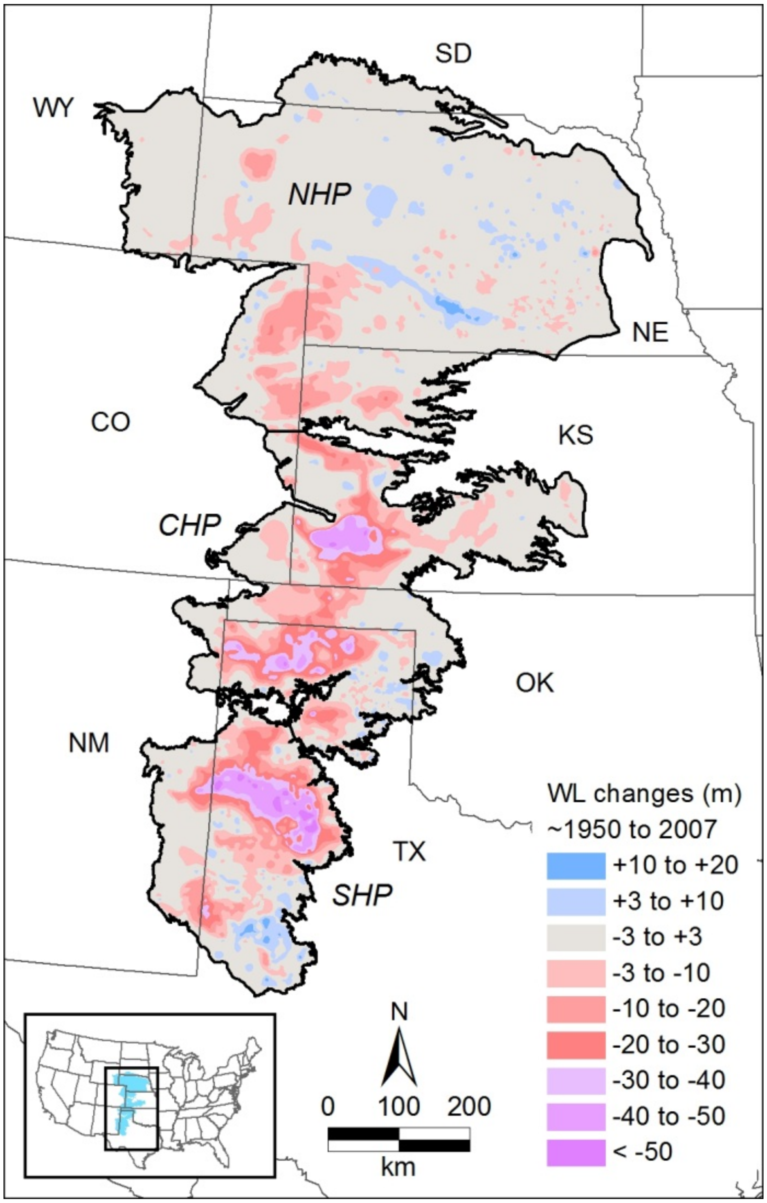
Impact of Droughts Related to Climate Change on Water Resources in the High Plains Aquifer



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Executive Summary

Drought is a critical issue, greatly increasing stress on limited water resources. The objective of this study was to assess the impacts of droughts, both past and potential future droughts, on water resources in the High Plains aquifer, which extends from Texas to Nebraska. Specific subtopics included examining impacts of **paleoclimate** on water resources and the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5) 10–30 yr **decadal hindcasts** from 1960 through 2005 and the **decadal climate prediction** from 2006 through 2035, and specifically **drought** conditions, in this region. Specific subtopics addressed included evaluation of **consumptive use requirements of irrigated lands** as they relate to droughts and also the assessment of potential impacts on stream flow through stream **baseflow discharge** and **groundwater quality** related to agricultural practices.

The High Plains aquifer was greatly impacted by severe long-term droughts in the 1930s and 1950s, and more recently in 2011 through 2013. There is considerable debate about the causes of these droughts, ranging from random atmospheric forcing to sea surface temperature (SST). Understanding the causes of these droughts is important for predicting whether such droughts are likely to occur in the future. Will intensification of the hydrologic cycle increase the severity and/or limit the length of future droughts? Is there evidence from recent climate records in this region that the hydrologic cycle has been intensifying? The **IPCC AR5** model outputs provided hindcasts and forecasts for 30 yr intervals at half-degree spatial resolution that were used to quantify variations in climate forcing.

Whereas many studies focus on impacts of climate change on water supply by varying groundwater recharge, impacts on water demand may be much greater because water resources in the High Plains region is dominated by demand. Groundwater depletion exceeds recharge by a factor of 20 in the central High Plains. An estimated 97% of groundwater resources are consumed by irrigated agriculture. Kansas has a state-of-the-art program in quantifying water use in its WIMAS (Water Information Management and Analysis System) program that provides extensive records on impacts of recent climate change on **water demand** during the past 30 yr. The irrigation-metering program has greatly expanded in the central High Plains in Texas in the last decade. Satellite approaches, including the **GRACE** (Gravity Recovery and Climate Experiment), show promise in quantifying impacts of climate forcing on water resources through variations in demand by providing data on changes in groundwater storage. Changes in groundwater storage documented in the extensive water-level monitoring program in this region are shown to be related to variations in **baseflow** to streams, such as the Canadian, Arkansas, Republican, and Platte Rivers.

Outputs from this study include an evaluation of paleoclimate impacts on water resources in the High Plains, and the effects of past and projected future climate change on water resources, focusing on water demand through irrigation; evaluation of satellite and ground-based tools for monitoring variations in groundwater storage; and assessment of differences in groundwater demand on surface water resources through changes in baseflow to streams in this region. The data generated by this study provides essential information for water-resource managers to better understand potential impacts of

climate change on future droughts in this region and quantify impacts of such droughts on water resources through changes in water demand.

Technical Project Description

1.0 Problem Description

Water resources are critical to supplying water for urban and industrial purposes and for irrigated agriculture in semiarid regions. Traditionally, surface water has been retained in reservoirs to manage water supply to meet demands and to reduce the potential for flooding. For example, a large number of dams have been built in the High Plains to supply water for irrigated agriculture and for industrial and municipal usage. Understanding inflows to these reservoirs and relationships to climate and groundwater pumpage is critical to predicting future water availability in the reservoirs.

In the past couple of decades, however, dam construction has greatly declined because of negative environmental impacts, and reliance on groundwater resources has greatly increased. With projected intensification of the water cycle associated with climate change resulting in more frequent, severe droughts interspersed with intense floods (Tebaldi et al. 2006), water storage requirements have increased. Variability of precipitation and associated reductions in soil moisture and surface water will continue to increase reliance on groundwater resources. Kundzewicz and Doll (2009) assessed the possibility that groundwater resources can be used to ease stress on freshwater resources under climate change.

In the High Plains, 97% of groundwater consumption is for irrigation (Maupin and Barber, 2005). The High Plains aquifer is one of the largest in the world, with an estimated 3,700 km^3 of drainable water in 2000. The economic value of agricultural products of this region ranges from \$200 to \$300 billion. In the past, groundwater resources have been heavily relied upon to enhance crop production in semiarid regions through irrigated agriculture. Understanding potential impacts of climate change on water resources is essential for assessing the future of this region in terms of water resources for agriculture and urban and industrial processes and the economy of the region. Groundwater depletion can also greatly affect inflow to reservoirs. One of the other large agricultural regions in the U.S., the California Central Valley, faces stresses similar to those of the High Plains region in terms of limited water resources, particularly during droughts (Faunt, 2009). With increasing consumption of water resources for irrigated agriculture, less water will be available for urban and industrial uses.

1.1 Will Climate Change Affect Water Resources through Variations in Water Supply or Water Demand?

Although many previous studies focus on impacts of climate change on water supply through changes in recharge, impacts on water demand are more likely to affect the system. Gurdak et al. (2007) attributed correlations between groundwater-level fluctuations and variations in climate forcing related to the El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and other climate drivers to variations in recharge in the system. Kundzewicz and Doll (2009) also emphasized relationships between climate change and recharge in many aquifers. However, recent studies in the High Plains indicate that water depletion recorded from groundwater-level data exceeds groundwater recharge by a factor of

~20 in the Central High Plains (Scanlon et al., submitted). Therefore, it is much more likely that changes in water demand related to climate change will control impacts of climate change on water resources in these systems.

1.2 How has Past Climate Change Affected Water Resources?

An understanding of the impacts of past climate change on water resources should help in an assessment of potential future impacts of climate change. Previous studies show that climatic conditions during the Pleistocene were much more conducive to recharge in the High Plains. Unsaturated zone studies based on soil physics and environmental tracers, primarily chloride, indicate that recharge occurred during Pleistocene times, as evidenced by wet soils and low soil water chloride concentrations (Scanlon et al., 2003). Precipitation during the Pleistocene was up to two times greater than that during the Holocene, and temperatures were up to 5° cooler. Transition to Holocene climatic conditions, associated with less precipitation and warmer temperatures, eliminated recharge in most regions and resulted in buildup of chloride bulges in soils that provide evidence of lack of flushing or recharge in these regions. The only recharge that occurred was through ephemeral lakes or playas and is estimated to have been ~6 to 11 mm/yr in the Central High Plains (Wood and Sanford, 1997).

Groundwater dating in the High Plains also suggests that much of the water was recharged during Pleistocene times (McMahon et al., 2004). Therefore, much of the aquifer is essentially fossil water, and any extractions constitute mining of water resources because of the low rates at which groundwater is being replenished. Although modeling studies suggest that recharge under irrigated agriculture has greatly increased, recent unsaturated zone studies in the Central High Plains indicate that recharge from irrigation return flow is negligible because of the low-permeability clay loam soils in much of this region.

Impacts of more recent climate variability are not as readily apparent or have not been examined in detail. Specifically, impacts of large-scale droughts, including the 1930s and 1950s drought on water resources, have not been documented in detail. Although the intense drought of the 1950s did lead to large-scale expansion of irrigation and depletion of water resources. More detailed analyses of these impacts are required to better understand relationships between droughts and water resources.

1.3 How does Large Scale Climate Conditions Impact Past and Future Droughts in the Plains?

Understanding historical drought mechanisms and identifying which mechanisms are controlled by large scale climate factors is a critical step toward assessing future large scale climate conditions to imply future drought characteristics. Many models suggest that climate change should be associated with increased frequency of droughts interspersed with more intense flooding (Tebaldi et al., 2006). There seems to be anecdotal evidence to suggest that the frequency of droughts and floods is increasing; however, detailed quantitative analysis of droughts and floods is not available. Extreme drought occurred in 2006 in the High Plains and severely impacted crop production and water resources in that region (Figure 1). Intense precipitation in September–October 2004 extended across much of the southern High Plains, with annual precipitation occurring in a 1- to 2-month period.

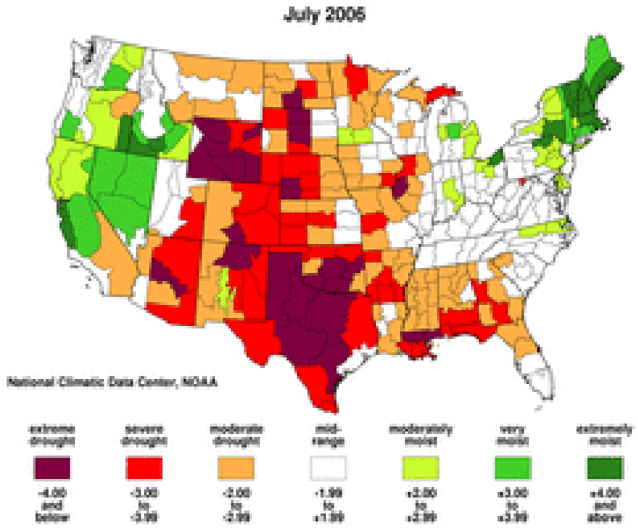

Figure 1. Palmer Drought Severity Index for July 2006 showing extreme drought in Texas High Plains and parts of Nebraska High Plains, and severe drought throughout much of the High Plains (www.ncdc.noaa.gov).

What impact will changing intensity of the hydrologic cycle have on future droughts and floods? Past long-term droughts in the 1930s and 1950s had large-scale impacts on water resources and crop production. Are such long-term droughts less likely in the future because the water cycle is intensifying? Will shorter-term droughts in the future be more intense than previous long-term droughts and have a greater impact because of much greater demand for water resources than in the 1930s and 1950s? There is much less buffer in the system with over-allocation of water resources and overexploitation of groundwater for intense agricultural productivity.

2.0 Goals of this Study

The primary goal of this study was to assess the impacts of projected climate change on water resources in the U.S. High Plains. The High Plains provides an ideal test bed for evaluating impacts of climate change on water resources because of the large range in climate conditions from north to south, and observed large-scale depletion of groundwater resources (Figure 2) (McGuire, 2009). Impacts of paleoclimate were addressed through review of previous studies and evaluation of groundwater-age data to determine whether most of the groundwater is of Pleistocene in age. Long-term average recharge rates were estimated using groundwater chloride data. Past climate change impacts on water resources we re-quantified by relating climate forcing to water demand. Also, because of the limited availability of information on water demand, a variety of approaches were examined to estimate water demand, including (1) evaluation of groundwater-level monitoring data (McGuire, 2009), (2) irrigation-metering data from the central High Plains in Texas and from the WIMAS in Kansas, (3) estimates from crop water-demand modeling, and (4) GRACE satellite data (Strassberg et al., 2007, 2009; Longuevergne et al., in press). Variations in climate forcing in the past, including quantification of temporal variability in droughts and floods, are examined. Various drought indices are evaluated, focusing primarily on the Standardized Precipitation Index (SPI) for 6- and 12-month periods. The use of temperature data as an indicator of soil moisture and drought conditions is also evaluated. To better understand the potential for future droughts, such as those experienced in the 1930s and 1950s, we examine different potential causes for those droughts, including variations in SST and atmospheric fluctuations.

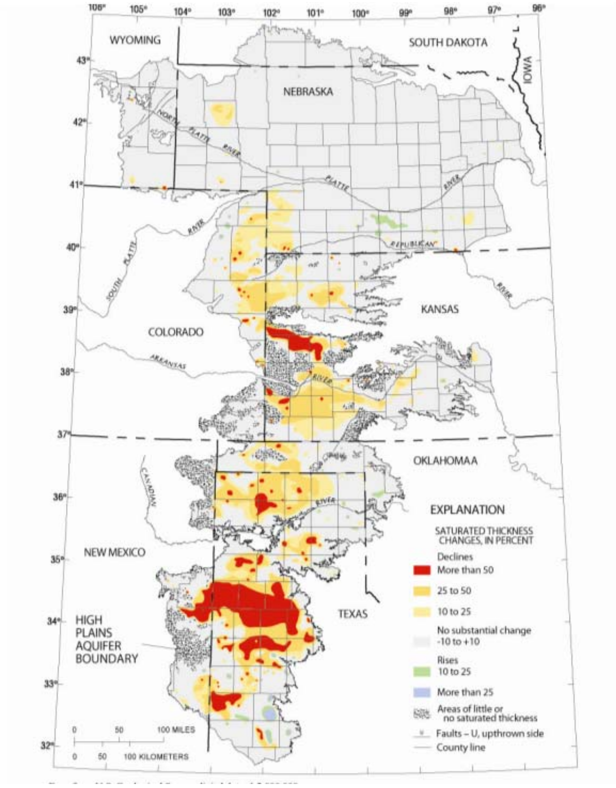

Figure 2. Groundwater depletion in the High Plains aquifer from predevelopment (~1950) to 2007 (McGuire, 2009). Note concentration of depletion in the High Plains in Texas and Kansas. About 40% of the depletion occurs in 4% of the land surface.

One of the distinctive features of the droughts was their length, and we evaluate atmospheric data to determine potential causes of the cessation of these droughts. IPCC AR5 data is used to assess past (decadal hindcasts for ~30 yr, 1960–2005) and future (decadal forecasts, 2006–2035) climate forcing. We do not focus on climate change impacts on the magnitude of precipitation in this region, but we examine the data to determine the frequency and severity of droughts and floods. Because of this focus, we did not downscale global climate model (GCM) data, but used the general information provided by the GCMs at the scale of the models (i.e., 0.5° for IPCC AR5). This comprehensive approach greatly enhanced our understanding of the linkages between climate forcing and water resources, which is an essential prerequisite to estimating impacts of future climate change on water resources.

3.0 Potential Impacts of Proposed Study on Enhancement of Water Management

Management of water resources requires basic information on water supply and demand and controls on these fluxes. **Paleoclimate analyses** provided critical information on the dynamics of groundwater flow in this system. Groundwater-age data was used to determine whether most of the groundwater was recharged during Pleistocene times. Recharge rates we reevaluated using groundwater chloride data, which provided information on regional recharge rates throughout the High Plains aquifer. Because the High Plains aquifer is essentially a fossil aquifer that received much of its recharge during the past glacial period, information on the amount of water remaining in storage is required to predict the lifespan of the aquifer on the basis of projected water demands.

Variations in groundwater recharge were accurately quantified in recent studies conducted for the Bureau of Reclamation (Scanlon et al., in press. a, b, submitted); however, information on **water demand** is not as accurate. Water demand in the Texas High Plains has been based largely on (1) crop-water models for groundwater modeling studies (Dutton et al., 2001; Blandford et al., 2003; (2) irrigation metering, which has been expanding greatly in this region, with ~600 m currently operating in the Texas Panhandle; irrigation pumpage has been metered for ~30 yr in the Kansas High Plains and is recorded in the WIMAS database; (3) information on groundwater storage changes, which is available from the GRACE satellite (Strassberg et al., 2009; Longuevergne et al., in press); and (4) intensive groundwater-level monitoring throughout the High Plains, which also provided valuable information on groundwater pumpage (McGuire, 2009). In this study we compared water-demand estimates from the various approaches, providing guidance on optimization of future irrigation-metering programs to ensure that irrigation water demands are being accurately quantified. Variations among the different estimates provide information on uncertainties in water demand and use.

Because the Central High Plains aquifer is essentially a fossil aquifer with very limited current recharge focused beneath playas (~6–10 mm/yr), the aquifer cannot be managed sustainably. Therefore, information on water storage and fluxes were used to project the **lifespan of the aquifer**. This type of analysis is based on GIS data on water-level trends generated from the extensive monitoring of groundwater levels in the aquifer (~9,000 wells throughout the High Plains aquifer, McGuire, 2009). Incorporating the impact of climate change on water demand on the basis of the results of this study may be able to provide more realistic projections of the lifespan of the aquifer that can consider future climate change impacts.

There are many reservoirs throughout the High Plains listed under Bureau of Reclamation projects (e.g., Lake Meredith in Texas; Norton, Kirwin, and Webster in Kansas; and Enders, Trenton, Box Butte, and Virginia Smith in Nebraska). Records from these reservoirs provide a wealth of information that relates climate forcing, reservoir management, and water resources. Some of these reservoirs are experiencing reductions in flows that are attributed to upstream groundwater depletion. Better understanding of the linkages between groundwater and surface water and climate forcing from this study can be used to predict future availability of water resources in these reservoirs and their ability to meet water demands.

By conducting a detailed analysis of past and projected future climate forcing using output from the IPCC AR5 models, we better understand the frequency and intensity of droughts and floods in this region. Evaluation of hindcasts provided by the AR5 models help determine which models in the system more reliably simulate climate forcing in this region. Climate projections from these models can then be used to better predict future climate in the region. With the linkages between climate forcing and water demand developed in this study, water managers will have a much better predictive understanding of potential impacts of future climate on water resources.

4.0 Information, Knowledge, and Tools for Assessing Impacts of Climate Change on Water Resources

Various types of information, knowledge, and tools were compiled and developed for assessing impacts of climate change on water resources from the proposed study, including:

- Reliability of climate models for accurate climate simulation in the High Plains on the basis of IPCC AR5 hindcasts, compared with actual climate data for the past 30 years;
- Optimization of water-metering programs from monitoring irrigation-water demand;
- GRACE analyses of water-storage changes in response to climate variability;
- Comparison of approaches for quantifying water demand on the basis of satellite (ET, GRACE) and ground-based data (irrigation meters, groundwater-level monitoring data and specific yield) and modeling analyses (groundwater-availability models);
- Linkage between climate forcing and water demand based on data for the past 60 years (1950–2010);
- Relationship between groundwater storage in the High Plains aquifer, baseflow to streams, and inflow to reservoirs in the High Plains;
- Quantitative analysis of changes in intensity of the hydrologic cycle based on past records and future model predictions;
- Assessment of drought frequencies and intensities since the 1950s to better understand changes over time that may be related to climate change; and,
- Statistical mechanistic model of future water demand based on climate projections.

Task 1. Analysis of Past Climate Records

Task 1a. *Analysis of existing SPI data or calculation of SPI for the High Plains region for 6- and 12-mo periods to evaluate spatiotemporal variability in the distribution of drought in the High Plains from the 1950s through 2010.*

We first undertook an empirical orthogonal function (EOF) analysis of 6-month, 9-monthly and 12-monthly SPI data based on 0.125°x0.125° precipitation data from 1950-1999 to identify the main modes of drought variability over the High Plains. We rotated the leading 5 EOF modes to discern leading physical modes of variability. The mode that captures the 1950s drought in SPI6, SPI9 and SPI12 shows the central High Plains having opposing climatic conditions to the eastern and western High Plains. Although the High Plains is generally subdivided into north, central, and south High Plains based on the hydrology and temperature data, SPI is based purely on precipitation and shows an east – west gradient, similar to the precipitation gradient. In other words, it shows that when the central plains are drought free the eastern and western plains are in drought (Supporting Information Task 1a, Figure S1-1).

We next studied whether there was any discernible change in drought incidence at different timescales over the period 1950-1999. For this we compared 1950-1970 with 1971-1999 using the Maurer et al (2002) 0.125°x0.125° precipitation data. We find that severe to moderate droughts (-1.5<SPI<-0.5) show a slight increase in the left (negative) tails of the red lines in Figure 1-1. While there is no change in the mean of the distribution between both time periods, of interest is the marked skewedness towards the right tails (positive). This very likely indicates that the 1971-1999 period saw many more extreme wet events than dry events compared to the 1950-1970 period.

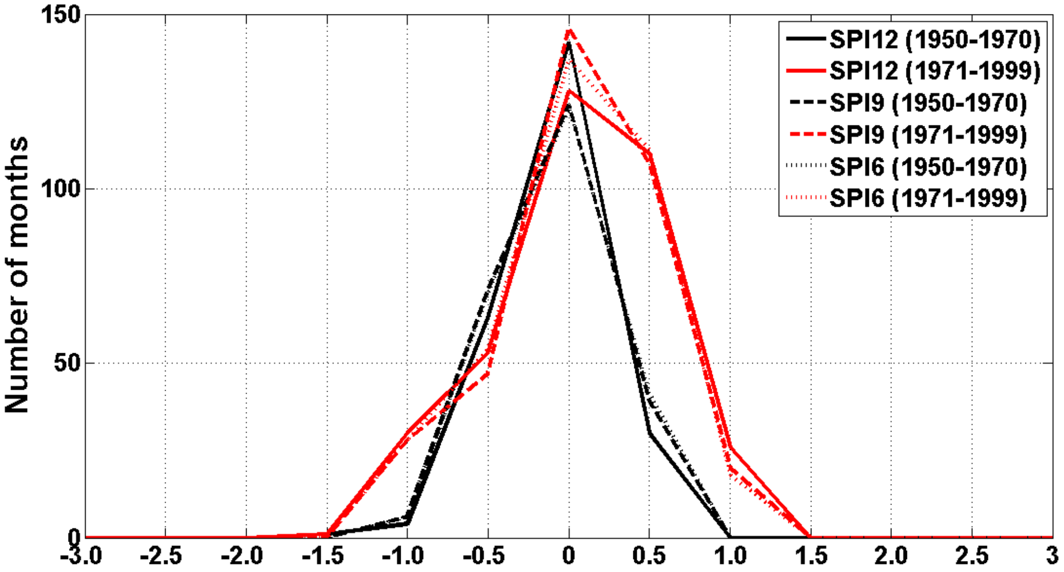

Figure 1-1: Comparative probability distribution function of number of months in drought categories SPI6, SPI9 and SPI12 in the High Plains for the period 1950-1970 (black) and 1971-1999 (red).

Task 1b. *Evaluation of precipitation and temperature data in the High Plains from 1950 through 2010 to assess changes in intensity of the hydrologic cycle (e.g., simple daily intensity index: annual precipitation divided by number of wet days, fraction of total precipitation due to events exceeding the 95th percentile of climatological distribution for wet day amounts) (Tebaldi et al., 2006).*

Results published in: Long, D., B. R. Scanlon, N. Fernando, L. Meng, and S. M. Quiring (2012), Are Temperature and Precipitation Extremes Increasing over the US High Plains?, Earth Interactions, V. 16, DOI: 10.1175/2012EI000454.1.,16 p.

The analysis focused on 1958 – 2010 to avoid the bias created by the 1950s drought. The analysis was limited because of the limited number of stations in the High Plains and also because of the averaging related to gridded data. The main results are:

- Reduction in extreme temperature range as a result of increasing low temperatures relative to high temperatures; therefore, a more appropriate description of the system would be getting less cold rather than warm.
- Strong local variability in precipitation trends
- Reduction in cumulative dry days restricted to the Northern High Plains, with a trend of -1 day/decade. Decrease in cumulative dry days corresponds to increasing no. of wet days based on previous studies (Pryor et al., 2009), suggesting wetter conditions.
- There was no trend in the fraction of total precipitation due to events exceeding the 95th percentile of climatological distribution for wet day amounts (R95T) throughout most of the High Plains with the exception of 12% of the station data in the Central High Plains.
- Analysis of the 1 month Standardized Precipitation Index (SPI) data indicates a decreasing trend in severe dry conditions (SPI < -1.5) from -8 to -4% and an increasing trend in floods (SPI > 1.0) from 10% (1961 – 1965, 1966 – 1970) to 20% (1996 – 2000; 2006 – 2010).
- The SPI data also indicate a reduction in the number of dry months (SPI < 0.0) from 10 mos in 1974, 1976 to 2 mos (1993, 1997, and 2007).

Therefore, the reduction in severe dry areas and number of months with dry conditions suggests increasing wetter conditions in the High Plains over the period from 1958 - 2010.

Task 1c. *Analysis of 1950s drought relative to SST forcing and forward modeling using SST to reproduce drought conditions, evaluation of atmospheric conditions to determine cause of cessation of 1950s drought.*

We modified this task to focus on the 2011 drought in Texas because this is the most severe drought on record. This analysis showed the role that sea surface temperature (SST) anomalies associated with La Nina played on driving an east-west gradient in geopotential height over the southern United States in the spring. The gradient drove an intensification of westerly winds at 850 hPa that advected warm dry air eastward resulting in a highly stable lower-to-mid troposphere where convection was suppressed right at the start of the rainfall season in late-April/early-May 2011. The work finds that such an increase in the westerly winds at 850 hPa in April is a common characteristic in seven other severe-to-extreme droughts, associated with La Nina, that had rainfall deficits that extended from the winter through the summer. The work also finds that cumulative soil moisture anomalies in spring lead the establishment of a high pressure system at 500 hPa by 1-2.5 months, indicating a significant role for land-surface coupling in maintaining drought from spring through to summer and drought intensification in the summer. This work was done by Dr. Nelun Fernando, a postdoc supported in part by UCAR and a paper is being submitted to Climate Dynamics on this work.

Pending Publication Title: Evolution of the 2011 Drought Event and Implications for Drought Predictability over Texas Authors: D. Nelun Fernando, Kingtse C. Mo, Rong Fu, Bridget R. Scanlon, Ruben Solis, Lei Yin, Tong Ren, Kai Zhang, Adam Bowerman, Robert Mace and John R. Mioduszewski

Task 1d. *Use of temperature as an indicator of drought by analyzing temperature data during and outside droughts and relating to soil moisture data when available from observations and simulations.*

We performed a preliminary analysis of this work and determined that temperature is not a good indicator of soil moisture or drought; therefore, we did not pursue the analysis further.

Task 2. Ability of Climate Models to Simulate Climate in the High Plains

Task 2a.

We downloaded output from climate models in the IPCC AR5 program for the High Plains region. This work has been conducted for Texas and the entire High Plains. The GCMs analyzed are: NCAR-CCSM4, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-R, IPSL-CM5A-LR, MIROC5, MPI-ESM-LR, MRI-CGCM3. Observations are from the 1/8th degree gridded dataset developed by Maurer et al. (2002). We used both the raw GCM output from these models, obtained from the CMIP5 archive (http://cmip-pcmdi.llnl.gov/cmip5/data_portal.html), and the downscaled CMIP5 Climate and Hydrology Projections from the archive at http://gdodcp.ucllnl.org/downscaled_cmip_projections. Detailed information on the modeling group, model name and the number of ensemble runs downscaled under the different forcing scenarios (i.e. RCP2.5, 4.5 and 8.5) is available on at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/downscaled_climate.pdf (pages 8-9).

Task 2b. *Compare GCM output with precipitation and temperature observations for the High Plains to assess reliability of different models.*

The shift in mean climate affects the tails of the distribution curve and can result in more extreme climatic events (Tebaldi et al., 2006). Given the interest in hydrological extremes, we report here on the ability of the GCMs listed in Task 2a to capture three indicators of climate change. These are: consecutive dry days (CDD), consecutive wet days (CWD) (Frich et al., 2002) and number of days when maximum temperature at the surface exceeded 100°F (Tmax > 100°F). The third indicator is proposed as a proxy for heat waves over the High Plains. We compared the ability of the raw GCM output with U.S. Bureau of Reclamation downscaled output at capturing the observed spatial variability and statistical properties (namely, the mean and standard deviation) of these climate indicators over the period 1950-1999. We find that the downscaled data perform much better than the raw model output at capturing the observed spatial variability and frequency of CDDs and CWDs and the variability in these indices. However, the raw model output perform better at capturing the spatial variability and frequency of the number of days when Tmax >100°F. More details on the results of the comparison are included in Supporting Information (Task 2b). This finding could indicate that there is a cold bias in the downscaled temperature data. Further investigation is recommended.

Task 2c. *Select models from IPCC AR5 that provide the most reliable simulations of past climate for the High Plains region for analysis of future climate predictions.*

This task was conducted for Texas and we used the selected models for Texas for the entire High Plains. These models are the: CCSM4, GFDL-ESM2G, GISS-E2-R and MPI. Results for Texas are described in:

Results published in: Fu, R., N. Fernando, L. Yin, T. O. Ren, Z. F. Yang, A. Bowerman, and R. E. Dickinson (2012), Assessing future changes of climate and drought over south-central United States projected by the CMIP5 models, J. of Climate.

Task 3. Development of Tools to Quantify Water Demand

Task 3a. *Evaluation of GRACE satellite data to assess changes in water storage.*

We applied GRACE analysis to Texas because the 2011 drought was focused in this area. The GRACE derived Total Water Storage correlates with the Palmer Drought Severity Index indicating the value of GRACE Total Water Storage as a drought indicator. However, the study showed that disaggregating total water storage into surface water, soil moisture, and groundwater using monitored reservoir storage and soil moisture storage from land surface models was too uncertain to accurately estimate drought impacts on groundwater storage. Large variability in simulated soil moisture storage from six different land surface models precluded reliable estimation of groundwater storage changes from GRACE satellite data. Results of this study were published in Geophysical Research Letters.

