TRENDS IN YELLOWSTONE RIVER BASIN WATER SUPPLY AS INTERPRETED THROUGH HYDROLOGIC ANALYSIS, 1898-2007

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ABSTRACT

The Yellowstone River and its tributaries provide an important case study in the changes in magnitude and timing of discharge. As part of a review of water demands on the river and potential effects on fish and other aquatic biota, we assessed long term trends (1898-2007) and more recent changes (1970-2007) in the hydrographs of the Yellowstone River and its tributaries using data from 18 USGS Hydro-Climatic Data Network Stations. We evaluated seven variables used to characterize the discharge: 1) annual discharge, 2) magnitude of discharge, 3) absolute annual minimum discharge, 4) monthly discharge, 5) date when half of annual volume passed station, 6) date when maximum daily mean occurred, and 7) date when discharge returned to baseflow. Declines in volume and magnitude of annual and seasonal discharges are present in the basin, more so in areas where there are no water storage facilities. Timing of flow events are occurring earlier in the year throughout the basin, leaving less water in the summer and fall when water demands are the greatest. The appearances of significant trends have increased over the period 1970-2007, and it is expected that they will continue without serious changes in the basin. Lessened flows and altered timing stands to greatly affect all users of water in the basin, as is occurring in the rest of western North America. Effects on the native biota inhabiting the river can also be expected.

Keywords: Montana, streamflow, discharge,instreamflows, fishes

INTRODUCTION

In the past century, substantial declines in annual discharges have been documented throughout many of the rivers and streams of the western United States. Changes observed in magnitude and timing of runoff (Cayan et al. 2001; Stewart et al. 2004, 2005; Gibson et al. 2005), and the magnitude of peak discharge have been attributed to a wide range of human activities on the landscape (Zelt et al. 1999; Gibson et al. 2005). Observed changes in the timing of discharge have been most commonly characterized as an earlier peak and an earlier runoff pattern (Cayan et al. 2001; Regonda et al. 2004; Stewart et al. 2004, 2005; Gibson et al. 2005). In interior river basins with temperate climates, most annual discharge (often 50 to 80 percent of the total; Stewart et al. 2004) originates from snowmelt in spring and early summer. Despite high spring flows, discharge by late summer can be low, water withdrawals for human uses high as a percentage of total daily discharge, and instream water shortages severe. Earlier runoff and declining annual discharge can result in less water available for late summer demands for all competing uses (fish and wildlife, municipal, industrial, irrigation, etc.). Earlier runoff can also result in a protracted period of baseflow conditions and in severe cases can result in decreases

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in average baseflow because of diminished groundwater recharge (Arnell 1999).

Such changes in runoff can have substantial implication for ecological processes and aquatic communities in rivers. The quantity and timing of discharge is of critical importance in a free-flowing river for fish and fish habitat. Ecological processes can be regulated by the timing of peak discharge (Poff et al. 1997) and by the timing and magnitude of baseflow. Decreased volume, earlier discharge, and lower and longer periods of base flow can have negative impacts on the local fauna and a river's ecological functioning during the dry season. Many fish species in different areas have evolved specialized adaptations effective under the historic timing of runoff. They subsequently can develop a dependence on these cues (Cayan et al. 2001; Stewart et al. 2004, 2005; Gibson et al. 2005). Low water conditions reduce a river's ability to buffer against high temperatures and pollution, and can potentially disconnect riverine habitats causing isolation and mortality of native fauna (Gido et. al 2010). Late summer is a time when habitat for native fish and aquatic life can be minimal and potentially limiting due to decreased discharge and warmer water temperatures (Arismendi et al. 2012).

The Yellowstone River and its tributaries provide an important case study of the changes in magnitude and timing of discharge (Fig. 1). The Yellowstone River mainstem, which is unregulated, and its tributaries experience a dominant bi-modal natural hydrograph because of snow melt dominated flows. The first rise is a response to early melting of snow in lower elevation areas in the basin, usually occurring in the early spring (March or April). A second, more significant rise happens later in the summer when most of the snowpack in the higher elevations is being depleted (late May or June; Vorosmarty et al. 2000).

Irrigation withdrawals are the largest of all water withdrawals in the Yellowstone River Basin (YRB; approximately 96.5 percent; Miller and Quinn 1997). Irrigation withdrawals persist through late summer into the fall with many water

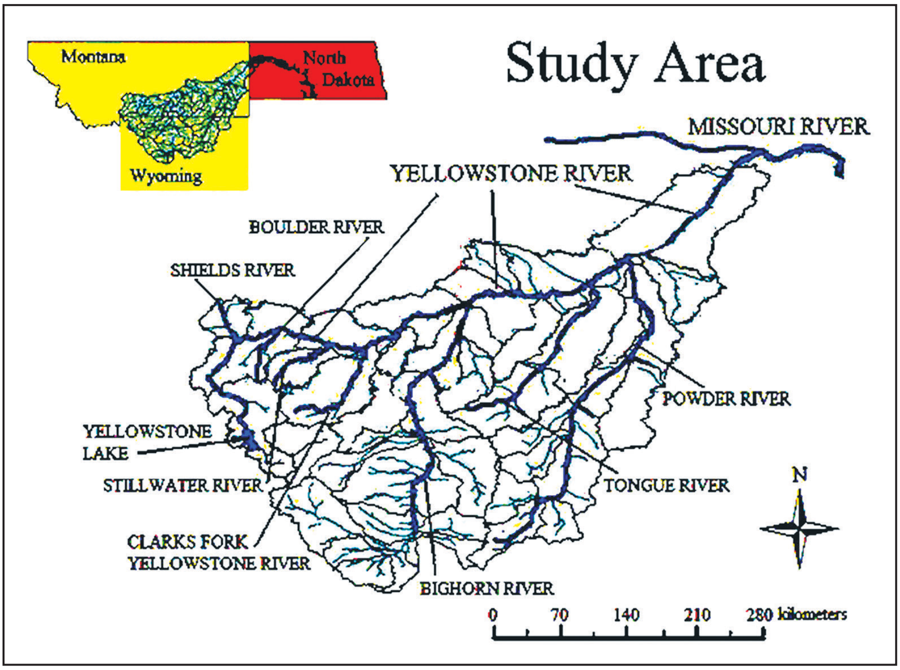

Figure 1. United State Geological Survey (USGS) Hydro-Climatic Data Network sites on the Yellowstone River and its seven major tributaries: Shields River, Boulder River, Stillwater River, Clarks Fork of the Yellowstone River, Bighorn River, Tongue River, and Powder River.

permits expiring as late as October 31 (MTDNRC 2008). Determining the effects of this dominant water use on the natural hydrograph in the basin is crucial to understanding potential effects on fish and other aquatic life.

The magnitude of absolute minimum flows for rivers varies widely throughout the basin. Some of the rivers frequently or periodically experience near zero flow conditions (e.g., the Powder River; Hubert 1993), whereas others continue to flow at levels that may or may not provide sustainable conditions for the aquatic life dependent upon it. Absolute minimum flow is a direct reflection of the ground water table along a river, and can be used to determine the amount of use or overuse throughout time (Smakhtin et al. 2001). The gradual reduction in surface water supply from groundwater development can lead to ecological effects that may not be fully realized for years. It also greatly complicates the administration of water rights.

As a first step in understanding water supply, use, and demands in the YRB, we conducted an analysis of the trends in monthly flows at its gauging stations over the period 1898-2007. The objective of this study was to assess long term trends and recent changes in the hydrographs of the Yellowstone River and its tributaries based on timing and magnitude of peak flows, seasonal flows, and base flows. Detailed time series analyses were used to test statistical validity of any apparent trends (Parrett 2006).

