# Declining annual streamflow distributions in the Pacific Northwest United States, 1948–2006

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[1] Much of the discussion on climate change and water in the western United States centers on decreased snowpack and earlier spring runoff. Although increasing variability in annual flows has been noted, the nature of those changes is largely unexplored. We tested for trends in the distribution of annual runoff using quantile regression at 43 gages in the Pacific Northwest. Seventy-two percent of the stations showed significant ($\alpha = 0.10$) declines in the 25th percentile annual flow, with half of the stations exceeding a 29% decline and a maximum decline of 47% between 1948 and 2006. Fewer stations showed statistically significant declines in either median or mean annual flow, and only five had a significant change in the 75th percentile, demonstrating that increases in variance result primarily from a trend of increasing dryness in dry years. The asymmetric trends in streamflow distributions have implications for water management and ecology well beyond those of shifted timing alone, affect both rain and snow-dominated watersheds, and contribute to earlier timing trends in high-elevation watersheds. **Citation:** Luce, C. H., and Z. A. Holden (2009), Declining annual streamflow distributions in the Pacific Northwest United States, 1948–2006, *Geophys. Res. Lett.*, *36*, L16401, doi:10.1029/2009GL039407.

## 1. Introduction

[2] The changing climate and water cycle of the Western U.S. are impacting water resources and ecology [*Barnett et al.*, 2008; *van Mantgem et al.*, 2009; *Westerling et al.*, 2006]. Very few locations show trends in mean annual runoff, but widespread changes in spring snowpack, streamflow timing, and interannual coefficient of variation have been noted [*Hamlet and Lettenmaier*, 2007; *Jain et al.*, 2005; *Mote et al.*, 2005; *Pagano and Garen*, 2005; *Regonda et al.*, 2005; *Stewart et al.*, 2005]. The nonstationarity in variability is potentially more important than a trend in the mean, with consequences for both ecology and water resources [*Milly et al.*, 2008]. While the specific implications of increased variability in the annual water budget have been explored for peak flows [*Hamlet and Lettenmaier*, 2007], little has been done to explore how widespread or severe annual dry spells might be. While increased drought persistence is important for water managers [*Jain et al.*, 2005; *Pagano and Garen*, 2005], individual dry years test most of the water supply infrastructure in the west. Similarly forest and stream ecosystems are vulnerable to individual dry years, and some of the ecological changes that have been ascribed to earlier

snowmelt and runoff and warmer temperatures, such as increased wildfire occurrence and spread or drought-related mortality, could also result from more frequent years of given dryness or an increasing severity of dry years. Furthermore, under certain circumstances, trends in extremes of precipitation can contribute to trends in flow timing, even in the absence of statistically significant trends in the mean because of non-linear relationships between snow accumulation and snowmelt timing.

## 2. Methods

[3] We examined changes to the distribution of annual streamflow from 43 Hydroclimatic Data Network (HCDN) gages [*Slack et al.*, 1993] in the Pacific Northwest of the United States between 1948 and 2006 using both least squares and quantile regression [*Koenker and Hallock*, 2001]. As implied by its name, least-square regression is defined as a minimization problem. If we estimate the expected value of a response variable $y$ conditioned on predictors, $X$, with a linear function,

$$E[y|X] = \beta X + \varepsilon \qquad (1)$$

the $\beta$'s satisfy the minimization of the summed error function,

$$\min \sum_i \xi(y_i - \beta X_i) \qquad (2)$$

$$\text{where } \xi(u) = u^2 \qquad (3)$$

Similarly, linear quantile regression finds the $\tau$th quantile ($\tau \in [0, 1]$) of y conditioned on x

$$Q_\tau[y|X] = \beta X + \varepsilon \qquad (4)$$

where the $\beta$'s again satisfy equation (2), but equation (3) is replaced with a $\tau$-dependent

$$\xi_\tau(u) = \begin{cases} u\tau & u \geq 0 \\ u(\tau - 1) & u < 0 \end{cases} \qquad (5)$$

which looks like an absolute value function, symmetric for $\tau = 0.5$, rotated to the right for $\tau < 0.5$ and left for $\tau > 0.5$. While the $\beta$'s for least square regression can be found analytically, in quantile regression, linear programming can be used to numerically find the minimum. In least-square regression, a single relationship, the conditional mean, is sought, whereas in quantile regression there may be an interest in many quantiles to describe trends in a distribution.

