Are low flows changing in Puget Sound streams?

A re-assessment of the indicator for *Summer Stream Flows*

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Version of July 26, 2018

***Summary**: Long-term trends in summer low flows (up to 87 years) were assessed using daily flow data from a sample of 13 flow gauges on 9 unregulated streams. After factoring out seasonal rainfall, low flows declined at 11 gauges (9 significantly), and increased at only two (1 significantly; these were the only gauges in the sample on glacier-fed streams). Since declines were prevalent on streams experiencing different levels of anthropogenic abstraction (zero to high), causal factors are implicated at the regional level. At least four candidate factors have been expected and/or observed: evapo-transpiration has increased and snowpack diminished due to increasing seasonal temperatures (also accounts for increasing low flows on glacier-fed streams); winter westerly wind speeds have declined, diminishing orographic rainfall enhancement; evapo-transpiration has increased due to forest growth following logging; and rainfall has intensified, increasing runoff at the expense of infiltration. Regardles of cause, results affirm that declining – not stabilizing – low flows should be our null expectation (reverse on streams that are glacier-fed), independently of rainfall, and of any effects of anthropogenic abstraction. One implication is that effects of abstraction will be harder to detect, but more important to understand and, where necessary, minimize or mitigate.*

Rationale: The *Summer Stream Flows* Vital Sign addresses concerns that low flows in some Puget Sound streams may be declining due to human activities. In 2011, 29 streams were selected as indicators for this Vital Sign, indexed by linear regressions of annual minimum 30-day mean streamflow on years since 1975 [*http://www.psp.wa.gov/vitalsigns/in-summer-low-flows.php*]. This indicator tracks net effects on low flows of all factors combined, including rainfall, which typically has the greatest effect. A drawback of this approach is that rainfall, and thus streamflow, in the Puget Sound region is influenced by cycles in sea surface temperature, including the Pacific Decadal Oscillation and El Nino Southern Oscillation. If variation due to rainfall is not accounted, flow trends will depend in part on when data series begin and end within these oscillating cycles, whether or not there is anthropogenic decline in low flows. We re-assessed trends in annual low flows for a sample of unregulated Puget Sound streams using a multiple regression approach that included, as independent variables, cumulative rainfall in seasons prior to annual low flows for each year (summer, spring, and winter+fall), as well as years in a given record. This allowed year-to-year variation in rainfall to be factored apart from trends in low flows over time.

Data: Series of daily flow estimates from 13 gauges on 9 unregulated streams in the Puget Sound region, the earliest beginning in 1915, were selected from a flow database featuring 580 streams provided by USGS (*https://waterdata.usgs.gov/nwis*). The annual low-flow statistic used in this analysis is the minimum 30-day mean streamflow value for each year. Low flow dates each year fell between August and October, but typically in September.

Daily rainfall data series were downloaded from online databases (mostly NOAA's Cooperative Observer Network: *https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/cooperative-observer-network-coop*), drawing from a list of stations in the Puget Sound region with long data series (supplied by Karin Bumbaco, Office of the Washington State Climatologist). Flow data for each gauge were matched with rainfall data from weather monitoring stations that were geographically close (up to 25 miles). While such data may provide only a biased estimate of rainfall (given that rain gauges were rarely located in focal catchments), the key assumption was made that any bias *does not change over time*. No analysis was found that quantifies spatial autocorrelation of rainfall in the Puget Sound region. However, that annual rainfall in the Willamette watershed is spatially autocorrelated – with distance as well as elevation – was quantified by Phillips et al. (1992) using semi-variograms. Estimates of semi-variogram 'range' (a term referring to the distance over which autocorrelation is detectable) varied between 40 and 53 miles. Assuming that weather patterns and processes in the Willamette watershed approximate those in the Puget Sound region (see MGS Consultants, Inc. 2002), data from distances separating rainfall and flow gauges in this analysis (<25 miles) should provide a valid, if biased, *index* of rainfall.

Models and analysis: Streamflow results from continuous input of water from several sources, but can be separated into 'fast-response' and 'slow-response' components. The fast-response component typically represents surface and shallow-subsurface runoff lasting up to a few weeks after recent rain or rapid snowmelt during warm periods. The slow-response component represents steady inputs to a steam from deeper groundwater flow, lakes, and sustained snowmelt (e.g., from permanent snowfields or glaciers). Thus, low flows in streams can be influenced by precipitation inputs over a range of time scales. Prior analysis of several streams had shown that annual 30-day low flows responded to different combinations of rainfall (R), summed over preceding intervals designed to approximate conditions in summer (0-90 days), spring (91-180 days), and fall + winter seasons (181-360 days) prior to low flows.

