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RESEARCH ARTICLE

A multidecadal oscillation in precipitation and temperature series is pronounced in low flow series from Puget Sound streams

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Abstract

In Pacific Northwest streams, summer low flows limit water available to competing instream (salmon) and out-of-stream (human) uses, creating broad interest in how and why low flows are trending. Analyses that assumed linear (monotonic) change over the last ~60 years revealed declining low flow trends in minimally disturbed streams. Here, polynomials were used to model flow trends between 1929 and 2015. A multidecadal oscillation was observed in flows, which increased initially from the 1930s until the 1950s, declined until the 1990s, and then increased again. A similar oscillation was detected in precipitation series, and opposing oscillations in surface temperature, Pacific Decadal Oscillation, and Interdecadal Pacific Oscillation series. Multidecadal oscillations with similar periods to those described here are well known in climate indices. Fitted model terms were consistent with flow trends being influenced by at least two drivers, one oscillating and the other monotonic. Anthropogenic warming is a candidate driver for the monotonic decline, and variation in (internal) climatic circulation for the oscillating trend, but others were not ruled out. The recent upturn in streamflows suggests that anthropogenic warming has not been the dominant factor driving streamflow trends, at least until 2015. Climate projections based on simulations that omit drivers of multidecadal variation are likely to underestimate the range, and rate of change, of future climatic variation.

KEYWORDS
low flow, precipitation, temperature, oscillation, internal climatic variation, anthropogenic warming

1 | INTRODUCTION

In the Puget Sound region of western Washington, 59 salmonid populations are listed as threatened under the Endangered Species Act (1973, Public Law No. 93-205, 87 Stat. 884) and are the subject of prodigious recovery efforts (Beechie et al., 2013). Streamflow is one of many impacted ecosystem attributes that limit salmonid productivity (Warkentin et al., 2022), often indexed by the lowest flows of the year, which typically occur in late summer. "Summer low flows" define lower limits of water available to competing instream (e.g., salmon) and out-of-stream (human) uses, at times when water supply is lowest and demand highest. Maintaining sufficient summer low flows is critical to salmon recovery in the Puget Sound region (Lombard & Somers, 2004), creating broad interest in how and why summer low flows are trending.

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Research Impact Statement

In Puget Sound streams, recent increases in summer low flows reflect a multidecadal oscillation in remote climatic drivers.

For many streams in the Pacific Northwest (PNW), analyses that assume monotonic change show summer low flows to have declined over recent decades (e.g., Kormos et al., 2016; Luce & Holden, 2009). Causes are not clear, partly because low flows are largely baseflows, the component of streamflow contributed by groundwater (Konrad & Rumsey, 2019). Many natural and human-related factors affect groundwater recharge (reviewed by Price, 2011), but unlike surface flows, groundwater dynamics are hard to observe. Proximate factors are well known; however, the most important being basin-specific precipitation and temperature regimes over preceding days to years. Additional factors include physical relief, geological substrate, and land cover, which affect rates of runoff versus infiltration.

Concerns that human impacts have contributed to declining low flows have focused on two main candidate causes. The first is anthropogenic climate warming. This impacts low flows largely by reducing the proportion of precipitation falling as snow in winter, which, in turn, reduces subsequent runoff from melting snowpack in spring and summer (Safeeq et al., 2014). Warmer summers are also drier (lower rainfall), with increased evapotranspiration (Mauger et al., 2015). The second candidate cause is local development of various types, including urbanization (Bhaskar et al., 2020; Kauffman et al., 2009; Kennedy et al., 2007; Rosburg et al., 2017), and abstraction of groundwater via wells in rural areas (e.g., Flores et al., 2020). Here we focus on the role of climate drivers and climate change, free of development effects, by analyzing flow data from streams in undeveloped or "minimally disturbed" basins. A recent assessment of flow trends in 42 minimally disturbed streams in the PNW between 1948 and 2013 found declining trends in most seasonal flow metrics, many of them were statistically significant (Kormos et al., 2016). Such consistent declines over such a large region implicate changing climate as a principal driver of flow trends.

We further analyzed streamflow trends in minimally disturbed streams, addressing three related questions. First, prior assessments have used nonparametric methods or first-order models to detect linear (straight line) trends in flow data series. By definition, these approaches do not admit nonlinearity or inflection. Has this constraint masked nonlinearity? Second, the perception is widespread that anthropogenic warming is a principal cause of declining streamflows. While declining flow trends are consistent with expectations for a warming climate, they have not been exclusively linked to anthropogenic forcing. Are other climatic drivers also operating? Finally, to what extent do trends in flows accord with trends in (1) local precipitation and surface air temperature, and (2) two indices of sea surface temperature anomalies (SSTAs) that are associated with climatic variation in the PNW, if not causally, at least via shared remote drivers? The first is the Pacific Decadal Oscillation (PDO) (Newman et al., 2016), an index of SSTAs in mid-latitudes of the north Pacific Ocean. The second is the Interdecadal Pacific Oscillation (IPO) (Dong & Dai, 2015), a measure of interdecadal variability in the wider Pacific Ocean.

We addressed these questions by fitting polynomial models to the longest available flow, precipitation, and temperature series (68–87 years), as well as PDO and IPO series, retaining as many inflections as were statistically supported. This afforded a longer perspective on trends from a time when anthropogenic warming was barely detectable. Since low flows depend largely on climatic conditions prevailing over the previous year, separate analyses were conducted for each season of the water year (Abatzoglou et al., 2014a), as well as the full year, for each of the five focal variables. This captured any opposing trends among seasons that would cancel out in analyses of annual totals or means.

