

Hydroclimatology of the Missouri River Basin

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SUPPLEMENTAL MATERIAL

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T-tests between teleconnection indices and streamflow

Based on the GPH and SST patterns described in section 4a and shown in Figures 7-9 of the main text, we tested the association between teleconnection indices and streamflow in the Upper Missouri River Basin (UMRB) and Lower Missouri River Basin (LMRB) in the corresponding year and one year prior to the streamflow year. For estimates of ocean-atmosphere oscillations of potential importance to the basin, we used the following indices (Table S1): mean November-March North Pacific Index (NPI) for 1912-2011 as a measure of the strength of the Aleutian Low (Trenberth and Hurrell, 1994); the mean October-March PNA to estimate meridional versus zonal flow (Wallace and Gutzler, 1981; Leathers et al., 1991); the mean June through November Southern Ocean Index (SOI) as a measure of the atmospheric component of ENSO (Ropelewski and Jones, 1987; Redmond and Koch, 1991); the mean October through March and April through July NAO to estimate Atlantic pressure patterns (Hurrell 1995; Jones et al., 1997); and the mean water-year AMO as a measure of Atlantic SSTs (Enfield et al., 2001; McCabe et al. 2004).

Time series of the climate indices for 1912-2011 were compared with time series of naturalized water-year streamflow for 86 river records, including 18 naturalized records from the main stem of the Missouri River from the U.S. Army Corps of Engineers (see Table S2). We compared mean water-year flows during and one year after years when the climate indices had extreme negative values (≤ -0.75 standard deviation) to those when the indices had extreme positive values ($\geq +0.75$ standard deviation) using two-tailed permutation t -tests ($p \leq 0.1$; 10,000

23 iterations). Because of the potential for finding significant correlations by chance when testing at
24 multiple gauges, we checked for significance of obtaining a given fraction of significant results
25 for the UMRB and LMRB (significance level $\alpha = 0.1$) by testing against a binomial distribution
26 (Livezey and Chen 1983) using PCAs on the correlation matrices to estimate effective sample
27 size (Bretherton et al. 1999; Luce and Holden 2009). Results (Table S3 and Fig. S2) show
28 strongest associations between UMRB flow and PNA and LMRB flow and NAO.

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64 Table S1. Teleconnection index data summary.

Data Description	Years	Source
Atlantic Multidecadal Oscillation (AMO)	1912-2011	NOAA Climate Prediction Center ¹
North Atlantic Oscillation (NAO)	1912-2011	Climate Research Unit ²
North Pacific Index (NPI)	1912-2011	Trenberth and Hurrell ³
Pacific North American Mode (PNA)	1950-2011	NOAA Climate Prediction Center ¹
Southern Oscillation Index (SOI)	1912-2011	Climate Research Unit ²

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66 ¹ <https://www.esrl.noaa.gov/psd/data>67 ² <http://www.cru.uea.ac.uk/data/>68 ³ <https://climatedataguide.ucar.edu/guidance/north-pacific-index-npi-trenberth-and-hurrell-monthly-and-winter>

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70 Table S2. List of 86 streamflow records from the Missouri River Basin used in the comparison of
71 streamflows using permutation *t*-tests. Reported results are based on the analysis of data with
72 periods of record within 1912-2011 (i.e., some incomplete records analyzed). The same analysis
73 on smaller sets of streams with complete records for 1930-2010 and 1951-2010 gave comparable
74 results and are not shown. USGS denotes US Geological Survey; USACE denotes US Army
75 Corps of Engineers, HCDN denotes USGS Hydro-Climatic Data Network and n.a. denotes not
76 applicable.