Results published in: Long, D., B. R. Scanlon, L. Longuevergne, A. Y. Sun, D. N. Fernando, and S. Himanshu (2013), GRACE satellites monitor large depletion in water storage in response to recent drought in Texas Geophys. Res. Lett., 40:3395-3401.

Task 3b. *Comparison of Irrigation Metering with Climate Forcing*

Water use from the Water Information Management and Analysis System (WIMAS) database were compared with PRISM precipitation data at the state level (Kansas) and also for the three Groundwater Management Districts on the High Plains aquifer based on data from 1990 through 2008. Irrigation water use in Kansas is negatively correlated with total annual precipitation, both statewide and in the Ogallala GMD areas, indicating that in general more irrigation water is used during drier years. Correlation is moderately strong at the state level (r=-0.77) and moderate in the Ogallala GMD areas (r=-0.57).

The relationship between water use, groundwater levels, and SPI are described by Butler et al. (2013) and Whittemore et al. (2014) and were not repeated in this work. The Whittemore et al. (2014) paper is currently in review for the Intl. Assoc. of Hydrologic Sciences journal. Results of this work are included in Supporting Information Task 3b and the abstract from Butler et al. (2013) is also included.

Task 3c. *Results from the water-metering programs will be compared with output from crop models on water consumption for irrigation in the High Plains.*

Because the results from existing water metering programs are not considered very reliable at this time we did not conduct this analysis. Preliminary evaluation of the metering data is described in Turner et al. (2011).

Task 4. Establishing Linkages between Water Demand and Climate Forcing

Task 4a. *Compare groundwater pumpage information from the WIMAS data base with observational climatic forcing (precipitation) data to assess linkages.*

The results of this analysis are described under Task 3b.

Task 4b. *Evaluate the ability of irrigation to provide sufficient water for crop production during droughts using past records, focusing on drought periods, such as summer 2006 and 2008.*

To assess the impact of droughts on crop production, we compared the crop distribution from the US Dept. of Agriculture Crop Data Layer (CDL) for 2010 – 2012 for the US High Plains (Figures S4-1 through S4-3). Precipitation in 2010 was high and in 2011 was the lowest in the Texas region of the High Plains. However, the mapped distribution of major crops shows no obvious differences at the scale of the US High Plains.

To evaluate temporal variability in crop production related to droughts, we compared planted and harvested acreages for the period 1980 through 2012 for different crops and different regions using National Agricultural Statistics (NASS) database (http://www.nass.usda.gov/Data_and_Statistics/). Major crops include corn, wheat, cotton, sorghum, and soybeans. Planted cropland area has remained generally constant in the northern High Plains (NHP) region but has decreased in both the central High Plains (CHP) and southern High Plains (SHP) regions since the early 1980s (Figure S4-5a). The percentage of harvested cropland relative to planted area remained high in the NHP region during this period, averaging 92% of planted area (range 85% to 96%) (Figure S4-5b).

In the CHP, the percentage of harvested area was somewhat lower, averaging 84% (range 65% to 92%) of planted area. In the SHP, the percentage of harvested area was initially similar to the CHP but has declined overall since the early 1980s from an average of about 80% to an average of 64% since 2000. SHP harvested areas were lowest during drought years in 1998 (54%), 2006 (54%), 2011 (32%), and 2012 (50%). CHP harvested area relative to planted area was lowest during 2002 (65%), 1989 (69%), and 2011 (74%). NHP harvested area was lowest during 1983-84 (85-86%) and 2002 (85%). These results indicate that droughts have least impacts on harvested cropland in the NHP and most in the SHP. These differences between NHP and SHP may reflect greater water availability for irrigation in the NHP relative to the SHP, allowing cropland production to decouple from drought forcing.

Task 4c. *Relate water-level data in the High Plains aquifer to baseflow discharge in streams in the region, including the Canadian River.*

The results of this task are discussed in Supporting Information.

Task 5. Climate Projections of Future Droughts

Task 5a. *Use the most reliable models from the IPCC AR5 program to predict future climate in the High Plains for the next 30 years, focusing primarily on precipitation and temperature.*

We investigated the impact of climate change on extreme events – primarily drought events – over the High Plains using climate projections from the Representative Concentration Pathway (RCP) 4.5 (a moderate emissions scenario) and RCP 8.5 (worst case scenario) runs. The coarse resolution (~ 2.5° x 2.5°) of Global Climate Models (GCMs) makes it difficult for hydrologists and water planners to translate information on likely regional climate change into detailed projections of water availability in the future. To overcome this mismatch between GCM fields and the data requirements of water planners, the United States Bureau of Reclamation released a downscaled dataset of precipitation, minimum, maximum, and mean temperatures, from the Intergovernmental Panel on Climate Change (IPCC) Coupled Model Intercomparison Project Phase 3 (CMIP 3) and Phase 5 (CMIP5) GCMs for the United States (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/).

Previous studies have shown that droughts over the US Great Plains are mainly initiated by La Niña-induced large-scale circulation anomalies in late fall and winter, with anomalously high geopotential or anticyclonic circulation centered over the western and central US (Lyon and Dole, 1995; Mo et al., 1991, Trenberth et al., 1988; Wallace and Gutzler, 1981). Such anomalous centers shift synoptic weather disturbances away from the Great Plains and central US, leading to a reduction of rainfall and facilitate droughts, especially in winter and early spring. The anomalous mid-tropospheric high established in spring tends to persist through summer (Namias, 1991), in part due to feedbacks from dry land surface and a stronger cap inversion due to westerly advection from the Rockies or the Mexican Plateau (Myoung and Nielsen-Gammon 2010).

Fu et al. (2013) evaluated the performance of GCMs participating in the Intergovernmental Panel on Climate Change (IPCC) Coupled Model Intercomparison Project Phase 5 (CMIP5) in capturing the large-scale circulation variables known to influence drought over the US Great Plains. They examined the relationship between regional climate change and the global warming trend, rather than a regional climate trend alone[1]. They also analyzed the relationship between large-scale circulation variables and the El Niño Southern Oscillation (ENSO) and the warming pattern of global sea surface temperatures (SSTs) to evaluate the credibility of the climate models.

The models that were able to capture the spatial pattern of global SST warming model, as represented by the leading mode of the REOF of the global SST anomalies, were the CCSM4, GFDL-ESM2G, GISS-E2-R

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[1] An evaluation of trends for the period of a few decades with a few climate model simulations can be strongly influenced by random internal variability (Deser et al. 2012). Therefore, an agreement between a modeled and observed variable can be a random coincidence, rather than a demonstration of the capability of a model for prediction.

and MPI. The CCSM4 and GFDL-ESM2G are best able to capture the observed teleconnections with ENSO.

Task 5b. *Calculate SPI from predicted climate data to estimate the distribution of future droughts.*

Using the downscaled projections of precipitation from the CCSM4, GFDL-ESM2G, GISS-E2-R and MPI models, we evaluated changes in the likelihood of drought in the late-21st century (i.e. 2050-2099) by analyzing box-whisker plots of the 6-, 9- and 12-monthly Standardized Precipitation Index (SPI) derived using projected rainfall from the RCP4.5 and RCP8.5 runs. The results help ascertain how the frequency of drought of different lengths over the High Plains might respond to moderate and high emission scenarios respectively.

The box-whisker plots of SPI6, SPI9 and SPI12 from the RCP4.5 runs shows a reduction in drought magnitude in 2050-2099 compared to 1950-1999 (Supporting Information Task 5b: Fig. 1) at these timescales (Figures 5-1 through 5-3). This result is counter-intuitive considering that the raw models indicate a decrease in surface water availability in the winter, spring and fall months (Fu et al., 2013). Further investigation is required to identify plausible reasons for such a result.

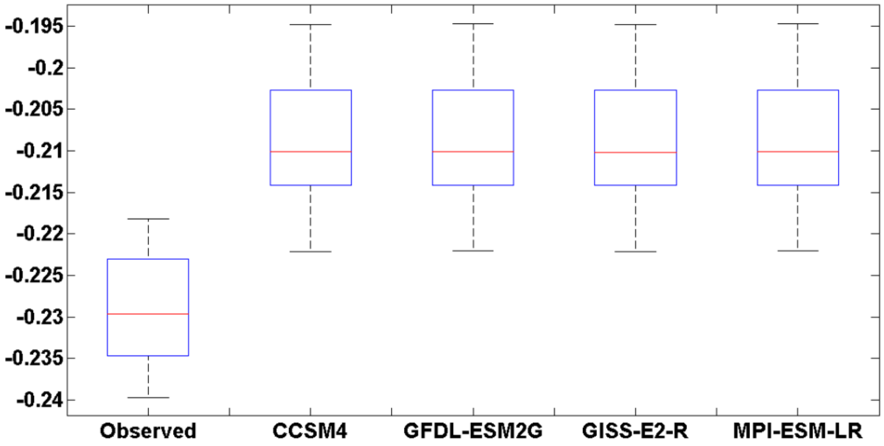

Figure 5-1. Boxplot comparing observed SPI6 (1950 – 1999) versus normalized RCP4.5 projected SPI6 (2050 – 2099) over the High Plains.

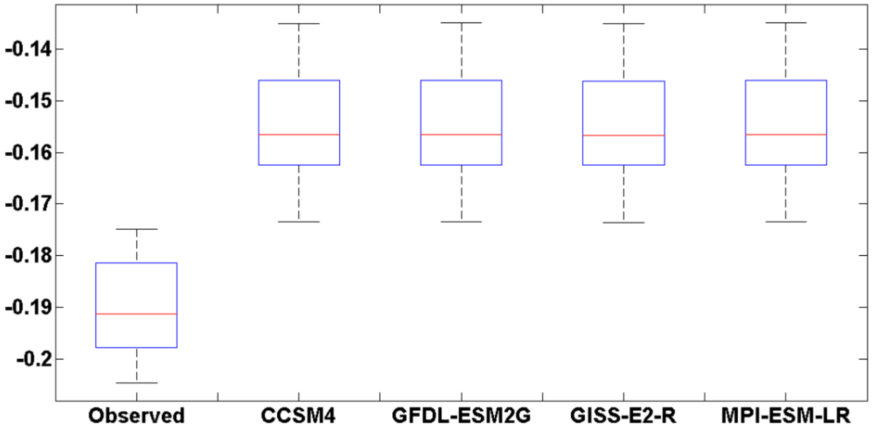

Figure 5-2. Boxplot comparing observed SPI9 (1950 – 1999) versus normalized RCP4.5 projected SPI9 (2050 – 2099) over the High Plains.

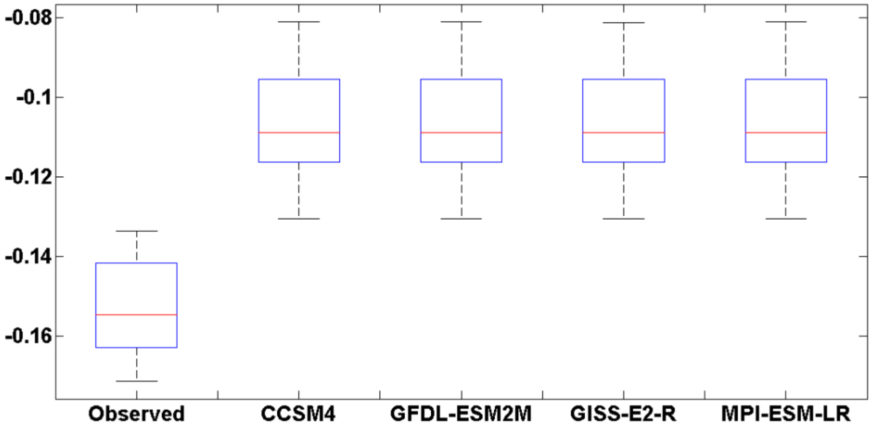

Figure 5-3. Boxplot comparing observed SPI12 (1950 – 1999) versus normalized RCP4.5 projected SPI12 (2050 – 2099) over the High Plains.

Task 5c. *Develop a statistical mechanistic model of future water demand that is based on climate projections in the region.*

Because of large uncertainties in climate projections and preliminary nature of analysis of CMIP5 output, it is judged premature to develop models of future water demand based on such uncertain data.

Task 6. Project Findings Related to Bureau of Reclamation Studies in the Region

Task 6a. *Examine the water budgets of reservoirs in Bureau of Reclamation programs in the High Plains, and relate the water balance to climate forcing and groundwater depletion.*

Water budgets for major reservoirs were evaluated over the period of record. Data from 10 reservoirs in Nebraska were examined, including inflows, outflows, and reservoir evaporation (Figures S6-2 through S6-12). Reservoir storage changes were calculated from inflows – outflows and compared with reservoir capacity to estimate percent full. The ratio of inflows to outflows is also plotted. Two reservoirs are located on the Niobrara River, Box Butte and Merrit. The Box Butte reservoir has variable storage, generally low in the 2000s and high towards 2010. Merrit Dam impounds the Snake River and seems to be a constant level reservoir at ~ 100% of capacity much of the time.

Reservoirs on the Loup River include Calamus and Davis Creek, located within or adjacent to the Sand Hills. Storage in the Calamus Reservoir ranges from ~ 20 – 60% of capacity and is generally low towards 2010 and 2011. The Davis Creek reservoir has low capacity in the 2000s.

Several reservoirs are located in the Republican Basin, from upstream to downstream Bonny, Enders, Hugh Butler, Harry Strunk, Keith Sibelius, and Harlan County. The reservoirs generally function for flood control and most provide water for irrigation. Storage has been decreasing in Bonny Reservoir since early 1990s and is almost empty by 2011. Storage in Enders reservoir has been declining since the late 1960s and 1970s with storage declining form 40% to 10% of capacity. Reductions in storage are attributed to water table declines in this region. Harry Strunk and Hugh Butler reservoirs are also characterized by variable storage. Keith Sibelius reservoir was low in the 1970s and 1980s, ~ 10 – 20% of capacity but has been higher and more variable recently.

The dominant control on reservoir storage is most likely water table declines in the Republican Basin. Variations in other reservoirs may reflect variations in management. It is difficult to understand controls on these systems based on this type of reconnaissance evaluation.

Task 6b. *Assess potential impacts of climate predictions on reservoir performance.*

Because of the poor relationship between climate parameters and past reservoir storage, it seems that other factors, rather than climate, impact reservoir storage more directly, such as land use change and groundwater depletion. Therefore, we did not pursue this subtask because of the findings from Task 6a.

General

We submitted a paper comparing water resources in the High Plains and the Central Valley that was published in Proceedings of National Academy of Sciences. This paper includes the new recharge map developed for the High Plains and also indicates the region in the Central and Southern High Plains where fossil groundwater is being depleted. In contrast, high recharge in Nebraska results in sustainable groundwater development with minimal groundwater depletion.

Publication: Scanlon, B. R., C. C. Faunt, L. Longuevergne, R. C. Reedy, W. M. Alley, V. L. McGuire, and P. B. McMahon (2012), Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley, *Proceedings of the National Academy of Sciences of the United States of America*, *109*(24), 9320-9325.

Dr. Scanlon participated in the National Climate Assessment and worked on the section related to the Great Plains.

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Supporting Information Task 1

Task 1a: Historical Standardized Precipitation Analysis for the High Plains

We first undertook an empirical orthogonal function (EOF) analysis of 6-month, 9-monthly and 12-monthly SPI data based on 0.125°x0.125° precipitation data to identify the main modes of drought variability over the High Plains. We only report on the results for SPI9 because the results for SPI6 and SPI12 were very similar. The first 5 modes accounted for 52% of the variance in the SPI-9 dataset. The first mode, accounting for 23% of the variance shows a pattern of negative loadings over -110W to -95W over the entire latitudinal domain (Figure S1-1a). Eastward of -95W, is a region of positive loadings. The second mode (Figure S1-1b), accounting for 13% of the variance, shows a sharp east-west gradient with positive loadings in the west and negative loadings in the east. The third mode (Figure S1-1c), shows positive loadings in the central High Plains and negative loadings to the east and west. We used rotated empirical orthogonal function (REOF) analysis using the first 5 modes in a bid to discern actual physical modes of variability and their associated time series. The rotated mode that captures a pattern similar to EOF mode 3, shows the protracted 1950s drought and the 1980 drought in its associated time series (Figure S1-2).

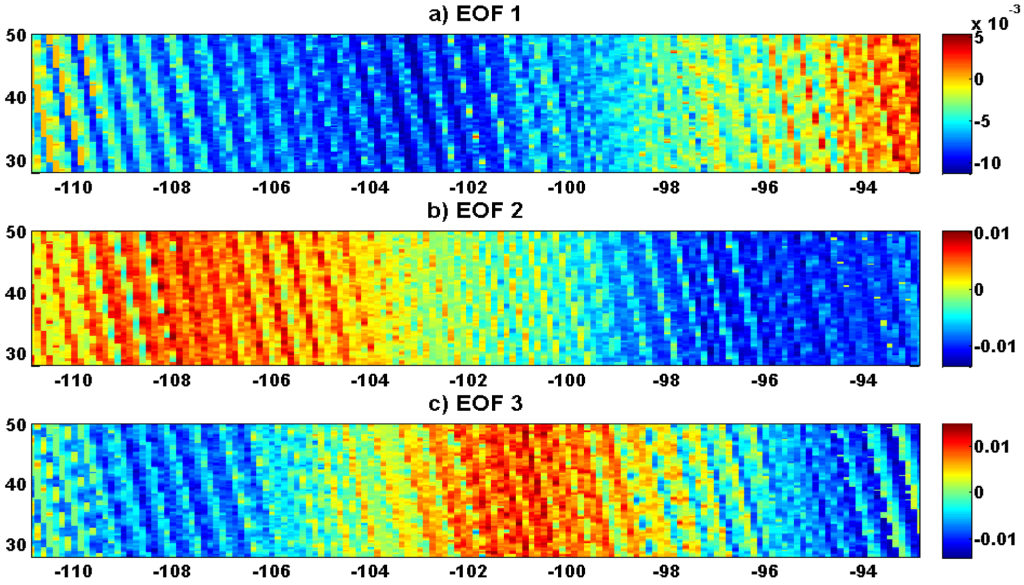


Figure S1-1: First three EOF modes of SPI9 from 1951-1999.

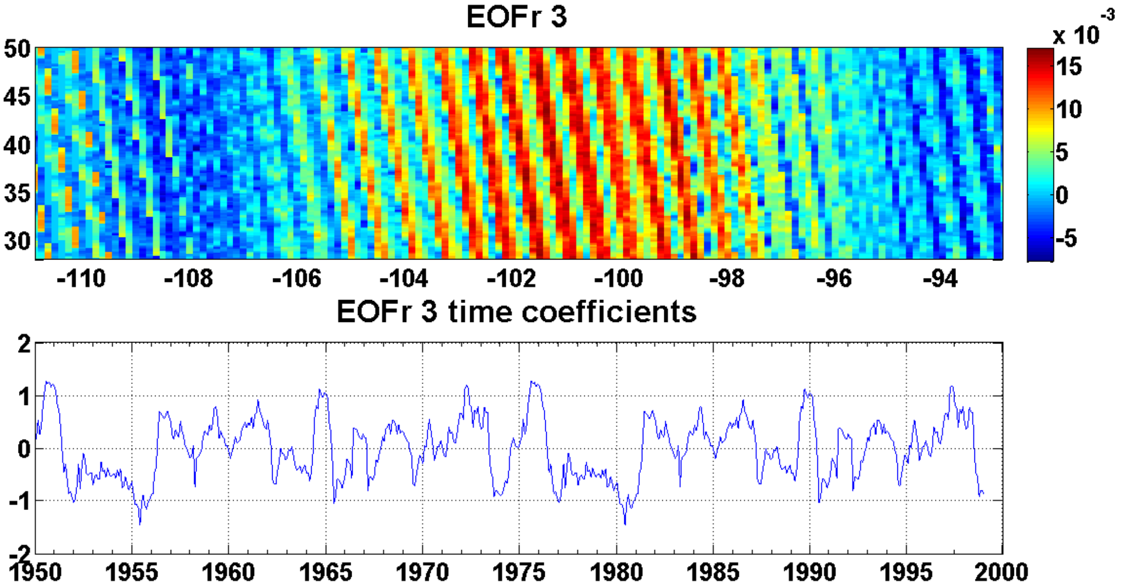


Figure S1-2: Rotated SPI9 mode 3 and associated time series.

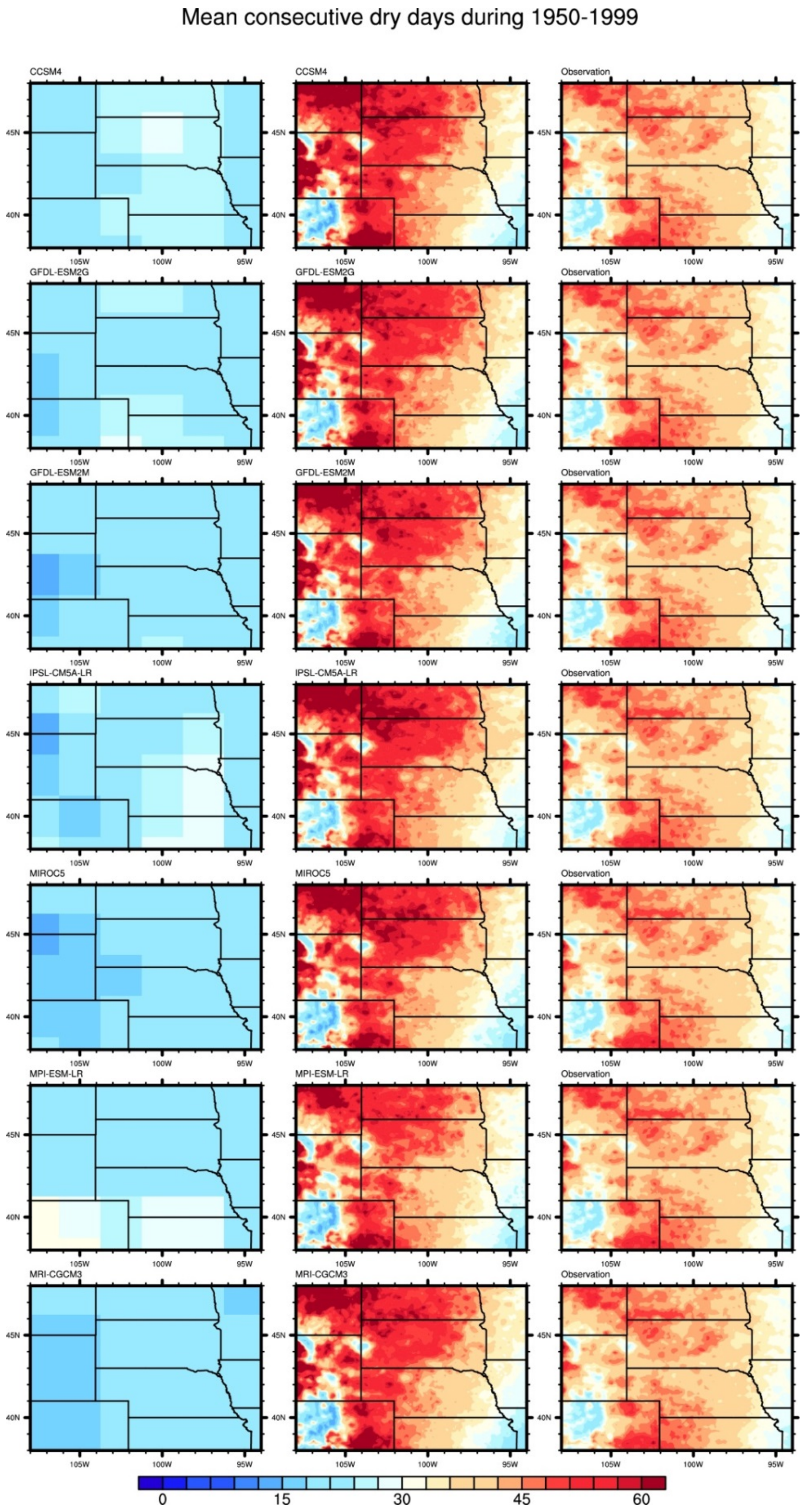
Task 2b: Compare GCM output with precipitation and temperature observations for the High Plains to assess the reliability of different models.

The shift in mean climate affects the tails of the distribution and can result in more extreme climatic events (Tebaldi et al., 2006). Given the interest in hydrological extremes, we report here on the ability of the GCMs to capture three indicators of climate change. These are: consecutive dry days (CDD), consecutive wet days (CWD) (Frich et al., 2002) and the number of days when maximum temperature at the surface exceeded 100 degrees Fahrenheit (Tmax > 100°F). The third indicator is proposed as a proxy for heat waves over the High Plains. We compare the ability of the raw GCM output with U.S. Bureau of Reclamation downscaled output at capturing the observed spatial variability and statistical properties (namely, the mean and standard deviation) of these climate indicators over the period 1950-1999.

The GCMs analyzed are: NCAR-CCSM4, GFDL-ESM2G, GFDL-ESM2M, IPSL-CM5A-LR, MIROC5, MPI-ESM-LR, MRI-CGCM3. Observations are from the 1/8 degree gridded dataset developed by Maurer et al. (2002).

Figure S1-3 depicts the mean number of CDDs. The raw model output clearly underestimates CDD. It fails to capture the spatial variability of observed CDD. The downscaled CMIP5 data do well at capturing both the observed spatial variability and, to a large extent, the frequency of CDDs over the High Plains. All of the models over-estimate CDDs over the northern and southern High Plains. The MPI-ESM-LR comes closest to the observations in getting the frequency right. Figure S1-4 shows the standard deviation of CDDs. The central High Plains has a greater variability in CDDs as depicted by the concentration of darker brown shades in the observed data. This spatial pattern is captured very well in the downscaled CMIP5 data, albeit for a slight over-estimate in the variability. The raw model output fails to capture the observed spatial variability in CDDs. When it comes to CWDs, the raw model output captures the spatial distribution of observed CWDs quite well, with a greater concentration of CWDs in the southwestern High Plains region (Figure S1-5). This pattern is captured very well in the downscaled CMIP5 data. Again, in the downscaled output, there is a slight over-estimate of CWDs in regions where observations show a higher concentration of CWDs and a slight under-estimate of CWDs in regions of lower CWD concentrations, such as the northern and central High Plains. The spatial variability of CWDs is loosely captured in the raw model output, while the downscaled data do a good job at capturing the observed variability (Figure S1-6).

The raw model output from the CCSM4 and MIROC5 perform better than the downscaled data at capturing the spatial variability and number of days when surface temperature exceeded 100 F (Figure S1-7). None of the downscaled models capture the observed frequency of the number of days with Tmax >100F. Only the raw model output from CCSM4 and the MIROC come close to capturing the observed variability of hot days (Figure S1-8).



Mean consecutive dry days during 1950-1999

Figure S1-3: Mean number of consecutive dry days.

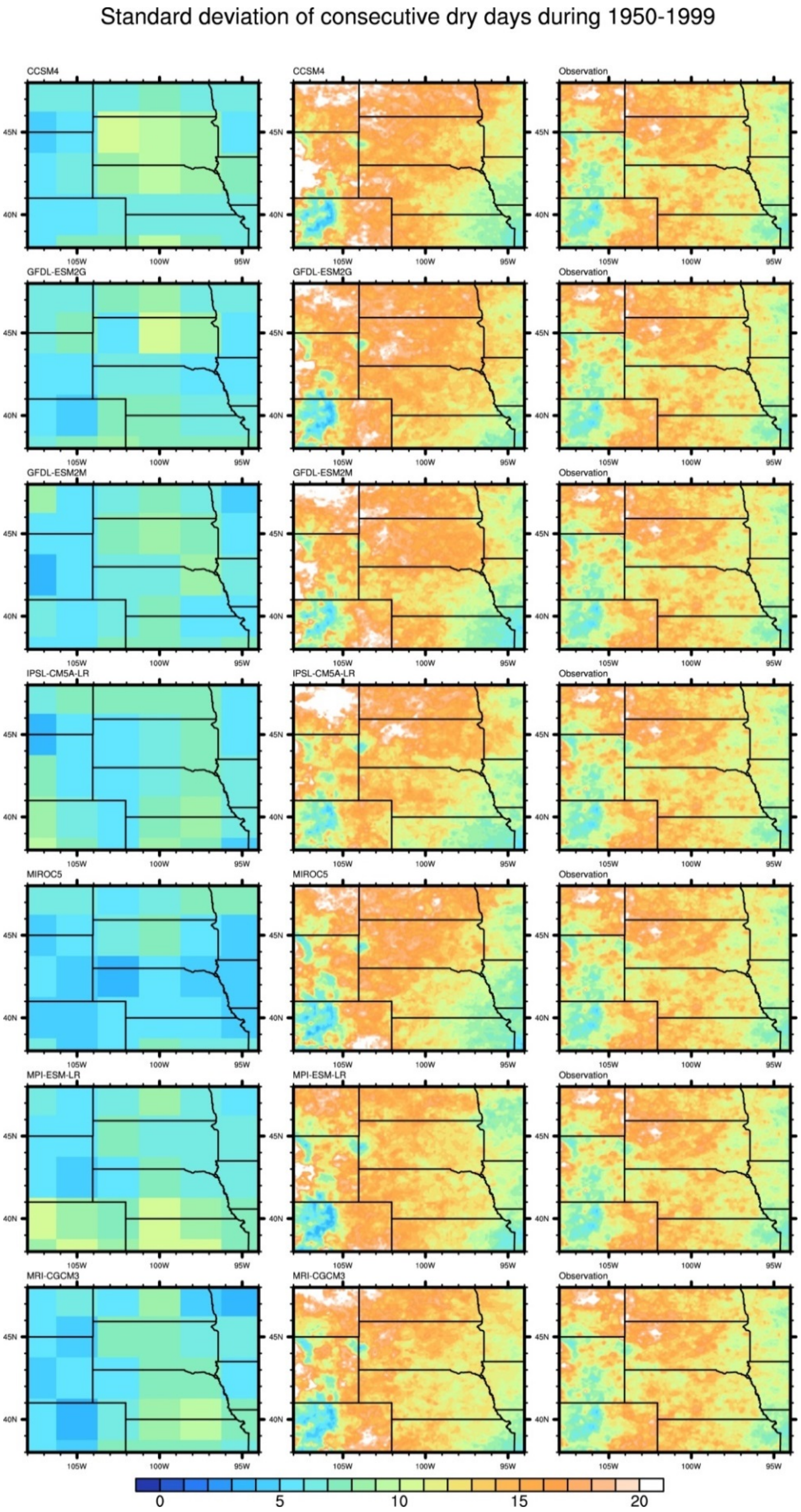


Figure S1-4: Standard deviation of consecutive dry days.

