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Annual Stream Runoff and Climate in Minnesota's River Basins

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ABSTRACT

Stream flows recorded by the USGS from 1946 to 2005 at 42 gauging stations in the five major river basins of Minnesota and tributaries from neighboring states were analyzed and related to associated climate data. Goals of the study were (1) to determine the strength of the relationships between annual and seasonal runoff and climatic variables in these river basins, (2) to make comparisons between the river basins of Minnesota, and (3) to determine trends in stream flows over time. Climatic variables were air temperature, precipitation, the Palmer Drought Severity Index (PDSI), and the Palmer Hydrological Drought Index (PHDI); the latter are common indices of soil moisture. Water year averages showed stronger correlations than calendar year averages. Precipitation was a good predictor of stream flow, but the PDSI was the best predictor and slightly better than PHDI when linear regressions at the annual timescale were used. With an exponential regression PDSI gave a significantly better fit to runoff data than PHDI. Five-year running averages made precipitation almost as good a predictor of stream flow (runoff) as PDSI.

A seasonal time scale analysis revealed a logical stronger dependence of stream flow on precipitation during summer and fall than during the winter and spring, but all relationships for seasonal averages were weaker than for annual (water year) averages. Dependence of stream runoff on PDSI did not vary significantly by season.

On a monthly timescale the strength of correlation between precipitation and runoff dropped off significantly, while PDSI was still a decent predictor in all months but the spring.

Annual stream flow in the Upper Mississippi River Basin, including the Minnesota River Basin, had the strongest dependence on precipitation and PDSI. The Red River of the North Basin showed lower than average dependence on precipitation and average dependence on PDSI.

The Rainy River Basin and the Lake Superior Basin showed the weakest dependence of annual stream flow on precipitation and PDSI.

The relationship between stream flow and precipitation can be expressed most easily by an annual average runoff coefficient, i.e. the ratio of runoff to precipitation in a year. Runoff coefficients vary significantly across the state of Minnesota, from more than 0.4 in the northeast to less than 0.1 in the northwest. Trends in runoff coefficients were estimated from averages for 20-year periods from 1926-1945 to 1986-2005, although data for 1926-1945 were sparse. According to our analysis, runoff coefficients in some of the major river basins of Minnesota have increased significantly during the last 40 years.

The Lake Superior and Rainy River Basins have high and invariant characteristic runoff coefficients around 0.35. The Red River Basin has the lowest characteristic runoff coefficient at ~0.14 but its value has consistently increased from the beginning of the record. The Mississippi Headwaters Basin characteristic runoff coefficient has increased to ~0.24. The Minnesota River Basin runoff coefficient (from the Minnesota River at Jordan, MN station) has also increased significantly and consistently to 0.19. The largest increases in runoff coefficients were found in the Red River and the Minnesota River Basins, the two basins with the lowest runoff coefficients; runoff coefficients in some tributary or sub-watersheds have doubled. In the Lake Superior and Rainy River Basins, and in the St. Croix River watershed, little change in runoff coefficients was found.

Overall runoff coefficients drop significantly from east to west in Minnesota. This distribution does not seem to have changed over time. Increases in runoff coefficients over time have been highest in the west, and lowest in the east of Minnesota. One can hypothesize that changes in stream flow in Minnesota's west are mainly due to land use changes that have lead to faster and easier surface runoff from the land since the beginning of European settlement. An explanation based on climatological factors can, however, also be offered. Precipitation has increased in all of the river basins of Minnesota over the time period of 1926 to 2005, but the largest changes have occurred in the south and west and little change in the northeast of Minnesota.

Changes in total annual runoff (in/yr) between 1946 - 1965 and 1986 – 2005 increased at 38 of 42 stream gaging stations analyzed. Only 4 gaging stations, 3 in the Lake Superior and Rainy River Basins showed decreases, with all being less than 3%. The largest increases in average annual runoff were at 19 gaging stations in the Red River and Minnesota River Basins; at 17 of these, increases were from 60% to 132%, and at the remaining two stations the increases were 19% and 20%. The southern Minnesota watersheds with the largest increases in runoff also had the largest increases in precipitation.

Overall, stream flow, expresses as annual runoff (in/yr), has increased since the beginning of stream gaging in Minnesota and the Upper Midwest, although periods of substantially lowered stream flows have occurred, e.g. in the drought period of the 1930s. Not only has the runoff (cm/yr) increased, but runoff coefficients, i.e. the ratio of runoff to precipitation, have also increased. When viewed as a percent change of annual runoff, the largest stream flow changes have occurred in the western part and the lowest in the eastern part of Minnesota. Increases in absolute values of annual runoff, percent of runoff, and runoff coefficients have been quantified in this study.

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1. INTRODUCTION

Minnesota is the headwaters region of rivers that drain into the Gulf of Mexico, the Gulf of St. Lawrence and into Hudson Bay. Water originating in Minnesota's river basins is important not only to the state, but also to other U.S. states and Canadian provinces. Historical annual stream flow and climate data of Minnesota and its neighboring states are analyzed in this report.

Stream flow information is needed to assess water balances, to plan water supplies, to design river bank and flood protection works, to manage water quality and recreational water uses, and more. The availability of fresh water is affected by urbanization, agricultural land use changes, and global climate change; freshwater availability is of increasing concern in many regions of the world. Many cities, including several in Minnesota, get their water supply from rivers or groundwater, and discharge treated wastewater into rivers. Streams and rivers in Minnesota are also used for hydropower and recreation (e.g., boating and fishing). The Mississippi and the Minnesota River are navigable waterways. Stream flows depend on climatologic, geographic, geologic, and anthropogenic factors. Land use changes, especially urbanization and agriculture, affect the amount of rainfall that is lost to evapotranspiration and infiltration and therefore affect the amount of runoff and the time over which the runoff occurs. Urban development and agricultural drainage tends to increase runoff and leads to higher flow rates in the streams and rivers that receive the runoff. Stream flow is without doubt important to Minnesota, and analyzing and projecting stream flows is therefore of interest.

The hydrologic cycle is driven by meteorological variables, notably precipitation and evaporation. Precipitation in the form of rain and snow is the major water input for the vast majority of watersheds in the world. Air temperature affects evapotranspiration in many types of watersheds of different climate, vegetation, and land use. Changes in precipitation and air temperature can be expected to play roles in changes of stream flow.

The hydrologic cycle also responds strongly to watershed characteristics. Indices have been developed to assess the overall moisture conditions of regions on different spatial and temporal scales. Some of these indices have been created to determine when an area is experiencing drought and when it is experiencing water surplus. A well known and widely used index is the Palmer Drought Severity Index (PDSI) (Palmer 1965). The PDSI is region-specific and is based on a supply and demand model of soil moisture. PDSI is calculated based on the hydrologic characteristics of the region and on the precipitation and temperature data recorded during and preceding the time period of interest. The PDSI is centered at zero; negative numbers indicate that the region is experiencing drought and positive numbers indicate wetter than normal conditions. It is to be expected that PDSI is correlated with stream flow. Other indices such as the Palmer Hydrological Drought Index (PHDI) and the Standardized Precipitation Index (SPI) also give indications of the moisture availability of a region. Weber and Nkemdirim (1998) reviewed the PDSI and PHDI indices and recommended that PDSI be used for future hydrologic planning such as reservoir operation as it responds at least one month faster to changing moisture conditions. Their study, however, did not look at the relationship between the indices and stream flows.

There has been much speculation on the impact of global climate change on global water resources. Increases in global air temperatures are expected to create a more active hydrologic cycle, leading to more intense and larger precipitation events as well as increasing evapotranspiration rates (IPCC 2007). If strong relationships between climatic variables and stream flows can be determined from past records, the projected climatic variables can be used to estimate future stream flow rates. Kletti and Stefan (1997) attempted to model seasonal flows in three Minnesota streams using just four climatic parameters and no watershed inputs and had disappointing results, although they did obtain some decent fits (max $r^2 = 0.69$). Climate inputs from global circulation models have been used to project climate change effects on runoff (Kletti and Stefan, 1997) and water quality (Hanratty and Stefan, 1998) with differing results. Models for predicting future stream flows from historical relationships with minimal to no model input about the geology, topography, and land use of a basin could be simpler and more reliable than existing process-based hydrologic runoff models, for example the U.S. Department of Agriculture's Soil and Water Assessment Tool (SWAT) or the Army Corps of Engineers Hydrologic Modeling System (HEC-HMS). One of the objectives of this study is to look for direct relationships between flows in Minnesota's streams and rivers, and climatic variables that could be used for future modeling.

Previous studies have shown that stream flows in Minnesota's watersheds and around the United States are changing. Novotny and Stefan (2007) found that peak summer flows in gaged Minnesota streams are increasing, as are the number of high flow days and base flow rates, while spring stream flows fed by snowmelt runoff are remaining relatively constant. Dadaser-Celik and Stefan (2009) analyzed flow duration curves created with daily flow data for two time periods, 1946-1965 and 1986-2005, and found that average annual and low flows in the Minnesota, Upper Mississippi, and Red River basins have increased from mid-1900s flows. Just north of Minnesota, with a major input from the Rainy River basin, mean annual flows in the Winnipeg River have increased by 58% since 1924, due mostly to increased winter flows (St. George, 2007).

In the Great Lakes Region, between 1956 and 1988, Southern Wisconsin and mainland Michigan streams saw linearly increasing mean annual flows due to increases in fall and winter runoff, while New York and eastern Ohio streams displayed sharply increased fall flows (Johnston and Shmagin, 2008). In Indiana, there have been increases in low and medium flows but high flows have remained relatively unchanged (Kumar et al., 2009). In the Pacific Northwest the variance in annual flows has increased, mainly due to lower flows in dry years, however, 75-percentile flows have remained largely unchanged (Luce and Holden, 2009).

We are not only interested in absolute runoff values, but also in runoff coefficients. A runoff coefficient is a dimensionless ratio of the volume of runoff during a time period to the volume of precipitation over the watershed in the same time period. A runoff coefficient shows the relationship between runoff and precipitation in a watershed over a certain time period, e.g. a year. Runoff coefficients can be calculated for individual watersheds over any time period in which flow and precipitation data were measured converted to height (e.g., mm) of water over the entire. Runoff coefficients theoretically vary between 0 and 1.0 and depend on geology, topography, soils, and land use, particularly perviousness and vegetation cover within the watershed, as well as rainfall intensities. Snowfall often produces no immediate runoff, and the short-term runoff coefficient is 0; melting snow will contribute to the long-term runoff coefficient; if precipitation runs off a paved surface without losses, the runoff coefficient is 1.0. Changes in runoff coefficients for given basins with respect to time can give insight into the effects of land use or climate change that have occurred.

An objective of this study is to analyze stream flows, and to determine annual runoff coefficients for the major river basins of Minnesota. We also want to determine if, where and by how much runoff (in/yr) and runoff coefficients (-) have changed over the time that stream flow has been gaged in Minnesota.

Changes in runoff coefficients in the Upper Midwest in the past 150 years are most likely more related to the dramatic land use changes that have occurred rather than climate changes. However, historical stream flow records cover only a much shorter period of 50 to 100 years, including potentially significant climate change effects in the recent 20 years. Our analysis of runoff and runoff coefficients in Minnesota may show significant changes, but may not fully explain the causes of the observed changes, because changes in climate, land use, and water use are potential causes of stream flow changes. Only in watersheds and over time periods in which two of the three have not changed, will the cause of stream flow change be obvious. In other situations, more detailed analysis will be necessary. Brief descriptions of the major river basins and the climate of Minnesota and the Upper Midwest are given in Dadaser-Celik and Stefan (2009) and are reproduced in Appendix A.

This report will present the methods, results, interpretations, and conclusions of an analysis of historic stream flows and climatic data in Minnesota. The report focuses on stream flow and different climatic variables and indices. Strengths of empirical relationships (correlation r^2 values), geographic distributions in Minnesota, and historical trends will be analyzed. Results will be given in terms of absolute values of annual stream flows (runoff) and precipitation, runoff coefficients, and historical trends and changes in terms of absolute values or percentages for the watersheds of Minnesota and portions of surrounding states.

2. OBJECTIVES AND METHODS

Stream flows recorded by the USGS from 1926 to 2005 at gauging stations in the major river basins of Minnesota and its tributaries from neighboring states will be analyzed and related to associated climate data. Goals of the study are (1) to determine the strength of the relationships between annual and seasonal runoff and climatic variables in river basins and tributary watersheds, (2) to determine trends in stream flows over time, and (3) to make comparisons between the major river basins of Minnesotae. In a previous version of this report stream flow was quantified in terms of cfs and precipitation in terms of inches per year. In this study stream flow will be analyzed in terms of runoff in cm/year; a dimensionless annual runoff coefficient will be calculated as the ratio of annual runoff to annual precipitation; change of runoff will be calculated as the difference between different periods, or as a percentage of previous stream flows. Climatic variables will be air temperature, precipitation, the Palmer Drought Severity Index (PDSI), and the Palmer Hydrological Drought Index (PHDI).

One major objective of this study is to determine relationships between climatic variables and stream runoff at different time scales in watersheds across the state of Minnesota. The analysis will be completed using stream flow data from USGS gaging stations across the state and a few from neighboring states. The climatic variables used in the analysis will come from a variety of sources, mostly through the Minnesota State Climatology Office at the University of Minnesota and National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA), and will include precipitation, air temperature, Palmer Drought Severity Index (PDSI), and Palmer Hydrological Drought Severity Index (PHDI).

The easiest way to express the overall relationship between precipitation and runoff in a watershed is by a runoff coefficient. The runoff coefficient is the ratio of runoff to precipitation for a watershed over a time period. It includes the cumulative effects of several watershed and rainfall characteristics, such as topography, surface geology, soil characteristics (permeability, porosity), vegetation cover and land use. The runoff coefficient is a dimensionless number and gives the fraction of the precipitation that runs off from a watershed over a given time period.

The runoff analysis will be completed mainly on the annual time scale, including the annual calendar (January-December) and water year (October-September) scales, but the seasonal and the monthly time scales will not be ignored. Overall period of record (P.O.R.) averages will be calculated as well as time period averages to analyze how runoff and runoff coefficients have changed over time. The time periods used were 1926-1945, 1946-1965, 1966-1985, and 1986-2005 for consistency with past analysis. The 1926-1945 period spans a period largely characterized by widespread and longterm drought. The 1946-1965 and 1986-2005 time periods were used earlier for change analysis as the 40 year difference between the period centers was considered sufficient to highlight changes that have occurred recently (Dadaser-Celik and Stefan, 2009).

Many large land use changes, including the conversion of vast areas of prairie and forests and drainage of wetlands for agriculture, basin wide clear-cut logging, mining, and initial urban development occurred well before the USGS and other agencies began continuously monitoring the stream flows in Minnesota, and thus data is unavailable to calculate historic runoff coefficients, although this information would no doubt be incredibly useful in determining land use change effects and the extent of hydrologic change that human settlement and development have caused.

The analysis will first be conducted for an annual time scales. Annual runoff will be correlated with annual precipitation, annual average temperature, and annual average PDSI and

PHDI for each basin. Correlation strength is described by the coefficient of determination (r^2). In first approximation the data will be described with a best fit linear regression, however exponential fits will also be explored. Running averages of average runoff, precipitation, and PDSI will be computed and analyzed to reveal relationships between multi-year parameter averages. It is hypothesized that total annual precipitation, PDSI, and PHDI are well correlated with annual runoff. There is little expectation that average temperatures would be well correlated with runoff.

The analysis will be expanded to seasonal and monthly time scales. *Cool* months are defined as November through April and *warm* months are defined as May through October. *Winter* months are December, January, and February, when air temperatures are mostly below freezing, and precipitation is in the form of snow which does not immediately run off. Stream flow in the winter is fed mostly by groundwater (baseflow) and infrequent snowmelt events. The relationship between precipitation and runoff in Minnesota in winter is expected to be poor. Stream flows in *spring* are very much controlled by snowmelt runoff and are therefore also not expected to have a good relationship with monthly precipitation and other monthly climatic variables, although air temperature may show correlation due to its role in snowmelt. Stream flow in the *summer* and *fall* months are expected to have the strongest relationships with climatic variables. Precipitation is a major contributor to stream flow and PDSI, calculated on a monthly scale, will be a good measure of general water availability in the region. Analyses will also be completed for individual months.

A gage will be required to have a minimum of 18 years of data for a 20-year period to be considered representative and used in calculations, with the exception of the earliest time period where 15 years will be accepted for the purpose of including more gages in the period when many gages were being installed. Average flow at a gage will be converted to total runoff in height of water (mm) over the watershed by determining the total flow volume and dividing by the watershed area. The total runoff will be divided by the total precipitation (also in mm) to calculate the runoff coefficient during the specific time period.

The accuracy of the runoff coefficient calculations depends on the accuracy of the watershed area. Digital information on watershed boundaries for each stream gage were needed for averaging of climatic variables from multiple weather stations, and for determining drainage areas needed for runoff coefficient calculations. In most cases, the locations of stream gages did not agree well with watershed boundaries defined in readily available GIS datasets (e.g., MN DNR) as the gages were not usually located at the watershed outlet. The USGS's National Elevation Dataset (NED) contains a 30-meter gridded digital elevation model (DEM) that covers the majority of the United States. NED data was obtained and used in ESRI ArcGIS 9.2 for semi-automatic watershed boundary delineation using the gage locations as watershed outlets. GIS tools (e.g., fill) were used to hydrologically correct the DEM. Flow direction and flow accumulation grids were generated and used to generate contributing watersheds for each gage location. The generated watershed shapefiles and calculated areas were compared to watershed boundary shapefiles and information published by the USGS (e.g., 8 digit HUCs) and MN DNR ("Major Watershed Index"). The DEM generated watershed boundaries agreed very well with published watershed boundaries and provided the watershed area contributing to flow at the gage. The calculated areas agreed very well with the gage areas published by the USGS, typically within 1%. To maintain consistency and repeatability, the areas given by the USGS gage information will be used for runoff coefficient calculation.

3. DATA

3.1. Stream Flow Data

Forty-two (42) U.S. Geological Survey (USGS) stream gaging stations in the states of Minnesota, Wisconsin, and North and South Dakota were used in this study. Thirty-six of the stations match those used by Novotny and Stefan (2007) and Dadaser-Celik and Stefan (2009), and six stations were added to better represent the drainage areas contributing to the flow in Minnesota's streams and rivers. The stations were selected based on record length and record completeness. All records used end with 2008, and record lengths vary from 59 to 108 full years of data. The 42 gaging stations are spread across five major river basins of the Upper Midwest. Twelve (12) stations are located in the Minnesota River Basin, five (5) stations in the Mississippi Headwaters Basin (those above the confluence with the Minnesota River), eleven (11) stations in the remaining Upper Mississippi Basin (those below the confluence with the Minnesota River), seven (7) stations in the Red River of the North Basin, five (5) stations in the Rainy River Basin, and two (2) stations in the Lake Superior Basin. Daily stream flow data were extracted from the USGS Water Data website for all 42 gaging stations and averaged into the needed time scales. Annual and monthly averages were calculated only for full records; no incomplete records were used. Monthly flow data was converted into total runoff (in mm) by integrating over time and dividing by the drainage area of the stream gage's watershed. The locations of the stream gaging stations and the major river basins are shown in Figure 1. Figure 2 shows the watershed boundaries that were delineated for each stream gaging station. Table 1 gives the name and general information for each USGS gaging station including drainage area and period of record.

3.2. Climate Data

Historical climatic data for the Upper Midwest are available from a variety of sources. Many of the records are from networks of volunteer observers or small weather stations. Some are short, inconsistent, incomplete, and unverified. After a review of potential sources, data from the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA) were selected for the analysis. The NCDC uses networks of volunteer observers as well as NOAA weather stations to reliably and accurately estimate precipitation and temperature data as single values across climate divisions on a monthly scale, with records dating back to 1895. The Minnesota State Climatologist's Office (University of Minnesota) makes compilations and analyses of this weather data available via the internet. The NCDC climate division data also include the PDSI and PHDI calculated for each climate division for the length of the record. It is assumed that a single value across a climate division is a good estimate, meaning that on annual or monthly time scales the precipitation and mean temperatures do not vary significantly across each climate division. To estimate the total precipitation and average temperature in the watershed of each USGS stream gage, area-weighted averages of the climate division data were calculated based on the watershed's area fraction in each climate division. The calculations were completed using ArcGIS to overlay the stream gage watersheds (described previously) and the climate division shapefiles to determine the resulting component areas. A few watersheds in northern Minnesota have contributing drainage area in Canada. Because historic monthly climate data for Canada were unavailable, it was assumed that the climate division data for Minnesota Climate Division 3 would be representative of the climate data in Canada. The climate divisions as defined by NOAA in the regions studied are shown in Figure 3 along with the stream gage locations and major river basin boundaries.

An additional source for climate data is the United States Historical Climatology Network (USHCN). The USHCN dataset provides daily and monthly precipitation and temperature data across the US. The stations are not uniformly distributed and do not contain as long a record as the NCDC climate division dataset. Interpolating watershed-specific information for the USGS gaging stations for continuous time periods would be very time consuming and was not completed. In analyses at time scales shorter than a month, however, the USHCN data could be very useful.

4. RESULTS

4.1. Correlations at the Annual (Calendar and Water Year) Time Scale

Annual (January-December) and water year (October-September) average runoff was plotted against mean annual air temperature, total annual precipitation, and average PDSI and PHDI (determined by averaging the monthly values over the course of each year) for all 42 stream gaging stations. The coefficients of determination (r^2) between runoff and each of the climate variables were calculated. Figures 4 to 9 show examples of the plots for precipitation and PDSI for the Mississippi River near Prescott, WI, the Rum River near St. Francis, MN, and the Pigeon River near Grand Portage, MN. The correlations for the Mississippi River near Prescott, WI were among the best observed, those for the Rum River were about average, and those for the Pigeon River were among the worst found in the analysis.

Correlations between average annual air temperature and runoff were always very weak, as had been expected; average and maximum r^2-values of 0.07 and 0.20, respectively, were found. Correlations of runoff against precipitation, PDSI, and PHDI were significantly stronger; PDSI and PHDI were better predictors of runoff than precipitation. The overall average and maximum r^2-values between precipitation and runoff for all 42 stations were 0.39 and 0.57, respectively. The overall average and maximum coefficients of determination between PDSI and runoff were 0.67 and 0.88, respectively (0.67 and 0.87 for PHDI). Table 2 lists the r^2-values of the correlations between water year average climatic variables and runoff for each gaging station as well as basin averages. Water year averages were found, on average, to have slightly better correlations than annual (calendar year) averages (Figure 10). Water year averages were retained for subsequent analysis.

The best correlations between total precipitation or average PDSI or PHDI and runoff were found in the Upper Mississippi River Basin below the confluence with the Minnesota River; the strongest correlations were for stream gaging stations on the main stem of the Mississippi River (e.g., $r^2 = 0.88$ at Prescott, WI and Winona, MN between PDSI and runoff). The importance of average moisture conditions throughout river basin drainage area and the compounded effect of the smaller drainage areas that feed them is illustrated by this result.

In the Minnesota River Basin, runoff showed above average correlation strength with precipitation ($r^2 = 0.44$) and average strength with PDSI ($r^2 = 0.67$). In the Mississippi Headwaters Basin runoff showed below average strength with precipitation ($r^2 = 0.34$) and above average strength with PDSI ($r^2 = 0.72$). The weakest correlations between runoff and precipitation were observed in the Rainy River Basin and the Red River Basin with averages of $r^2 = 0.27$ and 0.38, respectively. The Lake Superior Basin had the lowest average correlation strength between runoff and PDSI, with an $r^2 = 0.47$, while the Rainy River Basin averaged $r^2 = 0.57$, and the Red River Basin had $r^2 = 0.66$.

That runoff correlates more strongly with PDSI than with precipitation reinforces the concept that overall moisture conditions play a larger role in generating runoff than precipitation events alone. Soil infiltration capacity and groundwater levels are controlled by antecedent moisture conditions, and in turn provide baseflow to streams. For example, a rainfall event with significant precipitation will create more surface runoff during a wet time than a drought period because the amount of new water that can be stored in the watershed (in soils, groundwater, wetlands, ponds, etc.) will be lower in a wet period than a dry period.

Precipitation was found to have the highest correlations, on average, with linear regression, while PDSI and PHDI gave the best fit to runoff with exponential regressions, i.e., linear regression with the log of runoff (Figure 11). Exponential regressions were used between the drought indices and runoff for the remainder of the analyses. On average, PDSI and PHDI were equally good predictors of runoff (Figure 12). Because Weber and Nkemdirim (1998) found that PDSI responds at least one month faster than PHDI to changing moisture conditions, PDSI was used in subsequent analyses.

It was found that watershed size, i.e. the contributing drainage area at the stream gage location, had little influence on the strength of correlation between stream runoff and precipitation or PDSI (Figure 13). However, runoff at stream gaging stations with the largest drainage areas did tend to have stronger correlations, especially with PDSI.

Five- , ten- , and twenty-year running averages of the climatic variables and stream flows were also computed and analyzed. The average strength of the correlation between runoff and precipitation rose significantly when water year averages were replaced by 5-year running averages, but did not improve much further when 10- and 20-year running averages were used (Figure 14). Using running averages of PDSI did not change the correlation strengths significantly (Figure 15). The 5-year average of precipitation was, on average, a slightly worse predictor of runoff than the 5-year average of PDSI, and the 10- and 20-year averages of precipitation were slightly better predictors than the 10- and 20-year averages of PDSI (Figure 16).

These results suggest that PDSI and PHDI capture moisture conditions in a watershed well enough for runoff projection at the annual time scale as well as longer time scales. By comparison, precipitation data have to be extended from the annual scale to a multi-year (5-year) scale to become representative of soil moisture conditions in the watershed for runoff projection.

4.2. Correlations at the Seasonal Time Scale

From the annual (calendar year and water year) time scale, our analysis was extended to a seasonal time scale. *Cool* months were defined as November through April and *warm* months were defined as May through October. *Winter* months are December, January, and February, when air temperatures are mostly below freezing, precipitation is in the form of snow and does not immediately run off, and stream flow is fed mostly by groundwater (baseflow) and infrequent snowmelt events. Stream flow in *spring* (March, April, and May) is very much controlled by snowmelt runoff. Stream flow in the *summer* (June, July, and August) and *fall* (September, October, and November) is fed largely by rainfall and stored water.

In the analysis, seasonal runoff was related to seasonal average air temperature, seasonal average PDSI, and total seasonal precipitation for all 42 stream gaging stations. In addition, *winter* and *spring* climate variables were related to spring runoff in an attempt to capture the snowpack that accumulates over the winter and runs off during spring snowmelt. The coefficients of determination (r^2) were determined between the seasonal stream flow and each of the three climate variables.

Figure 17 shows the overall average correlation strengths (as r^2) of air temperature, precipitation, and PDSI against runoff for the seasonal time scales. The average water year r^2-values are given for comparison. In each of the river basins, the average correlation strengths at the seasonal time scale showed the same patterns as those at the annual time scale given in the previous section of this report. The Rainy River and Lake Superior Basins had the weakest correlations and the Upper Mississippi below the Minnesota and the Minnesota River Basins had the strongest. As in the yearly time scale analysis, the correlation strengths for PDSI were obtained by an exponential fit (i.e., linear regression with the log of runoff).

The correlation strengths (r^2-values) between seasonal average air temperature and stream runoff were again very weak. On average, the correlation strengths between precipitation and runoff were slightly higher during the *warm* months than the *cool* months. This is also reflected in the significantly higher average r^2-values between precipitation and runoff in the *summer* and *fall* months, compared to the *winter* and *spring* months, which is due to the importance of precipitation for generating stream flow in *summer* and *fall*. On the other hand, *winter* and *spring* precipitation regressed against *spring* runoff gave significantly higher r^2-values than just *spring* precipitation against *spring* runoff, because the snowpack runs off in *spring*. None of the average correlation strengths between precipitation and runoff at the seasonal time scales were higher than those found for the annual time scale. As in the water year analysis, PDSI was a much better predictor of runoff than precipitation. Average correlation strengths were similar in the *cool* and *warm* months and in *summer* and *spring*. Average correlation strengths in the *fall* were slightly higher, and average correlation strengths in the *winter* were slightly lower, implying a slightly higher importance of moisture conditions in generating fall runoff, and slightly smaller importance for generating winter runoff, which is typical for the Upper Midwest.

