HISTORICAL RAINFALL ANALYSIS AND CLIMATE IMPLICATIONS FOR
AGRICULTURE IN MIDWEST UNITED STATES

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HISTORICAL RAINFALL ANALYSIS AND CLIMATE IMPLICATIONS FOR AGRICULTURE IN MIDWEST UNITED STATES

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ABSTRACT

A historical analysis of precipitation using 72 years of data from Midwest stations focuses on the implications of climate change for agricultural interests. The number of precipitation events, consecutive days of precipitation, and a Fourier transformation on precipitation are included. Although increased precipitation can be of benefit in agricultural production resulting in yield benefits in the Midwest, excessive rainfall events lead to runoff, which does not improve soil water content and plant available water. To examine the beneficial nature of rainfall events in the Midwest, rainfall retention is estimated using the United States Department of Agriculture Soil Conservation Service (USDA-NRCS/SCS) method. This method can be described briefly as an empirical formula estimating the soil's ability to store water and the amount of runoff. It was found that not only has rainfall increased but so have the number of rainfall days and the number of consecutive days of rainfall. To apply the findings to an agricultural focus, spring and fall rainfall days were also found to increase implying that farmers may have fewer days to complete fieldwork in the current climate. With increasing precipitation, the potential for runoff also increases, losing valuable water needed for crops and contributing to lost nutrients in the soil.

CHAPTER 1. INTRODUCTION

BACKGROUND

The Third National Climate Assessment reports that the frequency and intensity of extreme precipitation have increased for the Midwest (Pryor et al. 2014). Although increased precipitation can be of benefit in agricultural production resulting in yield benefits in the Midwest, excessive rainfall events have the potential to harm lives and property through flooding. It is becoming more obvious to growers that the prior 20 years' weather conditions have been different than in former decades. Most climate change reports available to the public are focused on regions like the Arctic, coastal regions, or countries that already have limited resources to support their population. While those are all worthy goals and important to society, Missouri and the Midwest will also see the effects of a changing climate. Our citizens will have to make decisions based on an unclear view of the future. The more realistic, unbiased information that a scientist can provide may make a difference in the decision that growers make that will impact their yields and their operation's future.

The Midwest as a whole has experienced more rainfall driven by more intense rainfall days (Pryor et al. 2014). This research is focused on the increased precipitation amounts creating a higher likelihood of runoff. Providing information based on one of the impacts to agriculture that is already occurring increases awareness on how a future climate may impact agriculture.

STATEMENT OF NEED

The Midwest as a whole has experienced more intense rainfall but with more rainfall days in the past century. The agriculture industry is dependent on the environment more than other types of business and building resilience to handle differing climate conditions will take time to form. The weather cannot be controlled but growers can make decisions that allow their operation to be successful even in adverse conditions.

If growers know that a greater amount of rainfall will occur and that erosion will be harder to control in a future climate, they may invest more resources now to create resilience for the future. Resilience can include improving soil management techniques now that result in more infiltration of rainfall into the soil. Also, scientists and companies can innovate to better prepare for the changing conditions. With more information, scientists and companies can start to develop long-term solutions for the challenges that will be faced due to increased rainfall and runoff.

OBJECTIVES

The objective of this dissertation is to examine the nature of rainfall increase at stations across the Corn Belt/Midwest by examining precipitation increases, days with precipitation, consecutive days of precipitation, and potential runoff at the local level with a focus on the impacts to the agricultural industry. Also, this study will examine how the influence of larger-scale global oscillations contribute to precipitation during the year, to determine if the long-range predictability of precipitation days and consecutive days of precipitation is feasible. Considering the limitations of the NRCS-SCS CN, it will be used to estimate the runoff during the past when limited measurements are available.

This study will estimate runoff amounts from the past using the NRCS-SCS CN method to determine if the increased precipitation is useful for agriculture in the Midwest or if the increase is just lost to runoff.

DISSERTATION STRUCTURE

The dissertation will contain 3 parts. In the first section, historical rainfall will be analyzed using daily data (Menne et al. 2012a) from the past 70 years. Methods used to analyze the historical record will include a Fourier transformation. The second portion examines the consecutive days of precipitation occurring during the historical 72-year period and further examines the seasonality of consecutive days of rainfall. Consecutive days of precipitation have implications for the retention of rainfall since precipitation on previously saturated soil is more likely to be lost as runoff on a field level. The third portion of the dissertation will focus on precipitation that is lost to runoff. Total rainfall cannot be considered available for plants and agricultural needs in the Midwest, a portion of the rainfall escapes as runoff. As precipitation frequency and intensity are expected to increase, more rainfall is expected to be lost to run-off. To examine the beneficial nature of rainfall events in the Midwest, effective rainfall is estimated using the United States Department of Agriculture Soil Conservation Service (USDA-SCS) method (USDA NRCS 2004) currently known as the Natural Resources Conservation Service. This method can be described briefly as an empirical formula considering the soil's ability to store water and the amount of runoff. The SCS method assigns a curve number based on the soil type and management then approximates the amount for each event that is not infiltrated into the soil. Because of the limited number of inputs, the SCS method is used

in crop models. While the SCS method is not meant to replace observations of run-off, it can be used as a tool to estimate quantities when limited measurements and observations are available.

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CHAPTER 2. HISTORICAL RAINFALL DATA

ABSTRACT

Historical daily rainfall data is used to determine the nature of rainfall increase in the Midwest United States at 10 locations. Annual and monthly data for precipitation amounts and days with precipitation is shown with implications to agriculture. All of the stations examined showed an annual increase in precipitation amounts and days according to a linear trendline and a comparison of thirty-year means; however, not all months and seasons showed an increase. The Fourier Transform applied to the precipitation amounts and days showed a connection exists between precipitation amounts and interannual and interdecadal oscillations as well as precipitation days and interannual and interdecadal oscillations. It was found that precipitation amounts have a stronger correlation with PDO across the region whereas precipitation days showed a stronger correlation with the El Nino Southern Oscillation than with PDO.

INTRODUCTION

During the growing season, precipitation can be both appreciated and dreaded by farmers in the Midwest. The planting season typically begins in April when soil temperatures rise above 10 °C (50°F). Planting extends through May and even June during extremely moist years. An ideal spring would include ample moisture to allow the seed to germinate in the ground, but not so much that soils become saturated, or water stands on top of the soil. Excess precipitation during the spring can prevent growers from fieldwork including planting, applying fertilizers, and spraying herbicides. Farmers avoid

using heavy machinery in moist fields due to the likelihood of soil compaction and its threat to soil structure. A secondary effect of overly moist fields is that weeds can't be controlled before the soil is dry enough for herbicide application. Similarly, saturated conditions limit the opportunity to use foliar fungicides to protect against in-season disease pressures that thrive when there are extended periods of high relative humidity. Rainfall events timed around the application of herbicides, fertilizers, and fungicides can reduce the effectiveness.

Excess moisture can also increase disease presence such as *Pythium* and *Phytophthora*. *Pythium* infection increases in moist soil with cool temperature conditions (Martin and Loper 1999). In soybeans, *Pythium* is most virulent at temperatures between 15 to 20°C (Thomson et al. 1971). *Phytophthora* causes seed decay and root rot in wet and warm soil conditions, optimum development occurs between 25 to 30° C (Dorrance et al.). The Crop Protection Network indicates a decreasing trend in economic loss in soybeans due to *Phytophthora* since 1996 in the North Central portion of the United States, including the Corn Belt and Midwest States, as genetic resistance has helped to control this disease complex (Crop Protection Network 2019). Both diseases have the potential to cause substantial early season stand loss if conditions are optimal.

Excess precipitation during the growing season is a cause of the leaching of nutrients in the soil (Sawyer 2007). Nitrogen leaching is a concern for corn growers. It is both a cost monetarily and environmentally. During years with excessive rainfall, farmers can expect to see more nitrogen and nutrient loss from fields. Nitrogen application is a large cost for farmers and if it leached out of the soil farmers are paying for an input that

they did not receive any benefits from (Schnitkey 2018). Nitrogen leaching also has an effect on the environment as a whole (Keeler et al. 2016).

While precipitation in the spring can hinder the success of an operation, lack of precipitation during the summer is a limiting factor to crop yields. Hot, dry periods can limit the growth and production potential of crops. Precipitation can be more vital to crop production during specific crop phases such as reproduction (Hatfield et al. 2011). Humid summers are beneficial to crops because moisture loss from the stomata of the plants is reduced. Hot dry summers are more threatening to crop production than hot moist summers (Eck et al. 2020). Late season diseases in grain such as diseases in the Diaporthe stem disease complex and Phomopsis Seed Decay in soybeans, and numerous Ear Rots in corn can occur if harvest is delayed due to rainfall.

The impact that may be the hardest to quantify for farmers is the impact that water has on the soil conditions. Along large rivers, the land is drastically different after flooding. Years with excessive rainfall also contribute to increased erosion. There is not a quick remedy after the topsoil is lost.

Many studies document increased precipitation in the central United States compared to the early and mid-20th century and predicted a continuation of the increase into the 21st century. Groisman et al. 2012 found that very heavy and extreme precipitation events increased as well as the frequency of multiday extreme precipitation events. The study also considered the role of precipitation use and recycling in agricultural purposes playing a part in precipitation. Cook et al. 2008 found that models indicate that a more intense low-level jet (LLJ) due to a westward extension of the Bermuda high increases springtime precipitation as the 21st century continues. Feng et al.

2016 used satellites and precipitation data to show that increases in springtime rainfall are caused by the LLJ and more frequent and intense MCS are associated with the increase in springtime precipitation. Bartels et al. 2020 also showed that the number of precipitation days increased regionally in the United States in the Midwest and Northeast and predicted that an increase is expected within the next 30 years. Studies show that increased temperatures lead to increased water vapor in the air and fuel intense precipitation events (Trenberth 2011). However dry areas are expected to become drier. Future seasonal evapotranspiration rates were examined by Cowell and Urban 2010 and the effect of increased evapotranspiration rates on the water budget in a warmer climate. It was found that a distinctive contrast would be created between Great Plains and the more easterly Midwest in terms of soil moisture. Studies that examined the effects on agriculture include Liang et al. 2017 who compared the US Department of Agriculture's total factor productivity (TFP) estimates and climate variables and found that the TFP could drop by 2050 in high emission scenarios. Rosenzweig et al. 2002 found increased crop damage in the US from excess precipitation.

This study will examine the rainfall increase at the local level across the Corn Belt /Midwest by examining precipitation amounts, days with precipitation, and the monthly and seasonal trends in precipitation. The effects of large-scale climatic oscillation will be analyzed to acknowledge their effects on the precipitation patterns in the Midwest United States.

METHODS

Study Area

The focus of this study is to examine precipitation changes and their effect on the agriculture industry in the Central United States or the Corn Belt region of the Midwest. The Corn Belt encompasses the states South Dakota, Nebraska, Minnesota, Iowa, Wisconsin, Illinois, Indiana, and Ohio (Green et al. 2018). The Corn Belt is characterized as a region of the United States that produces a large majority of the country's corn and soybean supply. The success of the agricultural community affects the local economies of this region as well as large corporations and the greater nation. After harvest, the supply goes to feed livestock and people and as an input to many products worldwide. The climate is a continental type and the Köppen climate type of the region is Cfa. The climate is characterized as moist with mild winters, wet all seasons, and summers that are long and hot. Summertime precipitation can be localized in nature and convective. mesoscale convective systems (MCS) are also a dominant source of summer rainfall (Birk et al. 2010). Spring and fall are transitional seasons. Winter-time precipitation may fall as rain or snow as extratropical cyclones strengthen and progress over the region. Precipitation is highest during the late spring/early summer, decreases through the summer months and a secondary maximum in precipitation is achieved in the fall.

Data

Daily precipitation data was accessed from the National Centers for Environmental Information (NCEI) Global Historical Climate Network (GHCN) (Menne et al. 2012a,b). Stations were chosen from the Midwest region of the United States

specifically choosing stations that are inside the Corn Belt region (Green et al. 2018) where most corn and soybeans are grown. To be included in the study, the station had to have records dating back to 1 January 1948. The beginning date of 1948 was chosen because several stations only had full-year records extending back to that date. In addition, to ensure the ability to analyze the data each station needed to be defined by GHCN to have 100% continuous coverage for the period analyzed. Analyzed sites include Des Moines, IA (DSM), Evansville, IN (EVV), Fort Wayne, IN (FWA), Grand Island, NE (GRI), Huron, SD (HON), Madison, WI (MSN), Peoria, IL (PIA), Sioux City, IA (SUX), Springfield, MO (SGF), and Topeka, Kansas (TOP). Figure 2.1 illustrates the location of the 10 stations in the Midwest with precipitation records from 1948 to 2019. The focus will be on the growing season because agriculture impacts are more significant and eliminate the complication of precipitation falling on frozen soil.

Figure 2.1. Location of stations used with precipitation data from 1948- 2019.

Although GHCN reported the sites to have 100% continuous coverage of the period between 1948 and 2019, some sites were missing isolated days of data.

Information from neighboring sites was used to deduce the likely amount of rain at those stations. Missing data included 25 January 1997 at DSM. The missing value was replaced with 0 mm because the snow amount observation was 0 and the maximum temperatures reported that day was well below freezing indicating that no precipitation fell during the day. PIA was missing a record for 29 Feb 1948; since neighboring stations of Mackinaw and Chillicothe, IL reported no precipitation. The precipitation amount of 0 mm was used for the date.

Annual and Monthly Precipitation Methods

From the daily rainfall total, the monthly and annual totals were calculated. Running means were calculated using a 15-year centered moving average. When there are not enough values available for a centered moving average at the beginning or end of the series, then the average of the available values is plotted. A double moving average is also plotted for each station. The double moving average serves as a trendline. Since research indicates that precipitation is increasing in the Midwest the linear trendline is adequate to see the increase in precipitation for each station. The trendline is balanced by the double moving average in addition to two 30-year means for the later period of the study. Traditionally climate data is observed in 30-year periods. To show variations during that time a comparison of the mean for 30-year periods of 1960-1989 is shown against the most recent 30 years of data (1990-2019). The two later 30-year periods were chosen to calculate the mean because the 1950s is a well-known drought period (Karl et al. 1996), so an increase from the early 30-year period to the latest would not help the formulate conclusion on the increase in precipitation during the recent decades. Average

values for each month are presented for the full 72-year period for each station, as well as monthly averages during the two 30-year periods previously mentioned. The number of rainfall days is plotted for each year, and the average number of rainfall days is plotted for each month. Since only daily totals were measured in this study, a precipitation day and a precipitation event are used interchangeably. Although a day with precipitation could represent more than one incidence of precipitation.

Fourier Transformation

A Fourier Transformation is used to separate the larger signals in the rainfall data and conclude which large-scale oscillations affect the precipitation in Midwest locations as previously seen in Lupo et al. 2007, Birk et al. 2010, and Henson et al. 2016. A Fast Fourier Transformation is used to discern the interannual and interdecadal signals behind patterns in precipitation. The techniques used are described in Mokhov et al. (2004). The average period of each common oscillation will be used to connect the signal to an oscillation. Since the annual signal will be the strongest, it was removed by subtracting the mean value of the precipitation data, so that the focus will be on other signals, such as the Pacific Decadal Oscillation (PDO), and the El Nino Southern Oscillation (ENSO). Results from the Fourier transform are complex conjugates. They are squared and the absolute value is taken so that only the positive version is considered since the concern is the magnitude of the signal. The dominant periods in the time series will have the highest magnitude. Significance is tested using a white noise continuum which is based on the variance of the Fourier Transform (Wilks 2006) and a 95% level of significance using a Z-test. The white noise continuum was used due to precipitation being the focus and that

the expectation that all frequencies would be equally likely. In this analysis, the period represents the number of oscillations in the 72-year period. To get the length of the cycle the period is divided from the length of the record of study (72 years). As in Henson et al. 2016, interannual patterns are determined to be 2-7 years and are attributed to the El Nino Southern Oscillation (ENSO), interdecadal patterns are 10-15 years and represent the combination of ENSO and the Pacific Decadal Oscillation (PDO). Multidecadal patterns are greater than 20 years and attributed to PDO (Enfield and Mestas-Nuñez 1999; Mestas-Nuñez and Enfield 1999).

RESULTS

Des Moines, Iowa

DSM annual precipitation is plotted in Figure 2.2 with the 15-year double running average, the linear regression line, and the means for the 30-year period and the remaining 12 years. The linear regression line rises from approximately 700 mm in the mid-century to near 1000 mm in the present. However, the r squared value is 0.17. To provide an additional product as a trendline the 15-year double running average line was plotted. The double running average line shows an increase through the mid-1980s then decreases until the early 2000s, before increasing again in the present.