It was assumed that climatic and runoff patterns across the Puget Sound watershed were similar enough to be treated as a single response type for these purposes. This was supported by a classification of runoff response types across the western United States (U.S.) (Konrad & Rumsey, 2019), in which 1019 gages were clustered, based on the timing of low flows. Gages in the Puget Sound watershed comprised one of six principal clusters representing regional runoff types. In this analysis, data from seven recording locations in the Puget Sound watershed were combined, and analyzed using a mixed-effects model in which variance due not only to fixed, but also to random and repeated effects, could be accounted simultaneously.

2 | DATA SOURCES AND TREATMENT

2.1 | Flow data

Flow data were obtained from a collation of USGS daily flow records representing 580 gages in western Washington state, including available data to the end of 2015 (a file named *q_western_washington.csv*, provided by C. Konrad, USGS). From this collation, a sample of 7 gages was selected using four criteria: (1) Daily discharge records were long (68–88 years), and continuous up to 2015; (2) Flows above gages were "minimally disturbed" (unregulated, not diverted, with few or no wells in the basin); (3) Gage locations as a set represented the Puget Sound region as a whole (Figure 1); and (4) Within a short distance of each flow gage (<27 km; Figure 1; Table 1), there was a meteorological station with precipitation and temperature records at least as long as flow records.

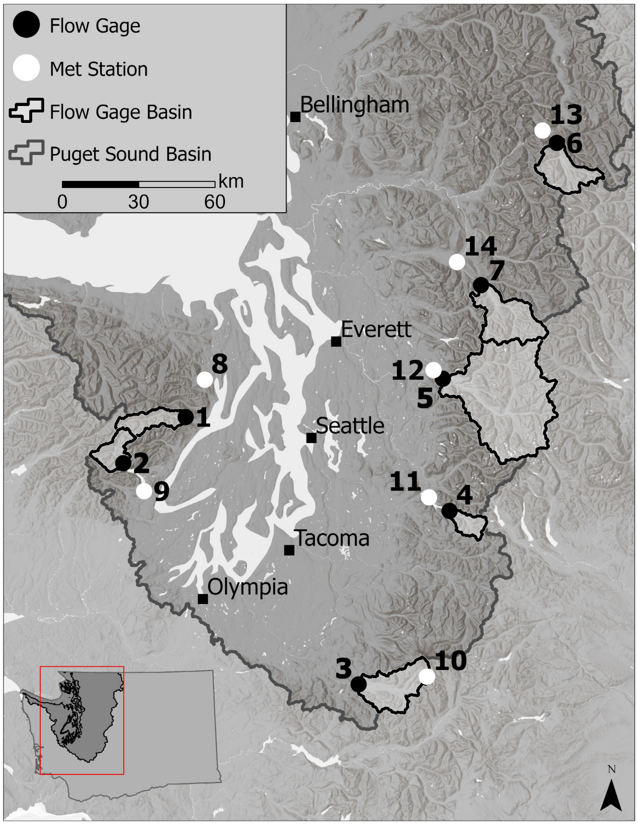

FIGURE 1 Map of the Puget Sound region, with locations of streamflow gages and precipitation/temperature recording stations (details in Table 1), data from which were used in this analysis.

To derive annual low flow estimates for each gage, daily flow data were converted to 7-day running averages (mean of daily flow records over the previous 7 days, sometimes referred to as *7q*), and the lowest 7-day flow (*summer min7q*) between June 1 and November 15 was extracted for each water year. Flow data were standardized by dividing each value by its catchment area.

2.2 | Precipitation and temperature data

Daily precipitation and maximum temperature records were used as the basis for this analysis, downloaded from NOAA's National Centers for Environmental Information database (https://www.ncdc.noaa.gov/cdo-web/search?datasetid=GHCND). A weather station was selected for each flow gage on the basis of geographic proximity to, and having continuous daily records at least as long as their paired flow gages (Table 1). Only one of the selected weather stations was located within the catchment of its paired flow gage, and all but one were at lower elevation. The exception in both cases was gage 12082500 (Nisqually river near National, WA) which was paired with Rainier Paradise Ranger Station (Figure 1). This pair was also separated by the greatest distance (27 km; distances for the remainder were <16 km), and the greatest elevation difference (1206 m). Extrapolating climatic conditions from lower to higher elevations is not straightforward because climate changes with elevation in ways that, given the paucity of high-elevation climate data, are not well understood. Cooper et al. (2018) used gridded interpolations to show that low flows in western U.S. mountain streams are more sensitive to change in summer potential evapotranspiration than to annual maximum snow water equivalent or winter precipitation. Gridded data were not used in this analysis because the same uncertainties relating to higher-elevation climates apply. The problem of higher-elevation climate uncertainty was largely skirted in this analysis by only comparing *trends* among causally related variables, and assuming that trends in precipitation and temperature at higher elevations were similar enough to trends at lower elevations to permit valid inferences to be drawn about the role of climate variation in flow variation.

Mean flow rates, precipitation totals, and maximum temperatures were derived from daily data for each season of each water year, with seasons defined as: fall, October 1–December 31; winter, January 1–March 31; spring, April 1–June 30; summer, July 1–September 30.

TABLE 1 List of flow gages featured in this analysis and their paired meteorological stations are listed with relevant geographic properties.

