the broader trajectory of the climate that increasingly governs the decline.

The management implications above rest on the attributed contributions of agriculture and climate, so it is worth being explicit about how far that separation can be trusted. Two qualifications bound the distinction between the two components. The first concerns the interpretation of the climatic component. Because it is recovered as the decline experienced by the reference catchment, it captures the full climatic signal—but that signal blends two contributions: the anthropogenic warming with natural multidecadal variability, including the phase of the Pacific Decadal Oscillation; and the severe post-2000 drought that defines the Modern period. Only part of that drought's severity has been attributed to human-caused warming (Williams et al., 2020). The shift from a cold to a warm oscillation phase around 1977 coincides with our Intermediate boundary (Mann and Gleick, 2015). The climate component should therefore be understood as the total climatic contribution to the decline, not as a purely anthropogenic one; disentangling the two would require a longer record or a modeling approach beyond the scope of this study.

The second qualification concerns the agricultural component and unrelated factors it may absorb. The paired-catchment method assigns to agriculture everything that distinguishes the Scott from its reference (Van Loon et al., 2019). Even minor influences on the Scott not shared with the Salmon—changes in forest cover and evapotranspiration, wildfire, diversions, or shifts in the gauge rating—is folded into the agricultural estimate and may inflate it. The significant snowpack losses at the SWJ and ETN courses, which van Kirk and Naman (2008) suggested may be partly vegetation-driven, are one such confound. The reference catchment itself is imperfect: its vapor pressure deficit did not rise significantly, hinting that it may warm slightly less than the Scott. Finally, the reported confidence intervals derive from the historic relationship alone and so describe how well that relationship is constrained. The true uncertainty on the separation is therefore wider than the intervals suggest. None of these qualifications reverses the central finding—the agricultural attribution rests on an independently validated difference to a well defined reference, and the climatic component's Modern dominance, in magnitude, far exceeds the uncertainty about that difference—but each widens the margin around the specific volumes.

The Scott is a single catchment, but the mechanism we found is not unique to it. The setting —that warming reduces the snowpack faster than it changes annual precipitation, shifting flow out of the dry season — holds across the seasonally

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snow-covered mountains of the western United States and of Mediterranean-climate regions more widely (Barnett et al., 2005; Berghuijs et al., 2014; Mote et al., 2018). The coupling of climatic and agricultural pressure, though, do not depend on snow or on Mediterranean seasonality. Where irrigated agriculture draws on an aquifer connected to a stream, rising vapor pressure deficit raises crop water demand, and meeting it by pumping intercepts water the stream would otherwise receive (Barlow and Leake, 2012; Sorooshian et al., 2014). Warming then stresses such systems from both sides: less water arrives in the dry season, and more is withdrawn from what remains. Groundwater-fed streams under irrigation are exposed to this compounding elsewhere as well (Famiglietti, 2014; Jasechko et al., 2021), making the Scott an early and well-documented instance rather than a special case.

5 Conclusions

The winter snowpack that once released its water slowly through the dry season is a diminishing store. In snow-reliant catchments the flow it sustains through late summer is declining. In the Scott River we set out to separate how much of that decline is driven by a warming climate and how much by local agricultural water use, and to test whether the roughly even division found two decades ago still holds. It does not. Both drivers have further reduced streamflow, but the total loss has nearly doubled, and climate change—not agriculture—has become its dominant cause, accounting for close to 90% of the most recent decline and two-thirds of the overall decline since the Historic period (mid-20th century).

That change in balance carries the central message. The summer-flow decline in the Scott is no longer a problem that curbing local water use to Historic period conditions can resolve on its own: curtailment acts on the smaller and slower-responding agricultural share, while the growing climatic share lies beyond the reach of any single catchment's management without also cutting into Historic period water use (where such may have existed). Upstream of developed aquifers and stream diversions, climate impacts on streamflow require additional measures beyond managing existing water use. Sustaining late-summer flow—and with it the passage of the salmon that depend on it—will require pairing local measures such as managed aquifer recharge with adaptation to a drier warm season, and ultimately with mitigation of the warming that increasingly governs the decline. For snow-reliant, agriculturally influenced catchments more broadly, the result is a caution: as warming proceeds, the balance of causes behind declining summer flow can shift beneath a management regime built for the balance of the past, and attribution is what reveals the point in time when that occurred or will occur.

Data availability. All data used in this study are publicly available from the agencies that produce them. Daily mean streamflow was obtained from the U.S. Geological Survey National Water Information System (https://waterdata.usgs.gov) through the *dataRetrieval* R package (de Cicco et al., 2018). Precipitation and maximum vapor pressure deficit were obtained from the PRISM Climate Group, Oregon State University (https://prism.oregonstate.edu). Snow water equivalent from snow courses was obtained from the USDA Natural Resources Conservation Service National Water and Climate Center (https://nwcc-apps.sc.egov.usda.gov) through the *RNRCS* R package (Lee and Roberti, 2018). Land cover data are from the National Land Cover Database (Dewitz, 2024). The gauges, snow courses, and catchments analyzed are listed in Tables A1 and B1.