Figure 2.2. Annual Precipitation amount in Des Moines, IA. with 15-year double running average, linear regression, and 30-year averages for 1960-1989 and 1990-2019. F-test indicates significance.

The number of days of precipitation per year during 1948 – 2019 for DSM is shown in Figure 2.3. Both the linear regression and the 15-year double running average show an increase in precipitation days. The linear regression line rises from 102 to 116 days, and the double running average increases from 100 to 113 days. However, the double running average increases steadily before reaching a maximum in the early 1990s and falling, the double running average then starts to increase again after 2005.

Figure 2.3. Annual Precipitation Days in Des Moines, IA. with 15-year double running average, linear regression, and 30-year averages for 1960-1989 and 1990-2019. F-test indicates significance.

Figure 2.4 shows the average monthly precipitation for DSM from 1948- 2019. The scale for precipitation amount is shown on the left side of the graph and the scale for the number of events is shown on the right side of the graph. DSM gets an increase in precipitation through the early months of the year before the number of events peaks in May and the precipitation amount peaks in June. The precipitation amount and events decrease in July. However, the precipitation amount peaks again at 100 mm in August before decreasing in fall and winter.

Figure 2.4. Average monthly precipitation and number of events for DSM

Figure 2.5a splits the average into two periods, 1960-1989 and 1990-2019. Thirty-year periods were used as the climatological tradition. The average monthly precipitation has increased from March through July. Most noticeably average precipitation in June increased to 170 mm, but April, May, August, September and October, and December also show a higher average in the most recent 12 years than the prior periods of the study. Average monthly precipitation events are shown in Figure 2.5b. The average number of events more closely resembles averages from the previous period. Each period's average falls within 5 events of the average of the other period. The most noticeable difference in this plot is that June precipitation events are around 12 events per month, but the previous periods are around 10 events per month.

a.

b.

Figure 2.5.a. Average monthly precipitation amounts and b. average monthly precipitation days for DSM shown for 1960-1989, and 1990-2019.

Evansville, Indiana

Annual precipitation amounts are shown in Figure 2.6. The trendline for precipitation amounts in Evansville, IN (EVV) 1030 mm to 1282 mm. There is a similar relationship between the trendline and the double running average except for the first few points of the record where the full 15 years are not available to calculate the moving average. In Figure 2.7, the linear trendline increases from 113 days to 119 days of precipitation during the period of record.

Figure 2.6. Annual Precipitation amount in Evansville, IN. with 15-year double running average, linear regression, and 30-year mean for 1960-1989 and 1990-2019. F-test indicates significance.

Figure 2.7. Annual Precipitation Days in Evansville, IN. with 15-year double running average, linear regression, and 30-year mean for 1960-1989 and 1990-2019. F-test indicates significance.

Figure 2.8 shows the monthly average precipitation amount and the number of precipitation days during each month for the full period of record. During March,

precipitation amounts sharply increase until June. The driest monthly averages and lowest precipitation days occur during August, September, and October. Then an increase occurs during November. January and February have approximately 80 mm of precipitation which is slightly higher than August, September, and October but the number of days of precipitation is more similar to the summer months of June and July.

Figure 2.8. Average monthly precipitation and number of events for EVV

The record of study is split into 2 periods in Figure 2.9a. and b. Noticeable features on the graph include the 129.7 mm average precipitation in the April date range is at least 28 mm higher than the average precipitation in the previous 30-year period. During May and June, the recent period also had a higher average than the prior 30-year period. Both fall (SON) and winter (DJF) months had precipitation that was higher in the most recent 30-year period than the previous period. Figure 2.9b shows the average precipitation days for each month for EVV. May received on average 2 more days of precipitation in 1990-2019 than in 1960-1989. Although small, average June and July

precipitation were also higher in the recent 30-year period. The months of March and August were drier.

Figure 2.9. a. Average monthly precipitation amounts and b. average monthly precipitation days for EVV shown for 1960-1989, and 1990-2019.

Fort Wayne, Indiana

Fort Wayne, Indiana (FWA) annual precipitation amounts, 12-year double running average, and the linear trendline are shown in Figure 2.10. **Error! Reference source not found..** In the early period of study, the 15-year running average is shown above the trendline but recall that if 15 years are not available to calculate the running average then only the years available are used. During the '60s, '70s, and '80s the running average falls below the trendline, but during the second half of the period of study the trendline and running average are closely matched. Through the period of record, the trendline goes from 884.3 mm to 1016 mm. Using the same method to graph

the annual number of precipitation days in Figure 2.11 **Error! Reference source not found.**, the trendline increases from 129.2 days to 136 days. The trendline and running average for precipitation days are closely matched through the period of record.

Figure 2.10. Annual Precipitation amount in Fort Wayne, IN. with 15-year double running average, linear regression, and 30-year mean for 1960-1989 and 1990-2019. F-test indicates significance.

Figure 2.11. Annual Precipitation amount in Fort Wayne, IN. with 15-year double running average, linear regression, and 30-year mean for 1960-1989 and 1990-2019. F-test indicates significance.

FWA monthly averages are shown in Figure 2.12 for the entire period of record.

February is the driest month for FWA, although the month has more days with precipitation than July, August, September, and October. The precipitation amounts increase through the spring and the month with the most precipitation is June closely followed by May. Precipitation sharply decreases in September and stays almost constant through the remaining fall and winter months. On average, FWA has the most precipitation days in April, by September that amount decreases to 9 days. December and January also have a considerable average number of precipitation days which are almost equal to April.

Figure 2.12. Average monthly precipitation and number of events for FWA.

Figure 2.13a shows the average monthly precipitation amounts for FWA. Only March and December have lower monthly averages in the 1960-1989 period than the 1990-2019 period. The largest difference between the 30-year averages occurred in May when 1990-2019 received 30 mm more precipitation than 1960-1989.

Considering average precipitation days for FWA, Figure 2.13b shows that the months with the most precipitation have shifted from March and April to April and May. On average, March had 2 fewer precipitation days during 1990-2019, and June received 2 more days with precipitation.

a.

b.

Figure 2.13. a. Average monthly precipitation amounts and b. average monthly precipitation days for FWA shown for 1960-1989, and 1990-2019.

Grand Island, Nebraska

The annual precipitation amounts for Grand Island, NE (GRI) are shown in Figure 2.14. GRI's linear trendline increases from 568.4 to 712.46 mm of precipitation. During the early study period until the 1980s the double running average closely follows the trendline. However, the double running average line rises above the linear trendline in the 1980s and 1990s before falling back below the trendline during the dry period of the early 2000s. The trendline and the linear regression line end near 700 mm.

Figure 2.14. Annual precipitation amount in Grand Island, NE. with 15-year double running average, linear regression, and 30-year mean for 1960-1989 and 1990-2019. F-test indicates significance.

The annual number of precipitation days for GRI is shown in Figure 2.15. The linear trendline shows that the annual number of events has increased from 85 to 91. The running average begins at 83mm then ends at 93 mm. After 2000, the running average has varied from the linear trendline as it incorporates the dry year of the early 2000s then rises due to the more recent moist years of 2015, 2018, and 2019.

Figure 2.15. Annual precipitation days in Grand Island, NE. with 15-year double running average, linear regression, and 30-year mean for 1960-1989 and 1990-2019. F-test indicates significance.

Figure 2.16 displays GRI monthly averages over the full 72-year period of this study. GRI typically sees a maximum of precipitation and events in May, with a decrease after that point. Comparing the most recent 30-year average to the earlier 30-year averages in Figure 2.17a and b, average monthly precipitation is higher or equal during the most recent 30-year period except for March and September.

Precipitation days have also increased in May, June, August, and November as shown in **Error! Reference source not found.**, but the increase is less than two days during each month. Average September precipitation is lower in 1990-2019 by approximately one day.

Figure 2.16. Average monthly precipitation amount and days (events) for GRI

a.

b.

Figure 2.17. a. Average monthly precipitation amounts and b. average monthly precipitation days for GRI shown for 1960-1989, and 1990-2019.

Huron, South Dakota

Huron, South Dakota (HON) annual precipitation is shown in Figure 2.18. The linear trendline increases from 442.2 to 625.7 mm. During the entire period, the linear regression line is closely related to the double running average. In Figure 2.19, the annual

precipitation days are shown. The trendline from this station shows an increase in precipitation days from 89 to 97 days during the period of record.

Figure 2.18. Annual precipitation amount in Huron, SD with 15-year double running average, linear regression, and 30-year mean for 1960-1989 and 1990-2019. F-test indicates significance.

Figure 2.19. Annual precipitation days in Huron, SD with 15-year double running average, linear regression, and 30-year mean for 1960-1989 and 1990-2019. F-test indicates significance.

Figure 2.20 shows the monthly average precipitation amounts and precipitation days for Huron SD. January's value for precipitation depth is 11.96 mm which appears very low. To support that this number is accurate, the climatological snow to liquid ratio in Huron, SD was found to be 14 to 1 during January (Baxter et al. 2005). Surrounding stations were analyzed using the National Center of Environmental Information's Climate at a Glance tool (2020). It was found that Pierre, SD receives an average of 0.49 in (12.45 mm) and Sioux Falls, SD gets 0.52 in (13.21 mm) of precipitation during January of the record of study (1948-2019). Through the complete period of record Huron averages the most precipitation in June and has the greatest number of rainfall days in May and June. During the winter months, HON receives very little measurable precipitation. Average precipitation in November, December, January, and February is less the 25 mm (1 in).

Figure 2.20. Average monthly precipitation and number of events for HON

When splitting the period of record into segments, shown in Figure 2.21a and b. HON's average precipitation amounts in the 1990-2019 period are greater or equal to the 1960-1989 period throughout the year with exception of March. The difference between the two 30-year periods is never more than 15 mm.

In Figure 2.21b, March has a lower average of precipitation days in 1990-2019. But the monthly averages of May, June, October, and December in the 1990-2019 period are higher than the corresponding months during the 1960-1989 period with the largest change occurring the September.

Figure 2.21. a. Average monthly precipitation amounts and b. average monthly precipitation days for HON shown for 1960-1989, and 1990-2019.

Madison, Wisconsin

Figure 2.22 shows the annual rainfall amount for the record of study. The increase in precipitation is shown using both the linear trendline and the running average. The trendline increase from 717.6 mm to 983.6 mm. Unlike the other stations in this study, the running average consistently increases after 1970, and the rate also increases after

2005. Because of the consistent increase, it makes sense to state the range in the running average 777.6 mm to 1013 mm. In Figure 2.23 precipitation days also show an increase in the running average, specifically from 1958- 1995, and 2009-2019. The linear trendline increases 114 to 127 days.

Figure 2.22. Annual Precipitation amount in Madison, WI with 15-year double running average, linear regression, and 30-year mean for 1960-1989 and 1990-2019. F-test indicates significance.

Figure 2.23. Annual Precipitation Days in Madison, WI with 15-year double running average, linear regression, and 30-year mean for 1960-1989 and 1990-2019. F-test indicates significance.

The monthly averages for precipitation amount and precipitation days are shown in Figure 2.24. The lowest amount of precipitation occurs in January, but the lowest amount of precipitation days occurs in February. June gets the largest amount of precipitation, but April and May have the greatest number of days with precipitation.

Figure 2.24. Average monthly precipitation and number of events for MSN

Figure 2.25a and b split the record of study into 2 segments. During the spring months, the most recent 30-year period had an increase in precipitation of approximately 20 mm, during April and May. Then on average, 41 mm in June and 16 mm in July. January, February, and October also slightly increased. Only September and December had a lower monthly average in 1990-2019. In Figure 2.25b, February precipitation days were 2 days lower in the 1960-1989 period. The most recent 30-year period is showing approximately 1 more day of precipitation than average compared to the previous 30-year periods during April, May, and June.

Figure 2.25. a. Average monthly precipitation amounts and b. average monthly precipitation days for MSN shown for 1960-1989, and 1990-2019.

Peoria, Illinois

The annual precipitation for PIA is shown in Figure 2.26 with the running averages, double running average, and trendline. The linear regression increases from 842 mm to 1000 mm, although the 15-year double running average resides above that trendline during the 1970s and below the trendline in the 90s and early 2000s. Since the new decade of 2010, the double running average has been above the trendline. In Figure 2.27, the double running average does not closely follow the trendline. The double running average varies from the trend line considerably throughout the period of record. It is due to this example, that both methods of modeling are useful for the analysis of data. One method does not fully summarize the trends tendencies of rainfall at the location. Continuing the description of rainfall days through the period of record, from 1948 through 1970 the double running average is below the trendline for the number of precipitation days, then remains above the trendline until the 90s where it falls below the trendline once again.

Figure 2.26. Annual Precipitation amount in Peoria, IL. with 15-year double running average, linear regression, and 30-year mean for 1960-1989 and 1990-2019. F-test indicates significance.

Figure 2.27. Annual Precipitation Days in Peoria, IL. with 15-year double running average, linear regression, and 30-year mean for 1960-1989 and 1990-2019. F-test indicates significance.

The monthly average for PIA Precipitation is shown in Figure 2.28. PIA typically sees an increase in precipitation through the early months of the year. May and June have

the same average number of rainfall days, but the maximum average precipitation amount falls in May. August is dry compared to the surrounding months, but overall, January and February are the driest months of the year. September and February have the least average precipitation days.

Figure 2.28. Average monthly precipitation amount and days (events) for PIA

Figure 2.29a and b show the average monthly precipitation and the average number of days of precipitation per month split into the two 30-year periods. Average monthly precipitation in the most recent 30-year period has increased by at least 26 mm in May. The years of 1990-2019 also had higher averages during August, October, November, and January but were lower in July and September by at least 12 mm. PIA sees approximately one more day of precipitation on average in May, June and, October during the 1990-2019 period than the earlier periods of record.

Figure 2.29. a. Average monthly precipitation amounts and b. average monthly precipitation days for PIA shown for 1960-1989, and 1990-2019.

Springfield, Missouri

As with previous locations, the annual precipitation and the number of precipitation days are shown for the period of record in Figure 2.30 and Figure 2.31. The linear regression shows that precipitation increased from 975.6 mm per year to 1199 mm. The 15-year double running average falls below that linear trendline before 1970 and remains above the trendline until the late 1990s. The number of precipitation days has only increased from 106.4 to 110.8 according to the linear trendline with periods rising above that trendline during the 1980s to mid-1990s then falling below the trendline after the new millennium.

Figure 2.30. Annual Precipitation amount in Springfield, MO with the 15-year double running average, linear regression, and 30-year mean for 1960-1989 and 1990-2019. F-test indicates significance.

Figure 2.31. Annual Precipitation Days in Springfield, MO with the 15-year double running average, linear regression, and 30-year mean for 1960-1989 and 1990-2019. F-test indicates significance.

The average monthly precipitation for SGF is shown in Figure 2.32. May has the highest number of precipitation days and events during the year closely followed by June. July and August are considerably drier in SGF, but the precipitation increases in September to recharge the soil even though the average number of days with precipitation stays near 8 days until March.

Figure 2.32. Average monthly precipitation amount and days (events) for SGF.

Figure 2.33a and b break down the full period of study into 2 segments of 30 years. In Figure 2.33a, the most recent periods show the highest rainfall amount in May while the 1960-1989 period has the greatest average precipitation amounts in June and September. Most obvious from the graph is the increase of over 35mm in the average amount of precipitation in May during the recent 30-year period compared to the previous 30-year period. Notable in Figure 2.33b is that the most recent 30-year period had 2 more days of precipitation in May and the 1960-1989 period had only an average of 7 days of precipitation in July.

a.

b.

Figure 2.33. a. Average monthly precipitation amounts and b. average monthly precipitation days for SGF shown for 1960-1989, and 1990-2019.

Sioux City, Iowa

SUX's annual precipitation is shown in Figure 2.34 with the 15 double running average and the linear regression line. The linear trendline increase from 607mm at the beginning of the record of study to 774 mm. During that time frame, the double running average closely corresponds with the trendline. Similarly, in Figure 2.35 the running average and the trendline overlap in the graph for the annual amount of precipitation days. The trendline in this graph only increases from 95 days with precipitation early in the record of study to 103 days late in the study.

Figure 2.34. Annual Precipitation amount in Sioux City, IA with the 15-year double running average, linear regression, and 30-year mean for 1960-1989 and 1990-2019. F-test indicates significance.

Figure 2.35. Annual Precipitation Days in Sioux City, IA with the 15-year double running average, linear regression, and 30-year mean for 1960-1989 and 1990-2019. F-test indicates significance.

The average monthly precipitation and number of rainfall days are shown in Figure 2.36, SUX on average receives very little precipitation in the winter months. On average the month with the highest number of events (May) appears to not match the month with the highest amount of precipitation (June), although the number of days with precipitation in this case only varies from 11.44 to 10.89 days so the difference between the average number of precipitation days in May and June is negligible. Precipitation amounts quickly drop in July and August and the bimodal visual that appears during increased rainfall days in Spring and fall is much weaker in SUX.