Methods

To evaluate the hydrographs within the YRB, we downloaded data available online from 18 United States Geological Survey (USGS) Hydro-Climatic Data Network stations on the Yellowstone River and its seven major tributaries: Shields River, Boulder River, Stillwater River, Clarks Fork of the Yellowstone, Bighorn River, Tongue River, and Powder River (Table 1; Fig. 2). We chose sites that were near the origin, the confluence, and state borders of the rivers to better detect any changes. On all but three of the tributaries (Shields, Boulder, and Stillwater), at least two sites were chosen for analysis. The following USGS stations were used: The Yellowstone River near Livingston, MT (USGS 06192500), at Billings, MT (USGS 06214500), at Miles City, MT (USGS 06309000), and near Sidney, MT (USGS 06329500); Shields River near Livingston, MT (USGS 06195600); the Boulder River at Big Timber, MT (USGS 06200000); the Stillwater River near Absarokee, MT (USGS 06205000); the Clarks Fork Yellowstone River near Belfry, MT (USGS 06207500), and near Edgar, MT (USGS 06208500); the Bighorn River at Kane, WY (USGS 06279500), near St. Xavier, MT (USGS 06287000), and Bighorn River at Tullock Creek near Bighorn, MT (USGS 06294500); the Tongue River near Dayton, WY (USGS 06298000), at the State Line near Decker, MT (USGS 06306300), and at Miles City, MT (USGS 06308500); and the Powder River at Sussex, WY (USGS 06313500), at Moorhead, MT (USGS 06324500), and near Locate, MT (USGS 06326500). The Sidney station (USGS 06329500) was used to represent the basin output and overall trend because the station was established in 1910, and the flow at this site represents nearly all of the total annual discharge leaving the basin as runoff. All calculations were made using the data available during the chosen periods. In general, data were complete for these stations over the period of 1898 to 2007 (Table 1).

Seven variables used to characterize the discharge, four for aspects of volume and three for aspects of timing, were obtained or computed from the USGS records (Stewart et al. 2004; Smakhtin et al. 2001). The four variables chosen to depict discharge volume were: 1) annual discharge, i.e., the total volume of discharge past a station during an individual water year (October 1 to September 30), 2) magnitude of peak discharge, i.e., the largest magnitude of daily averaged discharge past a station within an individual water year, 3) absolute annual minimum discharge, i.e., smallest annual magnitude of daily averaged water flowing past a station within an individual water year, and 4) monthly discharge –

Table 1. USGS Hydro-Climatic Data Network sites.

Code	Site Number	River	Location	Period of Data
1	06192500	Yellowstone	Livingston, MT	1898 - 1905, 1929 – 2007
2	06195600	Shields	Livingston, MT	1979 – 2007
3	06200000	Boulder	Big Timber, MT	1948 - 1953, 1956 – 2007
4	06205000	Stillwater	Absarokee, MT	1911 - 1914, 1936 – 2007
5	06207500	Clarks Fork Yellowstone	Belfry, MT	1922 – 2007
6	06208500	Clarks Fork Yellowstone	Edgar, MT	1922 - 1969, 1987 – 2007
7	06214500	Yellowstone	Billings, MT	1905, 1928 – 2007
8	06279500	Bighorn	Kane, WY	1929 – 2007
9	06287000	Bighorn	St. Xavier, MT	1935 – 2007
10	06294500	Bighorn	Bighorn, MT	1946 – 2007
11	06298000	Tongue	Dayton, WY	1919 – 2007
12	06306300	Tongue	Decker, MT	1961 – 2007
13	06308500	Tongue	Miles City, MT	1939 - 1941, 1946 – 2007
14	06309000	Yellowstone	Miles City, MT	1923, 1929 – 2007
15	062313500	Powder	Sussex, WY	1939, 1940, 1950 - 1957, 1979 – 2007
16	06324500	Powder	Moorhead, MT	1930 – 2007
17	06326500	Powder	Locate, MT	1939 – 2007
18	06329500	Yellowstone	Sidney, MT	1911 – 2007

i.e., average discharge during each month at a station. Three of the four variables had one value per year per station and the fourth variable (mean monthly discharge) had 12 values per year per station. The three variables chosen to depict timing of discharge were: 5) date during the water year when half of the annual volume of flow has passed a station, 6) date during the water year when the maximum daily mean was achieved, 7) date of return to baseflow (discharges below the 50th percentile flows) after spring rise.

The four volume variables used were annual discharge, peak discharge, annual minimum discharge, and average monthly discharge (in m³/s). They were calculated based on daily statistics from the USGS gauging records for the entire period of record at all 18 stations (Table 1).

The first of the three timing variables (the date of the water year when half of the flow has passed the gauging station) was calculated using historic daily averages from the USGS gauging records for the entire period of record at 9 of the 18 stations (1-5, 8, 11, 15, and 18) to detect for trends in timing of center mass of discharges in the basin. For this variable, the temporal centroid of streamflow (CT) measurement, a measurement of runoff timing (Stewart et al. 2004), was used to determine whether the snowmelt runoff in the basin is trending earlier or later in the water year. The CT used was the flow-weighted timing, or 'center of mass' of streamflow calculated as

$$CT = \Sigma(t_i q_i) / \Sigma q_i,$$

where t_i is the time in days from the beginning of the water year and q_i is the corresponding streamflow for water year day I (Stewart et al. 2004). The CT measurement was chosen because it is easily and reliably determined, insensitive

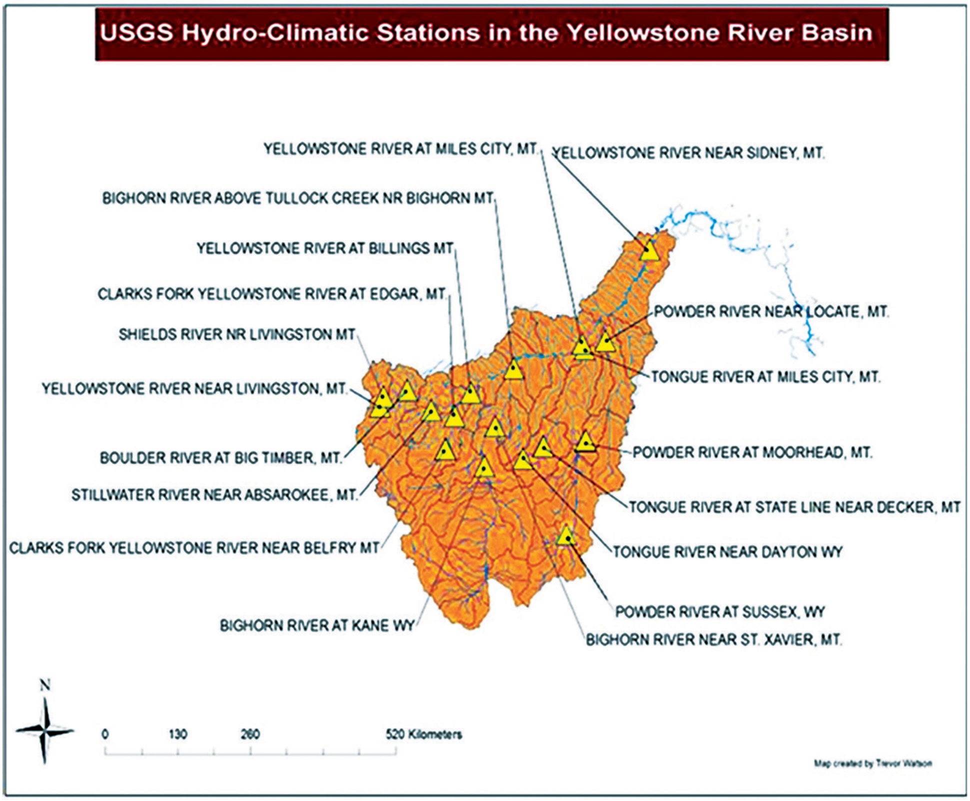

Figure 2. United State Geological Survey (USGS) Hydro-Climatic Data Network sites on the Yellowstone River and its seven major tributaries: Shields River, Boulder River, Stillwater River, Clarks Fork of the Yellowstone River, Bighorn River, Tongue River, and Powder River.

to spurious variations in flow, and it can be used to compare basins in different climatic regimes (Stewart et al. 2004). It has also been used effectively to detect a shift in timing of snowmelt runoff in many rivers in the Northwest (Roos 1987, 1991; Wahl 1992; Dettinger and Cayan 1995; Cayan et al. 2001; Stewart et al. 2004, 2005). The average CT was calculated from daily flow volumes for each of the eight snowmelt-dominated tributaries in the basin. The CT measurement was used only for the stations near the headwaters of the rivers, except on the Shields, Boulder, and Stillwater where there was only one station available, and the Yellowstone River where CT was also calculated at Sidney, site of the lowermost gauging station on the mainstem.

