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Human amplified changes in precipitation–runoff patterns in large river basins of the Midwestern United States

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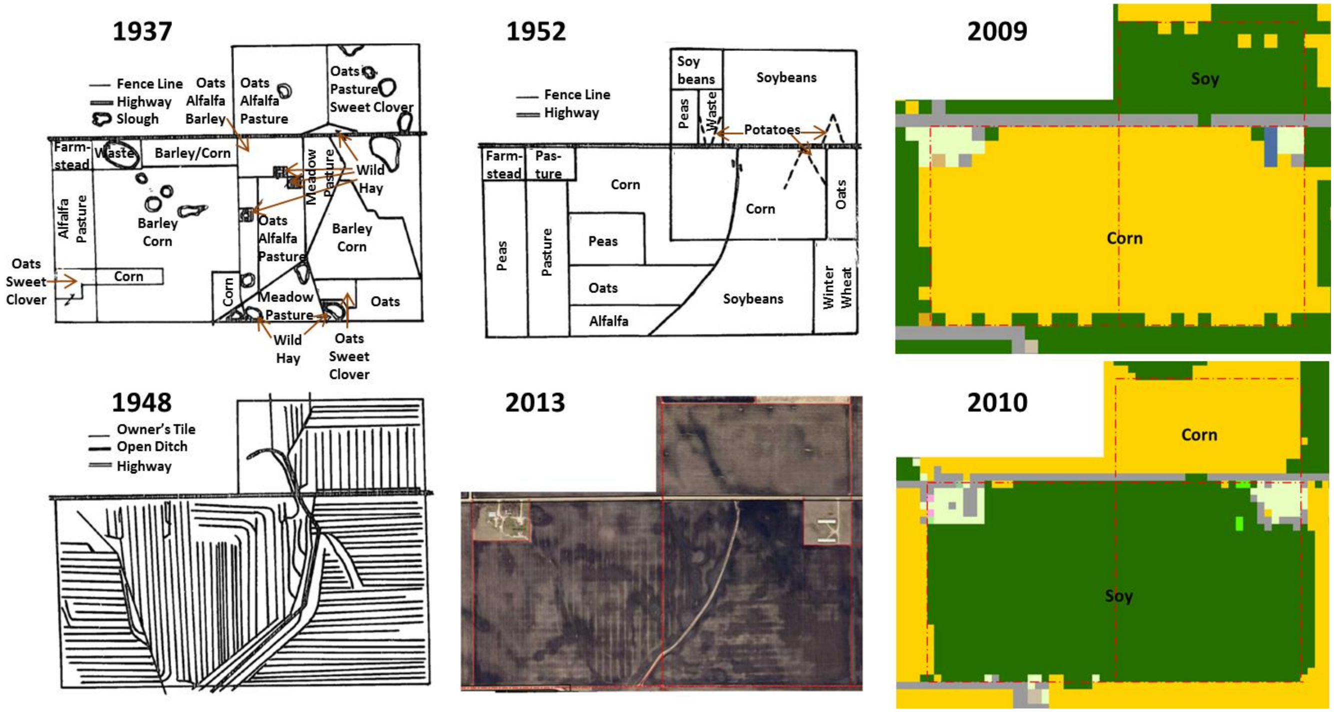

Figure S1: Field land use and tile arrangement before (1937) and after (1952) tile installation (1948) near Mapleton, MN (adapted from Burns, 1954); aerial photograph flown in spring 2013 shows the modern tile pattern remains relatively unchanged with a corn-soybean crop rotation (2009-2010), from the Cropland Data Layer (USDA NASS , 2013).