[1]US Forest Service, Boise, Idaho, USA.
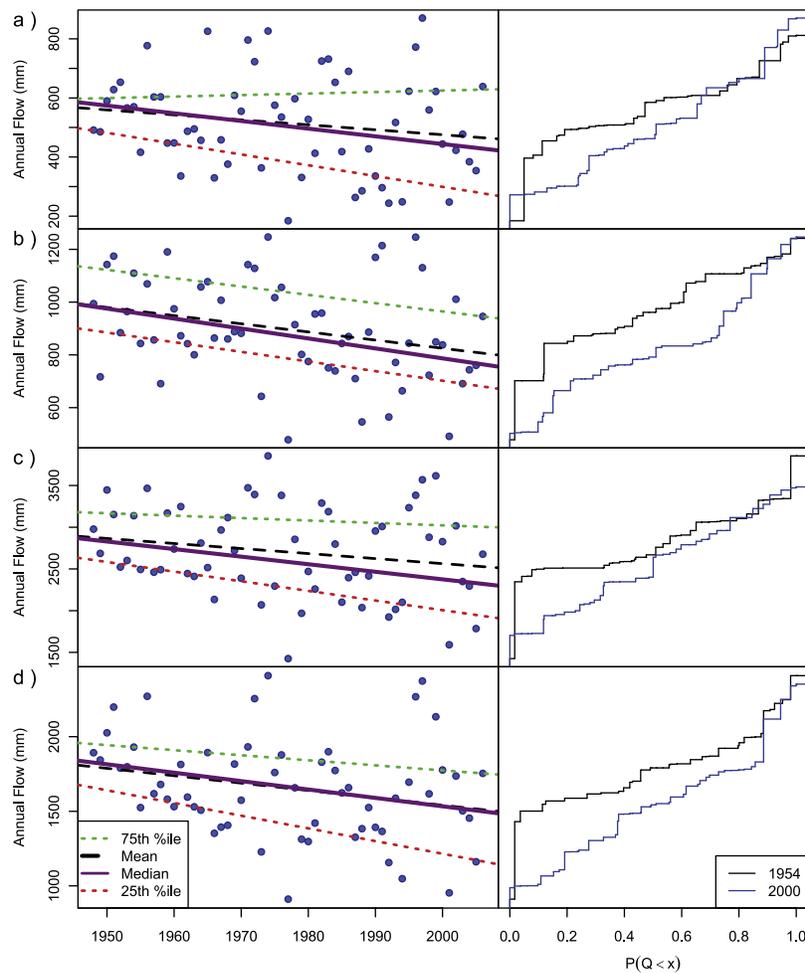[2]US Forest Service, Missoula, Montana, USA.

**Figure 1.** Example scatterplots with trends on left (top line 75th percentile, bottom line 25th percentile, conditional median and mean in center) and shifts in cumulative distribution between 1954 and 2000 on right for four stations scattered over the region (a) Boise R nr Twin Springs, ID (13185000), (b) MF Flathead R nr West Glacier, MT (12358500), (c) Naselle River nr Naselle, WA (1201000), and (d) N Santiam R blw Boulder Cr nr Detroit, OR (14178000).

[4] We analyzed linear trends in the mean and 25th, 50th, and 75th percentile annual flows to quantify changes to the distribution of annual flow. Some example trends geographically scattered across the region illustrate the nature of the analysis (Figure 1), showing both trends in measures of the distribution and a shift in the center of the distribution. Our analysis should not be confused with those of *Lins and Slack* [2005] and *Bowling et al.* [2000], who explored changes in percentiles of daily flow sampled annually. For example, their trend in 25th percentile flows is a least-square regression of the flow that is exceeded 273 days in a given year.

