Distinguishing climate change impacts from development impacts on summer low flows in Puget Sound streams

A report by

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Table of Contents

Summary

Rationale: 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 flows is critical to salmon recovery in the Puget Sound basin, but summer low flows have declined in many streams over recent decades, and are projected to decline further. Concerns that human impacts may be responsible for declining low flows have focused on two main causes: anthropogenic climate warming, and various types of local development, including urbanization, and, in rural areas, abstraction of groundwater. All of these factors impact streamflows to some degree, but detecting and quantifying their separate and relative effects has proved challenging. This uncertainty hinders the conception and design of strategies intended to conserve, restore, and enhance future low flows. We report results of an exploration of data relating to trends in low flows over recent decades, intending to define salient patterns and, where possible, identify causes.

Goals and Approaches: The primary goal was to distinguish climate from development impacts on low flows in Puget Sound streams, using data from gages with long-term flow records (>52 years, with all series ending in 2015). Critical to achieving our goals was the conversion of annual low flow values to anomalies, or 'z-scores'. This made flow rates scale-independent, permitting direct comparison of low flow anomaly time series among basins differing greatly in size. A spline model fit to anomaly time series of a given stream was referred to as its 'profile'. The analysis proceeded in two steps. First, low flow responses to climate variation alone were assessed in 23 basins that are 'minimally disturbed' by development (representing 21.2% of the Puget Sound terrestrial watershed). Second, low flow profiles of 5 streams in lowland developed basins were compared with the profile of a minimally disturbed lowland reference stream (only one lowland reference stream was found with sufficiently long flow records: Taylor Creek/12117000).

Key Findings

1. In our sample of minimally disturbed streams, most (18 of 23) could be classified, based on patterns of interannual variation in low flows, primarily as surface- or groundwater-dominated, and secondarily as snow- or rain-dominated. The same applied to most of the developed basins (16 of 21), but misclassification due to development could not be ruled out.
2. In minimally disturbed streams, low flows declined between ~1960 and ~1990, and increased thereafter (at least until 2015), yielding a ~80-year oscillation in low flows. This was probably caused by one or more remote climate drivers with multidecadal wavelengths.
3. The recent increase in low flows was less marked in streams at mid-elevations, most likely due to anthropogenic warming at elevations sensitive to the phase of precipitation (rain vs. snow), that is, greater than ~800 m. Conversely, in streams with basin mean elevations below ~800 m, low flows were not detectably affected by phase of precipitation.
4. In many developed basins, low flow profiles deviated from a purely climate-driven pattern in unique ways, presumably due to unique histories of development.
5. The expected inverse relationship between low flows and impervious land cover was not observed, suggesting that other factors related to development overrode direct effects of impervious cover on infiltration.
6. Effects on low flows of wells alone could be assessed in only one basin (Huge Creek/12073500), a rural area with low impervious cover, but high well density. In that case, low flow trends did not deviate below expectations based solely on climatic variation. Huge Creek is a groundwater-dominated stream, raising the possibility that low flows are more resilient to groundwater abstraction in groundwater-dominated reaches than in surface-dominated reaches. In Issaquah Creek nr. mouth/12121600, low flows declined faster and further than a purely climate-driven pattern. Factors related to development, including moderate well density and export of wastewater from the basin, may have contributed. The low flow profile for Mercer Creek nr. mouth/12120000 bore no resemblance to the purely climate-driven reference pattern, presenting an example of extreme profile deformation due to urbanization.

Conclusions

We assessed prevailing assumptions and uncertainties about trends in low flows in Puget Sound streams, and their causes, by analyzing available data in novel ways. Principal conclusions were:

1. Concerns about declining low flows in the Puget Sound region have focused on impacts of anthropogenic warming, and on factors related to development. While anthropogenic warming will likely continue to exert accumulating negative effects on low flows, other climate drivers, which oscillate with multidecadal wavelengths, will also continue to affect trends. Current GCMs do not accurately reproduce oscillating climate drivers with multidecadal wavelengths (Lee et al. 2021), or account interactions among these drivers. Uncertainty about future trends in low flows may have been underestimated.

2. Strategies intended to maintain or restore future low flows have emphasized offsetting impacts of private wells, and of reduced infiltration due to impervious cover. The analysis suggested that these impacts may be relatively small, compared to other impacts of urbanization, for example, export of wastewater to treatment plants outside focal basins, especially if water is supplied from wells within focal basins. Reconstructing the history of development in these basins, with a focus on changes in water budget components, could yield further insights about the impact on low flows of importing and exporting water from focal basins.

3. Urbanization impacts on low flows can be locally severe, but will be confined to a relatively small proportion of the Puget Sound lowlands (<~7% of the total land area in the region by 2100). By contrast, climate change will affect flows over the entire region, but especially above ~800m, where flows are sensitive to snowpack and glacier changes, and wherever high-elevation impacts are conveyed to the ocean in large streams. To a great extent, therefore, effects on low flows of climate change and of urbanization will be spatially separated.

4. Washington's Streamflow Restoration Act (RCW 90.94) required that strategic plans be created to boost low flows in developing basins. While focusing on private wells, many of these also made provision for anthropogenic warming. However, the plans do not apply beyond 2038, and only rapidly developing basins were included. Further assessment and modeling are needed to quantify projected declines in low flows due to anthropogenic warming beyond 2038, and remedial measures applied at least to 'priority areas'. The analysis also suggested that mapping stream properties such as degree of surface- vs. groundwater-domination, and snow- vs. rain-domination, may assist in identifying 'priority areas'. Further research, and continued monitoring, are needed to define the sensitivity of these properties to pressures exerted by climate change and development.

Research and monitoring recommendations

1. Monitoring: the 23 minimally disturbed streams with long flow records featured here provide a suitable – and valuable – set with which to monitor effects of climate change on low flows at different elevations, without confounding effects of development.
2. Monitoring: additional lowland reference streams are needed (minimally disturbed, with basin mean elevations <800m, and long flow records), especially for surface-dominated streams.
3. Research and monitoring: further evidence is needed to test if groundwater abstraction impacts low flows differently in surface vs. groundwater-dominated reaches, and to define the sensitivity of these properties to pressures exerted by climate change and development. This will require investment in groundwater monitoring, preferably using a carefully selected subset of the large number of existing monitoring wells.
4. Research: results suggested that mapping stream properties such as surface- vs. groundwater-domination, and snow- vs. rain-domination, will assist in identifying priority areas for actions intended to recover low flows.
5. Research: reconstructing the history of development in focal basins could yield further insights about the impact on low flows of importing water to, and exporting water from, focal basins.
6. Modeling: further assessment and modeling are needed to quantify projected declines in low flows due to anthropogenic warming, and remedial measures applied where needed.

Introduction

Among key components of the Puget Sound ecosystem impacted by a rapidly growing human population are stream habitats essential to threatened chinook and other salmonid species (Beechie et al. 2013, Warkentin et al. 2022). Freshwater *quantity* is one of many impacted stream attributes, 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 and Somers 2004), creating broad interest in how and why summer low flows are trending (Konrad and Booth 2002).

For many streams in the Pacific Northwest, summer low flows have shown generally declining trends over recent decades (Konrad and Booth 2002, 2005, Luce and Holden 2009, Kormos et al. 2016, Rosburg et al. 2017). Since low flows are comprised largely of baseflows (the component of streamflow contributed by groundwater; Konrad and Rumsey 2019), trends reflect the net effects of many natural and human-related factors that increase or decrease groundwater recharge (reviewed by Price, 2011; summarized in Box 1). Concerns that human impacts may be responsible for declining low flows have focused on two main causes: anthropogenic climate warming, and various types of development, including abstraction of groundwater via wells in rural areas, and urbanization. Anthropogenic warming impacts low flows mostly by diminishing precipitation falling as snow in winter, and as rain in summer, but also by increasing surface air temperature and evapotranspiration (Mauger et al. 2015). Groundwater abstraction via wells can draw down surface waters (e.g. Flores et al. 2020), especially in summer when flows and aquifer recharge are low, and demand and evapotranspiration are high. Urbanization – the conversion of rural land cover to high-density human uses – can cause summer low flows to decline or incline, depending on many factors (Rosburg et al. 2017; Box 1). Spreading impervious land cover (roofs, roads, and pavement) and drains can reduce low flows by increasing runoff at the expense of infiltration (e.g. Kauffman et al. 2009). Urbanization also entails major infrastructure changes: replacement of private wells with a public water supply, often piped in from outside a focal basin; and replacement of septic systems with sewers, which may export water to treatment plants outside a focal basin. Their contributions vary as development proceeds, reducing or increasing low flows over time (Kennedy et al. 2007, Bhaskar et al., 2020).

All of these factors impact streamflows to some degree, but detecting and quantifying their separate and relative effects has proved challenging. This is partly due to inherent variation in the weather, which obscures subtle effects, non-stationarity in the changing climate, which confounds isolation of causes, and paucity of data on groundwater flows, which hinders understanding of aquifer hydrodynamics. Recent studies have shown that climate effects are generally greater than any effects of urbanization (Bhaskar et al., 2016a; Ficklin et al., 2016), and confirmed the inconsistent summer low flow response to urbanization while controlling for effects of climate variability (Bhaskar et al., 2016b; Bhaskar et al., 2020; Dudley et al, 2020).

Despite this uncertainty – or more accurately because of it – Washington state's Streamflow Restoration Act (RCW 90.94) was implemented in 2018 to offset potential impacts on low flows of additional permit-exempt wells that will supply domestic water in rural areas expected to develop rapidly in the next 20 years. The focus on permit-exempt wells was precautionary rather than evidence-based, driven by concerns that failure to act now could irreversibly impact low flows in future.

Uncertainty about relative impacts of climate variation and development continues to hinder the conception and design of strategies intended to conserve, restore, and enhance future low flows. Our primary goal was to distinguish climate and development impacts on low flows in Puget Sound streams, using data from gages with long-term flow records. This was approached, first, by describing how annual low flows have varied with the climate over recent decades, at different elevations, in basins that are 'minimally disturbed' by development. The second approach was to compare annual low flow series in developed vs. minimally disturbed basins. This is challenging because all basins in the Puget Sound lowlands are developed to some degree, leaving few that are minimally disturbed, and even fewer with long-term flow records, indeed only one reference profile was found for lowland streams for this analysis.