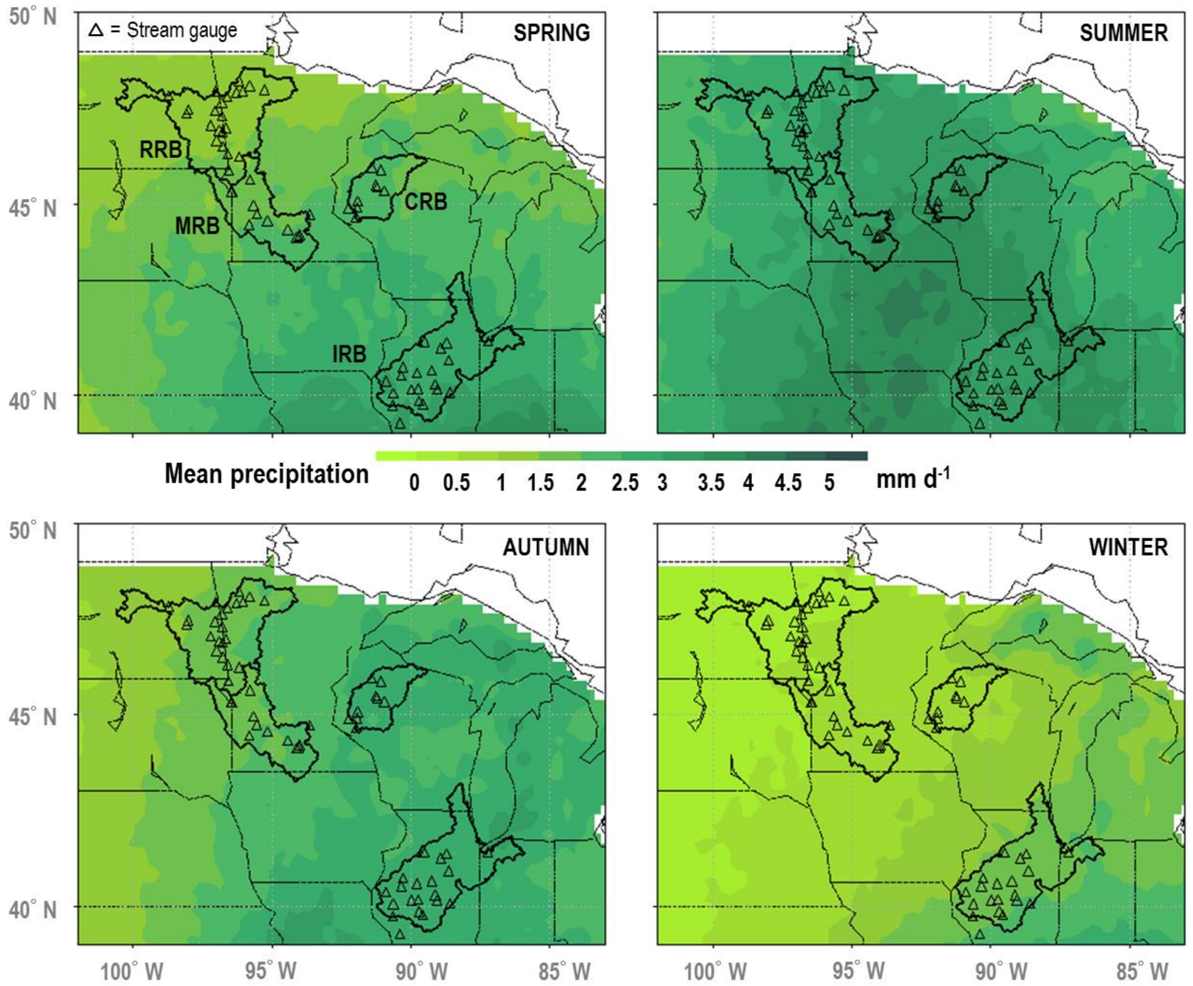

Figure S2. Seasonally averaged long term daily Parameter elevation Regression on Independent Slopes Model (PRISM) precipitation means (1981-2010) across the Upper Midwest: spring (MAM), summer (JJA), autumn (SON), and winter (DJF); USGS gauge locations for each study basin (Table 1) indicated by open triangles (PRISM Climate Group, 2004). Study basin acronyms are defined as: Red River of the North basin (RRB), Minnesota River basin (MRB), Chippewa River basin (CRB), and Illinois River basin (IRB).

Supplement of Section 3.2 - Climate records: precipitation and evapotranspiration

Comparison of monthly precipitation total reported as an average depth (cm) from Parameter elevation Regression on Independent Slopes Model (PRISM), used in this study, and Livneh et al. (2013) (L13) for each watershed is shown in Figure S3. If PRISM and L13 precipitation depths were equivalent in every month, then all points would plot on the 1:1 line. On average (1935-2011) the difference between the two monthly precipitation datasets is 1% for each study watershed.