Type	No.	Flow gage name	Agency code	Lat.	Long.	Flow gage elevation (m)	Basin mean elevation (m)	Basin area (km^2)	Proportion glaciated	No. of years in data series
Flow Gauges	1	Duckabush R. near Brinnon, WA	12054000	47.683	−123.012	86	1074	172	0.00233	77
	2	NF Skokomish R. nr. Hoodsport, WA	12056500	47.514	−123.330	232	990	147	0.00027	88
	3	Nisqually R. near National, WA	12082500	46.752	−122.083	448	1180	350	0.04220	72
	4	Cedar R. near Cedar Falls, WA	12115000	47.369	−121.625	479	1005	106	0.00000	68
	5	Skykomish R. near Gold Bar, WA	12134500	47.837	−121.667	66	1050	1386	0.00001	87
	6	Thunder Creek near Newhalem, WA	12175500	48.673	−121.073	376	1570	275	0.13620	85
	7	Sauk R. above Whitechuck R. nr. Darrington, WA	12186000	48.169	−121.471	283	1176	399	0.00589	87

	No.	Met station name	Agency code	Lat.	Long.	Met station elevation (m)	Elevation difference between flow gage and met station (m)	Distance between flow gage and met station (km)	No. of years in data series
Met Stations	8	Quilcene 2 SW	52	47.817	−122.917	37	−49	16	77
	9	Cushman Dam	29	47.417	−123.217	232	−1	14	88
	10	Rainier Paradise Ranger Stn	55	46.783	−121.733	1654	1206	27	72
	11	Cedar Lake	24	47.417	−121.733	475	−4	10	68
	12	Startup 1 E	64	47.867	−121.717	52	−14	5	87
	13	Diablo Dam	32	48.717	−121.150	110	−266	7	85
	14	Darrington Ranger Stn	31	48.250	−121.600	168	−115	13	87

Note: Flow gage and met station pairs are identified by numbers (1–7). Estimates of the proportion of each basin that is glaciated were derived from USGS's Streamstats webpage, accessed March 2021 (https://www.usgs.gov/mission-areas/water-resources/science/streamstats-streamflow-statistics-and-spatial-analysis-tools?qt-science_center_objects=0#qt-science_center_objects). All data series ended in 2015.

2.3 | Pacific Decadal Oscillation

Monthly data since 1929 were downloaded from NOAA's National Centers for Environmental Information, accessed January 2021 (https://www.ncdc.noaa.gov/teleconnections/pdo/), and converted to seasonal means.

2.4 | Interdecadal Pacific Oscillation

Monthly data since 1929 were downloaded from NOAA's Physical Sciences Laboratory, Climate Series webpage, accessed January 2021 (https://psl.noaa.gov/data/timeseries/IPOTPI/tpi.timeseries.ersstv5.data), and converted to seasonal means.

3 | METHODS

3.1 | Polynomial model specification and fitting

The same third-order (cubic) polynomial model, with Year as the fixed independent variable, was used to assess trends in time series of all five dependent variables (flow, precipitation, temperature, PDO, and IPO). Higher than cubic terms were tested but were never significant. For flow, precipitation, and temperature series, a mixed-effects model was used (*JMP 15.0* software, SAS Institute, Inc., Cary, NC, 1989–2019) because data combined from multiple recording locations has potential to be pseudo-replicated, as well as autocorrelated, both spatially and temporally. In model specification, polynomial terms of years were designated as fixed independent variables. Recording locations (flow gages or met stations) were treated as random independent variables. The "anisotropic repeated" covariance structure was used, with years, latitude, and longitude designated as repeated measures. For consistency, all fixed, random, and repeated effects were retained in all models. To test if fitted models with significant cubic terms (alpha $<$ 0.1) were the most efficient models, changes in Akaike information criterion, corrected for small sample sizes (AICc) values with and without the cubic term were derived. For these models, the timing of first and second inflections was estimated by solving quadratic equations that were the first derivatives of cubic polynomials.

Dependent variables were log-transformed to equalize variances and normalize residuals. For data that included negative values (temperature, PDO, and IPO), a constant was added to all observations to render all positive for log transformation. When results of computation were too small to be resolved by the precision of the software, dependent variables were multiplied by a constant factor.

3.2 | Magnitude-squared coherence

Magnitude-squared coherence (MSC) was used to assess similarities in the spectral densities of data series for seasons in which the cubic term was significant in the polynomial analysis (Figure 2; these were Low Flow, Summer Precipitation, and Winter Temperature). The variables selected were those with significant cubic terms in Figure 2. On a scale of zero to one, MSC quantifies the degree to which one signal can be predicted from another signal using a linear model (Malekpour et al., 2018). The *mscohere* procedure in MATLAB software (MATLAB and Statistics Toolbox Release, 2012) was used to estimate MSC values for pairs of data series from flow gages and met stations with the longest data series (85 years between 1931 and 2015). Prior to analysis, observations in each series were centered (transformed by subtracting the mean). The threshold of significance was estimated by averaging 5 neighboring frequency bands, which yielded 10 degrees of freedom (n), and a significance threshold of 0.77 (using $\sqrt{(6/n)}$; J. Thomson, email communication, August 30, 2022).

4 | RESULTS

4.1 | Mixed-effects models

Complete results of model fitting for all five variables (flows, precipitation, temperature, PDO, and IPO), each by season and by full year, are given in 26 separate worksheets of an Excel file in Supporting Information. Included are covariance parameter estimates for random and repeated effects, as well as parameter estimates for fixed effects. Random effects for flows, precipitation, and temperature were marginally significant, varying little among variables and seasons (Wald test p-values ranged from 0.084 for summer temperature to 0.094 for spring precipitation). By contrast, the significance of repeated effects varied greatly among variables and seasons. For flows, repeated effects parameter estimates for time, latitude, and longitude were significantly greater than zero in seasons with lower flows, that is, in summer, fall, and