For the second timing variable, annual peak discharge, we obtained peak discharge values and dates of occurrence for each water year from the USGS gauging records for the entire period of record at all 18 stations. We then fit the Julian date with the water year calendar and found the water year day that the peak discharges occurred.

For the third timing variable, baseflow, daily mean discharges were used for 17 of the 18 stations and the date of return to baseflow was calculated. Baseflow was identified as when the discharge equaled or exceeded 50 percent of the time, also known as Q50, as outlined by Smakhtin et al. (2001). We determined the water day when discharge, after the ‘spring rise’ fell below the Q50 designation. In years when the base flow was not met before the end of the water year, the last day of the water year (365; September 30) was used as its measurement. One of the 18 gauging stations, the site near St. Xavier on the Bighorn (site 9), was excluded because of its unnatural flows owing to its location directly downstream of Yellowtail Dam on the Bighorn River.

Prior to trend analyses, for each variable, Loess (local polynomial regression fitting) smoothing was used to serve as a visualization tool to better evaluate the data. The Loess smoothing approach to linear and non-linear regression (NIST/SEMATECH 2006) is best described as fixing a low-degree polynomial to small subsets of the data surrounding each point in the data set. Using weighted least squares, the polynomial fit was given more weight to data points near the response data being estimated and less to the ones further away (Appendix 1 in Watson 2014).

Seven null hypotheses were evaluated in the YRB: There were no changes or trends in 1) annual discharges, 2) magnitude of peak discharges, 3) magnitude of absolute annual minimum discharge, 4) average monthly discharges, 5) date of the CT measurements, 6) date of maximum daily means, and 7) date when flows return to baseflow conditions.

A non-parametric approach was used to test for trends for all seven variables. The four volume variables were tested for association between time and discharge; the three timing variables were tested for association between time and day, based on counts of concordant and discordant pairs. Tests were made using the Mann-Kendall Trend Analysis (Kendall Tau (KT)) test (Higgins 2004). Two analyses were run for each site, one using the entire time series of data present and the other from 1970 to 2007 based on observations of the Loess plots (Watson 2014). We separated the results (slopes) as positive or negative and assessed their significance at $P = 0.1$. Anything with a $P>0.10$ was determined to have no statistical trend, $0.05<P<0.10$ to have a trend detected but not significant, $P<0.05$ to be significant, and $P<0.01$ to be highly significant (Higgins 2004). Pearson's correlation coefficient (parametric), and the Spearman's rank correlation coefficient test (non-parametric) were used to measure the correlation between the two variables time and discharge for the four volume measurements and time and water day for the three timing measurements. The correlation coefficients ranged from -1 to 1 (Watson 2014).

RESULTS

Overall, annual discharges, magnitudes of peak discharge, and baseflow tended to decline on the tributaries free of upstream reservoirs. Runoff also tended to occur earlier in more recent years.

Magnitude of Discharge

Annual Average Discharge

Although we observed variability in the average annual discharge for all rivers when considering the entire period of record, there was far less variability at individual sites over the more recent period (1970-2007). There were highly significant declining trends at sites 3, 11, 12, and 18 ($P <0.01$), significant declining trends at sites 2, 8, 9, 10, and 17 ($P <0.05$), and no sites with negative but insignificant trends ($0.05 \leq P \leq 0.10$) when evaluated over the entire periods of record (Fig. 3). All sites but 7 and 15 had negative slopes (Kendall Tau; KT) over their entire periods of record.

There was more consistent evidence of declines in the average annual discharge for all rivers over the period 1970-2007 with highly significant declining trends at sites 3, 4, 7-14, and 18 ($P<0.01$), significantly declining trends at sites 1, 2, 5, 16, and 17 ($P<0.05$), and no sites with negative but insignificant trends ($0.05 \leq P \leq 0.10$). All sites had negative slopes (KT) over the period 1970-2007 (Fig. 3).

Magnitude of Annual Peak Discharge

Similar variability in the magnitude of annual peak discharge was observed for all rivers and their individual sites studied when considering their entire periods of record and over the more recent period 1970-2007. There were highly significant declining trends at sites 3, 8, 9, 14, 16, 17 and 18 ($P<0.01$), significant declining trends at sites 12 and 13 ($P<0.05$), and one site (2) with a negative but insignificant trend ($0.05 \leq P \leq 0.10$) when evaluating the entire period of record (Fig. 4). All sites but 1, 5, and 7 had negative slopes (KT) for the entire period of record.

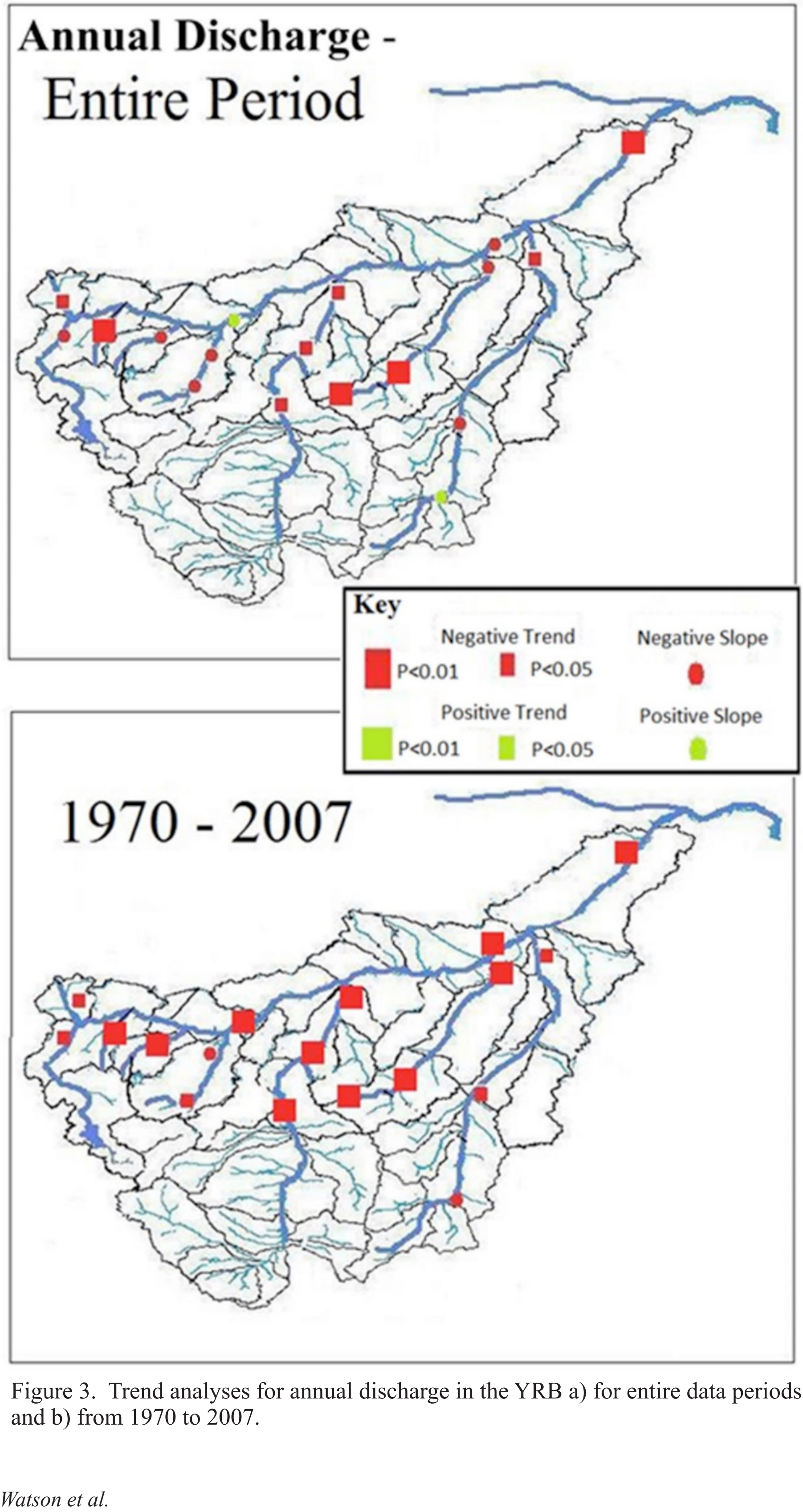

Figure 3. Trend analyses for annual discharge in the YRB a) for entire data periods, and b) from 1970 to 2007.