4.3. Correlations at the Monthly Time Scale

After analysis of annual and seasonal time scales, the analysis was extended to the monthly time scale, i.e. data were averaged over individual months and analyzed. Average monthly runoff at each of the 42 stream gaging stations was regressed against average monthly air temperature, monthly total precipitation, and monthly PDSI for each month of the year for the entire period of record. Figure 18 shows the overall average correlation strengths (as r^2) of air temperature, precipitation, and PDSI against runoff for individual months with the average water year r^2-values for comparison. Comparison of average correlation strengths by river basin at the monthly time scale and at the annual time scale showed the same patterns, The Rainy River and Lake Superior Basins showed the weakest correlations and the Upper Mississippi below the Minnesota and the Minnesota River Basins showed the strongest.

The best relationships were once again observed between PDSI and stream flow. Overall, r2-values at the monthly time scale were weaker than at the annual time scale. Noticeably stronger correlations were observed in the summer, fall, and winter months than in the spring months. The lower correlation strengths in the spring months are attributed to the fact that the major contributor to stream flow in spring is snow melt runoff, and the amount of snowmelt water is not well correlated with PDSI.

Correlations between precipitation and stream flow were very weak; the best month was June, with an average $r^2 = 0.25$. Lag time between precipitation and runoff at the gaging station was not accounted for in the analysis. The monthly timescale seems too short to capture the precipitation vs. runoff relationship, especially in the larger watersheds. An analysis of watershed time of concentration and appropriate lagging of precipitation events in the analysis could increase the strength of the correlations at the monthly timescale. The r^2-values between precipitation and runoff in the winter months were the very weakest, with averages from 0.01 to 0.04, because precipitation falls as snow in these months and produces little direct runoff.

The r^2-values between air temperature and flow were again very low indicating almost no correlation between runoff and air temperature at the monthly timescale. Small increases were observed in the correlations between temperature and runoff in February and March indicating a very slight dependence; however the average $r^2 = 0.13$ in March. The small increase may reflect the dependence of snowmelt on air temperature.

Overall, the monthly timescale is too short to relate stream runoff in major watersheds to climate variables. On shorter time scales watershed specific topography, ecology, geology, and land use cause a lag, and play much larger roles in determining runoff from precipitation events. More complex hydrologic runoff models must be applied to accurately predict runoff at the monthly time scale.

4.4. Analysis of Runoff Coefficients

The easiest way to express the overall relationship between precipitation and runoff in a watershed is by a runoff coefficient. For each of the 42 stream gaging stations and for each water year of record annual runoff coefficients were calculated by dividing the total observed annual runoff from the watershed during the year by the total annual precipitation. Averages for the period of record (P.O.R.) as well as 20-year averages were calculated. The 20-year periods used were 1926-1945, 1946-1965, 1966-1985, and 1986-2005. In Tables 3, 4, and 5 the average precipitation (cm), the runoff (cm), and the runoff coefficients (dimensionless), respectively, are listed for each stream gage and its associated watershed over the P.O.R. as well as over the shorter time scales. Figures 19 to 23 show the change in runoff coefficients in increments of 20-year periods from 1926 to 2005. Stream gaging stations are divided according to river basins: Tributaries of Lake Superior and the Rainy River Basin (Figure 19), the Red River Basin (Figure 20), the Mississippi Headwaters Basin (Figure 21), the Minnesota River Basin (Figure 22), and the Upper Mississippi Basin below the confluence with the Minnesota River (Figure 23).

A comparison of average runoff coefficients in the six furthest down river (most encompassing) river basins and their changes over the period 1926 to 2005 is given in Figure 24. The trend in runoff coefficients is upward in all river basins, except the Lake Superior Basin.

Annual average precipitation (cm/yr) and average annual average runoff (cm/yr) for the same basins and time periods are given in Figure 25. Note the overall upward trends in both precipitation and runoff in every major basin in Figure 25. For runoff coefficients to increase, the increase in runoff must be more severe than the increase in precipitation.

Figures 26 and 27 display maps that shows the geographic distribution of the runoff coefficients for the 1946-1965 and the 1986-2005 time periods, and Figure 28 shows the associated percent change in runoff coefficient per stream gage from the 1946-1965 period to the 1986-2005 period. Similarly, Figures 29 - 32 show maps of the distribution of values and changes in average annual precipitation (in both cm and percent) in and between the same time periods, and Figures 33 – 36 show the same for average annual runoff.

5. INTERPRETATIONS OF RESULTS

In the Lake Superior Basin both stream gaging stations had high average runoff coefficients (~ 0.43) in the period from 1966-1985 after an increase from the previous period, but subsequently runoff coefficients decreased back to their earlier averages (~ 0.36). Only the Pigeon River has a long enough record to obtain a runoff coefficient for the 1926-1945 period, which was actually higher (~ 0.44) than for the 1966-1985 period, despite considerable overlap with the drought period of the 1930s. The Rainy River Basin was also characterized by high runoff coefficients (0.3 to 0.4), with the maximum values in the 1966-1985 period. The Lake Superior and Rainy River Basins have no doubt seen the least amount of agricultural conversion and urbanization of the watersheds studied and both remain heavily forested. In both basins soil column lengths are short because the most recent glaciation scoured to bedrock, which is exposed in many areas. Both areas are considered part of the Canadian Shield, and have many lakes and wetlands. These features can explain both the high runoff coefficients and the relative lack of change observed over the time periods.

In the Red River Basin runoff coefficients have increased over time, some very significantly. Initial runoff coefficients were much lower than those of the Rainy River and Lake Superior Basin, ranging from ~0.03 to 0.08. Since the 1946-65 period, runoff coefficients have increased significantly to a range between ~0.08 to 0.15; the runoff coefficient for the Sheyenne River increased by 109%. The Red River Basin is characterized by very fine grained soils and flat topography as much of it was once the bottom of glacial Lake Agassiz. The land use in the basin is primarily agricultural. The Red Lake River near Crookston, MN and the Roseau River near Malung, MN watersheds both saw relatively little change in runoff coefficients between the time periods. The Roseau River watershed was the sole exception to low runoff coefficients and provided a value of ~0.33. Both the Red Lake River and the Roseau River watersheds are on the eastern side of the basin and likely have topography, geology, and land use characteristics more similar to the Rainy River and Mississippi Headwaters Basins than the rest of the Red River Basin.

In the Mississippi Headwaters Basin typical runoff coefficients were between 0.20 and 0.26 and were relatively stable between the 1946-1965 and 1986-2005 periods. Notable exceptions to this stability are the Mississippi River at Grand Rapids, MN, which is the only station with a record going back to the 1926-1945 period, and a significant leap from ~0.12 to 0.21 from that period to the next, and the Crow River at Rockford, MN, whose runoff coefficient increased steadily from ~0.12 to 0.21 from 1926-1945 to 1986-2005. Significant urbanization has occurred in the Crow River watershed, and some near Grand Rapids, while the main land uses in the Mississippi Headwaters Basin are forests and agriculture.

The most significant increases in runoff coefficients were obtained for the Minnesota River Basin, where agriculture makes up 92% of the basins area. In the 1946-1965 period, the runoff coefficients were from ~0.06 to 0.15 and many increased slightly or decreased in the 1966-1985 period. In the most recent period (1986-2005), however, the runoff coefficients jumped to between ~0.09 and 0.26. At many stream gaging stations runoff coefficients increased by ~70 to 80%; the Chippewa River at Milan, MN showed a 115% increase. The two stations that have longer records (Minnesota River at Montevideo, MN and Minnesota River at Mankato, MN) show even lower initial runoff coefficients (0.03-0.06) in the 1926-1945 time period. Both the Le Sueur River and the Blue Earth River at Rapidan, MN showed higher initial runoff coefficients than were typical of the Minnesota River Basin for each time period, but both stream gaging sites also had significant increases in runoff coefficients over time.

For stream gaging stations in the Upper Mississippi River Basin below the confluence with the Minnesota River runoff coefficients show two different patterns. The stream gaging stations on the St. Croix River that drains eastern central Minnesota and northwestern Wisconsin and the stations on the Chippewa River that drains western and central Wisconsin showed high runoff coefficients ranging from ~0.34 to 0.42. The St. Croix River watershed is heavily forested but interestingly the Chippewa River watershed is heavily used for agriculture, in particular dairy farming, and thus does not have the same basin characteristics that likely cause the high runoff coefficients found in northern Minnesota. The runoff coefficients in these watersheds have also remained relatively stable with time. The remaining stream gaging stations in the Upper Mississippi Basin below the confluence with the Minnesota River are in the 'Driftless Area', the area of southeastern Minnesota, western Wisconsin, and northern Iowa and Illinois that were not covered by glaciers during the last ice age, including two southern Minnesota streams that flow through Iowa before joining the Mississippi River further downstream. For each of these stream gaging stations runoff coefficients increased over time, from ~0.1 - 0.23 in 1946-1965 to a range of ~0.2 - 0.33 in 1986-2005.

Interesting results emerge by studying the runoff coefficients that are "characteristic" (most down-river) for the major river basins of Minnesota and surrounding states. In the north, the Lake Superior and Rainy River Basins have high and invariant characteristic runoff coefficients around 0.36 and 0.34, respectively. The Red River Basin in northwestern Minnesota and eastern North Dakota has the lowest characteristic runoff coefficient at ~0.14 but has consistently increased from 0.04 near the beginning of the period of record. The Mississippi Headwaters Basin characteristic runoff coefficient has increased to ~0.24 from 0.12 in the earliest time period. The Minnesota River Basin characteristic runoff coefficient (from the

Minnesota River at Jordan, MN station) has also increased significantly and consistently from 0.06 to 0.19. The low runoff coefficients from the Minnesota River combine with the higher runoff coefficients coming out of the Mississippi Headwaters and the even higher runoff coefficients coming out of the St. Croix and Chippewa River watersheds such that the basin characteristic runoff coefficient for the Upper Mississippi River Basin (from the Mississippi River at Winona, MN station) has increased to ~0.27.

Overall runoff coefficients increase significantly from west to east in the Upper Midwest region studied (Figures 26 and 27). This distribution does not seem to have changed over time. Increases in runoff coefficients have, however, been highest in the west, and lowest in the east of the geographic region studied (Figure 28). One can hypothesize that this gradient is mainly due to land use changes that have been more incisive in the west, and have lead to faster and easier surface runoff from the land in the west since the beginning of European settlement. An explanation based on climatological factors may, however, also be reasonable. It was found that precipitation has increased in all of the river basins studied over the time period of 1926 to 2005 (see Figures 25, 31, and 32) with the largest changes occurring in the southernmost of the watersheds studied and very little change being observed in northeastern Minnesota. If the relative increase in runoff is more than the relative increase in precipitation, than the runoff coefficients have increased.

The geographical distribution of average annual runoff (Figures 33 – 36) is similar to the distribution of the runoff coefficients, with the highest values occurring in the east and decreasing values to the west. When the change in total runoff (Figure 35) is expressed as the total difference between the 1946 - 1965 and 1986 – 2005 time periods, the largest changes in runoff are seen in the southernmost watersheds that also saw the largest increases in precipitation. These southern Minnesota watersheds also saw significant changes in runoff coefficients. These observations could lead to the hypothesis that much of the additional precipitation is directly running off into streams and rivers, without much additional infiltration. This can be illustrated using the Root River and the Cedar River watersheds; both have seen very similar increases in average annual precipitation and average annual runoff of 10 - 14 cm.

When the change in runoff is viewed as a percent change from the earlier period (Figure 36), the watersheds in the Red River Basin and the more upriver watersheds in the Minnesota River Basin are seen to have higher relative changes than the watersheds with the largest total runoff. The geographic distribution of the percent change, also displays an obvious east to west gradient, this time with the highest changes occurring in the west and the lowest in the east.

Overall, runoff, i.e. stream flow, has increased since the beginning of stream gaging in Minnesota and the Upper Midwest in the watersheds studied (see Figures 33 – 36), although periods of substantially lower stream flows have occurred, e.g. in the drought period of the 1930s, which is illustrated in the historical flow and precipitation records for the Mississippi River at St. Paul, MN in Figure 37. Not only has the runoff (cm/yr) increased but runoff coefficients, i.e. the ratio of runoff to precipitation, have also increased. Increases in runoff coefficients have been documented in this study. Further study is needed to conclusively determine the underlying causes of these findings, particularly research regarding land use, water use, and climate changes. In a specific watershed with given topography, geology and vegetation cover, runoff coefficients depend both on land use and precipitation (amount and intensity). Figures 38 and 39 show the relationships between 5-year average annual (water year) precipitation and runoff coefficient, and PDSI and runoff coefficient, respectively, for the Mississippi River at St. Paul, MN. A strong positive relationship (r^2 = 0.71 and 0.66, respectively) is observed at this station and similar results are seen at other stations. The strengths of the relationships at each stream gage between precipitation and PDSI against runoff coefficient are compared for the 5-year running averages and annual time scales (Figure 40). It is apparent that the 5-year running averages of precipitation have significantly stronger relationships with the runoff coefficient than at the annual time scale, highlighting the effects that antecedent moisture conditions have on runoff coefficients. At both time scales PDSI is an overall better predictor of runoff coefficient. The dramatic increase in correlation strength is not evident between PDSI and runoff coefficients from annual to 5-year running average scales, which is consistent with earlier findings that 5-year running averages of precipitation approach the general moisture conditions indicated by annual average PDSI. Low runoff coefficients in the 1926-1945 are representative of a dry period. Higher runoff coefficients in the 1986-2005 period may be due to increased precipitation leading to water surplus (and thus higher PDSI) and less available storage in the watershed.

6. SUMMARY AND CONCLUSIONS

Historical stream flow and climate data for major river basins in Minnesota and tributaries from neighboring states were analyzed. Stream flow data came from 42 USGS gauging stations. A goal of the study was to determine the strength of the relationship between runoff and climatic variables. Another goal was to study how stream flow in Minnesota has changed since the beginning of data collection and how changes related to changes in climatic variables. The climatic variables analyzed included precipitation, PDSI and PHDI, two common drought indices. A third goal was to compare streamflow and its changes in the vastly different major river basins of Minnesota. The analysis was conducted at annual (calendar and water year), multi-year (running averages), seasonal, and monthly time scales. The following conclusions were drawn from this study.

6.1 Relationships between Stream Flow and Climate Parameters

1) The drought indices (PDSI and PHSI) were determined to be much better predictors of stream flow (runoff) than precipitation alone; runoff showed a slightly higher dependence on PDSI than PHDI. This result highlights the importance on antecedent moisture conditions on the generation of runoff and stream flows.

2) Correlation strengths were improved significantly by using an exponential fit between runoff and the drought indices; correlations between runoff and precipitation were stronger with a simple linear model.

3) Drainage area does not have a crucial effect on the relationship between runoff (cm/yr) and climatic variables; however some of the strongest dependences were obtained for the furthest downstream gaging stations of the Mississippi River (e.g., Prescott, WI and Winona, MN).

4) Water year (October – September) averages showed slightly stronger correlations between the climatic variables and runoff than calendar year (January – December) averages.

5) Multi-year running averages improve the correlation strengths between precipitation and runoff significantly, but not between PDSI and runoff. Five-year running averages of (water year) precipitation are sufficient. A precipitation average over several years appears to account for the overall soil moisture conditions, as the drought indices do at shorter, e.g. the annual, time scales.

6) The seasonal time scale analysis yielded only some useful results: a strong dependence of runoff on precipitation during summer and fall, but a much weaker dependence during the winter. The correlation strength between PDSI and runoff did not differ greatly by season. PDSI can be a good indicator of moisture conditions when precipitation is falling as snow.

7) At the monthly time scale the dependence of runoff on precipitation was even more decreased. Precipitation was not a good predictor of runoff in any month. The snow melt months February and March had the weakest dependence of runoff on PDSI.

8) Among the river basins studied, the Upper Mississippi River Basin below the confluence with the Minnesota River has the strongest dependence on precipitation and PDSI. Runoff from the Minnesota River Basin showed above average dependence on precipitation and average dependence on PDSI, while runoff in the Mississippi Headwaters Basin showed below average dependence on precipitation and above average dependence on PDSI. The Red River of the North Basin showed lower than average dependence on precipitation and average dependence on PDSI. The Rainy River Basin and the Lake Superior Basin showed the weakest dependences of precipitation and PDSI on runoff. Geology, topography, and land use contribute to the differences observed between river basins.

6.2 Geographic Distribution and Changes in Annual Runoff and Runoff Coefficients

1) Annual average runoff coefficients, i.e. the ratio of runoff to precipitation averaged over at least 50 years, vary significantly across the state of Minnesota, from 0.4 in the northeast to less than 0.1 in the northwest. It was also found that runoff coefficients averaged over 20-year periods have increased during the last 40 years in many of the river basins in Minnesota and the Upper Midwest. The largest increase in runoff coefficients was found in the Red River of the North and the Minnesota River Basins, the two basins with the lowest runoff, located in the former prairie regions. Runoff coefficients in some tributary or sub-watersheds have doubled; there is more runoff and more total stream flow for the same amount of precipitation in these basins in more recent times. The smallest change in runoff coefficients was found in the Lake Superior and Rainy River Basins, and in the St. Croix River and Chippewa River (Wisconsin) watersheds, all in the eastern part of the region studied.

2) The highest observed precipitation and runoff changes in total amount (cm) were in some of the southernmost watersheds studied, while the most relative changes in percent (%) of previous annual precipitation and runoff values were in the western watersheds of Minnesota.

3) Some sub-watersheds in southern Minnesota have experienced increases in total runoff (in cm) that are similar in magnitude to the observed increase in precipitation. This suggests that most of the recently seen increase in precipitation could be running directly off to streams and rivers, with little new loss to infiltration or evapotranspiration.

4) The most significant increases in runoff are in basins that likely saw the largest land use changes in the form of agricultural practices and urbanization during the time period studied (Land use was not part of this study). An increase in average precipitation was, however, also observed in the river basins across the Upper Midwest, and the high correlations found between

precipitation and runoff suggest that this precipitation change has contributed significantly to the increases in stream flows.

5) Future analyses need to examine the combined role of land use changes and climate change on changing runoff. Annual runoff (cm/yr) and annual runoff coefficients (cm of runoff divided by cm of precipitation per year) are influenced by the topography, geology, soils, vegetation cover, land use, and water use of the watershed, but also by climatic variables such as total rain- and snow- fall, rainfall intensities, and dew points. In a given watershed, climate change alters several of the climate parameters, including precipitation amounts and intensities, and antecedent soil moisture conditions, and thereby affects the runoff and steam flow. At the same time, land use changes by agricultural conversion and urbanization, including drainage water withdrawals and applications for irrigation, industrial and domestic uses in several of Minnesota's river basins have been profound. Multi-parameter analysis techniques and hydrologic modeling are two approaches to partition the interactions of climate change and land use.

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Table 1: Information on USGS stream gauging stations studied.

USGS No.	Station Name	Period of Record	Full Years of Record	Drainage Area (km^2)	Contributing Climate Divisions
Tributaries to Lake Superior Basin					
04010500	Pigeon River near Grand Portage, MN	1924-2008	85	1577	MN 3
04024000	St. Louis River at Scanlan, MN	1908-2008	100	8884	MN 2,3,6
Red River of the North Basin					
05054000	Red River of the North at Fargo, ND	1902-2008	107	17612	MN 1,4; SD 3; ND 6,9
05059500	Sheyenne River at West Fargo, ND	1903-2008	81	8003	ND 2,3,5,6,9
05062000	Buffalo River near Dilworth, MN	1931-2008	77	2525	MN 1,4
05079000	Red Lake River at Crookston, MN	1902-2008	107	13649	MN 1,2
05082500	Red River of the North at Grand Forks, ND	1904-2008	104	77959	MN1,2,4; SD3; ND 2,3,5,6,9
05092000	Red River of the North at Drayton, ND	1950-2008	59	90132	MN1,2,4; SD3; ND 2,3,5,6,9
05104500	Roseau River near Malung, MN	1947-2008	62	653	MN 1,2
Rainy River Basin					
05127500	Basswood River near Winton, MN	1931-2008	76	4507	MN 3
05128000	Namakan River at outlet of Lac La Croix, MN	1923-2008	86	13390	MN 3
05130500	Sturgeon River near Chisholm, MN	1943-2008	66	466	MN 2,3
05131500	Little Fork River at Littlefork, MN	1929-2008	85	4351	MN 2,3
05133500	Rainy River at Manitou Rapids, MN	1929-2008	80	50246	MN 2,3
Mississippi Headwaters Basin					
05211000	Mississippi River at Grand Rapids, MN	1912-2008	107	8728	MN 1,2
05227500	Mississippi River at Aitkin, MN	1946-2008	63	15903	MN 1,2,3,6
05280000	Crow River at Rockford, MN	1935-2008	82	6838	MN 4,5,6
05286000	Rum River near St. Francis, MN	1934-2008	76	3522	MN 5,6
05288500	Mississippi River near Anoka, MN	1932-2008	85	49469	MN 1,2,3,4,5,6

Table 1: Continued.

USGS No.	Station Name	Period of Record	Full Years of Record	Drainage Area (km^2)	Contributing Climate Divisions
Minnesota River Basin					
05291000	Whetstone River at Big Stone City, SD	1932-2008	77	1031	SD 3
05292000	Minnesota River at Ortonville, MN	1939-2008	70	3004	MN 4; SD 3
05304500	Chippewa River near Milan, MN	1938-2008	71	4869	MN 4,5
05311000	Minnesota River at Montevideo, MN	1930-2008	87	16006	MN 4,5,7; SD 3,7
05313500	Yellow Medicine River at Granite Falls, MN	1940-2008	72	1720	MN 4,7; SD 7
05315000	Redwood River near Marshall, MN	1941-2008	68	671	MN 7
05316500	Redwood River near Redwood Falls, MN	1936-2008	74	1629	MN 4, 7
05317000	Cottonwood River near New Ulm, MN	1939-2008	74	3367	MN 7,8
05320000	Blue Earth River near Rapidan, MN	1950-2008	65	6242	MN 7,8; IA 1,2
05320500	Le Sueur River near Rapidan, MN	1950-2008	65	2875	MN 8
05325000	Minnesota River at Mankato, MN	1930-2008	87	38591	MN 4,5,7,8; SD 3,7; IA 1,2
05330000	Minnesota River near Jordan, MN	1935-2008	74	41958	MN 4,5,7,8; SD 3,7; IA 1,2
Upper Mississippi River Basin (below Minnesota River)					
05331000	Mississippi River at St. Paul, MN	1907-2008	108	95312	MN 1-9; SD 3,7; IA 1,2
05333500	St. Croix River near Danbury, WI	1914-2008	91	4092	WI 1
05340500	St. Croix River at St. Croix Falls, WI	1902-2008	98	16162	MN 6, WI 1
05344500	Mississippi River at Prescott, WI	1929-2008	79	116032	MN 1-9; SD 3,7; WI 1,4; IA 1,2
05356500	Chippewa River near Bruce, WI	1913-2008	94	4274	WI 1,2
05365500	Chippewa River at Chippewa Falls, WI	1888-2008	93	14634	WI 1,2,4
05369500	Chippewa River at Durand, WI	1928-2008	80	23336	WI 1,2,4
05378500	Mississippi River at Winona, MN	1929-2008	80	153328	MN1-9; SD 3,7; WI 1,2,4; IA 1,2
05385000	Root River at Houston, MN	1909-2008	75	3238	MN 9
05457000	Cedar River near Austin, MN	1945-2008	69	1033	MN 8,9
05476000	Des Moines River at Jackson, MN	1936-2008	73	3238	MN 7

Table 2: Coefficients of determination (r^2) for regressions between water year average climatic variables and stream runoff at USGS stream gaging stations. Basin averages are also given.

USGS No	Station Name	Temp vs. Runoff	Precip vs. Runoff	PDSI vs. Runoff	PHDI vs. Runoff
		Linear Regression	Linear Regression	Exp. Regression	Exp. Regression
		r^2	r^2	r^2	r^2
Tributaries to Lake Superior Basin					
04010500	Pigeon River near Grand Portage, MN	0.15	0.26	0.37	0.33
04024000	St. Louis River at Scanlan, MN	0.03	0.40	0.57	0.58
	Basin Averages	**0.09**	**0.33**	**0.47**	**0.46**
Red River of the North Basin					
05054000	Red River of the North at Fargo, ND	0.01	0.28	0.67	0.69
05059500	Sheyenne River at West Fargo, ND	0.01	0.26	0.72	0.72
05062000	Buffalo River near Dilworth, MN	0.01	0.24	0.60	0.62
05079000	Red Lake River at Crookston, MN	0.01	0.22	0.61	0.66
05082500	Red River of the North at Grand Forks, ND	0.00	0.27	0.69	0.72
05092000	Red River of the North at Drayton, ND	0.04	0.29	0.72	0.74
05104500	Roseau River near Malung, MN	0.09	0.38	0.58	0.53
	Basin Averages	**0.02**	**0.28**	**0.66**	**0.67**
Rainy River Basin					
05127500	Basswood River near Winton, MN	0.15	0.21	0.55	0.52
05128000	Namakan River at outlet of Lac La Croix	0.12	0.19	0.51	0.51
05130500	Sturgeon River near Chisholm, MN	0.20	0.30	0.63	0.60
05131500	Little Fork River at Littlefork, MN	0.11	0.40	0.52	0.44
05133500	Rainy River at Manitou Rapids, MN	0.18	0.26	0.62	0.54
	Basin Averages	**0.15**	**0.27**	**0.57**	**0.52**
Mississippi Headwaters Basin					
05211000	Mississippi River at Grand Rapids, MN	0.01	0.15	0.49	0.53
05227500	Mississippi River at Aitkin, MN	0.10	0.30	0.82	0.80
05280000	Crow River at Rockford, MN	0.02	0.47	0.76	0.77
05286000	Rum River near St. Francis, MN	0.01	0.37	0.67	0.75
05288500	Mississippi River near Anoka, MN	0.01	0.43	0.84	0.86
	Basin Averages	**0.03**	**0.34**	**0.72**	**0.74**

Table 2: Continued.

USGS No	Station Name	Temp vs. Runoff	Precip vs. Runoff	PDSI vs. Runoff	PHDI vs. Runoff
		Linear Regression	**Linear Regression**	**Exp. Regression**	**Exp. Regression**
		r^2	r^2	r^2	r^2
Minnesota River Basin					
05291000	Whetstone River at Big Stone City, SD	0.19	0.32	0.56	0.55
05292000	Minnesota River at Ortonville, MN	0.16	0.31	0.65	0.67
05304500	Chippewa River near Milan, MN	0.04	0.28	0.60	0.63
05311000	Minnesota River at Montevideo, MN	0.09	0.35	0.81	0.80
05313500	Yellow Medicine River at Granite Falls, MN	0.11	0.43	0.56	0.56
05315000	Redwood River near Marshall, MN	0.09	0.47	0.60	0.63
05316500	Redwood River near Redwood Falls, MN	0.08	0.53	0.58	0.60
05317000	Cottonwood River near New Ulm, MN	0.09	0.56	0.68	0.69
05320000	Blue Earth River near Rapidan, MN	0.09	0.57	0.75	0.79
05320500	Le Sueur River near Rapidan, MN	0.09	0.54	0.63	0.67
05325000	Minnesota River at Mankato, MN	0.09	0.50	0.83	0.82
05330000	Minnesota River near Jordan, MN	0.08	0.47	0.81	0.80
	Basin Averages	**0.10**	**0.44**	**0.67**	**0.68**
Upper Mississippi River Basin (below Minnesota River)					
05331000	Mississippi River at St. Paul, MN	0.03	0.50	0.85	0.86
05333500	St. Croix River near Danbury, WI	0.03	0.37	0.58	0.57
05340500	St. Croix River at St. Croix Falls, WI	0.01	0.45	0.69	0.66
05344500	Mississippi River at Prescott, WI	0.06	0.51	0.88	0.87
05356500	Chippewa River near Bruce, WI	0.03	0.49	0.75	0.70
05365500	Chippewa River at Chippewa Falls, WI	0.04	0.47	0.81	0.74
05369500	Chippewa River at Durand, WI	0.05	0.46	0.84	0.81
05378500	Mississippi River at Winona, MN	0.05	0.49	0.88	0.86
05385000	Root River at Houston, MN	0.00	0.43	0.63	0.61
05457000	Cedar River near Austin, MN	0.01	0.52	0.64	0.61
05476000	Des Moines River at Jackson, MN	0.09	0.53	0.67	0.72
	Basin Averages	**0.04**	**0.47**	**0.75**	**0.73**
Overall Averages		**0.07**	**0.39**	**0.67**	**0.67**

Table 3: Average annual (water year) precipitation in the watershed of each USGS stream gaging station for different time periods and the period of record (P.O.R.). Change in average runoff from the 1946-1965 to the 1986-2005 period is also given.