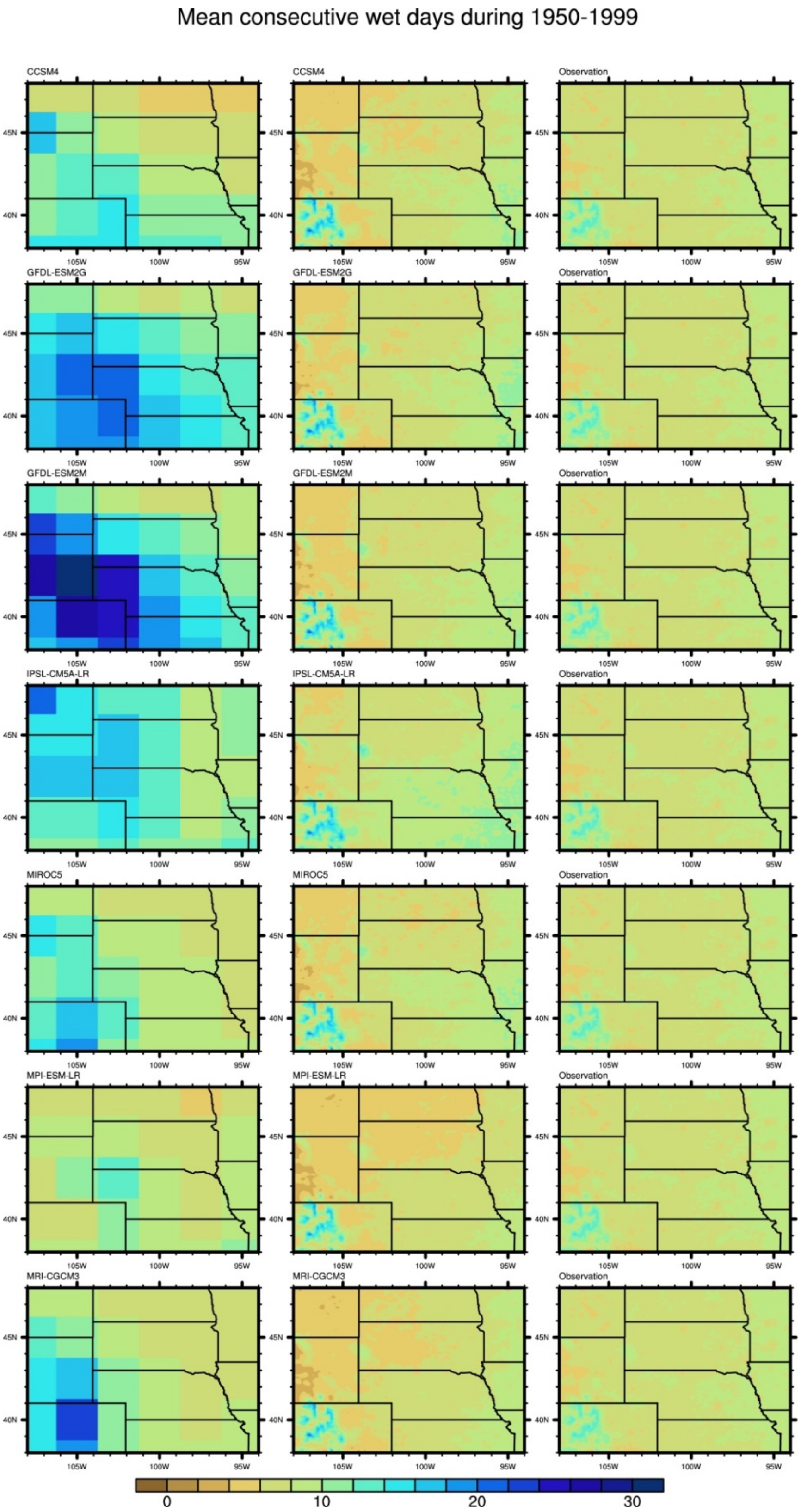


Figure S1-5: Mean number of consecutive wet days.

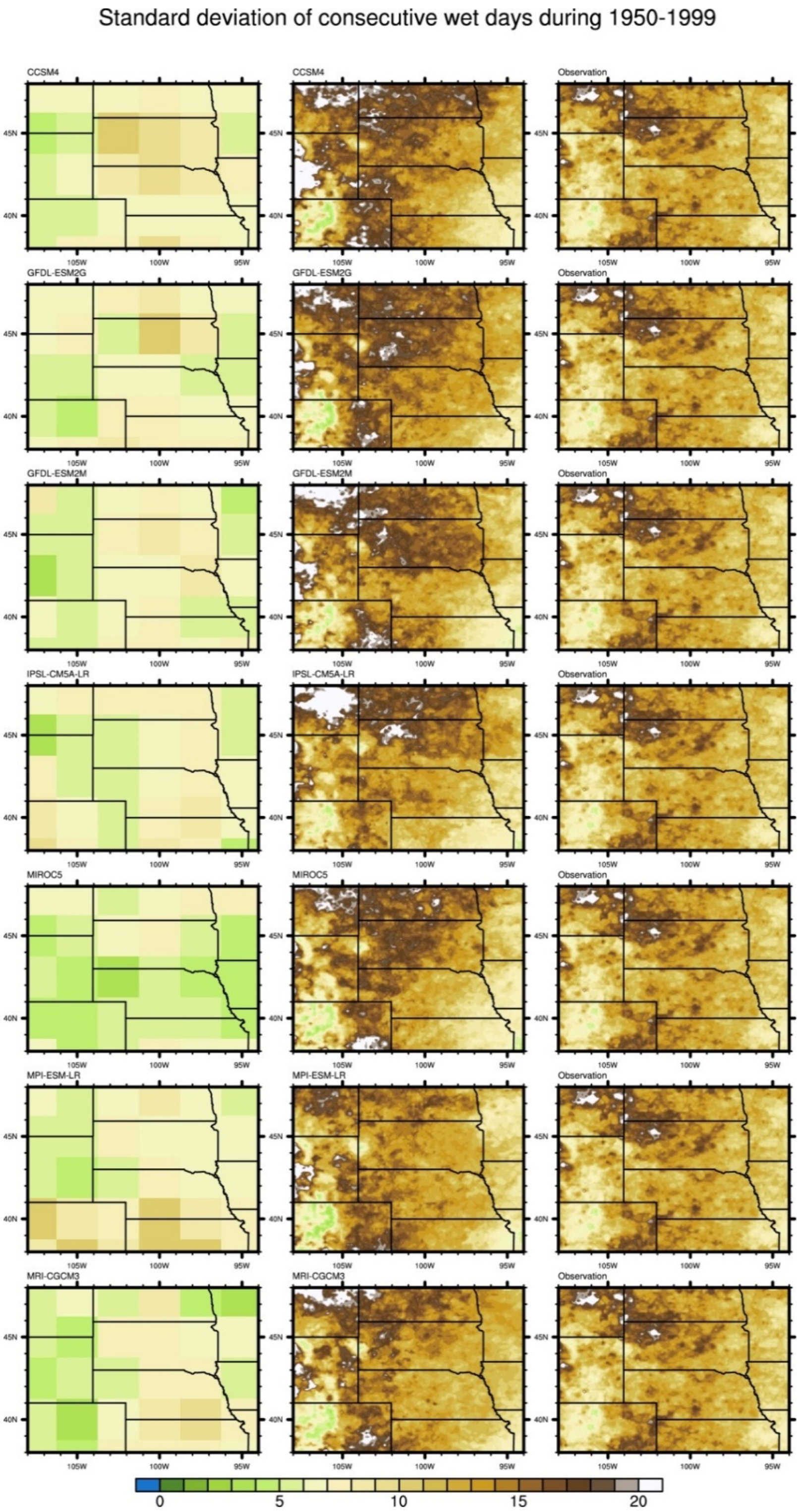
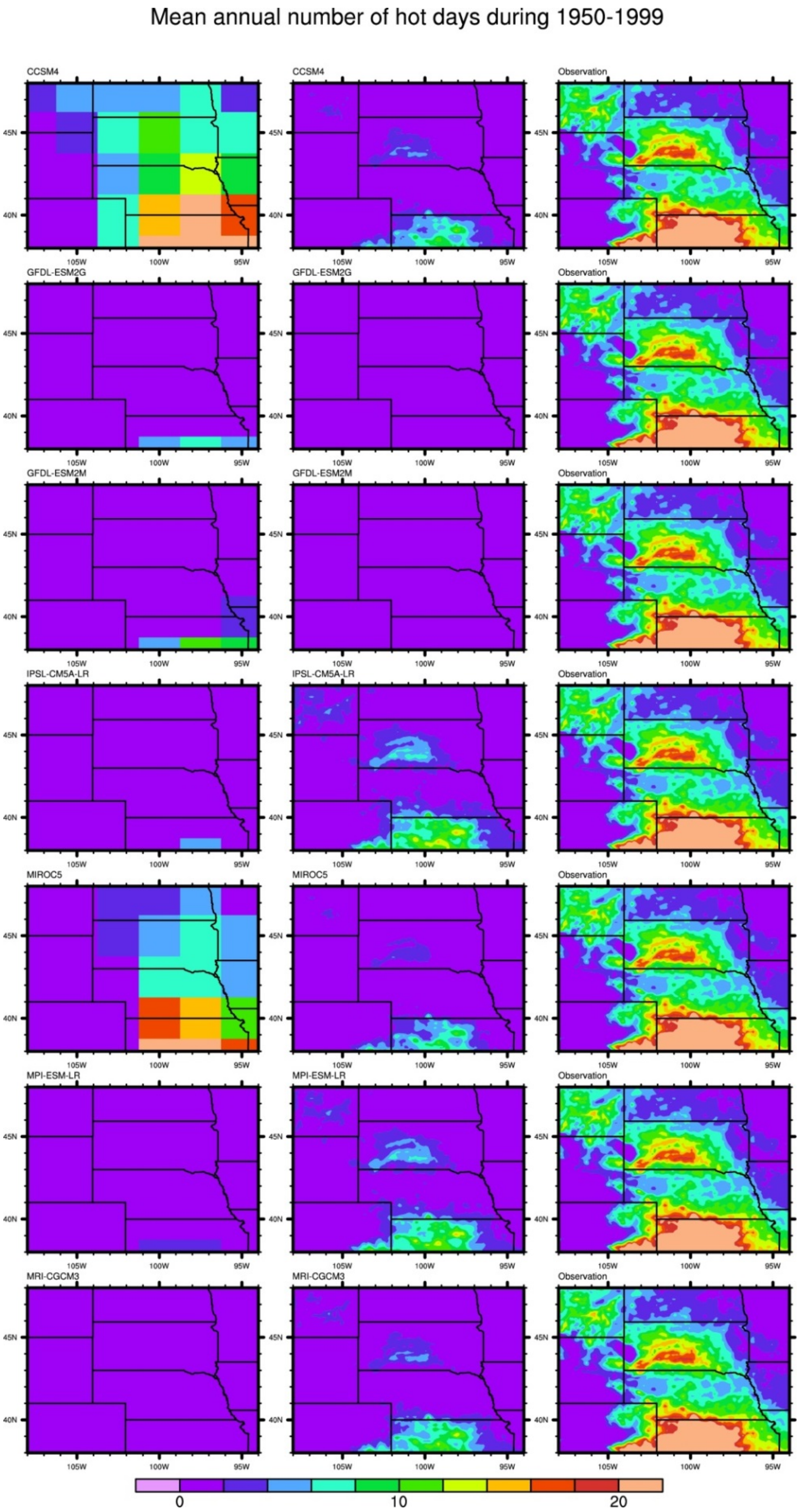


Figure S1-6: Standard deviation of consecutive wet days.


Mean annual number of hot days during 1950-1999

CCSM4

CCSM4

Observation

GFDL-ESM2G

GFDL-ESM2G

Observation

GFDL-ESM2M

GFDL-ESM2M

Observation

IPSL-CM5A-LR

IPSL-CM5A-LR

Observation

MIROC5

MIROC5

Observation

MPI-ESM-LR

MPI-ESM-LR

Observation

MRI-CGCM3

MRI-CGCM3

Observation

Figure S1-7: Mean number of days with Tmax > 100°F.

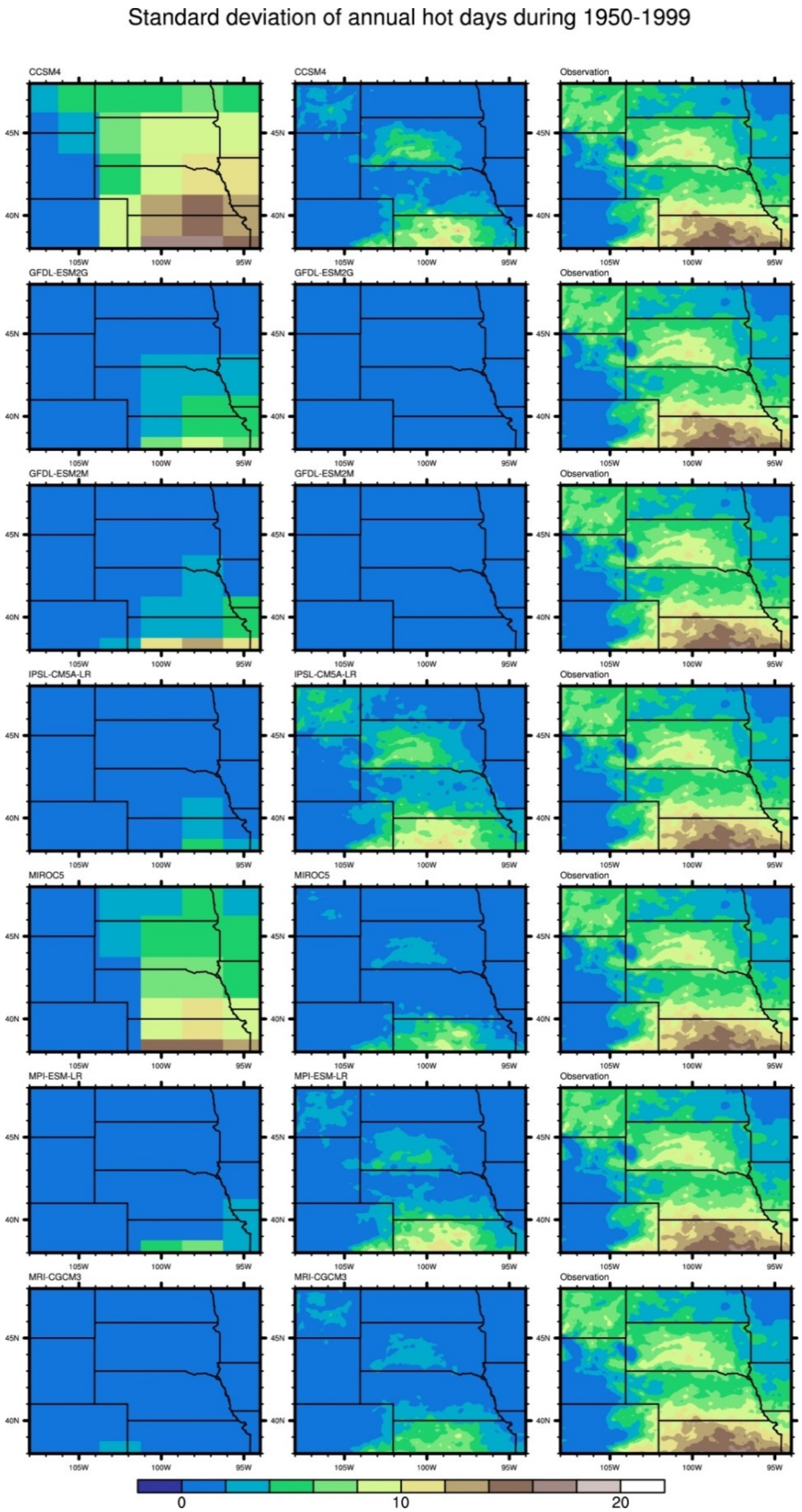


Figure S1-8: Standard deviation of days with Tmax >100°F.

Supporting Information Task 3

Task 3b. Comparison of irrigation pumpage data from WIMAS database with precipitation data from PRISM dataset.

The Kansas Department of Agriculture, Division of Water Resources (DWR) and Kansas Geological Survey (KGS) created the Water Information Management and Analysis System (WIMAS) program (http://hercules.kgs.ku.edu/geohydro/wimas/index.cfm). The WIMAS database includes information on water rights in the state and groundwater pumpage from 1990. Water rights in the eastern part of the state are mostly based on surface water whereas those in the western part of the state are based on groundwater (Figure S3-1). Groundwater irrigation water rights are concentrated in the western region (Figure S3-2). In Kansas, groundwater management districts, provide water-use administration, planning, and information (http://www.kgs.ku.edu/Hydro/gmd.html). There are a total of five GMDs that were established in the 1970s in the western and central parts of the state. Groundwater in the GMDs is used primarily for irrigation. The locations of the groundwater rights in the Groundwater Management Districts (GMD) on the Ogallala aquifer are shown in Figure S3-3.

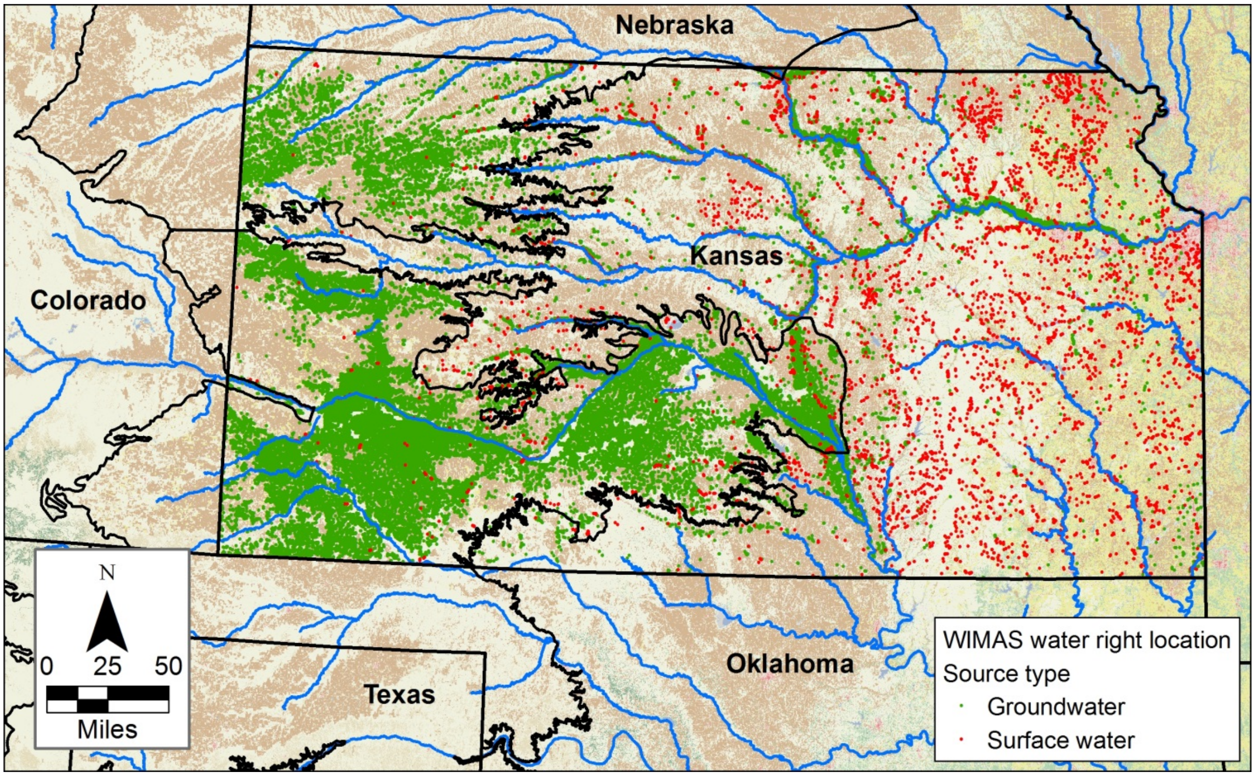


Figure S3-1. WIMAS water rights locations by water source type

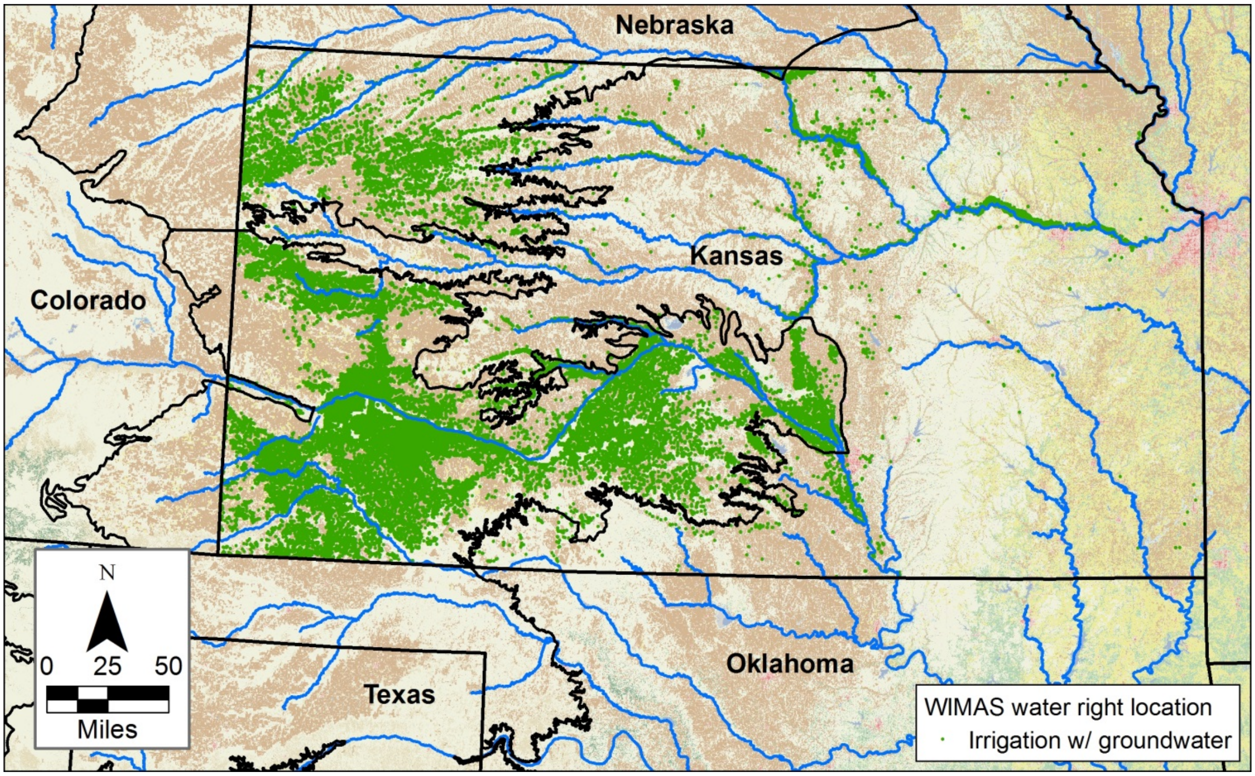


Figure S3-2. WIMAS statewide groundwater irrigation water rights locations

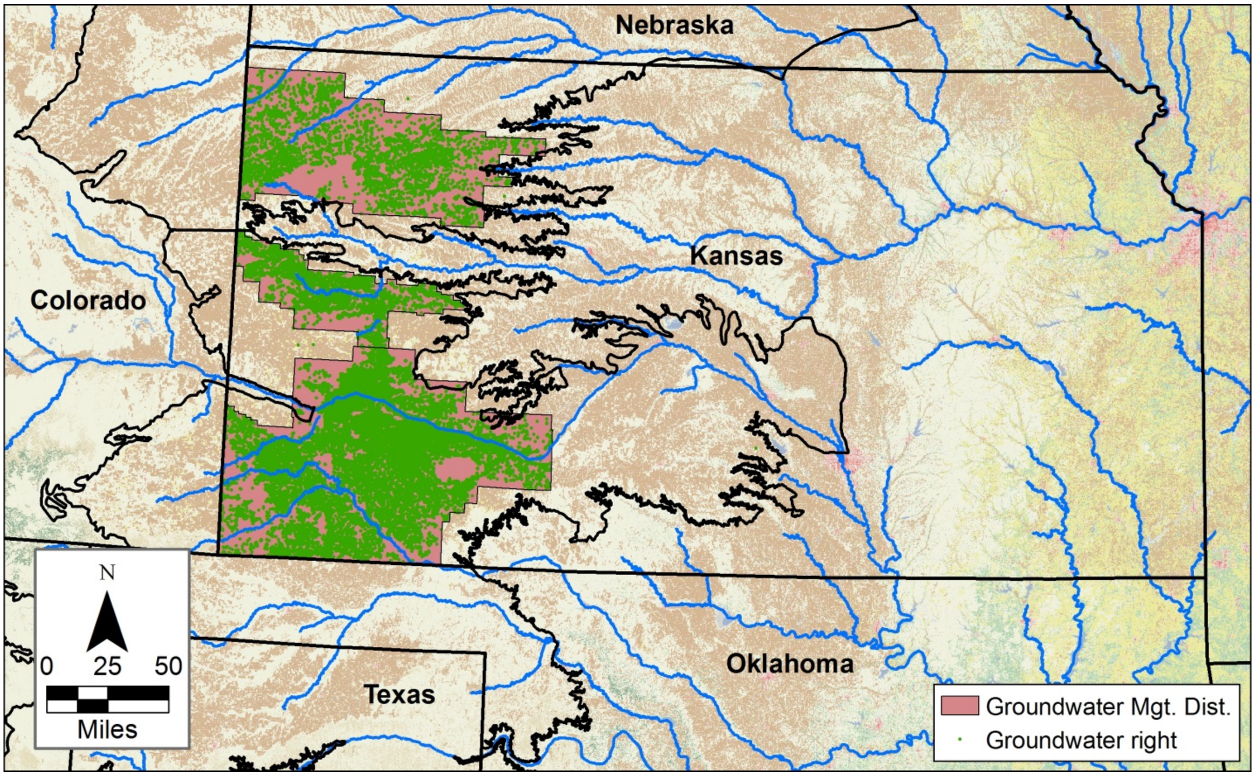


Figure S3-3. WIMAS groundwater rights in the Groundwater Management Districts (GMDs) on the Ogallala aquifer. GMD 4 is in the north (mostly in 4 counties and parts of other counties, GMD 1 is in the center (parts of 5 counties), and GMD 3 is in the south (mostly in 11 counties).

Data from 1992 – 2008 were evaluated, focusing on irrigation. At the statewide level, total water demand averaged 5.1 maf/yr (range 3.5-6.4 maf/yr), which was derived from groundwater (75%) and surface water (25%). Irrigation represents a mean of 73% of statewide total annual water demand (range 60% to 88%), of which 95% is derived from groundwater. Within the Groundwater Management Districts (GMDs), total water demand averaged 2.8 maf/yr (range 2.2-3.6 maf/yr), with 98% based on groundwater. Irrigation represents a mean of 97% of GMD area total annual water demand, of which 98% is derived from groundwater.

Irrigation water use in Kansas is negatively correlated with total annual precipitation, both statewide and in the Ogallala GMD areas, indicating that in general more irrigation water is used during drier years. Correlation is moderately strong at the state level (r=-0.77) and moderate in the Ogallala GMD areas (r=-0.57).

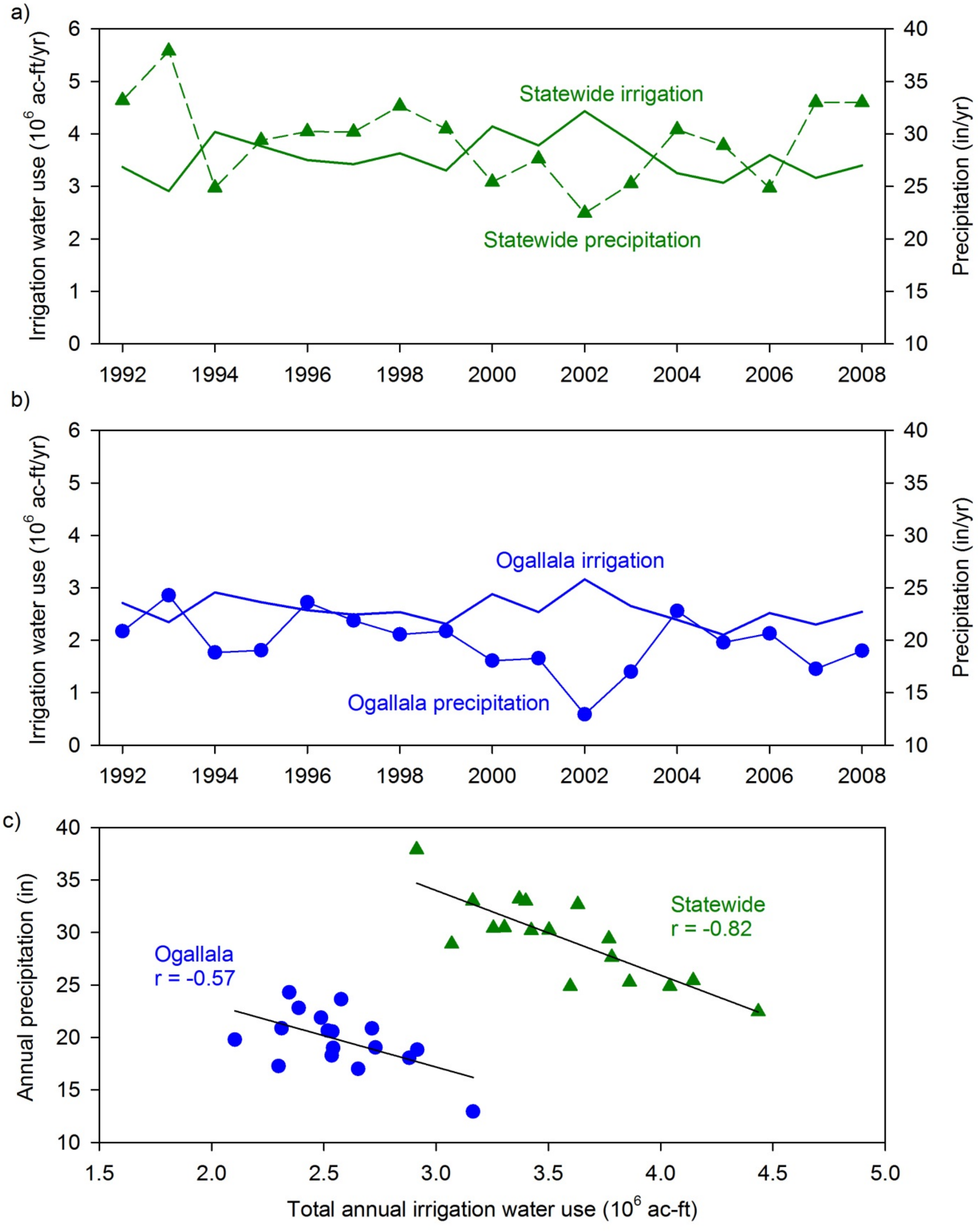


Figure S3-4. Comparison between temporal trends in total annual irrigation amounts and precipitation amounts for the a) statewide and b) Ogallala GMD areas and c) correlations between irrigation amounts and precipitation amounts.