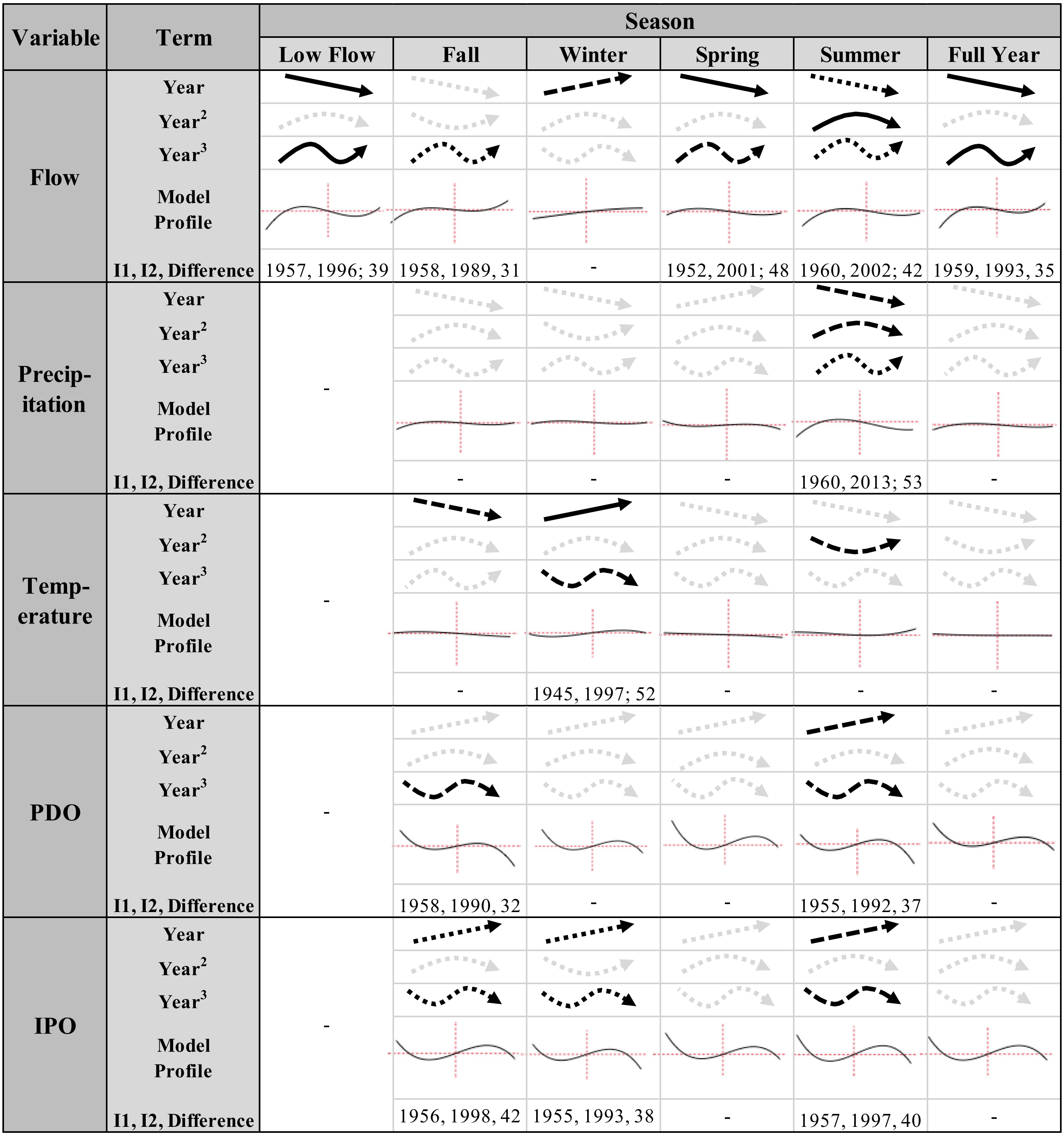

FIGURE 2 Summary of results of model fitting in graphic form for each of the five focal variables, in each season, for fixed effects only. These qualitative results are taken from quantitative results given in 26 worksheets of an Excel file provided in Supporting Information, corresponding to the 26 panels featured in this figure. Arrows are intended to graphically indicate the shape of trends: straight for first-order terms, curved for quadratic terms, and oscillating for cubic terms. Their precision is indicated by line type: solid, dashed, or dotted black to denote significance levels of $p < 0.005$, $p < 0.05$, and $p < 0.1$ respectively, or dotted gray if not significant ($p > 0.1$). Thumbnail "model profiles" depict the shape of the fitted model. A description of how to interpret these results is given in the narrative. IPO, Interdecadal Pacific Oscillation; PDO, Pacific Decadal Oscillation.

low flows, but not in winter, spring, or full year flows. For precipitation, all parameter estimates for repeated effects were greater than zero in all seasons as well as the full year. For temperature, repeated effects parameters were greater than zero only for Year, but this was true for all seasons as well as the full year. For PDO, Year was significantly autocorrelated for winter, spring, and full year models. For IPO, temporal autocorrelation was significant only in spring and over the full year.

Quantitative results for fixed effects are included in the Excel file provided in Supporting Information, including standard errors, and 95% confidence intervals for all parameters. Goodness of fit was improved by cubic terms in all models with significant cubic terms ($p < 0.1$), as showed by reductions in AICc values when compared to quadratic models (Table 2). This was especially true for Low Flows and Summer Precipitation. Patterns of statistical significance for model terms are also summarized graphically in Figure 2. In that figure, results for linear, quadratic, and cubic terms are represented by arrows signifying how flow components trended over time. The figure shows that the significance of fixed effects varied among variables and among seasons. Using Low Flow results to illustrate how to interpret the graphics, the arrow signifying the linear term was solid black and declining, showing that low flow trends included a significant declining component over the study period ($p < 0.003$; probabilities quoted in the narrative are taken from the relevant worksheet of the Excel file in Supporting Information). The dotted gray arrow in the row below shows that the quadratic term was not significantly convex. The solid black wavy arrow shows that the cubic term for low flows was highly significant ($p = 0.0017$), defining a single oscillation over the study period, with the first inflection being a maximum, the second a minimum. These undulating patterns are referred to as "oscillations" merely as a descriptor of their shape, without intending to imply that oscillations were repeating or periodic, or evoking a periodic driver. Also provided is a thumbnail depiction of the actual model profile, showing the net outcome of terms that in some cases were in opposition. Given in the last row of the panel are the years when inflections occurred in low flows, the first (I1) in 1957, the second (I2) in 1996, and the interval between them (39 years).