In general, linear trend analyses shown low flows to have declined over recent decades in streams of the Pacific Northwest (Luce and Holden 2009, Kormos et al. 2016). Such consistent trends over such a large region implicate changing climate as a driving factor. Anthropogenic warming is a leading causal candidate, given that both cause and effect appear to have changed monotonically, in opposition, and at slow rates. However, not all streams declined monotonically. Polynomial analysis of flow data series from seven minimally disturbed streams in the Puget Sound highlands revealed a multidecadal (~76 year) oscillation in flows, which increased initially from the 1930s until ~1960, then declined until the 1990s, when a second inflexion was detected (Georgiadis 2022). A similar oscillation was detected in precipitation series, and an opposing oscillation in temperature series (also in Pacific Decadal Oscillation, and Interdecadal Pacific Oscillation series). Multidecadal oscillations are well known in climate indices and their proxies, yet an expectation that flow trends should oscillate over multidecadal spans is not prevalent. Results suggest that anthropogenic warming has not been the only factor driving trends in flows, or even the dominant factor, else there would have been no recent inflexion in flows. This study extends the assessment of climate impacts on low flows down the elevation gradient, adding flow data from 17 minimally disturbed streams, and from 21 lowland streams in developed basins, to the original analysis (Georgiadis 2022).

Critical to achieving our goals was the conversion of low flow values to anomalies, or ‘z scores’. In effect, this made flow values scale-independent, permitting direct comparison, by graphical superimposition, of low flow series from basins that differ greatly in size.

Where known, the mechanisms most likely accounting for observed deviations were summarized for each basin. We also tested the expectations that low flows should decline with increasing impervious cover, and with well density, among basins differing greatly in degrees of development. Results provide a more incisive impression of the separate impacts on flows of climate change and development, and suggest new approaches for monitoring low flows in the Puget Sound region. In addition to providing results of this novel approach to distinguishing proximate and remote causes of trends in low flows, we summarize relevant information from the academic south fork literature. This report is intended for those who are concerned about low flows, but cannot access the literature, may not fully grasp the mechanisms, or need perspective on relative impacts.

Box 1. Factors affecting low flows

Many 'natural' and human-related factors affect summer low flows. In absence of human factors, groundwater recharge depends on the balance of precipitation and evapotranspiration, which in turn vary with solar radiation, cloud cover, humidity, soil moisture, and types of vegetation cover (Konrad 2019). Climate effects are further complicated by seasonal, annual, and longer-term variability that most importantly affect precipitation and temperature. Longer-term climate variability in the Puget Sound region is often characterized by climate indices like the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (e.g., Bowling et al. 2000; Barnett et al. 2008; Moore et al. 2008; Abatzoglou et al. 2014a).

Heterogeneity in Puget Sound basin geology and hydrology modulate climate effects (Tague and Grant, 2009; Safeeq et al., 2014). Geologic factors include soil and surface geology, which affect infiltration, and the rate at which recharge is translated to streamflow. Differences in subsurface geology affect groundwater storage and transport – sometimes resulting in transfer of water between basins (Dinicola, 2001). Lakes, reservoirs, and glaciers can store water that is released during summer. Precipitation increases and temperature declines with elevation, determining the proportion of precipitation that falls as snow. At higher elevations, water stored as snow effectively reduces winter flows, and enhances flows when it melts in spring. Summer flows in many Puget Sound basins are fed by glacier meltwater.

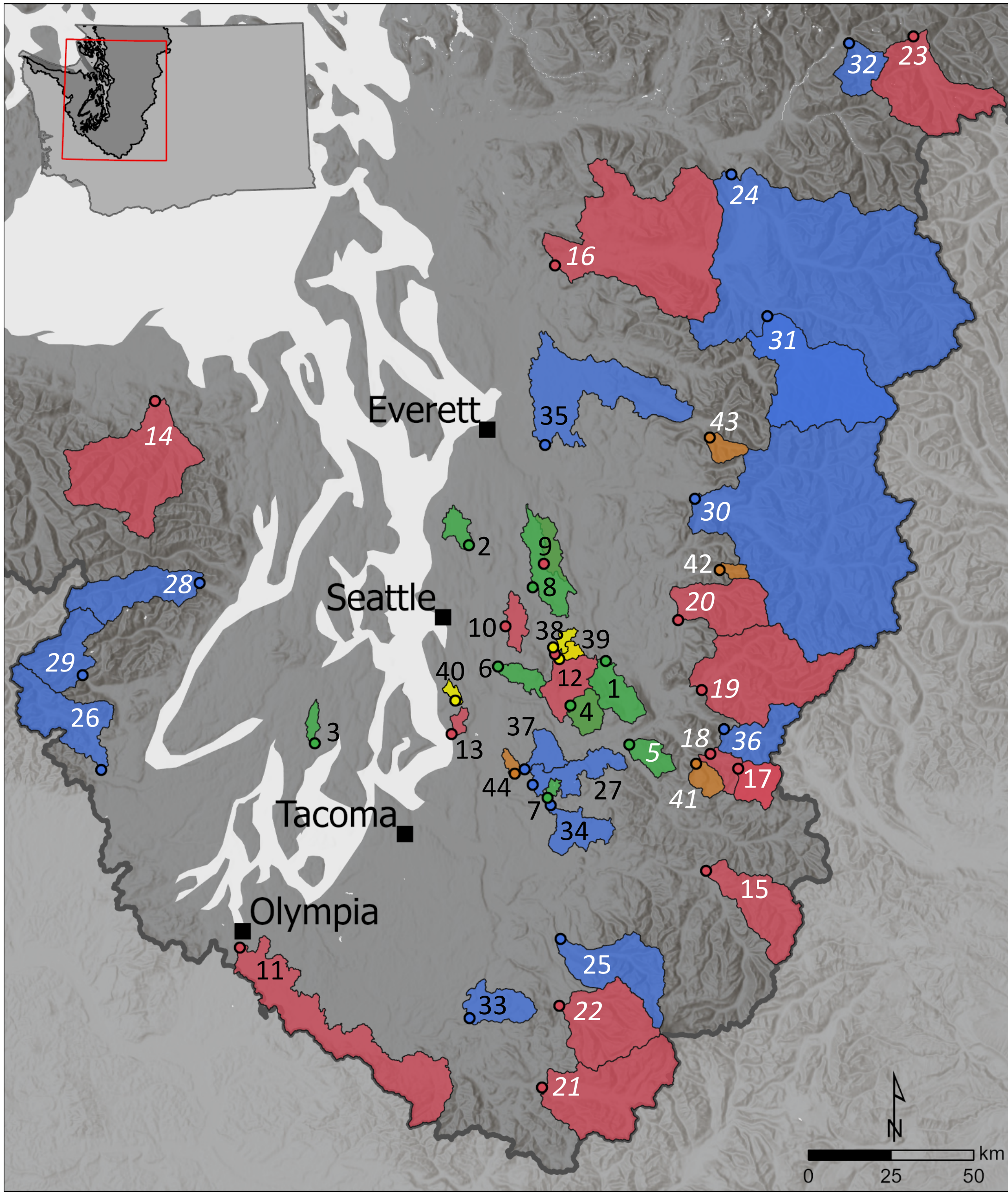
Human actions can cause summer low flows to increase or decline, depending on how water is supplied for local human use and how that water is disposed of. Increases in impervious cover and soil compaction associated with urbanization decrease recharge, but loss of forest cover associated with development reduces canopy interception of rain, and also evapotranspiration, increasing aquifer recharge. Recent studies have confirmed the inconsistent response of summer low flows to urbanization while controlling for effects of climate variability (Bhaskar et al., 2016b; Bhaskar et al., 2020; Dudley et al, 2020). The inconsistent flow response is due to a complex set of opposing factors that increase or decrease groundwater recharge (Konrad and Rumsey, 2019). These opposing factors are listed in Table 1. As an area urbanizes, their relative effects can change over time, with opposing outcomes (Kennedy et al., 2007).

The hydrologic processes that result in flows in streams and groundwater storage can be described using a water budget approach (Healy et al. 2007, California Department of Water Resources 2020). A water budget can be developed for any geographic area and time period using approaches that vary in complexity and data needs. A water budget can provide a foundation for effective water-resource management.

Development-related factors Impacting groundwater recharge positively and negatively (modified from Price 2011, who adapted it from Meyer 2002).

Factors increasing recharge	Factors decreasing recharge
Surface distribution of imported water (irrigation and other outdoor water uses)	Impervious surface coverage and soil compaction
Infrastructure leakage of imported water	Rapid transmission of event water through storm sewers and modified channels
Infiltration from stormwater detention facilities	Leakage of shallow groundwater into storm sewers
Leakage of event water into shallow groundwater via storm sewers	Shallow groundwater withdrawals
Reduction in canopy interception and evapotranspiration due to forest removal	Export of locally supplied water to wastewater treatment plants
	Export of groundwater via infiltration into wastewater collection system

Figure 1. Left: Outlines of the basins in the Puget Sound region that drain to the 44 gages featured in this study, distinguishing minimally disturbed basins (white labels) from developed (lowland) basins (black labels). Gages with >52-year flow records are italicized. Basins are colored according to cluster membership in the clustergram in Figure 2. Right: corresponding gage numbers and names.