USGS No.	Station Name	Water Year Average (St. Dev.) Precip (cm)					% Change from 1946 - 1965 to 1986 - 2005
		1926-1945	1946-1965	1966-1985	1986-2005	P.O.R	
Tributaries to Lake Superior Basin							
04010500	Pigeon River near Grand Portage, MN	25.65 (3.23)	27.84 (3.19)	28.67 (3.34)	28.25 (3.94)	27.74 (3.62)	1.46
04024000	St. Louis River at Scanlan, MN	25.65 (3.27)	27.78 (3.15)	28.65 (3.35)	28.31 (3.88)	27.72 (3.61)	1.91
Red River of the North Basin							
05054000	Red River of the North at Fargo, ND	20.21 (4.19)	22.20 (3.11)	21.65 (3.25)	23.67 (4.33)	21.78 (3.62)	6.61
05059500	Sheyenne River at West Fargo, ND	17.40 (3.92)	18.50 (2.49)	18.12 (2.48)	20.20 (3.47)	18.66 (3.05)	9.17
05062000	Buffalo River near Dilworth, MN	20.58 (4.00)	22.46 (2.97)	22.73 (3.30)	23.98 (3.95)	22.50 (3.51)	6.76
05079000	Red Lake River at Crookston, MN	21.95 (4.04)	23.43 (3.05)	24.09 (3.43)	24.81 (3.85)	23.69 (3.59)	5.85
05082500	Red River of the North at Grand Forks, ND	19.67 (3.96)	21.18 (2.66)	21.14 (2.84)	22.85 (3.47)	21.25 (3.21)	7.90
05092000	Red River of the North at Drayton, ND	19.53 (3.92)	20.97 (2.66)	20.95 (2.77)	22.63 (3.44)	21.08 (3.17)	7.91
05104500	Roseau River near Malung, MN	21.3 (4.01)	22.81 (3.04)	23.42 (3.43)	24.33 (3.91)	23.10 (3.57)	6.66
Rainy River Basin							
05127500	Basswood River near Winton, MN	25.65 (3.23)	27.84 (3.19)	28.67 (3.34)	28.25 (3.94)	27.74 (3.62)	1.46
05128000	Namakan River at outlet of Lac La Croix	25.65 (3.23)	27.84 (3.19)	28.67 (3.34)	28.25 (3.94)	27.74 (3.62)	1.46
05130500	Sturgeon River near Chisholm, MN	25.45 (3.29)	27.55 (3.12)	28.38 (3.31)	28.01 (3.88)	27.48 (3.59)	1.69
05131500	Little Fork River at Littlefork, MN	24.76 (3.60)	26.59 (3.07)	27.41 (3.32)	27.25 (3.77)	26.62 (3.61)	2.50
05133500	Rainy River at Manitou Rapids, MN	24.83 (3.57)	26.69 (3.07)	27.51 (3.31)	27.33 (3.78)	26.71 (3.60)	2.42
Mississippi Headwaters Basin							
05211000	Mississippi River at Grand Rapids, MN	23.58 (4.24)	25.01 (3.38)	25.80 (3.61)	26.00 (3.90)	25.19 (3.83)	3.99
05227500	Mississippi River at Aitkin, MN	24.33 (4.18)	25.75 (3.24)	26.78 (3.66)	27.19 (3.84)	26.04 (3.83)	5.60
05280000	Crow River at Rockford, MN	24.22 (4.52)	27.01 (4.50)	28.25 (4.54)	28.88 (5.65)	26.76 (4.82)	6.92
05286000	Rum River near St. Francis, MN	26.20 (4.70)	27.75 (4.11)	29.42 (4.48)	30.55 (5.34)	28.26 (4.67)	10.08
05288500	Mississippi River near Anoka, MN	24.33 (4.24)	26.39 (3.48)	27.49 (3.93)	28.15 (4.44)	26.43 (4.12)	6.69

Table 3: Continued.

USGS No	Station Name	Water Year Average (St. Dev.) Precip (cm)					% Change from 1946-65 to 1986-05
		1926-1945	1946-1965	1966-1985	1986-2005	P.O.R	
Minnesota River Basin							
05291000	Whetstone River at Big Stone City, SD	19.67 (4.16)	20.01 (3.47)	19.42 (3.56)	23.10 (4.70)	20.16 (3.95)	15.46
05292000	Minnesota River at Ortonville, MN	20.02 (4.18)	20.89 (3.43)	20.28 (3.55)	23.53 (4.68)	20.81 (3.90)	12.61
05304500	Chippewa River near Milan, MN	21.77 (4.53)	24.87 (3.71)	24.31 (4.15)	25.63 (4.93)	23.88 (4.25)	3.03
05311000	Minnesota River at Montevideo, MN	21.12 (4.33)	23.60 (3.52)	23.03 (3.88)	24.92 (4.74)	22.85 (4.02)	5.58
05313500	Yellow Medicine River at Granite Falls, MN	23.03 (3.92)	25.07 (3.66)	25.59 (4.32)	26.75 (5.05)	24.74 (4.18)	6.71
05315000	Redwood River near Marshall, MN	23.89 (3.90)	25.29 (3.96)	26.55 (4.87)	27.57 (5.51)	25.39 (4.49)	9.01
05316500	Redwood River near Redwood Falls, MN	23.88 (3.90)	25.29 (3.96)	26.54 (4.87)	27.56 (5.50)	25.38 (4.48)	9.00
05317000	Cottonwood River near New Ulm, MN	24.65 (3.90)	25.96 (3.80)	27.27 (4.45)	28.50 (5.57)	26.18 (4.40)	9.78
05320000	Blue Earth River near Rapidan, MN	27.57 (4.25)	28.38 (3.88)	29.99 (3.61)	31.63 (6.07)	29.10 (4.45)	11.44
05320500	Le Sueur River near Rapidan, MN	27.53 (4.38)	28.5 (4.03)	30.01 (3.56)	32.04 (6.27)	29.20 (4.58)	12.39
05325000	Minnesota River at Mankato, MN	23.72 (4.00)	25.61 (3.38)	26.08 (3.61)	27.70 (5.01)	25.45 (4.00)	8.17
05330000	Minnesota River near Jordan, MN	23.87 (4.02)	25.77 (3.41)	26.32 (3.62)	27.90 (5.04)	25.64 (4.03)	8.26
Upper Mississippi River Basin (below Minnesota River)							
05331000	Mississippi River at St. Paul, MN	24.18 (4.06)	26.16 (3.33)	27.04 (3.7)	28.12 (4.58)	26.14 (3.98)	7.48
05333500	St. Croix River near Danbury, WI	29.42 (4.32)	29.88 (4.48)	32.42 (3.84)	31.64 (4.87)	30.73 (4.31)	5.89
05340500	St. Croix River at St. Croix Falls, WI	27.89 (4.42)	28.82 (4.05)	30.95 (4.01)	31.19 (4.98)	29.55 (4.35)	8.19
05344500	Mississippi River at Prescott, WI	24.88 (4.04)	26.65 (3.32)	27.77 (3.7)	28.70 (4.55)	26.78 (3.96)	7.70
05356500	Chippewa River near Bruce, WI	30.05 (4.31)	30.11 (4.28)	32.54 (3.78)	31.71 (4.71)	31.02 (4.17)	5.30
05365500	Chippewa River at Chippewa Falls, WI	30.92 (4.40)	30.42 (4.09)	32.69 (3.79)	31.81 (4.58)	31.42 (4.07)	4.55
05369500	Chippewa River at Durand, WI	30.67 (4.40)	30.18 (4.04)	32.73 (3.75)	32.08 (4.33)	31.37 (4.00)	6.27
05378500	Mississippi River at Winona, MN	26.20 (3.95)	27.41 (3.26)	28.95 (3.51)	29.65 (4.39)	27.86 (3.80)	8.16
05385000	Root River at Houston, MN	29.49 (5.09)	29.02 (4.66)	32.5 (4.27)	33.59 (5.66)	30.92 (4.83)	15.76
05457000	Cedar River near Austin, MN	28.72 (4.60)	28.81 (4.16)	31.52 (3.72)	32.98 (5.58)	30.24 (4.51)	14.44
05476000	Des Moines River at Jackson, MN	23.89 (3.90)	25.29 (3.96)	26.55 (4.87)	27.57 (5.51)	25.39 (4.49)	9.01

Table 4: Average annual (water year) runoff at each USGS stream gaging station for different time periods and the period of record (P.O.R.). Change in average runoff from the 1946-1965 to the 1986-2005 period is also given.

USGS No	Station Name	Water Year Average (St. Dev.) Runoff (cm)					% Change from 1946 - 1965 to 1986 - 2005
		1926-1945	1946-1965	1966-1985	1986-2005	P.O.R	
Tributaries to Lake Superior Basin							
04010500	Pigeon River near Grand Portage, MN	11.20 (2.45)	10.51 (3.84)	12.51 (3.15)	10.30 (3.19)	11.04 (3.40)	- 2.03
04024000	St. Louis River at Scanlan, MN	8.62 (2.42)	9.53 (2.83)	11.03 (3.42)	10.40 (3.04)	9.42 (3.16)	9.12
Red River of the North Basin							
05054000	Red River of the North at Fargo, ND	0.57 (0.68)	1.31 (0.78)	1.45 (0.87)	2.50 (1.39)	1.44 (1.15)	90.74
05059500	Sheyenne River at West Fargo, ND	0.47 (0.32)	0.77 (0.52)	1.02 (0.48)	1.78 (1.11)	1.05 (0.82)	132.02
05062000	Buffalo River near Dilworth, MN		2.06 (1.01)	2.13 (1.38)	3.31 (1.83)	2.30 (1.56)	60.42
05079000	Red Lake River at Crookston, MN	1.69 (1.30)	3.18 (1.81)	4.13 (1.67)	3.82 (2.32)	3.11 (1.91)	20.22
05082500	Red River of the North at Grand Forks, ND	0.73 (0.58)	1.48 (0.85)	1.90 (0.90)	2.52 (1.38)	1.59 (1.09)	70.12
05092000	Red River of the North at Drayton, ND		1.45 (1.04)	1.87 (0.90)	2.45 (1.35)	1.98 (1.16)	68.81
05104500	Roseau River near Malung, MN		7.26 (4.31)	8.19 (5.18)	8.64 (5.82)	7.91 (5.04)	19.00
Rainy River Basin							
05127500	Basswood River near Winton, MN		10.53 (4.20)	12.37 (3.45)	10.24 (3.05)	10.74 (3.62)	- 2.78
05128000	Namakan River at outlet of Lac La Croix	9.20 (2.86)	10.21 (3.56)	11.60 (3.39)	9.92 (2.94)	10.02 (3.50)	- 2.92
05130500	Sturgeon River near Chisholm, MN		8.47 (2.56)	10.13 (2.92)	9.42 (3.09)	9.33 (2.88)	11.26
05131500	Little Fork River at Littlefork, MN	7.17 (2.83)	8.24 (2.71)	10.22 (3.36)	8.59 (2.91)	8.54 (3.11)	4.33
05133500	Rainy River at Manitou Rapids, MN	7.60 (2.66)	9.08 (2.66)	10.25 (3.18)	9.14 (2.91)	9.05 (2.99)	0.65
Mississippi Headwaters Basin							
05211000	Mississippi River at Grand Rapids, MN	2.79 (1.97)	5.17 (1.98)	5.97 (2.10)	5.92 (2.16)	4.94 (2.30)	14.53
05227500	Mississippi River at Aitkin, MN		6.14 (2.23)	6.82 (2.36)	6.65 (2.16)	6.44 (2.24)	8.33
05280000	Crow River at Rockford, MN		3.30 (2.25)	5.01 (2.93)	6.20 (3.37)	4.30 (3.00)	88.04
05286000	Rum River near St. Francis, MN		5.96 (2.75)	7.65 (2.83)	6.93 (3.02)	6.41 (2.96)	16.38
05288500	Mississippi River near Anoka, MN		5.52 (2.01)	6.76 (2.34)	6.80 (2.21)	5.80 (2.39)	23.33

Table 4: Continued.

USGS No	Station Name	Water Year Average (St. Dev.) Runoff (cm)					% Change from 1946 - 1965 to 1986 - 2005
		1926-1945	1946-1965	1966-1985	1986-2005	P.O.R	
Minnesota River Basin							
05291000	Whetstone River at Big Stone City, SD		1.80 (1.37)	1.8 (1.46)	2.97 (2.47)	2.07 (1.82)	65.34
05292000	Minnesota River at Ortonville, MN		1.30 (1.04)	1.11 (1.05)	2.27 (1.91)	1.62 (1.46)	74.95
05304500	Chippewa River near Milan, MN		1.94 (1.40)	2.69 (1.77)	4.25 (2.45)	2.77 (2.07)	119.29
05311000	Minnesota River at Montevideo, MN	0.72 (0.76)	1.83 (1.13)	1.98 (1.37)	3.39 (2.24)	2.05 (1.69)	85.29
05313500	Yellow Medicine River at Granite Falls, MN		2.42 (1.86)	2.83 (2.66)	4.13 (3.06)	2.94 (2.52)	71.00
05315000	Redwood River near Marshall, MN		2.55 (1.71)	3.13 (3.22)	5.51 (5.12)	3.70 (3.61)	116.25
05316500	Redwood River near Redwood Falls, MN		2.56 (1.70)	3.22 (2.96)	5.14 (3.91)	3.36 (2.99)	101.14
05317000	Cottonwood River near New Ulm, MN		2.85 (1.93)	3.98 (3.52)	5.97 (4.31)	4.05 (3.41)	109.72
05320000	Blue Earth River near Rapidan, MN		4.20 (2.95)	5.94 (3.92)	7.94 (5.51)	6.20 (4.33)	88.89
05320500	Le Sueur River near Rapidan, MN		4.48 (3.53)	6.99 (3.89)	8.86 (5.19)	6.85 (4.41)	97.86
05325000	Minnesota River at Mankato, MN	1.52 (1.27)	2.81 (1.58)	3.53 (2.12)	5.23 (3.12)	3.34 (2.44)	86.37
05330000	Minnesota River near Jordan, MN		2.92 (1.57)	3.78 (2.17)	5.45 (3.24)	3.82 (2.53)	86.73
Upper Mississippi River Basin (below Minnesota River)							
05331000	Mississippi River at St. Paul, MN	2.76 (1.60)	4.21 (1.67)	5.26 (2.05)	6.06 (2.49)	4.43 (2.18)	43.71
05333500	St. Croix River near Danbury, WI	10.44 (2.34)	11.84 (2.29)	11.94 (1.84)	11.73 (2.12)	11.27 (2.24)	- 0.97
05340500	St. Croix River at St. Croix Falls, WI	8.26 (2.96)	9.92 (2.80)	11.17 (2.7)	10.62 (2.92)	9.51 (3.05)	7.08
05344500	Mississippi River at Prescott, WI	3.75 (1.88)	5.24 (1.76)	6.26 (1.99)	6.78 (2.39)	5.57 (2.24)	29.32
05356500	Chippewa River near Bruce, WI	11.89 (3.80)	11.45 (2.96)	13.71 (2.28)	12.52 (3.52)	12.16 (3.25)	9.30
05365500	Chippewa River at Chippewa Falls, WI	12.26 (4.09)	11.28 (3.00)	13.29 (2.76)	11.92 (3.16)	12.03 (3.29)	5.69
05369500	Chippewa River at Durand, WI	11.40 (3.69)	10.41 (2.44)	12.87 (2.16)	11.92 (2.71)	11.56 (2.87)	14.54
05378500	Mississippi River at Winona, MN	5.09 (1.97)	6.08 (1.74)	7.56 (1.94)	8.18 (2.39)	6.78 (2.29)	34.51
05385000	Root River at Houston, MN	7.23 (2.06)	6.68 (1.91)	8.89 (3.53)	11.24 (2.67)	8.31 (3.06)	68.22
05457000	Cedar River near Austin, MN		5.77 (2.72)	8.68 (4.38)	11.18 (5.31)	8.53 (4.70)	93.74
05476000	Des Moines River at Jackson, MN		2.77 (1.98)	4.17 (4.02)	6.07 (5.07)	4.32 (3.88)	118.69

Table 5: Average annual (water year) runoff coefficients for the watersheds of the USGS stream gaging stations for different time periods and the period of record (P.O.R.). Change in average runoff from the 1946-1965 to the 1986-2005 period is also given.

USGS No.	Station Name	Water Year Average (St. Dev.) Runoff Coefficients					% Change from 1946 - 1965 to 1986 - 2005
		1926-1945	1946-1965	1966-1985	1986-2005	P.O.R	
Tributaries to Lake Superior Basin							
04010500	Pigeon River near Grand Portage, MN	0.44 (0.09)	0.38 (0.12)	0.44 (0.1)	0.36 (0.09)	0.40 (0.11)	-4.05
04024000	St. Louis River at Scanlan, MN	0.34 (0.08)	0.34 (0.09)	0.38 (0.1)	0.36 (0.07)	0.34 (0.09)	6.25
Red River of the North Basin							
05054000	Red River of the North at Fargo, ND	0.03 (0.03)	0.06 (0.03)	0.07 (0.04)	0.1 (0.05)	0.06 (0.05)	77.58
05059500	Sheyenne River at West Fargo, ND	0.03 (0.02)	0.04 (0.02)	0.06 (0.03)	0.08 (0.05)	0.05 (0.04)	108.97
05062000	Buffalo River near Dilworth, MN		0.09 (0.04)	0.09 (0.06)	0.13 (0.07)	0.10 (0.06)	48.43
05079000	Red Lake River at Crookston, MN	0.07 (0.06)	0.13 (0.07)	0.17 (0.07)	0.15 (0.08)	0.13 (0.07)	10.47
05082500	Red River of the North at Grand Forks, ND	0.04 (0.03)	0.07 (0.03)	0.09 (0.04)	0.11 (0.05)	0.07 (0.04)	55.07
05092000	Red River of the North at Drayton, ND		0.07 (0.04)	0.09 (0.04)	0.1 (0.05)	0.09 (0.05)	56.06
05104500	Roseau River near Malung, MN		0.31 (0.16)	0.34 (0.2)	0.33 (0.21)	0.32 (0.19)	8.28
Rainy River Basin							
05127500	Basswood River near Winton, MN		0.38 (0.13)	0.43 (0.11)	0.36 (0.09)	0.38 (0.11)	-3.97
05128000	Namakan River at outlet of Lac La Croix	0.36 (0.11)	0.37 (0.11)	0.4 (0.11)	0.35 (0.1)	0.36 (0.11)	-3.98
05130500	Sturgeon River near Chisholm, MN		0.31 (0.08)	0.36 (0.09)	0.33 (0.09)	0.33 (0.09)	8.11
05131500	Little Fork River at Littlefork, MN	0.29 (0.09)	0.31 (0.08)	0.37 (0.11)	0.31 (0.08)	0.32 (0.1)	0.98
05133500	Rainy River at Manitou Rapids, MN	0.31 (0.1)	0.34 (0.09)	0.37 (0.1)	0.33 (0.09)	0.34 (0.1)	-2.26
Mississippi Headwaters Basin							
05211000	Mississippi River at Grand Rapids, MN	0.12 (0.08)	0.21 (0.07)	0.23 (0.08)	0.22 (0.07)	0.2 (0.09)	9.09
05227500	Mississippi River at Aitkin, MN		0.24 (0.07)	0.25 (0.08)	0.24 (0.06)	0.24 (0.07)	2.53
05280000	Crow River at Rockford, MN		0.12 (0.06)	0.17 (0.08)	0.21 (0.09)	0.15 (0.09)	78.75
05286000	Rum River near St. Francis, MN		0.21 (0.08)	0.26 (0.09)	0.22 (0.08)	0.22 (0.09)	7.20
05288500	Mississippi River near Anoka, MN		0.21 (0.06)	0.24 (0.07)	0.24 (0.05)	0.21 (0.07)	16.32

Table 5: Continued.

USGS No.	Station Name	Water Year Average (St. Dev.) Runoff Coefficients					% Change from 1946 - 1965 to 1986 - 2005
		1926-1945	1946-1965	1966-1985	1986-2005	P.O.R	
Minnesota River Basin							
05291000	Whetstone River at Big Stone City, SD		0.09 (0.07)	0.09 (0.06)	0.12 (0.09)	0.09 (0.07)	38.57
05292000	Minnesota River at Ortonville, MN		0.06 (0.05)	0.05 (0.05)	0.09 (0.07)	0.07 (0.06)	49.99
05304500	Chippewa River near Milan, MN		0.08 (0.05)	0.11 (0.06)	0.16 (0.08)	0.11 (0.07)	115.35
05311000	Minnesota River at Montevideo, MN	0.03 (0.03)	0.08 (0.05)	0.08 (0.05)	0.13 (0.08)	0.08 (0.06)	74.00
05313500	Yellow Medicine River at Granite Falls, MN		0.09 (0.07)	0.1 (0.09)	0.15 (0.09)	0.11 (0.08)	56.55
05315000	Redwood River near Marshall, MN		0.1 (0.06)	0.11 (0.1)	0.18 (0.13)	0.13 (0.1)	87.99
05316500	Redwood River near Redwood Falls, MN		0.1 (0.06)	0.11 (0.09)	0.17 (0.1)	0.12 (0.09)	78.08
05317000	Cottonwood River near New Ulm, MN		0.11 (0.06)	0.14 (0.11)	0.2 (0.11)	0.14 (0.1)	86.10
05320000	Blue Earth River near Rapidan, MN		0.14 (0.08)	0.19 (0.11)	0.23 (0.12)	0.19 (0.11)	67.15
05320500	Le Sueur River near Rapidan, MN		0.15 (0.1)	0.23 (0.12)	0.26 (0.11)	0.21 (0.12)	78.50
05325000	Minnesota River at Mankato, MN	0.06 (0.04)	0.11 (0.05)	0.13 (0.07)	0.18 (0.09)	0.12 (0.08)	69.84
05330000	Minnesota River near Jordan, MN		0.11 (0.05)	0.14 (0.07)	0.19 (0.09)	0.14 (0.08)	69.96
Upper Mississippi River Basin (below Minnesota River)							
05331000	Mississippi River at St. Paul, MN	0.11 (0.05)	0.16 (0.05)	0.19 (0.06)	0.21 (0.07)	0.16 (0.07)	33.51
05333500	St. Croix River near Danbury, WI	0.35 (0.05)	0.4 (0.06)	0.38 (0.06)	0.37 (0.05)	0.37 (0.06)	-6.39
05340500	St. Croix River at St. Croix Falls, WI	0.29 (0.08)	0.34 (0.07)	0.36 (0.08)	0.34 (0.06)	0.32 (0.08)	-0.85
05344500	Mississippi River at Prescott, WI	0.15 (0.06)	0.19 (0.05)	0.22 (0.06)	0.23 (0.06)	0.2 (0.06)	20.38
05356500	Chippewa River near Bruce, WI	0.39 (0.1)	0.38 (0.07)	0.42 (0.07)	0.39 (0.08)	0.39 (0.08)	3.46
05365500	Chippewa River at Chippewa Falls, WI	0.39 (0.1)	0.37 (0.07)	0.41 (0.08)	0.38 (0.07)	0.38 (0.08)	2.35
05369500	Chippewa River at Durand, WI	0.37 (0.09)	0.34 (0.06)	0.4 (0.07)	0.37 (0.06)	0.37 (0.07)	7.83
05378500	Mississippi River at Winona, MN	0.19 (0.06)	0.22 (0.05)	0.26 (0.06)	0.27 (0.06)	0.24 (0.06)	24.48
05385000	Root River at Houston, MN	0.24 (0.05)	0.23 (0.06)	0.27 (0.09)	0.33 (0.05)	0.26 (0.07)	41.79
05457000	Cedar River near Austin, MN		0.2 (0.08)	0.27 (0.12)	0.33 (0.11)	0.27 (0.12)	67.58
05476000	Des Moines River at Jackson, MN		0.1 (0.07)	0.15 (0.12)	0.2 (0.13)	0.15 (0.11)	93.69

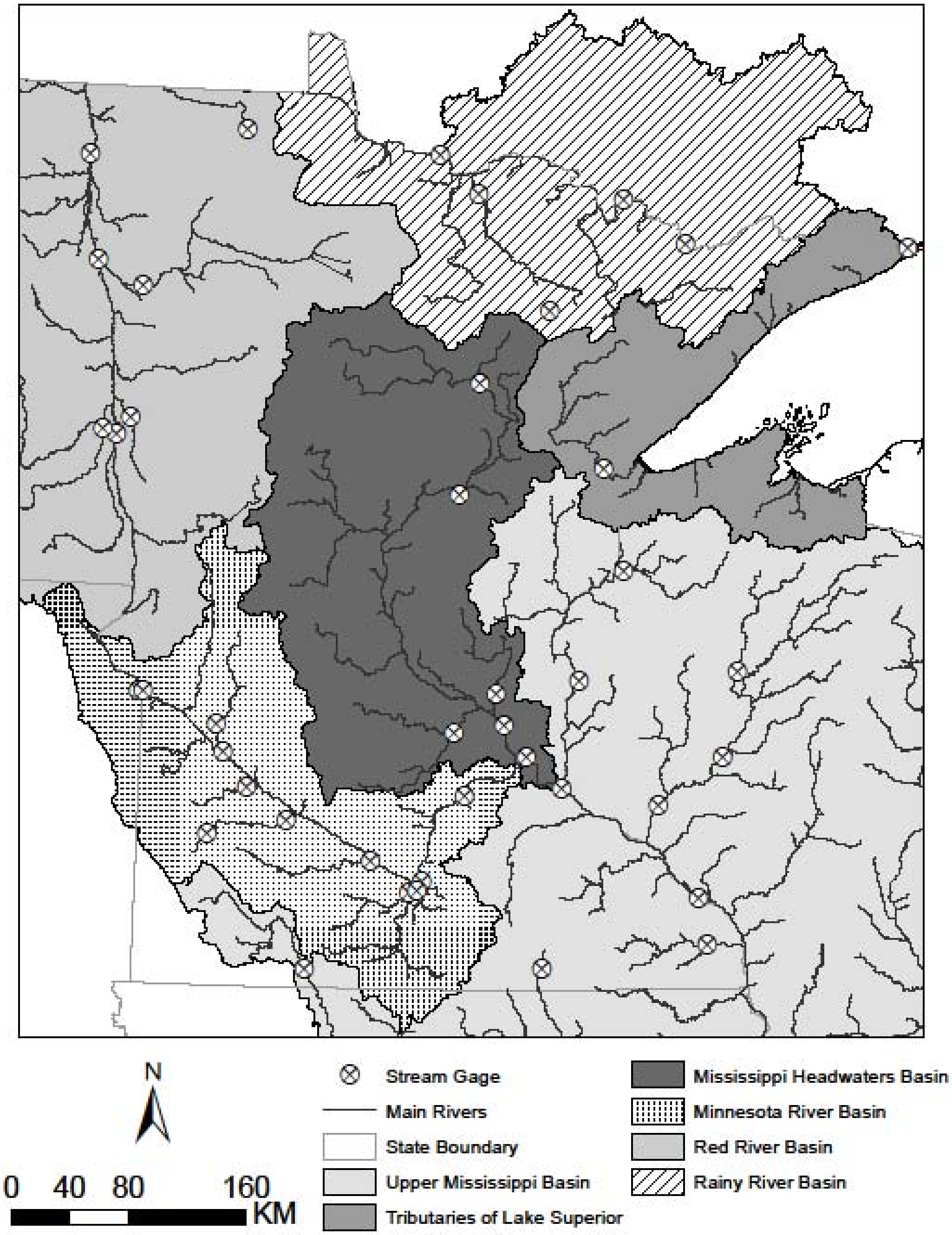


Figure 1: Major river basins of the Upper Midwest and USGS stream gage locations. Mississippi Headwaters and the Minnesota River Basins are part of the Upper Mississippi River Basin.