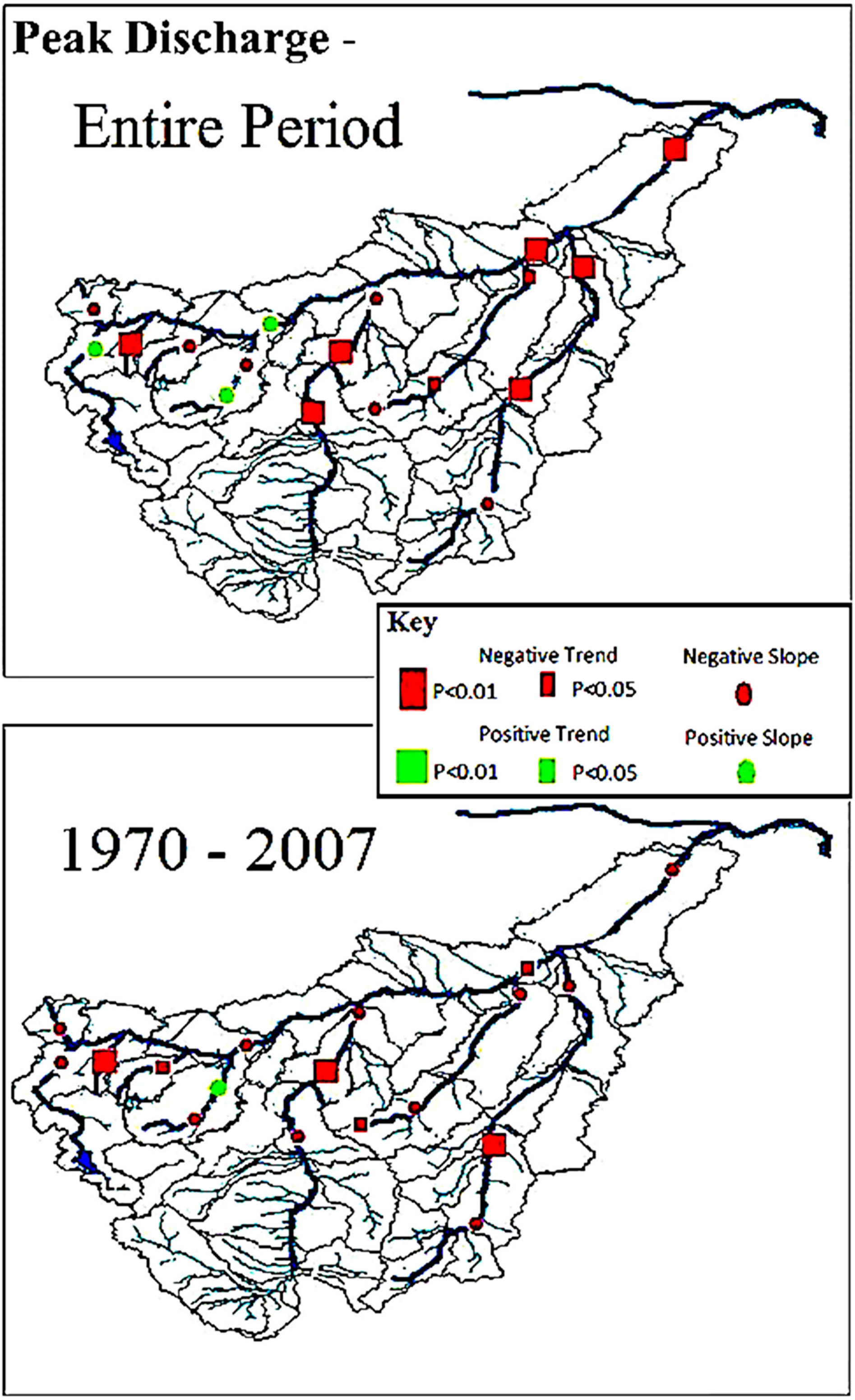

Figure 4. Trend analyses for magnitude of peak discharge in the YRB a) for the entire period and b) from 1970 to 2007.

For annual peak discharge over the period 1970-2007, we found highly significant declining trends at sites 3, 9, and 16 ($P<0.01$), significantly declining trends at three sites ($P<0.05$), and negative but insignificant trends at 3 sites ($0.05 \leq P \leq 0.10$). All sites but site 3 had negative slopes (KT) for the period 1970-2007 (Fig. 4).

Absolute Annual Minimum Discharge

Absolute annual minimum discharge showed highly significant ($P<0.01$) declining trends at sites 2, 5, and 6, highly significant ($P<0.01$) increasing trends at sites 8, 9, 10, and 14, significantly, declining trends at sites 3, 11, and 12 ($P<0.05$), and significantly increasing trends at site 16 ($P <0.05$). (Fig. 5).

Over the period 1970-2007 sites 2, 3, 5, 8, 11, 12, 13, 15, and 18 exhibited highly significant declining trends ($P<0.01$), and significantly declining trends at site 17 ($P<0.05$). No significant positive trends ($P<0.05$) were found in the basin for the period 1970-2007. (Fig. 5)

Average Monthly Discharges

Monthly discharges changed similarly throughout the basin by season regardless of river, with only a few deviations. A majority of the 18 sites on the eight rivers experienced declines late spring, summer, and early fall months (May-October), while showing increases in monthly discharges during the other months. The lowest station in the basin, Site 18 Yellowstone River near Sidney, Montana was a clear depiction of this pattern, showing the most summer and fall months with significant declines, while the other months experienced increasing flows. Overall there was little difference in decreasing versus increasing trends, but there were more sites with significantly and very significant decreasing trends than there were with increasing trends (Table 2).

Timing of Discharge

Overall, both the date of the CT measurement and the return date of baseflow measurements tended to occur days earlier during the more recent period evaluated within the YRB.

Centroid of Discharge

The center-time discharge results showed highly significant trends toward earlier runoff events at sites 8 and 18 ($P<0.01$), no sites with significant trends towards earlier runoff ($P<0.05$), and two sites (5 and 11) with insignificant trends but trending towards earlier runoff ($0.05 \leq P \leq 0.10$). All nine sites showed negative slopes however when evaluating the entire period of record for each site (Table 3).

Over the period 1970-2007, there were no sites with highly significant trends towards earlier runoff ($P<0.01$), significant trends towards earlier runoff at sites 4, 5, and 7 ($P<0.05$), and zero insignificant trends ($0.05 \leq P \leq 0.10$). All but site 8 exhibited negative slopes indicating earlier runoff events for the period 1970 to 2007 (Table 3).

Annual Peak Discharge

Annual peak discharge showed the least significance in changes or trends of all variables evaluated. No sites showed highly significant trends ($P<0.01$). We found a significant trend ($P<0.05$) toward earlier annual peak discharge at site 1, and found three sites (5, 7 and 8) with insignificant but negative trends ($0.05 \leq P \leq 0.10$) in the basin for their entire periods of record (Fig. 6; Table 4).

Similar results were found when evaluating the date of annual peak discharge for the more recent period1970-2007. Sites1 and 5 had highly significant trends ($P<0.01$) towards earlier in the year, no sites showed significant trends ($P<0.05$), and 1 site showed insignificant but negative trends ($0.05 \leq P \leq 0.10$) toward earlier in the year in the basin for the period 1970-2007 (Fig. 6; Table 4).

Annual Baseflow Conditions

Baseflow conditions showed highly significant ($P<0.01$) trends towards earlier in the year at sites 5, 10 and 18, significant trends ($P<0.05$) toward earlier in the year at sites 3 and 4, and site 8 had insignificant but negative trends ($0.05 \leq P \leq 0.10$) toward earlier in the year over their entire periods of record (Table 5; Fig. 7).