Butler, J. J., D. O. Whittemore, et al. (2013). "A Simple, First-Order Approach for Assessing Aquifer Response to Anthropogenic and Climatic Stresses: New Insights into the Future of the High Plains Aquifer in Kansas." AGU Abstracts with Programs Hydrology 13O: CONTROL ID: 1808761.

ABSTRACT: The main driver of water-level changes in many regional aquifers such as the High Plains aquifer (HPA) in the United States is the amount of **water pumped for irrigation**, which is often primarily a function of meteorological conditions. Correlations between climatic indices and annual water-level changes and between reported water use and annual changes may explain most of the observed water-level declines in these regional systems. In that case, these correlations can be used for rapid, first-order assessment of an aquifer's response to future climatic and development stresses. The potential of this general approach is demonstrated for the relatively data rich portion of the HPA in Kansas. The Kansas HPA is overlain by five groundwater management districts (GMDs) that spatially coincide well with four climatic divisions. Each winter, water levels are measured in about **1400 wells** distributed approximately evenly over the GMDs. The spatial **average of the annual water-level changes for a GMD, the reported water use within the GMD, and a climatic index (Standardized Precipitation Index [SPI]) f**or the spatially coinciding climatic division are the three time series considered here. The strong linear correlations (coefficients of determination from 0.71-0.78) between the SPI and annual water-level changes indicate that, under average (historic norm) climatic conditions, water levels will decline 0.2-0.6 m/yr across the Kansas HPA. As a result of such declines, there is growing interest in reducing pumping to extend the "usable lifetime" of the aquifer. The key issue is how much reduction is needed to significantly moderate the declines. Correlations between **reported water use and annual water-level changes, in conjunction with correlations between the SPI and annual changes,** can be used to show that pumping reductions of 20-30% would likely stabilize water levels, at least in the short term, over much of the Kansas HPA. Although this stabilization may be a product of enhanced recharge produced by past inefficient irrigation practices, and thus only of limited duration, it should help extend the usable lifetime of the resource and serve as a bridge to an economy based on a different mix of agricultural practices. This correlation-based approach is not envisioned as a replacement for process-based modeling. However, the rapid, first-order assessments that can be readily obtained should be of considerable value for those responsible for the management of heavily stressed aquifers.

Supporting Information Task 4

Task 4b. *Evaluate the ability of irrigation to provide sufficient water for crop production during droughts using past records, focusing on drought periods.*

To assess the impact of droughts on crop production, we compared the crop distribution from the US Dept. of Agriculture Crop Data Layer (CDL) for 2010, 2011, and 2012 for the US High Plains (Figures S4-1 through S4-3). Precipitation in 2010 was high but was low in 2011 in the Texas-Oklahoma-New Mexico region of the High Plains and again in 2012 when drought extended northward into Kansas and Nebraska (Figure S4-4). However, the mapped distribution of major crops shows no obvious differences at the scale of the US High Plains.

To evaluate temporal variability in crop production related to droughts, we compared planted and harvested acreages for the period 1980 through 2012 for different crops and different regions using National Agricultural Statistics (NASS) database (http://www.nass.usda.gov/Data_and_Statistics/). Major crops include corn, wheat, cotton, sorghum, and soybeans. Planted cropland area has remained generally constant in the northern High Plains (NHP) region but has decreased in both the central High Plains (CHP) and southern High Plains (SHP) regions since the early 1980s (Figure S4-5a). The percentage of harvested cropland relative to planted area remained high in the NHP region during this period, averaging 92% of planted area (range 85% to 96%) (Figure S4-5b). In the CHP, the percentage of harvested area was somewhat lower, averaging 84% (range 65% to 92%) of planted area. In the SHP, the percentage of harvested area was initially similar to the CHP but has declined overall since the early 1980s from an average of about 80% to an average of 64% since 2000. SHP harvested areas were lowest during drought years in 1998 (54%), 2006 (54%), 2011 (32%), and 2012 (50%). CHP harvested area relative to planted area was lowest during 2002 (65%), 1989 (69%), and 2011 (74%). NHP harvested area was lowest during 1983-84 (85-86%) and 2002 (85%). These results indicate that droughts have least impacts on harvested cropland in the NHP and most in the SHP. These differences between NHP and SHP may reflect greater water availability for irrigation in the NHP relative to the SHP, allowing cropland production to decouple from drought forcing.

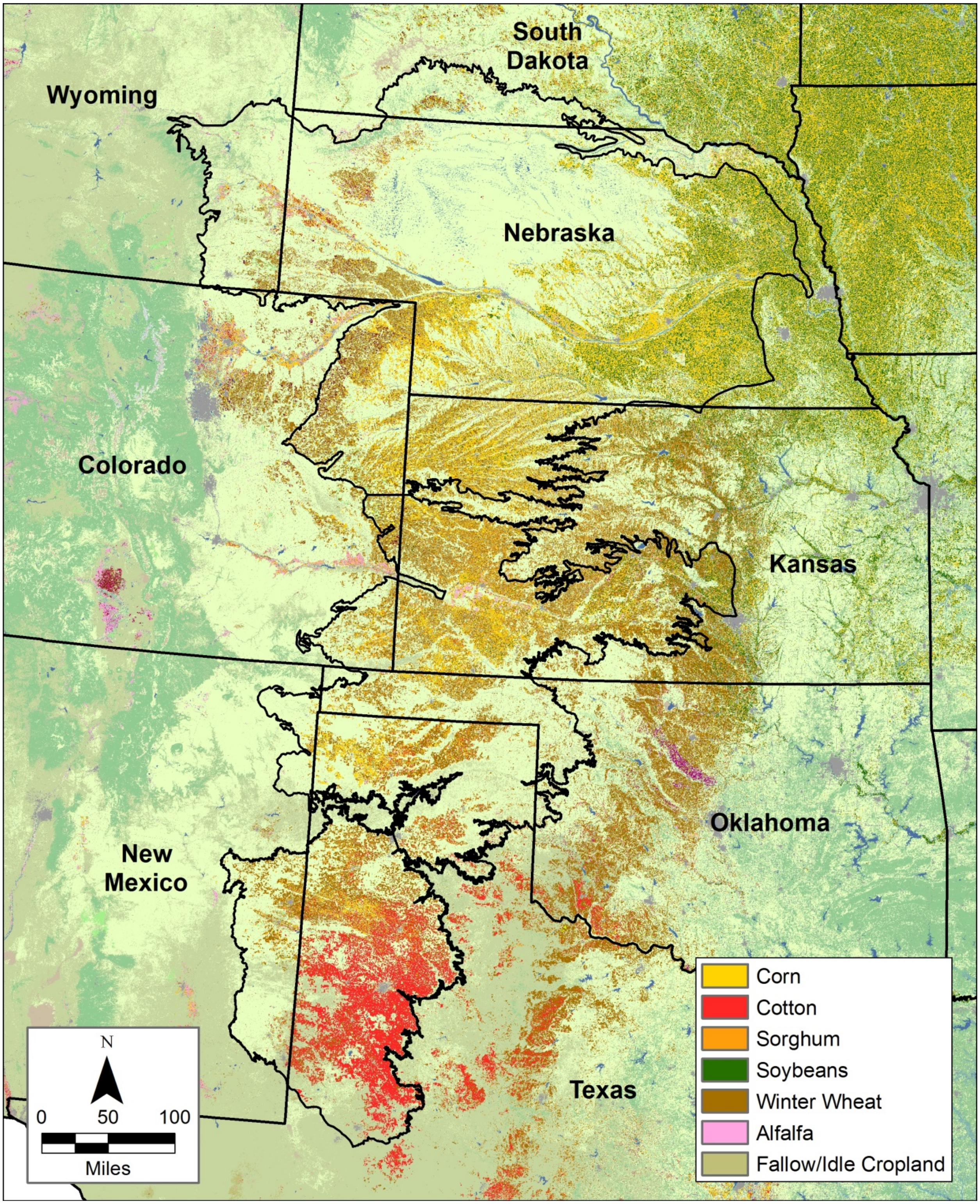


Figure S4-1. Distribution of major crops in the US High Plains in 2010 (Crop Data Layer, USDA).

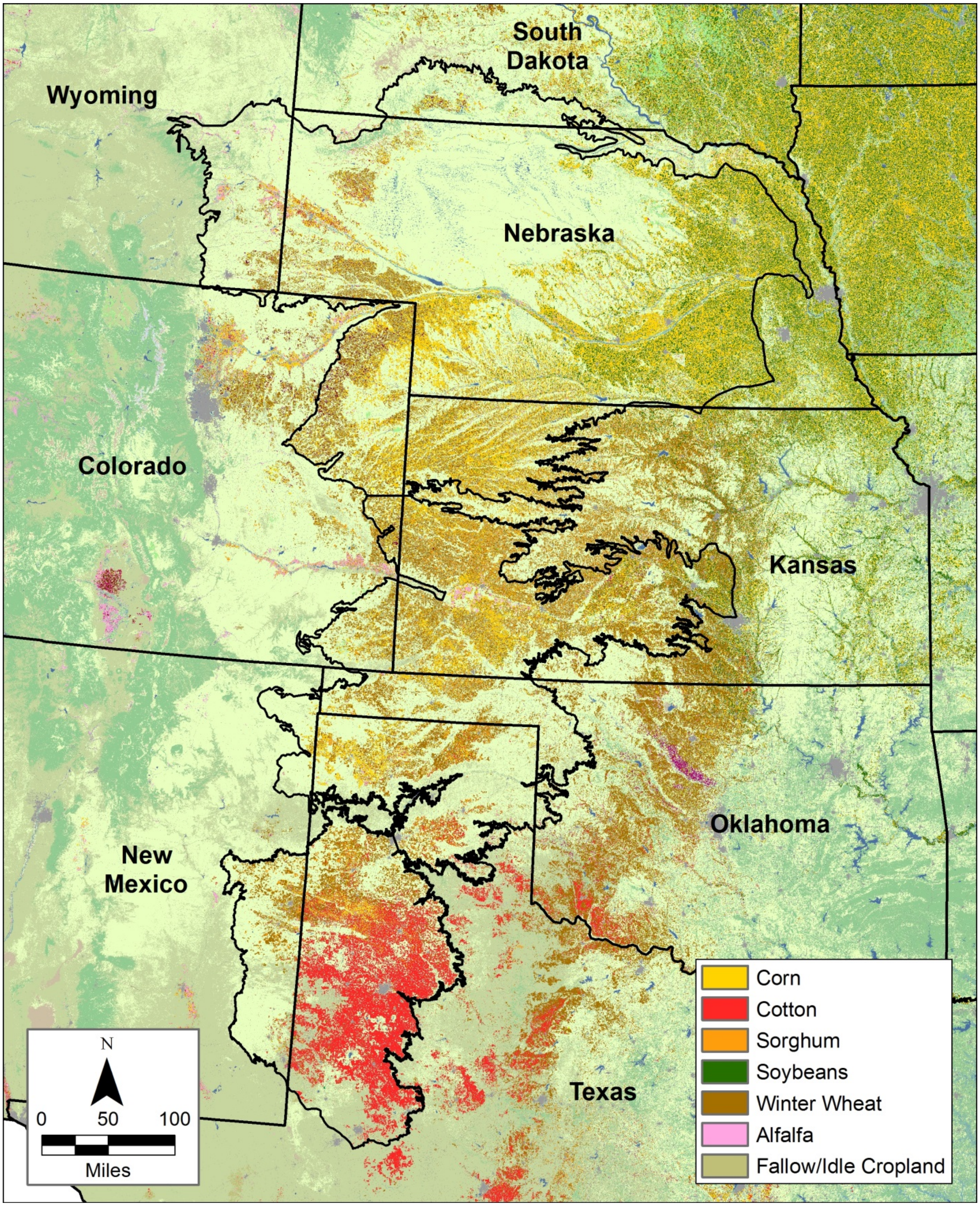


Figure S4-2. Distribution of major crops in the US High Plains in 2011 (Crop Data Layer, USDA).

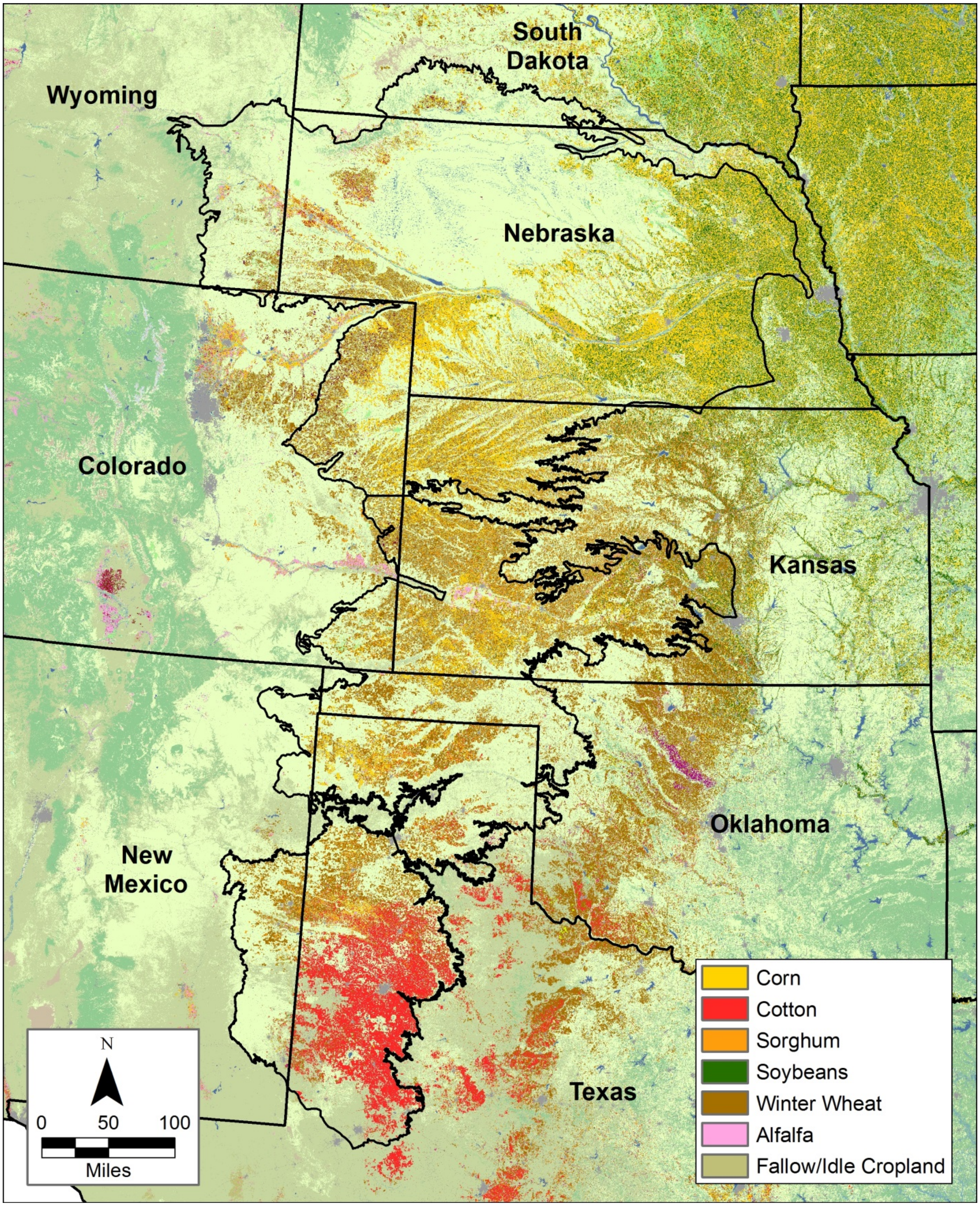


Figure S4-3. Distribution of major crops in the US High Plains in 2011 (Crop Data Layer, USDA).

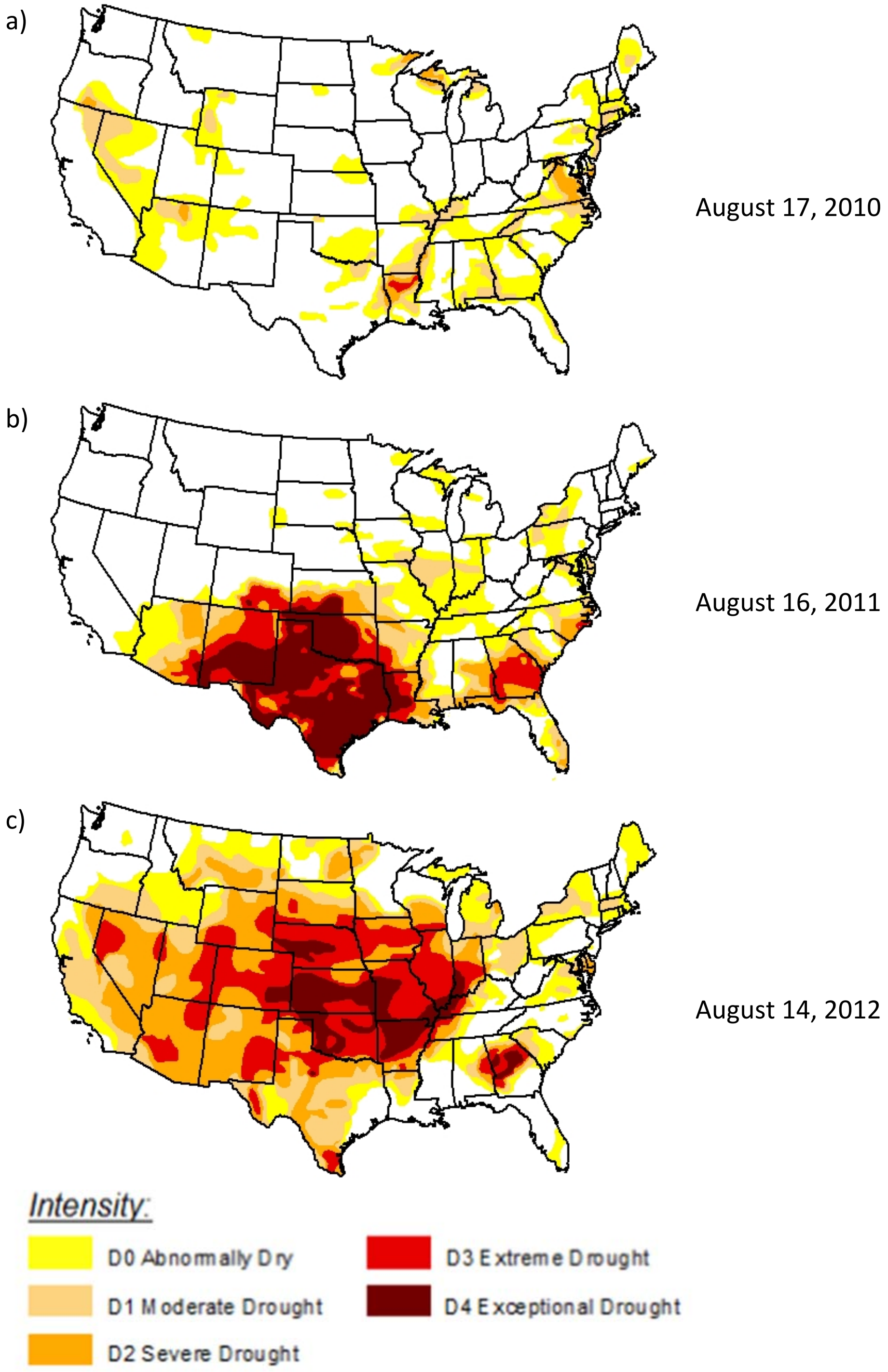


Figure S4-4. Palmer Drought Index (PDI) for the US during summers of a) 2010, b) 2011, and c) 2012. Drought conditions initially focused in the Texas – Oklahoma – New Mexico region during 2011 and expanded northward into the central US to include areas of Kansas and Nebraska during 2012.

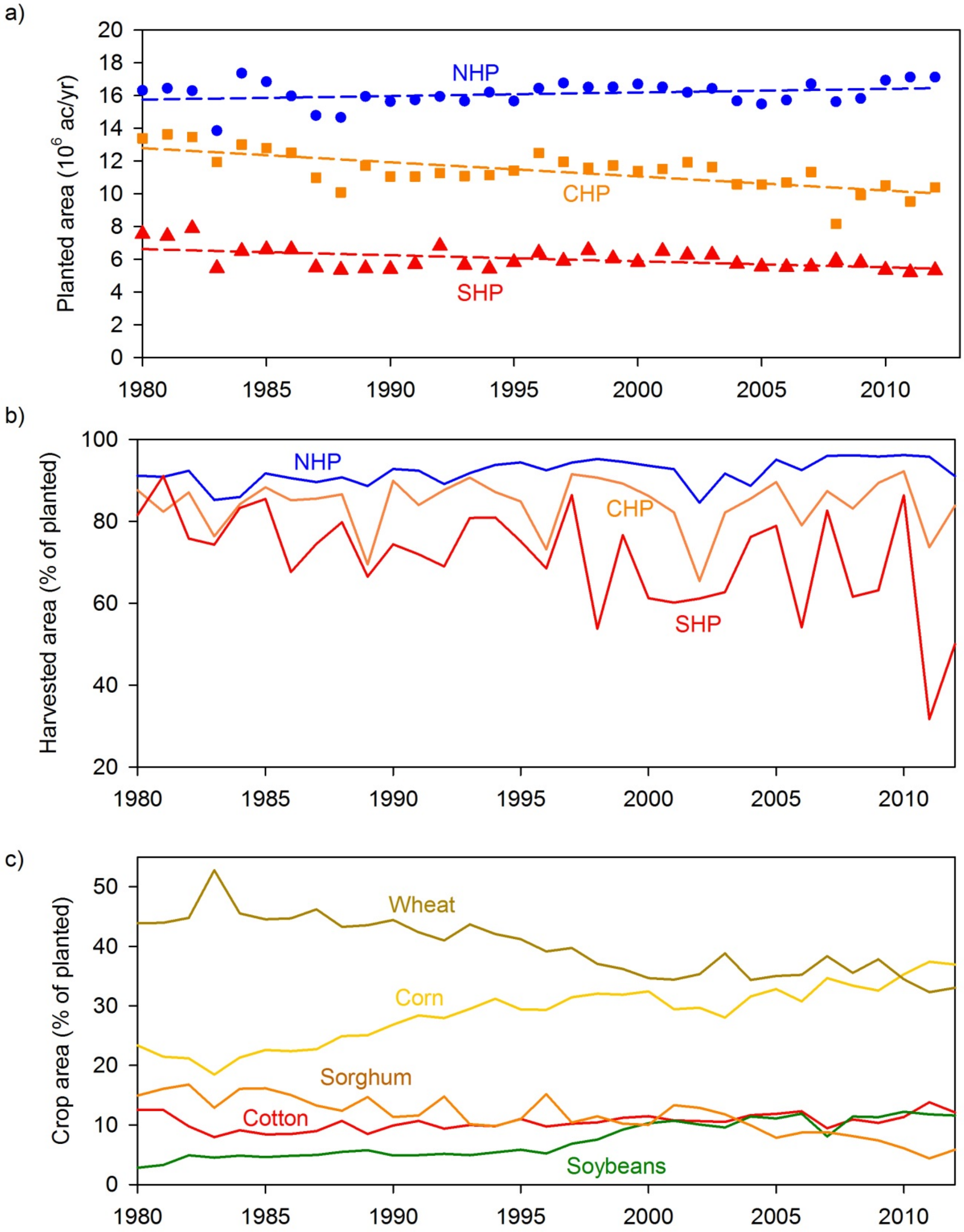


Figure S4-5. Temporal trends in a) total planted area and b) harvested area percentages by region in the High Plains and in c) crop types in the High Plains based on data from the National Agricultural Statistics Service (NASS) database.

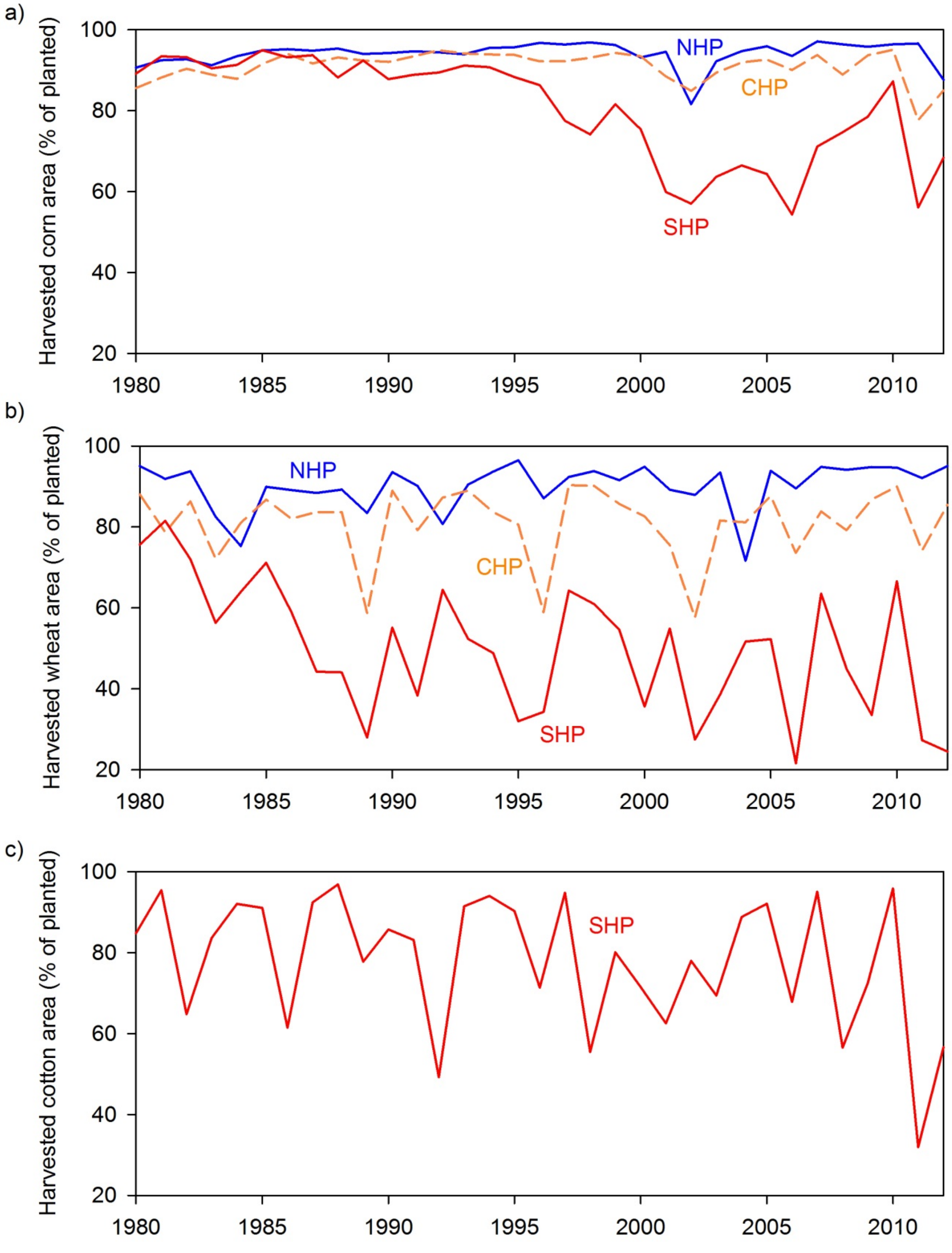


Figure S4-6. Temporal trends in harvested area percentages by region in the High Plains for a) corn, b) wheat, and c) cotton based on data from the National Agricultural Statistics Service (NASS) database.

Task 4c. *Relate water-level data in the High Plains aquifer to baseflow discharge in streams in the region, including the Canadian River.*

Water levels in 11,782 groundwater wells completed in the US High Plains aquifer were used to generate a water table elevation map (Figures S4-7 and S4-8). The latest water level for each well during the period 2000-2012 was used. Despite the large number of monitored wells, there are relatively large areas of the aquifer system with little or no data, particularly along the western margins in Wyoming, southern Colorado and western Kansas, and in New Mexico. However, most of the aquifer areas near flowing rivers have a high density of measurements increasing confidence in these areas (Figure S4-7). Water table elevation contours near drainages that exhibit a curvature such that they “point” upstream indicate that groundwater flow is generally toward the drainage and conditions favor a gaining stream or river reach in these areas. Such conditions are exhibited by some of the rivers that cross the US High Plains, and are particularly evident for the North Platte River in western Nebraska and the Niobrara River in and east of the Sand Hills region in north-central Nebraska (Figure S4-9). The Canadian River in Texas also seems to show evidence of gaining conditions with upstream pointed contours. Contours seem to cross many of the streams at right angles or show point slightly downstream, the latter would indicate slightly losing conditions with streams recharging the underlying aquifer. The stream gaining conditions in some of the Nebraska rivers suggests a strong connection between the aquifer and the rivers; therefore, indicating vulnerability of streamflow to groundwater depletion in these regions. Previous modeling analyses in Nebraska indicates that much of the groundwater pumpage is ultimately derived from capturing baseflow and that baseflow has been reduced to a minimum of 50% of streamflow in some rivers (Luckey and Cannia, 2006).

Streamflow from the 16 gages across the High Plains was analyzed from monthly data, baseflow index (BFI), and flow duration curves (Table S4-1, Figures S4-10 through S4-25). The BFI code was used to estimate baseflow index from the gage data. Flow duration curves provide information on whether a stream is perennial or ephemeral. The analyses of gage data may be affected by upstream reservoirs and may simply reflect reservoir operations. The basin areas range from 5,000 – 58,000 mi^2, averaging 23,000 mi^2. Length of gage records range from 20 – 109 years, averaging 69 years. The only obvious ephemeral stream is the Arkansas River at Garden City with a flow duration curve ≤0.7. Baseflow indices range from 0.51 – 0.91, averaging 0.77. Only two gages had values of BFI of 0.51 (Canadian River in Texas) and 0.54 (Loup River near Genoa). Many of the gages have fairly uniform BFI values, indicating that baseflow and streamflow seem to track each other relatively closely. Baseflow index in the Canadian River has been increasing over time as reservoir storage in Lake Meredith has declined below the dead pool storage (Figure S4-26).