Figure 2.36. Average monthly precipitation amount and days (events) for SUX.

In contrast to the monthly average from the full period of record, Figure 2.37 splits the record of study into 2 periods. During the most recent period, a bimodal appearance is clear compared to the earliest 30-year period. This bimodal appearance to

the graph is an important change because it could aid the soil recharge during the fall months after the dry season even if the usefulness of the rainfall is limited because crops are nearing the end of their growing season. During June and August, the recent 30-year period received respectively 20 mm more rain on average than the earliest 30-year period (1960-1989). Figure 2.37b shows that on average 1 more day of rain occurred in May during the most recent 30-year period compared to the previous period, and 2 more days occurred in June. One less day of precipitation in September was recorded in 1990-2019 than in 1960-1989.

Figure 2.37. a. Average monthly precipitation amounts and b. average monthly precipitation days for SUX shown for 1960-1989, and 1990-2019.

Topeka, Kansas

Annual precipitation for Topeka, Kansas is shown in Figure 2.38. The linear trendline increase from 836.3 to 957.7 mm. During the period of record, the running average closely follows the linear trendline. Annual precipitation days are shown in Figure 2.39. During this record of study, the trendline only increased from 95 to 99 days.

Figure 2.38. Annual Precipitation amount in Topeka, KS with 15-year double running average, linear regression, and 30-year mean for 1960-1989 and 1990-2019. F-test indicates significance.

Figure 2.39. Annual Precipitation Days in Topeka, KS, with 15-year double running average, and linear regression, and 30-year mean for 1960-1989 and 1990-2019. F-test indicates significance.

The monthly averages for precipitation amount and precipitation days are shown in Figure 2.40 for TOP. January is the driest month of the year and only sees an average

of 6 days of precipitation. On average, TOP sees the highest number of precipitation days in May, but the highest precipitation amounts occur in June. Another peak of precipitation occurs in August before decreases through the fall and winter months.

Figure 2.40. Average monthly precipitation and number of events for TOP

The segmented average monthly precipitation amounts and days for TOP are shown in Figure 2.41a. and b. An additional 20 mm of precipitation on average in August makes the graph in Figure 2.41a more bimodal than the previous 30-year averages. The remaining months during the record have very similar averages. Figure 2.41b shows that throughout the record, TOP monthly averages for precipitation days are very similar. Most discrepancies seen on the graph are less than a day off from the other periods.

Figure 2.41. a. Average monthly precipitation and b. precipitation days for TOP shown for 1960-1989, and 1990-2019.

Fourier Transformation

Figure 2.42 shows the result of the Fourier Transformation on the annual precipitation amounts time series. For DSM, a significant peak occurs at periods, 2, 7, 10, 17, and 21. Since the period analyzed was 72 years, this corresponds to a change in precipitation patterns occurring approximately every 36, 10, 7, 4, and 3 years, respectively. Sorting these peaks into variations in climatic oscillations, 36 years corresponds to the PDO cycle, 10 to the ENSO-PDO interaction. The remaining peaks fall in the range of 2-7 years which represents ENSO. The same procedure was used to examine the remaining locations, and then also for the number of precipitation days each location receives. Table 2.1 shows the magnitude of each peak and categorizes the period as being influenced by ENSO, ENSO-PDO, or PDO. The table lists values that rise above the white noise or significance level. The last column is the number of peaks that rose above the white noise line to show regionally how many stations are showing a correlation with the oscillation. Across the region of study, there several locations that

share a period that rises above the white noise line. Seven locations indicate that a correlation exists between PDO and precipitation amounts since they have a period of 2 (35-year cycle). Six locations correlate with a period of 7 and thus and correlate with the interaction of ENSO-PDO. Correlation with ENSO is much more scattered across Table 2.1, however, five locations correlate with a period of 10 and four locations with a period of 29 which represent approximately 7-year and 3-year cycles, respectively.

Results of the Fourier Transformation on the number of precipitation days are shown in Figure 2.43. Each station shows a relationship to ENSO, the combination of ENSO-PDO, and PDO. Note that the y-axis for TOP is different than the other locations to accommodate the large magnitude of the peak at a period of 37. Magnitudes for the number of precipitation days are lower than the magnitudes for the precipitation amounts. Different correlations exist between the number of precipitation days and the climatic oscillations shown in Table 2.2. The PDO is not a significant correlation for as many locations using precipitation days. Frequently occurring periods for locations across the Midwest include 7 (10-year cycle), 15 (5-year cycle), and 29 (3-year cycle) representing ENSO-PDO interactions and ENSO alone.

a.

b.

c.

d.

e.

f.

g.

h.

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j.

Figure 2.42. Fourier Transformation on precipitation amounts for 10 stations in the Midwest a. DSM, b. EVV, c. FWA, d. GRI, e. HON, f. MSN, g. PIA, h. SGF, i. SUX, j. TOP. The 95% confidence level against the white noise background continuum is shown by the dashed line. Magnitudes above the dashed line are significant.

	Period	DSM	EVV	FWA	GRI	HON	MSN	PIA	SGF	SUX	TOP	Maxima
PDO	1											0
	2	7.94	10.27	10.30		5.19	9.72		10.41	4.98		7
	3							10.44				1
ENSO-PDO	4					3.18						1
	5											0
	6											0
	7	11.05	8.73		8.85	5.99			7.32		7.02	6
	8											0
	9							9.11				1
ENSO	10	6.22			4.06		7.31	8.61		3.70		5
	11											0
	12											0
	13										7.82	1
	14		10.43									1
	15			5.49								1
	16					2.86						1
	17	7.26										1
	18											0
	19							8.44			6.67	2
	20											1
	21	6.80										1
	22											0
	23											0
	24						4.78				8.36	2
	25					6.48						1
	26										7.52	1
	27								8.07			1
	28											0
	29		12.94	5.20			7.07	11.06				4
	30											0
	31											0
	32									4.71		1
	33		10.87	5.41								2
	34									4.54		1
	35								7.84			1
	36											0
	37											0

Table 2.1. Magnitudes of peaks that are above the white noise line for each period amount for Fourier Transformation of Precipitation amounts (10^6). Blank cells indicate magnitude was below the white noise line. Period indicates correlation with an interannual oscillation, Pacific Decadal Oscillation (PDO), Combination of PDO and El Nino Southern Oscillation (ENSO), and ENSO alone.

a.

b.

c.

d.

e.

f.

g.

h.

i.

j.

Figure 2.43. Fourier Transformation on the number of precipitation days for 10 stations in the Midwest a. DSM, b. EVV, c. FWA, d. GRI, e. HON, f. MSN, g. PIA, h. SGF, i. SUX, j. TOP. The 95% confidence level against the white noise background continuum is shown by the dashed line. Magnitudes above the dashed line are significant.

	Period	DSM	EVV	FWA	GRI	HON	MSN	PIA	SGF	SUX	TOP	Maxima
PDO	1											0
	2						3.32					1
	3		3.15					5.30				2
	4				3.63							1
ENSO-PDO	5											0
	6											0
	7	7.24		3.35	6.39	3.64		3.33	4.39	5.99	5.10	8
	8											0
ENSO	9			1.97					3.12			0
	10				3.24			3.52		2.76	4.35	1
	11								2.56			1
	12				3.48		4.46					2
	13											0
	14											0
	15	4.73	2.06		2.69	2.61				2.79	3.77	6
	16											0
	17	8.71			2.70		3.99	5.44				4
	18											0
	19		2.94									1
	20			2.72								1
	21	4.20										1
	22											0
	23											0
	24											0
	25					5.81						1
	26						2.68					1
	27											0
	28											0
	29	4.41	5.25	3.56			2.99	8.88	3.67	3.55		7
	30											0
	31											0
	32											0
	33											0
	34											0
	35											0
	36											0
	37				3.24	1.99	3.88				1.05	4

Table 2.2. Magnitudes of peaks that are above the white noise line for each period amount for Fourier Transformation of Precipitation Days (10^4). Blank cells indicate magnitude was below the white noise line. The period indicates correlation with an interannual oscillation, Pacific Decadal Oscillation (PDO), Combination of PDO and El Nino, and ENSO alone.

CONCLUSIONS

Considering the linear trendline and 30-year means, each station showed an increase in both annual precipitation and annual precipitation days. The 15-year double running average is useful in the study to see the increasing trend in recent decades that is

not captured by the 30-year mean or the linear regression over the full 72-year period of study. The monthly averages indicate various times during the year that an increase was seen in the monthly average of precipitation and precipitation days. Increases shown on monthly precipitation days are small; usually, only one or two days in either direction. However, the number of months that an increase in precipitation/precipitation days is larger than the months where a decrease in precipitation is shown on the 30 years monthly averages. Monthly precipitation seems to increase in the months that already receive the most precipitation including months that agricultural operations need to complete fieldwork.

Seasonal precipitation amounts and precipitation days for the period of study can be found in the appendix. Several locations also show a seasonal increase in precipitation and precipitation days with the largest increases occurring during the spring and summer. Increased precipitation amounts with only a small increase in precipitation days, could mean that a portion of the increased rainfall amount is lost to runoff, and is not beneficial to crops. Runoff occurs when the precipitation rate is faster than the rate that water can be absorbed into the soil or when the soil is fully saturated and can no longer hold additional water. See Chapter 4 for additional information concerning the balance of precipitation to runoff and how much runoff is lost.

Seed treatments have helped prevent the vulnerability of early plants to disease thus farmers can plant earlier and beat the increased precipitation found in May and June (Munkvold 2009). The biggest impact of increased precipitation may come from the effects of farmers planting earlier. More research is needed on the impact saturated soils can have on early plant development, the prevention of field working days, and the

contribution to increased disease. The increased water vapor content due to the increased capacity of warmer air temperatures, saturated soils, and evapotranspiration can create conditions that contribute to earlier disease development.

Given the short nature of the data and the recent decades of increasing precipitation, it is important to acknowledge the influence that climatic oscillations have on the precipitation over the Midwest. Several stations share significant values for cycles correlating with the ENSO, the ENSO-PDO combination, and the PDO. Precipitation days correlate differently than precipitation amounts with climatic oscillations. The PDO signal for precipitation days is not significant for as many stations as it is for precipitation amounts. A 5-year cycle occurs for precipitation days at several locations, while only one station had a significant correlation between a 5-year cycle and precipitation amounts.

ENSO values were still scattered across various periods in both tables. ENSO is the shortest cycle included in this study and thus the cycle that repeats the most and therefore more data about the variation of ENSO is observed. If there were more years to include in the study, we may find similar variations in the longer cycles. The scientific community is learning more about the effects and ENSO and has observed various ways that ENSO phases affect weather in the mid-latitudes of North America. Distinct pattern types of ENSO were described in Kung and Chern 1995, Lupo et al. (2007, 2008) as well as differing ENSO signals while in alternating phases of the PDO. Transitions between the phases of ENSO and simply the quasi-periodic nature of both the PDO and ENSO could explain that range of significant periods that relate to ENSO.

Many stations showed an increase in precipitation during the April, May, and June period which was identified by Cook et al. (2008) to be the time period that would

experience more precipitation due to an intensified LLJ. Cook et al. (2008) found that the Great Plain LLJ would intensify during the 2079-99 time period but also related those changes to the intense precipitation during May and June of 1993. More research is needed to show that the increase of precipitation at these 10 Midwest locations is due to the strengthening of the LLJ due to the warming climate described by Cook et al (2008) are already occurring. Feng et al. 2016 showed that an increased frequency and intensity of MCS are occurring under an increased LLJ. This study also shows the increase in precipitation at the local level. The increase in precipitation is not equally observed throughout the stations in the Midwest. Precipitation at easterly stations increases more than the stations that approached the Great Plains. This study also considered effects to the agricultural industry, an important economic contributor to the region. More research is needed to understand if climatic oscillations like ENSO and PDO are playing a role in the precipitation cycle or if the increase in precipitation is entirely due to the influence of increased carbon dioxide concentrations and a warmer climate.

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APPENDIX

a.

b.

c.

d.

Figure 2.44. Seasonal precipitation for DSM a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.45. Seasonal Precipitation Days at DSM for a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.46. Seasonal precipitation for EVV a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.47. Seasonal Precipitation Days at EVV for a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.48. Seasonal precipitation for FWA a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.49. Seasonal Precipitation Days at FWA for a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.50. Seasonal precipitation for GRI a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.51. Seasonal Precipitation Days at GRI for a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.52. Seasonal precipitation for DSM a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.53. Seasonal Precipitation Days at HON for a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.54. Seasonal precipitation for MSN a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.55. Seasonal Precipitation Days at MSN for a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.56. Seasonal precipitation for PIA a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.57. Seasonal Precipitation Days at PIA for a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.58. Seasonal precipitation for SGF a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.59. Seasonal Precipitation Days at SGF for a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.60. Seasonal precipitation for SUX a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.61. Seasonal Precipitation Days at SUX for a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.62. Seasonal precipitation for TOP a. Spring, b. Summer, c. Fall, d. Winter

a.

b.

c.

d.

Figure 2.63. Seasonal Precipitation Days at TOP for a. Spring, b. Summer, c. Fall, d. Winter

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CHAPTER 3. HISTORICAL ANALYSIS OF CONSECUTIVE RAINFALL DAYS

ABSTRACT

Precipitation amounts, precipitation intensity, and precipitation days have increased in the central United States during the last century, but a focus on examining how much of that precipitation is useful for plant and agricultural purposes is needed. Consecutive days of precipitation are important to consider in a climate that experiences more precipitation. It was found that consecutive days of precipitation were increasing at 10 Midwest locations by examining annual, seasonal, and monthly time series. It was also found that the maximum monthly consecutive days shifted later in the year to early summer in all 10 locations. A Fourier transformation revealed weaker magnitudes and associations between consecutive days of precipitation to ENSO and PDO oscillations than precipitation amounts and precipitation days.

INTRODUCTION

Several studies demonstrate that precipitation amounts, precipitation intensity, and precipitation days are increasing in the Midwest United States (Trenberth 2008; Groisman et al. 2012; Cook et al. 2008; Bartels et al. 2020; Pryor et al. 2014). Consecutive days of precipitation also have implications for the amount of usable water available to plants from precipitation. While having a consecutive day of rainfall does not ensure that the second day's rain falls on saturated soil, it does increase the likelihood that the soil may become saturated during the consecutive day of rain. Many studies use consecutive wet days as an indicator of climate change (Frich et al. 2002; Zhang et al.

2011; Groisman et al. 2012; Zolina et al. 2013; Shi et al. 2018; You et al. 2020;).

Although consecutive days of precipitation have been studied in the past, it is imperative to focus the study on the season and examine the effects in the context of the region's significant economic industry. Examining consecutive rainfall days in the context of the agricultural influence in the central United States corn-belt region is especially significant during the more influential seasons of spring and fall. Spring-time planting date can significantly affect corn and soybean yield. Farmers have the ability to plant early in the spring and may risk a potential freeze (or early season disease) because seed treatments are available to combat the risk of early-season plant diseases. Crops that are planted earlier in the spring benefit by reaching mature stages while rainfall is plentiful and before the climatological dry period in late July and August occur. For example, a source of water during the pollination period after corn develops its silk and the grain filling period is especially important to maximize yield (Hatfield et al. 2011). Earlier planted soybeans see more daylight hours at a mature stage whereas late-planted soybeans are young and cannot fully benefit as strongly from long daylight hours if the canopy of leaves is not fully developed. Moist soil conditions increase the vulnerability of plants to disease and can increase the risk of disease development, especially diseases like *Pythium* root rot and *Phytophthora* root rot.

The number of intense consecutive precipitation days (days over 12.7 mm) has been examined (Groisman et al. 2012) in the Midwest. Examining all consecutive precipitation days, in general, is important because even a light rain contributes to the duration of moist soil conditions. Considering viable works days in the fall also is of great importance to farmers in the Midwest, so examining if the occurrence of a

consecutive day of rain can limit harvest days is necessary. If harvest becomes delayed due to rainfall grain quality can be affected by diseases in the *Diaporthe* complex, *Phomopsis* Seed Decay, and Ear Rots in corn. Fall rainfall is also important because recharge of the soil moisture occurs in fall before the ground freezes although may also occur during spring after the ground thaws.

This study will examine the consecutive days of rainfall on an annual, seasonal, and monthly basis to discern impacts of consecutive days of rainfall for an agricultural context and examine if a change has occurred the recent decades relative to the last century. Also, this study will examine the influence of larger-scale global oscillations contribute to the number of consecutive days of precipitation during the year, to determine if the long-range predictability of consecutive days of precipitation is feasible.