Map Label	Gage Code	Gage Name
1	12145500	Raging River nr. Fall City
2	35c	McAleer at Mouth
3	12073500	Huge Creek nr. Wauna
4	12120600	Issaquah Creek nr. Hobart
5	*12117000*	*Taylor Creek nr. Selleck*
6	37a	May Creek at Mouth
7	40d	Crisp Creek at Green River RD
8	02e	Bear Creek at Union Hill Rd.
9	02a	Bear Creek at 133rd ST NE, nr. Redmond
10	12120000	Mercer Creek nr. Bellevue
11	12080010	Deschutes River at E. St. Bridge at Tumwater
12	12121600	Issaquah Creek nr. mouth nr. Issaquah
13	11d	Des Moines Creek below SR 509, Des Moines (nr. mouth)
14	*12048000*	*Dungeness River nr. Sequim*
15	12097500	Greenwater River at Greenwater
16	*12167000*	*NF Stillaguamish River nr. Arlington*
17	12114500	Cedar River below Bear Creek, nr. Cedar Falls
18	*12115000*	*Cedar River nr. Cedar Falls*
19	*12141300*	*MF Snoqualmie River nr. Tanner*
20	*12142000*	*NF Snoqualmie River nr. Snoqualmie Falls*
21	*12082500*	*Nisqually River nr. National*
22	*12092000*	*Puyallup River nr. Electron*
23	*12175500*	*Thunder Creek nr. Newhalem*
24	*12189500*	*Sauk River nr. Sauk*
25	12094000	Carbon River nr. Fairfax
26	12060500	South Fork Skokomish River nr. Union
27	09a	Covington Creek nr. Mouth, Soos CR Watershed
28	*12054000*	*Duckabush River nr. Brinnon*
29	*12056500*	*NF Skokomish River below Staircase Rpds nr. Hoodsport*
30	*12134500*	*Skykomish River nr. Gold Bar*
31	*12186000*	*Sauk River above Whitechuck River nr. Darrington*
32	*12178100*	*Newhalem Creek nr. Newhalem*
33	12088000	Ohop Creek nr. Eatonville
34	12108500	Newaukum Creek nr. Black Diamond
35	12155300	Pilchuck River nr. Snohomish
36	*12143400*	*SF Snoqualmie River abv Alice Creek nr. Garcia*
37	26a	Jenkins Creek nr. Mouth - Soos Creek Watershed
38	15c	Laughing Jacobs Creek at E Lake Sammamish Pkwy
39	46a	Issaquah Creek, North Fork
40	42b	Miller Creek Detention Facility
41	*12115500*	*Rex River nr. Cedar Falls*
42	12137290	South Fork Sultan River nr. Sultan
43	*12147600*	*South Fork Tolt River nr. Index*
44	54h	Soosette Creek Above SR 18

Table 1. Summary of properties of the 44 basins featured in this analysis, distinguishing highland, minimally disturbed streams (white font) from lowland, developed (black font) basins. Minimally disturbed streams that qualified as reference gages by having >52-year flow records are given in italics. Data were assembled from USGS' StreamStats database unless otherwise indicated below.

Map Label	Gage Code	Gage Name	Basin Ctr. Latitude (decimal degrees)	Basin Ctr. Longitude (decimal degrees)	Mean Low Flow ($m^3.sec^{-1}$; a)	Basin Area (km^2)	Gage Elevation (m)	Basin Mean Elevation (m; b)	Basin Max. Elevation (m)	Basin Steepness Index	Precip-itation (mm)	Propn. Area Glaciated (c)	Propn. Area Impervious (c)	Well Density in 2015 (km^{-2}; d)	No. of Years
23	12175500	*Thunder Creek nr. Newhalem*	48.576	-121.033	5.54	275	375	1570	2762	68.1	2222	0.119	0.000	0.0	85
22	12092000	*Puyallup River nr. Electron*	46.870	-121.905	5.45	241	506	1419	4386	45.5	2387	0.067	0.000	0.0	67
32	12178100	*Newhalem Creek nr. Newhalem*	48.614	-121.219	1.19	72	302	1286	2472	66.7	2532	0.008	0.000	0.0	55
14	12048000	*Dungeness River nr. Sequim*	47.890	-123.191	3.16	404	176	1269	2370	53.8	1547	0.002	0.000	0.1	80
25	12094000	Carbon River nr. Fairfax	46.972	-121.869	3.62	205	378	1266	4296	48.1	2264	0.023	0.000	0.1	73
15	12097500	Greenwater River at Greenwater	47.086	-121.484	1.04	190	534	1215	2038	41.6	1674	0.000	0.000	0.0	71
21	12082500	*Nisqually River nr. National*	46.746	-121.896	7.26	350	442	1180	4388	40.2	2260	0.039	0.000	0.3	74
31	12186000	*Sauk River above Whitechuck River nr. Darrington*	48.052	-121.333	6.09	399	282	1176	2377	61.0	3097	0.007	0.000	0.0	87
24	12189500	*Sauk River nr. Sauk*	48.198	-121.305	32.88	1854	83	1151	3214	54.2	2691	0.019	0.000	0.1	87
28	12054000	*Duckabush River nr. Brinnon*	47.667	-123.191	2.00	172	82	1074	2058	62.8	2551	0.002	0.000	0.0	78
17	12114500	Cedar River below Bear Creek, nr. Cedar Falls	47.316	-121.497	0.56	67	576	1073	1659	42.9	2678	0.000	0.000	0.0	58
30	12134500	*Skykomish River nr. Gold Bar*	47.772	-121.337	16.10	1386	65	1050	2424	55.3	2776	0.004	0.000	0.2	87
36	12143400	*SF Snoqualmie River abv Alice Creek nr. Garcia*	47.403	-121.492	0.91	108	448	1042	1902	50.7	2840	0.000	0.000	0.1	53
19	12141300	*MF Snoqualmie River nr. Tanner*	47.516	-121.482	4.62	401	237	1038	2302	60.1	3121	0.002	0.000	0.0	53
43	12147600	*South Fork Tolt River nr. Index*	47.705	-121.558	0.12	14	567	1024	1651	61.6	3887	0.000	0.000	0.0	52
18	12115000	*Cedar River nr. Cedar Falls*	47.326	-121.530	0.85	106	480	1005	1659	44.3	2645	0.000	0.000	0.0	70
41	12115500	*Rex River nr. Cedar Falls*	47.322	-121.636	0.21	35	522	995	1445	36.1	2626	0.000	0.000	0.0	70
42	12137290	South Fork Sultan River nr. Sultan	47.927	-121.586	0.33	30	452	993	1591	63.2	3659	0.000	0.000	0.0	24
29	12056500	*NF Skokomish River below Staircase Rpds nr. Hoodsport*	47.555	-123.379	1.82	147	232	990	1949	61.6	3787	0.001	0.000	0.0	87
20	12142000	*NF Snoqualmie River nr. Snoqualmie Falls*	47.642	-121.589	1.41	165	349	931	1794	51.9	3360	0.000	0.000	0.0	72
5	12117000	*Taylor Creek nr. Selleck*	47.365	-121.785	0.62	45	289	696	1250	29.7	2508	0.000	0.000	0.0	59
16	12167000	*NF Stillaguamish River nr. Arlington*	48.305	-121.791	6.05	684	32	656	2079	37.7	2932	0.001	0.000	1.0	87
26	12060500	South Fork Skokomish River nr. Union	47.440	-123.384	2.40	198	33	600	1534	50.9	3509	0.000	0.000	0.0	87
33	12088000	Ohop Creek nr. Eatonville	46.881	-122.278	0.15	89	159	483	1129	18.4	1418	0.000	0.007	1.9	55
1	12145500	Raging River nr. Fall City	47.481	-121.882	0.29	79	76	463	1066	22.0	2157	0.000	0.012	1.7	55
4	12120600	Issaquah Creek nr. Hobart	47.445	-121.961	0.27	47	93	339	911	18.2	1774	0.000	0.024	5.1	27
11	12080010	Deschutes River at E. St. Bridge at Tumwater	46.847	-122.612	2.31	401	26	292	1180	16.8	1322	0.000	0.041	4.9	41
12	12121600	Issaquah Creek nr. mouth nr. Issaquah	47.486	-121.995	0.55	148	13	280	911	19.7	1616	0.000	0.065	6.4	52
35	12155300	Pilchuck River nr. Snohomish	48.030	-121.948	1.61	334	13	265	1610	14.6	1844	0.000	0.047	7.8	24
34	12108500	Newaukum Creek nr. Black Diamond	47.228	-121.986	0.38	81	70	259	941	8.6	1336	0.000	0.068	5.3	69
27	09a	Covington Creek nr. mouth, Soos CR Watershed	47.337	-121.987	0.06	88	103	231	976	9.3	1454	0.000	0.063	5.5	28
39	46a	Issaquah Creek, North Fork	47.557	-122.001	0.02	11	24	172	410	12.0	1358	0.000	0.220	4.6	28
6	37a	May Creek at mouth	47.510	-122.133	0.09	34	8	170	487	13.8	1211	0.000	0.172	6.4	27
7	40d	Crisp Creek at Green River RD	47.306	-122.052	0.12	8	54	153	187	5.5	1212	0.000	0.076	7.6	21
37	26a	Jenkins Creek nr. mouth - Soos Creek Watershed	47.373	-122.071	0.33	45	100	151	215	4.4	1259	0.000	0.219	10.3	28
38	15c	Laughing Jacobs Creek at E Lake Sammamish Pkwy	47.579	-122.020	0.01	12	12	129	186	6.8	1201	0.000	0.236	2.3	24
44	54h	Soosette Creek Above SR 18	47.353	-122.167	0.01	14	83	126	159	4.1	1124	0.000	0.309	6.4	22
8	02e	Bear Creek at Union Hill Rd.	47.748	-122.057	0.16	36	37	119	191	5.7	1180	0.000	0.090	5.1	21
40	42b	Miller Creek Detention Facility	47.482	-122.323	0.00	9	83	116	147	4.6	957	0.000	0.509	9.5	26
2	35c	McAleer Creek at mouth	47.784	-122.313	0.12	30	10	110	168	7.2	969	0.000	0.463	1.6	24
9	02a	Bear Creek at 133rd ST NE, nr. Redmond	47.719	-122.069	0.46	123	11	109	204	6.2	1142	0.000	0.140	5.6	28
3	12073500	Huge Creek nr. Wauna	47.426	-122.705	0.12	16	27	106	162	5.5	1368	0.000	0.045	17.9	60
13	11d	Des Moines Creek below SR 509, Des Moines (nr. mouth)	47.428	-122.307	0.03	14	8	100	156	5.1	958	0.000	0.559	4.9	24
10	12120000	Mercer Creek nr. Bellevue	47.611	-122.153	0.16	37	8	95	327	6.8	1053	0.000	0.443	10.2	61

(a) USGS flow flow data; (b) Derived from DEM; (c) Derived from NLCD imagery; (d) Derived from Dept. Ecology's Wells Database

Methods and Data

Selection of basins

For the assessment of climate impacts alone, 23 basins in the Puget Sound region were selected that were defined by gages on unregulated streams with long (>52 years), continuous discharge records up to 2015, that were 'minimally disturbed' (defined as having no impervious cover, and fewer than 1 well per km^2). For the comparison with developed basins in the lowlands, 21 basins were selected that were defined by gages on unregulated streams with continuous, >20-year discharge records up to 2015 (Figure 1, Table 1), all subject to disturbance by development. The combined area of all selected basins was 25.9% of total land area of the Puget Sound basin.