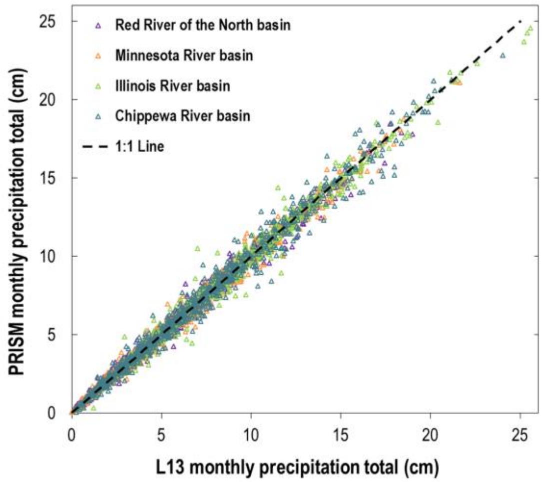

Figure S3. Spatially averaged, total monthly (cm) precipitation (1935-2011) for each watershed from Parameter elevation Regression on Independent Slopes Model (PRISM Climate Group, 2004) and Livneh et al. 2013 (L13) plotted with 1:1 line.

Figure S4 shows a comparison of monthly (March-November during 2001-2011) ET_a estimates produced by Livneh et al. (2013) (L13) with ET_p estimates (available from: http://agwx.soils.wisc.edu/uwex_agwx/sun_water/et_wimn) produced following the methods of Diak et al. (1998) (D98) for a location in the Minnesota River basin (MRB), 44 N, 94 W and the Chippewa River basin (CRB), 45.2 N, 91.6 W. On average, the estimates of ET_a are 19% (raw) and 26% (17% reduction in JJA ET_a) lower than estimates of ET_p in the MRB, and 16% (raw) and 24% (17% reduction in JJA ET_a) lower than estimates of ET_p in the CRB.

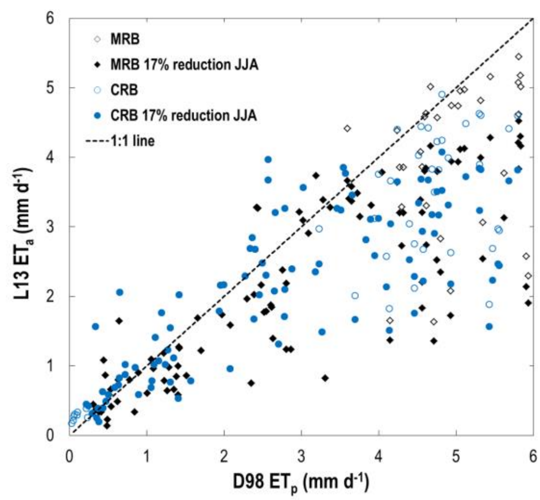

Figure S4. Monthly (March-November) average daily (mm d^{-1}) estimates of ET_p following methods of Diak et al., 1998 (D98) versus estimates of ET_a from Livneh et al., 2013 (L13) during 2001-2011.

Figure S5 shows average monthly ET_a from Livneh et al. (2013) compared against four AmeriFlux sites near the study watersheds (Table 2) as well as data from Bryan et al. (2015). In general, the L13 data show an earlier peak in ET_a for the cropland sites in Rosemount, MN and Bondville, IL, and overestimate average annual ET_a by 17% (raw) and 7% (17% reduction in JJA) for Bondville and 14% (raw) and 5% (17% reduction in JJA) for Rosemount. The L13 data overestimate ET_a at Willow Creek, WI (broadleaf deciduous forest) by as much as 31% (raw) and 19% (17% reduction in JJA) annually, and underestimate ET_a at Brookings, SD (grassland) by 29% (raw) and 34% (17% reduction in JJA) annually.