Flow trends for each season, as well as for the full year, are given in the remaining panels of the top row of Figure 2. The linear component of flows increased in winter, and declined over the study period in spring, summer, and over the full year. The quadratic term was significant only in summer, indicating an accelerating decline. The cubic term was significant in all seasons except winter. Although the profile of the oscillation was the same in all significant cases (in that the first inflection was always a maximum), the amplitude of the oscillation appeared to vary seasonally.

Significant trends were sparser in precipitation, temperature, PDO and IPO series (Figure 2). Whereas at least one flow term trended significantly in each season, precipitation did so only in summer, with all terms showing significant trends. Summer precipitation declined over the study period, the quadratic term showed a convex pattern suggesting an accelerating decline, and the cubic term showed an oscillation similar to that in flows. In seasonal results for temperature, linear trends were mixed, decreasing in fall, and increasing in winter. The cubic term was significant only in winter, but, in profile, opposed to the oscillation in flows and precipitation, in that the first inflection was a minimum. Similar oscillations were evident in PDO series for fall and summer, with monotonically increasing temperatures showing only in summer. Patterns for IPO were similar but also defined in winter.

4.2 | Comparison of inflection points

Estimates of the timing of low flow inflections from model fitting (1957 and 1996; Figure 2) agree with means derived from splines by eye (1960 and 1994; Figure SI.1). Examples of model fits with significant cubic terms are compared graphically in Figure 3 for low flow, summer precipitation, winter temperature, and summer PDO and IPO series. For a dependent variable recorded at multiple locations, the timing of an inflection point (vertical dotted line) approximates the mean among locations, which may differ due to local factors like microclimate. The timing of first

TABLE 2 Improvement in goodness of fit due to cubic terms in polynomial models with significant ($p < 0.1$) cubic terms (shown in Figure 2).

	AICc value		
Dependent variable	Quadratic model	Cubic model	Change in AICc
Low Flow	311.4	−17.5	−328.9
Fall Flow	−174.7	−176.5	−1.8
Spring Flow	7717.9	7714.2	−3.7
Summer Flow	−18.3	−19.6	−1.3
Full Year Flow	15132.1	15114.3	−17.8
Summer Precipitation	887.2	657.8	−229.4
Winter Temperature	6637.4	6633.5	−3.9
Fall PDO	48.5	46	−2.5
Summer PDO	81.2	77.1	−4.1
Fall IPO	233.7	233	−0.7
Winter IPO	198.9	197.2	−1.7
Summer IPO	193.5	190	−3.5