Focal streams and basins are referred to throughout by the name of the gage providing flow data, together with the gage number, separated by a forward slash (e.g. Issaquah Creek nr. Hobart/12120600)

Low 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). Annual low flow estimates for each gage were derived by converting daily flow data to 7-day running averages (mean of daily flow records over the previous 7 days, sometimes referred to as *7q*), and selecting the lowest 7-day flow (*summer min7q*) between June 1 and November 15 for each water year.

Low Flow Anomalies (z scores)

Anomalies (z scores) were calculated for each year, *i*, as: $z_i = (f_i - F) / \sigma$

where f_i is low flow value for year *i*
F is low flow mean
σ is low flow standard deviation

Means and standard deviations were calculated for the 20-year interval 1964-1983 for gages with >52-year discharge records.

Spline curve fitting

Low flow profiles for each gage were derived by fitting splines to the anomaly series for each gage. A smoothing factor, lambda, equal to 1 was used in all cases. This value yielded a cubic pattern (a curve with two inflexions) over the multidecadal span of available data, matching the cubic pattern that was found to be statistically significant in a polynomial analysis of some of the same data by Georgiadis (2022). In that analysis, polynomials of higher order than 3 were not significant.

Basin characteristics

Unless otherwise indicated in Table 1, basin characteristics were sourced from USGS's *StreamStats* database.

Linear model

To assess statistical signal in low flow anomaly series for all 18 minimally disturbed series, a linear model was used, featuring Year, Basin Mean Elevation (BME), and Gage Elevation as independent variables, each with quadratic terms, and interactions designed to accommodate the observed complexity (final model terms are listed in Table 2). To simplify the model, the time interval was confined to 1964-2015, so that no more than quadratic terms were required. Minimum AICc values were used to select the most efficient model, using *JMP 15.0* software, SAS Institute Inc., Cary, NC, 1989-2019.

Impervious Cover

Estimates of impervious land cover were derived from the Multi-Resolution Land Characteristics (MRLC) consortium's National Land Cover Dataset (NLCD) imagery. NLCD image classification distinguishes three intensities of impervious cover (low, medium, and high), defined as follows:

1. Developed, Low Intensity- areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units (mean proportion impervious = 0.35).
2. Developed, Medium Intensity -areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units (mean proportion impervious = 0.65).
3. Developed High Intensity-highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover (mean proportion impervious = 0.90).

The proportion of impervious cover in each basin and year was estimated using GIS to sum proportions of low, medium, and high intensity cover after weighting by the mean proportion that was impervious in each intensity (means in each class are given above).

Wells data

Numbers of wells in focal basins in each year were estimated from Department of Ecology's wells database, using GIS to spatially isolate and count wells located within focal basin boundaries.

Results and Discussion

Results are presented as a series of numbered topics, each with a Discussion section.

1. Clustering gages based on low flow series

A total of 44 gages were found with continuous daily flow data for at least 20 years. A clustering analysis, based on relative low flow rates between 1996-2015, revealed how their low flow profiles differ, and suggested what caused those differences. Most gages (83%) fell into one of three groups (blue, red, or green in Figure 2). For gages in the blue group, annual low flows were variable, but means were <50% of maximum values, with relatively synchronized peaks. Values tended to be lower mid-period, yielding a U-shaped trend. By contrast, for gages in the green group, annual low flows were relatively constant, with means >50% of maximum values, less synchronized peaks, and no overall trend. Patterns in the red group were intermediate between blue and green in these properties. Within the red group, and within the blue group with only 2 exceptions, highland and lowland gages clustered separately (black vs. white labels in Figure 2). Within both red and blue groups, a principal feature distinguishing upland and lowland patterns was that, in 2003-4, low flows peaked in the former but not in the latter (not distinguishable in Figure 2). In the green cluster, all gages were in basins that were at least partly developed, with one exception (Taylor Creek nr. Selleck/12117000). Of all the minimally disturbed gages, this gage had the lowest basin maximum elevation (1250m; Table 1).

The 7 remaining gages formed two small clusters, one having 3 gages (yellow), showing generally declining trends over the recorded period, the other having 4 gages (orange), with a pattern that peaked in mid-period. In the orange group, 3 highland gages clustered together, all representing small basins in the foothills of the Cascades range (Figure 1).

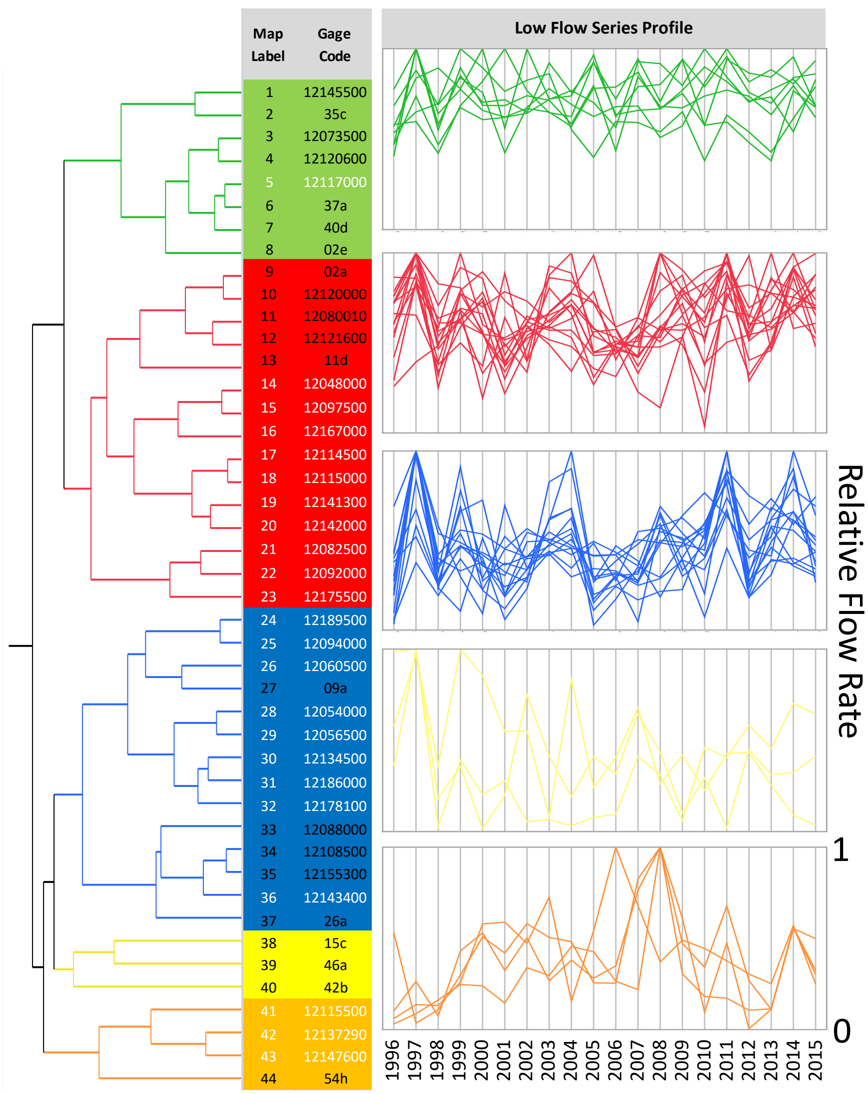


Figure 2. Clustergram (left) showing how 44 gages clustered, based on relative low flow patterns between 1996 and 2015 (parallel plots at right). The colors distinguish five basic clusters. Branches are labeled (center) with gage codes and map labels from Figure 1 and Table 1, for minimally disturbed (white) and developed (black) basins.

Discussion

What accounts for differences in low flow patterns among the three main clusters in Figure 2? Elevation alone does not account for the differences, since means for all three elevation properties (gages, basin mean, and basin maximum) were greater in red than blue groups, although not significantly. Basin steepness was greater in blue than red groups, (one-tailed t test, *P=0.02* on data in Table 1), but this too seems an unlikely primary causal factor, since blue and red basins in the highlands were far steeper than blue and red basins in the lowlands (Table 1).

Geological substrate provides a more likely candidate (Tague and Grant 2004, 2009, Carlier et al. 2018). Jefferson et al. (2008) classified flow patterns in the Oregon Cascades as dominated either by runoff, or by aquifer storage and release. In the latter, aquifer storage and associated slow summer recession rates sustain discharge even when the seasonal or annual water balance is negative. By contrast, in runoff-dominated watersheds, subsurface storage is exhausted every summer. Likewise, Mayer and Naman (2011) distinguished two major types of basin in the region (surface-dominated and groundwater-dominated), and further differentiated the former into 'rain basins' and 'snowmelt basins' on the basis of elevation and timing of winter runoff. They noted that warmer winter temperatures and snowpack reductions have caused significantly earlier runoff peaks in both snowmelt and groundwater basins in the region. This classification of streams as dominated primarily by surface vs. groundwater, and secondarily by rain vs. snow dominance is consistent with the blue vs. green cluster patterns in Figure 2. Streams in the red cluster were intermediate in these respects, but it is not clear what distinguished this as a third group in the clustergram (as opposed to a continuous transition between blue and green groups).