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Site Name	Gage Record Type	Lat	Long	USGS Gage Number	Start Year	End Year
Beaverhead River at Barretts MT	Est. Natural	45.12	-112.75	6016000	1929	1989
Big Hole River near Melrose MT	Est. Natural	45.53	-112.70	6025500	1925	2011
Bighorn River near St. Xavier MT	Est. Natural	45.32	-107.92	6287000	1936	2011
Clarks Fork Yellowstone River near Belfry MT	HCDN	45.01	-109.07	6207500	1923	2011
Dearborn River near Craig MT	Infilled/Extended	47.20	-112.10	6073500	1947	2011
Gallatin River at Logan MT	Est. Natural	45.89	-111.44	6052500	1930	2002
Jefferson River near Three Forks MT	Est. Natural	45.90	-111.60	6036650	1929	2002
Judith River near mouth near Winifred MT	Est. Natural	47.67	-109.65	6114700	1929	1989
Madison River below Ennis Lake near McAllister MT	Est. Natural	45.49	-111.63	6041000	1929	2011
Madison River near Three Forks MT	Est. Natural	45.82	-111.50	6042500	1930	2010
Marias River near Chester MT	Est. Natural	48.31	-111.08	6101500	1929	2010
Milk River at Nashua MT	Modeled. Natural	48.13	-106.36	6174500	1941	2011
Missouri River at Fort Benton MT	Est. Natural	47.82	-110.67	6090800	1912	2011

Site Name	Gage Record Type	Lat	Long	USGS Gage Number	Start Year	End Year
Missouri River near Landusky MT	Est. Natural	47.63	-108.69	6115200	1929	2011
Missouri River at Toston MT	Est. Natural	46.15	-111.42	6054500	1930	2011
Musselshell River at Harlowton	Est. Natural	46.43	-109.84	6120500	1930	2010
Musselshell River at Mosby MT	Est. Natural	46.99	-107.89	6130500	1930	2010
North Platte River Near Northgate CO	HCDN	40.94	-106.34	6620000	1917	2011
Powder River near Locate MT	Est. Unregulated	46.43	-105.31	6326500	1929	2011
Ruby River near Twin Bridges MT	Est. Natural	45.51	-112.33	6023000	1940	2002
Shoshone River below Buffalo Bill Reservoir WY	Est. Natural	44.52	-109.10	6282000	1944	2011
Smith River near Eden MT	Est. Natural	47.19	-111.39	6077500	1929	2010
South Platte River at South Platte CO	Est. Natural	39.41	-105.17	6707500	1916	2011
Sun at Gibson Reservoir near Augusta MT	Est. Natural	47.60	-112.76	6079500	1929	1989
Sun River near Vaughn MT	Est. Natural	47.53	-111.51	6089000	1929	2011
Teton River near Dutton MT	Est. Natural	47.93	-111.55	6108000	1929	2011
Teton River at Loma MT	Est. Natural	47.93	-110.51	6108800	1929	1999
Tongue River at Miles City MT	Est. Unregulated	46.38	-105.85	6308500	1929	2011
Wind River below Boysen Reservoir WY	Est. Natural	43.42	-108.18	6259000	1950	2011
Yellowstone River at Corwin Springs MT	Est. Unregulated	45.11	-110.79	6191500	1912	2002
Yellowstone River near Sidney MT	Est. Unregulated	47.68	-104.16	6329500	1912	2011
Missouri River at Hermann	USACE naturalized	38.71	-91.44	n.a.	1912	2011
Missouri River at Boonville	USACE naturalized	38.98	-92.75	n.a.	1912	2011
Missouri River at Waverly	USACE naturalized	39.21	-93.52	n.a.	1912	2011

Site Name	Gage Record Type	Lat	Long	USGS Gage Number	Start Year	End Year
Missouri River at Kansas City	USACE naturalized	39.11	-94.59	n.a.	1912	2011
Missouri River at St Joseph	USACE naturalized	39.75	-94.86	n.a.	1912	2011
Missouri River at Rulo	USACE naturalized	40.05	-95.42	n.a.	1912	2011
Fort Peck Dam Inflows	USACE naturalized	48.00	-106.43	n.a.	1912	2011
Garrison Dam Inflows	USACE naturalized	47.50	-101.42	n.a.	1912	2011
Oahe Dam Inflows	USACE naturalized	44.45	-100.40	n.a.	1912	2011
Big Bend Dam Inflows	USACE naturalized	44.05	-99.45	n.a.	1912	2011
Fort Randall Dam Inflows	USACE naturalized	43.06	-98.56	n.a.	1912	2011
Gavin's Point Dam Inflows	USACE naturalized	42.85	-97.48	n.a.	1912	2011
Missouri River at Sioux City	USACE naturalized	42.49	-96.41	n.a.	1912	2011
Missouri River at Omaha	USACE naturalized	41.26	-95.92	n.a.	1912	2011
Missouri River at Nebraska City	USACE naturalized	40.68	-95.85	n.a.	1912	2011
Missouri River at Bismark	USACE naturalized	46.81	-100.82	n.a.	1912	2011
Missouri River at Culbertson	USACE naturalized	48.12	-104.47	n.a.	1912	2011
Missouri River at Wolf Point	USACE naturalized	48.07	-105.53	n.a.	1912	2011
Yellowstone River at Billings MT	HCDN	45.80	-108.47	6214500	1929	2013
Shell Creek above Shell Creek Reservoir WY	HCDN	44.51	-107.40	6278300	1957	2011
Little Bighorn River at State Line near Wyola MT	HCDN	45.01	-107.62	6289000	1940	2011

