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Travis Shoemaker
Schnabel Engineering, tshoemaker@schnable-eng.com

Madhav Bista
IHE Delft Institute for Water Education, madhavbista.1@gmail.com

David Brandes
Lafayette College

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STREAMFLOW REGIME CHANGE IN THE DELAWARE RIVER BASIN

Travis SHOEMAKER
Schnabel Engineering, USA, tshoemaker@schnabel-eng.com
Madhav BISTA
M.Sc. Environmental Technology & Engineering, IHE Delft Institute for Water Education, Netherlands, madhavbista.1@gmail.com
David BRANDES, PhD
Lafayette College, Civil and Environmental Engineering Dept., USA

Abstract: The combined impacts of hydroclimatic change and land development are widely expected to increase the frequency and magnitude of flooding in the northeast United States, with potential implications to floodplain infrastructure and mapping, hydraulic structures, land management, and flood losses. Additionally, shifting flow regimes pose a challenge for engineers and regulators of stormwater management, dams, and levees because design storms are commonly based on historical data, with the stationarity assumption that the future flow regime will mimic the past. Here, we examine selected long-term (40 to 114 years of data) streamflow records from watersheds of varying size in the upper Delaware River basin to assess changes in streamflow regimes. A structural breakpoint analysis of the streamflow records indicated a break in time-series around the year 2000. Hypothesis testing comparing pre- and post-2000 streamflow metrics (annual peak, median, and 7-day low flows) confirmed a statistically significant shift around the year 2000. For example, median flows across the two time periods were statistically different with over 90% confidence for 14 of 28 gauges considered.

Keywords: Delaware River Basin, streamflow, regime change, hypothesis testing

INTRODUCTION

The combined impacts of hydroclimatic change and land development are widely expected to increase the frequency and magnitude of flooding in the northeast United States, with potential implications to floodplain infrastructure and mapping, hydraulic structures, land management, and flood losses (ASCE, 2015; USGCRP, 2014; EASTERLING et al., 2017). Additionally, shifting flow regimes pose a challenge for engineers and regulators of stormwater management, wastewater management, dams, and levees because design storms are commonly based on historical data. For example, NOAA Atlas 14 precipitation volumes, which are frequently used for peak flow design of storm-water management and dam and levees, are based on a stationary annual maximum series, assuming historical data represent present and future conditions. Additionally, low flows statistical methods, such as the Q7-10 statistic which is commonly used for wastewater effluent regulation, also assumes stationarity, or

"the idea that natural systems fluctuate within an unchanging envelope of variability" (MILLY et al., 2008).

With these approaches to water resources engineering and infrastructure management, uncertainty in hydrologic and hydraulic modelling decreases as time progresses because more observations are made each year. However, there have been numerous studies indicating that changes in land use and climate may invalidate the stationarity assumption for practical purposes. For example, MILLY et al. (2008) and WAGENER et al. (2010) assert that water-resource risk assessment and planning can no longer entertain stationarity as a default assumption because of anthropogenic disturbances in a river basin. IPPC (2007) and LALL et al. (2018) indicate that anthropogenic climate change alters means and extremes of precipitation, evapotranspiration, and rates of river discharges that should be taken into account to examine frequency of floods. Hence, models need to incorporate anticipated changes in flood risk due to both watershed change (e.g., land-use) and climate change (STEDINGER and GRIFFIS, 2011).

Here, we provide an assessment of streamflow regime change by examining selected long-term streamflow records from watersheds of varying size in the upper Delaware River Basin. This basin was selected as it is close to the urban centers of the northeast and has reportedly experienced an increase in precipitation over the past 60 years which may result in a corresponding increase in streamflow (USGCRP, 2009; KUNKEL et al., 2013; USGCRP, 2014). This study uses the most recent published streamflow datasets. Unlike land use change mapping and rain gauge data, stream gauge data directly considers the primary design, management, and regulation criteria: flow. Additionally, the streamflow gauges studied here are generally more spatially distributed and represent a longer history than land use maps and rain gauges. The assessment of streamflow regime change provided here will (1) statistically assess stream flow regime change in the upper Delaware Watershed and (2) stand as a case study of the validity of the stationarity assumption.