It is worth noting that in our sample of 44 gages were 4 streams each represented by 2 gages. In one pair (Sauk River above Whitechuck River/12186000 and Sauk River nr. Sauk/12189500), both clustered in the blue group. In another (Cedar River below Bear Creek/12114500 and Cedar River near Cedar Falls/12115000) both clustered in the red group. A third pair (Bear Creek at 133rd St/02a and Bear Creek at Union Hill Rd/02e) fell in red and green groups, respectively, and the last (Issaquah Creek nr. Hobart/12120600 and Issaquah Creek nr. Mouth/12121600) in red and green groups, respectively, with descending elevation (Konrad 2006). Therefore, streams are not necessarily of one type, rather, reaches can change from surface-dominated to groundwater-dominated – and even the reverse.

These clustering patterns and flow properties are instructive in the interpretation of low flow profiles featured elsewhere in this report.

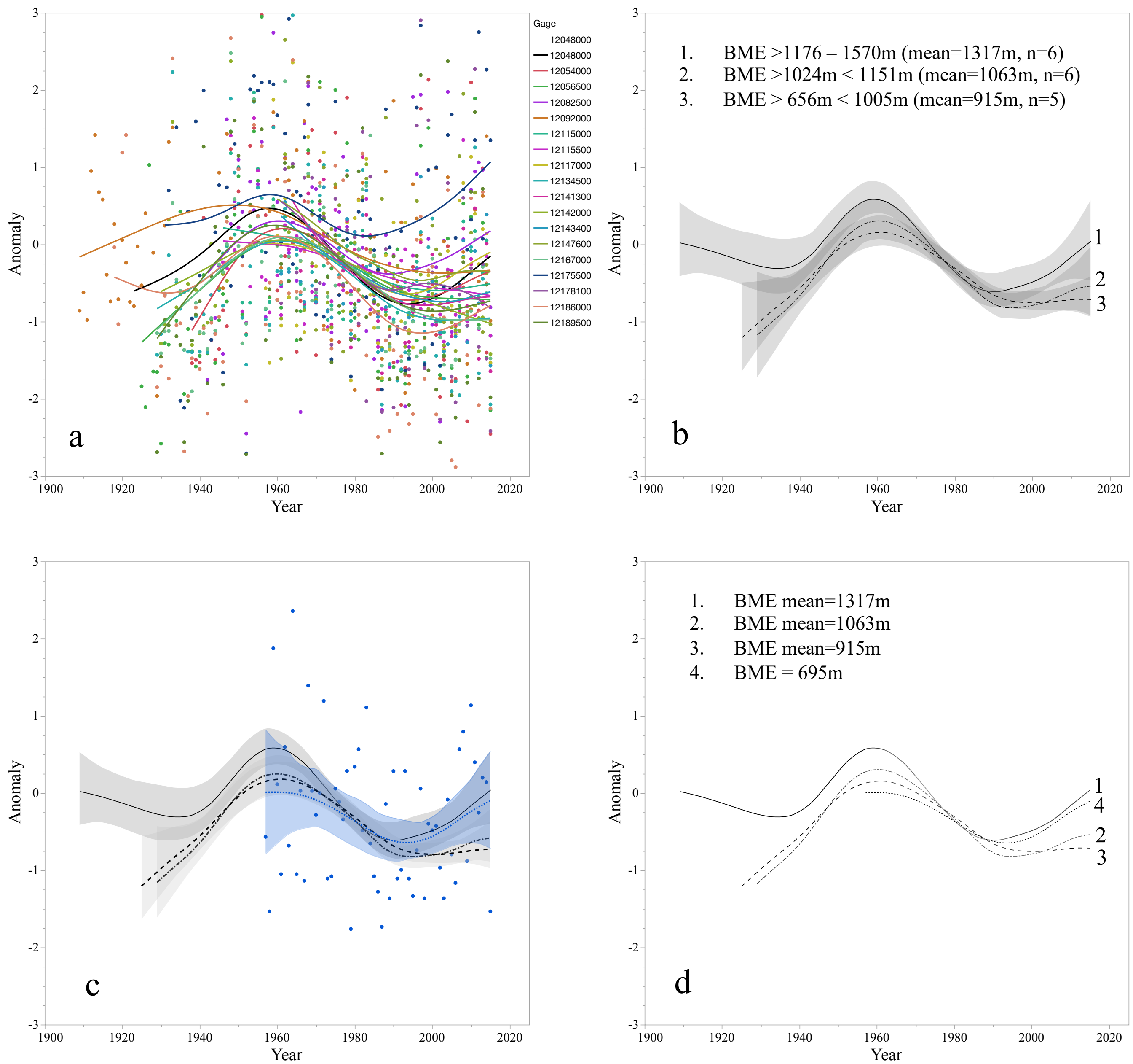
2. Low flow profiles in minimally disturbed streams

In this section, low flow anomaly profiles were defined for 18 minimally disturbed streams with daily discharge records >52 years, revealing how their profiles varied over time, and with elevation.

The anomaly series for each gage was modeled using a smoothed spline to reveal variation at multidecadal scales (Figure 3a; smoothing factor, lambda, was 1 in all cases). Most showed a single oscillation with maxima around the year 1960, but with staggered minima, starting in ~1985 with Thunder Creek nr. Newhalem/12175500, the basin with the highest BME. To show how profiles changed with elevation, 17 of the 18 series were assigned to one of three groups based on their BME (Figure 3b), aiming for equal numbers in each group. The fitted spline profiles for all groups peaked around 1960 (Figure 3b), but diverged thereafter. The group with the highest mean BME (>1176m; solid black line) had the highest maximum inflexion point, and the earliest minimum inflexion point (~1990). For the mid-elevation group (black dot-dash line) the year of minimum inflexion was ~1995. The profile for the group with lowest BMEs barely increased after ~2000 (<1005m; dashed line). Confidence intervals for the highest and lowest BME groups did not overlap after ~2007.

The profile for Taylor Creek nr. Selleck/12117000 was presented separately (Figure 3c, blue dotted line) because it was unique. Like the others, it peaked around 1960, but with the lowest anomaly value compared to the other groups, and then declined until ~1995. Thereafter, it turned upward as steeply as did the highest-elevation gages (solid black line), attaining a level in 2015 similar to its level in the 1960s.

Figure 3 a) Low flow anomaly series for 18 minimally disturbed streams with flow records longer than 52 years. Their gage numbers are listed to the right of the panel. Each is modeled using a spline with a smoothing factor (lambda) of 1. b) As in a, but after sorting all but one (Taylor Creek nr. Selleck/12117000) of the series into three groups, according to basin mean elevation (BME; ranges and means of each group are given at the top of the panel). Splines are shown with 95% confidence intervals (gray shading). c) Low flow anomaly data (blue dots), profile (blue dotted line), and 95% CI (blue shading) for gage Taylor Creek nr. Selleck/12117000, overlaid on the three group profiles from panel b. d) The four spline curves from panel c. Curve 4 (Taylor Creek nr. Selleck/12117000) is used as a reference profile for comparison with profiles of lowland basins in section 3.



To show that these patterns differed significantly with elevation and over time, a linear model was fitted to low flow anomaly series from all (18) minimally disturbed basins, between 1964 and 2015. The most efficient model (minimum AICc) showed high statistical significance of both linear and quadratic terms associated with Year, and with Gage Elevation (Table 2). Terms associated with BME, and with its interactions with Year were moderately significant. The model captured salient features of the patterns depicted in Figure 3d: declining, then increasing low flows over time, but in ways that varied with BME. Low flow anomalies increased in the 1990s at high and at low elevations more steeply than at mid-elevations. The BME at which low flow anomalies declined to their lowest value was ~970m (as in Figure 3d, curve 3). At lower BMEs, low flows became *less* sensitive to elevation because of diminishing snowpack. By extrapolation, low flows in basins with a mean elevation below ~800m have been little impacted by phase changes in precipitation.

Table 2. Results of the most efficient (minimum AICc) linear model fit to low flow anomaly data depicted in Figure 3a, over the interval 1964-2015. BME is Basin Mean Elevation.

Summary Of Fit	
RSquare	0.141593
RSquare Adj	0.135048
RMSE	1.015476
Mean of Response	-0.38082
Observations	926

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	156.1464	22.3066	21.6319
Error	918	946.634	1.0312	**Prob>F**
C. Total	925	1102.7805		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	4962.444	663.5546	7.48	<.0001*
Year	-5.025283	0.664001	-7.57	<.0001*
Year*Year	0.0012723	0.000167	7.63	<.0001*
BME	0.2544274	0.139134	1.83	0.0678
BME*BME	-0.00014	6.27E-05	-2.24	0.0255*
Gage Elevation	0.0006222	0.000209	2.97	0.0031*
Year*BME	-0.000129	0.00007	-1.85	0.0644
BME*BME*Year	7.13E-08	3.15E-08	2.26	0.0239*

Discussion

The single oscillation observed in low flows between ~1940 and 2015 mirrors an oscillation over the same period in precipitation, and an opposing oscillation in surface temperature (Georgiadis 2022; here, 'single oscillation' is used solely as a descriptor of this cubic pattern, without implying periodicity). The oscillation was originally observed in a polynomial analysis of data from seven flow gages in the highlands surrounding Puget Sound (also included in this analysis), each paired with precipitation and temperature data from a nearby weather station (Georgiadis 2022). Climatic oscillations with differing wavelengths have been described in the northeastern Pacific (Minobe 1997, Overland et al. 2006, Wills et al. 2018), for example, ENSO (Newman et al. 2016), and the Interdecadal Pacific Oscillation (Parker et al. 2007, Dong and Dai 2015). Candidate causes of oscillations with wavelengths as long as that observed in this case (~76 years) include intermittent vulcanism (Mann et al. 2021), oceanic eddies (Jüling et al. 2020), and a global stadium wave (Kravtzov et al. 2018), but their mechanisms and interactions are not clear (Johnstone and Mantua 2014a, b, Abatzoglou et al. 2014a, b). While low flows will likely continue to decline due to anthropogenic warming, current General Circulation Models (GCMs) do not accurately reproduce oscillating climate drivers with multidecadal wavelengths (Lee et al. 2021), or account interactions among these drivers. Uncertainty about future trends in low flows may have been underestimated.