Site Name	Gage Record Type	Lat	Long	USGS Gage Number	Start Year	End Year
North Fork Powder River near Hazelton WY	HCDN	44.03	-107.08	6311000	1947	2011
Little Missouri River at Marmarth ND	HCDN	46.30	-103.92	6335500	1939	2011
Little Missouri River near Watford City ND	HCDN	47.59	-103.25	6337000	1935	2011
Apple Creek near Menoken ND	HCDN	46.79	-100.66	6349500	1946	2011
Cannonball River at Regent ND	HCDN	46.43	-102.55	6350000	1951	2011
Cedar Creek near Haynes ND	HCDN	46.15	-102.47	6352000	1951	2011
Cannonball River at Breien ND	HCDN	46.38	-100.93	6354000	1935	2011
Moreau R near Faith SD	HCDN	45.20	-102.16	6359500	1944	2011
Cheyenne River at Edgemont SD	HCDN	43.31	-103.82	6395000	1947	2011
Castle Creek above Deerfield Res Near Hill City SD	HCDN	44.01	-103.83	6409000	1949	2011
Elk Creek near Elm Springs SD	HCDN	44.25	-102.50	6425500	1950	2011
Spearfish Creek at Spearfish SD	HCDN	44.48	-103.86	6431500	1947	2011
Bad River near Fort Pierre SD	HCDN	44.33	-100.38	6441500	1929	2011
White River near Oglala SD	HCDN	43.25	-102.83	6446000	1944	2011
Little White River near Rosebud SD	HCDN	43.33	-100.88	6449500	1944	2011
White River near Oacoma SD	HCDN	43.75	-99.56	6452000	1929	2011
James River near Scotland SD	HCDN	43.19	-97.64	6478500	1929	2011
Big Sioux River near Brookings SD	HCDN	44.18	-96.75	6480000	1954	2011
Rock River near Rock Valley IA	HCDN	43.21	-96.29	6483500	1949	2011
Big Sioux River at Akron IA	HCDN	42.84	-96.56	6485500	1929	2011
Floyd River at James IA	HCDN	42.58	-96.31	6600500	1936	2011
N Platte River above Seminole Reservoir near Sinclair WY	HCDN	41.87	-107.06	6630000	1940	2011

Site Name	Gage Record Type	Lat	Long	USGS Gage Number	Start Year	End Year
Rock Creek above King Canyon Canal near Arlington WY	HCDN	41.59	-106.22	6632400	1955	2011
Medicine Bow River at Seminoe Reservoir near Hanna WY	HCDN	42.01	-106.51	6635000	1940	2011
Maple Creek near Nickerson NB	HCDN	41.56	-96.54	6800000	1952	2011
West Nishnabotna River at Randolph IA	HCDN	40.87	-95.58	6808500	1949	2011
Nishnabotna River above Hamburg IA	HCDN	40.60	-95.65	6810000	1929	2011
Little Nemaha River at Auburn NB	HCDN	40.39	-95.81	6811500	1950	2011
Turkey Creek near Seneca KS	HCDN	39.95	-96.11	6814000	1950	2011
Chapman Creek near Chapman KS	HCDN	39.03	-97.04	6878000	1955	2011
Soldier Creek near Topeka KS	HCDN	39.10	-95.72	6889500	1936	2011
Stranger Creek near Tonganoxie KS	HCDN	39.12	-95.01	6892000	1930	2011
Little Blue River near Lake City MO	HCDN	39.10	-94.30	6894000	1949	2011
Little Osage River at Fulton KS	HCDN	38.01	-94.70	6917000	1949	2011

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80 TABLE S3. Fractions of gages in Upper Missouri River Basin (UMRB) sub-region 1 and Lower Missouri
 81 River Basin (LMRB) sub-region 6 showing effects of climate oscillations on naturalized flow during
 82 1912-2011 as assessed by permutation *t*-tests ($p \leq 0.1$ significance level) for the same year and with the
 83 river flow lagging the climate indices by one year (t+1). Colors denote field significance (*p*): green $p \leq$
 84 0.01; blue $p \leq 0.05$; yellow $p \leq 0.1$; grey not significant $p > 0.1$.