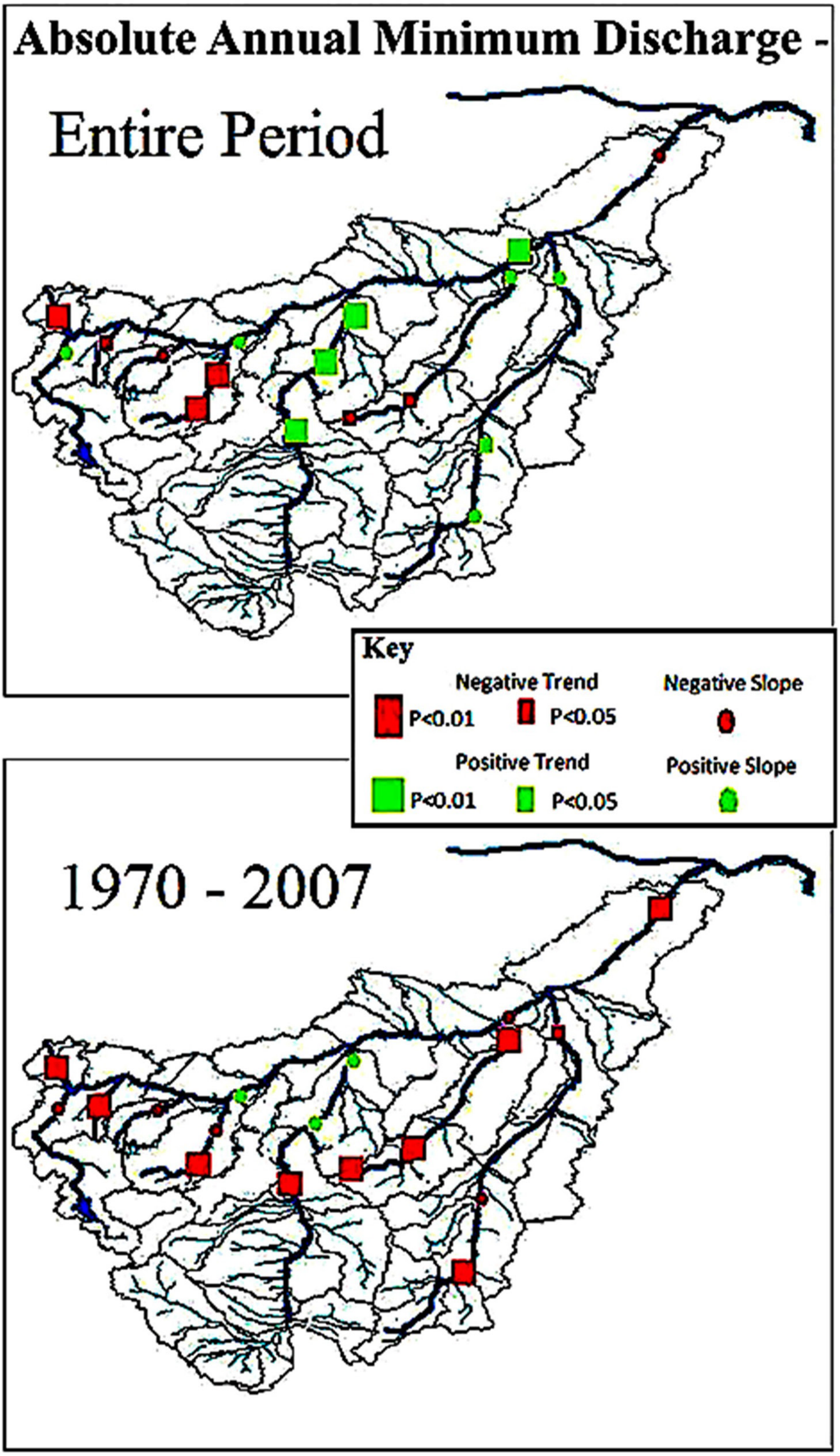

Figure 5. Trend analyses for absolute minimum annual discharge in the YRB a) for the entire period and b) from 1970 to 2007.

Table 2 Significant trend results for Annual Monthly discharges

	Decrease			Increase		
Months	$P<0.01$	$0.01\leq P\leq 0.05$	Trending Down*	$P<0.01$	$0.01\leq P\leq 0.05$	Trending Up*
January	2	1	3	3	5	4
February	3	1	3	3	2	6
March	1	3	8	1	0	5
April	0	2	9	1	0	6
May	2	2	8	0	2	4
June	6	2	10	0	0	0
July	1	5	11	0	0	1
August	3	1	8	0	0	6
September	4	1	7	0	0	6
October	1	2	5	0	0	10
November	1	4	3	0	1	9
December	3	2	2	2	1	8
Totals	**27**	**26**	**77**	**10**	**11**	**65**

*Trending down or up but not statistically significant $0.05\leq P\leq 0.10$.

Over the period 1970-2007, sites 1, 4, 7, and 13 exhibited highly significant trends ($P<0.01$) towards an earlier onset of baseflow conditions, significant trends ($P<0.05$) towards an earlier onset of baseflow conditions at sites 3, 5, 8, 10, and 18, and sites 7 and 14 changed to negative trends. (Fig. 7; Table 5).

Overall, for the seven variables, we rejected all seven of the null hypotheses evaluated. There were many significant ($P<0.05$) and highly significant ($P<0.01$) trends identified for the variables throughout the basin. The significant results were scattered throughout and are summarized in detail in Watson (2014).

Discussion

Hydrographic trends from the tributaries and the mainstem provide consistent indications that the historic magnitude and volume of discharge is declining in the YRB. Similar results have been documented in similar snow melt dominated systems along the Rocky Mountains in North America and the Pacific Northwest (Rood et. al 2005; Schindler and Donahue 2006; Luce and Holden 2009). For example, Rood et al. (2005) found that there were significant declines in total annual flow for many Rocky Mountain watersheds near the hydrographic apex of North America, and Luce and Holden (2009) found that the Pacific Northwest was experiencing the same declines.

Although several studies of various river systems in the West show that there are quantified changes occurring in the observable hydrograph (Lapp et al 2005; Rood et al. 2005; Mote et al. 2005; Barnett et al 2005; Cayan et al 2001), most focus on how it affects the timing of water and less so on the amount of water (Luce and Holden 2009). Part of this bias is due to the science of climate modeling, where there is greater confidence in temperature increases regionally (and thus changes in timing of runoff) than what will occur with magnitude of discharge resulting from precipitation at smaller scales in the Western region (Lapp et al. 2005; Rood et al. 2005; Mote et al. 2005).

The analyses also indicate that the declines in the YRB are prevalent basin-wide from headwaters to mouth (Watson 2014; Figs. 3-7). In contrast, some other studies (e.g., Rood et al. 2005) that identified declines in discharge, saw within-basin differences, e.g., greater changes in higher

Table 3. Trend analysis results for CT measurements in the Yellowstone River Basin.

USGS Sites		Kendall Tau		Pearson's Correlation		Spearman's Correlation	
		KT Statistic	P-value	Pearson	P-Value	Spearman	P-Value
Yellowstone River at Livingston	All Data	-0.094	0.21	-0.142	0.2044	-0.152	0.1731
	1970	-0.175	0.122	-0.232	0.1614	-0.266	0.1068
Shields River	All Data	-0.132	0.3199	-0.179	0.3531	-0.198	0.3036
Boulder River	All Data	-0.080	0.3758	-0.150	0.2596	-0.120	0.3682
	1970	-0.177	0.119	-0.256	0.1212	-0.271	0.0993*
Stillwater River	All Data	-0.053	0.5155	+0.427	0.0002***	-0.069	0.5695
	1970	-0.302	0.0137**	-0.435	0.0113 **	-0.425	0.0138**
Clarks Fork River at Belfry	All Data	-0.122	0.0962*	-0.181	0.0959*	-0.182	0.0928*
	1970	-0.254	0.0252**	-0.319	0.0509*	-0.351	0.0308***
Bighorn River at Kane, WY	All Data	-0.220	0.0044***	-0.297	0.0082***	-0.315	0.05* * *
	1970	+0.007	0.9499	-0.002	0.9882	+0.018	0.9154
Tongue River near Dayton, WY	All Data	-0.145	0.0646*	-0.229	0.0465**	-0.212	0.0658*
	1970	-0.241	0.0346**	-0.381	0.0184**	-0.346	0.0332**
Powder River at Sussex, WY	All Data	-0.082	0.5183	-0.045	0.8112	-0.121	0.5175
	1970	-0.149	0.309	-0.289	0.1712	-0.220	0.3005
Yellowstone River at Sidney	All Data	-0.298	< 0.0001***	-0.382	0.0001***	-0.421	< 0.0001***
	1970	-0.098	0.3856	-0.137	0.4111	-0.15	0.3626