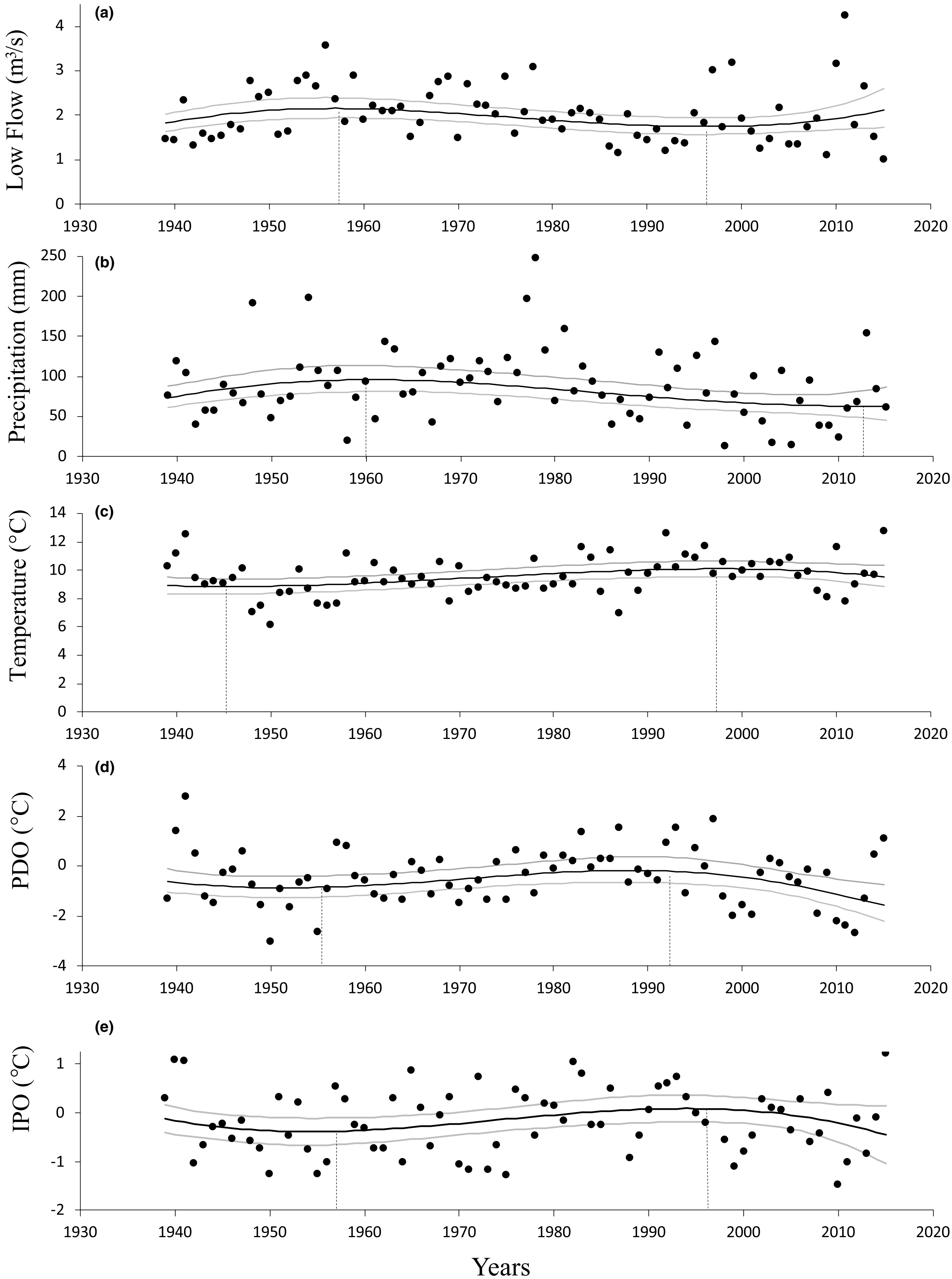

FIGURE 3 Examples of significant model fits (curved black lines) to data for each of the five variables featured in this study. (a) Low flow from gage 12054000; (b) summer precipitation and (c) winter temperature from the Quilcene 2 SW met station; summer fits for (d) the Pacific Decadal Oscillation and (e) the Interdecadal Pacific Oscillation. Vertical dotted lines mark inflection points. Gray lines mark 95% confidence intervals.

inflection points did not differ significantly among all variables, and the same applies to the timing of second inflection points. However, given the flatness of these curves, and allowing for their wide confidence intervals, the precision is too low to draw this conclusion with confidence, or to make meaningful multiple comparisons. Indeed, the timing of inflection points among variables is not expected to coincide for several reasons. For example, monotonic trends are removed from SSTA indices using Empirical Orthogonal Function analysis (Dong & Dai, 2015), but not from land-based flow, precipitation, and temperature. Second, the phase of climatic oscillations varies widely around the world (e.g., Jüling et al., 2020), and SSTA data were recorded at widely separated locations from the land-based variables.

4.3 | Magnitude-squared coherence

Results are presented as MSC values plotted against Normalized Frequencies for each of the four flow gage-met station pairs that were analyzed in Figure SI.2 (see the second worksheet of the Supporting Information). MSC values failed to exceed threshold significance in 11 of 12 signal pairs (the exception was Low Flow—Winter Temperature from Figure SI.2d). Given the inconsistency displayed across all results, significance in one instance is quite likely to happen by chance. Accordingly, no inferences could be drawn about the relatedness of these signals.

5 | DISCUSSION

A single, multidecadal oscillation spanning most of the last century was observed in flow data series from "minimally disturbed" streams of the Puget Sound uplands. Best defined in low flows, an initial increasing trend from the 1930s until ~1960 was followed by a declining trend until the 1990s, when a second inflection was detected. The ~40-year decline is consistent with results of several linear trend analyses of flows in western U.S. streams (Kormos et al., 2016; Luce & Holden, 2009), which support widely held perceptions of monotonically declining low flows over recent decades. The recent upturn is subtle, but statistically significant. Similar oscillations were detected, although not as clearly, in precipitation and temperature series, and in PDO and IPO series. Because the analysis was confined to "minimally disturbed" streams, most factors relating to human development or activity can be ruled out as contributors to these flow patterns. They are most likely responses to changes in climate. Discussion focuses on what the analysis revealed about how climate has influenced flow trends in Puget Sound streams at higher elevation over recent decades.

5.1 | Four patterns in results of model fitting

The first focuses on patterns of significance among terms in results of model fitting for all variables (Figure 2). Linear (12/26 instances), quadratic (3/26 instances), and cubic (12/26 instances) terms were sometimes significant, but in differing frequencies (here, the term "linear" refers to the first order term in polynomial models; since dependent variables were log-transformed, actual change was monotonic, but not necessarily in a straight line). Significant quadratic terms were few, but when they co-occurred with significant linear terms (two instances), they reinforced, rather than opposed, each other. Significant linear and cubic terms occurred together (10/15 instances) more often than on their own (5/15 instances), and when together they were always in opposition. These results are consistent with observed trends being influenced by two types of driver, one oscillating and the other monotonic. However, the same pattern could result from a sequence of opposing monotonic drivers.

The second pattern focuses on the oscillation in precipitation and temperature (Figure 2). In both variables, cubic terms were significant in only one season, but not the same season. Precipitation oscillated significantly only in summer, temperature only in winter. This variation is apparent in the amplitude of oscillations depicted by model profiles in Figure 2, which appears to wax and wane seasonally. Any physical mechanism posed to account for this apparently complex pattern is less plausible than a simplifying statistical interpretation: within precipitation and temperature series, the significance of cubic terms tended to decrease among seasons as absolute data values, and their variances, increased. It is likely that the oscillation was always present in both variables, just not detected in seasons with greater variability.

This interpretation was supported by the third pattern, in which the oscillation was more pronounced in flow series than in precipitation and temperature series, being detected in flows of all seasons except winter, and with greater significance. Here, a physical interpretation is more likely: the oscillation was more pronounced in flows because flows are a function of both precipitation and temperature, increasing with increasing precipitation and with decreasing temperature. In this interpretation, the oscillation was more pronounced in flows because the combined effects of precipitation and temperature were as waves interfering constructively. In addition, the oscillation may be more pronounced in low flows, compared to flows in other seasons, because low flows are the product of precipitation and temperature conditions in all seasons.