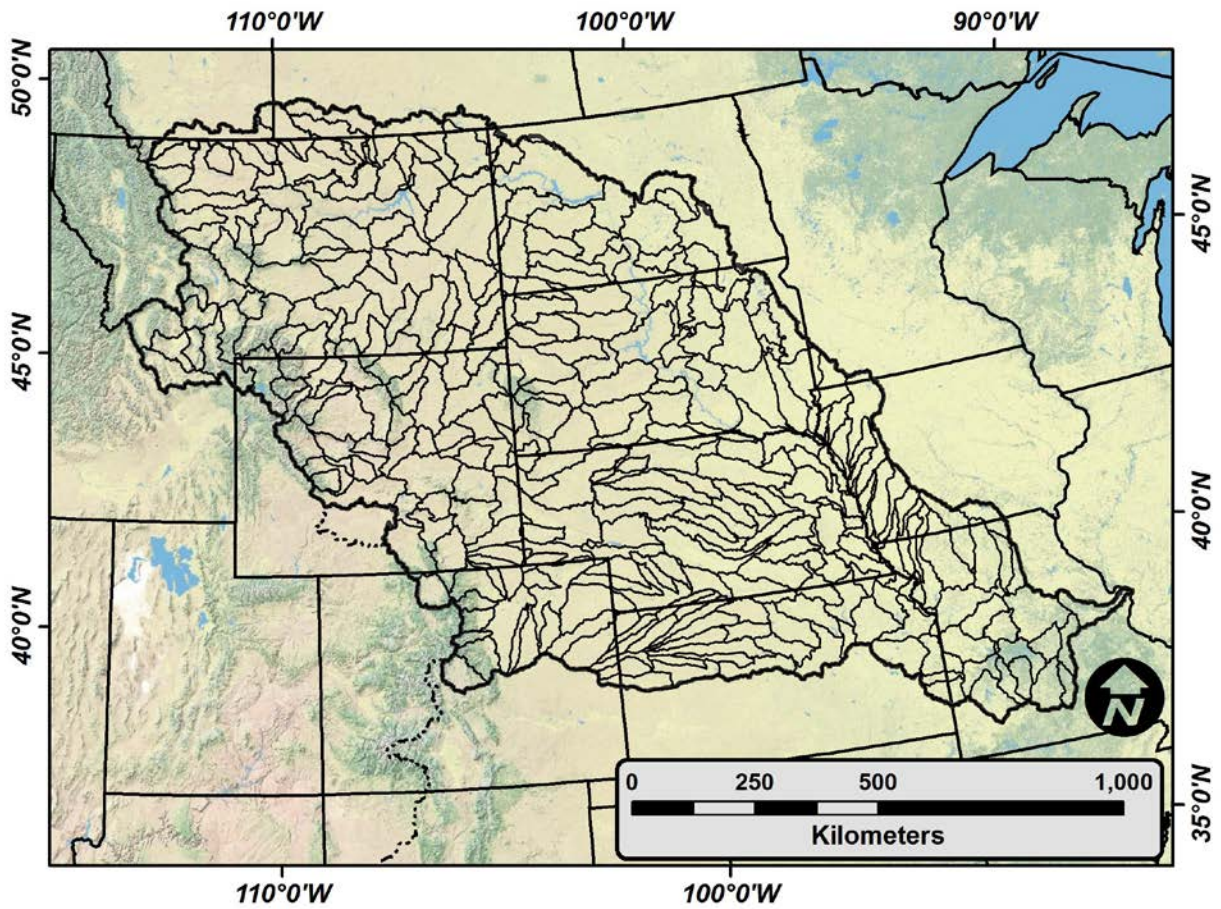
	UMRB	LMRB	UMRB (t+1)	LMRB (t+1)
NPI (Nov-Mar)	0.53	0.08	0.00	0.23
PNA (Oct-Mar)	0.78	0.00	0.00	0.00
SOI (Jun-Nov)	0.36	0.00	0.53	0.00
NAO (Oct-Mar)	0.08	0.08	0.33	0.00
NAO (Apr-Jul)	0.03	0.69	0.17	0.08
AMO (Oct-Sep)	0.58	0.31	0.50	0.69