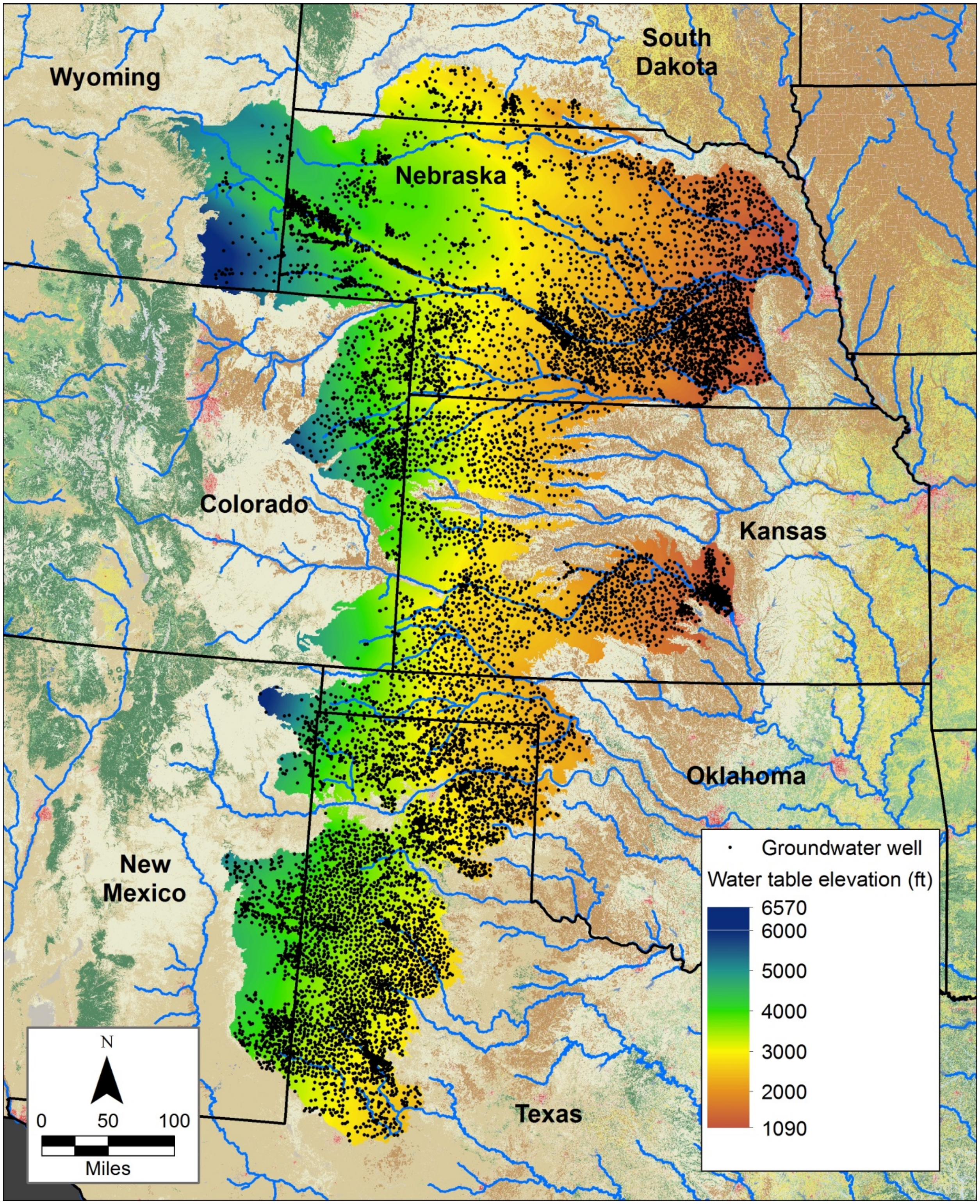


Figure S4-7. Locations of 11,782 groundwater wells with water level measurements used to generate water table map. Water levels represent latest measurement for the period 2000-2007 (McGuire). Shaded area represent the resulting groundwater table elevation surface.

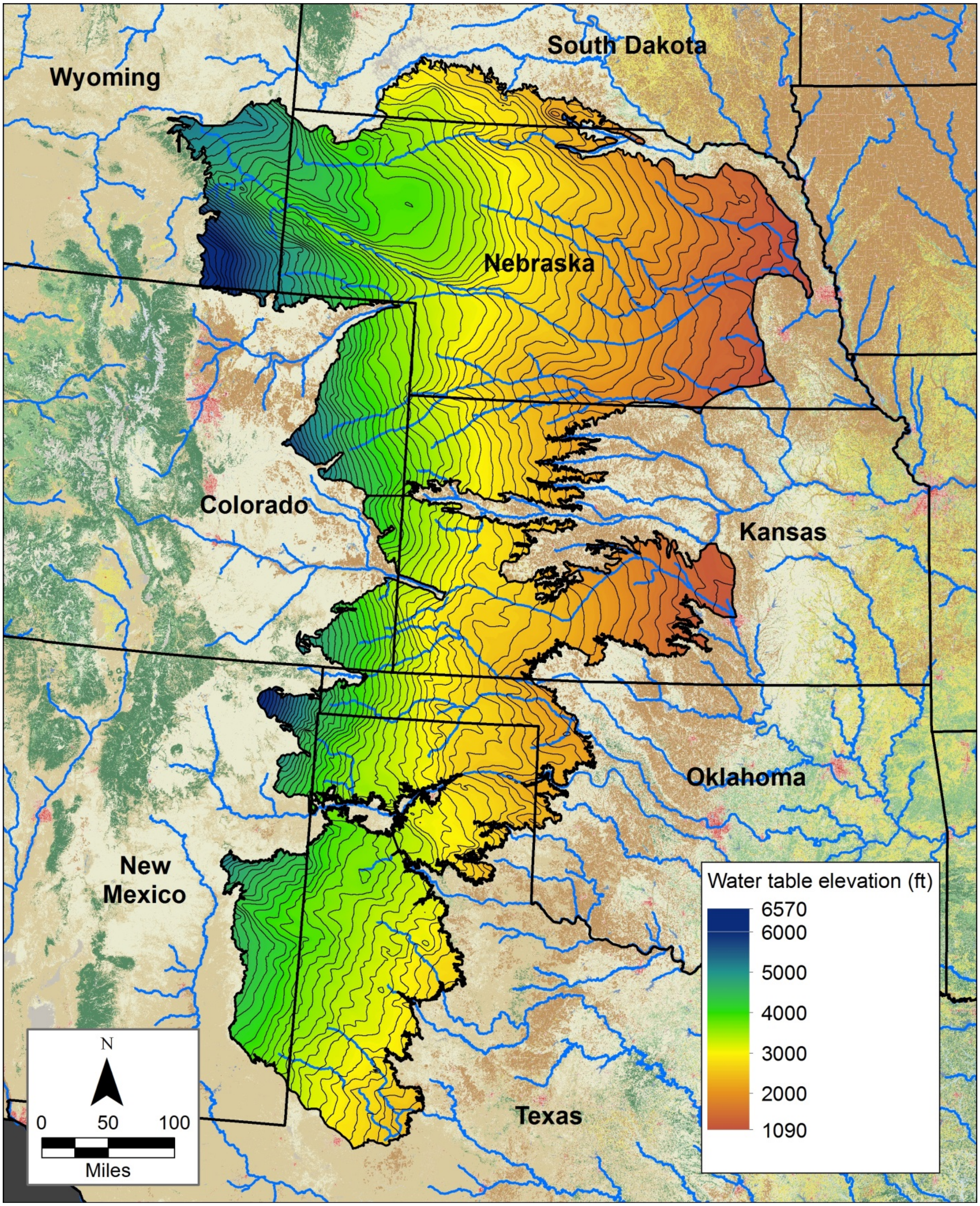


Figure S4-8. Groundwater elevation contours and shaded surface elevation map.

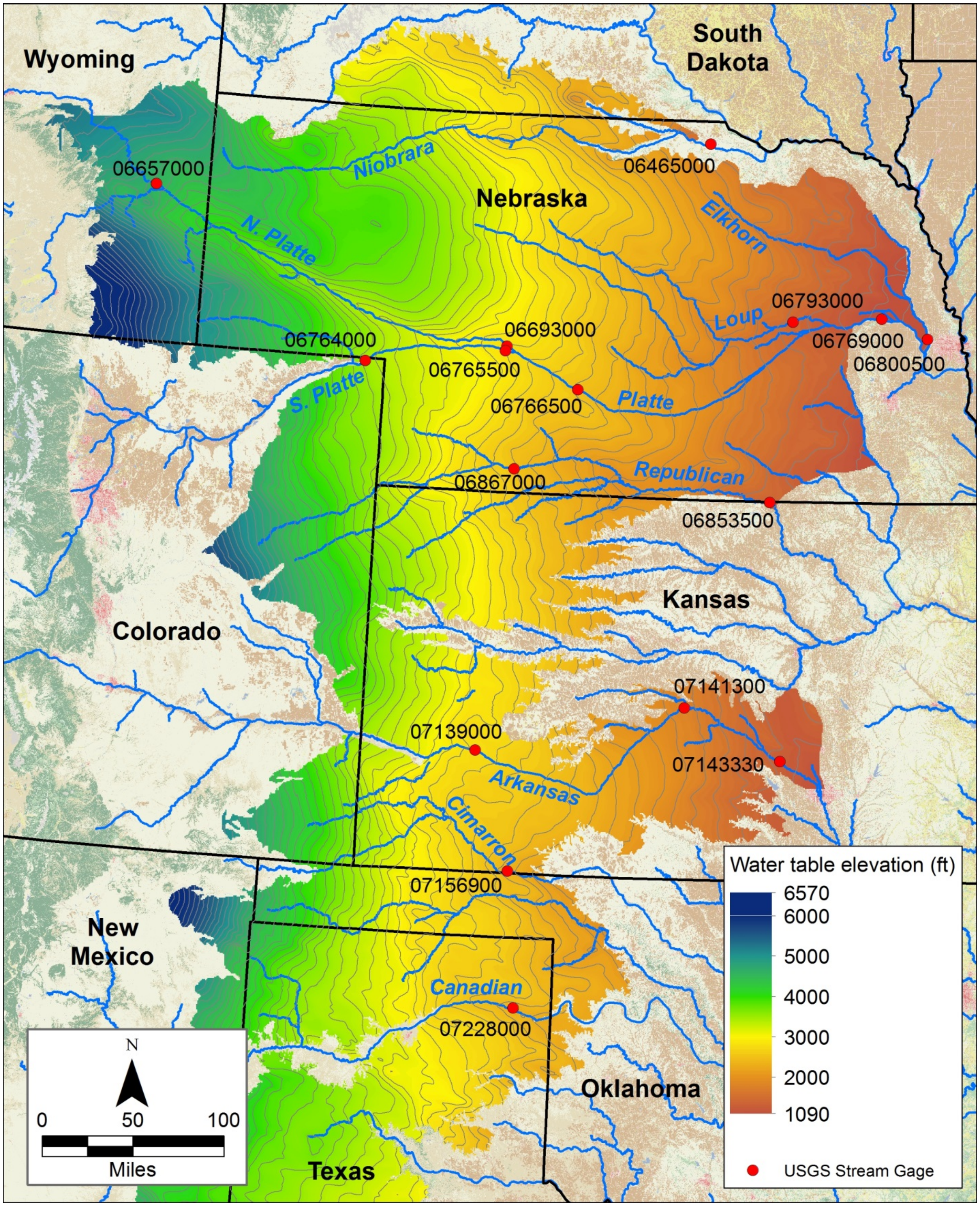


Figure S4-9. Locations of major rivers and USGS stream gages that monitor stream flow in the US High Plains. Groundwater elevation contours and shaded surface elevation map shown for reference.

Table S4-1. Base flow index (BFI) results based on historical flow records for 16 stream gages monitoring flow in the US High Plains region. Locations of the stream gages are shown in Figure S4-9.

Gage ID	*Station Name*	*Drainage area mi^2*	*Period of Record*	*Years Analyzed*	*BFI*		
					Mean	*Min*	*Max*
06465000	Niobrara River near Spencer, NE	11,070	1927 - 2001	72	0.85	0.75	0.92
06657000	North Platte River below Whalen Dam, WY	16,237	1915 - pres.	98	0.86	0.66	0.86
06693000	North Platte River at North Platte, NE	30,900	1974 - 1994	20	0.91	0.87	0.94
06764000	South Platte River at Julesburg, CO	22,824	1902 - 1912	109	0.85	0.36	0.96
06765500	South Platte River at North Platte, NE	24,300	1931 - 1994	63	0.86	0.51	0.95
06766500	Platte River near Cozad, NE	56,500	1940 - 1991	51	0.80	0.56	0.95
06793000	Loup River near Genoa, NE	5,620	1929 - pres.	72	0.54	0.28	0.88
06796000	Platte River at North Bend, NE	57,800	1949 - pres.	64	0.83	0.73	0.90
06800500	Elkhorn River at Waterloo, NE	5,870	1928 - pres.	84	0.77	0.55	0.91
06837000	Republican River at McCook, NE	12,240	1954 - pres.	58	0.85	0.63	0.96
06853500	Republican River near Hardy, NE	14,901	1904 - pres.	95	0.70	0.46	0.91
07139000	Arkansas River at Garden City, KS	24,703	1922 - pres.	62	0.61	0.04	0.94
07141300	Arkansas River at Great Bend, KS	28,354	1940 - pres.	74	0.68	0.18	0.97
07143330	Arkansas River near Hutchinson, KS	31,724	1959 - pres.	54	0.79	0.67	0.95
07156900	Cimarron River near Forgan, OK	5,200	1965 - pres.	48	0.85	0.45	0.95
07228000	Canadian River near Canadian, TX	22,866	1938 - pres.	77	0.51	0.13	0.93

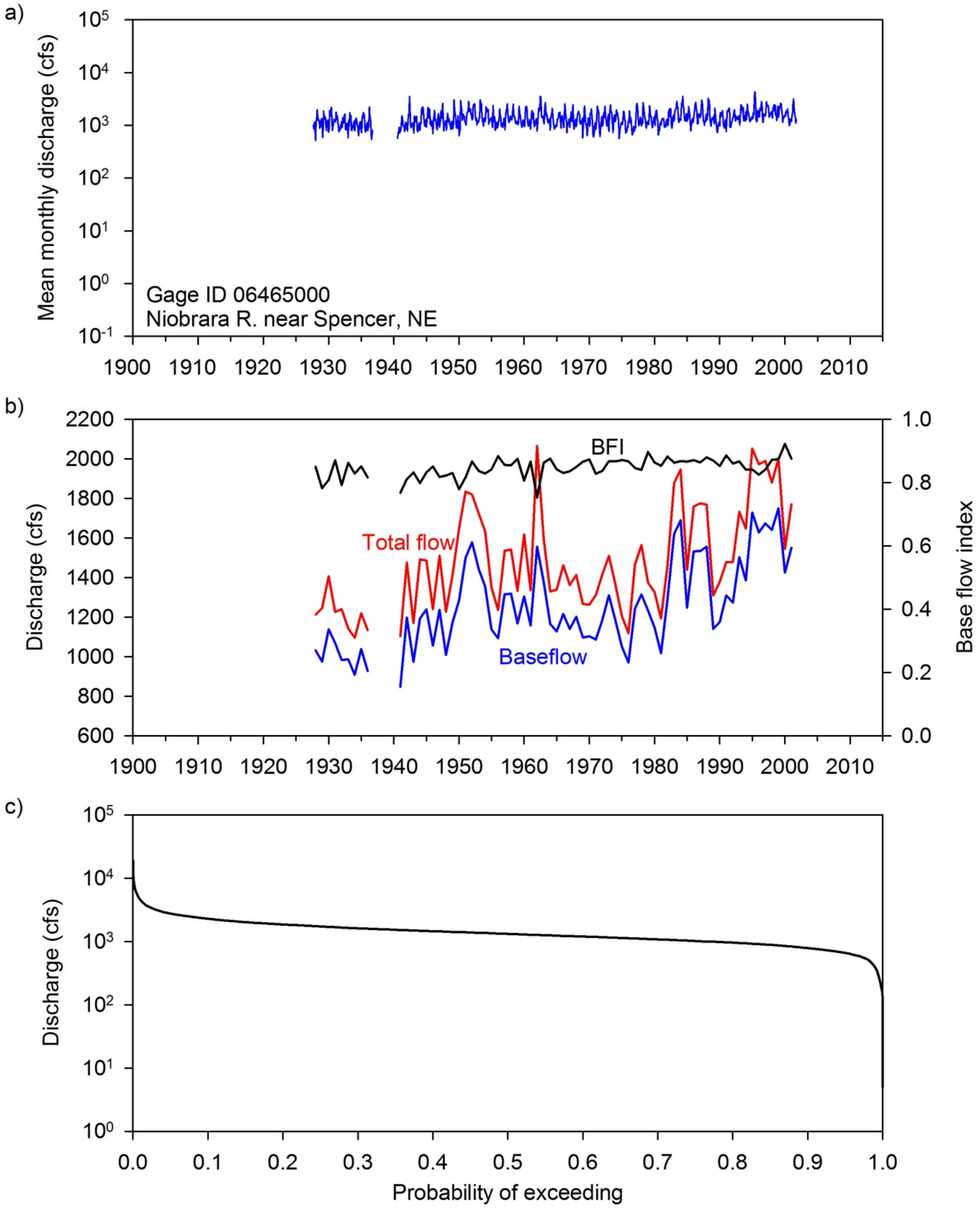


Figure S4-10. a) Streamflow hydrograph, b) flow separation and BFI, and c) flow duration curves for USGS Gage ID 06465000 period of record.

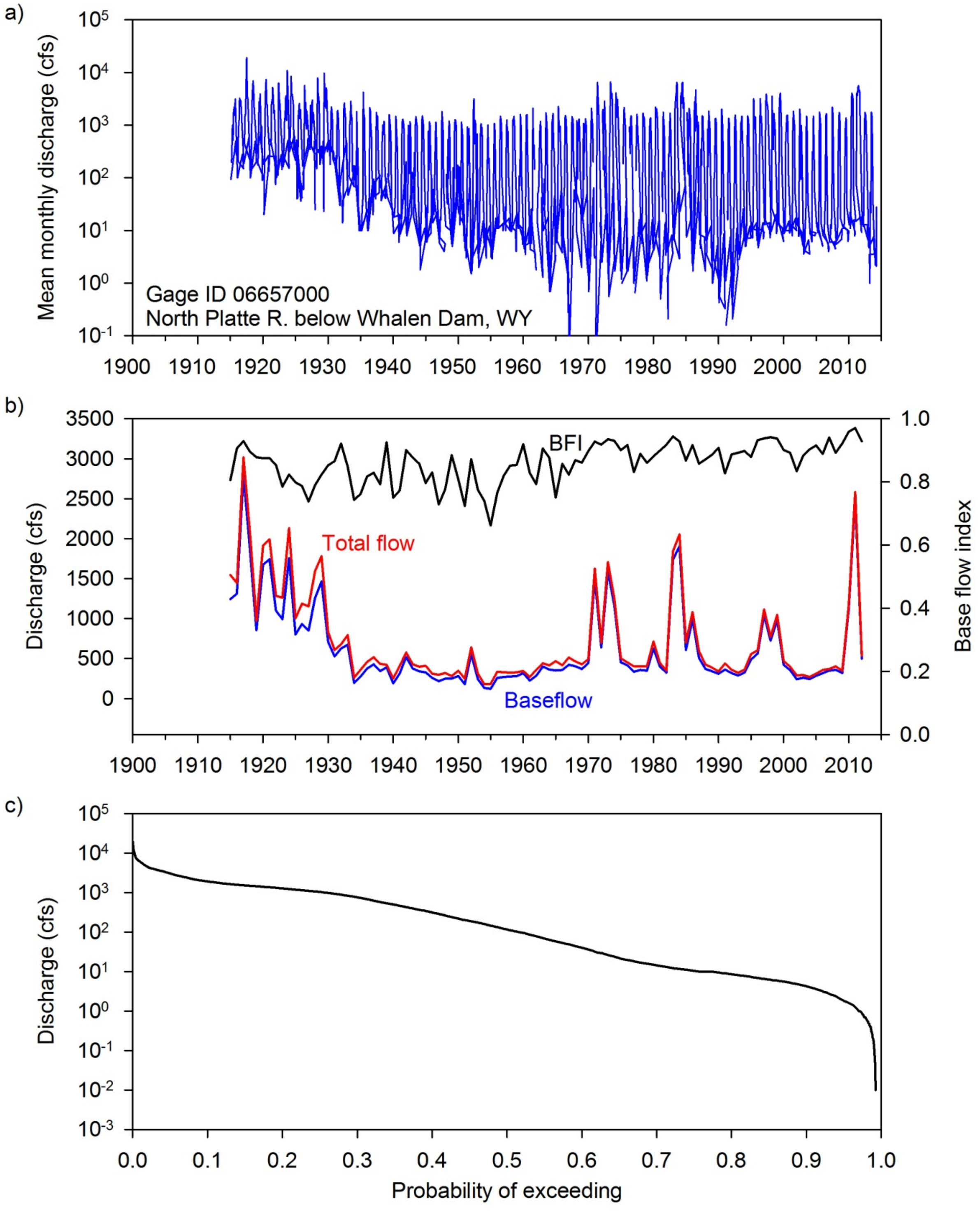


Figure S4-11. a) Streamflow hydrograph, b) flow separation and BFI, and c) flow duration curves for USGS Gage ID 06657000 period of record.

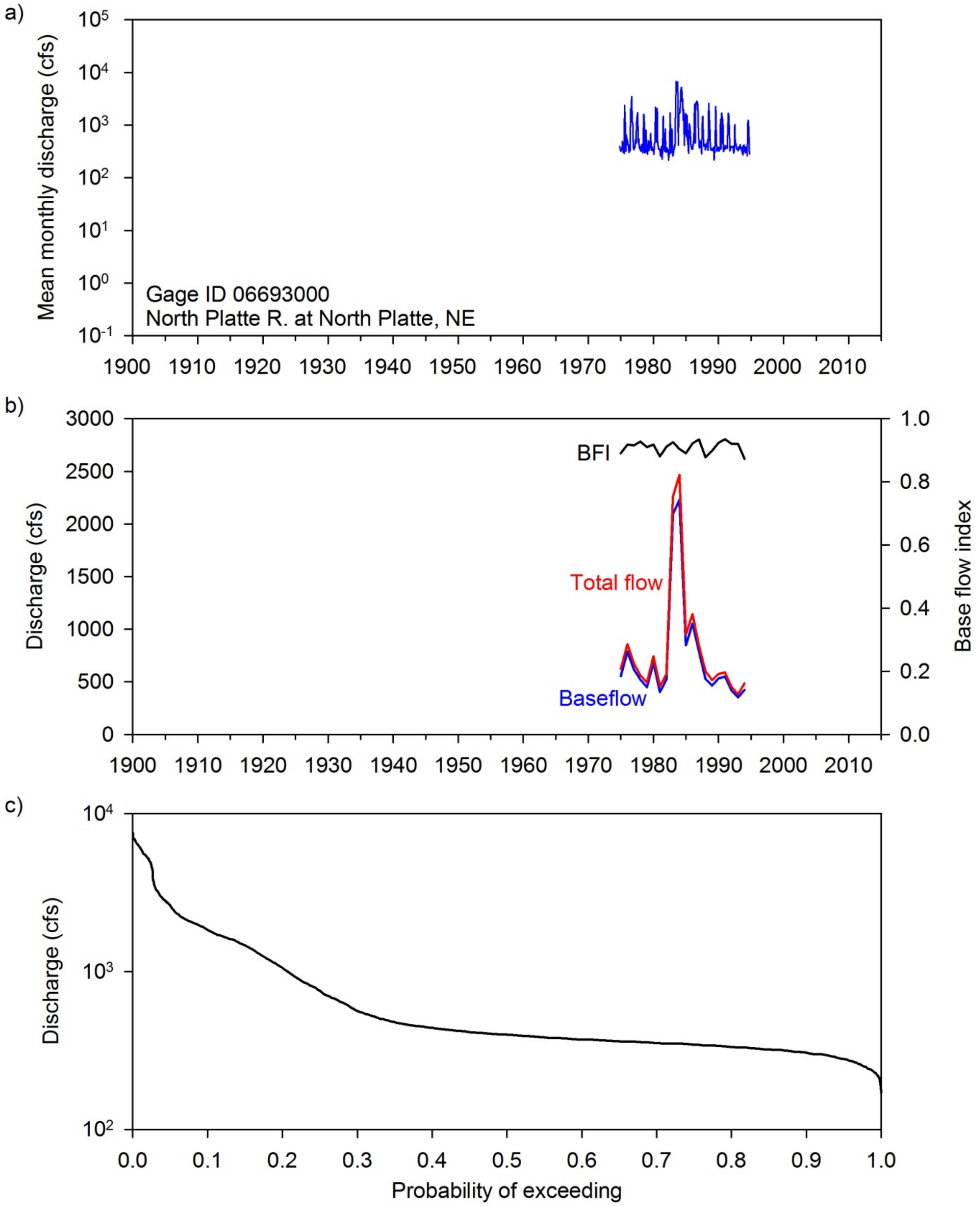


Figure S4-12. a) Streamflow hydrograph, b) flow separation and BFI, and c) flow duration curves for USGS Gage ID 06693000 period of record.

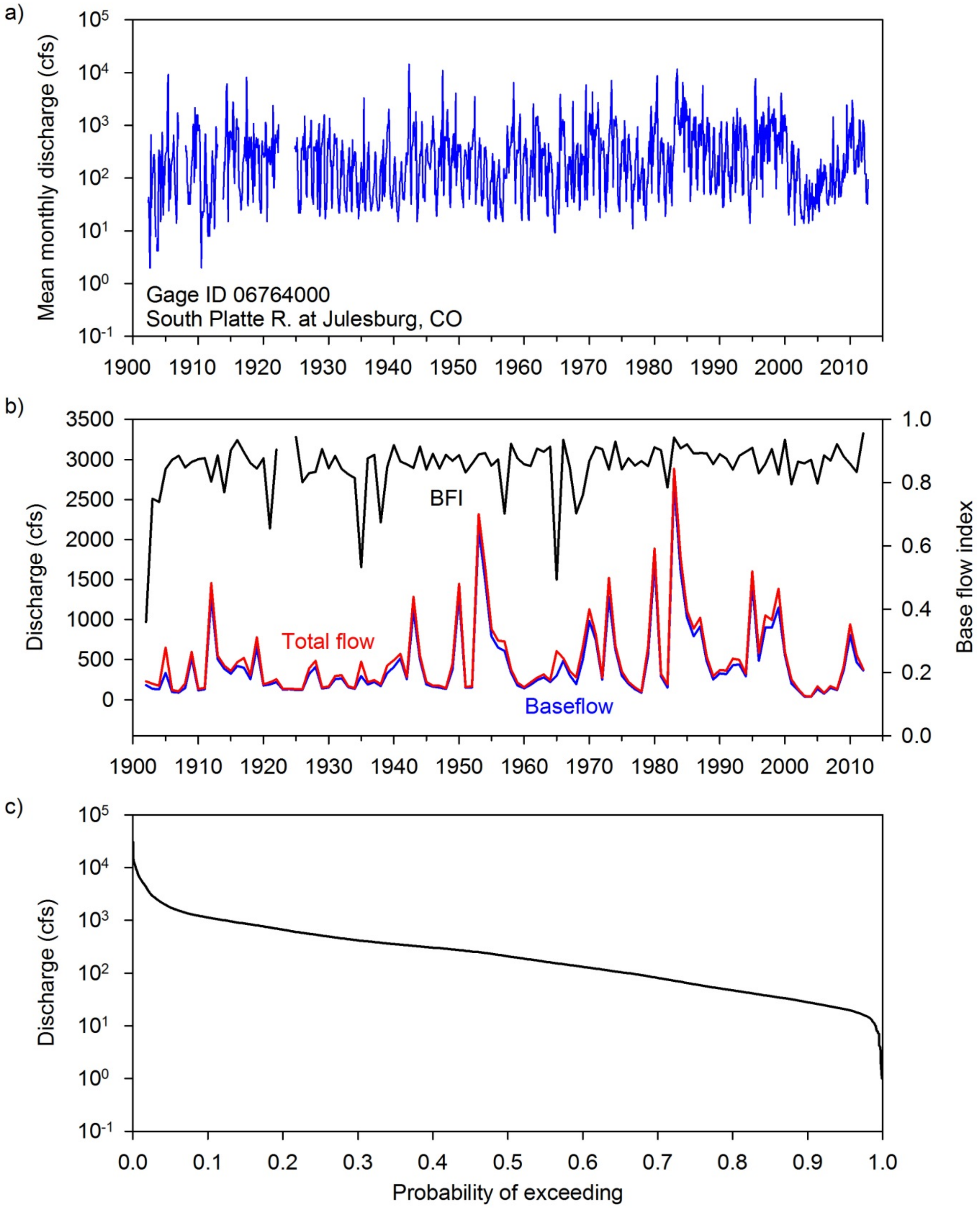


Figure S4-13. a) Streamflow hydrograph, b) flow separation and BFI, and c) flow duration curves for USGS Gage ID 06764000 period of record.

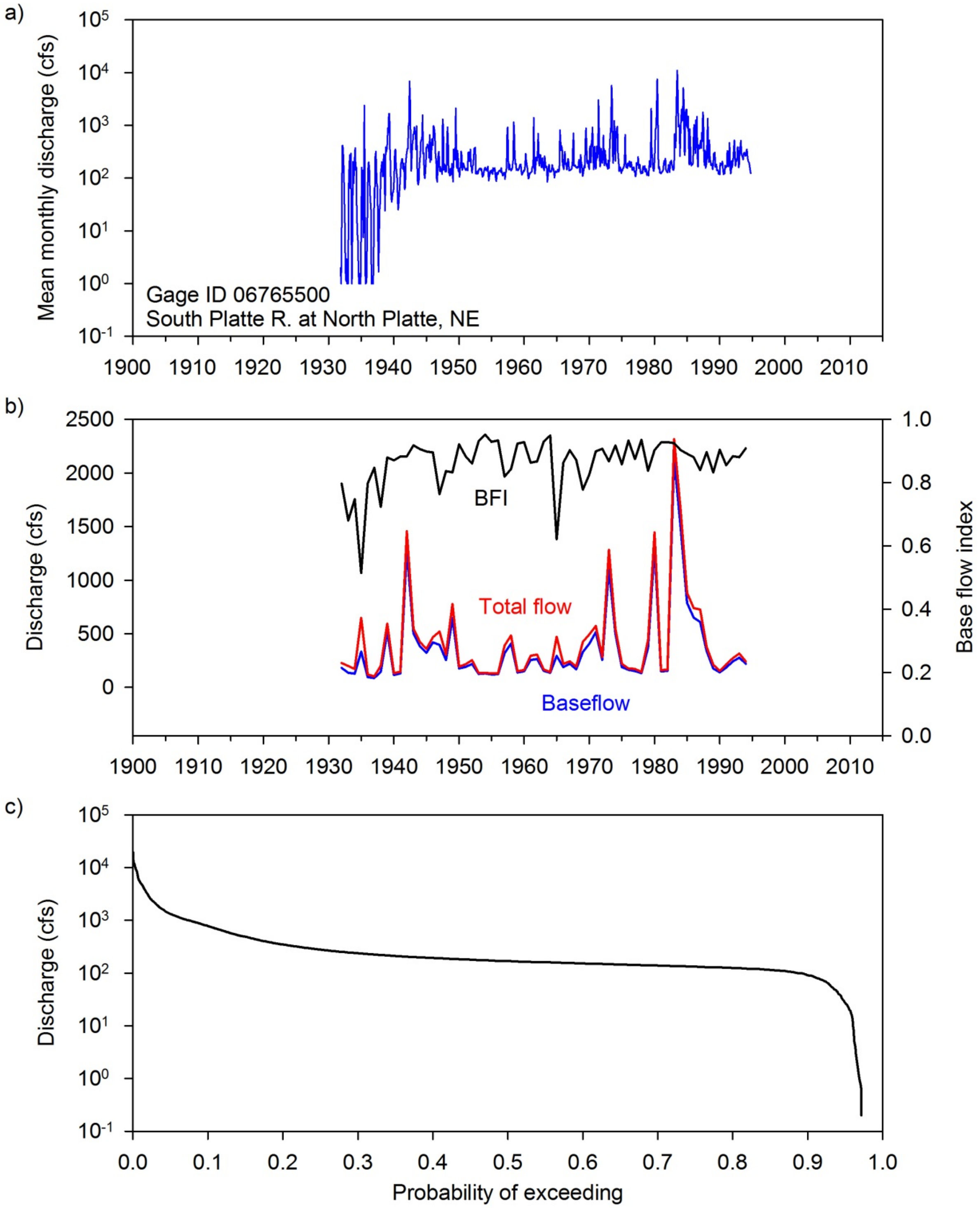


Figure S4-14. a) Streamflow hydrograph, b) flow separation and BFI, and c) flow duration curves for USGS Gage ID 06765500 period of record.