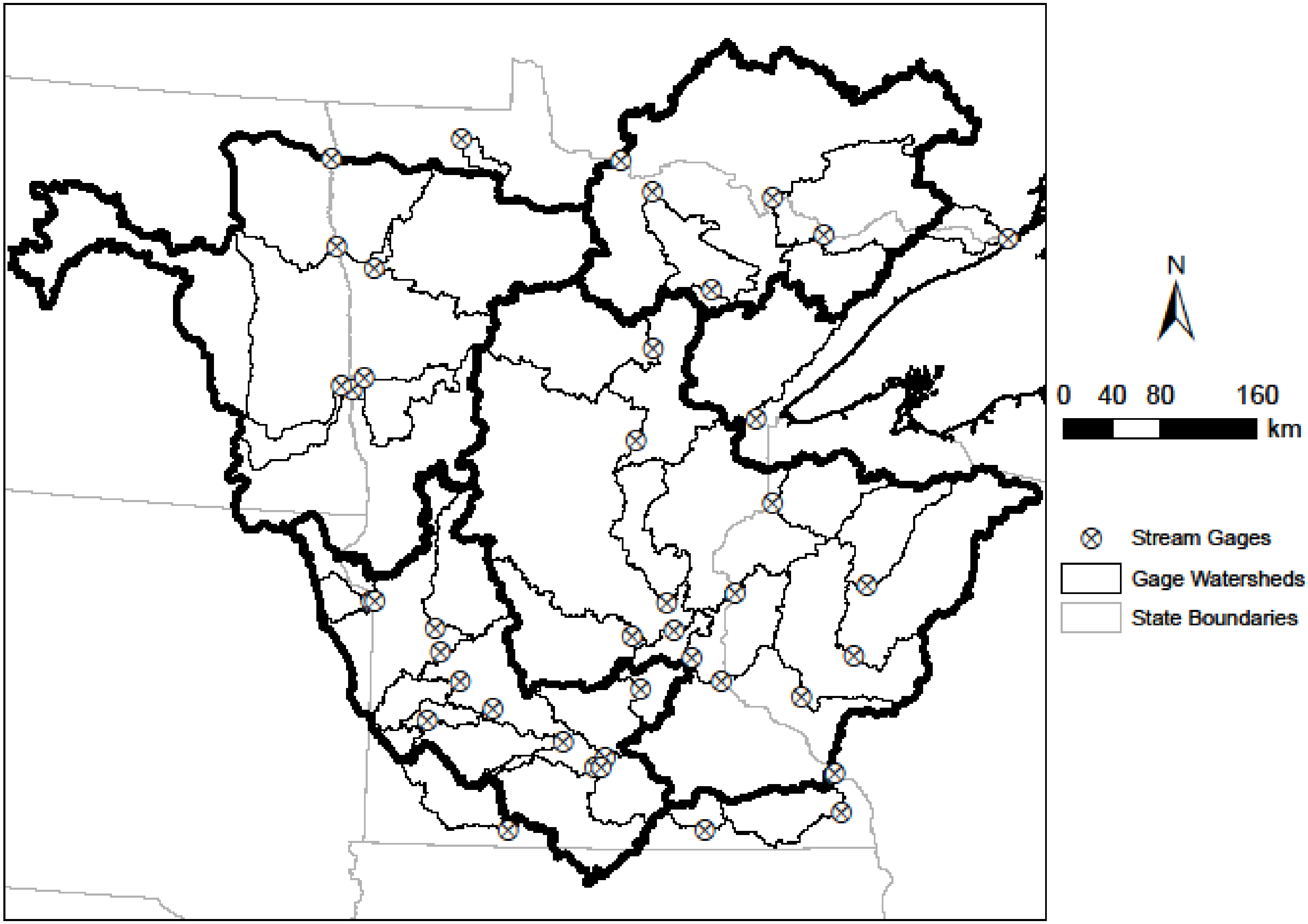


Figure 2: Watershed boundaries for each USGS stream gage. Major river basins (bold lines) are divided into tributary watersheds (thin lines).

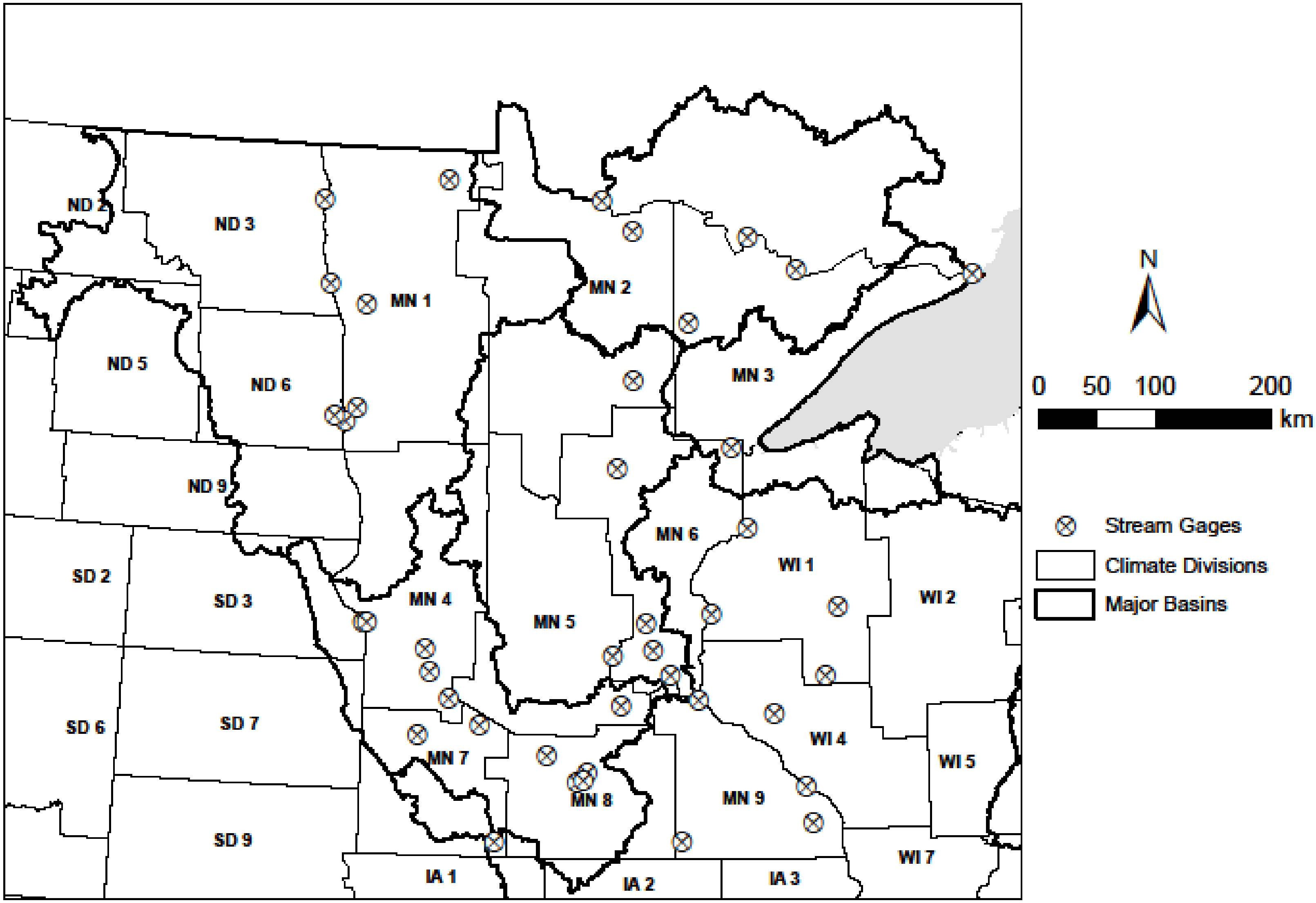


Figure 3: Upper Midwest climate divisions (NOAA), major river basins, and USGS stream gaging stations studied.

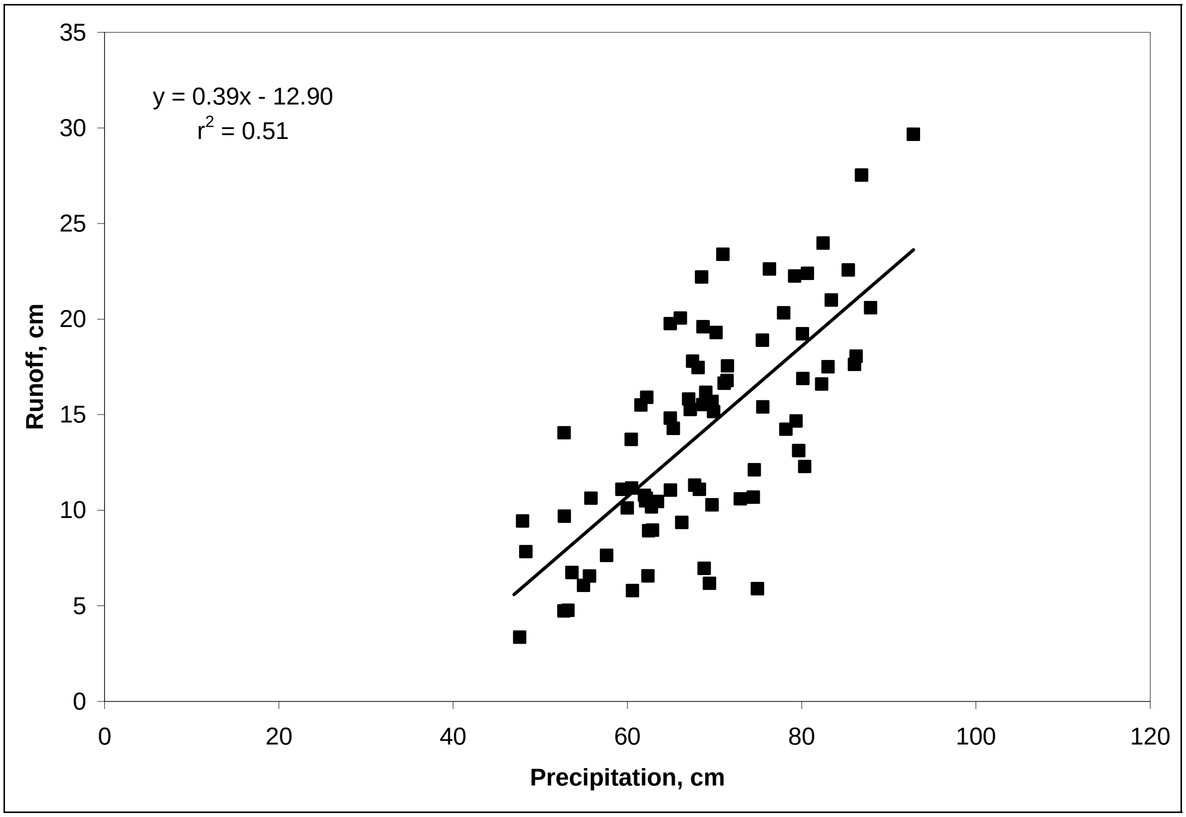


Figure 4: Annual average runoff in the Mississippi River near Prescott, WI, vs. annual precipitation in the watershed at the water year time scale.

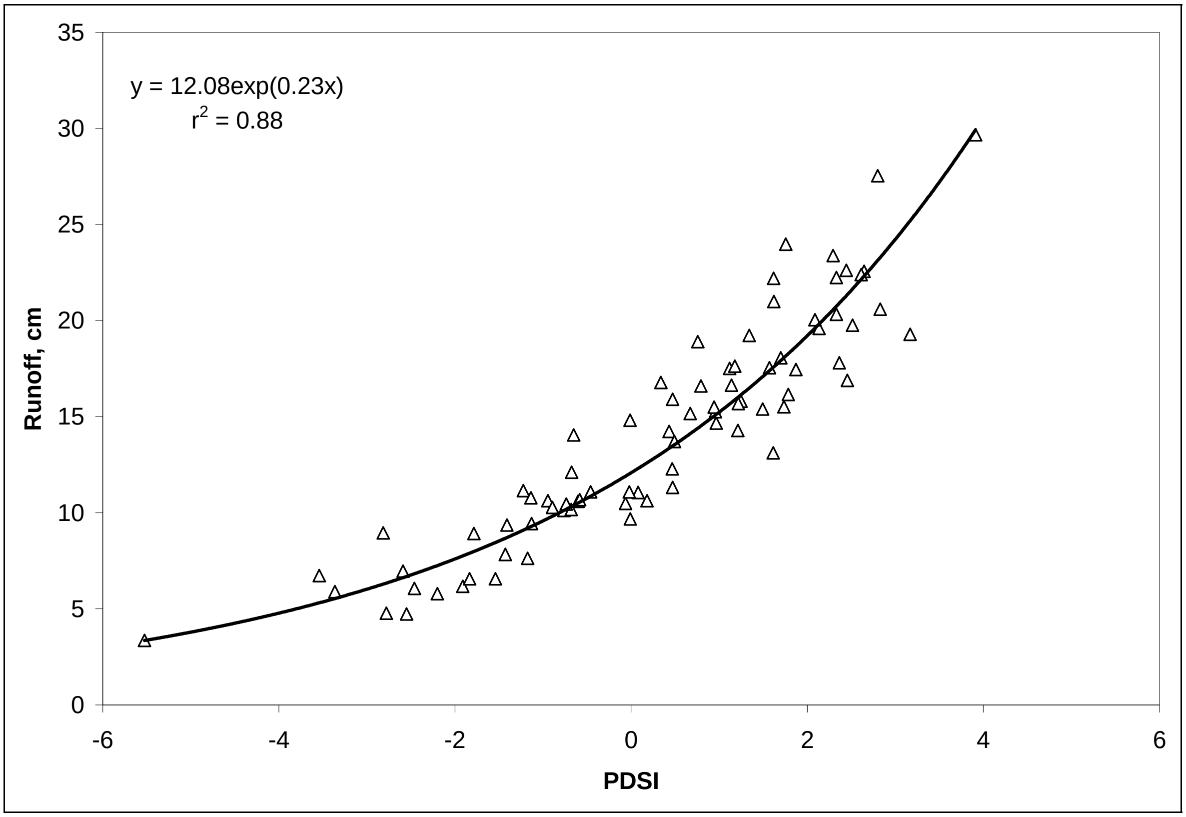


Figure 5: Annual average runoff in the Mississippi River near Prescott, WI, vs. annual average PDSI in the watershed at the water year time scale.

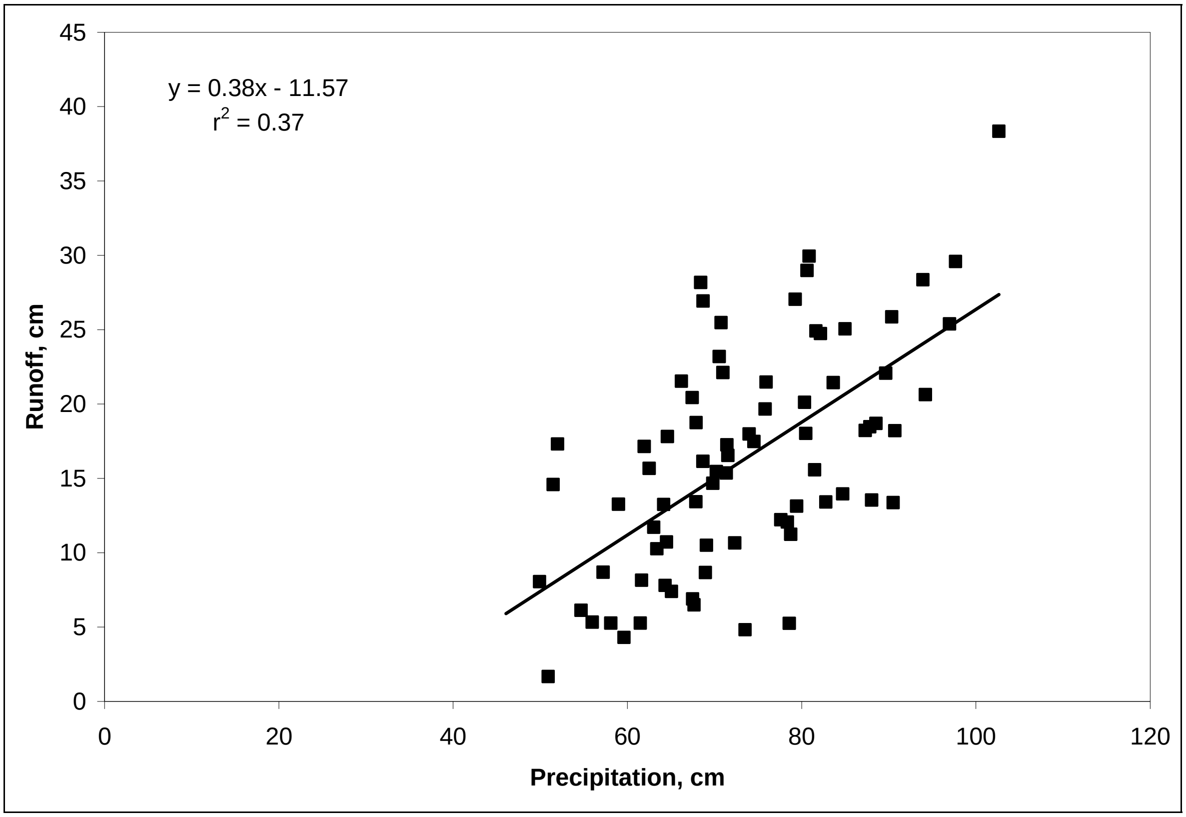


Figure 6: Annual average runoff in the Rum River near St. Francis, MN, vs. annual precipitation in the watershed at the water year time scale.

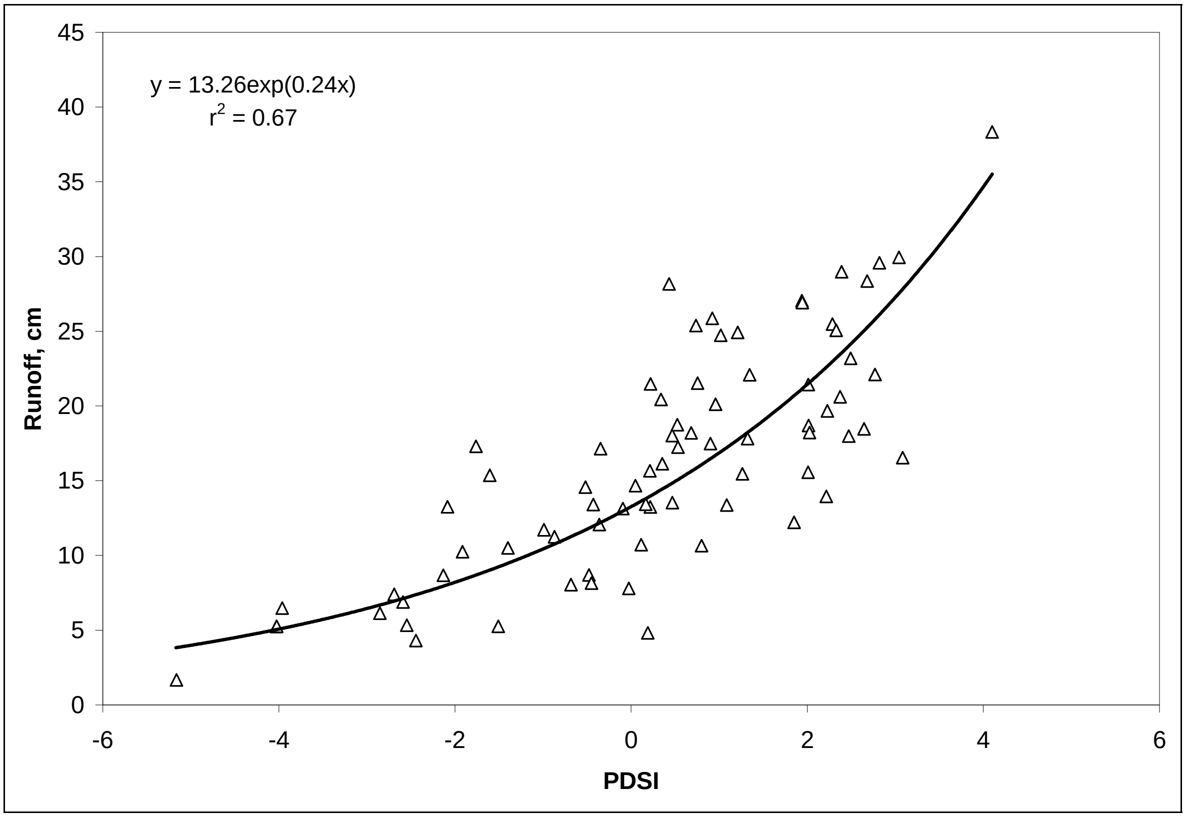


Figure 7: Annual average runoff in the Rum River near St. Francis, MN, vs. annual average PDSI in the watershed at the water year time scale.

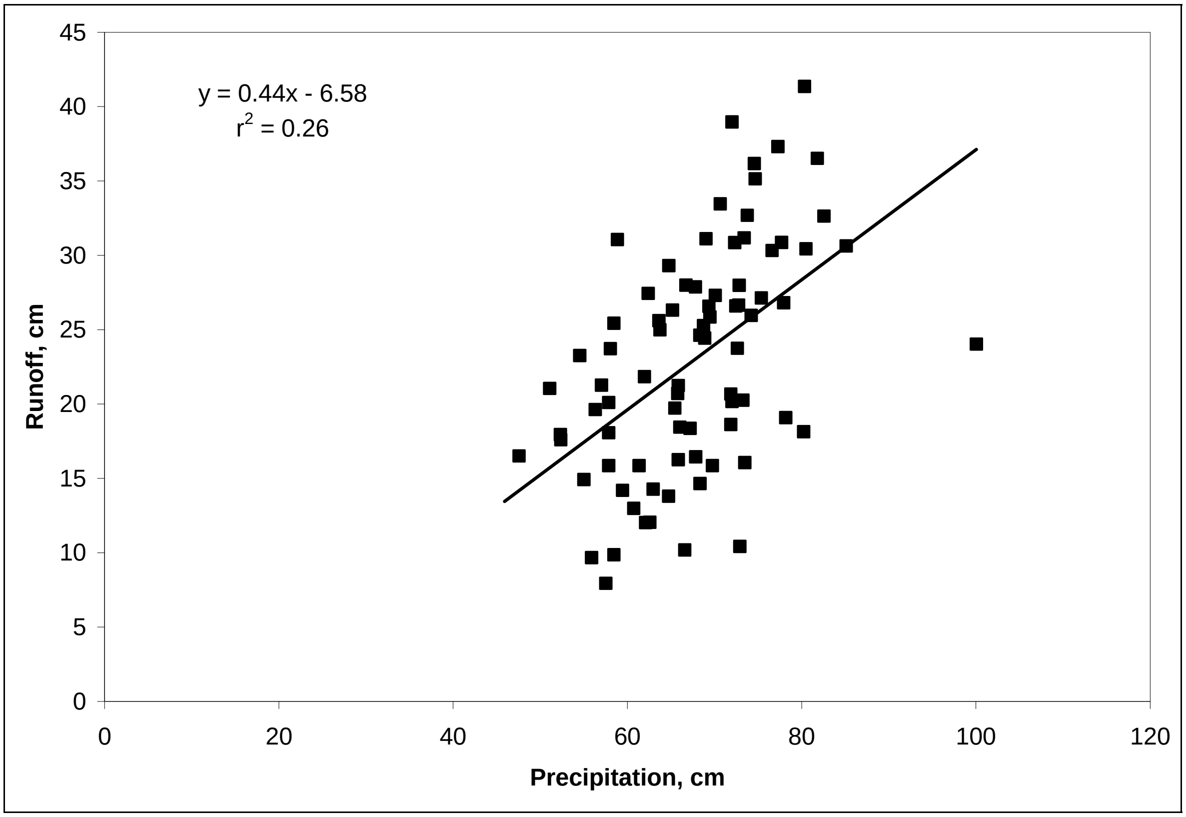


Figure 8: Annual average runoff in the Pigeon River at Grand Portage, MN, vs. annual precipitation in the watershed at the water year time scale.

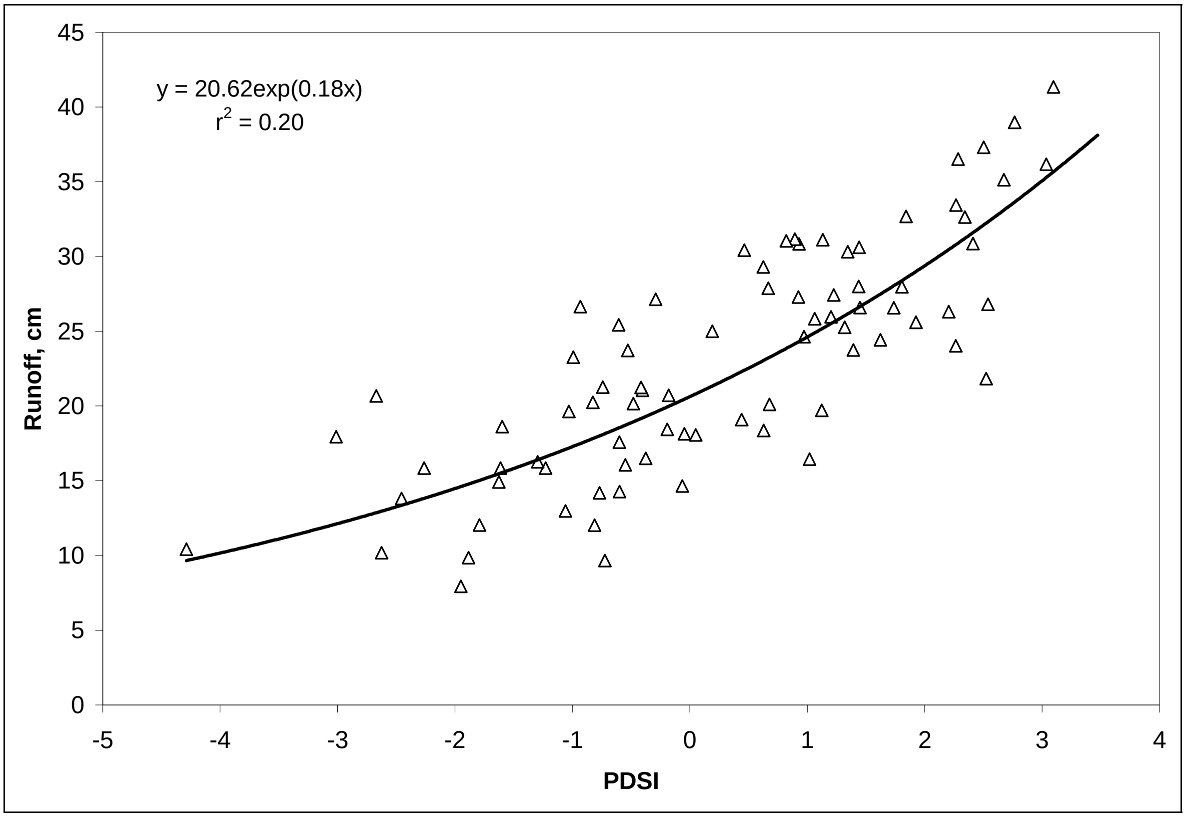


Figure 9: Average annual runoff in the Pigeon River at Grand Portage, MN, vs. annual average PDSI in the watershed at the water year time scale.

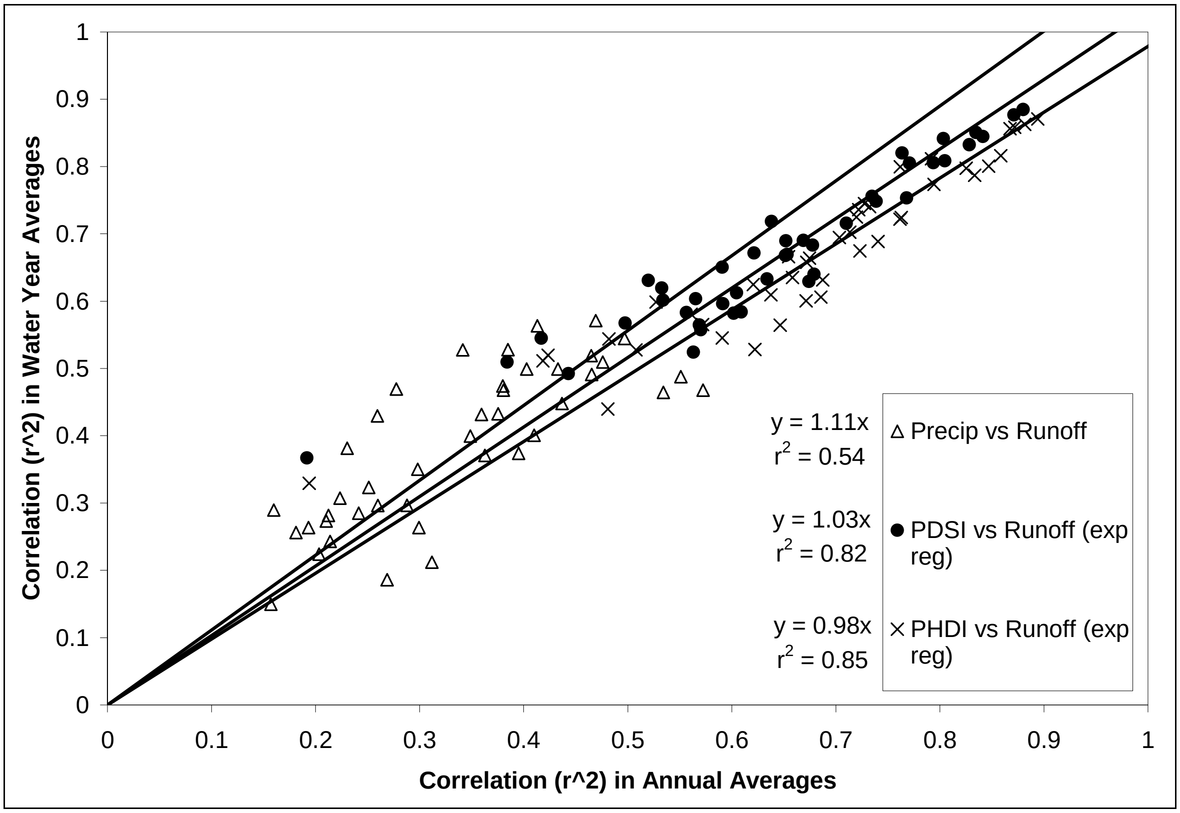


Figure 10: Average water year vs. calendar year correlation strengths between runoff and precipitation, PDSI, or PHDI.