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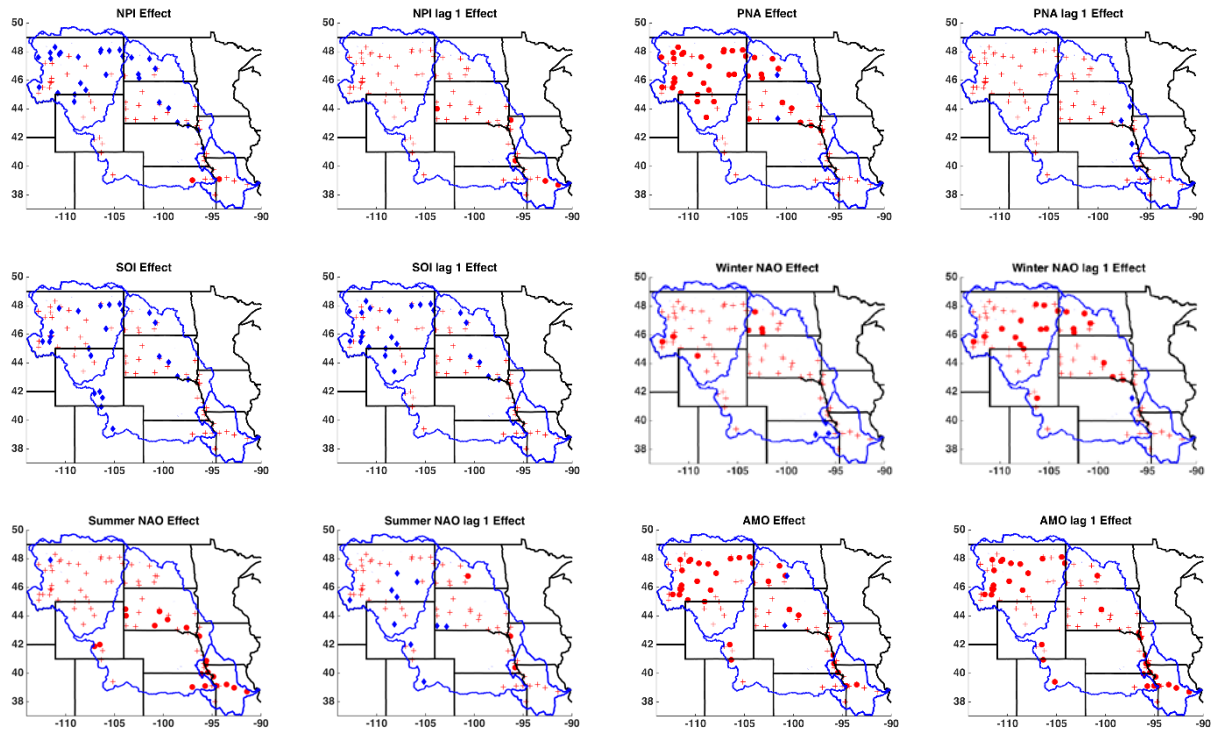
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FIGURES