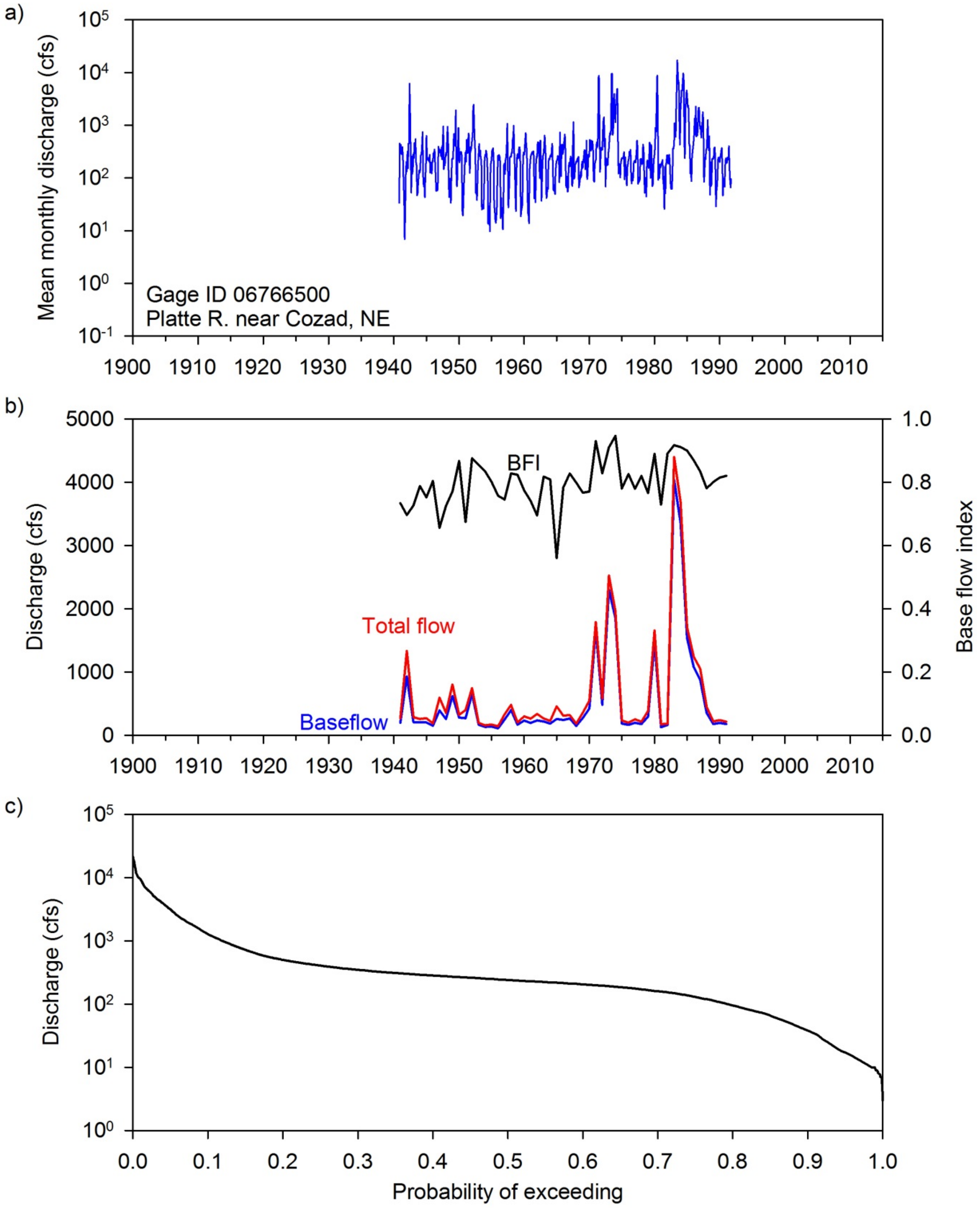


Figure S4-15. a) Streamflow hydrograph, b) flow separation and BFI, and c) flow duration curves for USGS Gage ID 06766500 period of record.

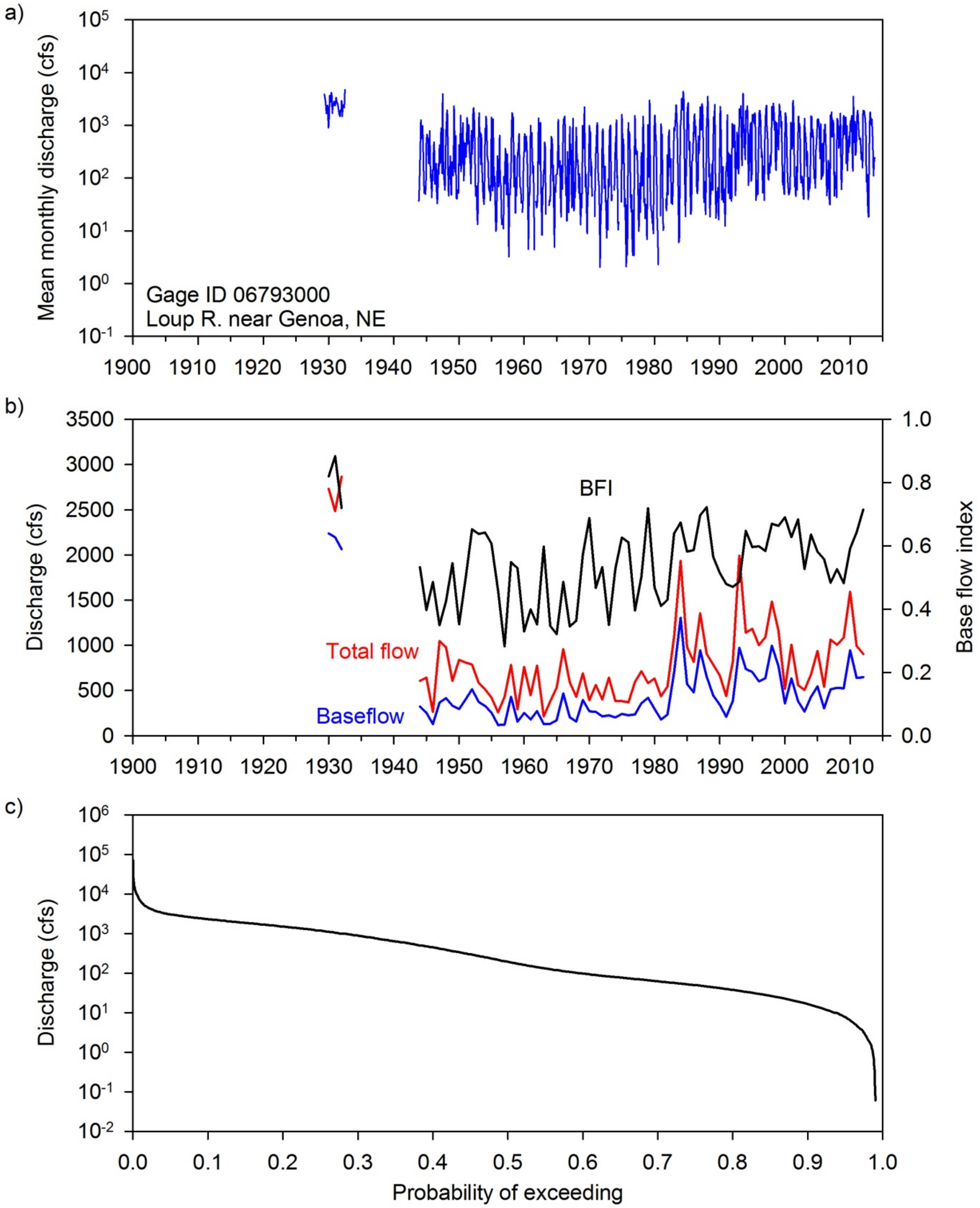


Figure S4-16. a) Streamflow hydrograph, b) flow separation and BFI, and c) flow duration curves for USGS Gage ID 06793000 period of record.

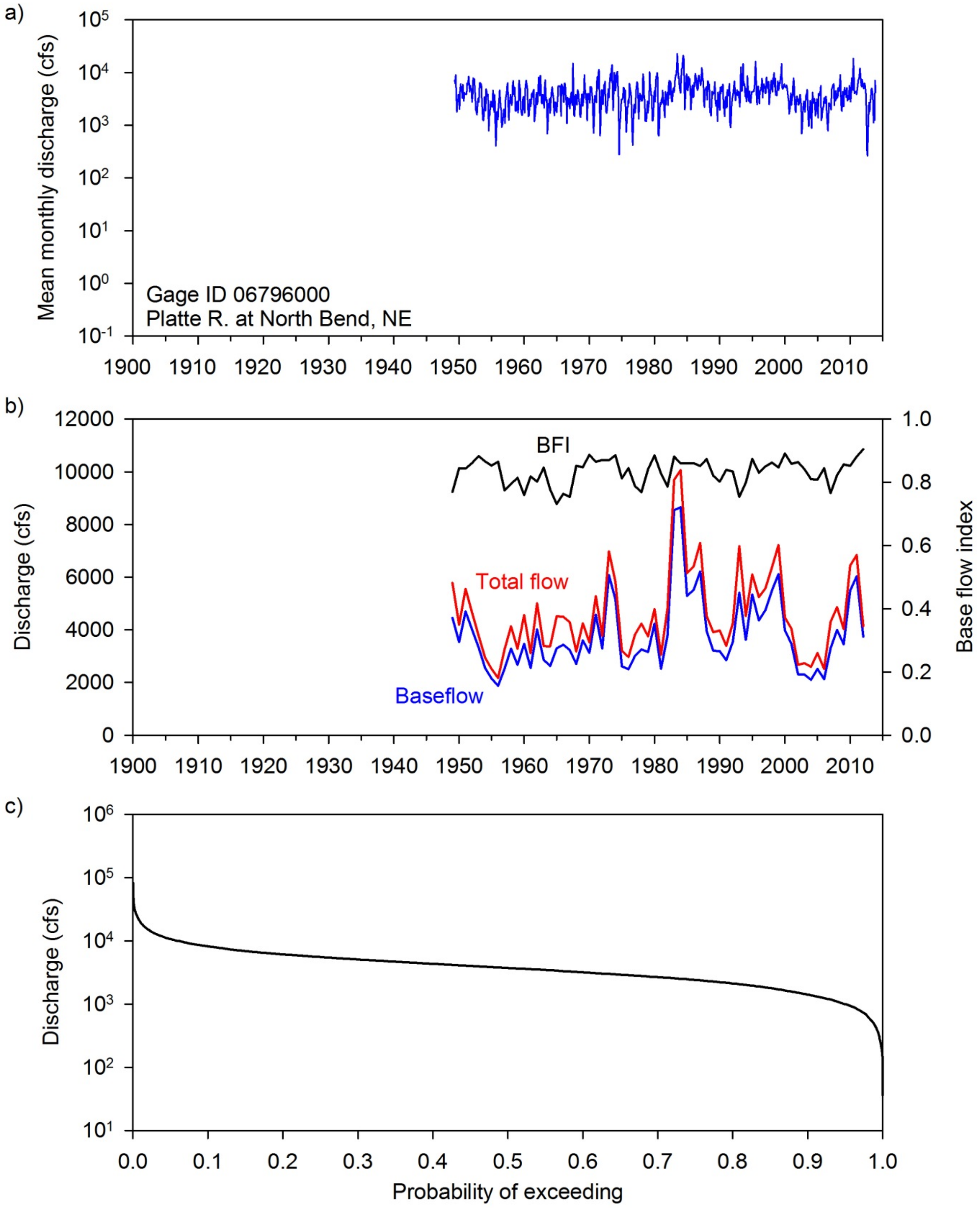


Figure S4-17. a) Streamflow hydrograph, b) flow separation and BFI, and c) flow duration curves for USGS Gage ID 06796000 period of record.

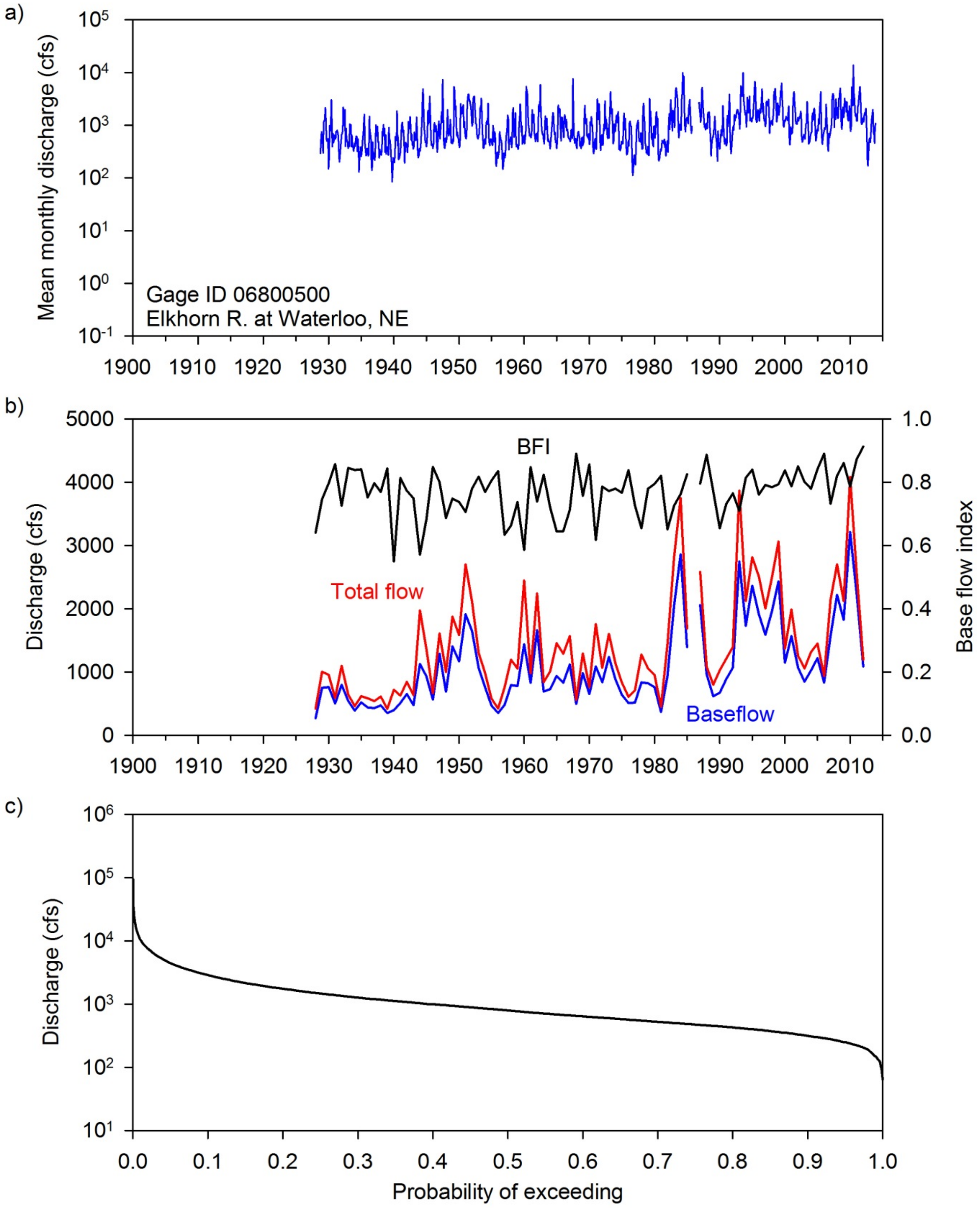


Figure S4-18. a) Streamflow hydrograph, b) flow separation and BFI, and c) flow duration curves for USGS Gage ID 06800500 period of record.

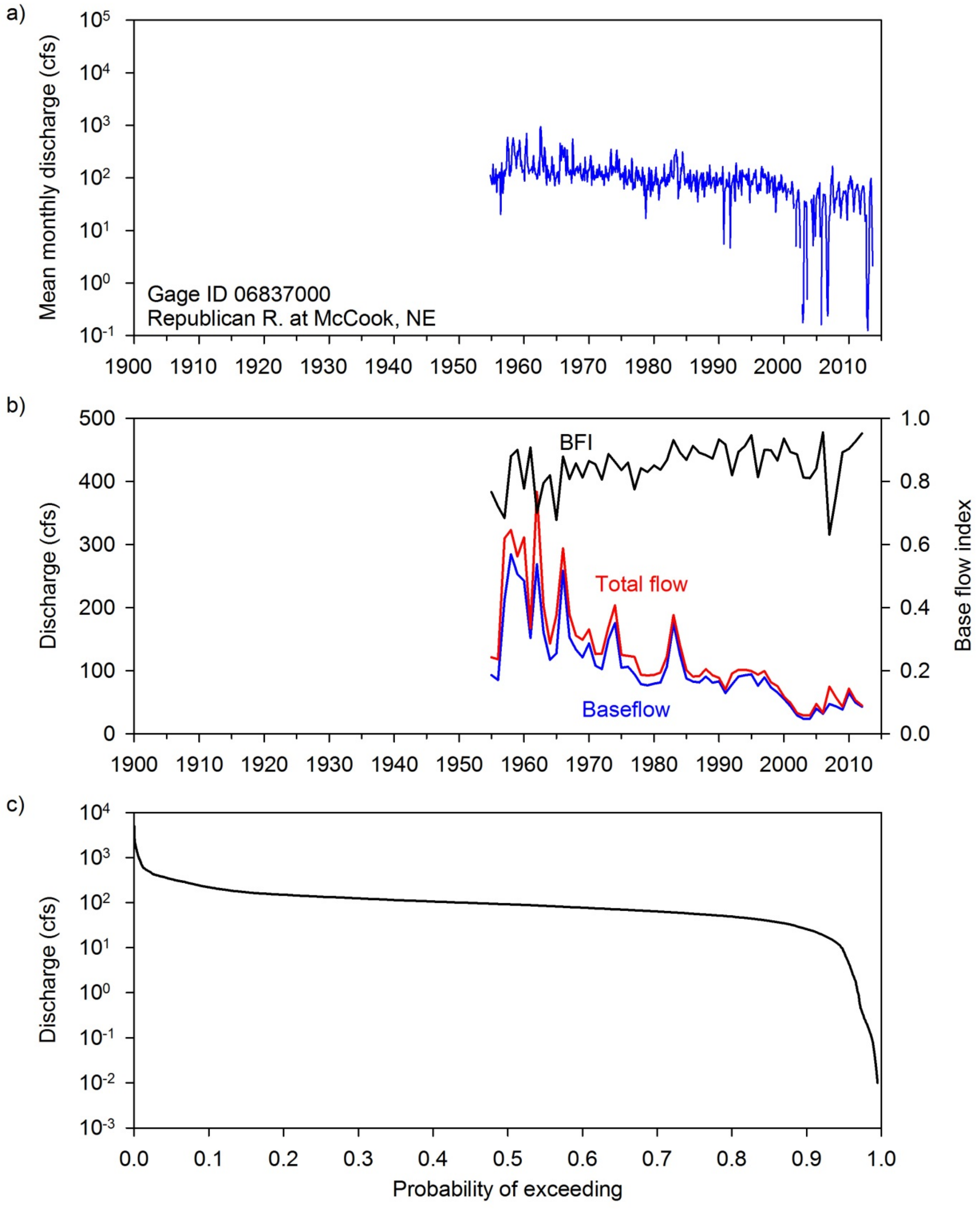


Figure S4-19. a) Streamflow hydrograph, b) flow separation and BFI, and c) flow duration curves for USGS Gage ID 06837000 period of record.

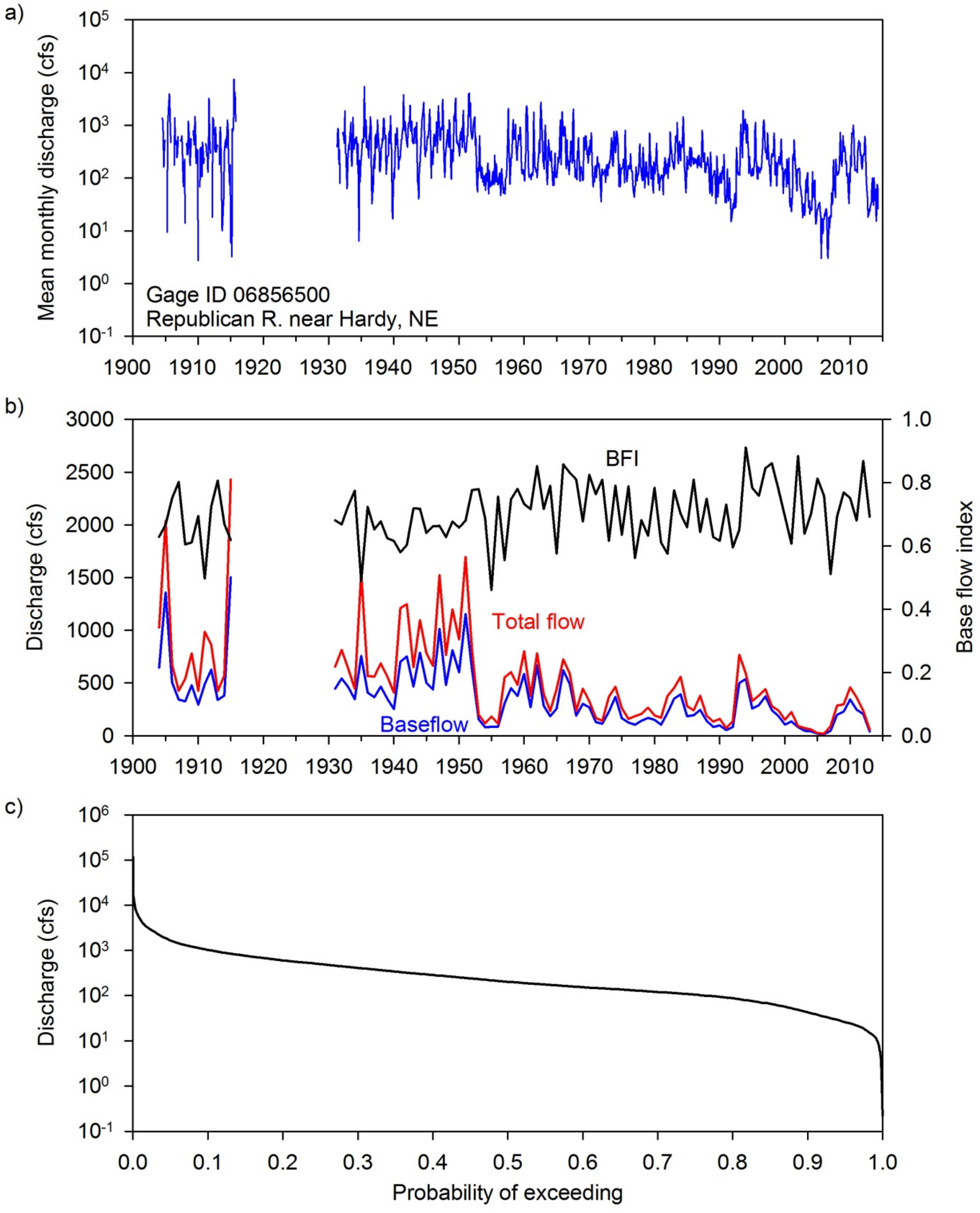


Figure S4-20. a) Streamflow hydrograph, b) flow separation and BFI, and c) flow duration curves for USGS Gage ID 06856500 period of record.

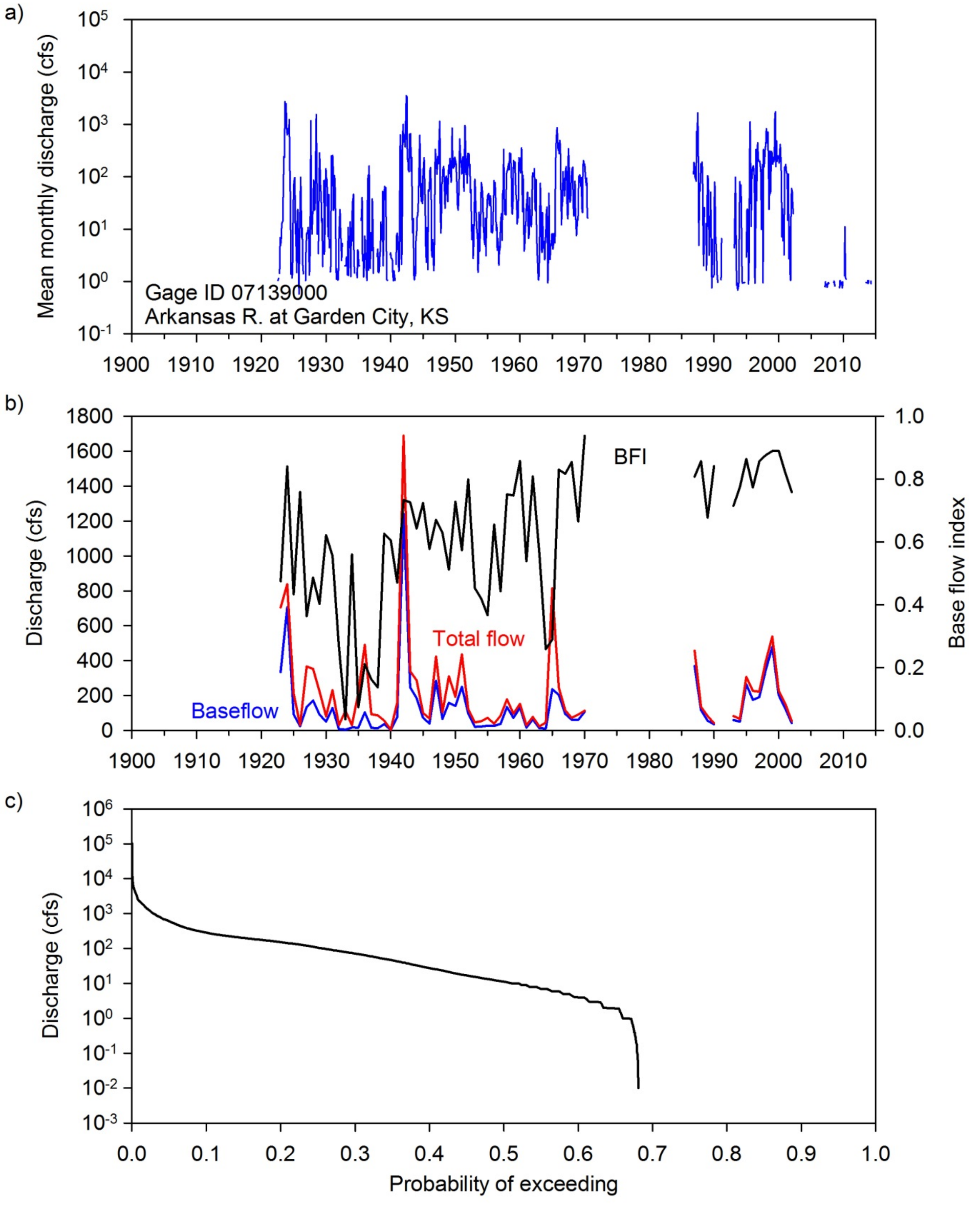


Figure S4-21. a) Streamflow hydrograph, b) flow separation and BFI, and c) flow duration curves for USGS Gage ID 07139000 period of record.

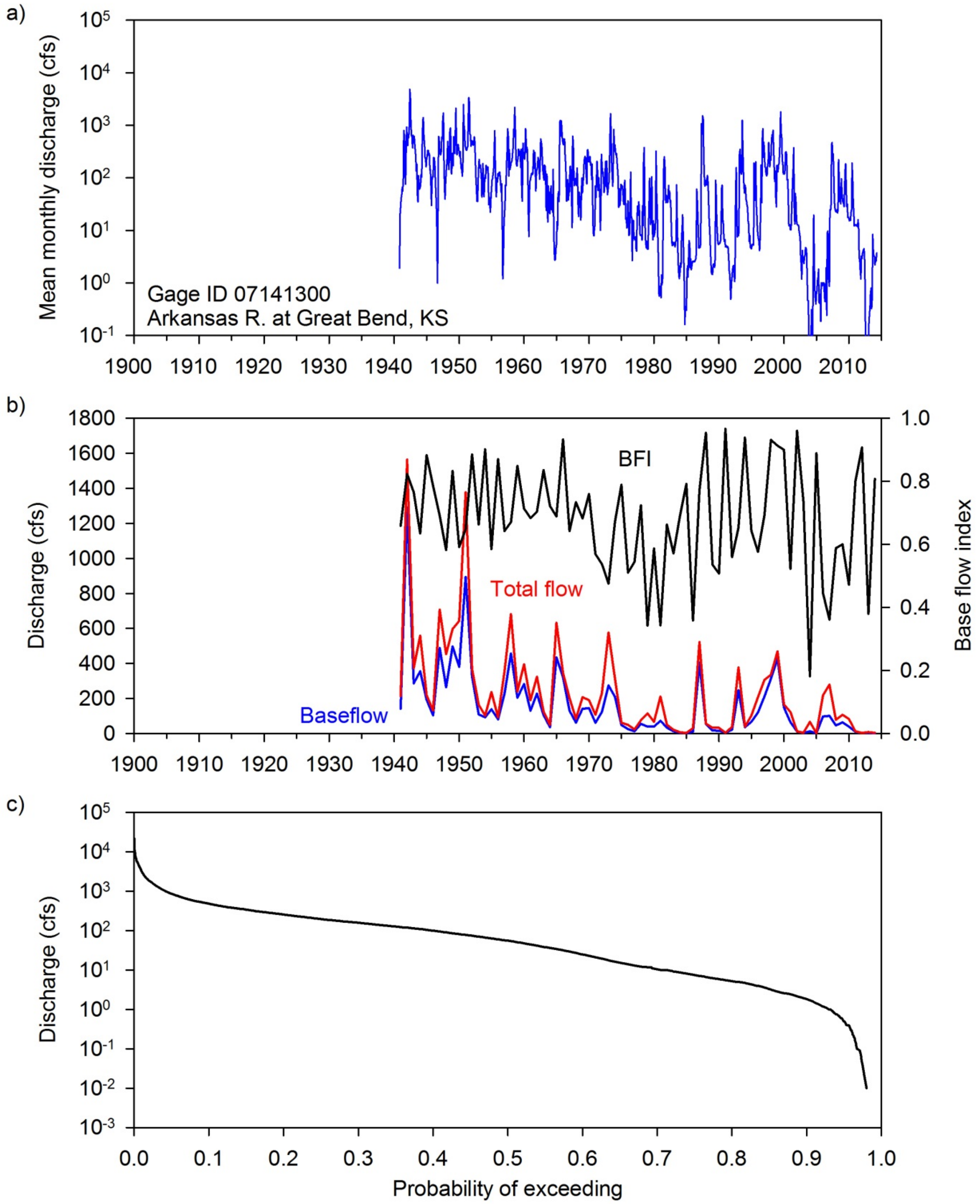


Figure S4-22. a) Streamflow hydrograph, b) flow separation and BFI, and c) flow duration curves for USGS Gage ID 07141300 period of record.