METHODOLOGY

This assessment of the probability of streamflow change in the upper Delaware River Basin involved the following steps:

- Select long term stream gauges
- Calculate annual statistics for each gauge
- Perform structural breakpoint analyses in time-series for each gauge
- Perform hypothesis testing for average flow change in pre- and post-breakpoint datasets

Each step of the process is explained in greater detail below.

<u>Selection of stream gauges</u>

Stream gauges were selected to (1) obtain full spatial coverage of the river basin, (2) obtain long continuous temporal coverage, (3) exclude the impacts of flow regulation, and (4) include sub-basins

undergoing urbanization. Although the specific numerical selection for some criteria, such as 10-km outside of the watershed, were chosen arbitrarily, all criteria were applied uniformly to all gauges. The following list of criteria was used for selecting stream gauges:

- Minimum of 40 years of data
- No data gaps greater than 1 year
- Gauge in operation until 2016 or later
- Within a 10-km buffer of the upper watershed
- Not more than 50 missing days of data per year used in the analysis
- Hydrologic Disturbance Index not greater than 20
- Density of major upstream dams not greater than 1.2 per 100 km^2

For this work, the upper Delaware watershed has been defined as the basin contributing to the Delaware River at Riegelsville, Pennsylvania. Riegelsville was chosen as the cut off between the upper and lower watershed as a balance between including major upstream tributaries, such as the confluence of the Lehigh and Delaware rivers 7-miles upstream of Riegelsville, and excluding the tidal effects of the Delaware Bay which extend to Trenton, New Jersey, approximately 35 miles downstream of Riegelsville. The watershed was delineated using USGS's StreamStats (Ver 3) application and was cross checked against an ArcMap produced delineation using 30-meter USGS quadrangle digital elevation models (DEMs). A 10-km buffer around the upper watershed was taken as the study bounds. This definition allows for inclusion of additional gauges in the most upper sub-basins of bordering watersheds, which may have similar hydrologic properties to the Delaware Watershed.

A key limitation of stream gauge data when studying hydroclimatic change and land development effects is the effect of direct streamflow regulation. This includes releases, diversions, and storages from dams, levees, mining operations, power plants, water treatment plants, wastewater treatment plants, etc. Therefore, limits on Hydrologic Disturbance Index (HDI) as defined by FALCONE et al. (2010) and density of major upstream dams have been set. The upper Delaware Watershed is an opportune basin to perform this study because the Delaware River is the longest free-flowing river in the Eastern United States; however, it must be recognized that there is some level of flow regulation within the watershed.

Figure 1 provides a map of the total 28 selected stream gauges, the study limits, and relevant dams. Table 1 provides a list of the selected gauges with relevant watershed data. For the selected gauges, the average HDI and density of major upstream dams were 14 and 0.1 per 100 km^2. The watershed area ranged from 29 km^2 to 850 km^2 with an average of 250 km^2.

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Fig. 1 – Map of Selected Gauges