METHODS

As in Chapter 2, daily precipitation data was found on the National Centers for Environmental Information (NCEI) Global Historical Climate Network (GHCN) (Menne et al. 2012a,b). The corn-belt region of the United States was identified using Green et al. 2018. The corn-belt region is where a majority of corn and soybeans are grown in the United States so the examination of this region will discern the effects of weather trends on the agriculture industry. Stations used in this study include Des Moines, IA (DSM), Evansville, IN (EVV), Fort Wayne, IN (FWA), Grand Island, NE (GRI), Huron, SD (HON), Madison, WI (MSN), Peoria, IL (PIA), Sioux City, IA (SUX), Springfield, MO

(SGF), and Topeka, KS (TOP). These stations were chosen based on having 100% continuous coverage through the period of 1948-2019 defined by the GHCN and were outside an urban setting.

From the daily precipitation data, the number of consecutive days of precipitation was found. For this study, a consecutive day is considered to be a day with precipitation that follows a previous day of precipitation. Thus, a consecutive day is counted starting from the second day of precipitation until no precipitation is recorded. Consecutive days are examined per year and season. Seasons are defined by months following climatological norms. Therefore, spring includes March, April, and May (MAM). Summer is defined as June, July, and August (JJA). Fall includes September, October, and November (SON), and winter is December, January, and February (DJF). The double running average and 30-year means are analyzed for each of the sites.

To analyze the trends in consecutive days of precipitation a linear regression was used. Linear regression or a linear trendline is commonly used to illustrate trends in climate data, especially when there are many data points. There is a concern that the linear trendline oversimplified the data, so a double running average was also used to examine trends in the data. A benefit of using the double running average is that dry or wet periods are easily identified compared to the linear regression line. Even though

precipitation is increasing, locations should expect that droughts or dry periods will still occur. The double running average illustrates the dry and wet periods that have occurred in the past. Because the double running average line has gradual peaks and valleys, the trend is not as clearly shown in this method.

Monthly averages were calculated from the daily precipitation data for the full period of study and two 30-year periods: 1960-1989, and 1990-2019. The most recent 30-year periods were shown due to the widespread drought known to occur during the 1950s. Comparing 30 years at the beginning and end of the period would indubitably show an increase in rainfall for at least one of the stations, thus biasing the study toward showing an increase in precipitation.

The last procedure performed in this project is the Fourier Transform on the Annual data following methods found in (Lupo et al. 2007; Birk et al. 2010; Henson et al. 2016). Fourier transformation discerns a signal from a set of data. To complete the Fourier transformation in MATLAB, the Fast Fourier transformation (FFT) algorithm was used. The Fast Fourier transformation reduces the computation time to extract the signal from the data. The techniques used are described in Mokhov et al. (2004). The results from the Fourier Transformation reveal the magnitude of a cyclic period that is influencing the data; therefore, the length of a dominant period can be divided from the length of the study (in this case 72 years) to indicate how often the cycle occurs or the frequency of the cycle. In this case, the annual signal was removed by subtracting the precipitation mean from the precipitation amounts. Significance is tested using a white noise continuum which is based on the variance of the transform (Wilks 2006) and a 95%

level of significance using a Z-test. The white noise continuum was used due to precipitation being the focus and that the expectation that all frequencies would be equally likely. By comparing the length of the cycle to a well-known climatic oscillation, it can be inferred that the oscillation is the cause of the cycle. This assumption is an estimate. For this study, the El Nino Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) will be used since they are identified as having a strong link to central US precipitation (Lupo et al. 2007). ENSO will be associated with interannual cycles (2-7 years), a PDO-modulated ENSO (ENSO-PDO) with interdecadal (10-15 year) cycles, and PDO for multidecadal (20 year) cycle as in (Enfield and Mestas-Nuñez 1999; Mestas-Nuñez and Enfield 1999; Henson et al. 2016;).

RESULTS

Des Moines, Iowa

The number of consecutive days of rainfall for DSM is shown in Figure 3.1a. The trendline indicates that the number of consecutive days of precipitation increased from 43 to 53 days over the 72 years of study. From the earliest 30-year period to the middle 30-year period the mean increased by 2 days. After 1992 the double running average decreases before becoming approximately level after 2001. In Figure 3.1b, spring consecutive precipitation days are graphed. The trendline indicates an increase in consecutive precipitation days from 14 to 17 days. The mean during 1960-1989 is 16 days of consecutive precipitation but the second 30-year period (1990-2019) shows that 17 days of consecutive precipitation are recorded on average. During summer shown in Figure 3.1c, the trendline changes from 12 days of consecutive precipitation to 14 days of

consecutive precipitation, and the 30-year means increase from 12 to 14 days of consecutive precipitation. Analyzing the consecutive days of precipitation during the fall in Figure 3.1d, the trendline increases from 9 to 11 days of precipitation. However, during this period, the double running average varies from the trendline during the beginning of the period of record to 1960, the years of 1980 to 1990, and again during 1995 to the present. The 30-year means are 11 days (1960-1989) and 10 days (1989-2019). Wintertime averages (Figure 3.1) return to show an increase from 1960-1989 to 1989-2019, but the increase is less than 1 day.

a.

b.

c.

d.

e.

Figure 3.1: DSM a. annual, b. spring, c. summer, d. fall, and e. winter consecutive days of precipitation with the linear regression, double 15-year running average, and mean for each 30-year period (1960-1989, 1990-2019). F-test indicates significance.

Evansville, Indiana

Annual consecutive days of precipitation are shown in Figure 3.2a. During the record of study, the linear trendline increases from 52 to 56 consecutive days of precipitation. The double running average departs from the trendline during the 1960s, but also at the beginning of the record and the end of the period of record. As described in the methods section, when the double running average is computed if 15 years are not available for the computation then it uses the years available. The mean for the 30-year periods varies from 52 to 55 days. Figure 3.2b shows the consecutive days of precipitation during the spring season the trendline indicates that consecutive precipitation days increased from 16 to 18. The mean for 1960-1989 is 16 days which increases to 18 days during 1990-2019. It appears that the spring season in the 1960s contained fewer consecutive days of rainfall than other periods shown by the decrease in the double-running average. Summer consecutive days of rainfall are shown in Figure 3.2c. The mean for the 30-year period from 1960-1989 (11 consecutive days) is the same as the mean from the latest 30 years (1990-2019). The trendline covering the entire period of study decreases at this location from 12 days to 11 days. Fall consecutive days of precipitation are shown in Figure 3.2d. The trendline for fall consecutive days of precipitation shows an increase from 10 days to 13 days. The 30-year mean of consecutive days increases from 11 to 12 days. Winter consecutive days are shown in Figure 3.2e, neither the trendline nor the 30-year means show a change in consecutive days of precipitation.

a.

b.

c.

d.

e.

Figure 3.2: EVV a. annual, b. spring, c. summer, d. fall, and e. winter consecutive days of precipitation with the linear regression, double 15-year running average, and mean for each 30-year period (1960-1989, 1990-2019). F-test indicates significance.

Fort Wayne Indiana

Annual consecutive days of precipitation are shown for FWA in Figure 3.3**Error!**

Reference source not found.a. The trendline shows that annual consecutive days of precipitation have increased from 62 to 66 days, and the 30-year means are 62 days (1960-1989) and 65 days (1990-2019). During the spring (Figure 3.3b), the trendline indicates that consecutive days of precipitation have decreased but by less than one day. The 30-year averages for both of the 30-year periods are 19 days (1960-1989) and 20 days (1990-2019). Figure 3.3c shows the seasonal consecutive days of precipitation for Summer. The earliest 30-year period has the highest mean but only by less than a day. The increase shown on the linear trendline is also less than a day, from 12.68 to 13.22 days. Fall consecutive days of precipitation are shown in Figure 3.3d. The trendline for

fall increased from 12 to 15 days from the 1960-1989 to the 1990 to 2019 period. The difference between the 30-year means is less than a day. During this period, the double running average shows a steady increase in consecutive days of precipitation from 1955 to 1990 and has decreased since that time. For winter (Figure 3.3e), the 30-year means increase by 2 days in the later period, but the full trendline reveals an increase of 1 day for the full period of study.

a.

b.

c.

d.

e.

Figure 3.3: FWA a. annual, b. spring, c. summer, d. fall, and e. winter consecutive days of precipitation with the linear regression, double 15-year running average, and mean for each 30-year period (1960-1989, 1990-2019). F-test indicates significance.

Grand Island, Nebraska

The annual number of consecutive days of rainfall for GRI is shown in Figure 3.4a. **Error! Reference source not found.** The trendline for this location shows that consecutive days have increased from 35 to 37. However, the double running average shows a fairly constant increase until 1995 when the running average reaches a minimum then increases through the present. The period of drought in the early 2000s will influence the second 30-year average (1990-2019). The mean for the 30-year period of 1960-1989 is one day higher than the mean for the 30 years of 1990-2019. During the spring, the trendline decreases from 13 to 12 consecutive days of rainfall as shown in Figure 3.4b. The 30-year means also decrease by approximately the same amount. Summer consecutive days of precipitation are shown in Figure 3.4c. The trendline for summer increase by only a half-day, and the double running average shows variability during the period of study. The 1970s and 1980s have fewer days of consecutive precipitation than the surrounding decades. There are 2 days of change between the 30-year means. Fall consecutive days of precipitation are shown in Figure 3.4d. The trendline on this graph increases from 6 to 8 days but there is no change between the 30-year means. The largest increase in the double running average during the period of record occurs between 1965 and 1988, which is approximately 2 days. Wintertime consecutive days (Figure 3.4e) does not change in terms of the trendline or the 30-year means.

a.

b.

c.

d.

e.

Figure 3.4. GRI a. annual, b. spring, c. summer, d. fall, and e. winter consecutive days of precipitation with the linear regression, double 15-year running average, and mean for each 30-year period (1960-1989, 1990-2019). F-test indicates significance.

Huron, South Dakota

Figure 3.5a shows the annual number of consecutive days of precipitation for HON. During the period of study, the trendline shows an increase from 36.4 days to 38.5 consecutive days of precipitation. The mean of the 30-year periods changes by approximately one day. The double running average indicates that an increase occurs between 1995 and 2010. Spring consecutive days of precipitation in Figure 3.5b also shows very little variability between the two 30-year means. The trendline increase from 12 to 13 days of precipitation. The 30-year means and double running average closely relate to the trendline. Summer, fall, and winter show a similar lack of variability in Figure 3.5c, Figure 3.5d, and Figure 3.5e but during summer the season the trendline and means slightly decrease.

a.

b.

c.

d.

e.

Figure 3.5. HON a. annual, b. spring, c. summer, d. fall, and e. winter consecutive days of precipitation with the linear regression, double 15-year running average, and mean for each 30-year period (1960-1989, 1990-2019). F-test indicates significance.

Madison, Wisconsin

Figure 3.6a shows the annual number of consecutive days of precipitation for MSN. There is a strong increase in the trendline from 49 to 61 days. A majority of that increase occurs during the first 48 years of the period of study from 1948 to 1995 shown by the double running average also increasing. The thirty-year mean increase from 54 to 59 consecutive days of precipitation. In Figure 3.6b the spring consecutive days of precipitation are shown. The trendline for this season indicates that during the period of study consecutive precipitation days increased from 16 to 18 days and the 30-year means increased by approximately a day. Summertime precipitation shows more variability in Figure 3.6c especially in the latter half of the period of study. The trendline increases from 12 to 14 days and the double running average shows a sharp increase between 1980

and 1998. This is also reflected in the difference between the two 30-year means of 12 days (1960-1989) and 14 days (1990-2019). After 1998, the running average decreased into the present. Figure 3.6d shows the number of consecutive days of precipitation in the fall, again variability is shown but not during the entire period of study. The trendline increases from 11 to 14 days, while the 30-year means show a small decrease. The double running average indicates that an increase in consecutive days of precipitation occurred during 1955 through 1990. After 1990 the double running average decreases until 2005. An increase in each measure of variability occurs during the winter season (Figure 3.6e). Thirty-year means increase from 12 to 14 days, and the trendline increase from 11 to 15 days. The double running average only indicates that a decrease in precipitation occurred during the 1950s.

a.

b.

c.

d.

e.

Figure 3.6. MSN a. annual, b. spring, c. summer, d. fall, and e. winter consecutive days of precipitation with the linear regression, double 15-year running average, and mean for each 30-year period (1960-1989, 1990-2019). F-test indicates significance.

Peoria, Illinois

Annual consecutive days of precipitation are shown in Figure 3.7a. A dramatic increase occurs in the trendline for this location from 47 to 56 days. That increase is

influenced by the periods of 1955 to 1980 and after 2005 as shown by the double running average line. Also shown on the graph is a period from 1980 through 2005 that the double running average shows a decrease in consecutive days of precipitation. The 30-year means in this graph are 51 days and 54 days for 1960-1989 and 1990-2019, respectively. During the spring (Figure 3.7b), the increase in consecutive days of precipitation is much less dramatic than the annual graph. The trendline increased from 15 to 18 consecutive days, and the 30-year means are shown to be 17 days (1960-1989) and 18 days (1990-2019). Summer consecutive days of precipitation are shown in Figure 3.7c. The trendline shows an increase from 10 to 12 days of precipitation and the 30-year means increase from 11 days to 12 days for 1960-1989 and 1990-2019 respectively. Analyzing the fall consecutive days graph in Figure 3.7d, the linear trendline shows an increase from 10 days to 13 days. The double running average shows a solid increase from 1952 through 1990, then decreasing after that point. The 30-year means for fall consecutive days of rainfall are 12 days (1960-1989) and 13 days (1990-2019). In Figure 3.7e, the winter trendline increased from 11 to 13 days. Also notable in the graph is the lack of wintertime precipitation from 1985 to 2005 shown by the double running average.

a.

b.

c.

d.

e

Figure 3.7. PIA a. annual, b. spring, c. summer, d. fall, and e. winter consecutive days of precipitation with the linear regression, double 15-year running average, and mean for each 30-year period (1960-1989, 1990-2019). F-test indicates significance.

Springfield, Missouri

The annual consecutive days of precipitation for SGF are shown in Figure 3.8a. The trendline increases during the 72-year period from 49 to 50 days. The double running average is fairly constant at the beginning of the period, before gradually increasing around 1965 through 1990. After 1990 the double running average begins to decrease again then remains constant after 2007. The 30-year means increases from 49 days (1960-1989) to 50 days (1990-2019) for annual consecutive precipitation days. In Figure 3.8b the trendline for the spring consecutive days increases from 15 to 18 days. The 30-year means increases from 16 days (1960-1989) to 18 days (1990-2019). The double running average does not consistently increase during the period of record. It increases from 1967 to 1990, then decreases from 1990 until 2005 before increasing once again. Figure 3.8c

shows the summer consecutive days of precipitation. The trendline is essentially constant over the entire period of study but the double running average decreases from the beginning of record until 1979 then increases until it becomes consistent after 1995. The 30-year means decrease from 10 during 1960-1989 to 12 during 1990-2019. Fall consecutive days of precipitation are shown in Figure 3.8d. The linear trendline in the graph increase from 10 to 12 consecutive days of precipitation, but the double running average and 30 years means add more detail to that approximation. The 30-year means decrease by less than a day. The double running average increases from 1955 through 1970, levels off to a straight line before increasing in 1981 and then becoming consistent once again. After 1995 the double running averages decrease until the end of this period of study. Wintertime trends (Figure 3.8e) show a decrease in Figure 3.8e. The trendline goes from 12 to 9 days and 30-year means decrease from 12 to 10 days, with the most significant decrease in the running average occurring after 1990.

a.

b.

c.

d.

e.

Figure 3.8. SGF a. annual, b. spring, c. summer, d. fall, and e. winter consecutive days of precipitation with the linear regression, double 15-year running average, and mean for each 30-year period (1960-1989, 1990-2019). F-test indicates significance.

Sioux City, Iowa

Figure 3.9a shows the annual consecutive days of precipitation for SUX. The trendline for SUX shows that consecutive precipitation days have increased from 38 days to 44 days and the 30-year means increased from 40 to 43 days for 1960-1989 and 1990-2019 respectively. Figure 3.9b shows the number of spring consecutive days of precipitation. The trendline for this period of study increase from 14 to 15 days. The 30-year means are 14 days (1960-1989) and 15 days (1990-2019). Even though the period of the study shows an increase in the trendline and the 30-year means, after 1995 the double running average decreases to the present period. Summer consecutive precipitation days are shown in Figure 3.9c, the trendline increase from 11 to 13 days, and the 30-year means increase from 11 days (1960-1989) to 13 days (1990-2019). After starting

consistently during the beginning of the period of study, the double running average enters a trough that reaches a minimum in 1980 then increases until 2000. During the remaining period, the double running average decreases. Fall consecutive days are shown in Figure 3.9d, the trendline increases from 7 days to 9 days. The 30-year mean decreases by less than a day. During the majority of this period of study, the double running average increases until the late 1980s when the double running average shows a decrease in the number of consecutive precipitation days. Wintertime consecutive days in Figure 3.9e show steady trends compared to the other seasons.

a.

b.

c.

d.

e.