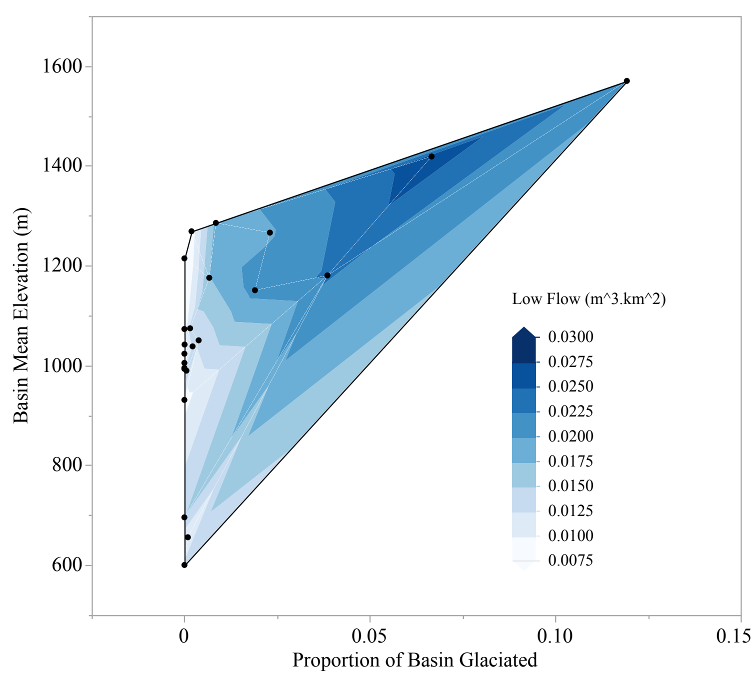
In addition to a cubic oscillation, the polynomial analysis of low flow series by Georgiadis (2022) also revealed first order (monotonic) declines in streamflows over the period of record, in all seasons except winter, when flows increased. Monotonic increases in winter and summer temperature were also detected. Increasing winter temperature likely caused less precipitation to fall as snow, increasing winter runoff, and leaving less snowpack to contribute to flows in spring and summer. Increasing summer temperature likely enhanced losses due to evapotranspiration, further reducing low flows. Anthropogenic warming is a likely contributor to the observed decline in low flows, but only in recent decades. Other drivers (described above) may also have contributed to earlier declines (~1960-1990s). Evidently, one or more of these drivers overrode effects of anthropogenic warming to cause the observed upturn in precipitation and flows, and decline in temperature, following the 1990s. These climatic changes would have caused snowpack to increase again at higher elevations (Siler et al. 2019), but, given warmer winters and summers, not at all elevations at the same time. After 1990, the upward trend in low flows was delayed at lower elevations (Figure 3b). This interpretation is consistent with simulated changes in flows due to anthropogenic warming (e.g. Mote and Salathé 2010, Wu et al. 2012, Tohver et al. 2014).

The same mechanism can explain the distinct profile of Taylor Creek nr. Selleck/12117000 (Figure 3d, curve 4). The steep upturn in the 1990s suggests that low flows at Taylor Creek nr. Selleck/12117000 were little affected by phase changes in precipitation, only by changes in temperature and rainfall. Of the minimally disturbed streams in our sample, Taylor Creek nr. Selleck/12117000 had the third-lowest basin mean elevation (696m), and the lowest basin maximum elevation (1250m; Table 1). The pattern for Taylor Creek nr. Selleck/12117000 resembles that of the highest-elevation streams (Figure 3d, curve 1) because they too are not much affected by phase changes in precipitation. Taylor Creek nr. Selleck/12117000 provided the closest to a reference profile for lowland basins in our sample, at least for groundwater dominated streams (Figure 2). It was added to the profiles of the three higher-elevation groups to create a set of four reference curves depicting how low flow profiles changed over time at different elevations (Figure 3d). The profile for Taylor Creek nr. Selleck/12117000 was used in Section 4 for comparison with low-flow profiles from lowland streams in developed basins.

3. Glacier melt contributions to low flows

How much does glacier melt contribute to low flows? While glacier recession in the region is well documented (e.g. O'Neal et al. 2015), this is a non-trivial question because low flows occur during the transition between summer and fall, when temperatures at high elevation may become low enough to halt melting before fall precipitation supplements streamflows (Mutzner et al. 2015). From daily flow data it is not obvious that glacier melt supplements low flows, and by how much. However, visual inspection of flow rates recorded every 15 minutes for highland gages (e.g. Puyallup river near Electron) revealed the characteristic 'sawtooth' pattern caused by melting during the day and freezing at night, even during the time of lowest summer flows. Thus, glacier melt can contribute to low flows, even if only from melting during the day.

Figure 4. Contour plot showing how low flows (z-axis) at 23 minimally disturbed gages vary with Basin Mean Elevation (y-axis) and Proportion of Basin Glaciated (x-axis).



Glaciers were present in most of the basins with BME>1100 m (Table 1). A contour plot

(Figure 4) shows little change in low flow rates with elevation for basins lacking glaciers (BME<1100 m). But for basins with glaciers, low flows increased with proportional glacier area, and with elevation. The data do not rule out contributions by snow that overlays ice persisting until late summer, but this would still be an effect of glacier cover. Melting snow and ice likely account for the steeper upturn in low flows at high elevations (Figure 3b and d, curve 1).

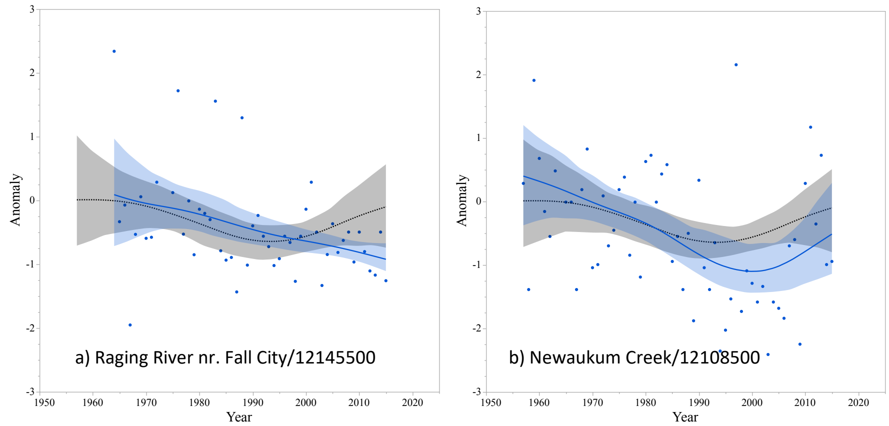
Discussion

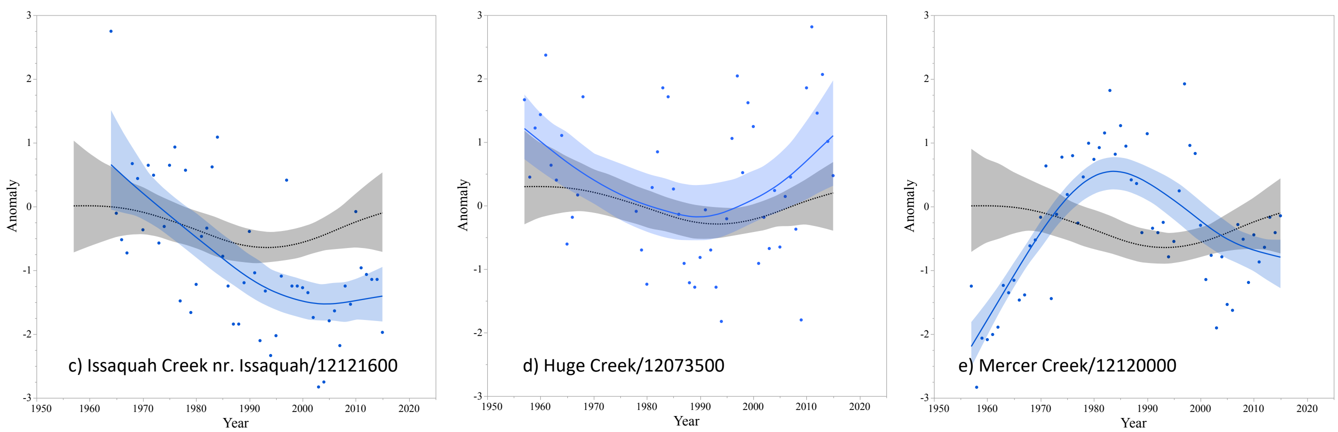
Rates of glacier recession are projected to increase over coming decades (Frans et al. 2018), but runoff from glacier melt and its relative contribution to streamflow may increase or decrease, depending on elevation. In high-elevation stream basins, enhanced glacier melt will buffer steep declines in seasonal snowpack and decreased late summer streamflow. These glaciers will become too small to support streamflow at historic levels later in the 21st century. By contrast, glacier melt contributions to flows have already peaked in lower-elevation basins. Declining snowpack and shrinkage of small glaciers will result in continued reductions in summer streamflow. Regardless of the trend direction in glacier melt discharge, its relative contribution to late summer streamflow will grow, due to declining seasonal snowmelt. Excepting high-elevation watersheds, this enhanced contribution of glacier melt and its capacity to buffer low flows is projected to decline around 2020–2040. In glaciated river basins experiencing more rapid retreat, declines in glacier melt can further exacerbate declining summer streamflow, given reductions in seasonal snowmelt, leading up to 80% reduction in late summer discharge volumes by the end of the century (Frans et al. 2018).