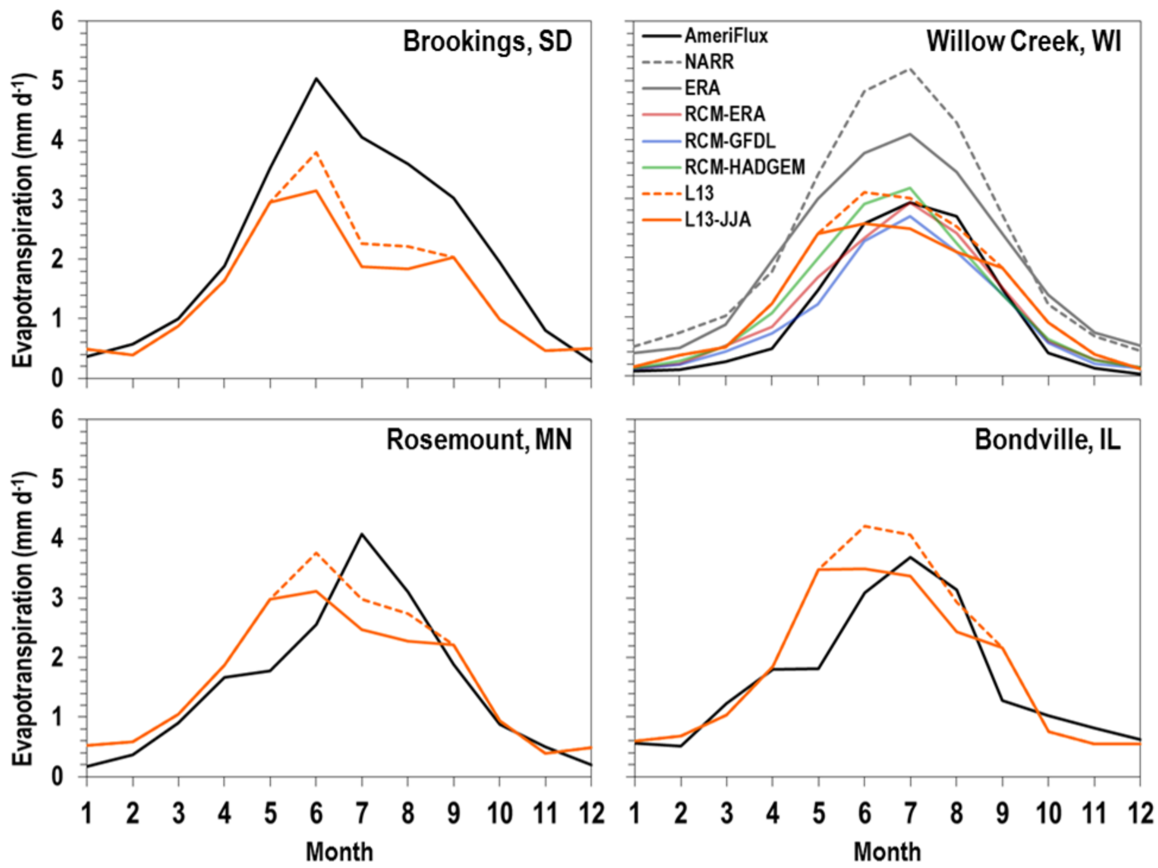

Figure S5. Average monthly evapotranspiration rate (mm d^{-1}) at four AmeriFlux sites (see Table 2) compared to modeled evapotranspiration rates used in this study (L13 & L13-JJA) and Bryan et al. 2015.

The L13 ET_a estimates were calculated in VIC using the Hansen et al. (2000) static global vegetation classification, and did not consider artificial drainage, Therefore, the dominant mechanism for losing soil water in May and June is expected to be through ET_a loss according to the L13 estimates. In contrast, ET_a losses in May and June at Ameriflux sites are relatively low since crops are absent or very young and soil water likely drains primarily via artificial drainage. We expect that the effects of drainage influence ET_a during the peak growing season as well. Because drainage improves crop growing conditions early in the growing season, late growing season ET_a may be higher in drained fields than undrained fields. This would be an interesting further line of study. Regardless, it seems reasonable that the L13 ET_a estimates would seasonally mismatch the Rosemount and Bondville Ameriflux station ET_a estimates, given the presence/absence of artificial drainage.