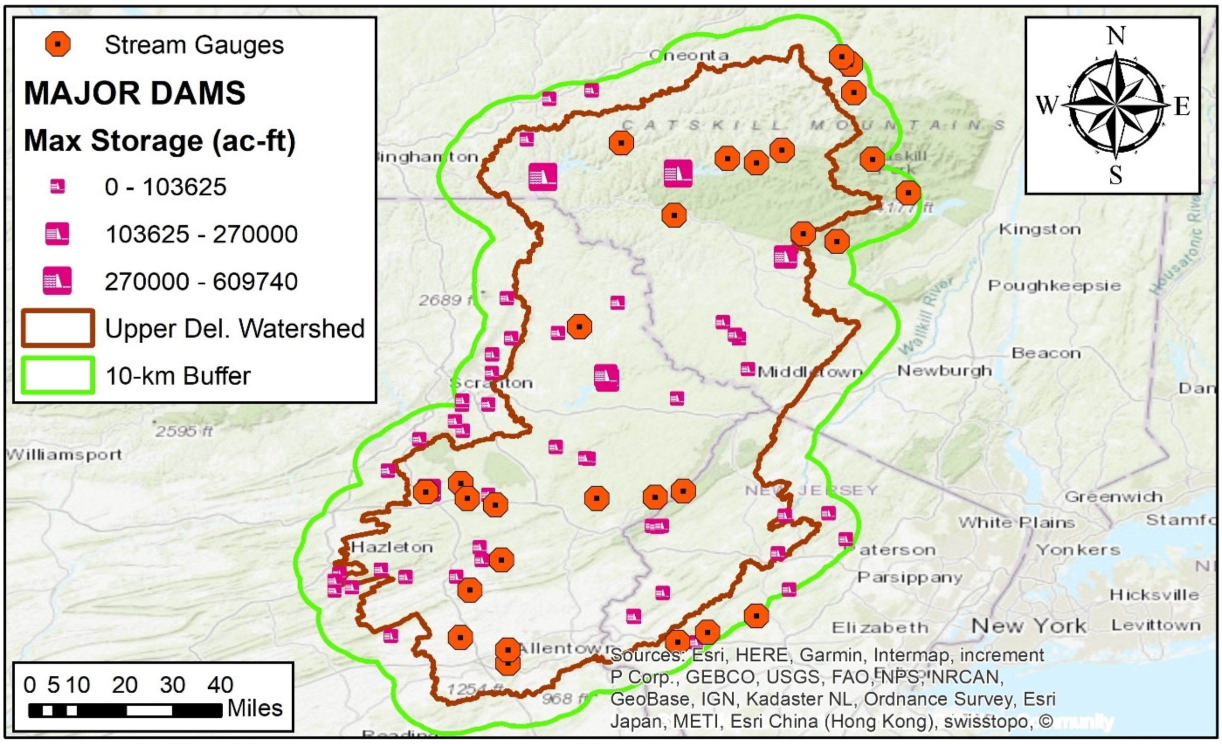

Table 1 – Selected Gauges and Relevant Watershed Data

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Station ID	Station Name	Watershed Area (km^2)	Hydrologic Disturbance Index (HDI)	Major Dam Density (Number per 100 km^2)	Starting Water Year	Ending Water Year	Watershed 2006 % Impervious
01350000	Schoharie Creek At Prattsville, NY	613	17	0.49	1904	2017	0.3%
01350120	Platter Kill At Gilboa, NY	29	12	0.00	1976	2016	0.3%
01350140	Mine Kill Near North Blenheim, NY	44	15	0.00	1976	2017	0.2%
01362200	Esopus Creek At Allaben, NY	169	15	0.00	1964	2016	0.2%
01362500	Esopus Creek At Coldbrook, NY	493	13	0.00	1932	2017	0.2%
01365000	Rondout Creek Near Lowes Corners, NY	100	8	0.00	1938	2016	0.0%
01396500	South Branch Raritan River Near High Bridge, NJ	163	15	0.00	1919	2017	3.2%
01396660	Mulhockaway Creek At Van Syckel, NJ	30	14	0.00	1978	2017	2.7%
01399500	Lamington (Black) River Near Pottersville, NJ	83	17	0.00	1922	2017	4.1%
01413500	East Br Delaware R At Margaretville, NY	424	11	0.00	1938	2017	0.2%
01414500	Mill Brook Near Dunraven, NY	64	9	0.00	1938	2017	0.0%
01415000	Tremper Kill Near Andes, NY	86	15	0.00	1938	2017	0.2%
01420500	Beaver Kill At Cooks Falls, NY	627	19	0.00	1914	2016	0.2%
01423000	West Branch Delaware River At Walton, NY	860	16	0.00	1951	2017	0.4%
01429500	Dyberry Creek Near Honesdale, PA	167	17	0.60	1944	2017	0.3%
01435000	Neversink River Near Claryville, NY	172	13	0.00	1939	2016	0.0%
01439500	Bush Kill At Shoemakers, PA	306	9	0.00	1909	2017	0.3%
01440000	Flat Brook Near Flatbrookville, NJ	168	11	0.00	1924	2017	0.2%
01440400	Brodhead Creek Near Analomink, PA	175	17	1.14	1958	2017	0.4%
01447500	Lehigh River At Stoddartsville, PA	240	13	0.00	1944	2017	0.5%
01447680	Tunkhannock Creek Near Long Pond, PA	52	9	0.00	1966	2017	0.6%
01447720	Tobyhanna Creek Near Blakeslee, PA	308	18	0.32	1962	2017	1.9%
01447800	Lehigh R Bl Francis E Walter Res Nr White Haven, PA	753	18	0.27	1958	2017	1.0%
01449360	Pohopoco Creek At Kresgeville, PA	129	14	0.00	1967	2017	2.5%
01450500	Aquashicola Creek At Palmerton, PA	198	20	0.00	1940	2017	1.7%
01451500	Little Lehigh Creek Near Allentown, PA	212	15	0.00	1946	2017	10.1%
01451800	Jordan Creek Near Schnecksville, PA	136	14	0.00	1967	2017	1.7%
01452000	Jordan Creek At Allentown, PA	197	20	0.00	1945	2017	3.8%