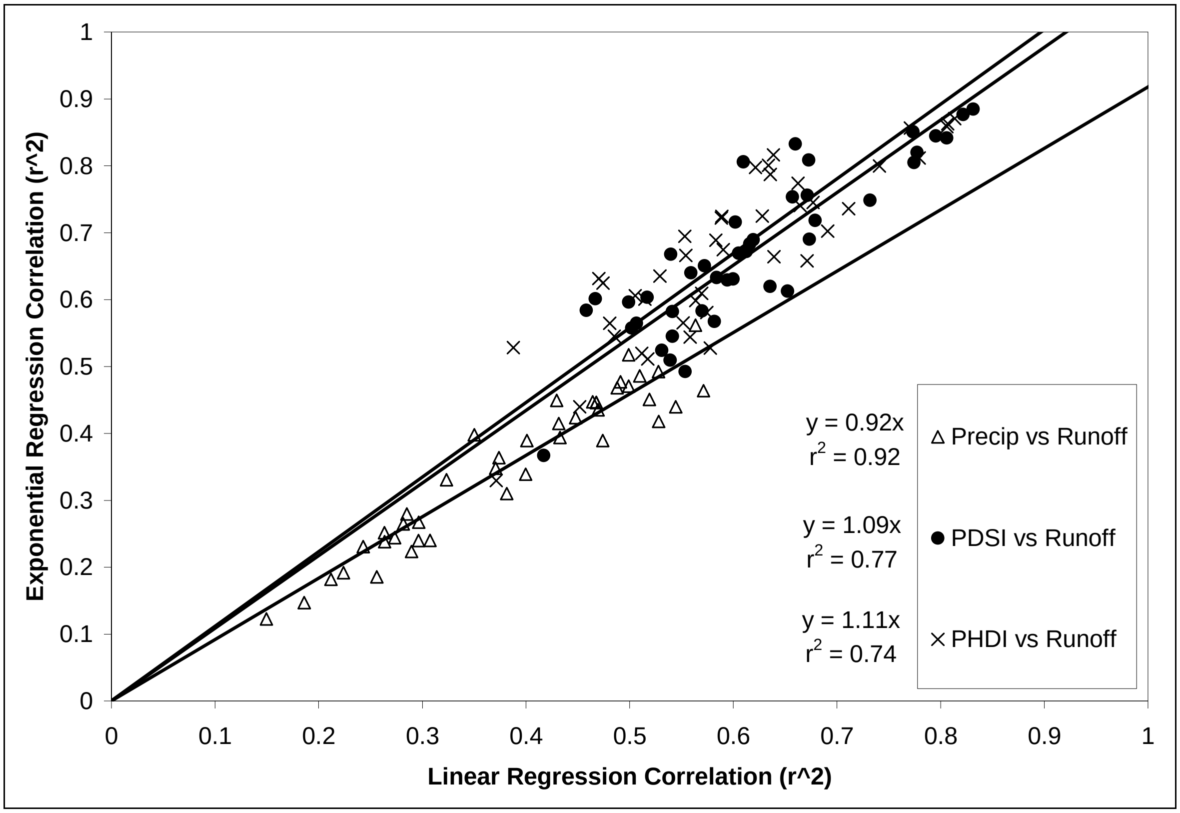


Figure 11: Exponential regression correlation vs. linear regression correlation strengths between runoff and precipitation, PDSI and PHDI at the water year time scale.

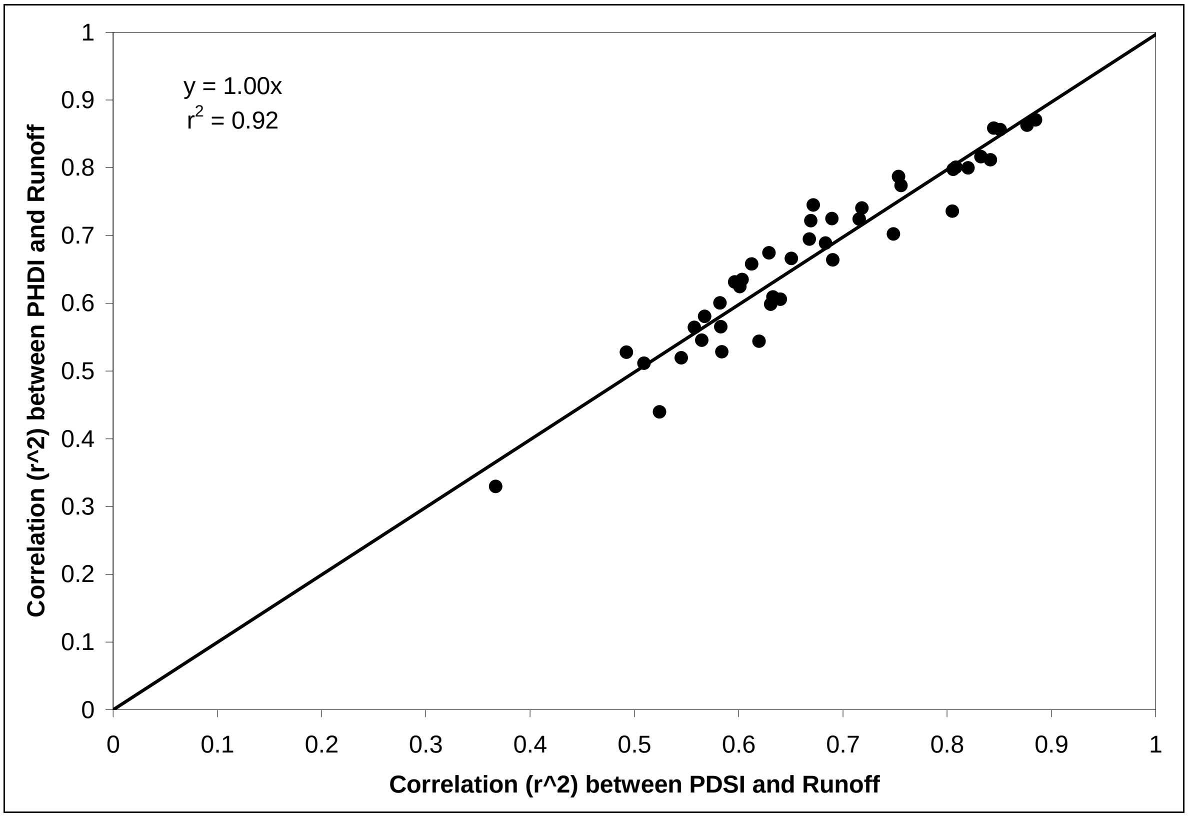


Figure 12: PHDI vs. PDSI correlation strengths as predictors of runoff at the water year time scale.

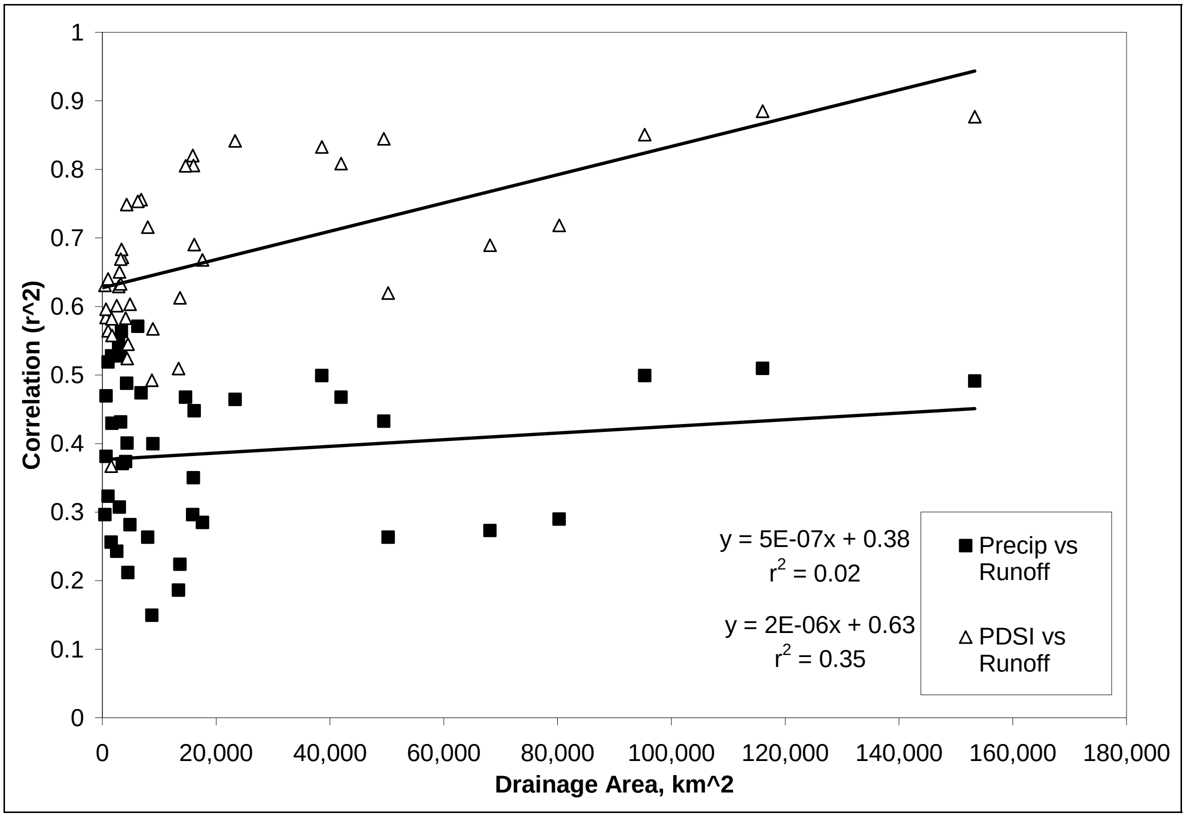


Figure 13: Correlation strength between runoff and precipitation or PDSI vs. drainage area at the water year time scale.

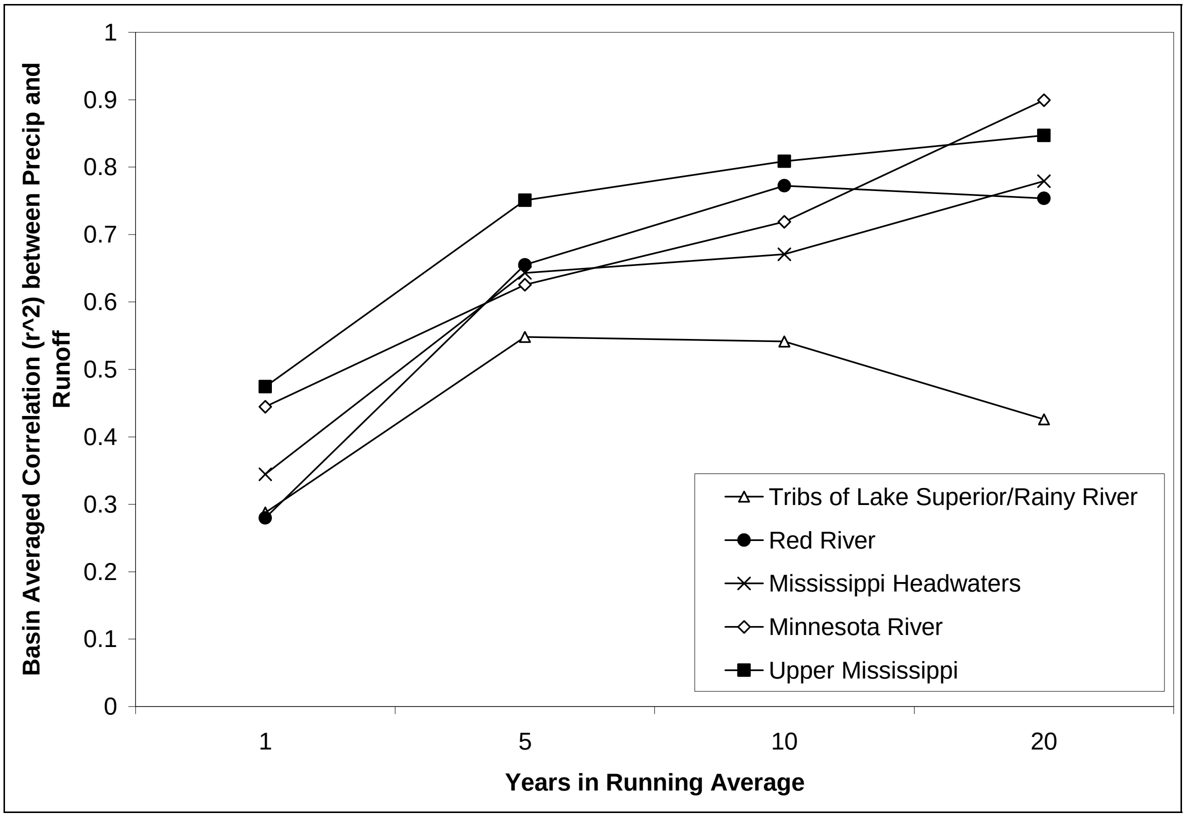


Figure 14: Basin average strengths of correlations between running average runoff and precipitation at the 1-year to 20-year running average time scales.

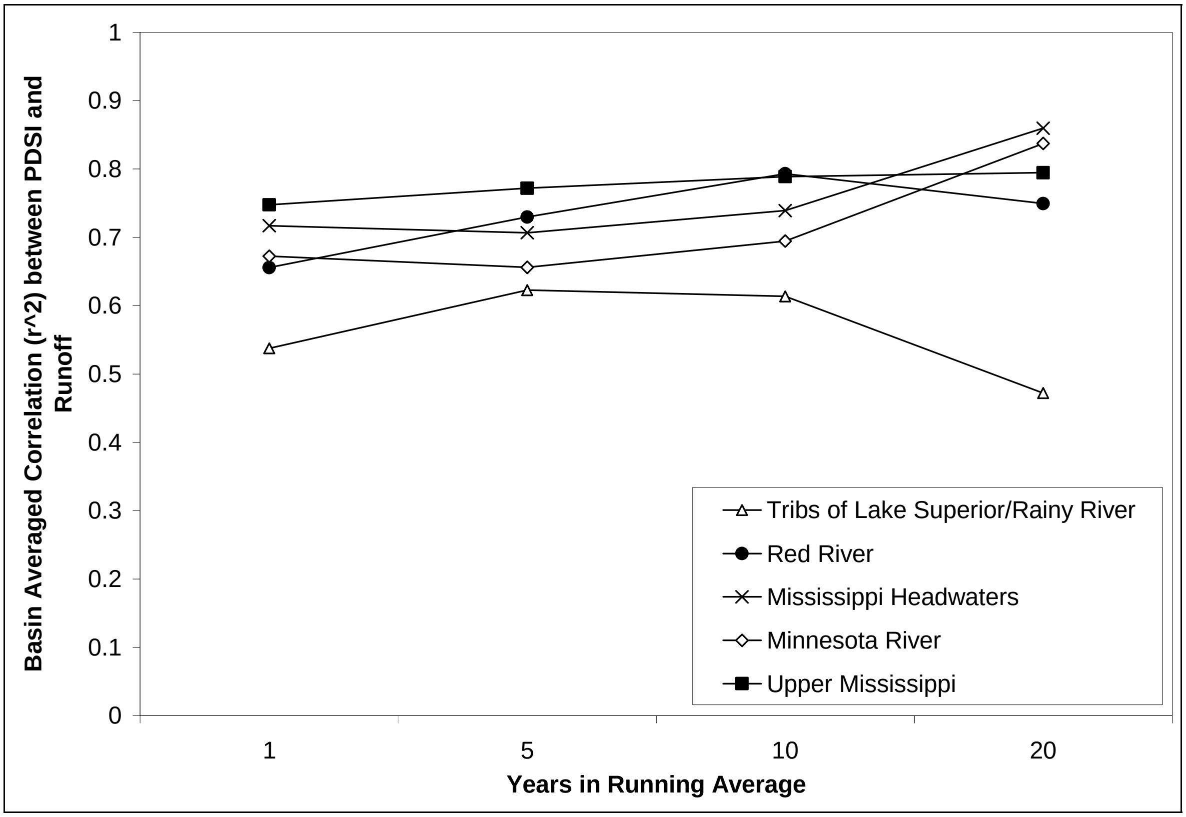


Figure 15: Basin average strengths of correlations between running average runoff and PDSI at the 1-year to 20-year running average time scale.

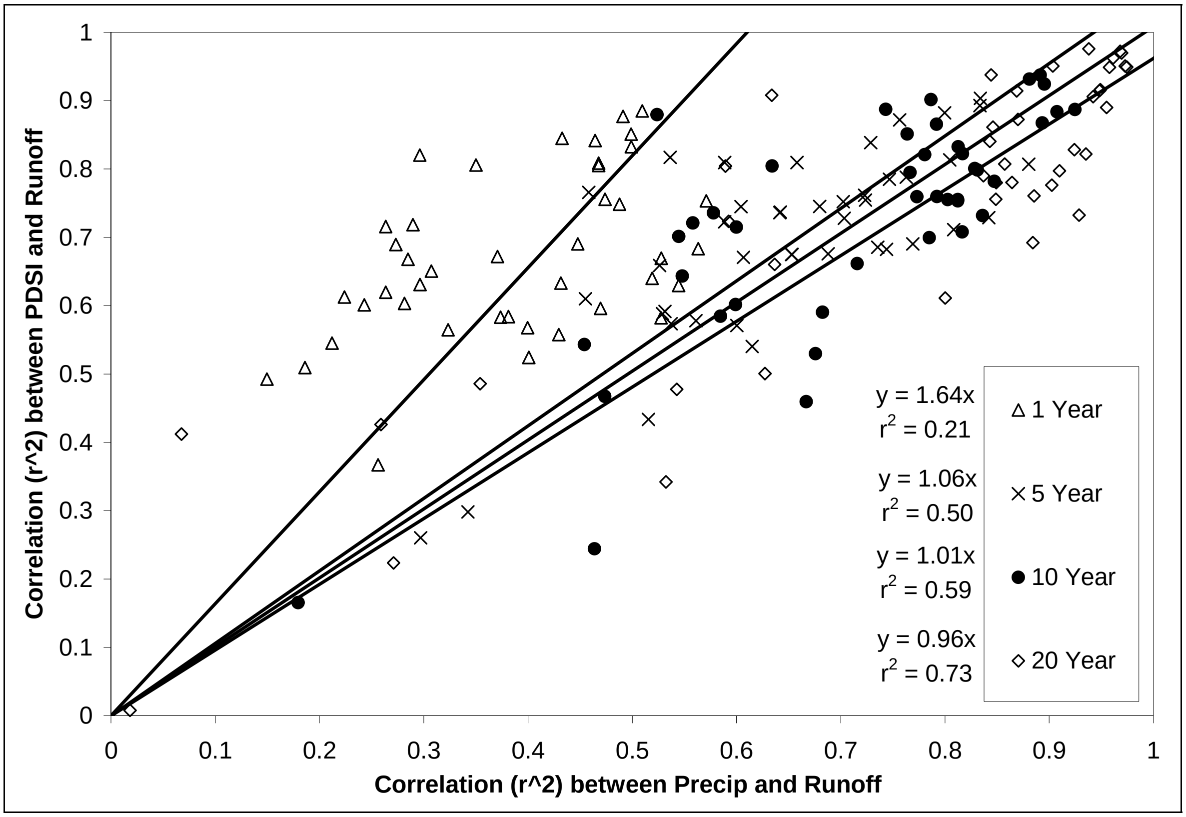


Figure 16: Strengths of correlation between average runoff and PDSI vs. strengths of correlation between average runoff and precipitation at the 1-year to 20-year running average time scales.

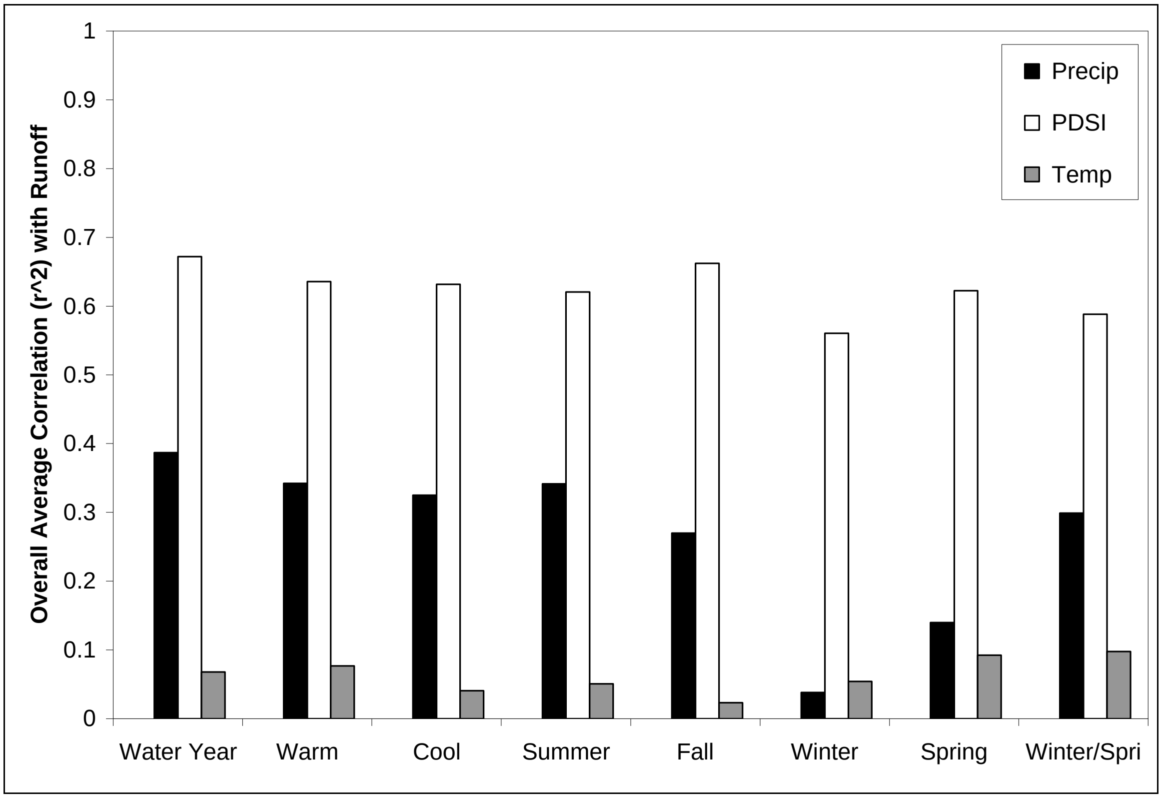


Figure 17: Overall average correlation strengths between climatic variables and runoff at seasonal time scales. Earlier results for the annual time scale are given on the left for comparison.

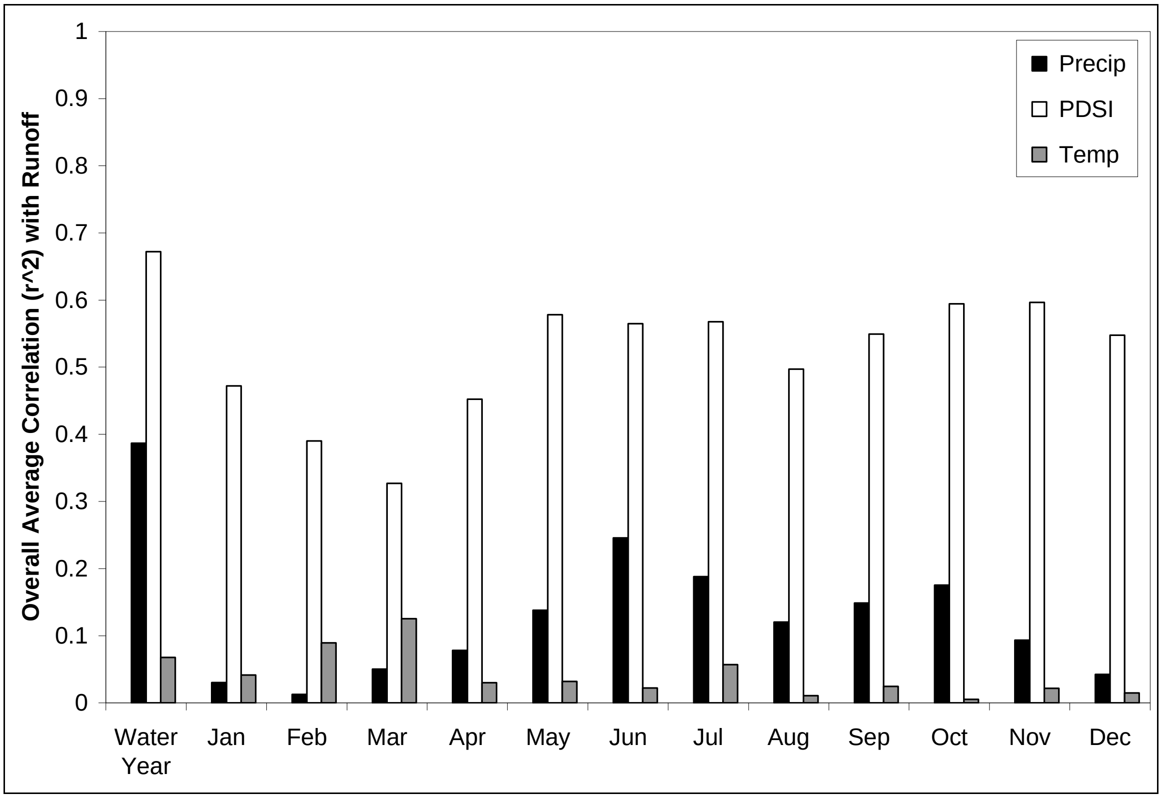


Figure 18: Overall average correlation strengths between climatic variables and stream runoff at the monthly time scale. Earlier results for the annual time scale are given on the left for comparison.

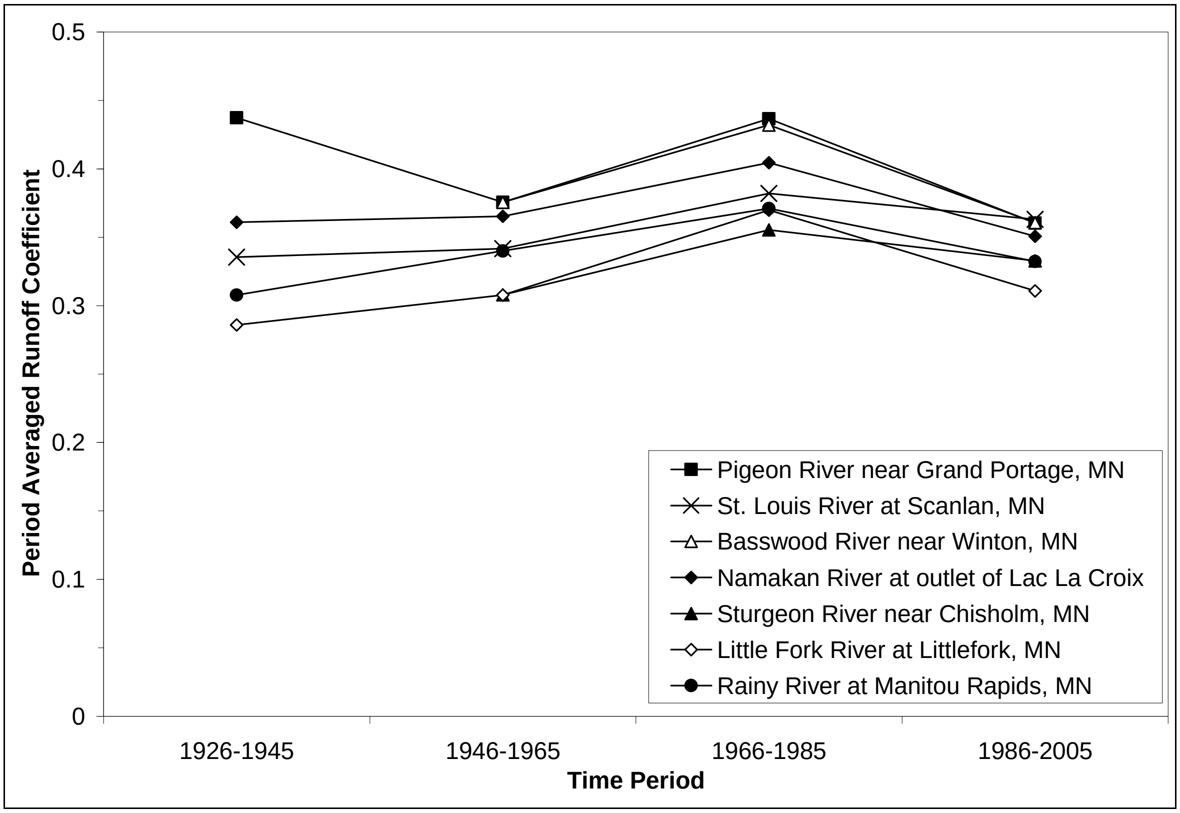


Figure 19: Runoff coefficients for streams in the Lake Superior and Rainy River Basins over four time periods.