4. Low flow profiles in lowland streams

In this section was ask how do the low flow anomaly profiles of lowland streams in developed basins deviate from a purely climate-driven pattern? Only five lowland gages, and only one minimally developed lowland reference stream (Taylor Creek/12117000; Figure 3d, curve 4), had sufficiently long (>52 years) and complete flow records to make these comparisons. The profiles of the developed streams were diverse (Figure 5a-e), differing from the reference profile, and from each other, in instructive ways. The profile for Raging River/12145500 (a) was linear and declining with, most notably, no upward inflexion after the 1990s. Ninety-five percent confidence intervals barely overlapped with the reference curve after ~2010 (there was no overlap with 92% confidence intervals). The profile for Newaukum Creek/12108500 (b) declined as steeply after 1960 as did the reference profile, but unlike the reference, continued to decline until ~2000 before turning upwards. Again, the 95% confidence interval barely overlapped with the reference profile – but 93% CIs did not overlap – in ~2005. The profile for Issaquah Creek nr. mouth/12121600 (c) declined more steeply, and for longer after 1960, than the reference profile, and did not turn upwards until ~2005. In this case, confidence intervals did not overlap following ~1993. For Huge Creek/12073500 (d), the profile was similar to that of the reference profile. While the rate of increase after the upturn appears higher than the reference curve, this was never significant. Finally, the profile for Mercer Creek nr. Bellevue/12120000 (e) bore no resemblance to any of the reference profile, increasing rapidly from 1960 until ~1985, a period when reference streams were declining, then declining over a period when low flows in reference streams were increasing.

Figure 5. Low flow anomaly profiles of 5 lowland gages (blue line with 95% confidence intervals indicated by blue shading), each superimposed on the lowland reference profile from Figure 3d, curve 4 (dotted black curve with 95% confidence intervals indicated by gray shading). In all except panel d, anomalies were calculated using a mean based on values for the twenty years from 1964 to 1983. In panel d, due to missing data, low flow values from the twenty years between 1964 to 1968, and 1978 to 1992, were used to calculate the mean.





Discussion

All five flow profiles deviated somewhat from a purely rainfall and temperature-driven pattern (Figure 5), implicating local human causal factors. What were the most likely causes in each case?

Unlike any of the others, the Raging River/12145500 profile did not turn upwards after the 1990s, and continued to decline, at least until 2015. In this basin, human population density is low, with all water supplied from wells (Figure 6). Although most are Group A or B systems[1] (including a commercial bottled water operation near Preston, WA), and located along the drainage, they do not include municipal wells that serve Fall City, which are located >2 miles below the gage. Hydrological estimates suggested that the combined abstraction via wells may not be large enough to have caused the observed impact (Northwest Hydraulics Consultants, Inc. 2005). Moreover, the area is not served by the regional wastewater system (Figure 6), so wastewater is not exported from the basin. This leaves forest management as a possible cause of continued decline. Visual inspection of historical imagery in Google Earth revealed that a large area of the Raging River basin was clear cut in or shortly before 1984, and another large area was cut in or shortly before 2003 (totaling more than 50% of the basin). Over initial decades of growth, planted forest stands can reduce summer flows due to increased ET (Perry and Jones 2017, Gronsdahl et al. 2019,

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[1] *Group A public well systems have more than 14 connections or serve 25 or more individuals for 60 or more days per year. All Group A systems are regulated by the State Department of Health Office of Drinking Water. Group B public water systems serve fewer than 15 connections and fewer than 25 people per day. Rules applying to Group B wells allow local health jurisdictions (LHJs) to adopt their own regulations, as long as they are not less stringent than the state rule. Group D wells are private and permit-exempt, typically serving one rural household.*

Moore et al. 2020), although many factors are involved (Goeking and Tarboton 2020). If clear cutting is causing low flows to decline in the Raging River basin, this should reverse as stands mature.

For Newaukum Creek/12108500 (Figure 5b), the declining phase appears climate-driven initially, but the upturn was delayed, relative to the climate-only reference. Local causal factors are plausible for this basin, given its history of hydrologic modification. Well density is moderate (Figure 6), but these include municipal wells that supply the city of Enumclaw, much of which is served by a sewer system that exports wastewater to a treatment plant just outside the basin to the south. Published estimates of net water extraction from the Newaukum basin derive from a report by Northwest Hydraulic Consultants, Inc. (2005), which includes water balance estimates for several study basins in the Green River basin (synthesized in King County 2009). A King County report from 2010 (their Table 3) estimated that summer flows in Newaukum Creek basin were depleted due to export of wastewater (at 2.1 cfs), and impervious cover (0.6 cfs). Given that there are no managed forests in the basin, these remain the most likely local contributor to declining low flows.

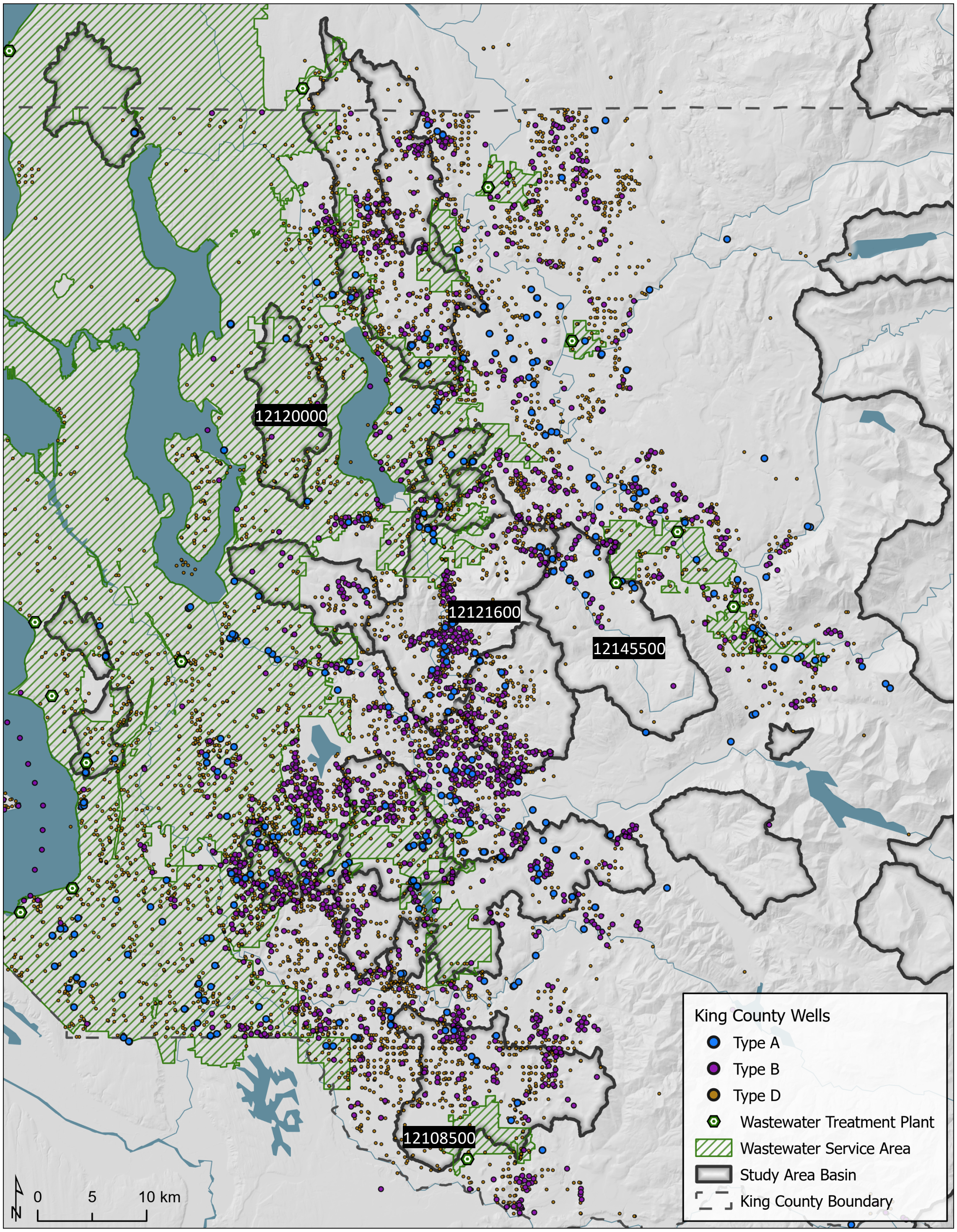
In Issaquah Creek nr. mouth/12121600, the steepness and extent of decline in low flows suggest that local human factors played a role, in addition to the changing climate (Figure 5c). Logging can be ruled out as a causal factor, since there has been little in the basin in recent decades. Water supply is from wells, which are at relatively high density in rural areas, especially along the drainage (Figure 6). Issaquah city is supplied from four municipal wells, all within the basin. Wastewater is treated by septic systems in rural areas, but city wastewater is exported to treatment plants outside the basin. Thus, wells of all types, and wastewater export, were the most likely contributors to declining low flows in Issaquah Creek nr. mouth/12121600, but from this analysis it was not possible to estimate their relative effects.

The profile for Mercer Creek nr. Bellevue/12120000 bore no resemblance to the reference profile at any point of the 55-year record (Figure 5e). The basin is entirely covered by the city of Bellevue, for which water has long been imported from the Cedar and SF Tolt rivers, and wastewater exported to treatment plants outside the basin. The cause of such an aberrant low flow profile is not known – there may be many. One candidate is that ~40% of pipes in Bellevue's water supply system are made from concrete asbestos, which leak with age, and have been gradually replaced over recent decades (City of Bellevue 2015).

The low flow profile of Huge Creek/12073500; Figure 5d) deviated least from the purely climate-driven pattern. The basin has rural (no urban) land cover, with domestic water supplied from wells, and waste treated by septic systems. Despite a high density of wells (Table 1), no negative impacts were evident, possibly because this is a groundwater-dominated stream (Figure 2).

These inferences would be made more robust by additional lowland reference streams with long flow records. If any exist, they are more likely to be found beyond the Puget Sound basin. Multiple examples of both groundwater and surface water-dominated reference streams would be ideal, since these would reveal if and how their profiles differ. Even so, these results illustrate how variable are low flow responses to development, indeed, each might be expected to be unique. In each case, precise reconstruction of the unique course and timing of development would probably reveal causality.