ET_a estimates may dramatically underestimate Ameriflux ET_a estimates in Brookings, SD due to differences in crop coefficients or misclassification of grasslands and croplands; corn has been found to have lower ET_a rates than some grasses (Hickman et al., 2010). Due to the coarse resolution of the global vegetation input for the L13 VIC model, parts of southern Wisconsin appear to be misclassified as broadleaf deciduous forest instead of cropland. Some studies in the Great Lakes region report broadleaf deciduous forest to have slightly higher annual ET_a rates than cropland (Mao and Cherkauer, 2009; Mishra et al., 2010). Likely of larger significance is that Livneh et al. (2013) and Maurer et al. (2002) do not suggest that they considered lake and wetland effects on evapotranspiration, which in the Great Lakes region can be significant (Bryan et al., 2015). Furthermore, the Hansen et al. (2000) global vegetation classification masks bodies of water, as the land cover input.

The fact that the L13 ET_a estimates mismatch Ameriflux estimates seasonally provides assurance that the L13 ET_a estimates are appropriate for testing our hypothesis. The lack of artificial drainage is what allows us to test whether factors beyond climate contribute to modern streamflow increases in the Midwestern US.

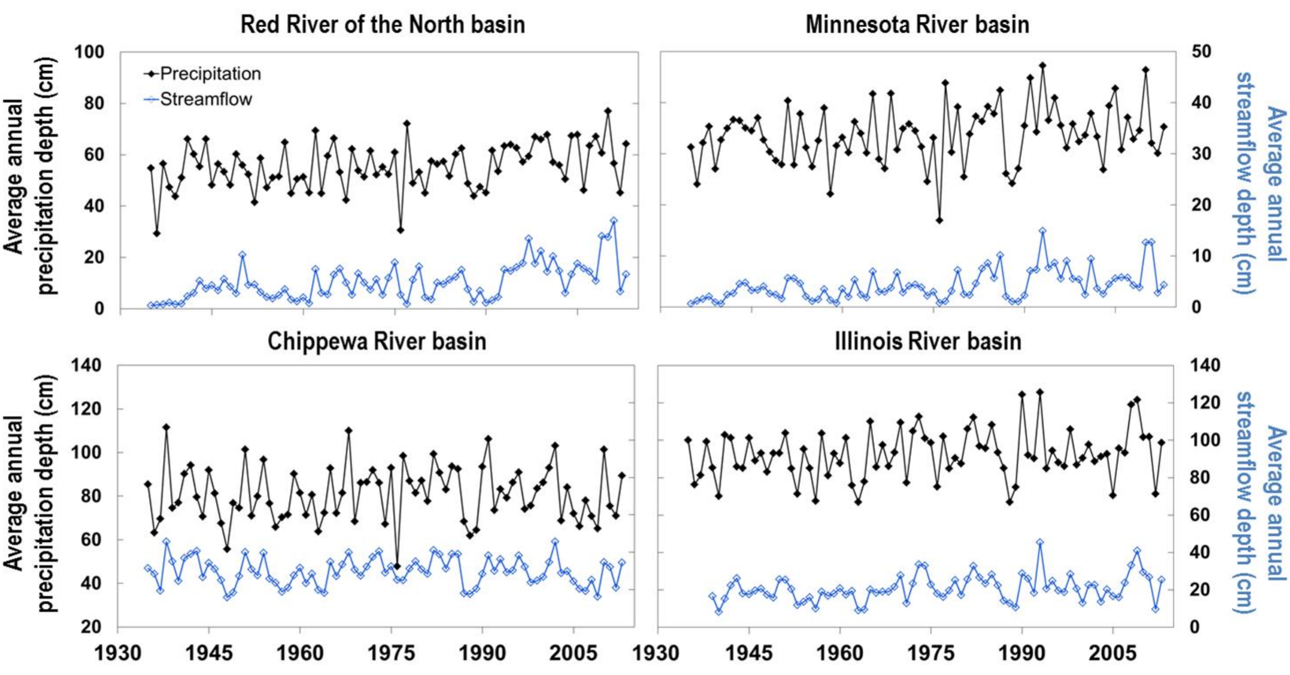

Figure S6. Annual, spatially averaged watershed precipitation and streamflow depths (cm) for each study basin.