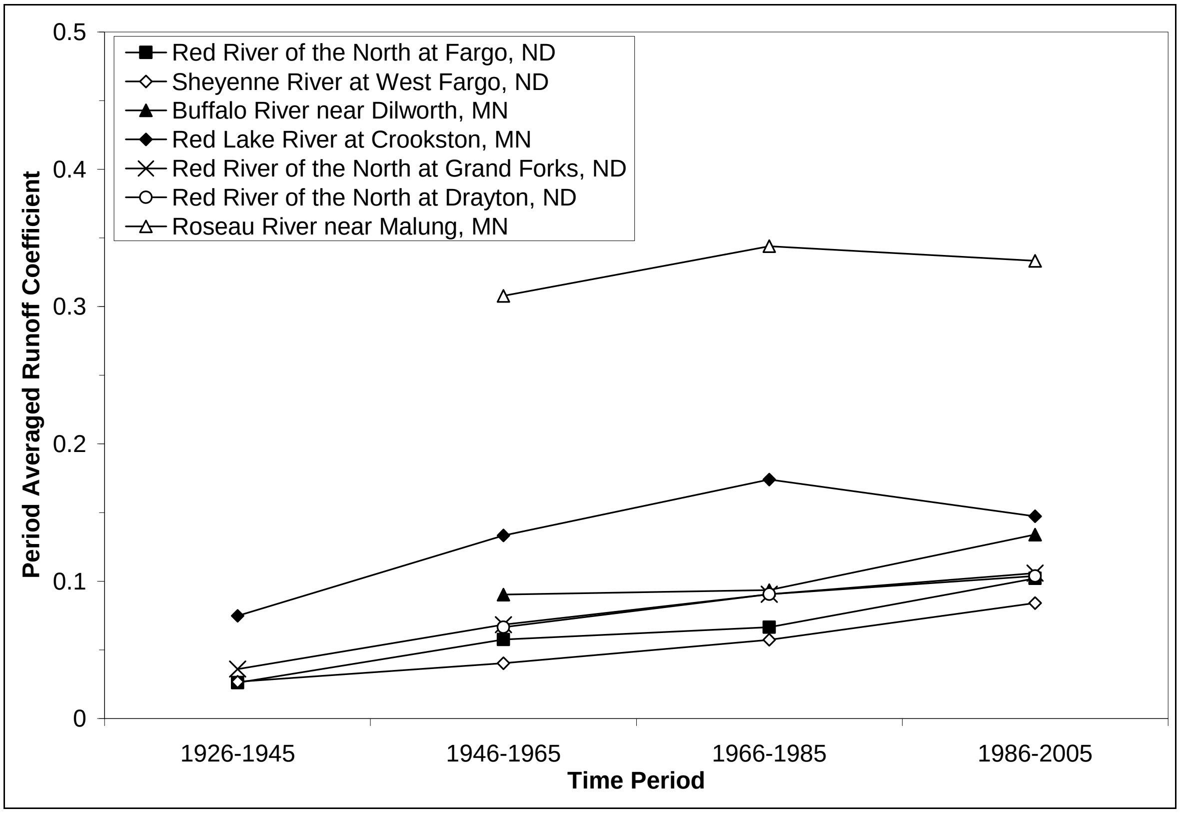


Figure 20: Runoff coefficients for streams in the Red River Basin over four time periods.

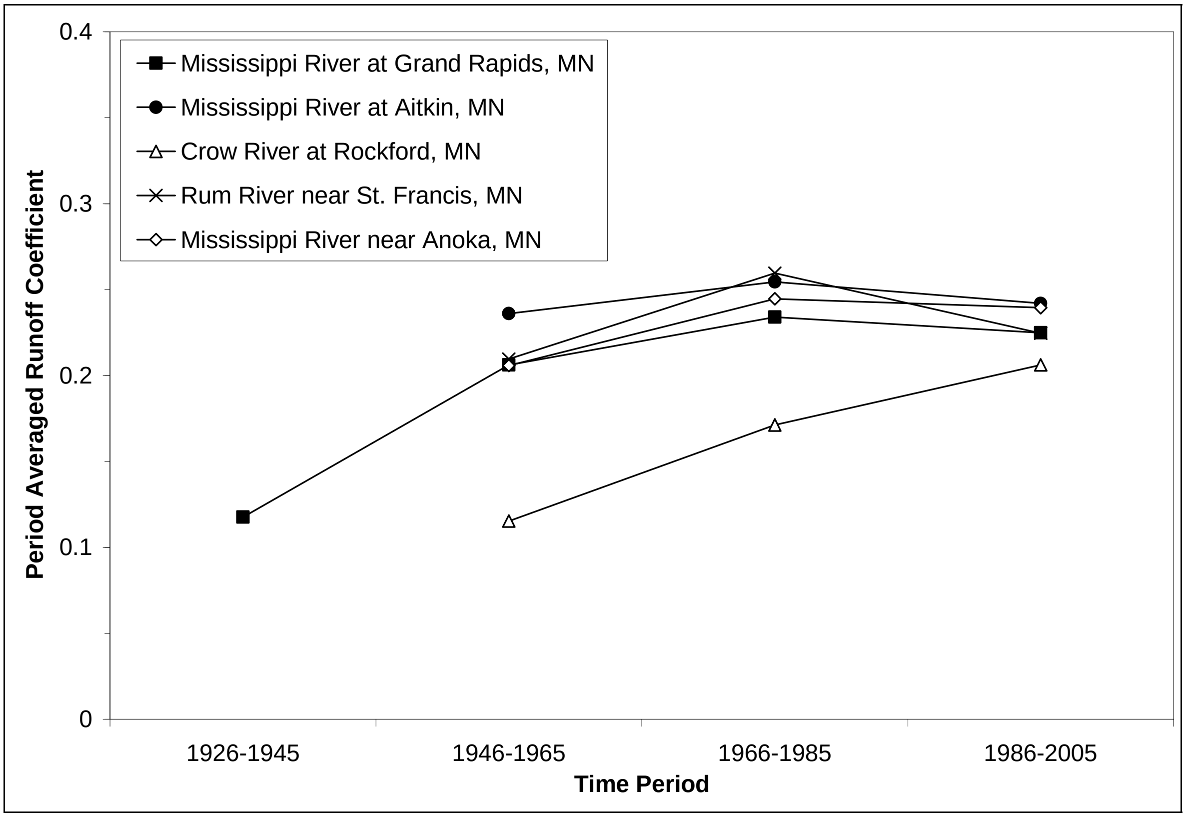


Figure 21: Runoff coefficients for streams in the Mississippi Headwaters Basin over four time periods.

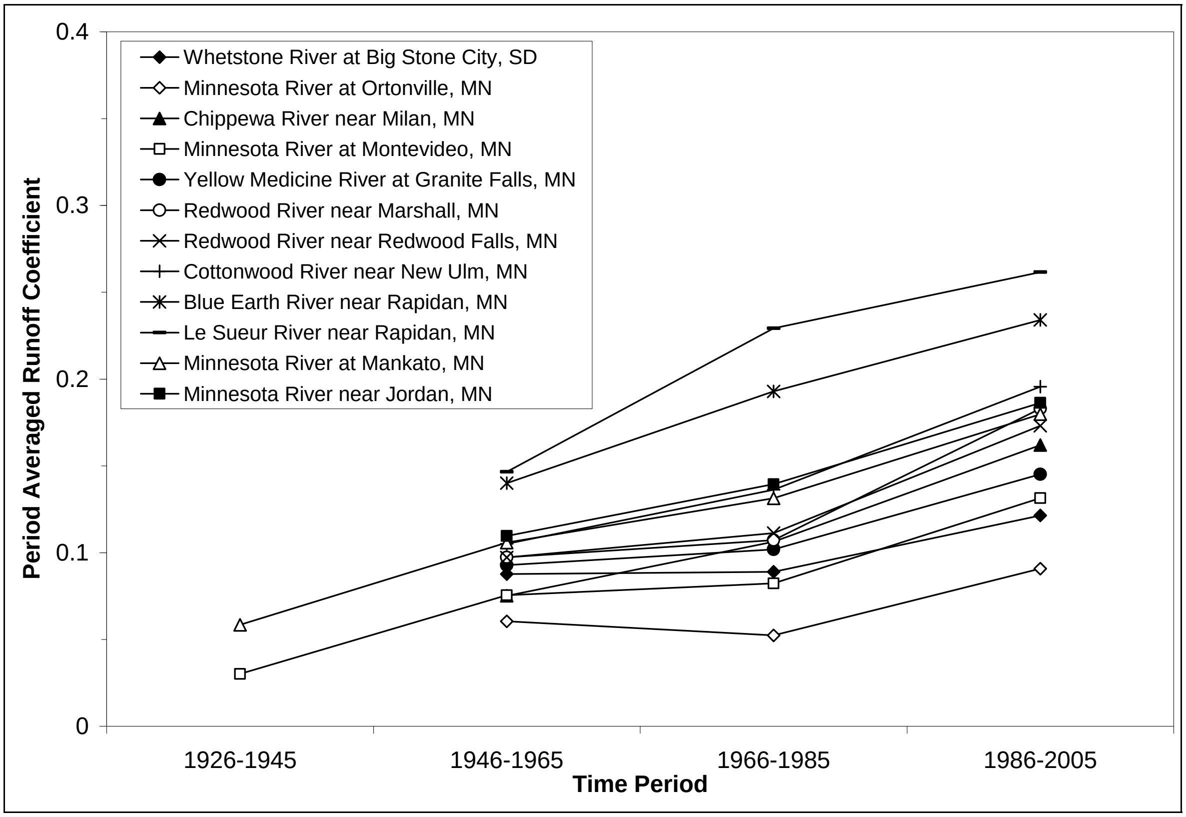


Figure 22: Runoff coefficients for streams in the Minnesota River Basin over four time periods.

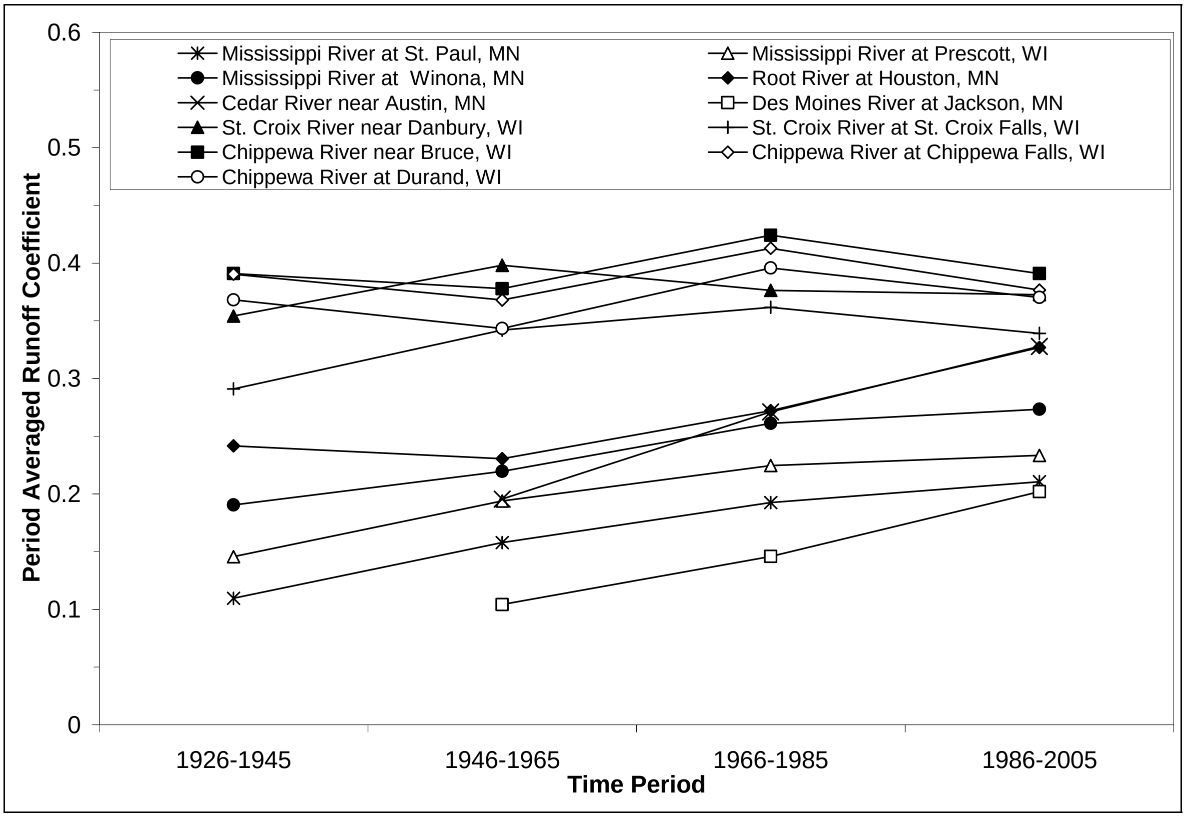


Figure 23: Runoff coefficients for streams in the Upper Mississippi River Basin below the confluence with the Minnesota River over four time periods.

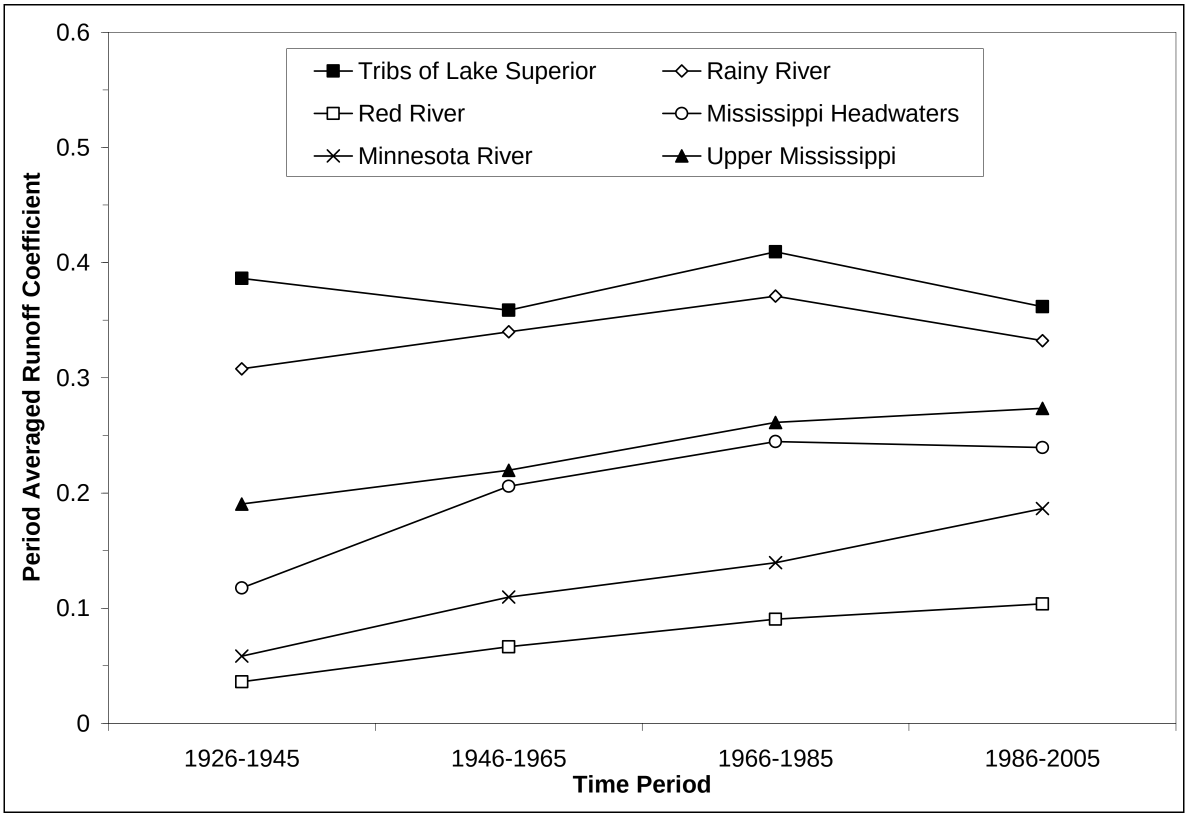


Figure 24: Runoff coefficients for lowest main stem stream in the major river basins of Minnesota over four time periods.

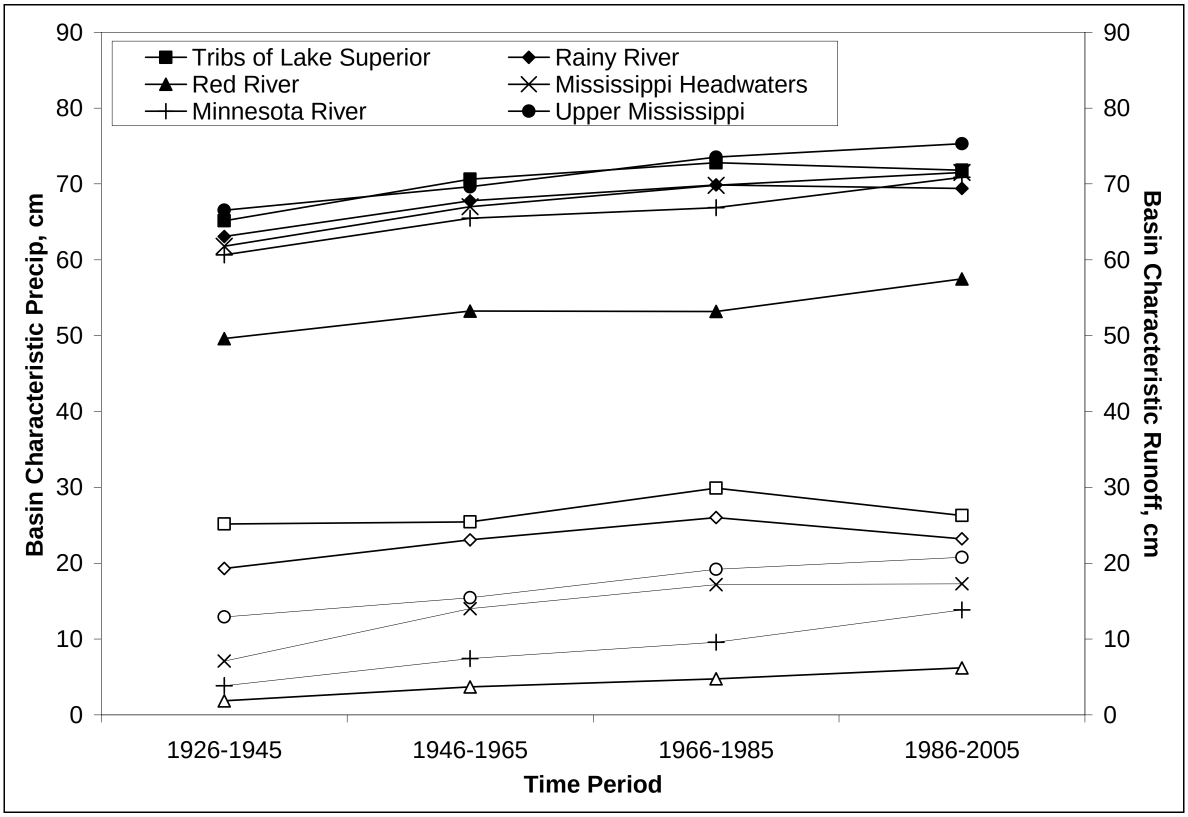


Figure 25: Average precipitation (black) and average runoff (white) in specific river basins of Minnesota over four time periods.

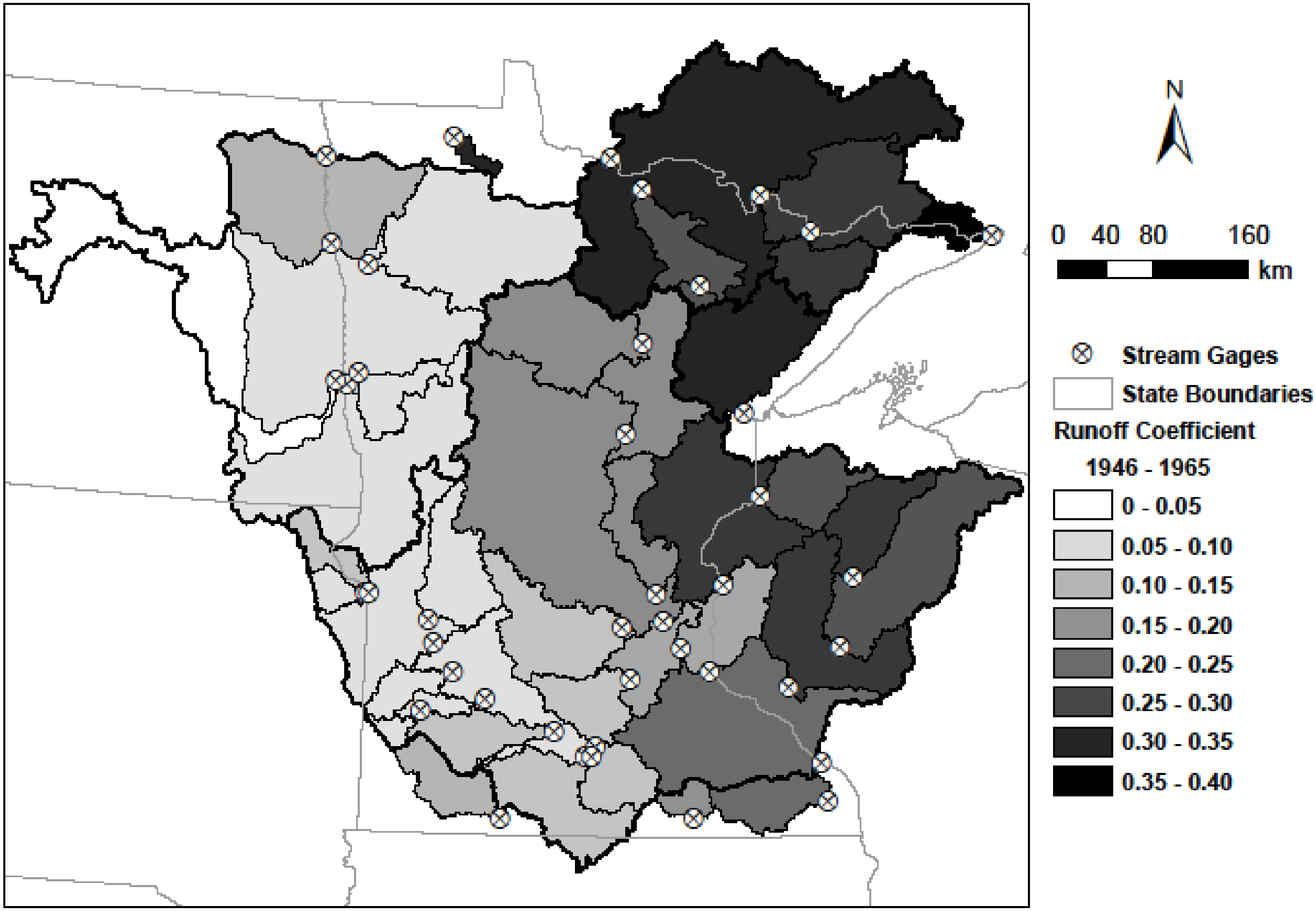


Figure 26: Geographic distribution of average runoff coefficients for the 1946-1965 time period.

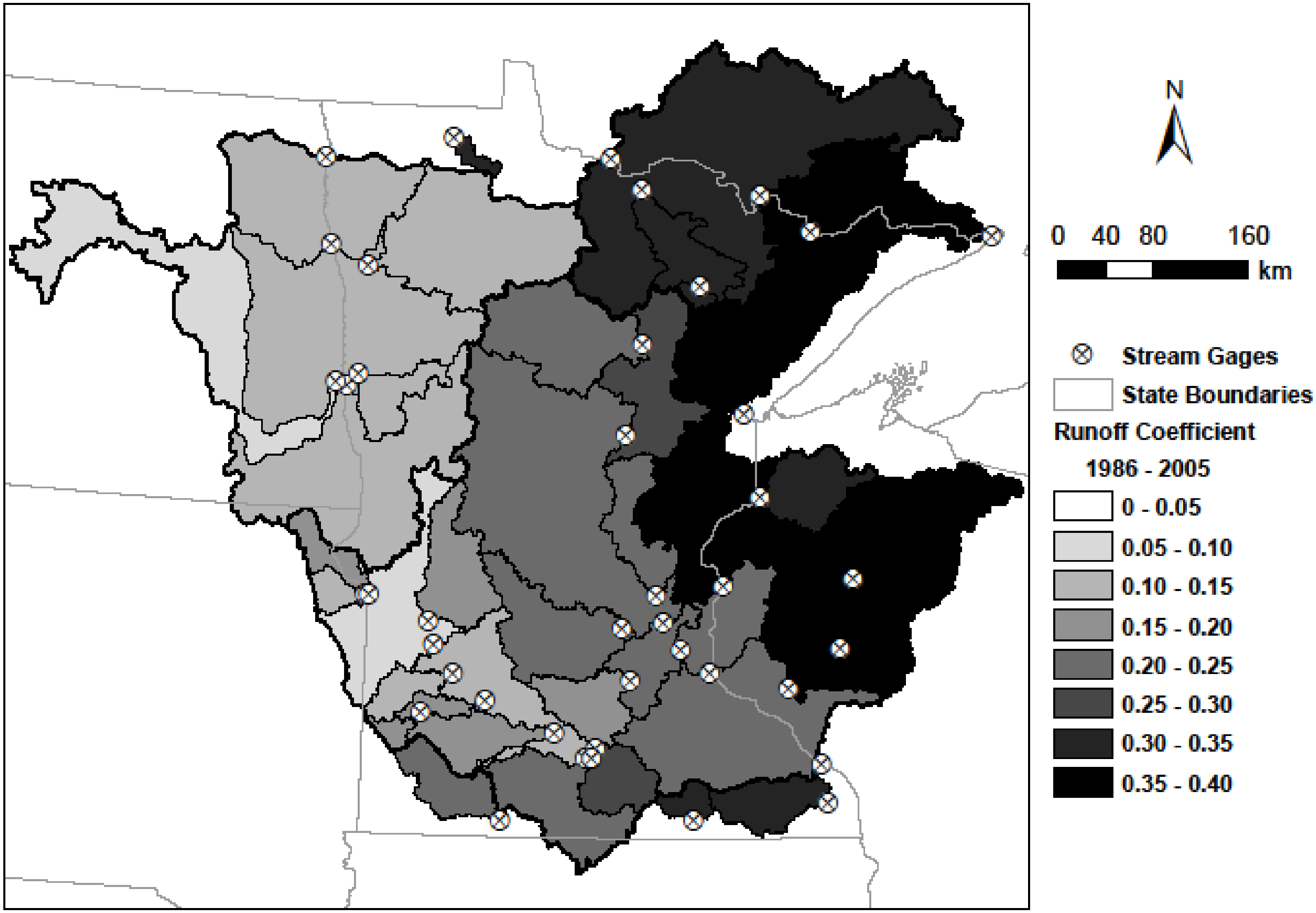


Figure 27: Geographic distribution of average runoff coefficients for the 1986-2005 time period.