Figure 3.9. SUX a. annual, b. spring, c. summer, d. fall, and e. winter consecutive days of precipitation with the linear regression, double 15-year running average, and mean for each 30-year period (1960-1989, 1990-2019). F-test indicates significance.

Topeka, Kansas

The annual number of consecutive days of precipitation for TOP is shown in Figure 3.10a. The trendline indicates that consecutive days of precipitation increased from 40 to 42 and the 30-year means increased from 40 days to 42 days. During the period of study, the double running average showed a trough during the 1960s and ridged during 1980s through 2000 before leveling off. Consecutive days during the spring are shown in Figure 3.10b. The trendline indicates that the springtime consecutive days of precipitation increased from 13 to 14 days the 30 years means also indicate those values for 1960-1989 and 1990-2019, respectively. Summer consecutive days of precipitation are shown in Figure 3.10c, during this period the trendline decreased by less than one day. The 30-year means were 11 days (1960-1989) and 12 days (1990-2019). Comparing the 30 years means and the double running average it appears that the last 15 years in the period of study affected the trendline showing a decrease even if it was small. Fall consecutive days of precipitation are shown in Figure 3.10d. The trendline indicates that an increase from 8 to 10 days occurred during the period of study. The 30-year means increased by less than a day. Wintertime consecutive days in Figure 3.10e show little increase or decrease in trends compared to the other seasons.

a.

b.

c.

d.

e.

Figure 3.10. TOP a. annual, b. spring, c. summer, d. fall, and e. winter consecutive days of precipitation with the linear regression, double 15-year running average, and mean for each 30-year period (1960-1989, 1990-2019). F-test indicates significance.

Monthly Averages

Average monthly consecutive days are shown in Figure 3.11 for the full period of study and the two 30-year means. The entire region of study is characterized by a peak in consecutive rainfall days in the late spring or early summer, with a decrease in the fall and a minimum sometime in the fall or winter. Comparing the number of precipitation days, the average maximum for the year during 1990-2019 was higher than the peak for 1960-1989, however, the peak may be in a different month. At each station, a shift occurred in the 1990-2019 mean compared to the other period of record. It appears that the peak for consecutive days of precipitation occurred later in the spring than the previous 30-year means.

a.

b.

c.

d.

e.

f.

g.

h.

j.

i.

Figure 3.11. Average monthly consecutive days of rainfall for a. full period of study (1948-2019), and two 30-year periods (1960-1989, 1990-2019) for a. DSM, b. EVV, c. FWA, d. GRI, e. HON, f. MSN, g. PIA, h. SGF, i. SUX, j. TOP.

Fourier Transforms

Figure 3.12 shows the results of the Fourier Transform for the 10 locations. To get the length of the cycle from the period, the length of the study is divided by the period of a significant peak. Significant peaks rise higher than the dashed white noise line. For DSM, significant peaks appear at the periods of 2, 7, 9, 17, 21, and 29. A cycle of 10 years is obtained by dividing seven from 72. High magnitudes at this value at the period of 7 indicate a relation to PDO-ENSO. Results of the significant peaks and the oscillation

that correlates with the peaks are shown in Table 3.1. The order of magnitude shown for consecutive days of precipitation is lower than the order of magnitude reported in Chapter 2 analyzing the precipitation amount and precipitation days. Across the region, common periods for consecutive days of precipitation are seven and seventeen relating to PDO modulated ENSO and ENSO, respectively.

a.

b.

c.

d.

e.

f.

g.

h.

i.

j.

Figure 3.12. Fourier Transformation on Annual Consecutive days of Precipitation for a. DSM, b. EVV, c. FWA, d. GRI, e. HON, f. MSN, g. PIA, h. SGF, i. SUX, j. TOP. The 95% confidence level against the white noise background continuum is shown by the dashed line.

	Period	DSM	EVV	FWA	GRI	HON	MSN	PIA	SGF	SUX	TOP	Maxima
PDO	1											0
	2	2.02										1
	3		1.62				2.33	1.74			1.13	4
	4				1.57		1.90					2
ENSO-PDO	5			1.18								1
	6											0
	7	4.84		2.71	4.50	1.25		1.71		3.04	3.66	7
	8											0
ENSO	9	2.48							2.02			2
	10							2.09		1.25	1.38	3
	11				2.05				1.51			2
	12						3.66					1
	13											0
	14											0
	15					0.95					1.15	2
	16											0
	17	4.00	2.17		1.46		3.49	3.43	1.59		1.27	7
	18											0
	19		2.18					2.21				2
	20			1.42		0.84						2
	21	2.05	2.22									2
	22								1.55			1
	23											0
	24											0
	25					4.29				1.28		2
	26											0
	27									1.61		1
	28											0
	29	2.51	2.94	2.70				5.88	1.65			5
	30											0
	31									1.67	1.41	2
	32											0
	33		1.63	1.64								2
	34											0
	35											0
	36											0
	37				1.56	1.17	3.61				5.76	4

Table 3.1. Magnitudes (10^4) of peaks that are above the white noise line for each period amount from the Fourier Transformation of Consecutive Precipitation Days. Blank cells indicate magnitude was below the white noise line. The period indicates correlation with an interannual oscillation, Pacific Decadal Oscillation (PDO), Combination of PDO and El Nino Southern Oscillation (ENSO), and ENSO alone.

CONCLUSIONS

Locations that experience a decrease in consecutive days of precipitation are bolded in Table 3.1. Five out of the 10 locations decreased their 30-year means during

fall, 3 locations decreased means in the winter and 2 locations decreased mean in the spring. Each location saw an increase in the trendline for the full period of study, although not every location increased during all 4 seasons. Out of the forty graphs that examine seasons, 6 locations that include a decrease in the trendline during the 72-year period (Table 3.3).

	DSM	EVV	FWA	GRI	HON
Annual Mean 1960-1989	48.7	51.7	61.7	36.0	37.2
Annual Mean 1990-2019	50.9	55.0	65.3	37.1	37.9
Spring Mean 1960-1989	15.8	16.3	19.4	12.6	12.9
Spring Mean 1990-2019	16.9	17.9	19.9	12.1	12.8
Summer Mean 1960-1989	12.4	11.0	12.5	10.1	10.5
Summer Mean 1990-2019	13.8	11.1	13.4	11.8	10.6
Fall Mean 1960-1989	10.7	10.6	13.4	7.2	7.3
Fall Mean 1990-2019	10.2	11.8	13.8	7.2	7.6
Winter Mean 1960-1989	9.6	13.9	16.2	6.1	6.5
Winter Mean 1990-2019	10.2	13.8	18.1	5.8	6.7
	MSN	PIA	SGF	SUX	TOP
Annual Mean 1960-1989	53.9	51.1	48.1	40.4	39.7
Annual Mean 1990-2019	59.2	53.9	50.6	43.2	42.4
Spring Mean 1960-1989	16.7	16.5	15.3	14.3	13.3
Spring Mean 1990-2019	18.2	18.0	17.3	15.4	14.1
Summer Mean 1960-1989	11.6	10.9	10.4	10.5	11.1
Summer Mean 1990-2019	14.1	12.2	11.9	13.3	12.4
Fall Mean 1960-1989	13.3	11.9	12.3	8.8	9.3
Fall Mean 1990-2019	13.1	11.8	11.6	8.4	9.4
Winter Mean 1960-1989	12.2	12.4	11.6	7.2	6.0
Winter Mean 1990-2019	13.7	12.8	9.7	7.3	6.4

Table 3.2 Summary of mean consecutive days of precipitation for the 30-year periods of 1960-1989 and 1990-2019. Bold values indicate the earlier period of 1960-1989 is larger than the period of 1990-2019.

Location	Season	Decrease over 72 years
EVV	Summer	1 day
FWA	Spring	< 1 day
GRI	Spring	1 day
HON	Summer	1 day
SGF	Winter	3 days
TOP	Summer	<1 day

Table 3.3. Locations with a decrease in the linear regression (trendline) during 72-year seasonal

There are occurrences that the trendline decrease but not the 30-year means, and vice versa. The trendline measures the whole 72 years of data while the 30-year means in combination only measure 60 years. Also, consider that the 1950s are at the beginning of the study and are known to be an extreme drought affecting the US.

Annual and seasonal graphs indicate that consecutive precipitation days are increasing mostly during spring and summer. The stations in the western portion of the study area showed fewer changes during the period of record. While graphing annual and season days of consecutive precipitation the double running average closely followed the trendline so notable changes were not reported in this chapter like the previous chapter.

There was little variability in the winter graphs, excluding MSN, PIA, FWA, and SGF. The first three stations listed are similar geographically and all experienced an increase in either the 30-year mean, trendline, or both. These locations could be impacted by a decrease in the length of time between the first frost in the fall and thaw in the spring. SGF was the only station that experienced a decrease in wintertime precipitation according to the trendline and 30-year means.

Overall, most stations had an increase in consecutive days of precipitation during the spring and summer. An increase in spring rainfall can have consequences for working

days during the planting season, as well as an effect on soil temperatures. When plants are less mature in the spring they are not using as much water intake, which can lead to an increased probability that the soil becomes saturated and increases runoff. During the summer, most rain is welcome to the agricultural community. Although planting dates can extend through June, and from the monthly analysis of average consecutive days, it is evident that those days are occurring in early spring.

While a shift of the maximum number of consecutive days to a later month occurs for all 10 stations. It is important to consider that the increase is never more than 2 days. Considering that a month is only 30 days and precipitation occurs only a limited number of days, a small number is expected. The seasonal increase in consecutive precipitation days was shown to represent any consecutive days that may have span the end of the month and beginning of the next month.

Groisman et al. 2012 found an increase in multiday extreme precipitation events over the central United States. This study found that multiday or consecutive precipitation days are increasing as well and continued the examination into seasonal and monthly consecutive days of precipitation. More research is needed to connect the increase in consecutive days of precipitation to the known effects of climate change to precipitation in the Midwest described by Cook et al. 2008, and Feng et al. 2016 as an intensification of the low-level jet.

This study extended the results found correlating precipitation amounts to the climatic oscillations found in (Lupo et al. 2007; Birk et al. 2010; Henson et al. 2016). Like precipitation amounts and precipitation days, the number of consecutive days of precipitation shows a correlation to PDO, PDO modulated ENSO, and ENSO. While

there are locations that shows significance for certain periods. Values in the table are scattered indicating locations respond differently to climatic oscillations and consecutive days of precipitation. Similar to conclusions from Chapter 2, the varied nature of significant peaks could be due to the quasi-period nature of both PDO and ENSO, and the different ways they affect weather patterns in the United States.

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CHAPTER 4. ESTIMATION OF RUNOFF BASED ON EMPIRICAL FORMULA AND PROBABILITY OF EXCEEDANCE

ABSTRACT

The Third National Climate Assessment reports that the frequency and intensity of extreme precipitation have increased for the Midwest (Pryor et al. 2014). Although increased precipitation can be beneficial for the agricultural industry and economics of the Midwest, excessive precipitation events lead to runoff which does not improve soil water content and plant available water. In addition, excessive precipitation events have the potential to harm lives and property. To examine the beneficial nature of precipitation events in the Midwest, runoff is calculated using the United States Department of Agriculture Soil Conservation Service (USDA-SCS) curve number method. The probability of exceedance is also calculated to understand the occurrence of the threshold of precipitation needed to create runoff. A comparison of the 30-year probability of exceedance is shown to understand the role of climate change in precipitation events.

INTRODUCTION

The Third National Climate Assessment (Pryor et al. 2014) states that “Generally, annual precipitation increased during the past century (by up to 20% in some locations), with much of the increase driven by intensification of the heaviest precipitations.” The increased intensity of rainfall events is due to the water holding capacity of air (Trenberth 2011). While increased precipitation can be considered a positive impact of climate change, total precipitation cannot be considered available for plants and agricultural

needs. Groisman et al. 2012 reported that the number of heavy precipitation days and multiday precipitation events is increasing in the central US.

After the soil is saturated, a portion of the precipitation escapes as runoff, so heavier more intense precipitation events are not necessarily increasing the amount of water available to plants. Heavier precipitation events and increased runoff can also contribute to flooding potential. As precipitation intensity is expected to increase, more precipitation is expected to be lost to runoff. Since summertime moisture is a limiting factor in the productivity of the agriculture community in the Midwest, retaining water lost to runoff is a priority. A calculation of historical runoff follows, including values for 10 locations in the Midwest and analysis of monthly and annual runoff amounts. The scope of this study only computes surface runoff. Surface runoff can occur because the soil is saturated and cannot absorb additional water or because the intensity of the precipitation exceeds the infiltration rate of the surface causing water to pool on the surface. In either case, the water pooled at the surface can move due to the slope of the land. Infiltration rate can be affected by a surface seal or crust forming over the soil that does not water enter the subsurface of the soil.

In this study, the Natural Resources Soil Conservation Service- Soil Conservation Service curve number (NRCS-SCS CN) method is used to estimate runoff. The Soil Conservation Service (SCS) was formed to study and recommend the best practices to prevent erosion and encourage soil health. In 1994 SCS was renamed and expanded to the Natural Resources Conservation Service (USDA NRCS). The method of measuring runoff was developed by the SCS before the NRCS was in existence but in literature is referred to as the SCS method or the NRCS method for estimating runoff. To eliminate

confusion, this paper will refer to it as the NRCS-SCS CN method. The NRCS-SCS CN method is an empirical formula based on observations of runoff and the soil water budget equation. It is meant to calculate surface runoff when the precipitation rate is higher than the infiltration rate. Several assumptions are made to the conditions of the environment when the formula is in use to estimate runoff which are detailed in section 2. The NRCS-SCS CN method assigns a curve number based on the soil type and management, then approximates the amount for each event that is not infiltrated into the soil. To compute the curve number in the NRCS-SCS CN method, a soil hydrological group is needed. The hydrological group for the 10 locations used in this study was obtained through the NRCS web soil survey (Soil Survey Staff 2019). The history and detail about the development and current state of the method are compiled in Hawkins et al. 2009.

While the SCS method is not meant to replace observations of runoff, it has often been used as a tool to estimate quantities when limited measurements and observations are available. The SCS method is used in urban runoff models including WinTR55, Storm Water Management Model (SWMM), Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS) (USDA NRCS 2009; USEPA 2010; US Army Corp of Engineers), and in agricultural models including the Soil Water Assessment Tool (SWAT), Agricultural Policy/Environmental Extender (APEX) Agricultural Non-Point Source Pollution (AGNPS) (USDA ARS Grassland Soil and Water Research Laboratory; Texas A&M AgriLife Research 2018; Texas A&M AgriLife Research 2017; Young et al. 1989). NRCS-SCS CN method is also used to estimate the soil moisture in Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al. 2003; Ritchie 1998) and to determine crop damage under increased precipitation

(Rosenzweig et al. 2002). The WEPP model (Ii et al. 1995) can be used to predict erosion and hydrologic processes and uses the CREAMS model (W. G. Knisel and K. R. Douglas-Mankin 2012) embedded within it to calculate runoff, which is an example of the CN method being used continuously to model manage soil moisture content (Hawkins et al. 2009). Pruski and Nearing (2002a) used the WEPP model to estimate runoff and soil erosion then expanded their results to 21st century (Pruski and Nearing 2002b).

Many studies estimating runoff do so in service of finding the soil water content for drought, flood potential, or to understand feedback to the atmosphere. Huang et al. 1996 created a reanalysis model of soil moisture to understand the effect of soil moisture on the atmospheric conditions. Shukla and Wood 2008 used a standardized runoff index for use in hydrology models to simulate drought. Which uses runoff from simulations and fits a probability distribution to the sample which in turn can be used for a normal cumulative distribution function. Now the availability of satellite measurement of soil moisture reduces the need to estimate runoff to calculate the soil moisture using the water balance equation. Grace and SMAP are two of the satellites that are equipped to provide an observation of soil moisture (Wahr et al. 2004; Zhang et al. 2017). Although, more examples exist internationally that are in use to measure soil moisture.

Considering the limitations of the NRCS-SCS CN, it will be used to estimate the runoff during the past when limited measurements are available. This study will estimate runoff amounts from 1948 to 2019 using the NRCS-SCS CN method, then determine the nature of how runoff is occurring annual and monthly using 30-year averages to determine if the increased precipitation is useful for agriculture in the Midwest or if the increase is likely just lost to runoff.