The fourth pattern focuses on linear and quadratic terms. Significant linear trends of opposing sign were observed among seasons for temperature, and for flows (Figure 2). For temperature, the rate of increase in winter was highly significant ($p < 0.0001$), and more than double the rate of decrease in fall, which was marginally significant ($p = 0.0415$). Increasing trends in winter and summer temperature are consistent with an observed increase in regional mean temperature over the last century (e.g., Abatzoglou et al., 2014a, 2014b; Johnstone & Mantua, 2014a, 2014b). Flows increased in winter ($p = 0.0192$), but declined in all other seasons (not significantly in fall). Quadratic terms were consistent with linear terms, indicating an accelerated increase in summer temperature, and accelerated decreases in summer precipitation and flows. Any interpretation of opposing seasonal trends for temperature evokes complex effects of climate drivers over the period of record (assuming the temperature decline in fall is not a Type I error). By contrast, a relatively simple causal interpretation is available for opposing linear patterns among seasons in flows. With increasing winter temperature, more precipitation fell as rain than as snow, increasing winter runoff, and thus flows. This, in turn, diminished snowpack and infiltration, causing declines in the linear components of spring, summer, and low flows.

Summarizing, results suggest that opposing, multidecadal oscillations in temperature and precipitation were present throughout the year, and these drove a similar but better-defined oscillation in flows, especially in low flows. The observed patterns of variation in local precipitation, temperature, and flows over the last century could result from interacting oscillating and monotonic drivers, or opposing monotonic drivers (further discussed below).

5.2 | Snowpack trends

Snowpack trends in the western US over the last 90 years have been analyzed extensively, showing largely declining trends from the 1930s, when records began. Most allude to increasing temperature as the leading cause. For example, Mote et al. (2018; extending their previous work in Mote et al., 2005) affirmed that most snowpack monitoring sites across the western US showed declines of 15%–30% between the mid-1900s and 2016, citing warming trends as the principal driver.

Two accounts went further, partitioning drivers of temperature change between two separate processes: "natural" atmospheric circulation, which may oscillate, and anthropogenic warming, which does not. Stoelinga et al. (2010) found that, from 1950 to 1997, snowpack declined in the Cascade range by a large and statistically significant amount (48%), of which most (80%) was "connected to changes in the circulation patterns over the North Pacific Ocean that vary naturally on annual to interdecadal time scales." After Pacific circulation variability was removed, the residual time series of Cascade snowpack displayed a relatively steady loss rate of 2.0% per decade, or 16% between 1930 and 2007. This loss rate was "nearly statistically significant" and may have included impacts of anthropogenic global warming.

Siler et al. (2019) used (daily) SNOTEL data to show that spring snowpack in western US has not declined substantially since records began in 1983, noting that changes due to atmospheric circulation have offset much of the decline due to global warming. Atmospheric circulation and historical sea surface temperature simulations suggested that observed circulation changes may have been driven by "internal atmospheric variability, and a shift in Pacific SSTs toward the cool phase of the IPO." Removing the influence of natural variability revealed a robust anthropogenic decline in western U.S. snowpack since the 1980s, particularly during the early months of the accumulation season (October–November). They "found that such SST/circulation trends … are likely associated with low-frequency natural variability that will eventually subside, ushering in a period of accelerated snowpack loss."

Oscillating trends in temperature, precipitation, and flows reported here for the Puget Sound region, including declines from the mid-1900s, and a recent inflection in the 1990s, are therefore consistent with snowpack trends in the western U.S.

5.3 | Glacier melt

Melting glacier ice is a local factor hitherto unaccounted in this analysis. Of the streams featured in this study, all but one are glacier fed (the exception is 12115000; Table 1). Rates of glacier recession in the western U.S. over the last century have been well documented, and attributed largely to increasing summer temperatures (e.g., Moore et al., 2009; O'Neal et al., 2015; Pelto, 2008). Frans et al. (2018) projected that recession rates will increase over coming decades, but runoff from glacier melt and its relative contribution to streamflow may increase or decrease, depending on elevation. Their models suggest that glacier melt contributions to flows have already peaked in lower-elevation basins. In high-elevation basins, enhanced glacier melt is expected to buffer steep declines in seasonal snowpack and decreased late summer streamflow. These glaciers will become too small to support streamflow at historic levels later in the 21st century (Frans et al., 2018).

Given the recent accelerating increase in summer temperatures (see model profile in Figure 2), it is likely that glacier melt supplemented low flows in the glacier-fed streams featured in this analysis. However, glacier melt was likely not the only factor enhancing recent low flows, for two reasons. First, significant cubic terms for Summer Precipitation and Winter Temperature (Figure 2) suggest that these factors also contributed to enhanced flows, via atmospheric circulation effects on snowpack, as described by Siler et al. (2019). Second, upturns were evident in flows of seasons in which glacier melt contributes negligibly to total flows, as significant cubic terms for Fall, Spring, and Summer Flows in Figure 2.

5.4 | PDO and IPO

Bowling et al. (2000) observed that flow trends related to variation in the PDO were most apparent in low flows. Newman et al. (2016) characterized the PDO as "not a single phenomenon, but … the result of a combination of different physical processes, including both remote tropical forcing and local North Pacific atmosphere–ocean interactions, which operate on different time scales to drive similar PDO-like SST anomaly patterns." The PDO has also been characterized as a combination of oscillations of differing wavelengths (Minobe, 1997; Wills et al., 2018). Overland et al. (2006) showed that 33% of the variation in the PDO over the last century could be explained by a 76-year square wave oscillator, and 43% by the combination of 76- and 40-year square wave oscillators (their Figure 2). The 76-year period found by Overland et al. (2006) approximates the 64- to 74-year oscillation periods for PDO derived in this analysis (by doubling the interval between inflection points; Figure 2).