[5] We focused our analysis on the Pacific Northwest (PNW) because it shows the strongest changes in streamflow timing, snowpack accumulation, and fire occurrence [*Mote et al.*, 2005; *Regonda et al.*, 2005; *Stewart et al.*, 2005; *Westerling et al.*, 2006] while also showing some of the strongest contrasts in drivers of timing and accumulation changes [*Moore et al.*, 2007; *Mote et al.*, 2005; *Regonda et al.*, 2005; *Stewart et al.*, 2005]. In addition, it has a higher density of gages than the rest of the western U.S. [*Pagano and Garen*, 2005]. Table S1 of the auxiliary material provides the name, location, basin size, and average runoff for

each station.[1] Average annual runoff ranges from 3900 mm on the Olympic Peninsula to 49 mm in southern Idaho (Figure S1).

[6] We used 1948 for a starting date to be consistent with related papers [*Mote et al.*, 2005; *Regonda et al.*, 2005; *Stewart et al.*, 2005] and because there was little gain in the number of stations for using slightly shorter records and some loss in stations when using a longer record. Those authors have noted a trend in the Pacific decadal oscillation (PDO) [*Mantua et al.*, 1997] over this period, which affects Pacific Northwest precipitation. In addition, interannual variability of Pacific Northwest streamflow is tied to the El Niño Southern Oscillation (ENSO) [*Redmond and Koch*, 1991]. We briefly examined quantile regression models using indices of PDO and ENSO as predictors to clarify their contribution to trends by calculating the Akaike information criterion (AIC) [*Burnham and Anderson*, 2002] weights at each station to compare the 7 potential combinations of the 3 predictors. The ENSO time series that we used was the

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL039407.
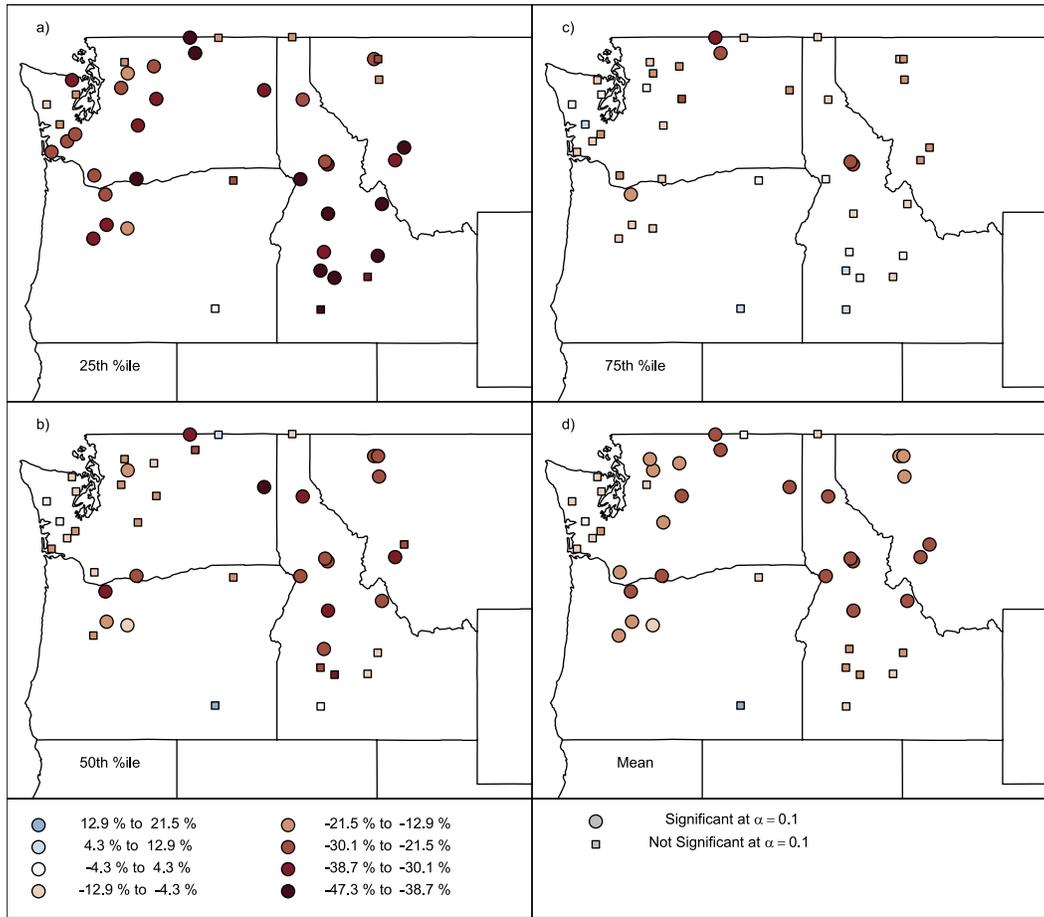
**Figure 2.** Maps of changes to (a) 25th percentile annual flow, (b) 50th percentile annual flow, (c) 75th percentile annual flow, and (d) mean annual flow across HCDN stations in the Pacific Northwest 1948–2006.