METHODOLOGY

Study Area

Daily Precipitation values were obtained for 10 cities in the Midwest from the National Centers for Environmental Information (NCEI) Global Historical Climate Network (GHCN) (Menne et al. 2012a,b). Cities were chosen based on the extent of years available and the proximity to urban development. Records in this project cover 72 years from 1948 to 2019 and each station was chosen because it was defined as having a 100% continuous record during that period. Stations also had to be considered to be within the Corn Belt region of the United States. Arguably, some stations approach the Ozark region or the Great Plains region but the climatological number of thunderstorms, and concern about the eastward expansion of the Great Plains in future climates brings appropriate comparison material to the study. Since runoff values are high on an impervious urban surface, locations near extensive urban development were eliminated from consideration. The stations included in this study are the same as the stations in Chapter 2. Analyzed sites include Des Moines, IA (DSM), Evansville, IN (EVV), Fort Wayne, IN (FWA), Grand Island, NE (GRI), Huron, SD (HON), Madison, WI (MSN), Peoria, IL (PIA), Sioux City, IA (SUX), Springfield, MO (SGF), and Topeka, Kansas (TOP).

Figure 4.1. Location of stations used with precipitation data from 1948- 2019.

Table 4.1 summarizes precipitation data for each of the stations in this study. Of consideration in Table 4.1 is the increase in precipitation days from west to east in the Midwest. The number of days with precipitation amounts of 10, 25, 50, 100, 125, and 150 mm are also shown. SGF or EVV had the most days with rain for each threshold. These stations are the southernmost locations in this study. they also receive a greater number of thunderstorms (Koehler 2020). Convective events produce higher amounts of rainfall than stratiform events amounts during their short, but more intense, duration.

	DSM	EVV	FWA	GRI	HON	MSN	PIA	SGF	SUX	TOP
Avg rain days per year	110	116	133	88	93	122	115	108	99	97
Days > 10 mm	1961	2656	2233	1455	1157	1874	2142	2473	1557	2010
Days > 25 mm	570	859	564	413	298	520	637	866	448	714
Days > 50 mm	116	182	70	72	44	90	90	178	86	155
Days > 100 mm	6	10	2	6	3	2	7	17	5	7
Days > 125 mm	1	3	0	2	1	0	1	4	2	2
Days > 150 mm	1	2	0	1	0	0	0	2	0	0
Median (mm)	3.3	4.6	3.3	2.8	2	2.8	3.6	4.6	2.8	3.8
Max (mm)	157	162.6	111.8	165.1	134.9	114.6	128.5	159.3	139.7	142.5

Table 4.1. Precipitation statistics for stations in the Midwest from the period 1948-2019. The median was calculated using only values above zero.

Estimation of Runoff

To calculate runoff from precipitation amounts The NRCS-SCS CN method (USDA NRCS 2004) was used to estimate runoff amounts and retention amounts for each date at each location.

$$Q = \begin{cases} \frac{(P-I_a)^2}{(P-I_a)+S}, & P > I_a \\ 0, & P \leq I_a \end{cases} \quad (1)$$

$$S = \left(\frac{1000}{CN} \right) - 10 \quad (2)$$

$$I_a = 0.2S$$

Where Q is the depth of runoff, P is the depth of precipitation, I_a is the initial abstraction, S is maximum potential retention, all in mm. CN is the curve number representing the hydrologic soil group, cover type, treatment, hydrologic condition, and antecedent runoff condition. CN was derived by first finding the hydrological group from USDA web soil survey (Soil Survey Staff, Natural resources Conservations Service 2019). To find the hydrologic group, an area of interest (AOI) was chosen in the soil data explorer around the weather observation location. A hydrologic soil group was listed in the Soil Properties and Qualities section under Soil Qualities and Features for the AOI. From the hydrologic soil group and area listed for each location, a weighted CN was calculated using the method described in Chapter 10 of the National Engineering Handbook (USDA NRCS 2004). For row crops in poor hydrologic condition with limited

conversation management values for the CN are Group A -72, Group B - 81, Group C – 88, Group D – 91 as described in (USDA NRCS Conservation Engineering Division 1986). Using the CN and the daily precipitation amount, the daily runoff was calculated, then extrapolated to get monthly and annual amounts for the full 72-year period. The I_a value calculated for each location is shown in Table 4.2.

	DSM	EVV	FWA	GRI	HON	MSN	PIA	SGF	SUX	TOP
I_a (mm)	8.23	9.82	7.36	12.91	8.75	12.92	10.41	8.51	9.70	8.99

Table 4.2 Initial Abstraction (I_a) amount for each station.

While the SCS method is not meant to replace observations of runoff, it can be used as a tool to estimate quantities when limited measurements and observations are available. In this case, it will serve as a tool for comparison of precipitation-dependent runoff for the mid-20th century and the present. More examination is needed to discriminate useful precipitation from precipitation that evaporates, gets held by plants before reaching the surface, or percolates deep into the soil. It is hypothesized that as the frequency and intensity of rainfall increases going into the 21st century that runoff amounts will also increase. Because of the limited number of inputs, those models in turn can be used to compare growing conditions in future climates with the past. It is critical to examine past precipitation using this method and emphasize the weakness of the method before examining conditions in the future. Assumptions that are made in general to use the SCS-NRCS method and particular assumptions for this study are included below.

- Soil conditions remain constant throughout 70 years.

- Previous precipitation events or prior water content of the soil are not considered in the calculation of each day's runoff.
- Daily precipitation is considered one precipitation event.
- Soil characteristics considered in the equation are limited to the hydrologic group number.
- Curve Number was based on row crops in poor hydrological condition.
- SCS-NRCS method does not consider frozen soil, thus the focus will be on the growing season.
- Precipitation intensity and duration and surface roughness are not considered.

To examine the accuracy of the NRCS-SCS CN method, precipitation, and observed runoff data were used from the Grazinglands Research Laboratory: Water Resources and Erosion (WRE) Watersheds in El Reno, Oklahoma (Nelson et al. 2020a). From that data, it was found that there was a 14% reduction in runoff depth per day from watersheds in native tallgrass prairie and maximum disturbance, and it was presumed that a threshold exists at which precipitation will predominately runoff since there was a similar mean runoff depth of the native tallgrass prairie and maximum disturbance plots (Nelson et al. 2020b). Table 4.3 summarizes the treatment of each plot at WRE Watersheds, adapted from Nelson et al. 2020b.

Watershed	Treatment		Slope	Dates
	Land Use	Management Regime		
1	Native grasses	Native tallgrass prairie	2.6 %	1977-1999
2	Native grasses	Native tallgrass prairie	2.9 %	1977-1999
3	Native grasses	Native tallgrass prairie	3.2 %	1977-1999
4	Native grasses	Native tallgrass prairie	3.6 %	1977-1999
5	Native grasses	Native tallgrass prairie	3.5 %	1977-1978
	Wheat	Max disturbance		1979-1983
	Wheat, Sorghum	Min disturbance/summer forage		1984-1999
6	Native Grasses	Native Tallgrass prairie	2.9 %	1977-1978
	Wheat	Max disturbance		1979-1999
7	Native Grasses	Native Tallgrass prairie	2.9 %	1977-1978
	Wheat	Max disturbance		1979-1983
	Wheat	Min disturbance		1984-1999
8	Native Grasses	Native Tallgrass prairie	2.7 %	1977-1978
	Wheat	Max disturbance		1979-1999

Table 4.3. A summarized description of Land management in the WRE watershed treatments for 1977-2000. Adapted from Nelson et al. 2020b.

Figure 4.2 shows the results of comparing observed precipitation and runoff from El Reno, OK to the calculated runoff from the NRCS-SCS CN method. The hydrologic group was found for each plot using the NRCS Web Soil Survey to determine the curve number then runoff was calculated for conditions of both straight row (SR) crops in poor hydrologic condition and SR crops with crop residue in good hydrologic condition. Data from the WRE encompasses a selection of precipitation events through the years 1977-1999. The date for each event and original precipitation data and observed runoff are shown in the appendix, Table 4.15-Table 4.22. Note that the days are not consecutive, and they occur independently of each other. Items with missing dates, precipitation, or runoff were excluded from the figures. Items that had multiples of the same data were also excluded since it was not clear if the runoff was measured more than once a day or if an error was being corrected. Event number corresponds with value on the x-axis.

Precipitation is shown on the figures to give the reader background information on the changes in runoff compared to precipitation amounts. There are several precipitation days that very little runoff is observed, while there are also days that precipitation and observed runoff are almost equal.

Calculated runoff in Figure 4.2, for all eight sites, is usually overestimated compared to the observed runoff. However, there are events that the observed runoff exceeds the calculated runoff and even events where a large portion of the original precipitation was lost as runoff. Possible explanations for this occurrence could be that precipitation fell on already saturated soil, that the precipitation occurred during a quick, intense storm or runoff included moisture measured from a previous rainfall event.

Another odd occurrence in Figure 4.2 is the events where runoff exceeded the precipitation. Event 27 on WRE6 shows 119.975 mm of precipitation and observed runoff of 14.701 cm (147.01mm). Similarly, event 96 at WRE6 shows 3.05 mm of rain and 2.68 cm (26.8 mm) of runoff, and event 91 shows 13.775 mm rain, 4.85 cm of runoff (48.5 mm). These occurrences were likely due to human error in units of measurement, or the runoff contained moisture from previous rainfall events.

a.

b.

c.

d.

e.

f.

g.

h.

Figure 4.2. Precipitation, observed runoff, and calculated runoff in poor and good hydrologic conditions using the NRCS-SCS CN method using data from 8 plots at the Grazinglands Research Laboratory in El Reno, Oklahoma.

The calculated runoff has many discrepancies from the observed runoff. However, the trend between the observed and calculated data is similar and the calculated runoff amounts are comparable enough to be a useful estimation of runoff if there were no other options available. The calculated runoff performed better on plots WRE 5-8 that had

treatments that included an agricultural land use of wheat or sorghum. That is to be expected since the chosen CN for those plots more closely resembles the actual land use. The calculation may be made more accurate if additional curve numbers were used to approximate soil characteristics of the native tallgrass prairie plots WRE1-4. The poor hydrological calculation and the good hydrological calculation appeared to have few discrepancies between the calculations. It is also worth noting that an additional study occurring at the Grazinglands Research Laboratory WRE measured runoff on grazed, ungrazed, fallow, and summer legume lands with simulated 15 min, 100 mm storms and found a large portion of precipitation was lost to runoff occurring on fallow, grazed lands (Daniel et al. 2006). Also, in the study, a mitigation strategy of placing surface water impoundment and catchment below an area of high runoff was suggested.

Precipitation Probabilities

Daily precipitation amounts from 1948 to 2019 were analyzed and the probability of exceedance was calculated using the observed data using the number of days above a given threshold then the total number of precipitation days. Note that the days without rain were not considered in this calculation of probability.

The threshold amounts from 10 to 150 mm at increments of 10 mm were used to calculate the probability of exceedance (PE) of a precipitation day receiving at least the threshold amount compared to the total number of precipitation days. Using the probability of exceedance, the return period (T_{days}) for the actual observations is calculated as $T_{\text{days}}=1/P$. Then the return period in terms of years was also calculated $T_{\text{years}}=365/P$.

RESULTS

Calculation of Soil Runoff

Results from the calculation of soil runoff for each of the 10 stations are shown below in

Figure 4.3. Runoff amount widely varied to under 50 mm of runoff per year to 450 mm. Runoff was largely dependent on the hydrological group found from the web soil survey which influences the I_a amount. GRI and MSN had the highest I_a value of the stations in this study. Each station showed an increase in the mean runoff between the two periods of 1960-1989, and 1990-2019. As stated in Chapter 2, the 30-year periods were chosen due to the 1950s being a known period of severe drought. Each station also saw an increase in mean precipitation during the same 30-year period. Many stations also saw an increase in the linear trendline.

a.

b.

c.

d.

e.

f.

g.

h.

i.

j.

Figure 4.3. Annual runoff amounts, with 15-year double running average, linear regression, and 30-year mean for 1960-1989 and 1990-2019 at a. DSM, b. EVV, c. FWA, d. GRI, e. HON, f. MSN, g. PIA, h. SGF, i. SUX, j. TOP. F-test indicates significance.

Monthly runoff estimates are shown in Figure 4.4 for the full period of study as well as the two 30-year periods, 1960-1989, and 1990-2019. There is considerable variation within each location and even between the 30-year period at each site. The pattern generally follows the expected increase in runoff through the spring, and summer, before decreasing in fall. Many sites experience a lull in runoff during summer months (specifically July and August) due to the limited number of rain events that may occur during those months including, DSM, GRI, MSN, PIA, SGF, TOP. The locations of FWA, HON, and MSN were stacked in a way that is indicative of increasing precipitation as the site entered the 21st century, the signal from the other sites is more complicated.

a.

b.

c.

d.

e.

f.

Figure 4.4. Average monthly runoff for the full period of record 1948-2019, 1960-1989, and 1990-2019 for a. DSM, b. EVV, c. FWA, d. GRI, e. HON, f. MSN, g. PIA, h. SGF, i. SUX, j. TOP.

Extreme Precipitation

The result of the PE calculation is shown for each station in Table 4.4 - Table 4.13. At some locations, the threshold amount of precipitation did not occur. When this occurred, the return period and probability of exceedance are marked as not applicable (N/A) because those quantities could not be calculated using current records. Also, the probability of exceedance and the number of days a location received over the threshold amount of precipitation is shown for each 30-year period from 1960-1989, and 1990-

2019. Values are shown in bold when the PE for the earlier period of 1960-1989 is larger than 1990-2019.

Notice, that several stations did not have records of a precipitation event that went up to 150 mm. The probability curve only extends to the highest threshold amount attained, since not enough records exist to calculate a probability from an observed event. Also, note the repeating values of the probability of exceedance and return period. This happens when the thresholds have the same number of events occurring. For example, DSM's highest recorded precipitation amount was 157 mm. From the threshold amounts of 120 to 150 mm, this event is the only event that occurred, so the probability of exceedance for the 120, 130, 140, 150 thresholds are identical. Similar situations also occur at the other stations. In theory, the probability of reaching each threshold is not identical, but with only a limited recorded history this is as much as we can calculate using this method. A linear fit applied to the probability to resolve this issue is shown in the cumulative frequency distribution graphs in Figure 4.5.

c.

d.

e.

f.

g.

h.

Figure 4.5. Cumulative Frequency Distribution graph with a linear fit for a. DSM, b. EVV, c. FWA, d. GRI, e. HON, f. MSN, g. PIA, h. SGF, i. SUX, j. TOP.

Note in Table 4.13 at TOP, for 10 mm and 40 mm, a decrease in PE occurred between the 30-year periods but an increase in days of precipitation above the threshold occurred. The denominator of the probability formula is responsible for the contradiction. The period between 1960-1989 received 2874 precipitation days but 1990-2019 received 2958 days.

Precip Value (mm)	PE 1948-2019	Return Period		PE		Days	
		(days)	(years)	1960-1989	1990-2019	1960-1989	1990-2019
10	0.2484	4	0.01	0.2375	0.2671	781	910
20	0.1063	9	0.03	0.0995	0.1186	327	404
30	0.0502	20	0.05	0.0502	0.0549	165	187
40	0.0269	37	0.10	0.0280	0.0282	92	96
50	0.0147	68	0.19	0.0161	0.0147	53	50
60	0.0079	127	0.35	0.0070	0.0094	23	32
70	0.0038	263	0.72	0.0036	0.0044	12	15
80	0.0024	415	1.14	0.0024	0.0032	8	11
90	0.0010	987	2.70	0.0012	0.0012	4	4
100	0.0008	1316	3.60	0.0009	0.0009	3	3
110	0.0004	2631	7.21	0.0006	0.0003	2	1
120	0.0001	7894	21.63	0.0003	N/A	1	0
130	0.0001	7894	21.63	0.0003	N/A	1	0
140	0.0001	7894	21.63	0.0003	N/A	1	0
150	0.0001	7894	21.63	0.0003	N/A	1	0
Total Number of Precipitation Days						3288	3407

Table 4.4. Threshold precipitation value, probability of exceedance (PE), return period in days, and return period in years for DSM. Bold values indicate the earlier period of 1960-1989 is larger than the period of 1990-2019.

Precip Value (mm)	PE 1948-2019	Return Period		PE		Days	
		(days)	(years)	1960-1989	1990-2019	1960-1989	1990-2019
10	0.3171	3	0.01	0.3076	0.3242	1058	1150
20	0.1528	7	0.02	0.1454	0.1573	500	558
30	0.0729	14	0.04	0.0672	0.0818	231	290
40	0.0392	26	0.07	0.0355	0.0434	122	154
50	0.0217	46	0.13	0.0189	0.0254	65	90
60	0.0118	85	0.23	0.0090	0.0152	31	54
70	0.0063	158	0.43	0.0047	0.0082	16	29
80	0.0030	335	0.92	0.0029	0.0037	10	13
90	0.0019	524	1.43	0.0017	0.0025	6	9
100	0.0012	838	2.29	0.0009	0.0017	3	6
110	0.0006	1675	4.59	N/A	0.0014	0	5
120	0.0005	2094	5.74	N/A	0.0011	0	4
130	0.0002	4188	11.47	N/A	0.0006	0	2
140	0.0002	4188	11.47	N/A	0.0006	0	2
150	0.0002	4188	11.47	N/A	0.0006	0	2
Total Number of Precipitation Days						3439	3547

Table 4.5. Threshold precipitation value, probability of exceedance (PE), return period in days, and return period in years for EVV. Bold values indicate the earlier period of 1960-1989 is larger than the period of 1990-2019.