* Insignificant trend; P < 0.10
** Significant; P < 0.05
*** Highly Significant; P < 0.01

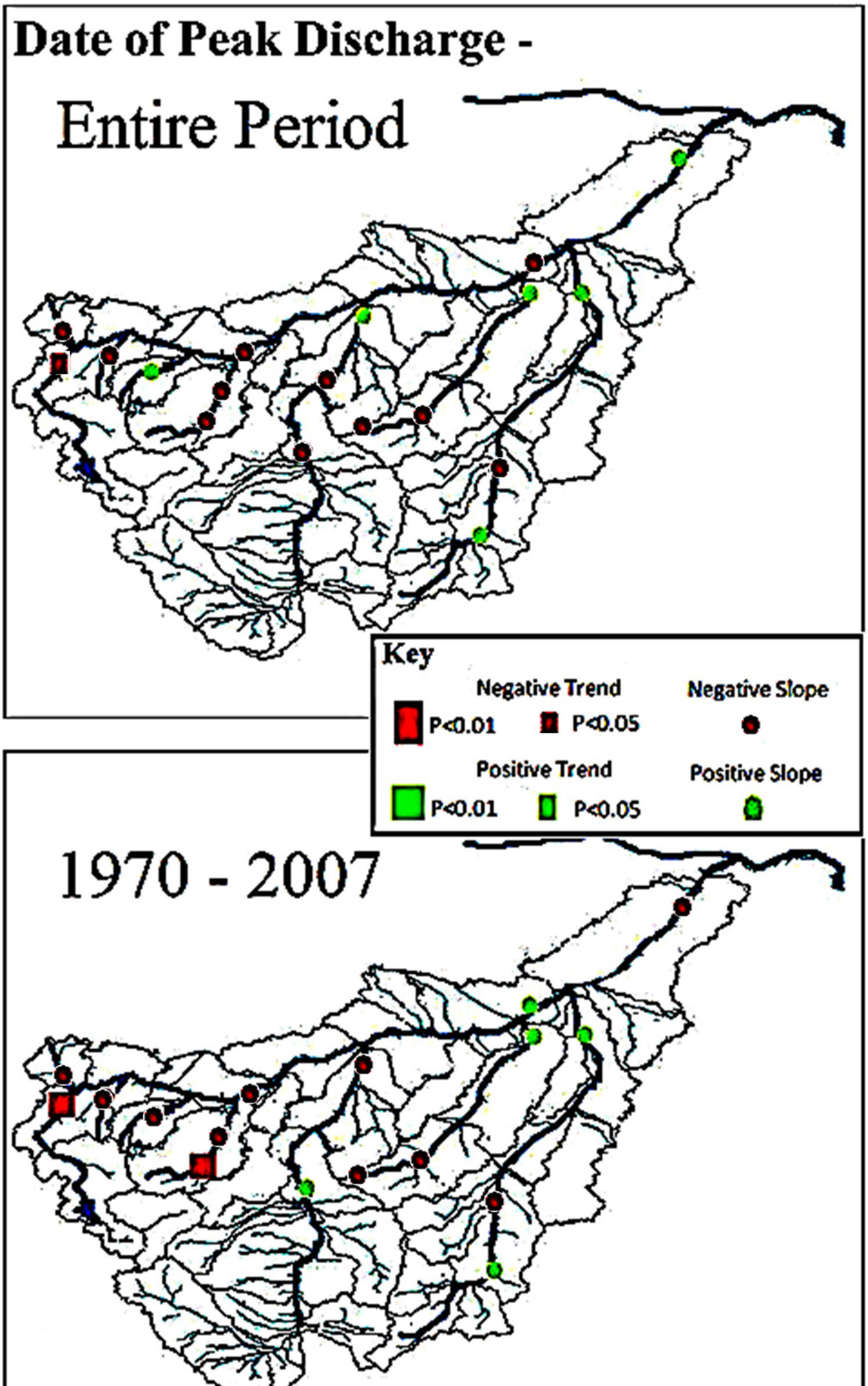

Figure 6. Trend analyses for peak discharge date in the YRB a) for the entire period and b) from 1970 to 2007.

Table 4. Trend analysis results for timing of annual peak discharge dates in the Yellowstone River Basin.

USGS Sites		Kendall Tau		Pearson's Correlation		Spearman's Correlation	
		KT Statistic	P-value	Pearson	P-Value	Spearman	P-Value
Yellowstone River at Livingston	All Data	-0.197	0.0103**	-0.266	0.0153**	-0.275	0.0119**
	1970	-0.350	0.003***	-0.464	0.0033***	-0.481	0.0023***
Shields River	All Data	-0.020	0.8806	-0.045	0.8149	-0.08	0.9656
Boulder River	All Data	-0.052	0.5699	-0.055	0.6768	-0.070	0.5945
	1970	-0.180	0.1213	-0.245	0.1382	-0.266	0.1065
Stillwater River	All Data	+0.059	0.4621	+0.106	0.3609	+0.092	0.4259
	1970	-0.048	0.6776	-0.079	0.6356	-0.066	0.6949
Clarks Fork River at Belfry	All Data	-0.133	0.0725*	-0.183	0.0916*	-0.201	0.0639*
	1970	-0.298	0.0097***	-0.386	0.0166**	-0.431	0.007***
Clarks Fork River at Edgar	All Data	-0.087	0.3063	-0.203	0.0965*	-0.141	0.2523
	1970	-0.067	0.6722	+0.004	0.9865	-0.058	0.8012
Yellowstone River at Billings	All Data	-0.137	0.0737*	-0.153	0.1732	-0.202	0.0711*
	1970	-0.150	0.1900	-0.216	0.1931	-0.226	0.1656
Bighorn River at Kane, WY	All Data	-0.137	0.0781*	-0.150	0.1906	-0.199	0.0803*
	1970	+0.001	0.99	+0.191	0.2496	+0.031	0.8545
Bighorn River at St. Xavier	All Data	-0.036	0.6542	-0.293	0.0119**	-0.058	0.6288
	1970	-0.034	0.7627	-0.188	0.2599	-0.057	0.7328
Bighorn River near Bighorn	All Data	+0.111	0.4405	+0.158	0.452	+0.155	0.4603
Tongue River near Dayton, WY	All Data	-0.101	0.1952	-0.141	0.2192	-0.154	0.1780
	1970	-0.207	0.0682*	-0.309	0.0592*	-0.317	0.0527*
Tongue River at Stateline	All Data	-0.080	0.4353	-0.053	0.7233	-0.095	0.5251
	1970	-0.019	0.8701	-0.046	0.7851	-0.005	0.9750

Table 4. Continued

USGS Sites		Kendall Tau		Pearson's Correlation		Spearman's Correlation	
		KT Statistic	P-value	Pearson	P-Value	Spearman	P-Value
Yellowstone River at Livingston	All Data	-0.197	0.0103**	-0.266	0.0153**	-0.275	0.0119**
Tongue River at Miles City	All Data	+0.04.5	0.599	+0.077	0.5391	+0.066	0.601
	1970	+0.063	0.58	+0.082	0.6239	+0.079	0.6386
Yellowstone River at Miles City	All Data	-0.047	0.5463	-0.093	0.4136	-0.079	0.4871
	1970	-0.121	0.2958	-0.057	0.7347	-0.168	0.3131
Powder River at Sussex, WY	All Data	+0.048	0.6828	-0.053	0.7599	+0.074	0.6701
	1970	+0.153	0.2827	+0.159	0.449	+0.207	0.321
Powder River at Moorhead	All Data	-0.097	0.2147	-0.135	0.2403	-0.148	0.1976
	1970	-0.089	0.4454	-0.103	0.5501	-0.163	0.3419
Powder River at Locate	All Data	+0.024	0.7686	+0.054	0.6563	+0.024	0.844
	1970	+0.126	0.2683	+0.154	0.3566	+0.143	0.3933
Yellowstone River at Sidney	All Data	+0.041	0.569	+0.059	0.567	+0.062	0.5526
	1970	-0.077	0.5047	-0.021	0.8987	-0.099	0.5560

*	Insignificant trend;	$P < 0.10$
**	Significant;	$P < 0.05$
***	Highly Significant;	$P < 0.01$

Table 5. Trend analysis results for return date of baseflow conditions after spring pulse in the Yellowstone River Basin.