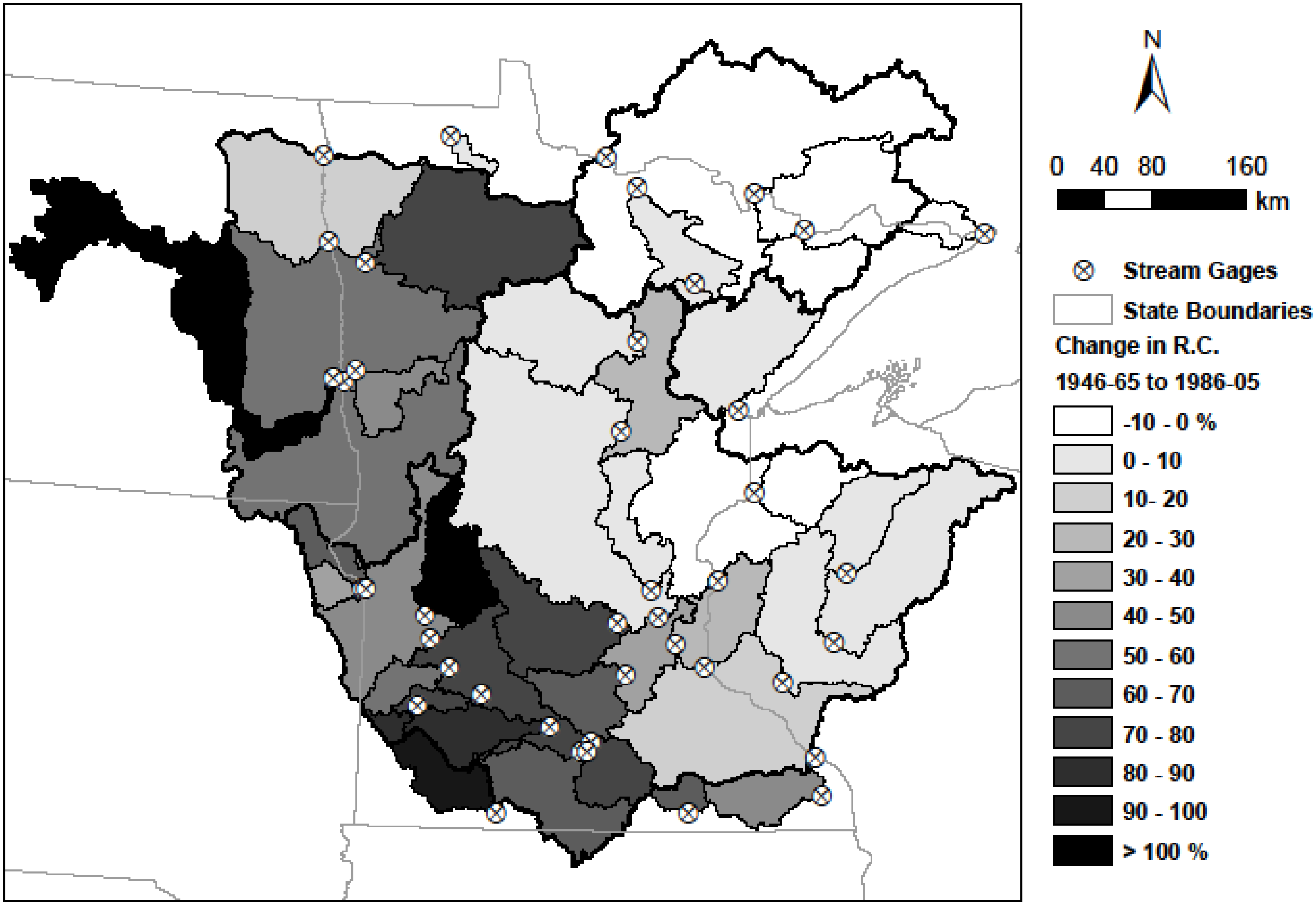


Figure 28: Geographic distribution of average runoff coefficient change (in percent) between the 1946-1965 and 1986-2005 time periods.

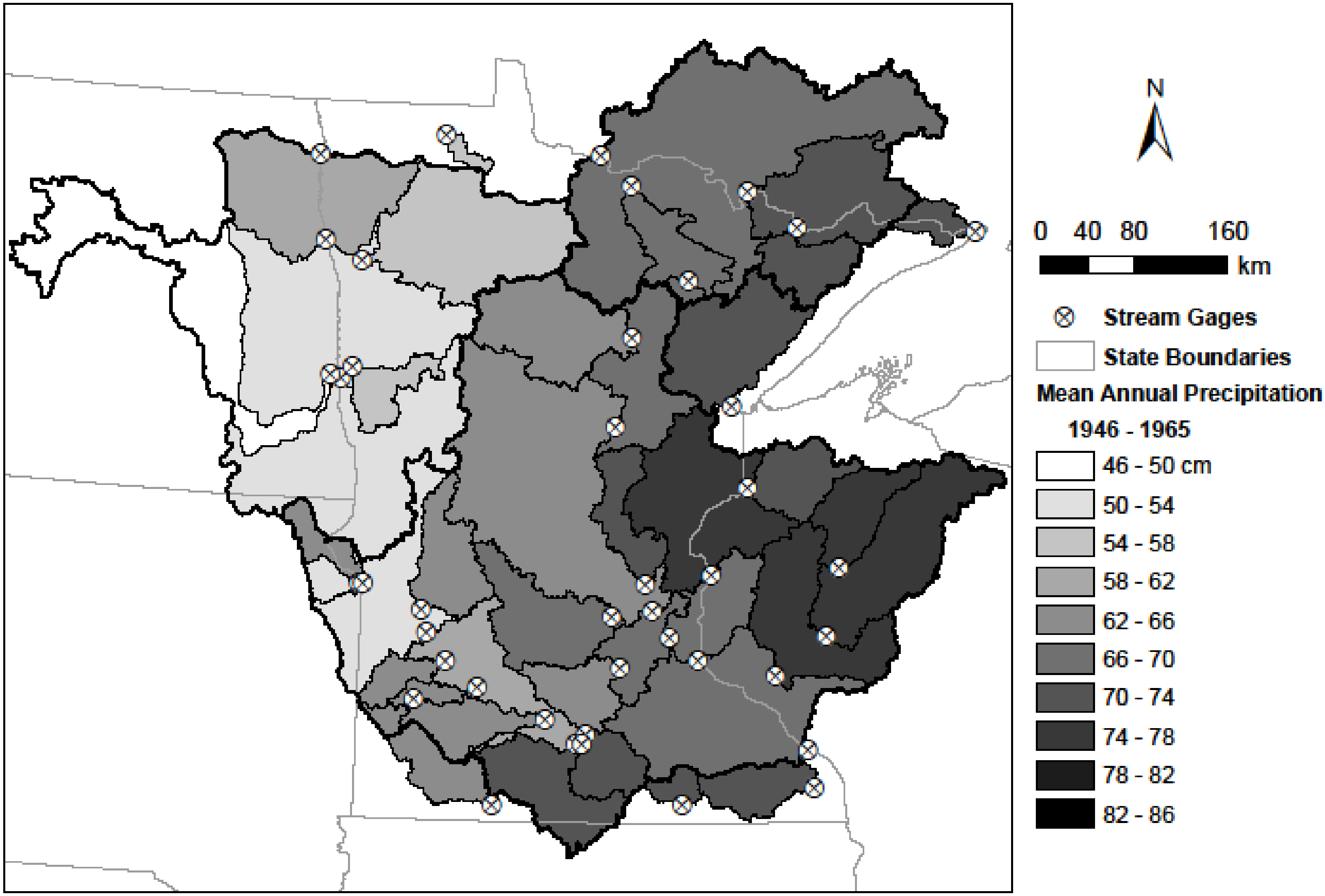


Figure 29: Geographic distribution of average annual precipitation for the 1946-1965 time period.

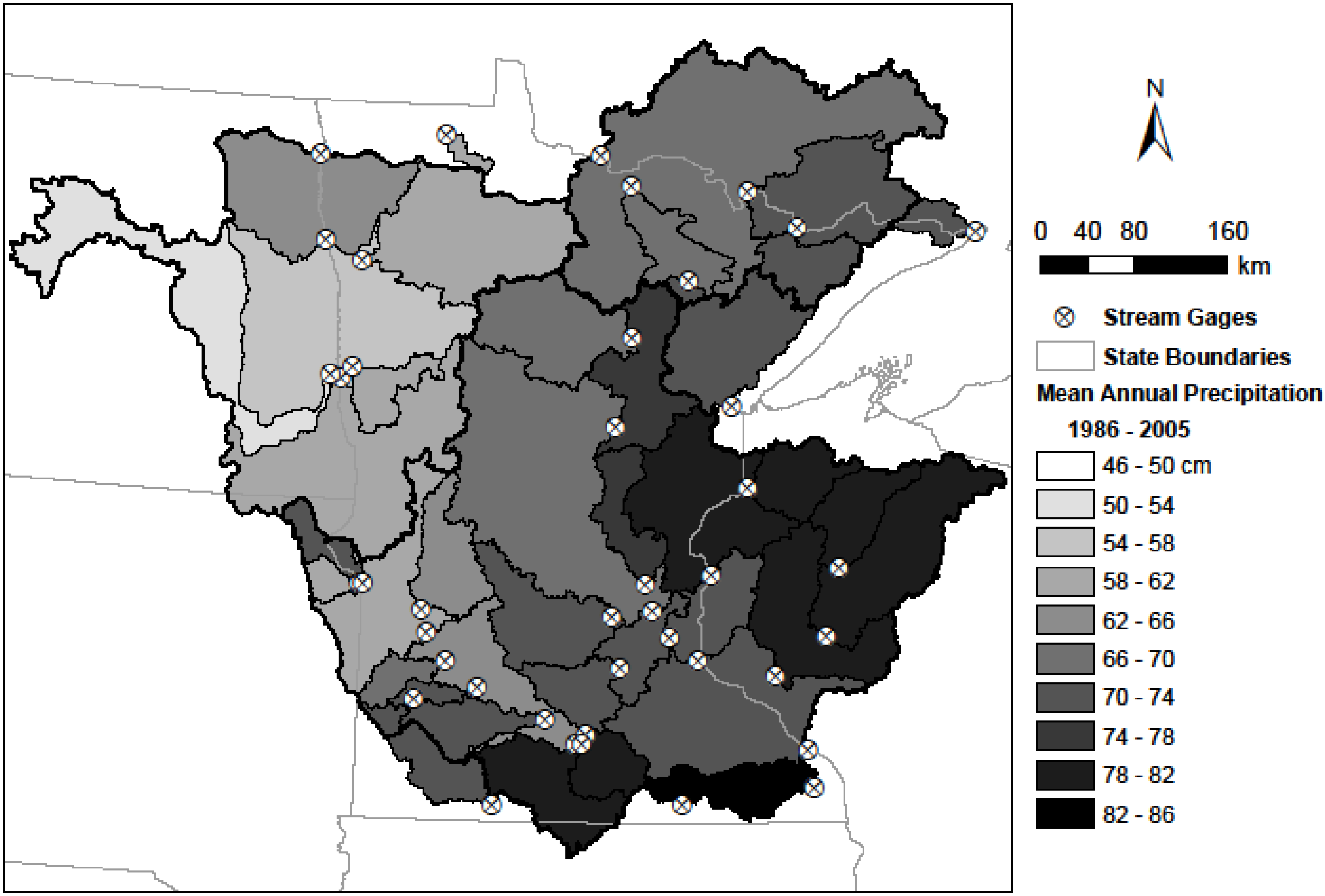


Figure 30: Geographic distribution of average annual precipitation for the 1986-2005 time period.

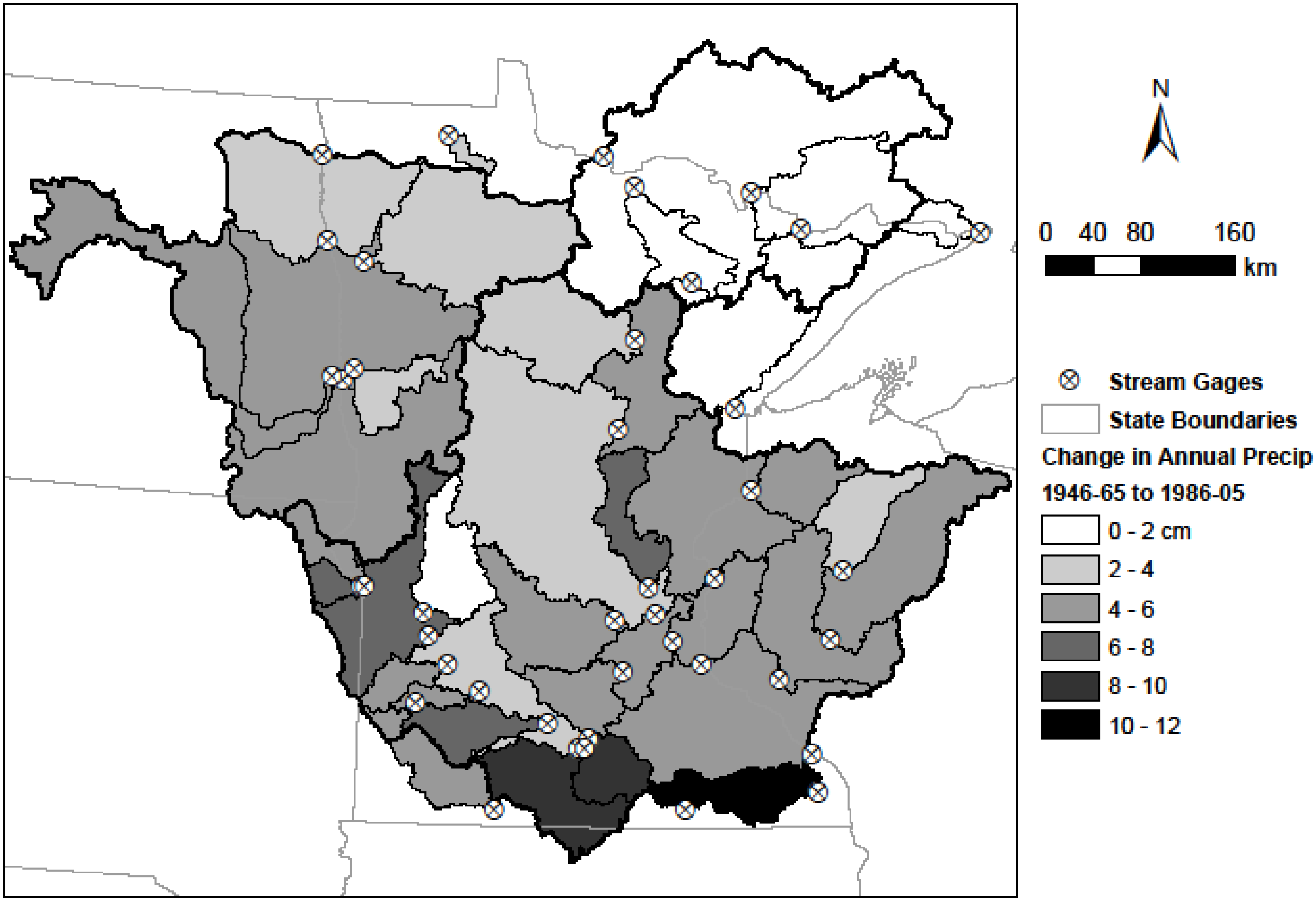


Figure 31: Geographic distribution of average annual precipitation change (in cm) between the 1946-1965 and 1986-2005 time periods.

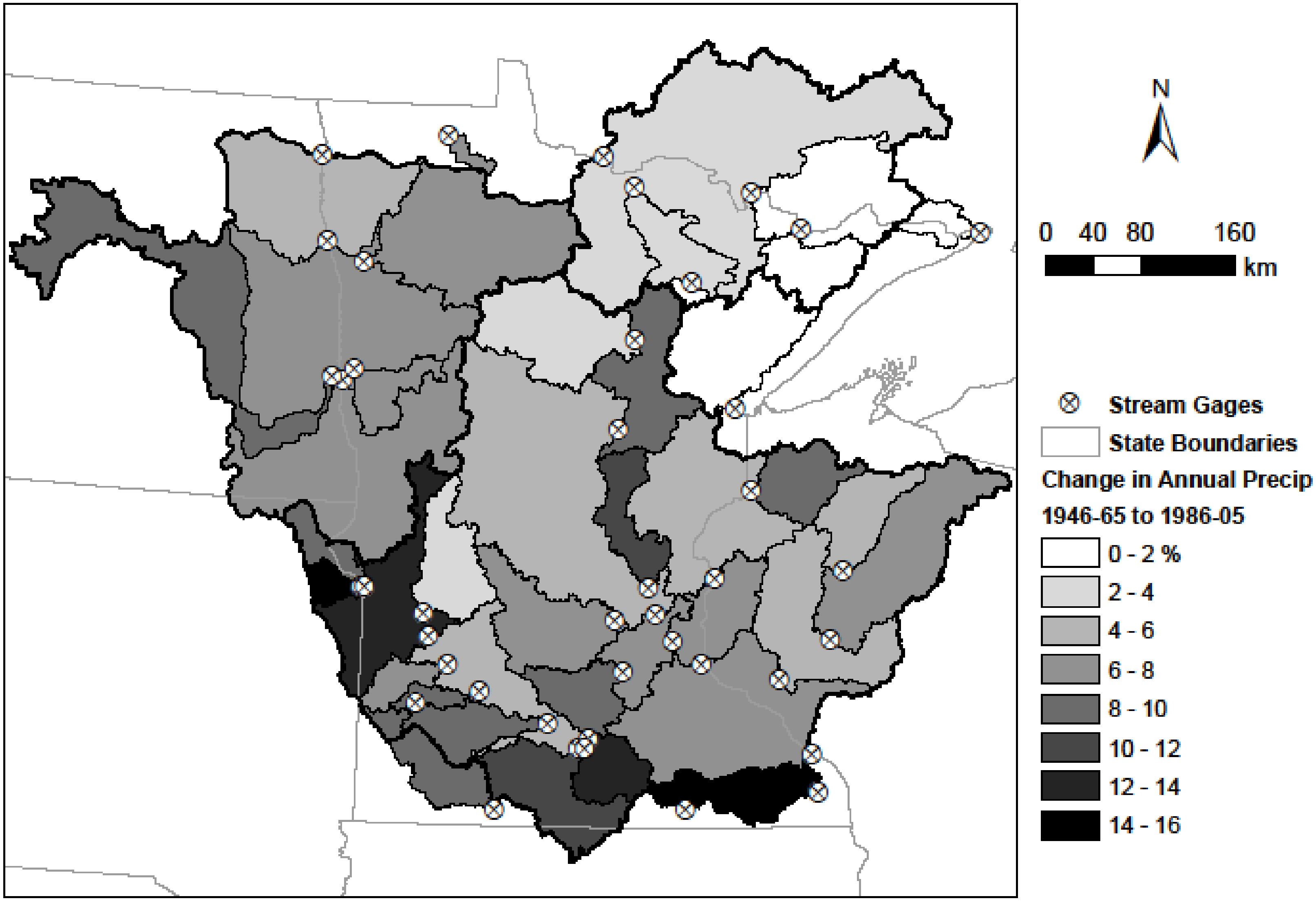


Figure 32: Geographic distribution of average annual precipitation change (in percent) between the 1946-1965 and 1986-2005 time periods.

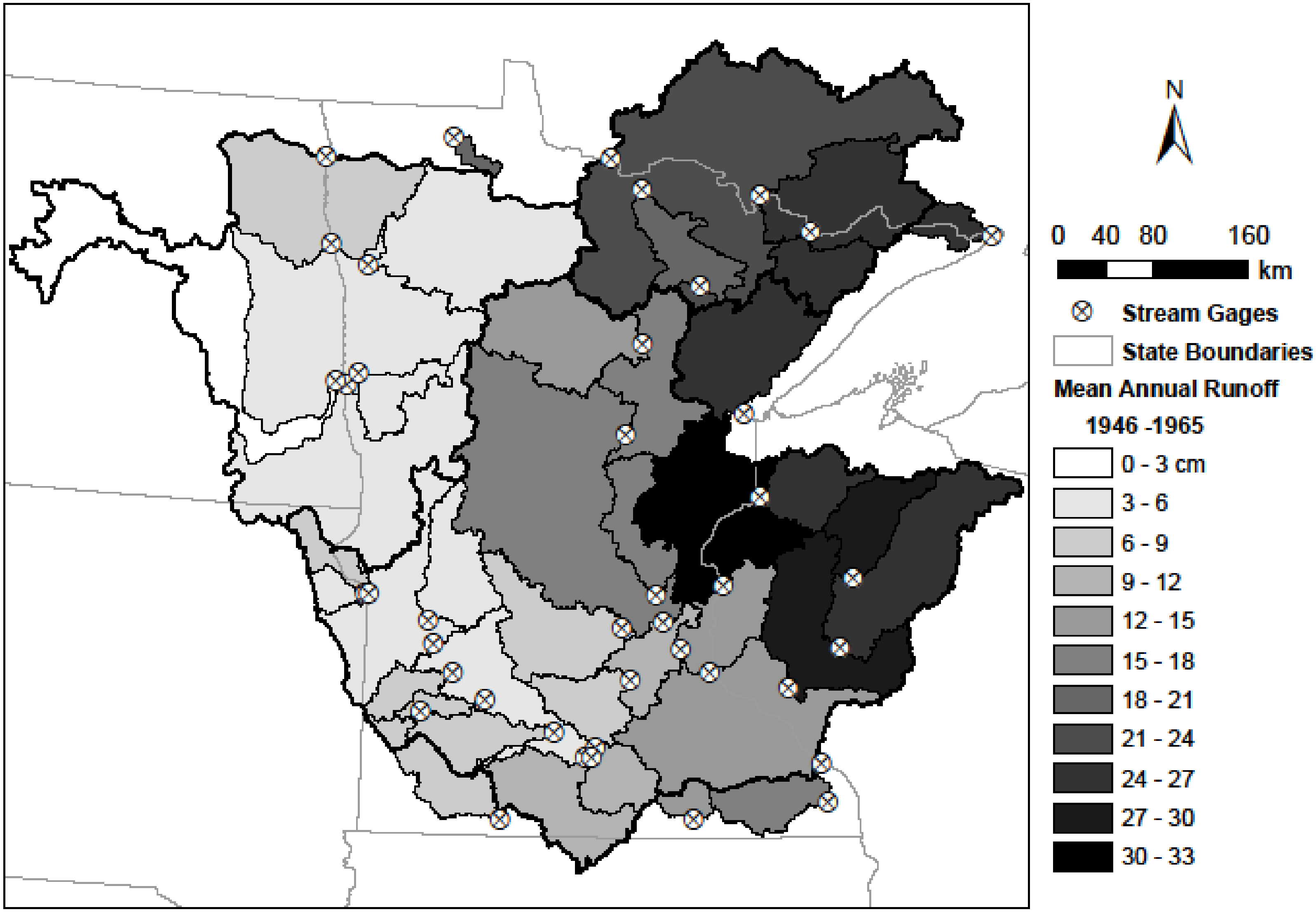


Figure 33: Geographic distribution of average annual runoff for the 1946-1965 time period.

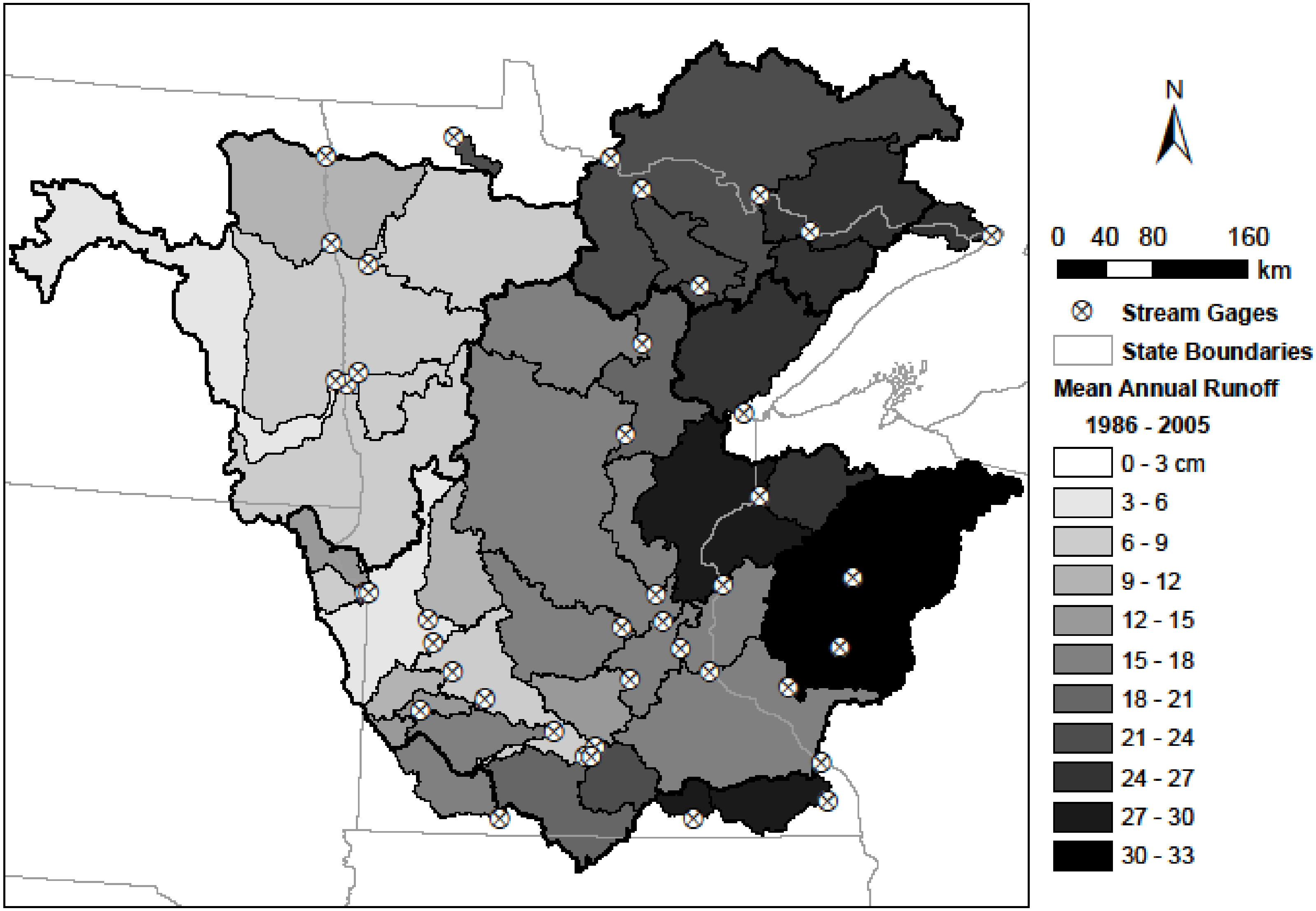


Figure 34: Geographic distribution of average annual runoff for the 1986-2005 time period.

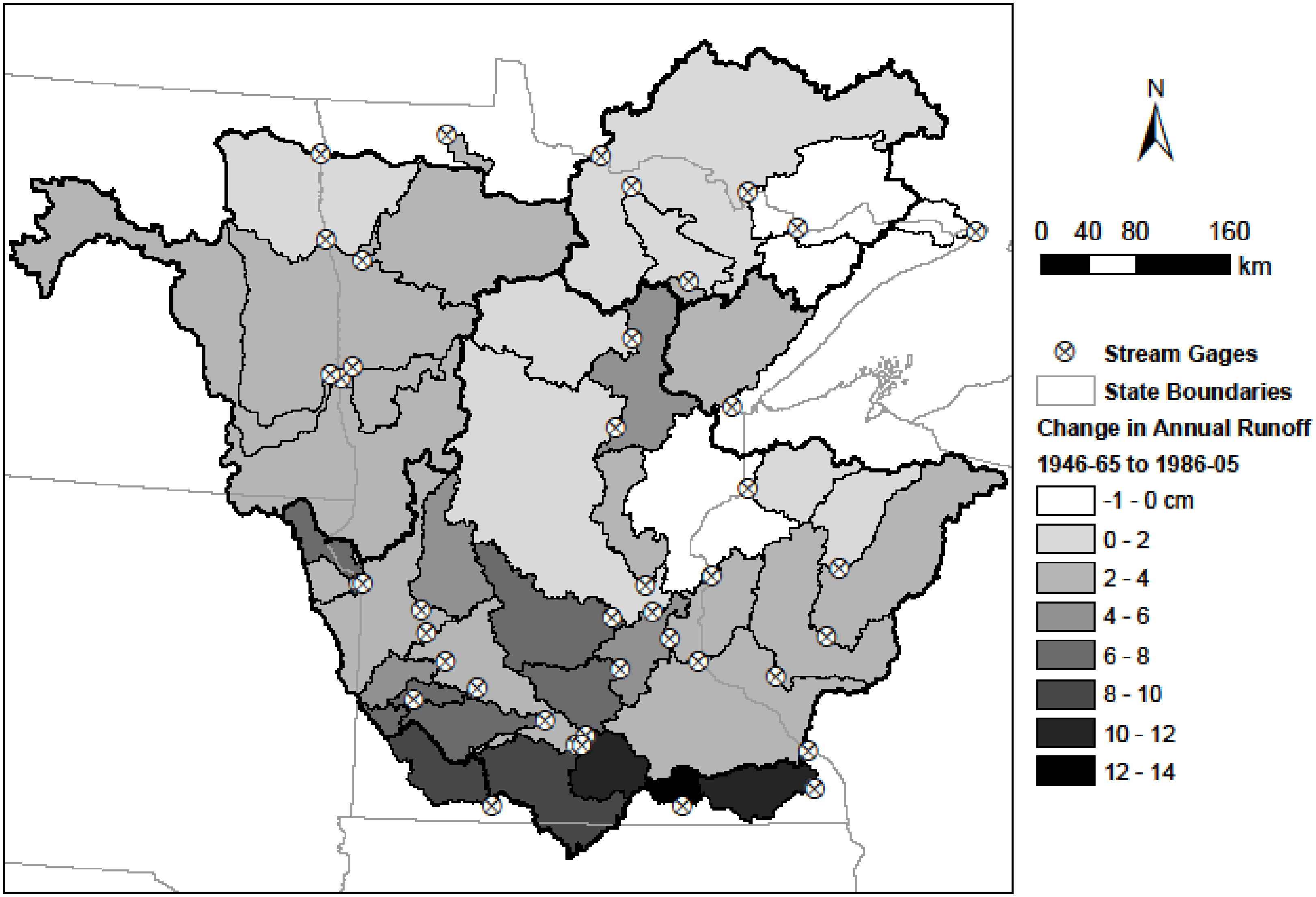


Figure 35: Geographic distribution of average annual runoff change (in cm) between the 1946-1965 and 1986-2005 time periods.