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Appendix A: Appendix 1

Table A1. Overview of the nine study catchments in the lower Klamath basin.

Name	ID	Reservoir Capacity [Mm^3]	Area [km^2]	Mean Elevation [m a.s.l.]	First Measuring Year	Percentage of Agriculture	Number of snow courses
Sacramento (Delta)	11342000	32.07	1099.32	1,263	1944	0.1 %	5
Shasta (Yreka)	11517500	70.44	2047.28	1,228	1933	11.4 %	3
Scott (Fort Jones)	11519500	0.43	1713.7	1,321	1941	7.3 %	5
Trinity (Center)	11523200	0	383.39	1,628	1957	0.0 %	0
Trinity (Hyampom)	11528700	1.09	1980.61	1,123	1965	0.0 %	0
Trinity (Hoopa)	11530000	1.17	1683.77	958	1911	0.0 %	8
Illinois (Kerby)	14377100	0.29	985.2	881	1961	0.1 %	3
Indian (Happy Camp)	11521500	0	309.5	1,128	1956	0.0 %	0
Salmon (Somes Bar)	11522500	0	1944.28	1,299	1911	0.0 %	0

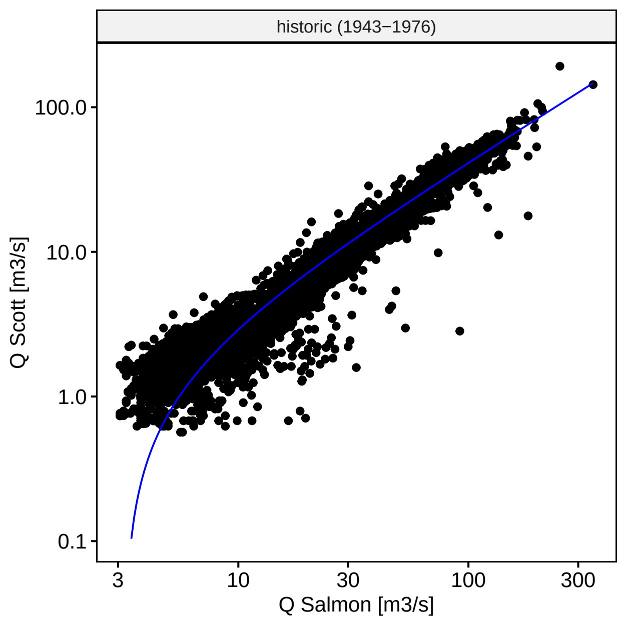

Figure B1. LOC regression of Salmon and Scott River summer discharge for the Historic period. Regression function: $y = 0.42x - 1.35$

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Table B1. Snow course overview and April 1 SWE trends. Trend column: direction and Kruskal–Wallis significance of the between-period change (↓ declining; $^{*}\,p < 0.05$, $^{**}\,p < 0.01$, $^{***}\,p < 0.001$; ns, not significant; n/a, not tested). † marks a change already significant between the Historic and Intermediate periods; unmarked significant declines were reached only in the Modern period.

Catchment Name	Catchment ID	Snow course ID	Elevation [m]	Mean SWE Historic [mm]	Mean SWE Intermediate [mm]	Mean SWE Modern [mm]	Trend
Sacramento (Delta)	11342000	SLT	1737	29.57	28.18	20.03	ns
		HIG	1838	34.00	35.05	26.39	ns
		GYR	1890	44.68	47.90	41.15	ns
		SFT	2073	42.87	41.80	38.71	ns
		NFS	2103	24.56	25.15	21.61	ns
Shasta (Yreka)	11517500	SWT	1783	14.81	11.27	12.79	ns
		LSH	1890	21.10	16.44	14.05	↓**
		PRK	2042	37.29	34.61	28.93	ns
Scott (Fort Jones)	11519500	SWJ	1676	41.30	27.80	22.40	↓***†
		DYM	1737	19.45	17.17	14.58	ns
		ETN	1798	37.62	20.86	20.27	↓***†
		MB3	1890	28.00	28.14	24.67	ns
		MBL	2012	31.82	31.87	26.61	ns
Trinity (Hoopa)	11530000	BFT	1554	15.86	10.53	8.86	↓*
		WHN	1646	21.96	18.75	14.76	ns
		MUM	1722	26.52	20.19	14.21	ns
		WLC	1875	35.64	36.10	29.12	ns
		SHM	1951	50.88	49.00	40.77	ns
		BBS	1981	37.91	38.63	30.40	ns
		RRM	2042	43.74	43.43	35.41	ns
		DDF	2195	33.07	33.73	26.77	ns
Illinois (Kerby)	14377100	23G05	1234	4.00	0.92	0.65	n/a
		23G04	1393	7.55	3.24	5.09	n/a
		23G16	1500		14.04	13.47	n/a

Author contributions. All authors designed the analysis. JP conducted the analysis wrote the first draft. All authors revised and approved the final manuscript.

https://doi.org/10.5194/egusphere-2026-4870
Preprint. Discussion started: 31 August 2026

Competing interests. The authors declare that they have no conflict of interest.

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