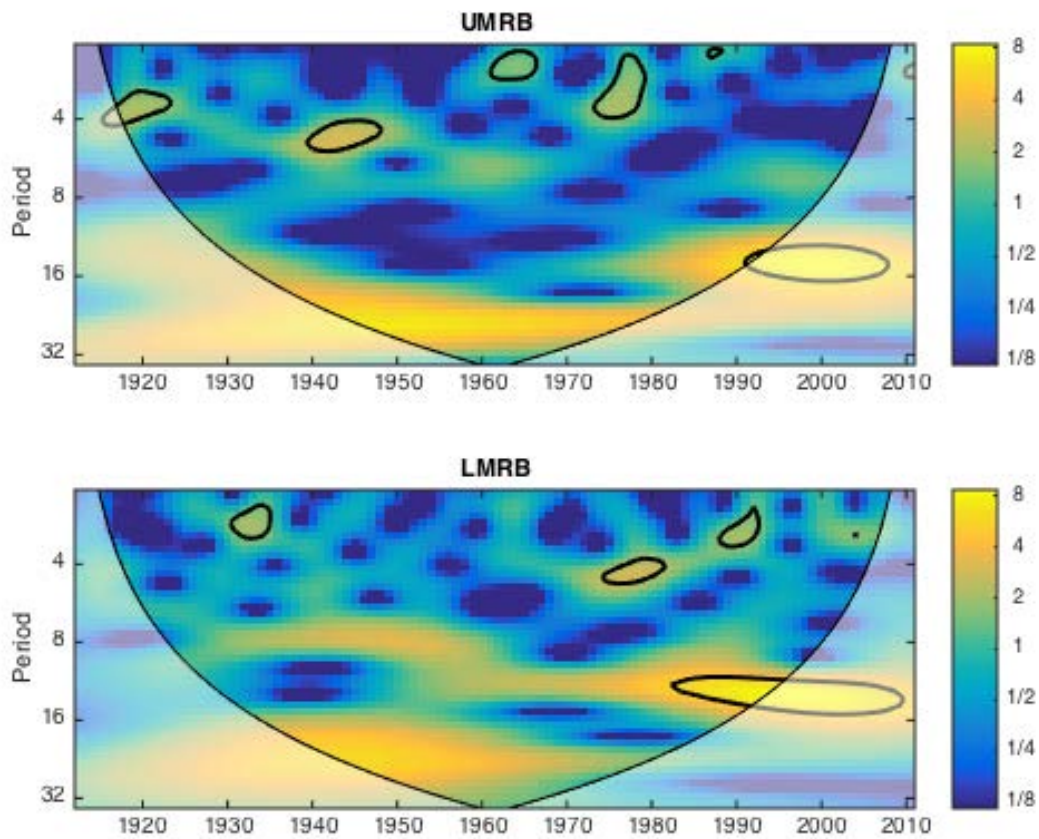
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Fig. S1. Boundaries of the 311 U.S. Geological Survey 8-digit hydrologic units in the Missouri River Basin used in the analyses described in sections 3a and 3b of the manuscript. Dot-dash line indicates the position of the Continental Divide.



96 Fig. S2. Comparisons of mean water-year streamflows during years when climate indices had
 97 extreme negative values to those when the indices had extreme positive values, using two-tailed
 98 permutation t -tests ($p \leq 0.1$) for 86 unregulated and naturalized rivers in the UMRB and LMRB
 99 (outlined in blue) for 1912-2011. Comparisons were made with mean water year flows from the
 100 same years as the climate index values and with mean water year flows from the following year
 101 of the climate index values (lag 1). A red circle denotes that flow is higher during extreme
 102 negative events of the climate index than during extreme positive events. A blue diamond
 103 denotes that flow is higher during extreme positive events of the climate index than during
 104 extreme negative events. A cross denotes no significant differences in flow between the two
 105 types of events.

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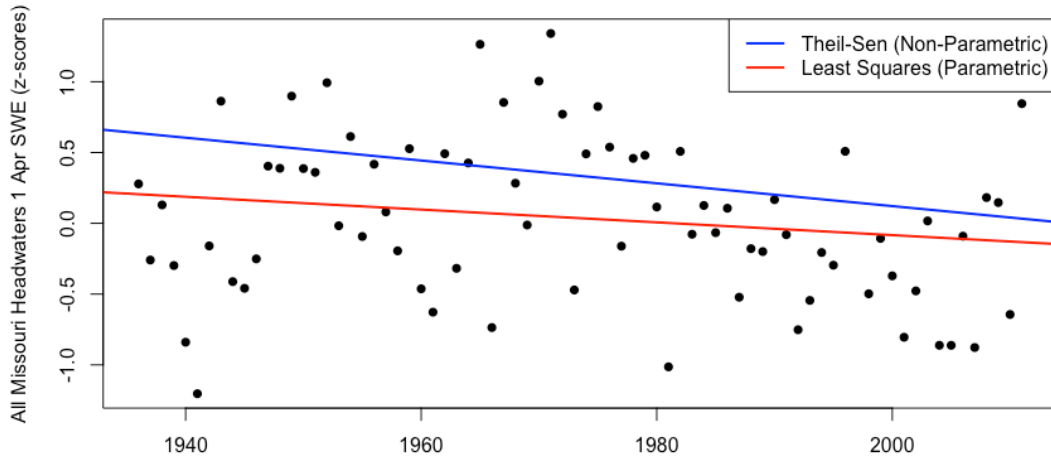