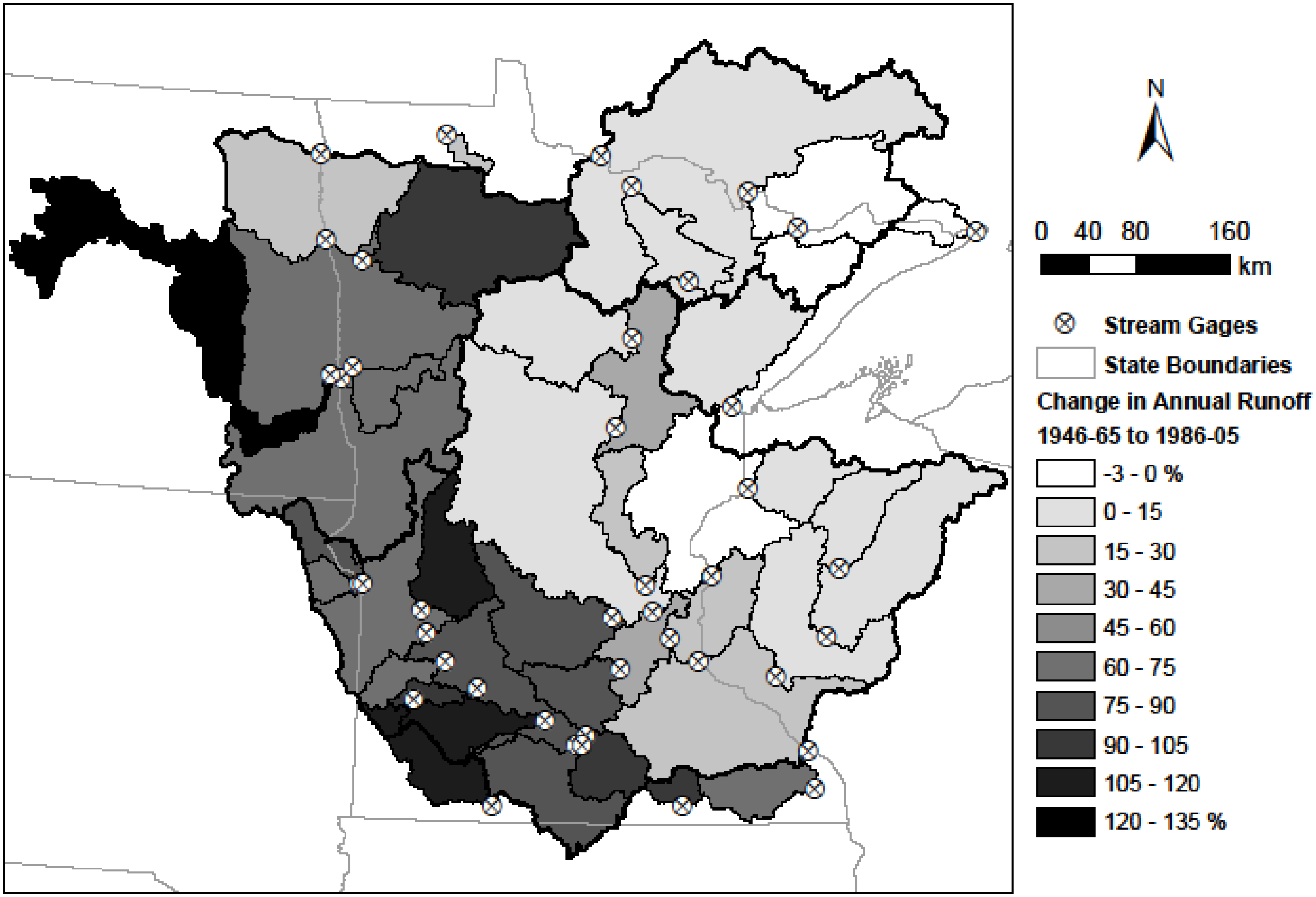


Figure 36: Geographic distribution of average annual runoff change (in percent) between the 1946-1965 and 1986-2005 time periods.

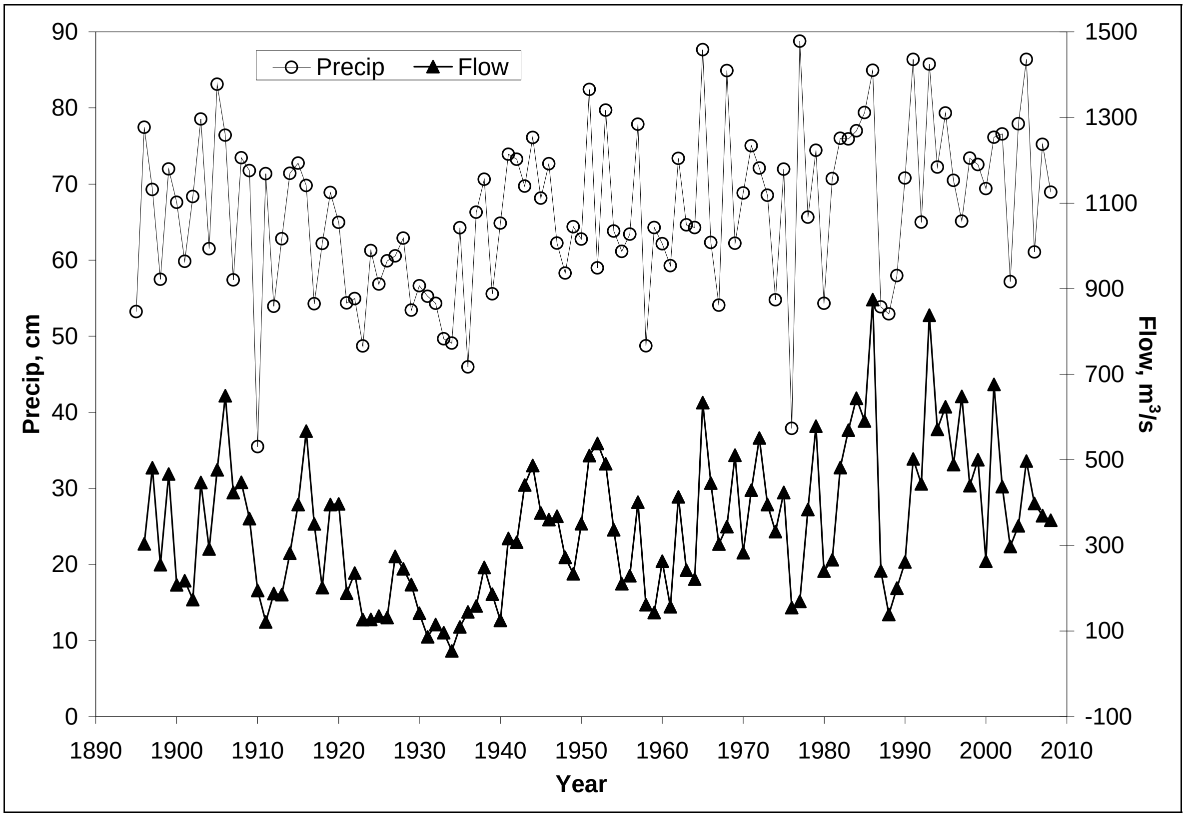


Figure 37: Historical annual flow and precipitation records for the Mississippi River at St. Paul, MN.

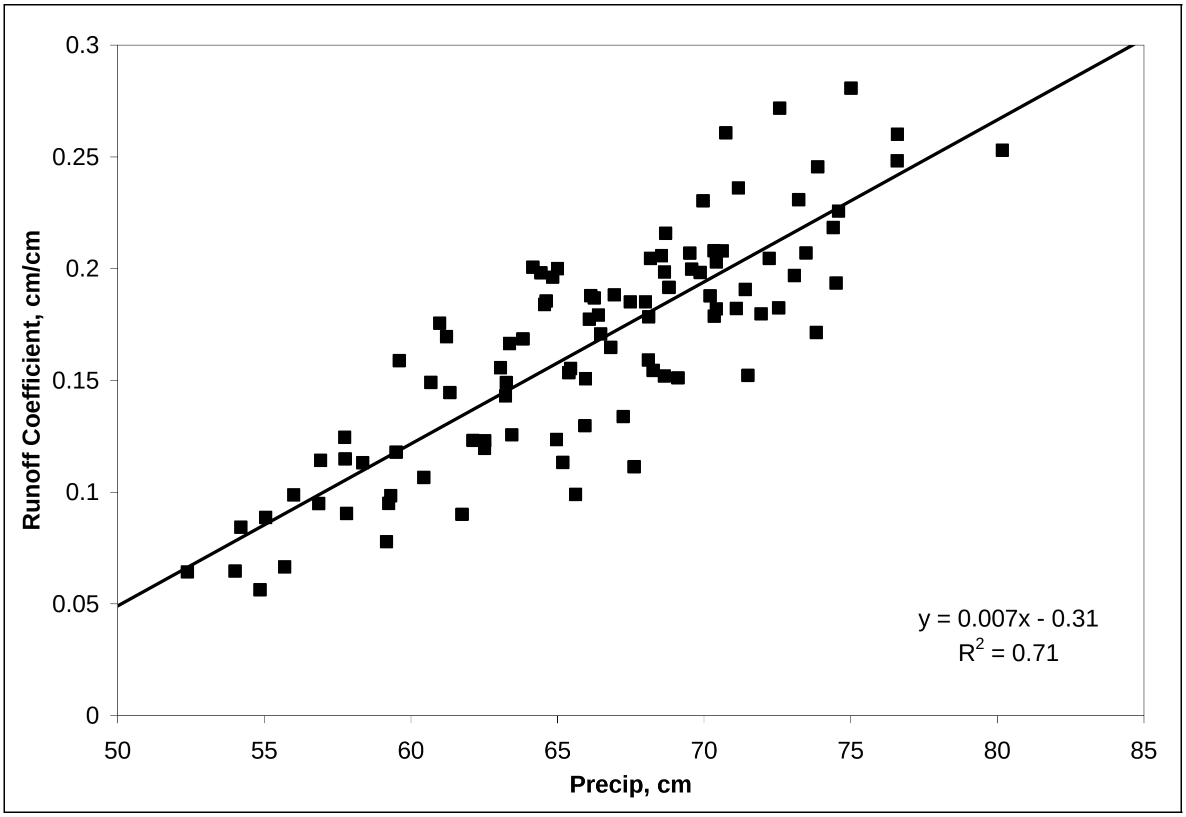


Figure 38: Runoff coefficient vs. precipitation for the Mississippi River at St. Paul, MN for the 5-year running average time scale.

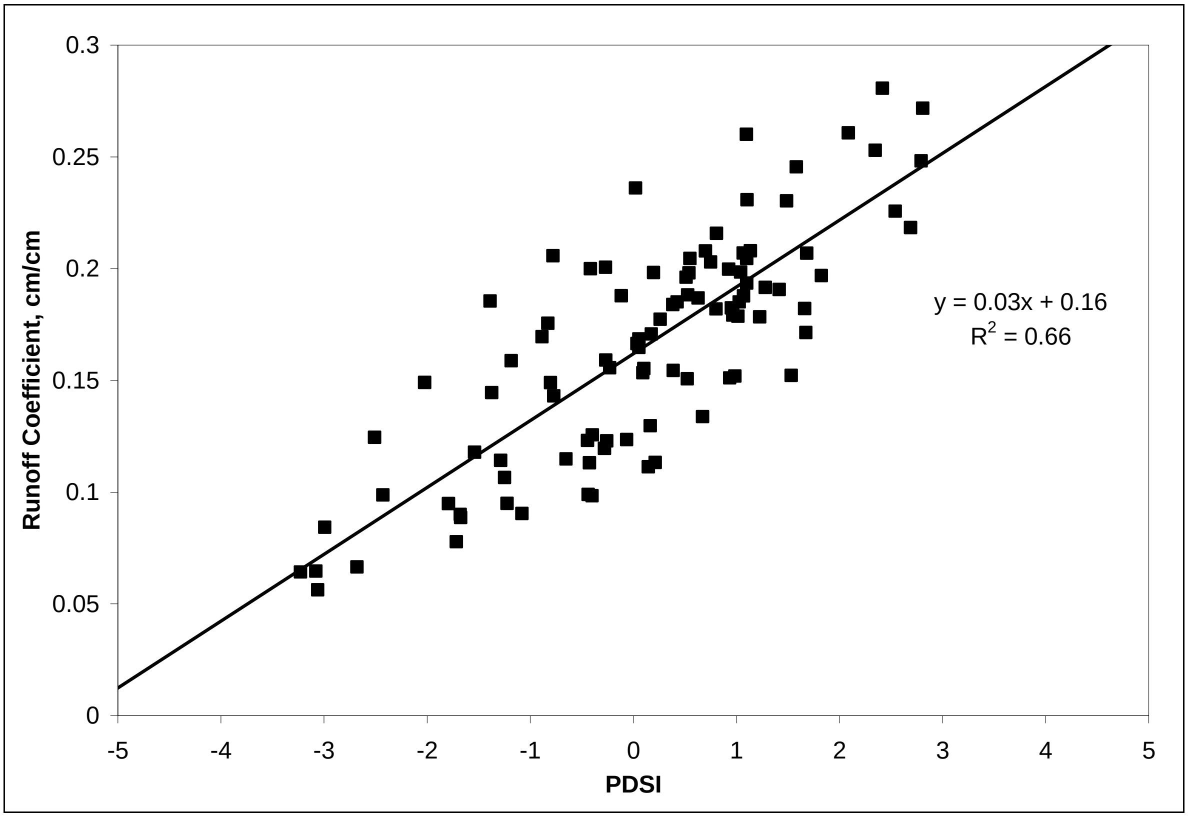


Figure 39: Runoff coefficient vs. PDSI for the Mississippi River at St. Paul, MN for the 5-year running average time scale.

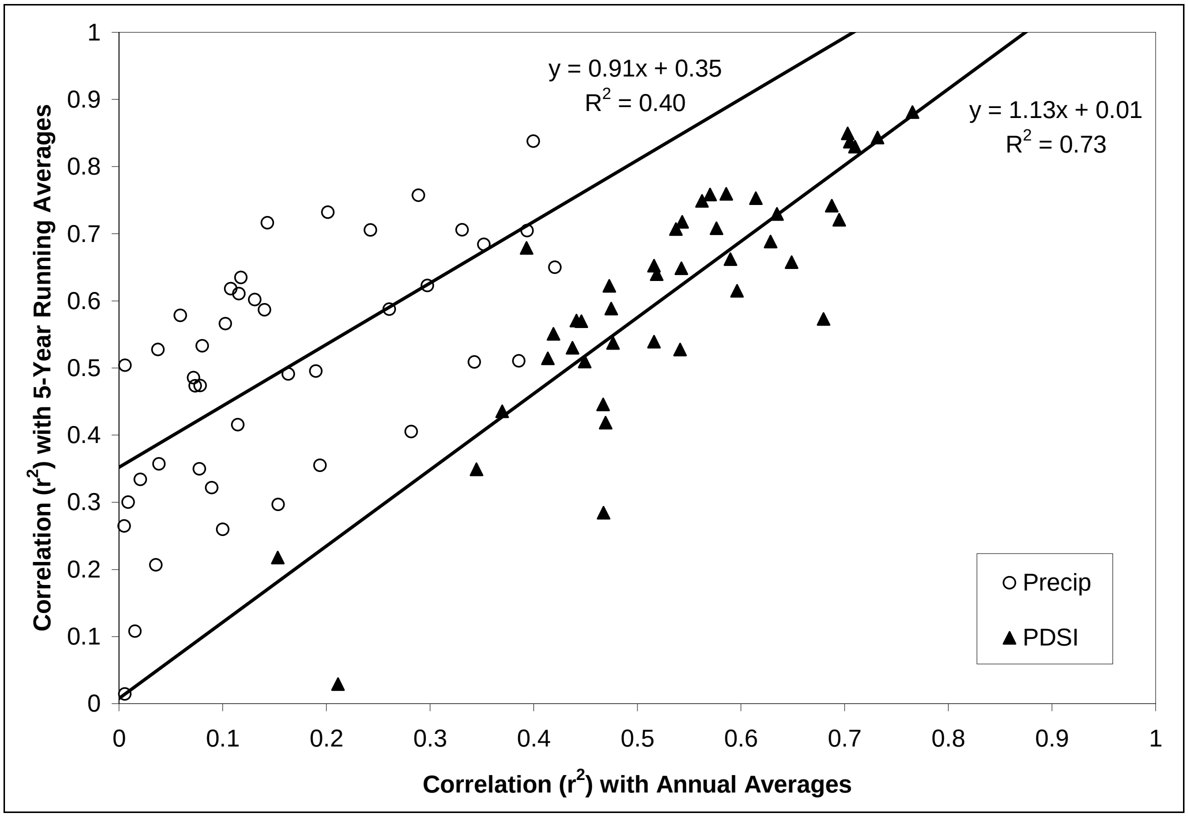
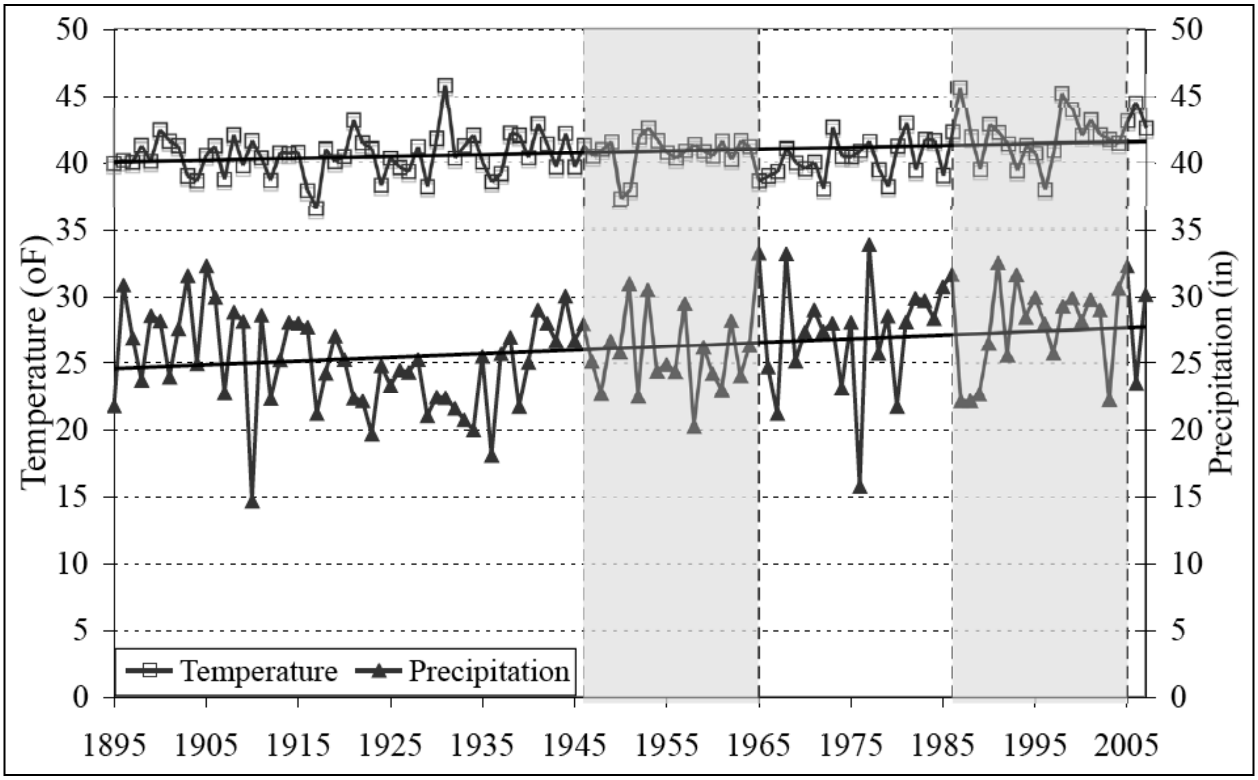


Figure 40: Strength of correlations between runoff coefficient and precipitation or PDSI at the 5-year running average timescale vs. the annual time scale.



Note: 1 in = 25.4 mm and 1.8 ^{o}F = 1.0 ^{o}C

Figure A.1: Annual average temperatures and annual precipitation in Minnesota for the period 1895-2007. Study time periods 1946-1965 and 1986-2005 are highlighted in gray. (From Dadaser-Celik and Stefan (2009)).

APPENDIX: DESCRIPTION OF MINNESOTA'S RIVER BASINS AND CLIMATE

The following descriptions of Minnesota's major river basins and climate are provided by Dadaser-Celik and Stefan (2009)**.**

A.1 Study Area

Minnesota is located in the Upper Midwest of the U.S. is in the headwaters of three continental drainage systems, although its elevation is relatively low, ranging from about 180 m (600 ft) to 690 m (2300 ft) amsl. The state's drainage area is 223,000 km^2 (87,000 square miles). Major rivers and river basins, as well as USGS stream gauging stations are shown in Figure 1. Ice sheets sculpted most of the states current landscape; the last glaciation ended 12,000 years ago. Glaciers covered all of Minnesota except the far southeast, known as the Driftless Area and left behind 15 m (50 ft) or more of glacial till as they retreated (Ojakangas, 2001).

Besides being the *Land of 10,000 Lakes* (11,840 lakes over 10 acres in size) Minnesota also has about 42,900 km^2 of wetlands, and 6,560 natural streams and rivers that cumulatively flow for 111,000 km (69,000 miles). Because continental divides meet in north-central Minnesota, surface runoff can follow the Mississippi River south to the Gulf of Mexico, the St. Lawrence Seaway east to the Atlantic Ocean, or the Hudson Bay watershed to the Arctic Ocean. The Mississippi River begins at Lake Itasca and is joined by the Minnesota River at Fort Snelling, by the St. Croix River near Hastings, by the Chippewa River at Wabasha, and by many smaller streams. The Red River of the North drains the northwest part of the state northward toward Hudson Bay and the Rainy River forms the U.S. border with Canada.

Minnesota's streams and rivers were described by Waters (1977), and are important as wildlife habitat, for recreation, as a source of water supply, and as recipients of waste water. There are five major river basins of substantially different geologic, topographic, ecologic and land use characteristics. The five basins are named after the Minnesota River, the Red River of the North, the Rainy River, Lake Superior and the Upper Mississippi River, and are hydrologically quite different. They will be described and analyzed below.

The ***Minnesota River Basin*** covers about 16,770 square miles, and is located in southern Minnesota (http://mrbdc.mnsu.edu/mnbasin/fact_sheets/fastfacts.html), except for small portions that extend into South Dakota and Iowa (Figure 1). 92% of the basin area is used for agriculture. A large range of climatic, hydrologic, landscape and soil characteristics can be seen in the Minnesota River Basin. Annual precipitation ranges from 22 inches in the northwestern to 32 inches in the southeastern portion of the basin. Annual runoff ranges from 2 inches in the west to 6 inches in the east (http://www.soils.umn.edu/research/mn-river/doc/mbtext.html). Soil drainage ranges from well drained to poorly-drained. The basin includes an extensive network of agricultural drainage tiles and man-made ditches. Other hydrologic features include lakes, wetlands, and permanent and intermittent streams. Sediments deposited during recent glacial recessions are continuing to be eroded. Erosion potential of agricultural cropland and stream banks is significant. The Minnesota River valley was formed by the post-glacial River Warren which drained the former gigantic Lake Agassiz southward towards the Mississippi River.

The ***Red River of the North Basin*** comprises 37,100 square miles of land in Minnesota, South Dakota and North Dakota. 17,730 square miles of it is in Minnesota. The majority of the land in the Minnesota is used for agriculture (66%), some land on the fringes of the basin is covered by forests (12%), and some is urban land (8%) mostly in North Dakota (Paakh et al., 2006). The Red River flows towards the north across the lakebed of the former Lake Agassiz. The river itself began after Lake Agassiz drained, about 9,500 years ago. The river's floodplain is remarkably flat and has a gradient of about 1:5000 from its origin in Minnesota to the international border. When water levels of Red River rise, "overland flooding" appears across the floodplain. Several floods occurred in the Red River of the North Basin in the past following heavy snows or rains on saturated or frozen soil and they were often made worse when snowmelt started in the warmer south, and northward flowing water was dammed or slowed by ice (http://en.wikipedia.org/wiki/Red_River_of_the_North).

The ***Rainy River Basin*** covers a total area of 27,114 square miles, of which 11,244 square miles are located in northern Minnesota, and the remainder in Ontario, Canada. The majority of the Rainy River Basin is covered by forests, lakes, and wetlands (MPCA, 2001). The Rainy River drains Rainy Lake and discharges into Lake of the Woods, a distance of about 135 km (85 miles). The basin is in the Canadian Shield region, and is characterized by thin soil covers. Most of the water storage is in surface water bodies.

The ***Lake Superior Watershed Basin*** in Minnesota is 6,200 square miles in size, and is covered mainly by forests, with little agriculture and several urban areas. It is also in the Canadian Shield formation.

The ***Upper Mississippi River Basin*** covers 30,800 square miles entirely within the state of Minnesota. Land cover in this part of the Upper Mississippi River Basin ranges from conifer and hardwood forests to agriculture where corn, soybean, and forage crops are cultivated (MPCA, 2000). In St. Paul the Minnesota River discharges into the Mississippi River and puts its imprint on Mississippi River flows. Downstream from St. Paul the St. Croix River, which drains portions of eastern Minnesota and western Wisconsin, enters the Mississippi River at Prescott, WI. Downstream from Prescott additional portions of western Wisconsin and southeastern Minnesota become part of the Mississippi River drainage (Figure 1). The Twin Cities metropolitan area is in the Mississippi River drainage.

A small piece of southwestern Minnesota (Figure 1) drains into the Missouri River, and another into the Upper Mississippi River through Iowa; both are not included in the study.

A.2 Climate

Minnesota has a continental climate with cold winters and warm summers. The state's location in the Upper Midwest causes a wide variety of weather with four distinct seasons. Normal precipitation is lowest in winter (1-3 inches in Dec to Feb) and highest in summer (9 to 13 inches in June to Aug). Mean annual precipitation for the entire state has been on the rise (Figure A.1) and has reached approximately 28 inches/yr. The lowest annual average precipitation (510 mm or 20 in/yr) occurs in the northwest of the state and the highest (890 mm or 35 in/yr) in the southeast. Snow is the main form of precipitation from Nov to March, and a snow cover of 1inch (25mm) or more exists for 110 days per year on average.

Average annual air temperature for the state has risen to 5.5 ^{o}C or 42 ^{o}F, but mean annual air temperatures in the north (3^{o}C or 37.4 ^{o}F in International Falls) and in the south (9 ^{o}C or 49 ^{o}F in Winona) are substantially different. Minnesota extends from 43^{o}34’ to 49^{o}23’ latitude, a distance of 650 km (407 miles), and is divided into 9 climate divisions shown in Figure 3. Climate (precipitation and air temperature) in the five major river basins differs substantially because of geographic location, and seasonal variations are significant as well.