difference in Pacific sea surface temperatures (SST) between south and north of 20°N latitude (downloaded from http://jisao.washington.edu/data_sets/globalsstenso/). The PDO time series is the leading EOF of November-March Pacific SST anomalies north of 20°N (downloaded from http://jisao.washington.edu/data_sets/pdo/). Both monthly time series were averaged over the water year to provide annual values.

[7] Because of the potential to find significant correlations by chance when testing trends at multiple stations, we checked for significance of obtaining a given fraction of significant results, $f$, and our significance criterion ($\alpha = 0.10$) by testing against a binomial distribution [*Livezey and Chen*, 1983]. The significance of each kind of regression for the region is given by

$$P = 1 - \sum_{i=0}^{\lfloor n_{ef} f \rfloor} \binom{\lfloor n_{ef} \rfloor}{i} \alpha^i (1-\alpha)^{\lfloor n_{ef} \rfloor - i} \qquad (6)$$

Although $n = 43$ stations were sampled, the effective degrees of freedom represented by $n_{ef}$ in equation (6) are expected to be lower because of correlation in annual flow between stations. We estimated the effective number of stations in two ways. From the covariance matrix of

streamflows, $\mathbf{C}$, $n_{ef}$ can be estimated as [*Bretherton et al.*, 1999]

$$n_{ef} = \frac{\left( \sum_{i=1}^{n} C_{ii} \right)^2}{\sum_{i,j=1}^{n} C_{ij}^2} \qquad (7)$$

It can also be estimated as the number of leading principal components needed to explain approximately 86% of the variance [*Bretherton et al.*, 1999].

[8] Although we analyzed trends in annual flows here, summer low flows are a common related interest, particularly with respect to changes in dry years. To support limited inferences regarding low flows, we also estimated the linear correlations between the total annual flow and total flow from 15 July to 15 September of each water year.

## 3. Results

[9] The most spatially consistent significant trend is a decrease in the 25th percentile flow (Figure 2a) with 72% of the stations (31) showing significance on a two-tailed t-test at $\alpha = 0.10$ (Table S2). The effective number of stations from equation (7) is 3.26, and 4 principal components explained

87% of the variance. Using $n_{ef} = 3.26$ in equation (6) yielded $P = 0.001$; so the large number of significant stations is not by chance. The interpretation is that the driest 25% of years are getting drier across the majority of the PNW. The change is substantial, with most streams showing decreases exceeding 29% and some showing decreases approaching 50% between 1948 and 2006.

[10] In stark contrast, changes to the 75th percentile flow are mostly non-significant, with a slight trend in sign from negative in the north to positive in the south (Figure 2c). Where the 75th percentile trends negative with the 25th percentile, changes in variance are less likely to be significant if one compares to *Pagano and Garen* [2005]. Much of the previously reported increase in variance [*Hamlet and Lettenmaier*, 2007; *Jain et al.*, 2005] seems to result from a decrease in the lowest annual flows. Regionally, the significance of the trend is $P = 0.27$.

[11] Mean and median streamflows show decreases with patterns similar to one another, but are less consistently statistically significant and are smaller in magnitude than changes to the lowest quartile expressed as percentage (Figure 2). Considering the increasing spread in the data, the significance of the trend in the mean may be underestimated. Trends in the mean are more likely to be statistically significant where the 75th percentile shows negative trends. Regionally, $P = 0.028$ for both mean and median.