Two studies have reported periodicity in series of PDO proxies reconstructed over the last millennium with similar periods to those reported here. Gedalof et al. (2002) derived a composite chronology of climatic variation in the north Pacific from five published PDO proxies based on tree ring and coral data, the longest starting in CE 1001. Spectral analysis of the chronology yielded oscillatory modes with periods of about 85, 23, and 20 years (the latter two may have been "artifacts of differences in biological processes or … analytical approaches"). MacDonald and Case (2005) used tree-ring chronologies to reconstruct a PDO proxy series from CE 993 to 1996, and wavelet analysis to assess long-term variability in its strength and periodicity. They found that a 50- to 70-year periodicity in the PDO was typical for the past 200 years, [but] was only intermittently a strong mode of variability prior to that. Intermittent multidecadal oscillations with similar periods to those reported here have therefore been detected in the PDO and in its proxies over the last millennium.

The IPO "is the leading mode of Pacific climate variability on decadal to multidecadal time scales, representing a quasi-oscillation with a period of 40–60 years" (Dong, 2017) … having "essentially the same interdecadal variability as the Pacific Decadal Oscillation…, which can be regarded as the North Pacific expression of the IPO." Phases of the IPO corresponding with these multidecadal oscillations have been described as either predominantly warm or cool, with the following sequence: warm (1924–1944), cool (1945–1976), warm (1977–1998), and cool (1999–2015; Dong & Dai, 2015). Assuming inflections occurred at midpoints in these phases, there was a minimum in 1960, a maximum in 1988, and a minimum in 2007. The minimum in 1960 is consistent with estimates of first inflection points in this analysis (Figure 2), the maximum in 1988 was slightly earlier than the range of second inflection points estimated in this analysis (1992–2012; Figure 3), and a third inflection was not detected in this analysis.

Summarizing, multidecadal oscillations with periods similar to those observed in this study (64–84 years) have been observed in PDO and IPO series over the last century, and in their proxies over the last millennium, at least intermittently. Since the precision of oscillation inflections and periods are typically not estimated, their similarity or distinction remain unresolved.

5.5 | Remote drivers

Oscillating patterns with similar timing and multidecadal wavelengths to those described here for flows, precipitation, and temperature in the PNW have long been described in sea surface temperature data for the North Atlantic (Enfield et al., 2001; Mantua et al., 1997), and around the world (e.g., Jüling et al., 2020; Kalicinsky & Koppmann, 2022; Kravtsov et al., 2018). Despite intense scrutiny using sophisticated climate simulations, the identity and mechanisms of those drivers is not settled. For example, Johnstone and Mantua (2014a, 2014b) attributed the observed warming trend over the last century to internal climatic variability. This was disputed by Abatzoglou et al. (2014b), who (using different data) invoked external anthropogenic forcing. In another example, Siler et al. (2019) invoked low-frequency natural variation due to internal atmospheric variability and a shift in Pacific SSTs, in addition to anthropogenic forcing, to account for observed snowpack dynamics in the PNW over recent decades. Jüling et al. (2020) invoked oceanic eddies as a causal factor. Mann et al. (2021) and Mann (2021) concluded that "the apparent ~50-y[ear] oscillatory signal in the instrumental surface temperature record is … an artifact of the competition between long-term greenhouse warming and the more recent decrease in sulfate aerosol cooling in the late twentieth century, rather than a natural long-term climate oscillation." Mann et al. (2021) further concluded that multidecadal spectral peaks evident in climate model simulations of the past millennium "are a consequence of the coincidental multidecadal pacing by explosive volcanism in past centuries." Omrani et al. (2022) showed that multidecadal climate trends in the northern hemisphere can be recovered using a "damped coupled stratosphere/troposphere/ocean-oscillation framework." Clearly, causal mechanisms for multidecadal climate oscillations are complex and lack consensus. But all agree that a better understanding of natural climate variability is needed to improve projected impacts of anthropogenic warming.

6 | CONCLUSIONS

1. Polynomial models revealed a single multidecadal oscillation in flow series from minimally disturbed streams in the Puget Sound highlands. An oscillation with similar wavelength was also detected in precipitation and temperature series from local weather stations, and in indices of sea surface temperature (PDO and IPO).

2. The oscillation in temperature series was opposed to the oscillation in precipitation and flow series. Presumably, this opposing pattern was one reason that the oscillation was more pronounced in flow series, especially in summer low flows, than in precipitation or temperature series.
3. Multidecadal oscillations with comparable periods to those described here are well known in climate variables and their proxies, but their causes are not clear. Fitted model terms were consistent with flow trends being influenced by at least two drivers, one oscillating and the other monotonic. Variation in (internal) climatic circulation and (external) anthropogenic warming, respectively, are candidates for these drivers, but others were not ruled out.
4. An upturn in flow trends since ~1990 suggests that anthropogenic warming has not been the dominant factor driving flow trends in the Puget Sound region, at least until 2015. Resolving the causes of variation in flow trends awaits better understanding of climate drivers other than anthropogenic warming.
5. As others have pointed out, climate projections based on simulations that omit drivers of multidecadal variation are likely to underestimate the range, and rate of change, of future temperature variation.

AUTHOR CONTRIBUTIONS

Nicholas J. Georgiadis: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; validation; visualization; writing – original draft; writing – review and editing. **Joel E. Baker:** Formal analysis; funding acquisition.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data series are provided for all 5 variables featured in this study in an Excel file with 2 worksheets [Georgiadis_Low_Flow_Oscillation_Data]. The first provides flow, precipitation, and temperature data. The second provides PDO and IPO data. All data are formatted for analysis by JMP software.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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