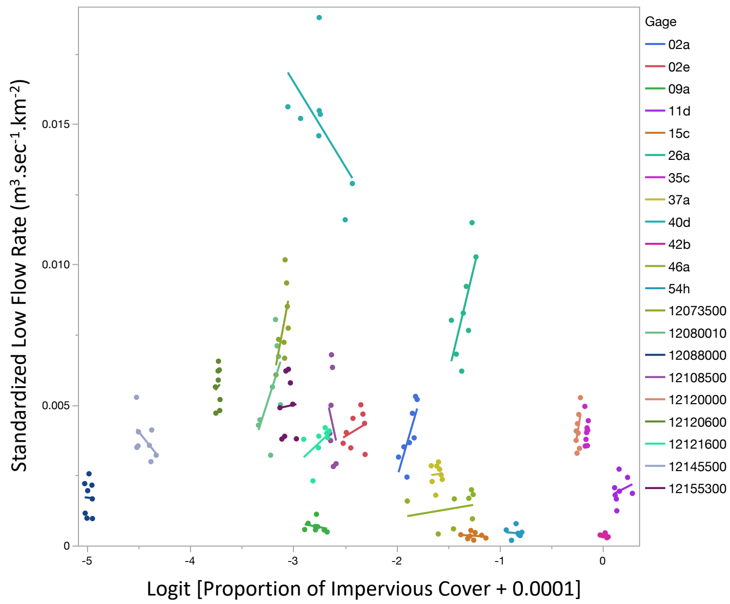
Figure 6. Map of focal basins in the Puget Sound lowlands (those that are labelled are mentioned in the narrative), showing areas served by sewers (diagonal hatching), wastewater treatment plants, and wells of three types. Spatial data source: King County GIS.[Maybe add river/creek names as well as gage #s to the map?]



5. *Do low flows decline with impervious land cover?*

To test the expectation that low flows should have declined as impervious cover spread, the proportion of each lowland basin that was impervious was estimated from NLCD satellite imagery in each of the (eight) years between 2001 and 2019 for which imagery was available. In all basins, impervious cover either increased or barely changed, but did not decline, over the 19-year period.

Figure 9. Plot of standardized Low Flow values between 2001 and 2019 against Proportion of Impervious Cover for all 21 lowland basins in our sample (listed at right). Lines are linear splines.



Standardized annual low flows were plotted against the proportion of total impervious cover for each basin (Figure 9). The expected decline in low flows with increasing impervious cover was not evident, within or among lowland basins. Rather, flow trends differed widely among basins, with some decreasing, some increasing, and others not changing much.

A mixed effects linear model was fit to these data, which included Total Impervious Cover and Year as independent variables. After model selection based on minimizing AICc, the random effects covariance parameter associated with gages was significant (Wald p-value = 0.0017), but neither of the independent variables (Year, and Total Impervious Cover) accounted for significant variance. Thus, there was no consistent trend in low flows as impervious cover increased over time.

Discussion

Several factors weaken this approach as a test for effects of impervious cover. First, nineteen years is a relatively short fraction of the total time it takes most basins to develop. Second, effects may change in a non-linear fashion with impervious cover. Total impervious cover tended to increase more in moderately developed basins than in undeveloped or developed basins. This is expected, given that development in rural areas usually does not include urbanization, while in developed basins, growth is more likely to be vertical than horizontal. Third, there is no consensus about how to estimate statistical power in linear mixed models.

Even so, the expected decline in low flows with impervious cover was not observed, even in moderately urbanizing basins. By implication, factors other than the varying climate or impervious cover were causing low flows to increase or decrease sharply in these basins. These factors may be related to installation of water infrastructure (public water supply and sewers) that is typically associated with urbanization, especially if this involved import or export of water to focal basins. A detailed history of the timing and type of development is needed to interpret the causes of low flow trends in these basins. Continued monitoring of growth and low flows in these focal basins should resolve most of these uncertainties.

6. *Do low flows decline with well density?*

A similar analysis was attempted to test if low flows decline with well density, using the only available longitudinal data in Washington Department of Ecology's wells database. Cumulative number of water wells in each lowland basin was extracted for each year until 2019. However, when well densities for 2016 were calibrated against an inventory of wells in King County in 2016, including 18 of 21 lowland basins in our sample, there was no correspondence between estimates of well density in each basin ($P>0.05$). We concluded that the data from Dept. of Ecology's database are not suitable for this kind of longitudinal analysis, and no results are given here (reporting to inform others who may attempt the same analysis).

7. The relative impact on low flows of development vs. climate change

The analysis offers initial impressions of relative impacts on future low flows of climate change vs. factors related to development. How can these impressions be refined? In rural areas, water supply is mostly from private wells. Since these are typically paired with a septic system, which return much of the abstracted water to the ground (if not the aquifer), the impact of private wells on low flows is likely to be minor. Private wells had no detectable impact on low flows in Huge Creek/12073500 basin, a groundwater-dominated stream in a rural area with a high density of private wells. In other basins, wells may have had a greater impact, especially where municipal wells supply urban areas, from which wastewater is exported via sewers to treatment plants outside a focal basin, as in the Issaquah Creek nr. mouth/12121600 basin. While diminished infiltration may not be the dominant effect of urbanization on low flows, impervious cover is a useful proxy for urbanization. Analysis of remote sensing data revealed that, in 2019, ~4.8% of the terrestrial Puget Sound basin was impervious (analysis by K. Bogue not shown here). Assuming that growth will continue after 2019 at the same rate as between 2001 and 2019, the total area of impervious cover is expected to increase by only 0.026% per year, and at that rate, for example, <7% of the total basin is expected to be impervious by the end of the century. Thus, effects of urbanization on low flows can be locally intense, but will largely be confined to a small area at low elevations in rainfall-dominated basins. By contrast, anthropogenic warming will reduce low flows over the entire basin. Below ~800m, this will largely be via increased evapotranspiration, and decreased summer rainfall. Above ~800m, diminishing snowpack and glacier melt will add to ET-induced losses at progressively higher elevations.

Washington's Streamflow Restoration Act (RCW 90.94) required that strategic plans be created to offset expected reductions in low flows in rapidly developing basins of Washington State, due to the addition of private wells over the 20 years between 2018 and 2038. In the Puget Sound region, strategic plans have been prepared for at least 8 basins, comprising ~25% of the total land area. While many of these plans also made provision for anthropogenic warming, they do not apply beyond 2038, and no provisions were made for basins with little expected development (~75% of the land area). Further effort is needed to resolve spatial and temporal impacts on low flows of these factors, and make further provisions accordingly.

8. Research and monitoring recommendations

1. Monitoring: the 23 minimally disturbed streams with long flow records featured here provide a suitable – and valuable – set with which to monitor effects of climate change on low flows at different elevations, without confounding effects of development.
2. Monitoring: additional lowland reference streams are needed (minimally disturbed, with basin mean elevation <800m, and long flow records), especially for surface-dominated streams.
3. Research and monitoring: further evidence is needed to test if groundwater abstraction impacts low flows differently in surface vs. groundwater-dominated reaches, and to define the sensitivity of these properties to

pressures exerted by climate change and development. This will require investment in groundwater monitoring, preferably using a carefully selected subset of the large number of existing monitoring wells.

4. Research: results suggested that mapping stream properties such as surface- vs. groundwater-domination, and snow- vs. rain-domination, will assist in identifying priority areas for actions intended to recover low flows.
5. Research: reconstructing the history of development in developed basins could yield further insights about the impact on low flows of importing water to, and exporting water from, focal basins.
6. Modeling: further assessment and modeling are needed to quantify projected declines in low flows due to anthropogenic warming, and remedial measures applied where needed.

Conclusions

We assessed prevailing assumptions and uncertainties about trends in low flows in Puget Sound streams, and their causes, by analyzing available data in novel ways. Principal conclusions were:

1. Concerns about declining low flows in the Puget Sound region have focused on impacts of anthropogenic warming, and on factors related to development. Results of this analysis suggest that declines in low flows were widespread between ~1960 and the 1990s, but, contrary to widespread assumption, anthropogenic warming was not the only – or even the dominant – climate driver of this trend. Oscillating climate drivers with multidecadal wavelengths also contributed, not only to declines, but also to recent increases in low flows. While low flows will likely continue to decline due to anthropogenic warming, current GCMs do not accurately reproduce oscillating climate drivers with multidecadal wavelengths (Lee et al. 2021), or account interactions among these drivers. Uncertainty about future trends in low flows may have been underestimated.

2. Strategies intended to maintain or restore future low flows have emphasized offsetting impacts of private wells, and of reduced infiltration due to impervious cover. The analysis suggests that these impacts may be relatively small, compared to other impacts of urbanization, for example, export of wastewater to treatment plants outside focal basins, especially if water is supplied from wells within focal basins. Reconstructing the history of development in these basins, with a focus on changes in water budget components, could yield further insights about the impact on low flows of importing and exporting water from focal basins.

3. Urbanization impacts on low flows can be severe, but will be confined to a relatively small proportion of the region, for example, <~7% of land area by 2100. By contrast, climate change will affect flows over the entire region, especially at higher elevations, where flows are sensitive to snowpack changes, and wherever high-elevation impacts are conveyed to the ocean in large streams.

4. Washington's Streamflow Restoration Act (RCW 90.94) required that strategic plans be created to boost low flows in developing basins. While focusing on private wells, many of these also made provision for anthropogenic warming. However, the plans do not apply beyond 2038, and only rapidly developing basins were included (~75% of the Puget Sound region was not covered by a plan). Further assessment and modeling are needed to quantify projected declines in low flows due to anthropogenic warming beyond 2038, and remedial measures applied at least to 'priority areas'. The analysis also suggested that mapping stream properties such as degree of surface- vs. groundwater-domination, and snow- vs. rain-domination, may assist in identifying 'priority areas'. Further research, and continued monitoring, are needed to define the sensitivity of these properties to pressures exerted by climate change and development.

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