[12] ENSO, PDO, and Year all showed a degree of correlation (ENSO-PDO: R = 0.72 P < 0.001; ENSO-Yr: R = 0.37 P = 0.004; PDO-Yr: R = 0.54 P < 0.001) although the variance inflation factors (ENSO, 2.1; PDO, 2.5; and Year, 1.4) do not rule out a model using all three. Of the 7 models evaluated, the model regressing the 25th percentile annual flow on Year and ENSO was almost twice as likely (avg. $w_{aic} = 0.27$) as the next best model (Table S3), which was the one using all three predictors (avg. $w_{aic} = 0.15$), suggesting that the strength of the ENSO-PDO correlation essentially causes the 3-predictor model to be overfit. This can be interpreted to say that a model with time as a trend and ENSO describing interannual-scale variability more commonly provides better prediction of the 25th percentile annual flow than one using PDO. Slopes in the ENSO+Yr model were all negative for significant relationships, consistent with physical expectations.

[13] Correlations between total annual and summer (15 Jul–15 Sep) flows were highly significant ($P < 0.001$) in 37 out of 43 basins; one other was still significant ($P = 0.025$) though not as strongly (Table S2). The remaining 5 stations, all located in southwestern Washington State, did not have significant correlations ($\alpha = 0.10$). These five stations are predominantly rain-fed, and the local seasonality of flows may not be well captured by these simple metrics. All stations showed a positive correlation, and the median $R^2$ of stations with a significant correlation was 0.61.

## 4. Discussion

[14] It has been argued that shifts in snowpack accumulation and timing caused by temperature changes are among the most important changes occurring in the hydrologic cycle of the Western United States [*Barnett et al.*, 2008].

The substantial magnitude of the decreased streamflow of dry years illustrated here suggests that changes in the water budget may be important as well. Like others [*Regonda et al.*, 2005; *Stewart et al.*, 2005], we saw scattered significance in trends in the mean and median of the distribution, although here we note that even 40–50% of the stations having significant changes represents a significant fraction of the region showing a trend in the center part of the distribution.

[15] Water allocation will become increasingly difficult with increasingly low annual streamflows. A broader spread in the distribution emphasizing changes in lower quartile translates into greater uncertainty for water users and supply system operators. Most irrigation supply systems have less than a year of storage, and a very few have multi-year storage capacity. With dry years becoming drier, more users will be affected, and users who have rarely been limited before may be asked to stop withdrawing water more frequently. The strong correlations between annual and summer flows over most of the region suggest that diversions on streams without upstream storage will face more severe shortages as well, and more users of such systems will be cut off earlier in the summer.

[16] Storage design will be affected as well. Shifts in snowmelt timing and earlier streamflows recommend adding storage to systems with less than one year of storage, to make up for lost seasonal scale storage in snowpacks. Where the mean streamflow is declining significantly, there are some obvious concerns about the ability to fill multi-year storage. Where the 25th percentile trends downward, there may also be a decreasing probability of filling sub-annual scale storage each year, depending on current storage and operational constraints. A lack of statistical significance in mean flow trends does not indicate stationarity in the rest of the distribution. In general, changes to the dry end of the distribution of annual flows have been greater than those of the mean, and these changes are important to consider when estimating the potential benefits of increased storage.

[17] Trends in the distribution of annual flow can affect streamflow timing as well. In high elevation basins, solar radiation is a primary driver of melt [*Cline*, 1997]. Over the course of the snowmelt season, sun angles increase sinusoidally until June 21st. For simplicity, consider a simple linear model of increasing snowmelt rate, $dW/dt$, with time t. With an initial condition that the melt rate at peak accumulation, t = 0, is 0,

$$\frac{dW}{dt} = kt \tag{8}$$

For maximum accumulation, $W_{mx}$, the timing of the center of mass of snowmelt, $t_c$, will be reached when

$$\frac{W_{mx}}{2} = k \int_0^{t_c} t \, dt \tag{9}$$

with solution

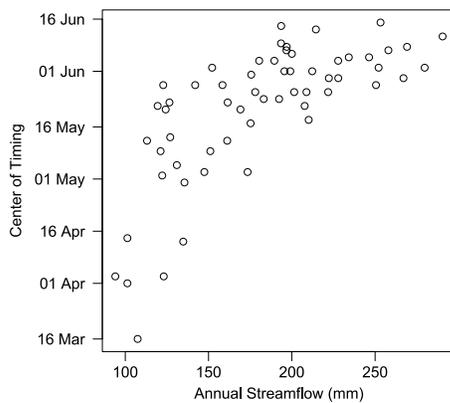$$t_c = \sqrt{\frac{W_{mx}}{k}} \tag{10}$$

**Figure 3.** Relationship between total annual flow and the timing of the center of mass for that year's flow for Salmon River at Salmon, ID (13302500).