USGS Sites		**Kendall Tau**		**Pearson's Correlation**		**Spearman's Correlation**	
		KT Statistic	**P-value**	**Pearson**	**P-Value**	**Spearman**	**P-Value**
Yellowstone River at Livingston	All Data	-0.123	0.1072	-0.199	0.0732*	-0.194	0.0807*
	1970	-0.340	0.0031***	-0.462	0.0035***	-0.472	0.00274**
Shields River	All Data	-0.193	0.1481	-0.125	0.5189	-0.268	0.1606
Boulder River	All Data	-0.198	0.0311**	-0.272	0.0388**	-0.309	0.0184**
	1970	-0.292	0.0114**	-0.364	0.0247**	-0.415	0.0095***
Stillwater River	All Data	-0.168	0.0339**	-0.223	0.0516*	-0.232	0.0422**
	1970	-0.344	0.003***	-0.440	0.0057***	-0.482	0.0022***
Clarks Fork River at Belfry	All Data	-0.26D	0.0005* * *	-0.362	0.0006***	-0.375	0.0004***
	1970	-0.232	0.0435**	-0.440	0.0057***	-0.471	0.0029***
Clarks Fork River at Edgar	All Data	-0.118	0.1599	-0.196	0.1064	-0.173	0.1561
	1970	-0.044	0.7853	+0.004	0.9871	-0.058	0.8031
Yellowstone River at Billings	All Data	+0.031	0.6868	+0.038	0.7355	+0.039	0.7338
	1970	-0.316	0.0057***	-0.444	0.0053***	-0.464	0.0033***
Bighorn River at Kane, WY	All Data	-0.142	0.0664*	-0.146	0.1988	-0.199	0.0792*
	1970	-0.232	0.0435**	-0.296	0.0715*	-0.343	0.0349**
Bighorn River near Bighorn	All Data	-0.080	0.3856	-0.263	0.0485**	-0.131	0.3308
	1970	-0.186	0.1288	-0.335	0.0568*	-0.283	0.1101
Tongue River near Dayton, WY	All Data	-0.239	0.0037***	-0.312	0.0058***	-0.316	0.0051***
	1970	-0.294	0.013**	-0.409	0.0108**	-0.389	0.0156**
Tongue River at Stateline	All Data	-0.162	0.1221	-0.190	0.2058	-0.241	0.1072
	1970	-0.154	0.1889	-0.253	0.1306	-0.245	0.1435

Table 5. Continued.

USGS Sites		**Kendall Tau**		**Pearson's Correlation**		**Spearman's Correlation**	
		KT Statistic	**P-value**	**Pearson**	**P-Value**	**Spearman**	**P-Value**
Tongue River at Miles City	All Data	-0.029	0.7461	+0.033	0.7993	-0.035	0.7915
	1970	-0.058	0.6235	-0.109	0.5267	-0.090	0.6025
Yellowstone River at Miles City	All Data	-0.033	0.6686	-0.048	0.6996	-0.057	0.6180
	1970	-0.360	0.0017***	-0.535	0.0005***	-0.512	0.0010***
Powder River at Sussex, WY	All Data	+0.130	0.2917	+0.125	0.489	+0.169	0.348
	1970	-0.077	0.6021	-0.256	0.2280	-0.112	0.6015
Powder River at Moorhead	All Data	-0.074	0.3461	-0.105	0.3644	-0.103	0.3738
	1970	-0.126	0.2816	-0.184	0.2832	-0.197	0.2485
Powder River at Locate	All Data	-0.032	0.7013	-0.189	0.1194	-0.037	0.7615
	1970	-0.079	0.4891	-0.226	0.1723	-0.100	0.5488
Yellowstone River at Sidney	All Data	-0.213	0.0026***	-0.262	0.0103**	-0.307	0.0025***
	1970	-0.254	0.0268**	-0.362	0.0257**	-0.385	0.0169**

* Insignificant trend; $P < 0.10$
** Significant; $P < 0.05$
*** Highly Significant; $P < 0.01$

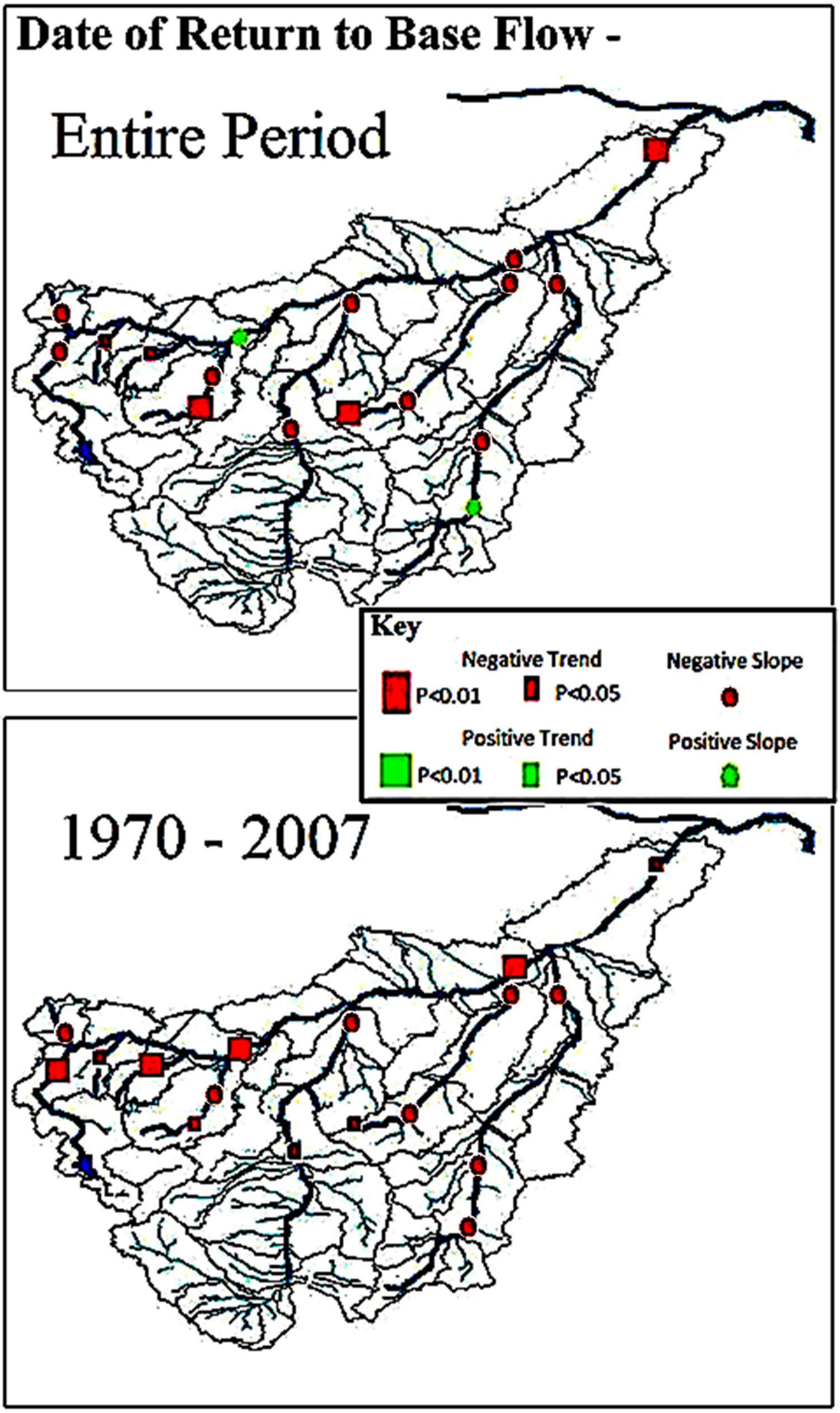

Figure 7. Trend analyses for date of return to baseflow in the YRB a) over the entire period, and b) from 1970 to 2007.

elevation areas than in areas lower in the basin. Much of this difference may be the result of the Yellowstone River mainstem and its tributaries having few large storage reservoirs that can unnaturally alter runoff patterns differentially between the tributaries and mainstem.