Calculate annual statistics

Peak annual, median annual, and 7-day low annual flows were selected to represent the entire streamflow regime: high to low flows. Median and 7-day low flows were calculated from USGS historical surface water daily reported flows. 7-day low flow was defined as the lowest average flow in a 7-day period for a given water year. Daily data disrupted by ice flows were excluded from the analysis and included in the missing days requirement. Peak annual flows were taken directly from the USGS database and represent the maximum flow recorded for each water year.

Structural breakpoint analysis

The statistical programming and computing language R (Version 3.4.1) and the package “strucchange” were used to perform Bai-Perron (BP) tests to detect structural breaks and choose a particular year in a time-series to allow for the comparison of pre and post breakpoint flow statistics. For each gauge, all flow types (7-day low, median, peak) were analyzed individually as well as combined. As criteria for performing BP tests, the following two main assumptions about time-series were made:

1. Independent and identically distributed data: Because the time-series is composed of annual flow data, we can assume non-dependence and same probability distribution of the values.

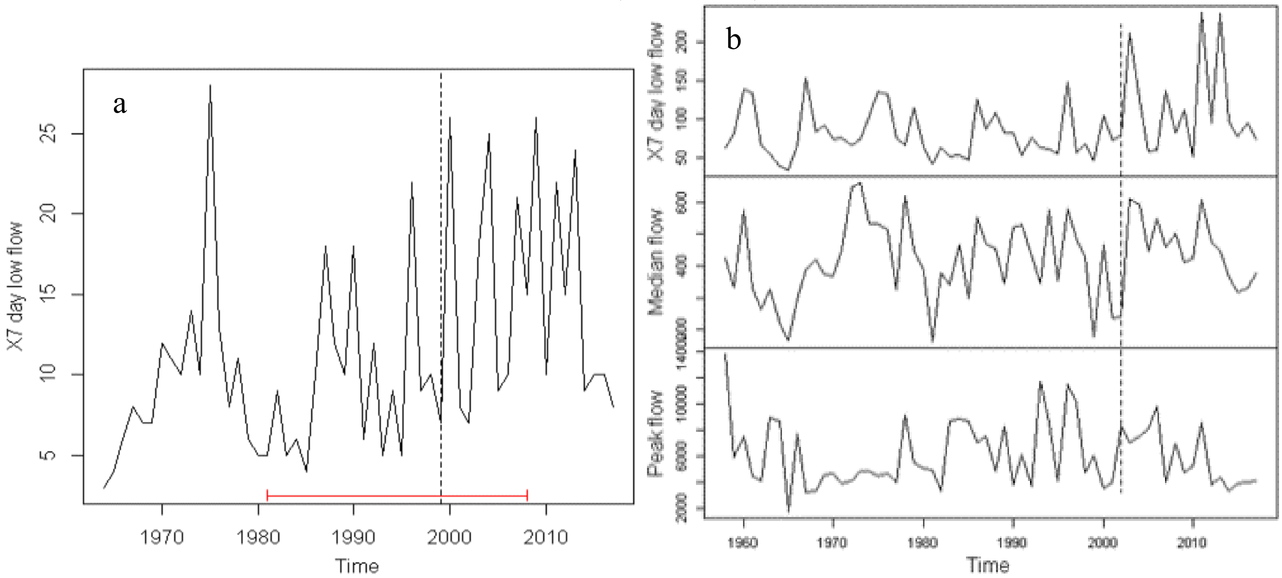
2. No serial autocorrelation between the data: This was validated by flow-time plots for each time-series.