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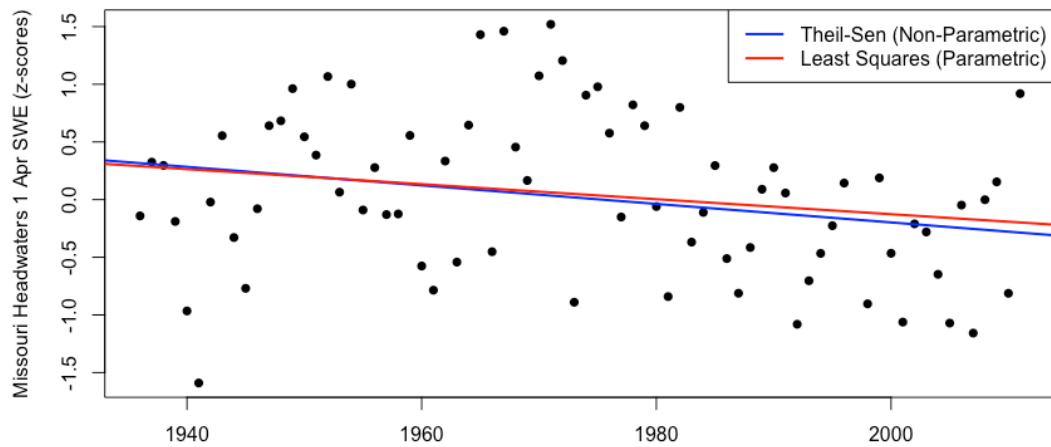
108 Fig. S3. The continuous wavelet power spectra for UMRB (top) and LMRB (bottom)
 109 streamflow. The thick black contours represent the 95% confidence level based on a red-noise
 110 background; the cone of influence, where edge effects might distort the results, is shown with
 111 lighter shading. Streamflow records were log-transformed for normality prior to wavelet
 112 analysis.

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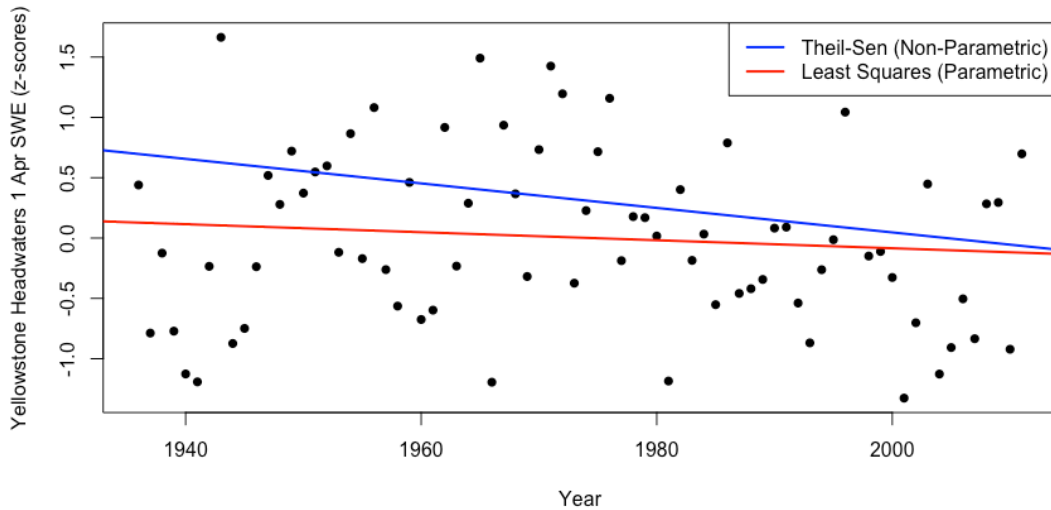
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117 Fig. S4. Comparison of calculated trends in 1 April SWE using the parametric ordinary least
118 squares and the non-parametric Theil-Sen regression approach for the entire Missouri
119 Headwaters area and the major contributing headwaters shown in Figure 10a of the main text.