Table S1. Resulting p-values of 624 statistical tests (t-test and Kolmogorov–Smirnov [KS]-test) comparing pre-period and post-period flow and precipitation based on the 1974/1975, piecewise linear regression (PwLR), and land cover transition (LCT) breakpoints for each basin (Table 3). P-values are highlighted based on their significance: bolded values are p-values with 95% confidence level or greater, grey values are p-values with less than a 95% confidence level, and black values are p-values where significance depends on the breakpoint. Italicized grey values reported for the CRB are not reliable because the post-period includes fewer than 10 years of data.

		Flow: t-test			Flow: KS-test			Precipitation: t-test			Precipitation: KS-test		
		74/75	**PwLR**	**LCT**	**74/75**	**PwLR**	**LCT**	**74/75**	**PwLR**	**LCT**	**74/75**	**PwLR**	**LCT**
Chippewa River basin	January	0.341	0.893	*0.846*	0.653	0.958	*0.902*	0.278	0.097	*0.214*	0.223	0.050	*0.082*
	February	0.372	0.680	*0.851*	0.449	0.878	*0.953*	0.337	0.039	*0.309*	0.446	0.071	*0.367*
	March	0.566	0.871	*0.525*	0.219	0.749	*0.205*	0.188	0.369	*0.574*	0.234	0.348	*0.700*
	April	0.468	0.267	*0.719*	0.506	0.152	*0.416*	0.192	0.277	*0.258*	0.169	0.308	*0.575*
	May	0.826	0.485	*0.264*	0.482	0.311	*0.622*	0.933	0.374	*0.187*	0.906	0.697	*0.445*
	June	0.900	0.552	*0.211*	0.908	0.628	*0.142*	0.833	0.434	*0.117*	0.945	0.587	*0.246*
	July	0.706	0.775	*0.308*	0.584	0.893	*0.606*	0.463	0.609	*0.358*	0.567	0.794	*0.360*
	August	0.174	0.508	*0.364*	0.354	0.450	*0.200*	0.496	0.945	*0.769*	0.760	1.000	*0.856*
	September	0.517	0.990	*0.723*	0.357	0.958	*0.654*	0.286	0.912	*0.752*	0.657	0.925	*0.654*
	October	0.103	0.778	*0.593*	0.110	0.887	*0.817*	**0.022**	**0.026**	*0.304*	0.097	0.073	*0.423*
	November	0.240	0.894	*0.713*	0.337	0.887	*0.902*	0.510	0.905	*0.806*	0.375	0.944	*0.874*
	December	0.263	0.973	*0.806*	0.387	0.971	*0.931*	0.380	0.135	*0.062*	0.337	0.175	*0.045*
	Annual	0.499	0.793	*0.340*	0.721	0.918	*0.291*	0.243	0.571	*0.295*	0.246	0.764	*0.614*
Illinois River basin	January	0.123	0.030	0.092	0.136	0.079	0.265	0.543	0.250	0.529	0.454	0.425	0.211
	February	0.355	0.082	0.184	0.353	0.043	0.216	0.224	0.108	0.764	0.433	0.359	0.899
	March	0.035	0.062	0.045	0.104	0.114	0.099	0.649	0.777	0.619	0.619	0.836	0.828
	April	0.174	0.438	0.158	0.335	0.479	0.353	0.780	0.832	0.588	0.883	0.947	0.638
	May	0.182	0.344	0.155	0.126	0.398	0.161	0.212	0.113	0.326	0.063	0.063	0.138
	June	0.105	0.077	0.280	0.082	0.071	0.117	0.798	0.742	0.845	0.811	0.643	0.954
	July	0.451	0.411	0.525	0.518	0.436	0.614	0.453	0.585	0.214	0.585	0.519	0.443
	August	0.090	0.249	0.212	0.181	0.508	0.259	0.054	0.408	0.257	0.037	0.475	0.108
	September	0.004	0.062	0.009	0.003	0.111	0.041	0.511	0.465	0.118	0.685	0.728	0.113
	October	0.074	0.147	0.065	0.082	0.139	0.142	0.142	0.072	0.363	0.113	0.143	0.378
	November	**0.034**	**0.007**	**0.041**	0.075	0.008	0.074	0.023	0.004	0.109	0.053	0.013	0.045
	December	**0.021**	**0.011**	**0.010**	**0.040**	**0.019**	**0.022**	0.122	0.081	0.039	0.136	0.203	0.050
	Annual	**0.011**	**0.019**	**0.017**	**0.012**	**0.018**	**0.020**	0.086	0.075	0.085	0.117	0.141	0.183
Minnesota River basin	January	**0.000**	**0.000**	**0.000**	**0.001**	**0.000**	**0.000**	0.096	0.520	0.182	0.369	0.672	0.338
	February	**0.000**	**0.000**	**0.000**	**0.002**	**0.000**	**0.000**	0.722	0.842	0.659	0.540	0.938	0.604
	March	**0.007**	**0.005**	**0.002**	0.089	0.055	0.074	0.017	0.394	0.060	0.107	0.515	0.148
	April	**0.041**	**0.039**	**0.016**	**0.011**	**0.034**	**0.003**	0.159	0.164	0.239	0.489	0.344	0.684