The model used was: $y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + e$

where:
y is annual minimum 30-day mean streamflow,
x_1 is year,
x_2 is rainfall summed (each year) over 90 days prior to date of low flow (summer),
x_3 is rainfall summed over 91 to 180 days prior to date of low flow (spring),
x_4 is rainfall summed over 181-360 days prior to date of low flow (winter+fall),
b_i are coefficients,
e is residual error.

To test for collinearity, Variance Inflation Factors (VIF) were calculated for all independent variables in models for all flow gauges using:

$$\boxed{VIF_j = \frac{S_{x_j}^2 (n-1) SE_{b_j}^2}{S^2}}$$

VIF values ranged between 1.02 and 2.28 (mean was 1.18) across all gauges and variables, indicating that collinearity was low (a conventional threshold for concern about collinearity is a VIF value of 4). Temporal autocorrelation was sought using Durbin-Watson statistics, but not detected.

Results: Results for each gauge (Table 1) show that model fits were acceptable for most gauges, with accounted variance ranging from 17% (Nisqually) to 70% (Cedar). Rain falling in all seasons positively affected low flows in all instances (cells shaded green), significantly so in 85% of cases (cells shaded dark green). Low flows declined with years at all but two gauges (cells shaded red), significantly so in 82% of cases (cells shaded dark red). On all streams with more than one gauge, rates of decline increased with distance downstream.

Gauge Name	**N**	**Mean Low Flow**	**R^2**	***Prob.***	**Model Coefficients**			
					Summer Rain	**Spring Rain**	**Winter+Fall Rain**	**Years**
Nisqually near National	72	8.98	0.17	1.37E-02	0.027	0.071	0.032	0.005
					4.58E-01	*7.37E-03*	*2.60E-02*	*7.06E-01*
Puyallup River near Orting	84	6.89	0.22	*4.42E-04*	0.171	0.162	0.095	0.021
					1.71E-02	*2.72E-03*	*1.43E-03*	*2.71E-02*
NF Stillaguamish near Arlington	87	7.61	0.42	*3.17E-09*	1.006	0.228	0.110	-0.025
					4.54E-08	*4.47E-02*	*1.62E-02*	*4.79E-02*
Issaquah Creek near mouth	52	0.61	0.70	*1.11E-11*	0.030	0.022	0.008	-0.008
					2.19E-04	*4.52E-06*	*1.23E-04*	*3.02E-08*
Deschutes River near Rainier	53	0.90	0.67	*5.12E-11*	0.047	0.038	0.006	-0.004
					3.51E-04	*2.33E-08*	*2.90E-03*	*3.26E-05*
Deschutes River near Tumwater	40	2.40	0.60	*4.05E-06*	0.137	0.108	0.026	-0.007
					5.83E-03	*3.75E-05*	*5.92E-04*	*1.71E-02*
North Fork Snoqualmie	71	2.40	0.55	*1.01E-10*	0.348	0.034	0.022	-0.005
					1.59E-11	*2.64E-01*	*8.34E-02*	*2.27E-01*
South Fork Snoqualmie	53	1.28	0.68	*3.14E-11*	0.148	0.032	0.008	-0.010
					3.18E-10	*1.03E-02*	*1.47E-01*	*2.99E-03*
Snoqualmie River near Carnation	85	22	0.42	*6.17E-09*	1.462	0.045	0.158	-0.110
					2.86E-09	*7.08E-01*	*1.31E-03*	*5.86E-03*
Snohomish near Monroe	47	44.92	0.60	*5.09E-08*	7.914	2.319	0.717	-0.268
					5.81E-08	*4.59E-03*	*3.52E-02*	*8.72E-02*
Cedar River above Chester Morse Dam	70	1.12	0.70	*2.26E-16*	0.084	0.012	0.005	-0.004
					5.82E-15	*6.94E-03*	*2.26E-02*	*4.45E-03*
Soos Creek	49	29.40	0.52	*1.40E-06*	1.533	1.193	0.119	-0.119
					2.46E-03	*5.53E-07*	*2.23E-01*	*1.10E-02*
Newaukum Creek	62	16.30	0.52	*8.19E-09*	0.722	0.772	0.171	-0.080
					1.08E-03	*7.21E-07*	*5.36E-04*	*6.45E-05*

Table 1. Results of GLM analysis, showing, for each gauge, model fits, and values of model coefficients (with P-values given below each coefficient in italics). Green denotes a positive effect on low flows, and red a negative effect. Darker shades denote significance at alpha=0.05).