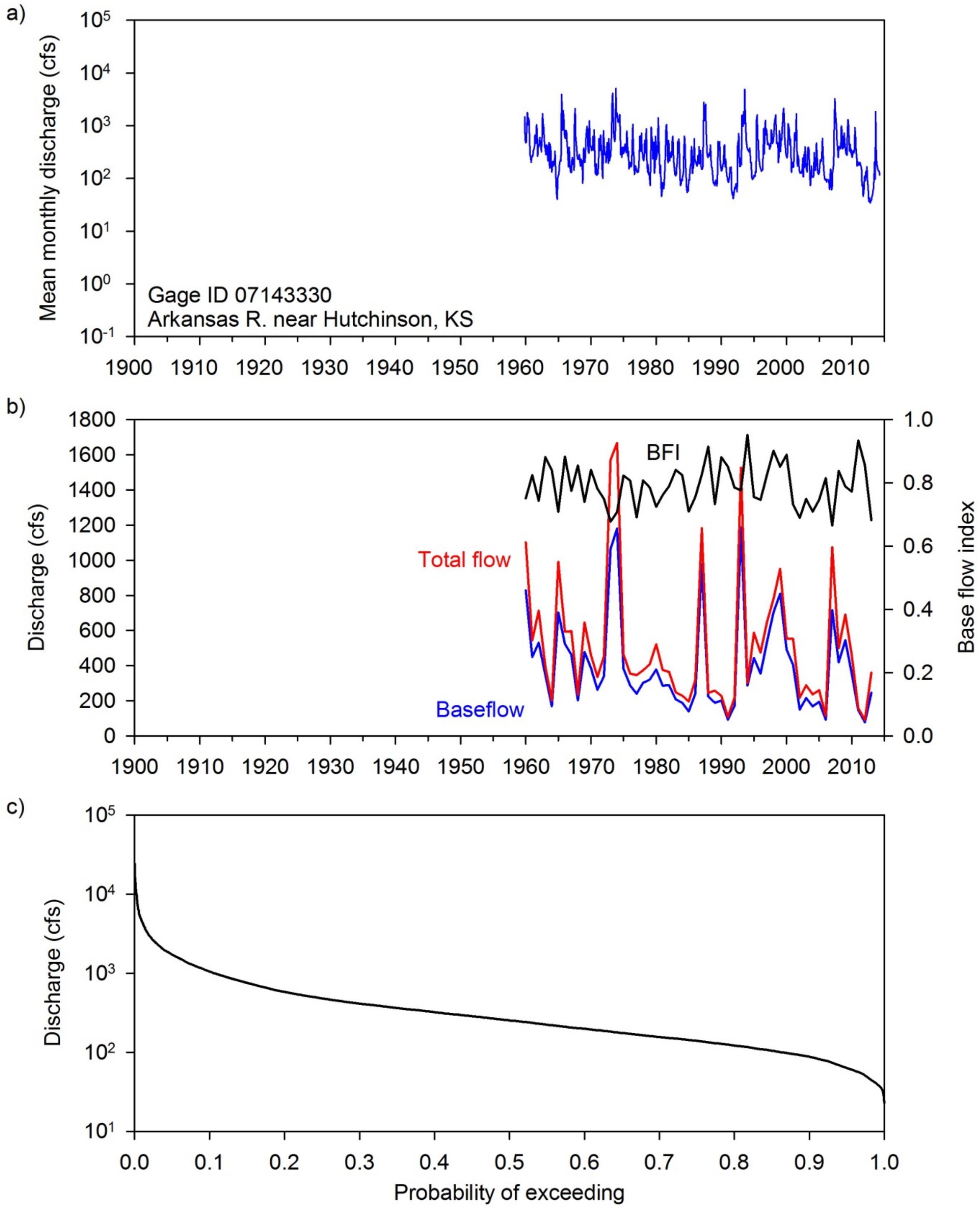


Figure S4-23. a) Streamflow hydrograph, b) flow separation and BFI, and c) flow duration curves for USGS Gage ID 07143330 period of record.

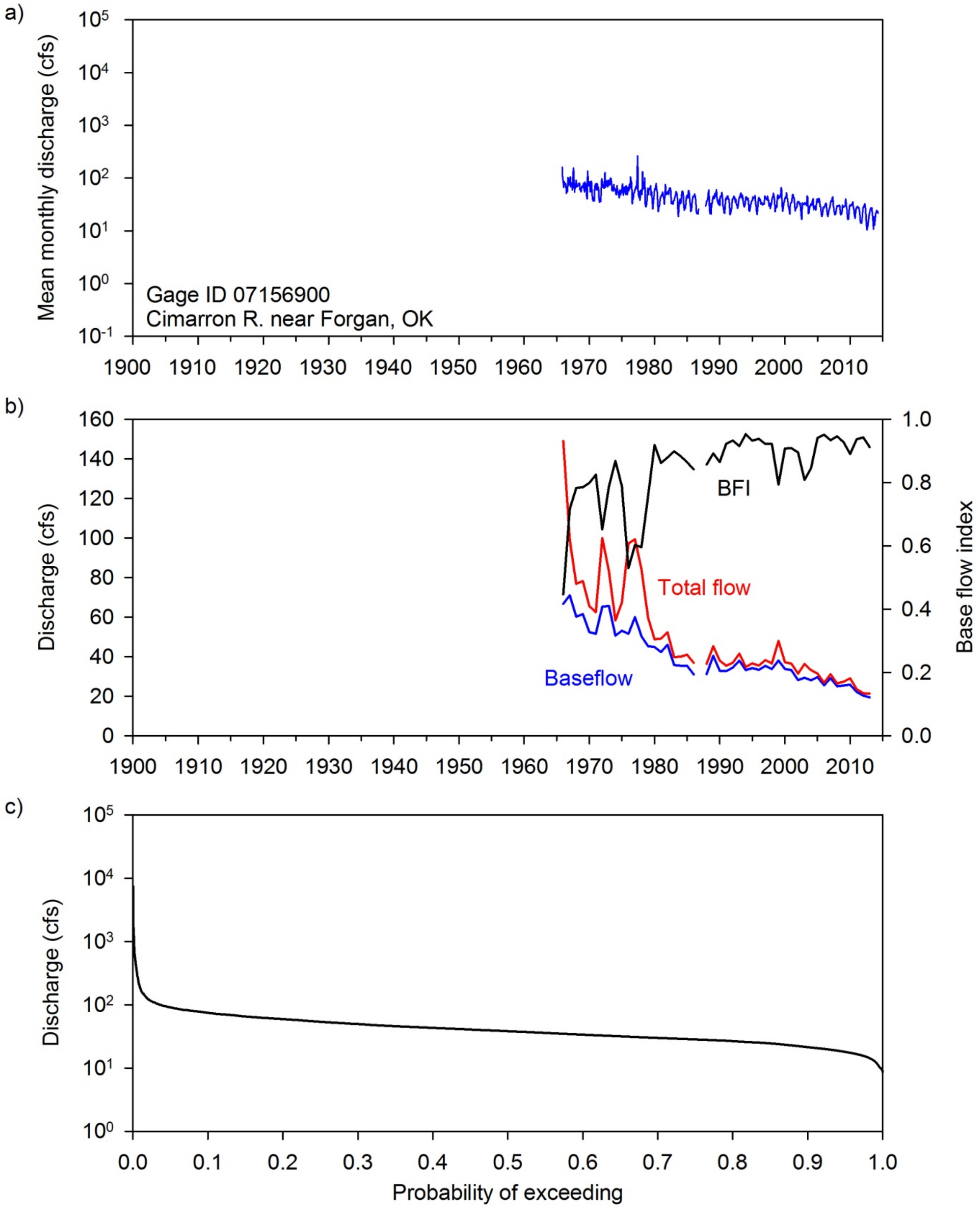


Figure S4-24. a) Streamflow hydrograph, b) flow separation and BFI, and c) flow duration curves for USGS Gage ID 07156900 period of record.

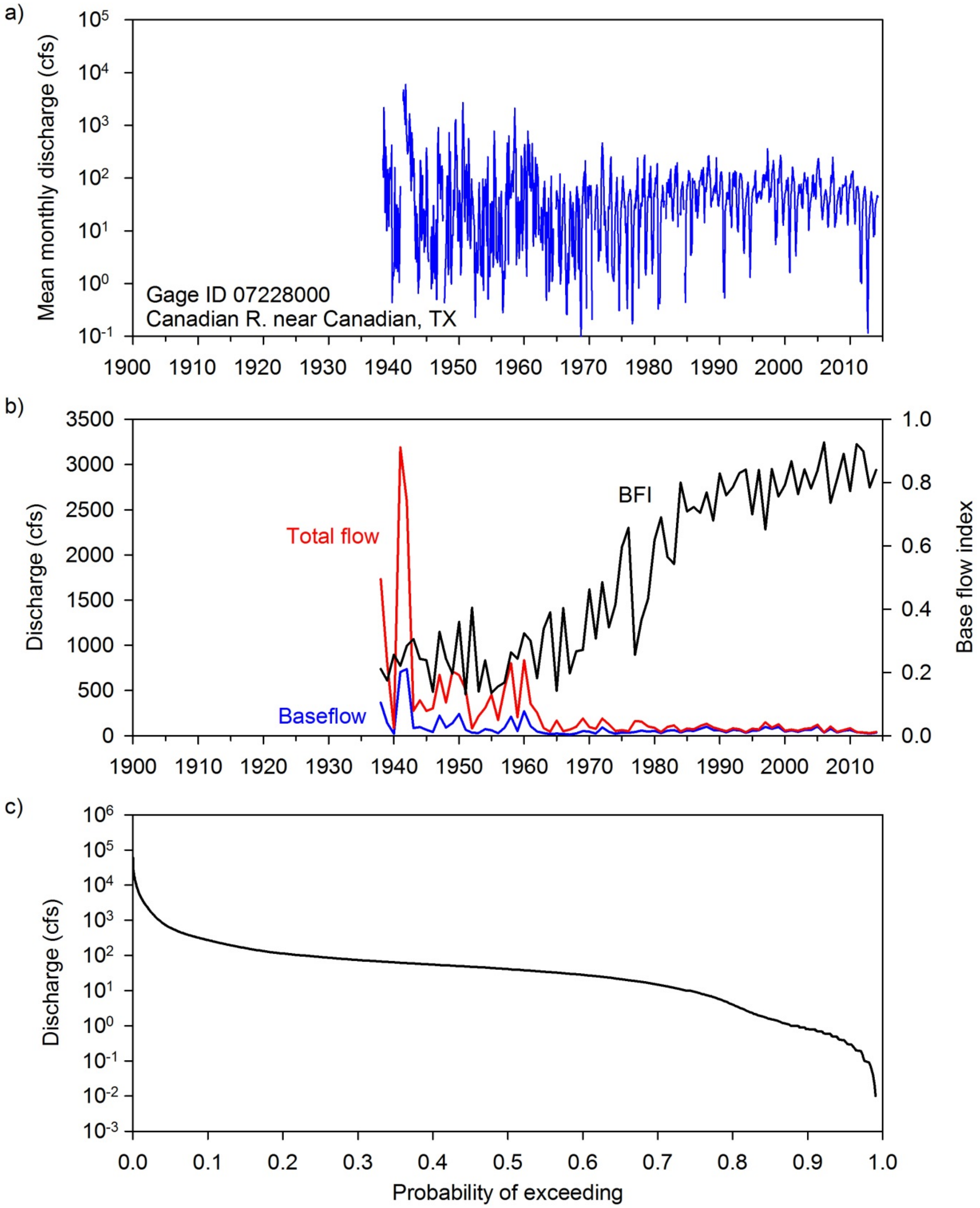


Figure S4-25. a) Streamflow hydrograph, b) flow separation and BFI, and c) flow duration curves for USGS Gage ID 07228000 period of record.

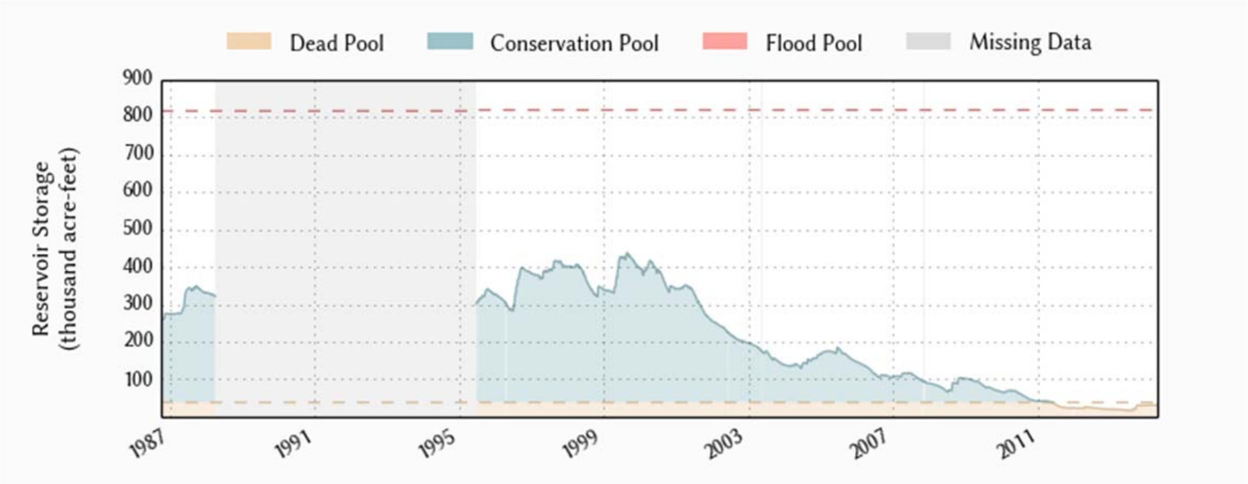


Figure S4-26. Reservoir storage in Lake Meredith (http://www.waterdatafortexas.org/reservoirs/individual/meredith).

Supporting Information Task 6

Task 6a. *Examine the water budgets of reservoirs in Bureau of Reclamation programs in the High Plains, and relate the water balance to climate forcing and groundwater depletion.*

Water budgets for major reservoirs were evaluated over the period of record. Data from nine reservoirs in Nebraska and one reservoir in each of Colorado and Kansas (Figure S6-1) were examined, including inflows and outflows and reservoir evaporation (Figures S6-2 through S6-12). Reservoir storage changes were calculated from inflows – outflows and compared with reservoir capacity to estimate percent full. The ratio of inflows to outflows is also plotted. Two reservoirs are located on the Niobrara River, Box Butte and Merrit. The Box Butte reservoir has variable storage, generally low in the 2000s and high towards 2010. Merrit Dam impounds the Snake River and seems to be a constant level reservoir at ~ 100% of capacity much of the time.

Reservoirs in the Loup River drainage area include Calamus and Davis Creek, located within or adjacent to the Sand Hills. Storage in Calamus Reservoir ranges from ~ 20 – 60% of capacity and is generally low towards 2010 and 2011. The Davis Creek reservoir had low storage in the 2000s.

The remaining seven monitored reservoirs are located in the Republican River drainage area, and from generally upstream to downstream include Bonny, Swanson, Enders, Hugh Butler, Harry Strunk, Keith Sibelius, and Harlan County reservoirs. These reservoirs generally function as flood control and most also provide water for irrigation. Storage had been decreasing in Bonny Reservoir since the early 1990s and was completely drained in 2011 resulting from a US Supreme Court decision related to Republican River Compact agreements. Storage in Enders reservoir has been declining since the late 1960s and 1970s with storage declining from 40% to 10% of capacity. Reductions in storage are attributed to water table declines in this region. Harry Strunk and Hugh Butler reservoirs are also characterized by variable storage. Keith Sibelius reservoir was low in the 1970s and 1980s, ~ 10 – 20% of capacity but has been higher and more variable recently.

The dominant control on reservoir storage is most likely water table declines in the Republican basin. Variations in other reservoirs may reflect variations in management. It is difficult to understand controls on these systems based on this type of reconnaissance evaluation.

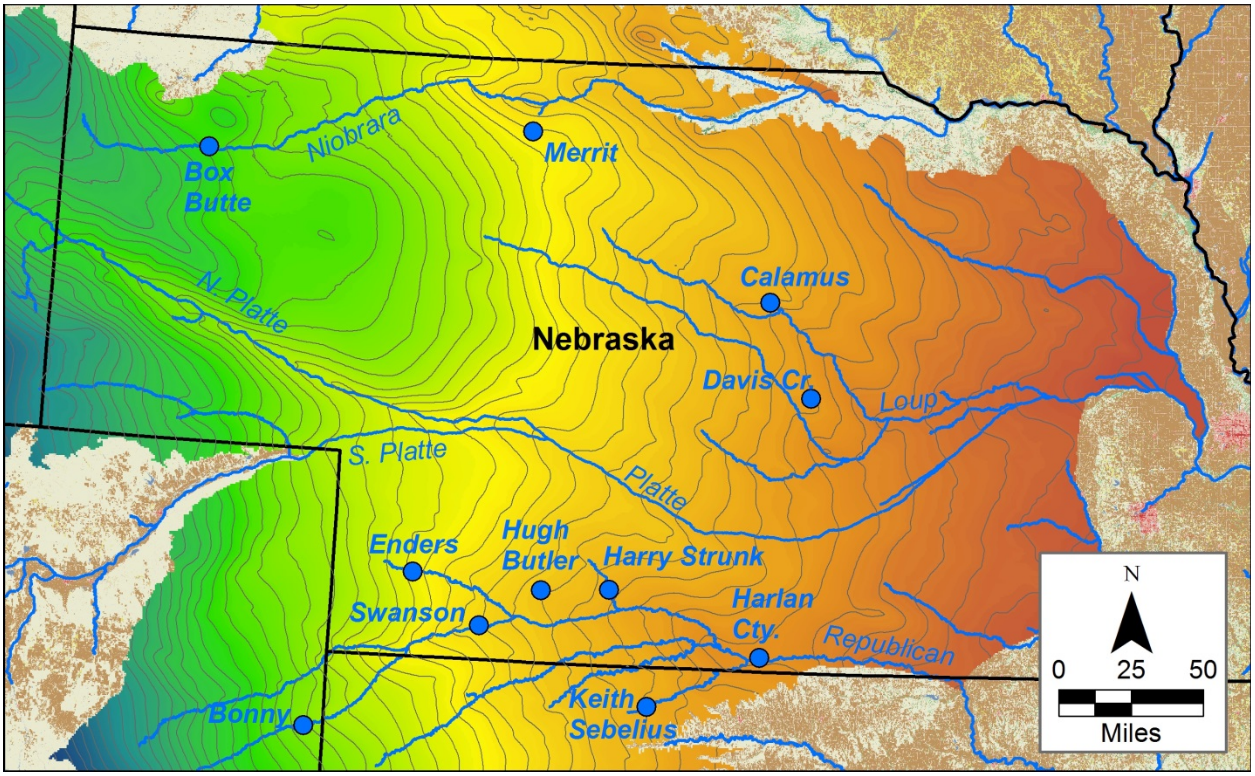


Figure S6-1. Locations of monitored US Bureau of Reclamation reservoirs in the US High Plains. Groundwater elevation contours and shaded surface elevation map shown for reference.

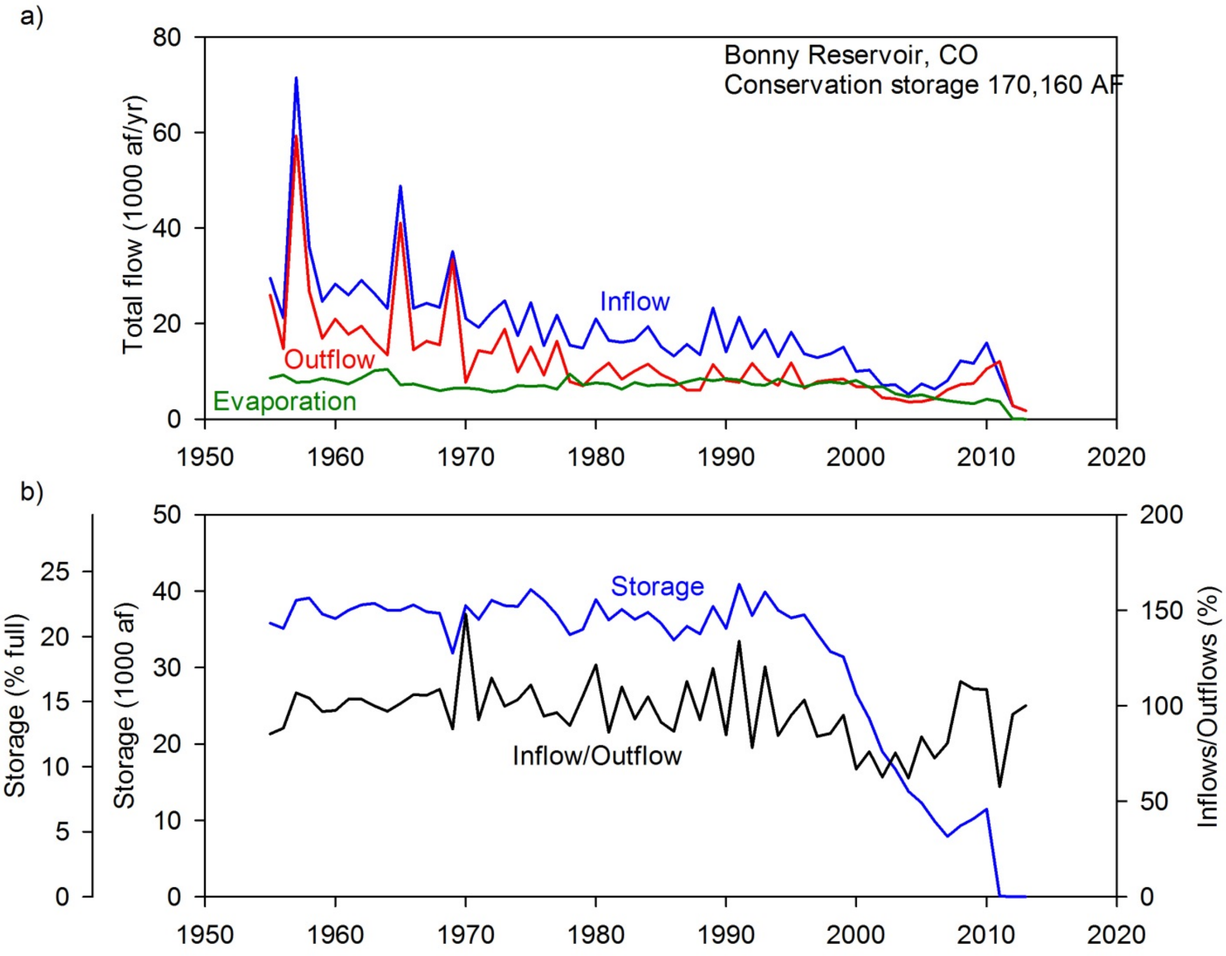


Figure S6-2. a) Annual total inflow, outflow, and evaporation volumes and b) total storage volume and the inflow/outflow ratio for Bonny Reservoir, Colorado.

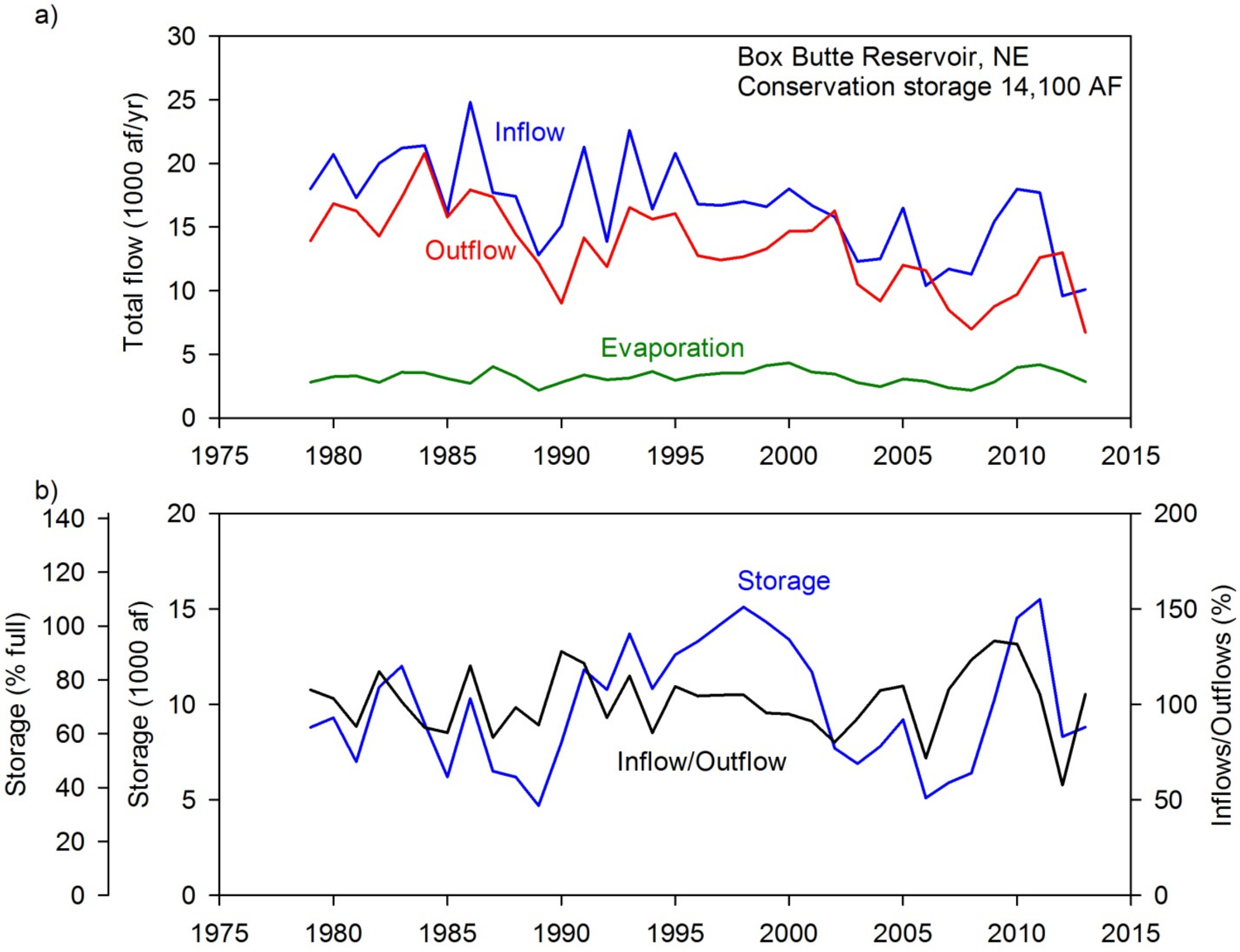


Figure S6-3. a) Annual total inflow, outflow, and evaporation volumes and b) total storage volume and the inflow/outflow ratio for Box Butte Reservoir, NE.

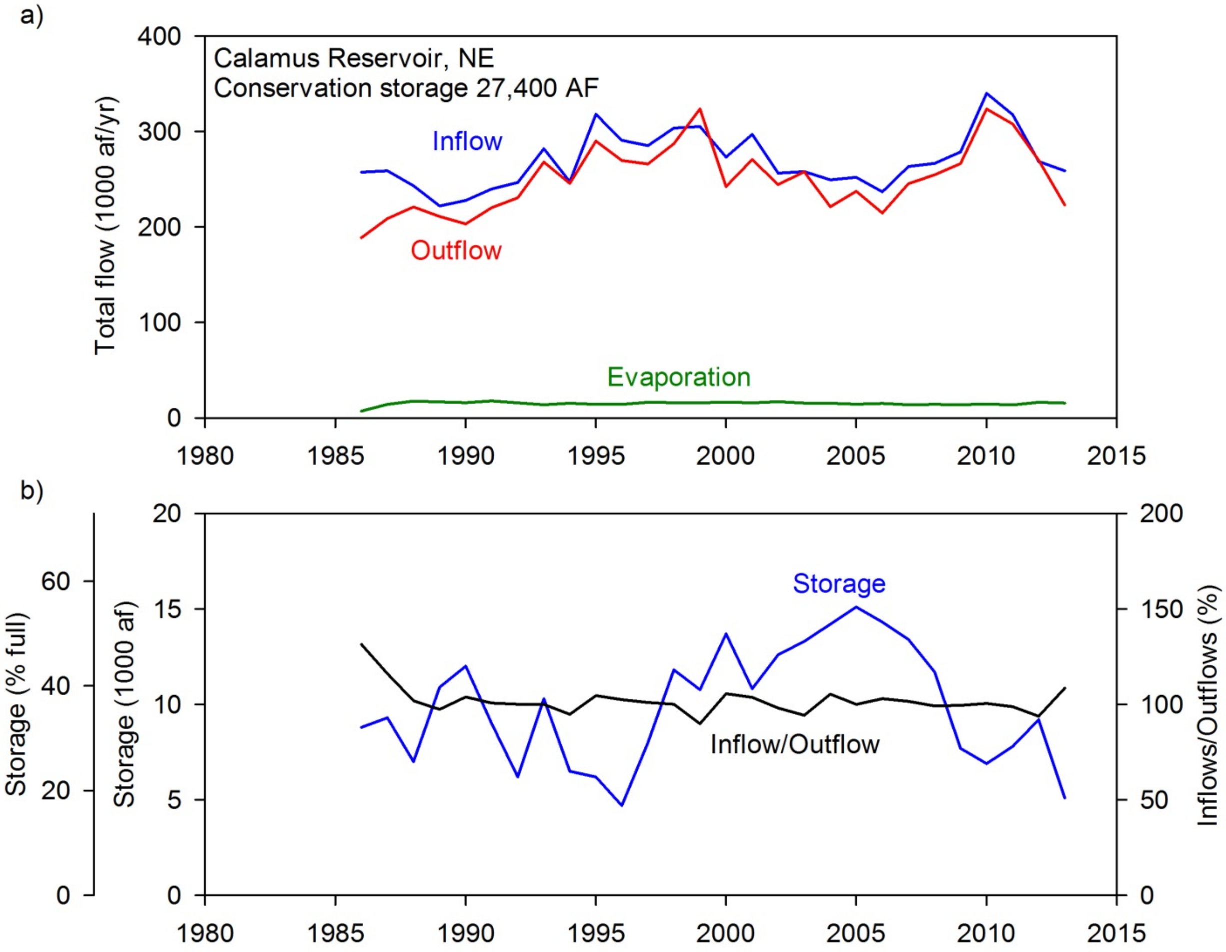


Figure S6-4. a) Annual total inflow, outflow, and evaporation volumes and b) total storage volume and the inflow/outflow ratio for Calamus Reservoir, NE.