However, results of the regulated portions of the YRB (e.g., Bighorn and Tongue Rivers) must be interpreted more cautiously because of potential effects of reservoirs and dam releases. For evaluating the date of return to baseflow, the exclusion of the St. Xavier on the Bighorn River (site 9) from analysis was implemented because of unnatural flows owing to its location directly downstream of Yellowtail Dam (completed 1967) on the Bighorn River. This variable would be likely to be especially affected by dam operations. Other Bighorn River Basin tributary impoundments potentially influencing time series analyses results include Buffalo Bill Reservoir (completed 1910) on the Shoshone River and Boysen Reservoir (completed 1952) on the Wind River. The effects of the completion of Yellowtail Dam in 1967 can be considered, at least indirectly, by comparing results from the entire time series for three Bighorn River stations (Kane, WY: 1929-2007; St. Xavier, MT, 1937-2007; Bighorn, MT, 1946-2007) with those of the post Yellowtail Dam period 1970-2007. Although trends for these stations were similar between the two periods for most variables (e.g., annual discharge (Fig. 3), peak discharge (Fig. 4), date of peak discharge (Fig. 6), and date of return to base flow (Fig. 7), a notable difference occurred in the absolute minimum discharge (Fig. 5). Less positive trends in the more recent period (1970-2007) may reflect the effects of retaining water in the spring for later release, leading to higher minimum discharge in many years. Absolute minimum discharge trends also differ markedly in the Tongue River between the entire time series and the more recent period (1970-2007; Fig. 5). How impoundments affect the hydrograph in these systems will vary depending on reservoir operations in response to annual water conditions and demands in each basin.

In addition to magnitude of discharge, the significantly altered timing of runoff found in this study in the YRB is consistent with that reported in numerous studies in the West (Cayan et al. 2001; Baron et al. 2002; Regonda et al. 2004; Stewart et al. 2004, 2005; Gibson et al. 2005; Mote et al. 2005; Rood et al. 2008). For example, Cayan et al. (2001) found that not just hydrological fluctuations in spring snowmelt, but also phenological fluctuations as well with earlier onset of bloom timing dates for lilacs (*Syringa volgaris*) and honeysuckles (*Lonicera tatarica* and *Lonicera korolkowii stopf*), both strongly related to the springtime temperature variations observed mainly since the 1970's. Mote et al. (2005) also found that the rising temperatures in the west, no matter the cause, were resulting in declines in snow water equivalent (SWE) for snow packs in the west, primarily in the Cascades of Oregon. It has been argued that the most important changes occurring in the hydrological cycle in the West is the declining snowpack accumulation and earlier runoff timing caused by temperature changes (Barnett et al. 2008).

Although occasional significance in trends was found when looking at the three timing variables basin-wide, the most prevalent statistically significant trends were those indicating an earlier return of baseflow conditions (Fig. 7; Table 5). Other studies have reported similar results for return to baseflow (Baron et al. 2002; Regonda et al. 2004; Stewart et al. 2004, 2005; Gibson et al. 2005; Rood et al. 2008). For example, Rood (2008) found the greatest changes in late summer flows, when demands are the greatest, were observed in the rivers draining the east slope of the Rocky Mountains, some at a rate of 0.2 percent per year. The substantial onset of earlier runoff and earlier return to baseflows in the basin reported here suggest that the free-flowing Yellowstone River and most of its tributaries are going to be measurably affected by these changes if observed trends remain the same.

The scope of our study was limited largely to an analysis of discharges along with an investigation of water withdrawals in the basin. (Watson 2014; Watson et al., In Press). We were unable, with existing constraints, to specifically investigate broader climatic indices such as precipitation and air temperature, nor to evaluate the issue of climate change. Although the contributing causes of observed changes in this study may be many, hydrograph changes such as we observed have been attributed in various studies to increasing consumptive water use within river basins (Baron et al. 2002; Mote et al. 2005; Rood et al. 2005, 2008) and to climate change (Vorosmarty et al. 2000; Schindler and Donahue 2006; Hall et al. 2015; Dettinger et al. 2015). For example, the magnitude of peak discharge can be affected by anthropogenic activities such as irrigation withdrawals, land use practices increasing runoff, damming of rivers, as well as changes in climate (Zelt et al. 1999; Gibson et al. 2005). Changes in the timing of peak discharge in relation to climatic factors can also differ depending on the subsurface geology as it affects how shallow and deep pathways for water contribute to the streamflow (Safeeq et al. 2013). The observed changes in stream flow magnitude and volume are thus generally consistent with current perspectives on declining snowpack, climate change, and anthropogenic forcing (e.g., water withdrawals; Vorosmarty et al., 2000; Meehl et al., 2004; Barnett et al., 2005; Mote et al., 2005; Lapp et al., 2005; Leppi 2010). The cause of the more recent changes (i.e., the 1970-2007 analysis) in magnitude and timing appears to coincide well with estimates of warming and prolonged droughts studied during the same period (Vorosmarty et al., 2000; Schindler and Donahue 2006; IPCC 2007).

There are major potential implications for competing water uses and agricultural development with declining discharges and earlier returns to baseflow. With lower discharges, especially during low flow periods, future water allocation decisions can be expected to become increasingly difficult, especially in over allocated systems, such as the Powder River. With earlier base flow, and demand for water in the basin persisting into the fall with irrigation water users withdrawing water until they harvest crops, an earlier return to baseflow will result in more users being affected on a more frequent basis. This change toward earlier baseflows may impact water allocation decisions (Dettinger 2015), and require modified water allocation strategies, such as establishing a water use hierarchy based on beneficial use or policy changes on salvage water allocations.

Of major concern is how hydrograph changes will affect each region specifically, and if the prolonged droughts and warming are going to become the norm (IPCC 2007; Luce and Holden, 2009). Lower discharge values and earlier return to baseflow have major implications for the YRB's rivers (Schindler 2001; Schindler and Donahue 2006; Arismendi et al. 2012). As the flows decline, the ability of rivers to dilute pollutant loads and avoid thermal thresholds is reduced (Schindler 2001). As the rivers are affected by an earlier onset of snowmelt and decreased discharges due to climatic and anthropogenic factors such as withdrawals (Poff et al. 1997), there will be fewer cold days and nights (IPCC 2007), warmer and more frequent hot days (IPCC 2007), and duration and frequency of droughts will increase in most land areas (Gibson et al. 2005). The natural flow reductions and reductions from withdrawals will provide little protection against rising stream temperatures (Schindler 2001; IPCC 2007). Also, it is predicted that the trend of lessening snow packs and more rising temperatures will continue (IPCC 2007). Declining trends in the magnitude and earlier return to baseflow in the highly turbid, low gradient lower mainstem will result in the water temperature increasing substantially (Arismendi et al. 2012). Site 18, representing the mouth of the YRB watershed, near Sidney, Montana, had very noticeable declines in all variables, especially since 1970. For the distinctive native fish community and important fisheries of the lower Yellowstone River (White and Bramblett 1993), the result from the Sidney Site (18), the most downriver, most cumulative site is of major concern because it provides the most accurate indication of how much water can be expected in that portion of the river.

Alterations in the magnitude and timing of flows identified in this study can be expected to affect the ecology of the river in many ways (Schindler 2001). Lower magnitude peak discharges and earlier timing of peak discharge could pose potential threats to fish and other aquatic or riparian species keying into them as cues for reproduction. Quantity and quality of in-river habitat for aquatic fauna will also be affected by the amount and timing of discharge and resulting temperature changes (Schindler 2001; Sabo and Post 2008). Declines in magnitude of discharge and earlier timing of runoff can thus be expected to have cascading effects through the ecosystem for fishes, aquatic organisms, riparian habitat and various ecological processes. Efforts to stabilize hydrographs in the face of anthropogenic factors such as irrigation withdrawals, the adjudication process, and human-induced climate change will be necessary to if the historical habitat and fauna of the Yellowstone River is to be maintained. To monitor the situation, analyses such as this study should be updated regularly to assess trends. Although the long period of analysis used in this study leads to confidence in the conclusions, continual updating of the study will provide insight into the potential influence of extreme drought or flood years on such analyses and to the conclusions reached.

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