This provides the theoretical basis for expectation of a concave-downward empirical relationship between total annual flow and the center of mass of flow in high elevation basins (e.g., Figure 3). Applying a square-root transformation to annual flow trends emphasizes departures below the mean in comparison to departures above the mean, increasing the significance of negative trends. Several high elevation basins in the eastern half of the region exhibit relationships like Figure 3, which may contribute to trends in timing absent strong temperature contributions to interannual snowpack variability [see e.g., *Mote et al.*, 2005, Figure 4].

[18] Implications of decreasing flows for aquatic ecology are fairly direct, as reductions in flow directly translate to the quantity and quality of habitat for aquatic species, and represent an increasingly frequent and severe loss of summer habitat [*Sabo and Post*, 2008]. Flow reductions will decrease available living space for aquatic organisms and may also reduce stream productivity by decreasing terrestrial interactions and throughputs of materials [*Harvey et al.*, 2006]. At the upper extent of perennial flow in headwaters, habitat may be eliminated entirely, which would have disproportionate effects because a greater proportion of length is in lower order streams. Studies on the effects of climate change on fish populations have focused primarily on stream temperature, and already project substantial decreases in habitat using only air temperature relationships [*Rieman et al.*, 2007]. Flow exerts a strong control on stream temperature, and flow reductions will likely exacerbate stream temperature increases caused by increased incoming long-wave and sensible heat.

[19] Terrestrial ecology would also be affected by a changing water balance distribution. Increased fire occurrence, increased forest mortality, and decreased growth trends have been noted [*Littell et al.*, 2008; *van Mantgem et al.*, 2009; *Morgan et al.*, 2008; *Westerling et al.*, 2006], and the fact that dry years are becoming drier is likely an important contributor, but based on lack of significance in trends of the mean being reported in the climatology literature, changes to the water balance have not been explored as a mechanism. Water availability during dry years exerts strong selective pressures in terrestrial ecosystems, and forests established in one climatic regime become stressed as significantly drier conditions begin to occur on a relatively frequent basis. Although we only analyzed stream-

flow, tree ring growth is commonly used to develop proxy records for streamflow [e.g., *Woodhouse et al.*, 2006], indicating correlation between moisture available to trees and streamflow.

[20] Trends in SST patterns that cycle naturally and, mechanistically, cause precipitation variations over this region would seemingly preclude inference about future trends with reference to monotonic climate changes. However, objective model selection favors a model combining a temporal trend with interannual-scale variability (ENSO) over models using the trending PDO. More sophisticated analyses considering other indices, temporal lags, and temporal autocorrelation of indices would likely elucidate more information and provide greater certainty, but this rough analysis presents interesting insights.

## 5. Summary

[21] Trends in the lower part of the distribution of annual streamflow in Pacific Northwest streams show strong and significant declines at a large majority of gauging stations. The driest 25% of years are becoming substantially drier. Reliance on tests of trends in the mean alone has promoted a view that only shifts in flow timing caused by temperature increases are occurring in snow dominated watersheds. This view could result in management adaptations that are locally inappropriate and may also lead to misinterpretation of ecological process. Because many aspects of managed and natural systems operate without impairment within some range of the mean, trends in less central parts of the distribution may be more important than trends in the mean. The decreasing trends in the lowest quartile, in particular, represent increasing challenges for land and water managers who must cope with water scarcity and its ecological consequences on more frequent and acute basis. Although some details of outcomes of the observed trend have been discussed here, more work will be necessary to clarify causality, impacts on low streamflows, ecological changes, and ties to flow timing.

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