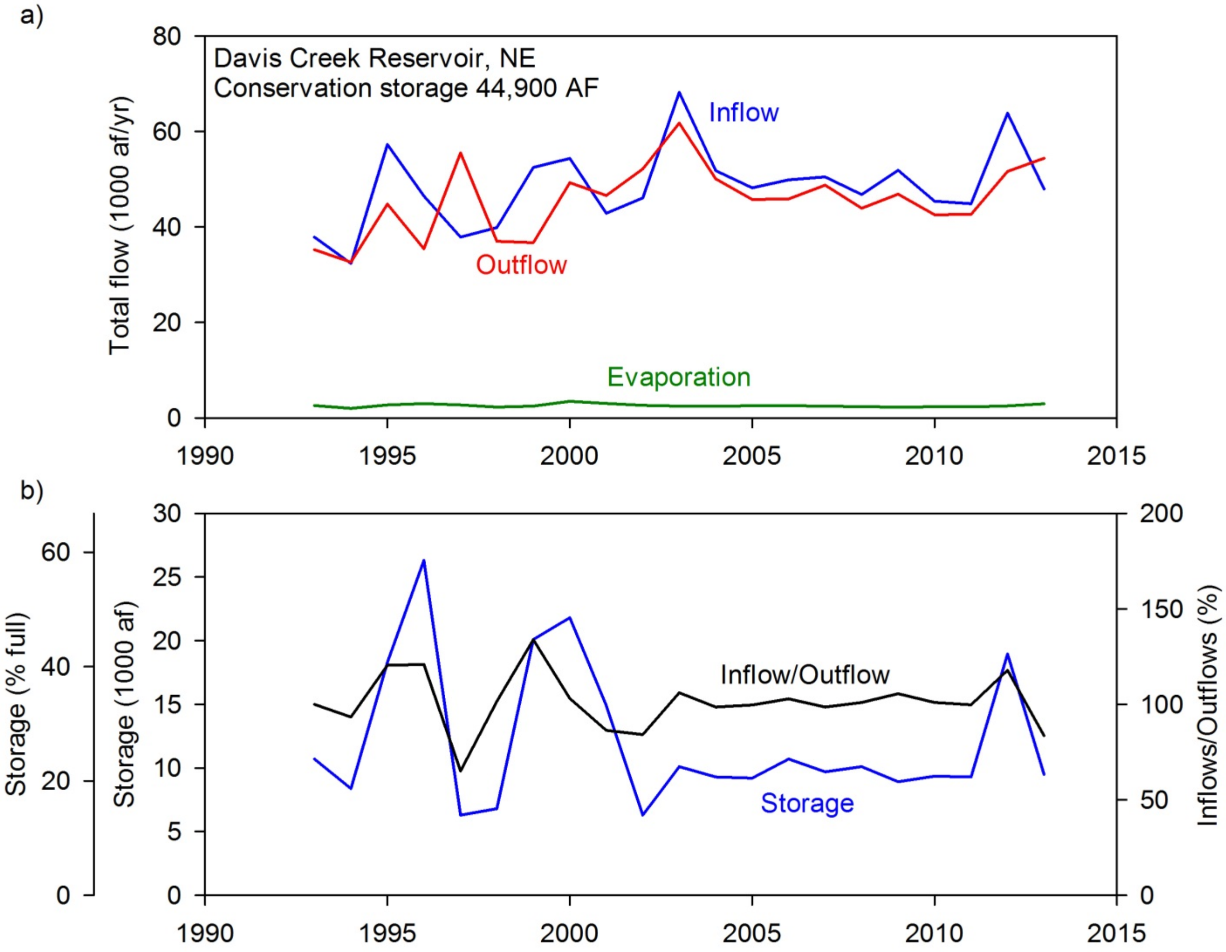


Figure S6-5. a) Annual total inflow, outflow, and evaporation volumes and b) total storage volume and the inflow/outflow ratio for Davis Creek Reservoir, NE.

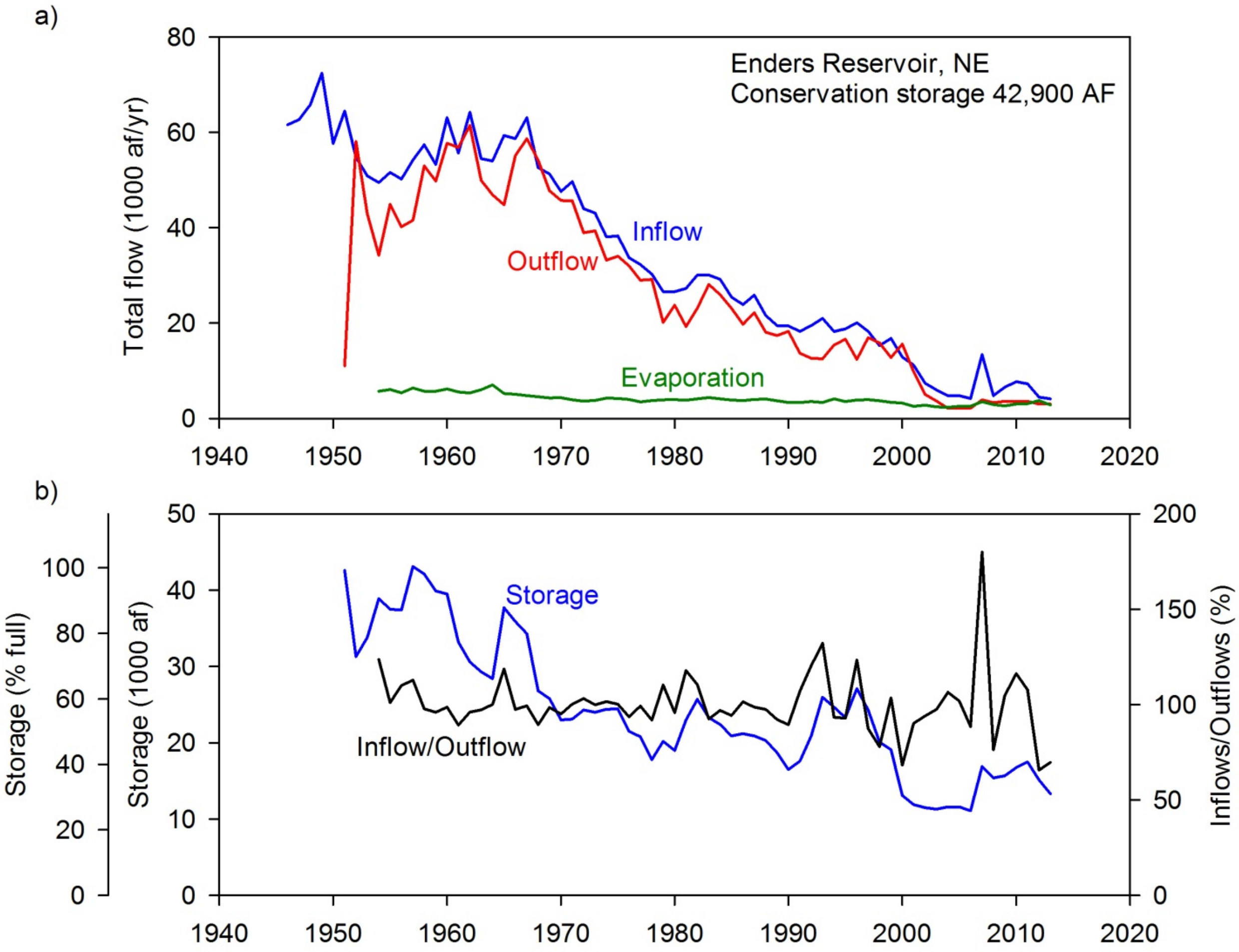


Figure S6-6. a) Annual total inflow, outflow, and evaporation volumes and b) total storage volume and the inflow/outflow ratio for Enders Reservoir, NE.

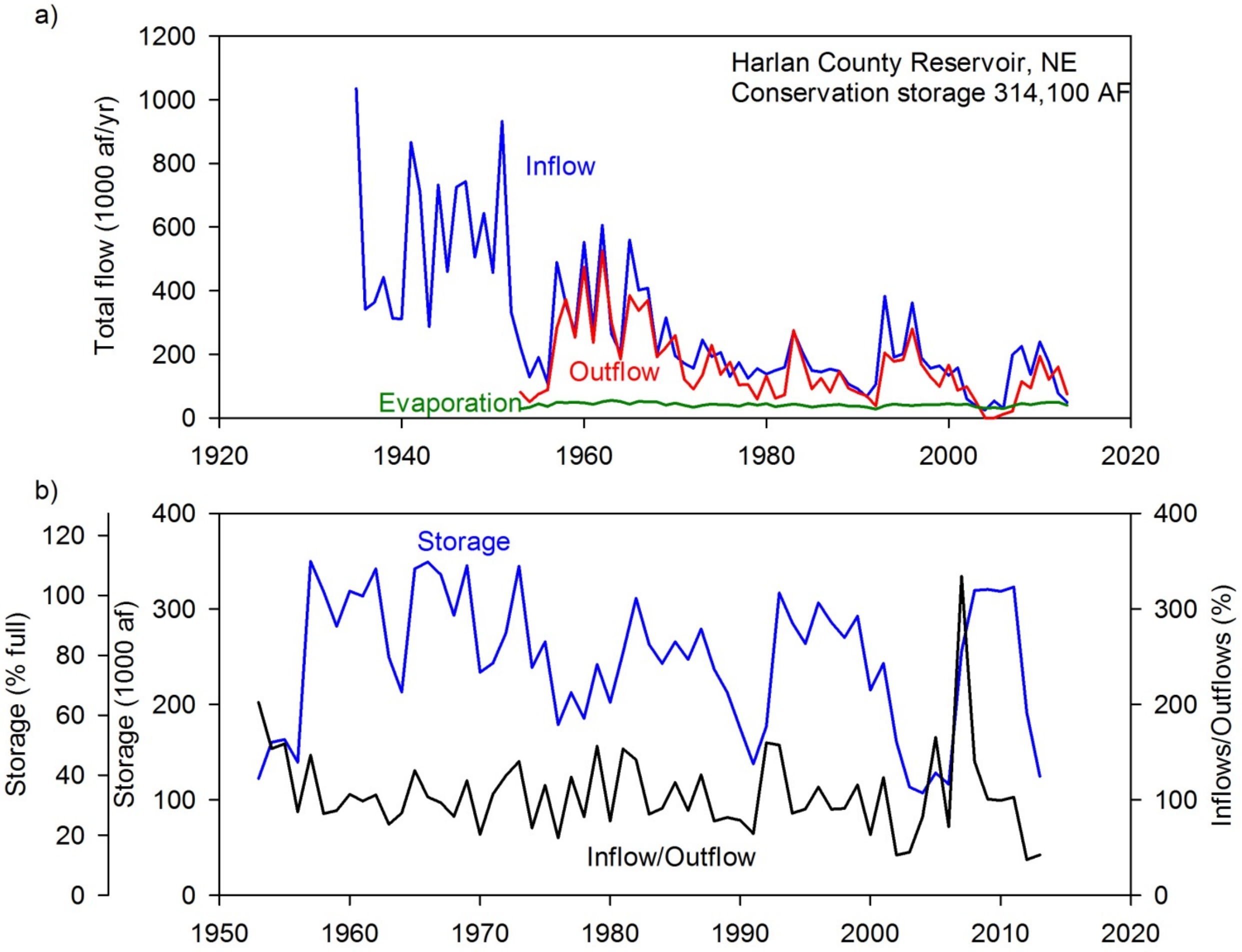


Figure S6-7. a) Annual total inflow, outflow, and evaporation volumes and b) total storage volume and the inflow/outflow ratio for Harlan County Reservoir, NE.

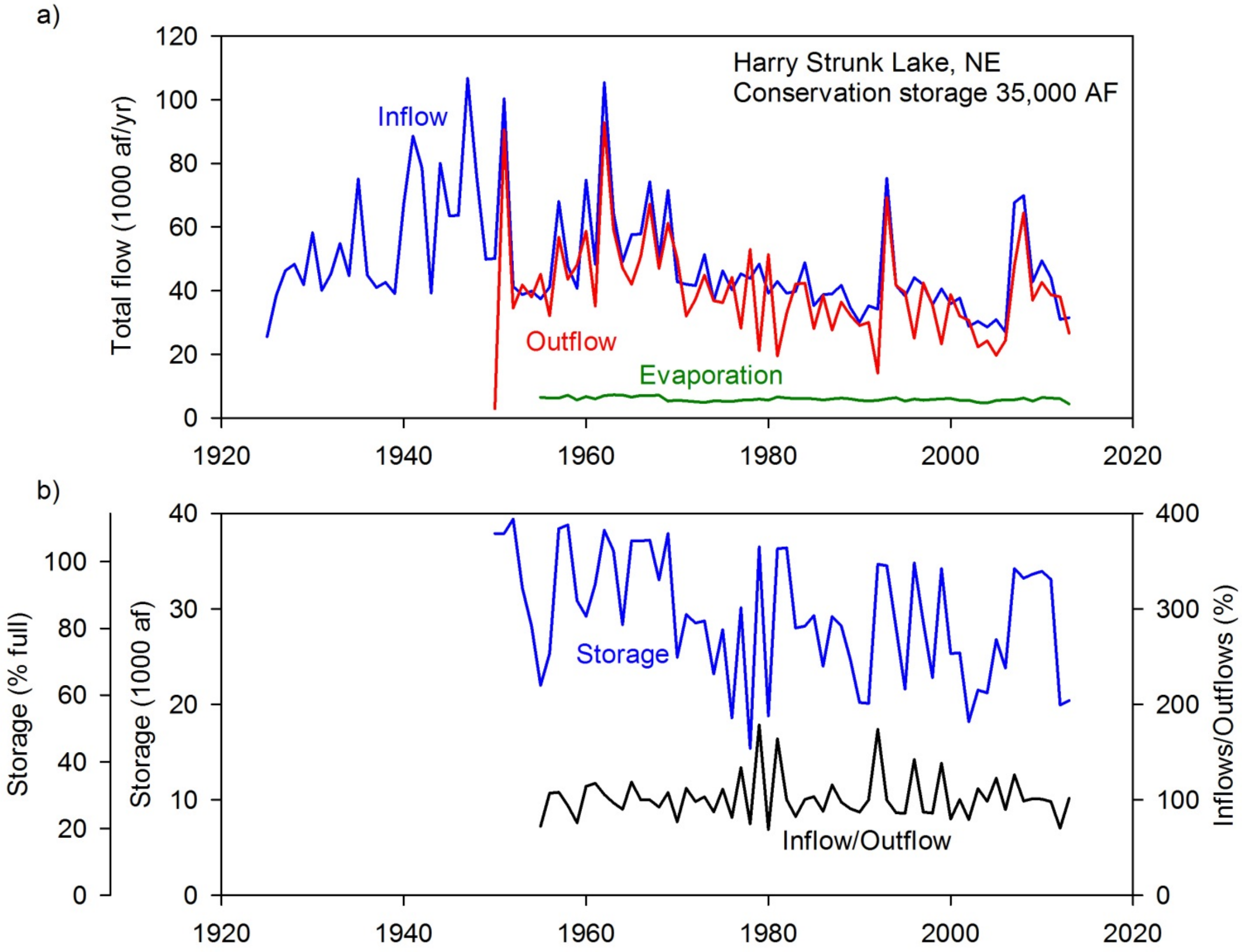


Figure S6-8. a) Annual total inflow, outflow, and evaporation volumes and b) total storage volume and the inflow/outflow ratio for Harry Strunk Lake, NE.

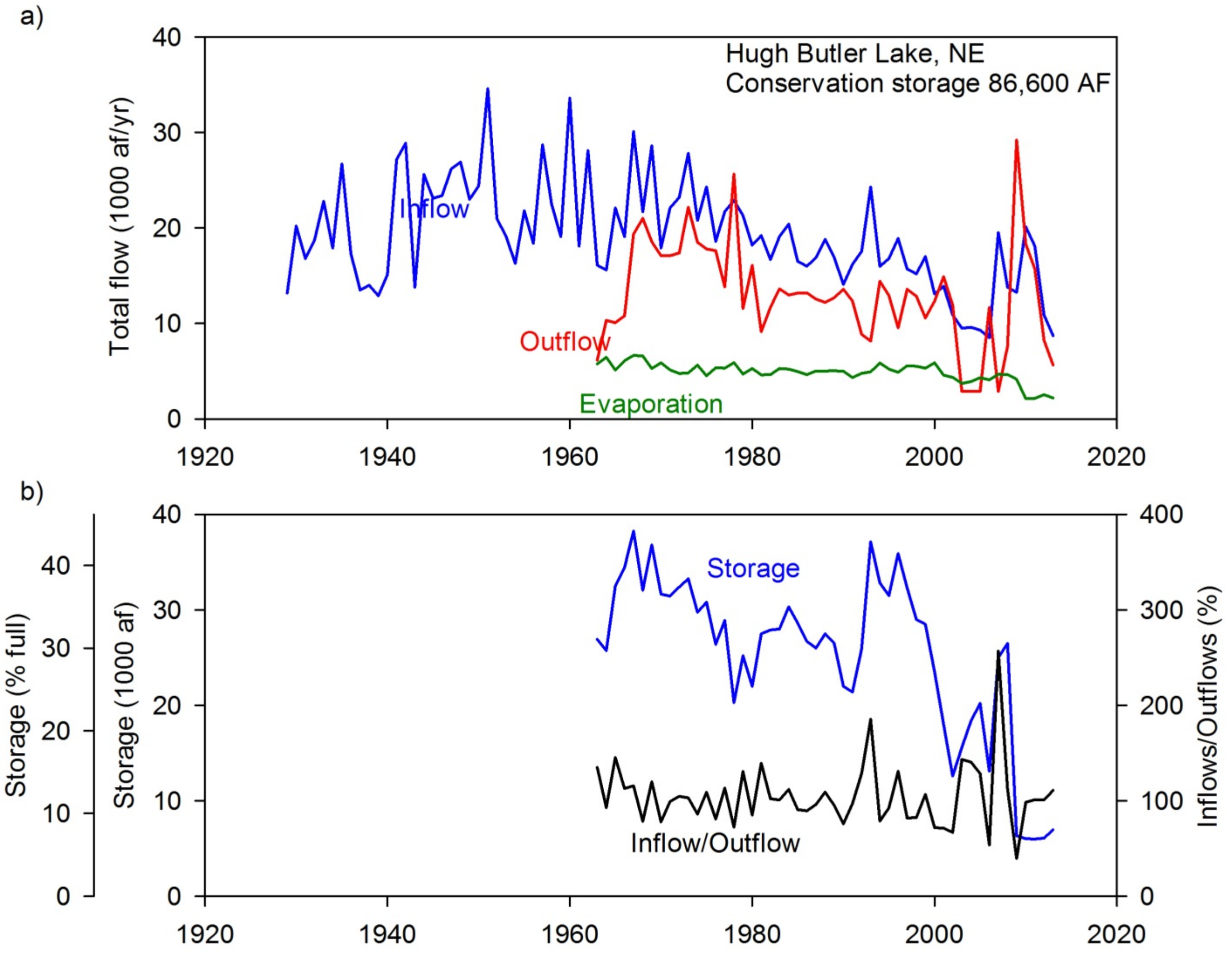


Figure S6-9. a) Annual total inflow, outflow, and evaporation volumes and b) total storage volume and the inflow/outflow ratio for Hugh Butler Lake, NE.

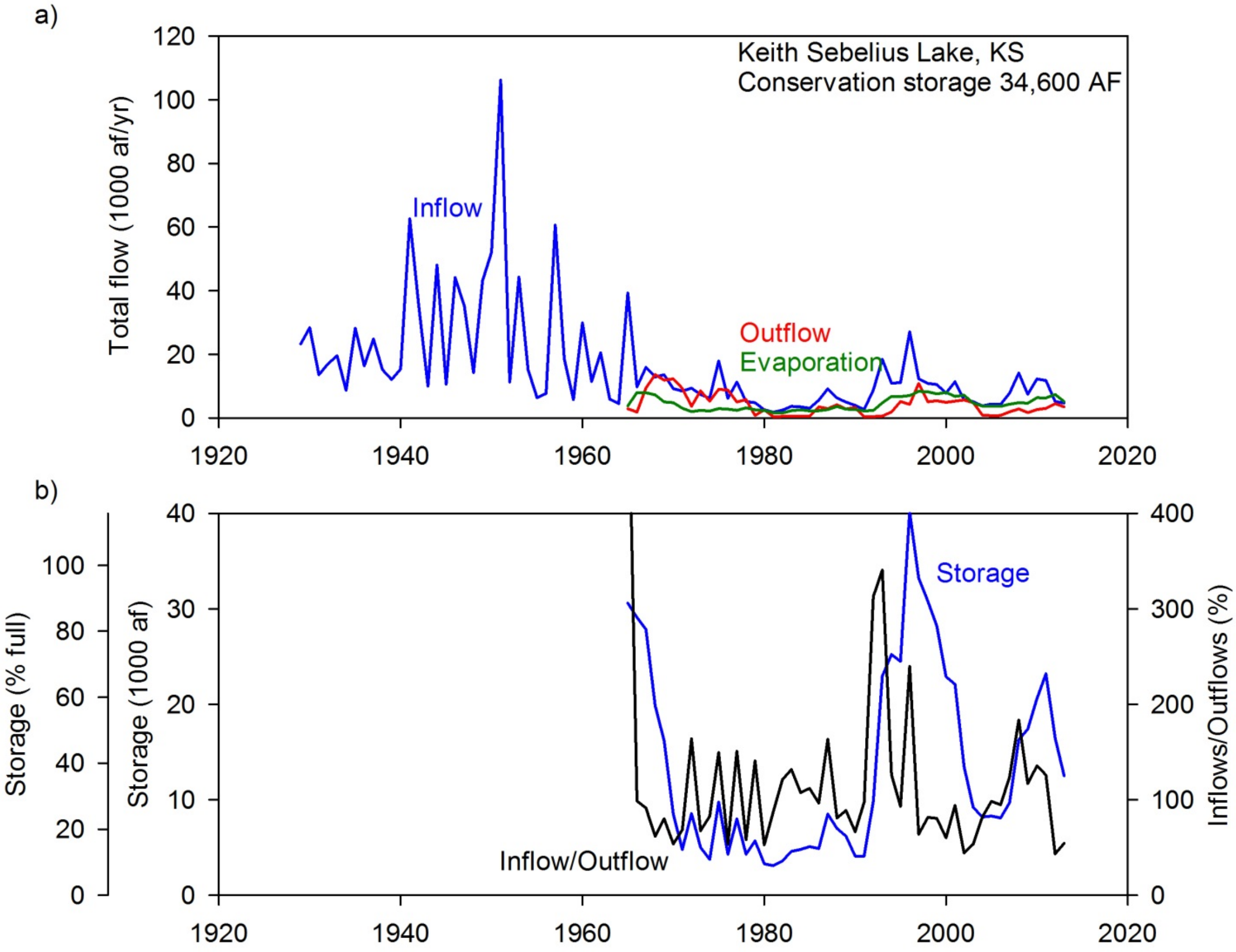


Figure S6-10. a) Annual total inflow, outflow, and evaporation volumes and b) total storage volume and the inflow/outflow ratio for Keith Sebelius Lake, KS.

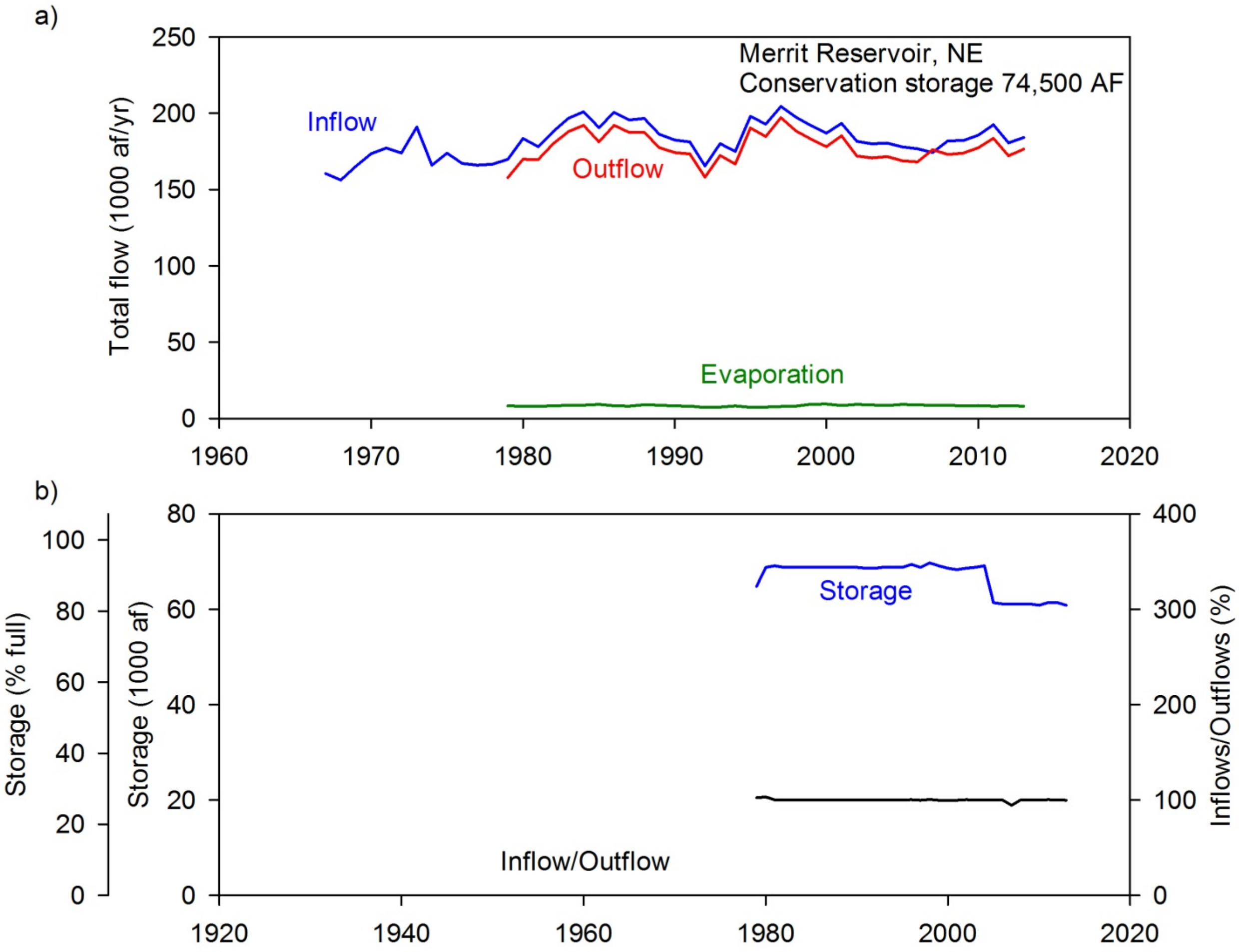


Figure S6-11. a) Annual total inflow, outflow, and evaporation volumes and b) total storage volume and the inflow/outflow ratio for Merrit Reservoir, NE.

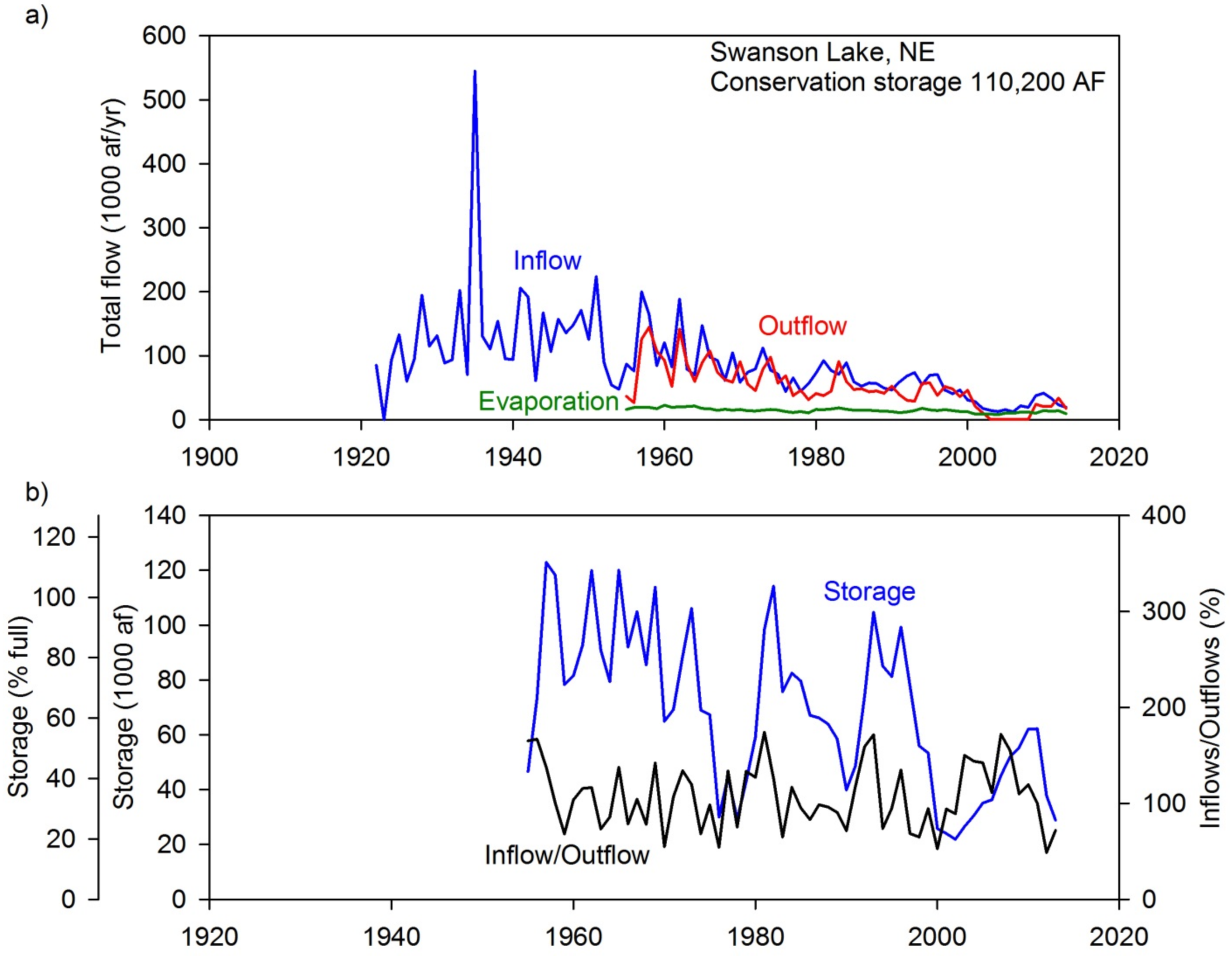


Figure S6-12. a) Annual total inflow, outflow, and evaporation volumes and b) total storage volume and the inflow/outflow ratio for Swanson Lake, NE.