Discussion: Rainfall trends can and do dominate trends in low flows, sometimes in one direction – increasing or declining – for decades (data not shown). It is perhaps no coincidence that a) concern about declining low flows grew during a period when the trend in rainfall was declining (1990s through 2000s, data not shown), and b) the Summer Stream Flows indicator recently showed an improving trend (PSP 2017 State of the Sound report), now that the rainfall trend is increasing again. Multiple regression permitted trends in low flows to be assessed independently of variation in rainfall. Results showed that flows at 9 of 13 gauges declined over time, and increased significantly at only one, due to factors *other* than total seasonal rainfall.

Such factors can be global, regional, or local, and their effects must be separated before management options can be assessed, and remedial measures designed. While such factors cannot be definitively identified by this analysis, in some cases they can be ruled out. Among gauges at which low flows declined were two (Cedar and SF Snoqualmie) located *above* the zone where abstraction (say by exempt wells) could influence low flows. Thus, low flows declined consistently among widespread streams experiencing widely differing levels of anthropogenic abstraction (Soos Creek provides a candidate example for high levels of abstraction from exempt wells). These patterns suggest that abstraction is not the only factor causing low flows to decline, and implicate at least one regional factor.

Accounts of at least four candidate regional factors have been published. In the lowlands of the Puget Sound region, where most of the rain gauges are located, total rainfall has not declined significantly over the last century (CIG in the Puget Sound Fact Book). But rainfall may have diminished in the highlands. Luce et al. (2013) posited that “declining lower-tropospheric winter westerlies across the region from 1950 to 2012 … have reduced orographic precipitation enhancement, yielding differential trends in precipitation across elevations and contributing to the decline in annual streamflow”. This would yield the pattern observed in this analysis, namely, declining low flows per unit of rainfall measured at *lower* elevations.

Another candidate factor that would contribute to observed patterns is temperature, which has increased in the Pacific Northwest by about 1.3°F over the last century, with statistically-significant warming occurring in all seasons except spring (Kunkel et al., 2013; Mote et al., 2013, also Johnstone and Mantua 2014). This would have manifold effects that would diminish low flows, for example, by increasing evapotranspiration, and decreasing snowpack (Mote et al. 2018). The same factor could cause low flows in glacier-fed streams to *increase*. It may therefore be no coincidence that the only gauges in this sample at which low flows did not decline were also the only gauges on glacier-fed streams (Nisqually and Puyallup).

A third candidate factor potentially causing low flows to decline is vegetation growth, via rainfall interception, evaporation, and transpiration. Using paired basin studies, Perry and Jones (2016) found that summer flows in 33-43 year old plantation forest were half that of reference old-growth forest. Series of remotely sensed images in Google Earth Pro revealed that catchments for many of the gauges featured in this analysis were logged shortly before the first available image (1984 in most cases), with little logging since.

A final factor is rainfall intensity, which is expected to increase with climate warming (CIG in the Puget Sound Fact Book), and probably has increased in recent decades. This would contribute to low flow declines if runoff increases at the expense of infiltration. All of these factors would contribute to the patterns observed in this analysis, namely, declining low flows per unit of rainfall.

Implications: The results of this analysis are not conclusive, and independent corroboration is warranted on a larger sample of streams. But they are consistent with the hypothesis that low flows are declining regionally, *independently of* variation in rainfall due to climate oscillations, and *in addition to* any local effects caused by anthropogenic abstractions. Given multiple mechanisms adversely affecting low flows, we should expect low flows to be declining in non-glacial rivers, even if they are not impacted by water abstraction.

One corollary of this expectation is that local anthropogenic effects on low flows (e.g. due to abstraction by exempt wells) will be that much harder to detect. Another is that we should expect (net) low flows to improve and decline as ocean temperatures and rainfall oscillate. However, improvements will be less marked, and declines will be greater, if these regional factors and anthropogenic abstractions intensify. The better we understand these factors and their interactions, the more any remedial strategies and actions are likely to succeed.

Review and revision of the SSF indicator is warranted, such that seasonal variation in rainfall is factored separately. Such an approach is limited by available rainfall data, but this could conceivably be resolved with spatically explicit interpolation and simulation models based on historical data.

Acknowledgments: This report was much improved by feedback from Tom Culhane, Curtis DeGasperi, Chris Konrad, and Bob McKane.

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