A BP test is comprised of two separate and independent parts. First, it sequentially locates breaks (one, two, and so on) in a time-series, regardless of statistical significance, based on the minimization of sum of square residuals (SSR) corresponding to the breaks. Second, it tests the significance of the existence of the identified breaks by the comparison (e.g., F-test) of SSR (BAI and PERRON, 1998; ANTOSHIN et al., 2008). For the purpose of this study, the second part was ignored. The BP tests were performed only to provide a mathematical rationale for choosing a certain break year. Even though breakpoints were highly significant (>95% confidence) in case of some gauges, the significance of a particular (break) year in general was not considered as important as the idea that streamflow change may have possibly occurred somewhere around that year. It is for this reason and for the practical purpose that gauges with breaks within +/- 5 years were assigned the same breakpoint. For example, the year 2000 was assigned to a gauge with a breakpoint belonging to the set (1995, 1996, …, 2005). Based on the greatest frequency across the gauges, the year 2000 was determined to be the most likely major breakpoint followed by 1970. Table 2 shows the frequency of the breakpoints. Figure 2 shows the R plots to illustrate the individual-flow (gauge 01362200) and combined-flow (gauge 01447800) analyses.

Table 2 – Breakpoint frequency

Flow statistics	No. of gauges with breakpoint	
	Year 2000	Year 1970
7-day low	20	16
Median	19	21
Peak	16	11
All three together	22	16

Fig. 2 - (a) Plot of 7-day low flow against time for the gauge 01362200. The BP test shows 1999 as a breakpoint with 95% confidence interval (1981, 2008). (b) Combined plot of 7-day low, median, and peak flow against time for the gauge 01447800. The BP test shows 2002 as a breakpoint with 95% confidence interval (1969, 2008).



For all the gauges in the basin, the breakpoint 2000 was chosen for further streamflow analysis because: (1) 2000 was the most frequent breakpoint across the gauges, and (2) although 1970 was also frequent, it was the secondary break which showed up together with 2000 for most of the gauges. Figure 3 shows a histogram showing the frequency of first and secondary breaks for all gauges.

Fig. 3 – Histogram of First and Secondary BP Breakpoints

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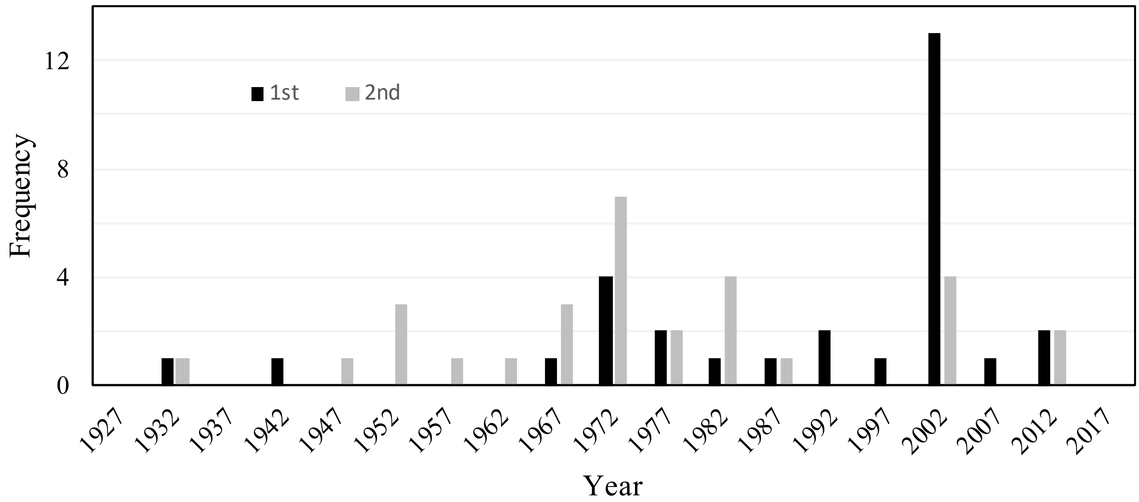

Hypothesis testing

The BP test shows breaks in a time-series based on analysis of structure and distribution of data. However, it does not conjecture on factors such as nature of the data before and after a break. Hence, hypothesis testing was done to evaluate if the change in average of the annual statistics occurred significantly before and after the breakpoint. For each time-series (for all 28 gauges), null and alternative hypotheses were formulated as follows:

Null hypothesis (H0): $\bar{X}1 - \bar{X}2 = 0$

Alternate hypothesis (HA): $\bar{X}1 - \bar{X}2 \neq 0$

where $\bar{X}1$ and $\bar{X}2$ are the average pre and post breakpoint year 2000 streamflow (cfs).