Precip Value (mm)	PE	Return Period		PE		Days	
	1948-2019	(days)	(years)	1960-1989	1990-2019	1960-1989	1990-2019
10	0.2333	4	0.01	0.2202	0.2381	863	967
20	0.0912	11	0.03	0.0799	0.0997	313	405
30	0.0354	28	0.08	0.0242	0.0463	95	188
40	0.0159	63	0.17	0.0084	0.0219	33	89
50	0.0073	137	0.37	0.0046	0.0094	18	38
60	0.0041	245	0.67	0.0028	0.0054	11	22
70	0.0017	598	1.64	0.0008	0.0025	3	10
80	0.0010	957	2.62	0.0003	0.0015	1	6
90	0.0004	2393	6.55	0.0003	0.0005	1	2
100	0.0002	4785	13.11	0.0003	0.0002	1	1
110	0.0002	4785	13.11	0.0003	0.0002	1	1
120	N/A	N/A	N/A	N/A	N/A	N/A	N/A
130	N/A	N/A	N/A	N/A	N/A	N/A	N/A
140	N/A	N/A	N/A	N/A	N/A	N/A	N/A
150	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total Number of Precipitation Days						3919	4061

Table 4.6. Threshold precipitation value, probability of exceedance (PE), return period in days, and return period in years for FWA. Bold values indicate the earlier period of 1960-1989 is larger than the period of 1990-2019.

Precip Value (mm)	PE	Return Period		PE		Days	
	1948-2019	(days)	(years)	1960-1989	1990-2019	1960-1989	1990-2019
10	0.2281	4	0.01	0.2273	0.2329	601	632
20	0.0972	10	0.03	0.0983	0.1039	260	282
30	0.0443	23	0.06	0.0435	0.0490	115	133
40	0.0211	47	0.13	0.0219	0.0247	58	67
50	0.0114	88	0.24	0.0117	0.0122	31	33
60	0.0062	160	0.44	0.0057	0.0081	15	22
70	0.0034	298	0.82	0.0034	0.0041	9	11
80	0.0018	568	1.56	0.0011	0.0026	3	7
90	0.0011	893	2.45	0.0008	0.0015	2	4
100	0.0010	1042	2.86	0.0008	0.0011	2	3
110	0.0005	2084	5.71	0.0004	0.0004	1	1
120	0.0003	3127	8.57	0.0004	0.0004	1	1
130	0.0003	3127	8.57	0.0004	0.0004	1	1
140	0.0003	3127	8.57	0.0004	0.0004	1	1
150	0.0002	6253	17.13	N/A	0.0004	0	1
Total Number of Precipitation Days						2644	2714

Table 4.7. Threshold precipitation value, probability of exceedance (PE), return period in days, and return period in years for GRI. Bold values indicate the earlier period of 1960-1989 is larger than the period of 1990-2019.

Precip Value (mm)	PE	Return Period		PE		Days	
	1948-2019	(days)	(years)	1960-1989	1990-2019	1960-1989	1990-2019
10	0.1732	6	0.02	0.1659	0.1941	456	551
20	0.0675	15	0.04	0.0582	0.0807	160	229
30	0.0284	35	0.10	0.0251	0.0338	69	96
40	0.0138	73	0.20	0.0113	0.0169	31	48
50	0.0066	152	0.42	0.0055	0.0085	15	24
60	0.0030	334	0.92	0.0025	0.0039	7	11
70	0.0022	445	1.22	0.0018	0.0028	5	8
80	0.0012	835	2.29	0.0007	0.0018	2	5
90	0.0007	1336	3.66	0.0007	0.0007	2	2
100	0.0004	2227	6.10	0.0007	0.0000	2	0
110	0.0001	6681	18.30	0.0004	0.0000	1	0
120	0.0001	6681	18.30	0.0004	0.0000	1	0
130	0.0001	6681	18.30	0.0004	0.0000	1	0
140	N/A	N/A	N/A	N/A	N/A	0	0
150	N/A	N/A	N/A	N/A	N/A	0	0
Total Number of Precipitation Days						2749	2839

Table 4.8. Threshold precipitation value, probability of exceedance (PE), return period in days, and return period in years for HON. Bold values indicate the earlier period of 1960-1989 is larger than the period of 1990-2019.

Precip Value (mm)	PE	Return Period		PE		Days	
	1948-2019	(days)	(years)	1960-1989	1990-2019	1960-1989	1990-2019
10	0.2138	5	0.01	0.2066	0.2218	744	843
20	0.0904	11	0.03	0.0811	0.1000	292	380
30	0.0397	25	0.07	0.0319	0.0471	115	179
40	0.0207	48	0.13	0.0164	0.0255	59	97
50	0.0103	97	0.27	0.0083	0.0126	30	48
60	0.0058	172	0.47	0.0047	0.0071	17	27
70	0.0030	337	0.92	0.0017	0.0042	6	16
80	0.0021	487	1.33	0.0011	0.0032	4	12
90	0.0013	797	2.18	0.0008	0.0018	3	7
100	0.0002	4383	12.01	0.0000	0.0005	0	2
110	0.0001	8765	24.01	0.0000	0.0003	0	1
120	N/A	N/A	N/A	N/A	N/A	0	0
130	N/A	N/A	N/A	N/A	N/A	0	0
140	N/A	N/A	N/A	N/A	N/A	0	0
150	N/A	N/A	N/A	N/A	N/A	0	0
Total Number of Precipitation Days						3601	3801

Table 4.9. Threshold precipitation value, probability of exceedance (PE), return period in days, and return period in years for MSN. Bold values indicate the earlier period of 1960-1989 is larger than the period of 1990-2019.

Precip Value (mm)	PE 1948-2019	Return Period		PE		Days	
		(days)	(years)	1960-1989	1990-2019	1960-1989	1990-2019
10	0.2589	4	0.01	0.2514	0.2704	869	953
20	0.1136	9	0.02	0.1085	0.1189	375	419
30	0.0516	19	0.05	0.0518	0.0536	179	189
40	0.0249	40	0.11	0.0269	0.0241	93	85
50	0.0109	92	0.25	0.0110	0.0105	38	37
60	0.0063	159	0.44	0.0064	0.0057	22	20
70	0.0037	267	0.73	0.0038	0.0031	13	11
80	0.0018	552	1.51	0.0023	0.0011	8	4
90	0.0012	827	2.27	0.0017	0.0003	6	1
100	0.0008	1182	3.24	0.0012	0.0003	4	1
110	0.0005	2069	5.67	0.0009	N/A	3	0
120	0.0001	8274	22.67	N/A	N/A	0	0
130	N/A	N/A	N/A	N/A	N/A	0	0
140	N/A	N/A	N/A	N/A	N/A	0	0
150	N/A	N/A	N/A	N/A	N/A	0	0
Total Number of Precipitation Days						3457	3524

Table 4.10. Threshold precipitation value, probability of exceedance (PE), return period in days, and return period in years for PIA. Bold values indicate the earlier period of 1960-1989 is larger than the period of 1990-2019.

Precip Value (mm)	PE 1948-2019	Return Period		PE		Days	
		(days)	(years)	1960-1989	1990-2019	1960-1989	1990-2019
10	0.3156	3	0.01	0.3078	0.3291	996	1090
20	0.1539	6	0.02	0.1527	0.1585	494	525
30	0.0817	12	0.03	0.0819	0.0851	265	282
40	0.0455	22	0.06	0.0433	0.0534	140	177
50	0.0228	44	0.12	0.0198	0.0272	64	90
60	0.0124	81	0.22	0.0108	0.0142	35	47
70	0.0077	130	0.36	0.0080	0.0082	26	27
80	0.0046	220	0.60	0.0062	0.0036	20	12
90	0.0033	308	0.84	0.0043	0.0027	14	9
100	0.0021	481	1.32	0.0031	0.0018	10	6
110	0.0013	769	2.11	0.0015	0.0012	5	4
120	0.0007	1538	4.21	0.0006	0.0006	2	2
130	0.0004	2563	7.02	0.0003	0.0003	1	1
140	0.0003	3844	10.53	0.0003	0.0003	1	1
150	0.0003	3844	10.53	0.0003	0.0003	1	1
Total Number of Precipitation Days						3236	3312

Table 4.11. Threshold precipitation value, probability of exceedance (PE), return period in days, and return period in years for SGF. Bold values indicate the earlier period of 1960-1989 is larger than the period of 1990-2019.

Precip Value (mm)	PE	Return Period		PE		Days	
	1948-2019	(days)	(years)	1960-1989	1990-2019	1960-1989	1990-2019
10	0.2187	5	0.01	0.2111	0.2237	626	686
20	0.0918	11	0.03	0.0910	0.0972	270	298
30	0.0392	26	0.07	0.0324	0.0483	96	148
40	0.0205	49	0.13	0.0162	0.0258	48	79
50	0.0120	84	0.23	0.0098	0.0147	29	45
60	0.0057	176	0.48	0.0051	0.0059	15	18
70	0.0027	370	1.01	0.0024	0.0029	7	9
80	0.0014	702	1.92	0.0013	0.0010	4	3
90	0.0010	1003	2.75	0.0010	0.0007	3	2
100	0.0007	1405	3.85	0.0010	0.0007	3	2
110	0.0006	1756	4.81	0.0007	0.0007	2	2
120	0.0003	3512	9.62	0.0003	0.0003	1	1
130	0.0001	7024	19.24	0.0003	0.0000	1	0
140	N/A	N/A	N/A	N/A	N/A	0	0
150	N/A	N/A	N/A	N/A	N/A	0	0
Total Number of Precipitation Days						2966	3067

Table 4.12. Threshold precipitation value, probability of exceedance (PE), return period in days, and return period in years for SUX. Bold values indicate the earlier period of 1960-1989 is larger than the period of 1990-2019.

Precip Value (mm)	PE	Return Period		PE		Days	
	1948-2019	(days)	(years)	1960-1989	1990-2019	1960-1989	1990-2019
10	0.2878	3	0.01	0.2884	0.2860	829	846
20	0.1383	7	0.02	0.1395	0.1403	401	415
30	0.0725	14	0.04	0.0738	0.0751	212	222
40	0.0428	23	0.06	0.0449	0.0439	129	130
50	0.0222	45	0.12	0.0209	0.0250	60	74
60	0.0117	85	0.23	0.0118	0.0132	34	39
70	0.0062	162	0.44	0.0059	0.0074	17	22
80	0.0039	259	0.71	0.0045	0.0041	13	12
90	0.0019	537	1.47	0.0021	0.0017	6	5
100	0.0010	998	2.73	0.0010	0.0010	3	3
110	0.0009	1164	3.19	0.0007	0.0010	2	3
120	0.0003	3492	9.57	N/A	0.0007	0	2
130	0.0001	6984	19.13	N/A	0.0003	0	1
140	0.0001	6984	19.13	N/A	0.0003	0	1
150	N/A	N/A	N/A	N/A	N/A	0	0
Total Number of Precipitation Days						2874	2958

Table 4.13. Threshold precipitation value, probability of exceedance (PE), return period in days, and return period in years for TOP. Bold values indicate the earlier period of 1960-1989 is larger than the period of 1990-2019.

As expected SGF, had the highest prediction for the 100-year event, while PIA had the lowest prediction for the 100-year event. Looking at the past observations, PIA has the highest average for precipitation days but the lowest amount for the maximum daily precipitation. However, PIA's median amount of precipitation was not the lowest. Both GRI and SUX had a lower median of daily precipitation of 2.8mm

Several stations had occurrences of the more recent 30 years showing a lower probability of exceedance than the previous 30 years which were shown in bold on each table. It was important to compare the number of events to the probability of exceedance; some decrease in probability was due to a single day or two of the threshold precipitations amounts. This occurrence while notable does not indicate that a decrease in precipitation will occur at that location due to climate change. Graphs showing the probability of exceedance for the entire period of study, 1960-1989, and 1990-2019 are shown in Figure 4.6.

a.

b.

c.

d.

e.

f.

g.

h.

Figure 4.6. Probability of exceedance of precipitation thresholds for 10 stations in the Midwest. a. DSM, b. EVV, c. FWA, d. GRI, e. HON, f. MSN, g. PIA, h. SGF, i. SUX, j. TOP.

CONCLUSIONS

Based on a comparison between the observed runoff and calculated runoff for El Reno Oklahoma, I_a was too high to be reasonable. There were several occurrences of observed runoff when the CN method showed no runoff occurred. In the eight plots, the I_a ranged from 9-11 mm for poor hydrological conditions and 13- 14 mm for good hydrologic conditions. However, during most of the recorded events at El Reno, the calculated CN runoff overestimated the amount of runoff compared to observation. The CN method also does not account for evaporation of moisture to the air, interception of rainfall by plants and other objects which then leads to evaporation of the moisture from surfaces, and the intensity of rainfall and thus time for percolation into the soil. Other studies that examine a historical record of runoff also have drawbacks. The historical reanalysis of runoff by Huang et al. (1996) calculates monthly runoff to estimate the water budget in the soil and ultimately soil moisture. Soil runoff is parameterized in the model. To create the parameterization, observed runoff data from streamflow's

Oklahoma was used and model performance was tested using observed soil moisture for a long-term dataset in Illinois. The parameters estimated in Oklahoma were applied to the entire United States. Fan and van den Dool 2004 expand the concept of Huang et al. (1996) to global data and explained why even if the parameterized evaporation and runoff are wrong, they will not cause an accumulating bias in the model. The main weight of accuracy in the model is based on accurate observations of precipitation. Huang et al. did not consider the characteristics in the soil to determine runoff amounts. The results were only used to determine monthly runoff amounts so that smaller intricacies could be overlooked. Pruski and Nearing 2002 used the WEPP model to estimate soil runoff and found that increased precipitation makes a larger contribution to runoff than an increased number of days of rainfall, although both methods will contribute to increased runoff in future climates. While the WEPP model has the CN method embedded in it due because of its use of the CREAMS model (Hawkins et al. 2009), it continuously accounts for the soil moisture of the system, but is still susceptible to the weaknesses mentioned in this study and in general of the CN method. More research is needed to find an efficient method to more accurately estimate runoff to consider the intensity of the rainfall, more complex soil and surface roughness conditions, prior soil moisture content, and the effects plants can have in intercepting rainfall.

For the curve number equation to result in a smaller amount of runoff, the initial abstraction amount must be smaller so that runoff is calculated more often for small precipitation days. Because the I_a is used in other portions of the equation, decreasing the I_a would also produce additional runoff creating more overestimation. Many models that incorporate the CN method use it in a continuous system and adjust the CN based on the

moisture of the soil instead of soil characteristics only (Hawkins et al. 2009). Because of the differing CN used and various soil types across the area of study, more observations of soil runoff are needed to test the ability of the CN method. The ground truth of one location is not adequate. It is certainly plausible that the NRCS-SCS CN method may perform well in some areas but poorly in others. More work is also needed to compare the ability of the NRCS-SCS curve number method with other methods for estimating runoff.

Initial abstraction amounts are shown in **Error! Reference source not found.**, similar to the El Reno case, the initial abstraction number was most likely too high for other locations. For example, at MSN initial abstraction is 12.91mm. The probability of any precipitation day being exceeding 10 mm (0.4 in) is 21% so there less than a 21% chance that a precipitation day will produce runoff considering the initial abstract alone at MSN. The probability of a precipitation event exceeding the I_a amount at the other stations in this study is in the range of 20-30% using the NRS-SCS curve number method. Only EVV and SGF had an I_a that had an exceedance probability above 30%.

Since only 20-30% of precipitation days produce runoff, the initial abstraction amount in the NRCS-SCS method may be too high compared to observations. Recent efforts have proposed that the I_a number should be adjusted to be 5% of S (Hawkins et al. 2009). Twenty percent was used in this study. More work is needed to check if an adjustment of I_a would produce more accurate results. Common rainfall intensities of stratiform and convective rain could be considered to produce a reasonable threshold where runoff begins.

The change in mean precipitation and mean runoff between 1960-1989 to 1990-2019 for each station is shown in Table 4.14. Since runoff is directly related to precipitation in the CN equation, the change in runoff was examined as a portion of the total change in precipitation. Results are shown in the third column of Table 4.14. The percentage of runoff to the total precipitation varies widely between the different stations because of the variation in soil type and hydrological group and thus the I_a amount.