	May	**0.000**	**0.001**	**0.000**	**0.001**	**0.001**	**0.001**	0.716	0.366	0.469	0.807	0.657	0.636
	June	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	0.500	0.957	0.418	0.807	0.879	0.677
	July	**0.002**	**0.007**	**0.000**	**0.021**	**0.020**	**0.003**	0.300	0.107	0.151	0.351	0.230	0.223
	August	**0.008**	**0.012**	**0.000**	**0.017**	**0.040**	**0.001**	0.239	0.641	0.133	0.097	0.806	0.064
	September	0.017	0.062	0.001	0.106	0.225	0.015	0.224	0.077	0.242	0.334	0.112	0.261
	October	**0.002**	**0.001**	**0.000**	**0.012**	**0.007**	**0.002**	0.082	0.015	0.029	0.115	0.088	0.116
	November	**0.001**	**0.000**	**0.000**	**0.006**	**0.000**	**0.001**	0.262	0.418	0.380	0.260	0.519	0.445
	December	**0.000**	**0.000**	**0.000**	**0.002**	**0.000**	**0.000**	0.435	0.138	0.385	0.608	0.457	0.413
	Annual	**0.000**	**0.000**	**0.000**	**0.001**	**0.001**	**0.000**	0.033	0.072	0.011	0.098	0.199	0.051
Red River of the North basin	January	**0.000**	**0.000**	**0.005**	**0.005**	**0.000**	**0.013**	0.117	0.169	0.412	0.112	0.105	0.368
	February	**0.000**	**0.000**	**0.016**	**0.003**	**0.000**	**0.034**	0.155	0.321	0.050	0.246	0.326	0.183
	March	0.006	0.012	0.171	0.011	0.005	0.217	0.050	0.108	0.021	0.062	0.247	0.054
	April	0.069	0.079	0.036	0.105	0.102	0.115	0.981	0.902	0.619	0.974	0.823	0.574
	May	**0.016**	**0.003**	**0.004**	0.059	0.013	0.014	0.321	0.039	0.046	0.312	0.129	0.186
	June	**0.015**	**0.000**	**0.001**	**0.038**	**0.002**	**0.001**	0.170	0.138	0.351	0.105	0.032	0.569
	July	**0.000**	**0.000**	**0.001**	**0.001**	**0.000**	**0.005**	0.288	0.251	0.886	0.244	0.418	0.943
	August	**0.000**	**0.000**	**0.013**	**0.000**	**0.000**	**0.043**	0.687	0.551	0.681	0.598	0.650	0.786
	September	**0.002**	**0.000**	**0.024**	0.002	0.000	0.084	0.094	0.036	0.047	0.009	0.013	0.081
	October	**0.003**	**0.000**	**0.010**	0.003	0.002	0.053	**0.010**	**0.015**	**0.002**	**0.011**	**0.003**	**0.004**
	November	**0.000**	**0.000**	**0.001**	**0.000**	**0.000**	**0.003**	0.409	0.560	0.918	0.270	0.341	0.943
	December	**0.000**	**0.000**	**0.000**	**0.001**	**0.000**	**0.013**	0.487	0.058	0.000	0.639	0.071	0.002
	Annual	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.005**	**0.019**	**0.004**	**0.009**	**0.010**	**0.008**	**0.027**

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