RESULTS

The results of the hypothesis testing indicate statistical change for low and median flows for many gauges. However, no stream gauges exhibited significant (95% confidence) change in peak flow. This may be attributed to two phenomena: (1) flow regulation from dams has prevented any significant change in peak flow, or (2) peak flows have high variability such that an assessment of change with statistical significance is not feasible. The authors have not attempted to quantify the impact of these two phenomena. The results of hypothesis testing are shown in Table 3.

Low frequency events, such as the 100-yr flood and Q7-10, guide the majority of decisions for water resource infrastructure design, management, and regulation. To put the results of this study into the context of water resource practice, estimates of Q7-10, 5-yr, and 25-yr flows have been calculated using the Log-Pearson III distribution with station skew and no outlier adjustment. Changes in these flows in addition to the 7-day low, median and peak flows are summarized in Table 4.

Table 3 - Summary of hypothesis testing results showing the number of gauges (out of 28) with streamflow change about the breakpoint year 2000

Flow statistics	No. of gauges with average streamflow change	
	95% confidence	90% confidence

Average 7-day low	14	16
Average Median	11	14
Average Peak	0	2

Table 4 - Changes in common statistics before and after the breakpoint year 2000

Flow statistics	No. of gauges with flow increase after 2000	Max flow increase	Max flow decrease	Average flow change
Average 7-day low	24	+109%	-18%	+33%
Average Median	24	+35%	-7%	+15%
Average peak	21	+61%	-29%	+12%
Q7-10	23	+216%	-23%	+32%
5-yr flow	22	+69%	-26%	+16%
25-yr flow	22	+133%	-55%	+28%

DISCUSSION AND CONCLUSIONS

Results of the hypothesis testing comparing streamflow before and after the year 2000 breakpoint indicated that statistically significant streamflow change has occurred for low flow and median flow for the majority of the selected gauges. However, peak flows did not exhibit statistically significant change. Changes in the average median streamflows range from 35% increase to 7% decrease. Although the changes varied significantly from gauge to gauge for each statistic, the majority of gauges exhibited an increase in flow, which aligns with past observations that this geographic area has experienced an increase in precipitation over the past 60 years (USGCRP, 2009; KUNKEL et al., 2013; USGCRP, 2014, EASTERLING et al., 2017). The Catskill Mountain (see Fig. 1) region's land use and development is strictly regulated, and this region has exhibited streamflow regime trends consistent with the rest of the study area. Additionally, changes in observed median streamflows were not correlated to watershed imperviousness. Consequently, the authors believe that the streamflow regime change is not solely a result of land use change; however, no attempt has been made to decouple the effects of hydroclimatic change (precipitation/evapotranspiration) and land use, and therefore, the authors recommend further research in this topic.

Results indicating statistically significant change pose a challenge to traditional engineering and management practice, which assumes a stationary streamflow regime. Engineers, operators, and regulators of water resources infrastructure should perform site specific analyses to access the validity of the stationarity assumption. In the context of risk studies, consideration should be made to assess risk over the life of the asset - not only risk in its current state. Considering gauge 01420500 as an example, the 5-yr streamflow calculated with the entire range of historical data (1914-2017) is 19,100 cfs and the streamflow calculated for the post-2000 data (2000-2017) is 29,300 cfs. Put differently, 19,100 cfs corresponds to a 20% probability (5 year turn period) when considering the life of the gauge; however, 19,100 cfs corresponds to a 63% probability (~2.7 year turn period) when considering only the post 2000 data. As risk analyses become increasing popular, land use change continues, and hydroclimatic change progresses, practitioners are encouraged to further study the

impact of the stationarity assumption and consider streamflow regimes as dynamic.

SYMBOLS

$\bar{X}1$ - Average streamflow (cfs) before the breakpoint year 2000

$\bar{X}2$ - Average streamflow (cfs) after the breakpoint year 2000

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