	Δ Precip (mm)	Δ Runoff (mm)	$\frac{\Delta \text{ Runoff}}{\Delta \text{ Precip}}$
DSM	102.6	52.5	51%
EVV	131	53.8	41%
FWA	156.8	35.9	23%
GRI	47.9	1.38	3%
HON	89.1	8.38	9%
MSN	154.7	24.63	16%
PIA	59.2	49.93	84%
SGF	81	42.5	52%
SUX	89.1	32.27	36%
TOP	39.4	8.4	21%

Table 4.14. Change(Δ) in mean precipitation (precip) and runoff between the periods 1960-1989 and 1990-2019. The last column represents the portion of the change in runoff compared to the larger change in precipitation.

Examining the increase in mean precipitation compared to mean runoff, most sites are getting a benefit to the increase in precipitation compared to the increase in runoff. Although the timing of the increase in rainfall will be an important factor to consider. Even though rainfall is a limiting factor in agricultural production. The amount of water that is lost to runoff isn't as dramatic of loss as other factors that may decrease plant available water such as increased evapotranspiration demand or long periods with dry days or drought. Reducing runoff is limited in its ability to increase resiliency to a

changing climate with more intense precipitation events and longer periods without rain. However, reducing runoff is important to reduce flood frequency and improving below-ground aquifer recharge.

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APPENDIX

WRE1

SiteID	Event Number	Date	Rainfall (mm)	Runoff (cm)
WRE1	1	05/20/1977	109.85	2.44
WRE1	2	05/26/1977	41.9	0.69
WRE1	3	05/27/1978	100.275	2.35
WRE1	4	06/21/1978	51.325	0.14
WRE1	5	03/22/1979	45.675	0.58
WRE1	6	04/10/1979	55.3	2.24
WRE1	7	05/04/1979	2.45	0.3
WRE1	8	05/21/1979	24.725	1.02
WRE1	9	05/15/1980	81.6	2.41
WRE1	10	05/17/1980	28.325	2.41
WRE1	11	05/29/1980	35.375	0.28
WRE1	12	05/12/1982	109.225	2.859
WRE1	13	05/16/1982	72.825	4.642
WRE1	14	05/24/1982	11.3	0.88
WRE1	15	05/26/1982	11.475	0.173
WRE1	16	05/27/1982	13.85	0.66
WRE1	17	05/20/1983	42.95	1.348
WRE1	18	06/10/1983	43.875	0.378
WRE1	19	06/28/1983	42.05	0.041
WRE1	20	10/20/1983	102.2	9.25
WRE1	21	03/22/1984	35.75	3.062
WRE1	22	03/28/1984	2.575	0.367
WRE1	23	04/07/1984	36.45	2.244
WRE1	24	06/09/1984	101.1	2.673
WRE1	25	02/22/1985	27.925	4.51
WRE1	26	03/03/1985	57.675	4.16
WRE1	27	03/20/1985	34.625	2.67
WRE1	28	03/30/1985	7.825	0.75
WRE1	29	04/27/1985	23.5	0.094
WRE1	30	04/29/1985	35.85	0.326
WRE1	31	05/16/1986	64.775	4.875
WRE1	32	06/16/1986	50.3	1.1367
WRE1	33	09/29/1986	177.85	4.51416
WRE1	34	10/02/1986	58.875	7.45373
WRE1		10/21/1986	50.775	3.83
WRE1		10/21/1986	50.775	
WRE1		10/22/1986	10.525	
WRE1	35	11/04/1986	49.025	3.21
WRE1	36	11/25/1986	23.875	0.67
WRE1	37	02/14/1987	22.6	1.5
WRE1	38	02/26/1987	11.825	0.74
WRE1	39	03/16/1987	24.9	1.03
WRE1	40	03/23/1987	19.7	0.86
WRE1	41	05/27/1987	112.2	7.45
WRE1	42	05/28/1987	32.525	2.44

WRE1	43	08/13/1987	87.575	0.02
WRE1	44	04/01/1988	48.375	6.79
WRE1	45	09/18/1988	151.7	0.156
WRE1	46	03/27/1989	69.025	0.22
WRE1	47	06/03/1989	86.375	0.01
WRE1	48	06/06/1989	35.1	0.12
WRE1	49	06/12/1989	13.7	0.87
WRE1	50	06/13/1989	33.55	0.02
WRE1	51	06/23/1989	24.2	1.7
WRE1	52	09/12/1989	72.375	0.05
WRE1	53	02/22/1990	14.175	0.4
WRE1	54	02/28/1990	28.125	0.32
WRE1	55	03/10/1990	105.575	0.1
WRE1	56	03/29/1990	23.675	0.03
WRE1	57	04/16/1990	59.125	0.15
WRE1	58	04/18/1990	10.45	0.11
WRE1	59	04/24/1990	6.45	0.22
WRE1	60	05/02/1990	73.375	0
WRE1	61	06/27/1992	0.95	0.83
WRE1	62	08/26/1992	39.625	0.07
WRE1	63	11/19/1992	48.925	0.41
WRE1	64	11/24/1992	36.5	0.07
WRE1	65	12/09/1992	13.775	0.26
WRE1	66	12/13/1992	21	0.09

Table 4.15. Rainfall and Runoff data collected at WRE1 Grazinglands Research Laboratory in El Reno, Oklahoma (Nelson et al. 2020b).

WRE2

SiteID	Event Number	Date	Rainfall (mm)	Runoff (cm)
WRE2	1	05/20/1977	109.85	1.47
WRE2	2	05/26/1977	41.9	0.42
WRE2	3	05/27/1978	100.275	1.81
WRE2	4	06/21/1978	51.325	0.06
WRE2	5	03/22/1979	45.675	0.48
WRE2	6	04/10/1979	55.3	1.78
WRE2	7	05/04/1979	2.45	0.04
WRE2	8	05/21/1979	24.725	0.46
WRE2	9	04/25/1980	39.125	0.57
WRE2	10	05/01/1980	11.025	1.77
WRE2	11	05/15/1980	81.6	2.54
WRE2	12	05/17/1980	28.325	2.54
WRE2	13	05/20/1980	15.875	0.37
WRE2	14	05/29/1980	35.375	0.56
WRE2	15	05/12/1982	109.225	4.323
WRE2	16	05/16/1982	72.825	4.912
WRE2	17	05/23/1982	30.725	1.365
WRE2	18	05/26/1982	11.475	0.298
WRE2	19	05/27/1982	13.85	0.724
WRE2	20	05/30/1982	19.1	1.029
WRE2	21	05/13/1983	30.825	0.129
WRE2	22	05/20/1983	42.95	1.526
WRE2	23	05/30/1983	35.225	0.53
WRE2	24	06/10/1983	43.875	0.276
WRE2	25	06/28/1983	42.05	0.058
WRE2	26	08/20/1983	110.125	0.492
WRE2	27	10/19/1983	119.975	8.351
WRE2	28	03/22/1984	35.75	3.486
WRE2	29	03/28/1984	2.575	0.4
WRE2		04/08/1984	10.625	2.705
WRE2		04/08/1984	10.625	
WRE2	30	06/09/1984	101.1	1.5
WRE2	31	02/22/1985	27.925	4.15
WRE2	32	03/03/1985	57.675	3.17
WRE2	33	03/20/1985	34.625	2.27
WRE2	34	03/30/1985	7.825	0.712
WRE2	35	04/27/1985	23.5	0.145
WRE2	36	04/29/1985	35.85	2.12
WRE2	37	05/16/1986	64.775	3.77
WRE2	38	06/16/1986	50.3	0.58
WRE2	39	09/29/1986	177.85	3.99
WRE2	40	10/02/1986	58.875	7.27
WRE2		10/21/1986	50.775	3.8
WRE2		10/21/1986	50.775	
WRE2		10/22/1986	10.525	
WRE2	41	11/04/1986	49.025	2.84
WRE2	42	11/25/1986	23.875	0.51

WRE2	43	02/26/1987	11.825	1.51
WRE2	44	03/16/1987	24.9	0.94
WRE2	45	03/23/1987	19.7	0.32
WRE2	46	05/27/1987	112.2	5.53
WRE2	47	05/28/1987	32.525	2.18
WRE2	48	08/13/1987	87.575	0.03
WRE2	49	03/02/1988	57.5	2.22
WRE2	50	04/01/1988	48.375	5.13
WRE2	51	09/18/1988	151.7	0.22
WRE2	52	03/27/1989	69.025	2.24
WRE2	53	06/06/1989	35.1	5.3
WRE2	54	06/12/1989	13.7	3.61
WRE2	55	06/13/1989	33.55	0.1
WRE2	56	06/13/1989	33.55	2.16
WRE2	57	06/23/1989	24.2	0.31
WRE2	58	09/12/1989	72.375	1.84
WRE2	59	02/22/1990	14.175	0.14
WRE2	60	02/28/1990	28.125	2.75
WRE2	61	03/10/1990	105.575	7.52
WRE2	62	03/14/1990	23.55	1.57
WRE2	63	03/29/1990	23.675	0.51
WRE2	64	04/16/1990	59.125	2.52
WRE2	65	04/18/1990	10.45	0.23
WRE2	66	05/02/1990	73.375	4.72
WRE2	67	04/03/1991	25.6	0.007
WRE2	68	06/13/1991	34.725	0.011

Table 4.16. Rainfall and Runoff data collected at WRE Grazinglands Research Laboratory in El Reno, Oklahoma (Nelson et al. 2020b).

WRE3

SiteID	Event Number	Date	Rainfall (mm)	Runoff (cm)
WRE3	1	05/20/1977	109.85	2.53
WRE3	2	05/26/1977	41.9	0.37
WRE3	3	05/27/1978	100.275	2.17
WRE3	4	03/22/1979	45.675	0.63
WRE3	5	04/10/1979	55.3	2.13
WRE3	6	05/04/1979	2.45	0.25
WRE3	7	05/21/1979	24.725	0.99
WRE3	8	05/01/1980	11.025	1.14
WRE3	9	05/15/1980	81.6	2.59
WRE3	10	05/18/1980	17.225	2.32
WRE3	11	05/20/1980	15.875	0.25
WRE3	12	05/29/1980	35.375	0.47
WRE3	13	05/12/1982	109.225	3.599
WRE3	14	05/16/1982	72.825	4.689
WRE3	15	05/23/1982	30.725	0.688
WRE3	16	05/26/1982	11.475	0.135
WRE3	17	05/27/1982	13.85	0.38
WRE3	18	05/30/1982	19.1	0.603
WRE3	19	07/06/1982	44.825	0.04
WRE3	20	05/20/1983	42.95	1.488
WRE3	21	05/30/1983	35.225	0.508
WRE3	22	06/10/1983	43.875	0.515
WRE3	23	06/28/1983	42.05	0.03
WRE3	24	08/20/1983	110.125	0.068
WRE3	25	10/19/1983	119.975	8.592
WRE3	26	03/23/1984	22.975	2.557
WRE3	27	03/28/1984	2.575	0.29
WRE3	28	04/08/1984	10.625	1.822
WRE3	29	06/09/1984	101.1	0.931
WRE3	30	02/22/1985	27.925	3.284
WRE3	31	03/30/1985	7.825	0.59
WRE3	32	04/22/1985	36.575	0.285
WRE3	33	04/27/1985	23.5	0.389
WRE3	34	04/29/1985	35.85	1.55
WRE3	35	05/14/1986	57.425	0.14
WRE3	36	05/16/1986	64.775	4.52
WRE3	37	06/16/1986	50.3	0.7
WRE3	38	09/29/1986	177.85	6.03
WRE3	39	10/02/1986	58.875	6.02
WRE3	40	10/21/1986	50.775	2.58
WRE3	41	11/04/1986	49.025	2.21
WRE3	42	11/25/1986	23.875	0.45
WRE3	43	02/14/1987	22.6	0.95
WRE3	44	03/16/1987	24.9	0.9
WRE3	45	03/23/1987	19.7	0.44
WRE3	46	05/22/1987	24.775	0.01
WRE3	47	05/27/1987	112.2	8.44

WRE3	48	05/28/1987	32.525	2.26
WRE3	49	03/02/1988	57.5	2.28
WRE3	50	03/03/1988	0.775	0.07
WRE3	51	04/01/1988	48.375	6.29
WRE3	52	04/10/1988	0.15	0.11
WRE3	53	04/17/1988	17.45	0.21
WRE3	54	04/29/1988	14.4	0.13
WRE3	55	09/18/1988	151.7	0.33
WRE3	56	03/27/1989	69.025	2.7
WRE3	57	05/17/1989	25.125	0.31
WRE3	58	06/03/1989	86.375	6.45
WRE3	59	06/06/1989	35.1	3.1
WRE3	60	06/13/1989	33.55	2
WRE3	61	06/23/1989	24.2	0.11
WRE3	62	09/12/1989	72.375	0.85
WRE3	63	02/28/1990	28.125	4.13
WRE3	64	03/10/1990	105.575	8.86
WRE3	65	04/18/1990	10.45	3.65
WRE3	66	04/24/1990	6.45	0.14
WRE3	67	05/02/1990	73.375	5.36
WRE3	68	06/02/1990	19.225	0.19
WRE3	69	11/19/1992	48.925	1.45
WRE3	70	11/24/1992	36.5	2.89
WRE3	71	12/09/1992	13.775	1.19
WRE3	72	12/13/1992	21	2.03

Table 4.17. Rainfall and Runoff data collected at WRE Grazinglands Research Laboratory in El Reno, Oklahoma (Nelson et al. 2020b).

WRE4

SiteID	Event Number	Date	Rainfall (mm)	Runoff (cm)
WRE4	1	05/20/1977	109.85	2.92
WRE4		05/25/1977	0	0.37
WRE4	2	05/27/1978	100.275	1.53
WRE4	3	06/21/1978	51.325	0.07
WRE4	4	03/22/1979	45.675	0.1
WRE4	5	04/10/1979	55.3	1.88
WRE4	6	05/20/1979	41.85	0.1
WRE4	7	05/21/1979	24.725	0.47
WRE4	8	05/01/1980	11.025	0.5
WRE4	9	05/15/1980	81.6	1.55
WRE4	10	05/29/1980	35.375	0.11
WRE4	11	05/12/1982	109.225	1.96
WRE4	12	05/16/1982	72.825	4.621
WRE4	13	05/23/1982	30.725	0.702
WRE4	14	05/26/1982	11.475	0.233
WRE4	15	05/27/1982	13.85	0.466
WRE4	16	05/30/1982	19.1	0.599
WRE4	17	07/06/1982	44.825	0.122
WRE4	18	05/20/1983	42.95	0.523
WRE4	19	06/10/1983	43.875	0.154
WRE4	20	08/20/1983	110.125	0.083
WRE4	21	10/20/1983	102.2	5.768
WRE4	22	03/22/1984	35.75	2.209
WRE4	23	03/28/1984	2.575	0.24
WRE4	24	04/07/1984	36.45	1.875
WRE4	25	06/09/1984	101.1	0.461
WRE4	26	03/03/1985	57.675	3.81
WRE4	27	03/20/1985	34.625	1.66
WRE4	28	03/30/1985	7.825	0.687
WRE4	29	04/13/1985	12.7	0.235
WRE4	30	04/22/1985	36.575	0.515
WRE4	31	04/22/1985	36.575	0.1
WRE4	32	04/27/1985	23.5	0.554
WRE4	33	04/29/1985	35.85	1.75
WRE4	34	05/14/1986	57.425	0.18
WRE4	35	05/16/1986	64.775	4.58
WRE4	36	09/29/1986	177.85	4.2
WRE4	37	10/02/1986	58.875	5.63
WRE4		10/21/1986	50.775	2.7
WRE4		10/21/1986	50.775	
WRE4		10/22/1986	10.525	
WRE4	38	11/04/1986	49.025	2.29
WRE4	39	11/25/1986	23.875	0.75
WRE4	40	02/26/1987	11.825	2.41
WRE4	41	03/23/1987	19.7	1.44
WRE4	42	05/27/1987	112.2	7.79
WRE4	43	05/28/1987	32.525	2.14

WRE4	44	03/02/1988	57.5	2.45
WRE4	45	04/01/1988	48.375	6.09
WRE4	46	04/17/1988	17.45	0.31
WRE4	47	04/29/1988	14.4	0.23
WRE4	48	09/18/1988	151.7	0.16
WRE4	49	03/27/1989	69.025	2.62
WRE4	50	06/03/1989	86.375	5.17
WRE4	51	06/06/1989	35.1	2.68
WRE4	52	06/13/1989	33.55	1.77
WRE4	53	06/23/1989	24.2	0.14
WRE4	54	09/12/1989	72.375	0.92
WRE4	55	02/22/1990	14.175	0.6
WRE4	56	02/28/1990	28.125	2.3
WRE4	57	03/10/1990	105.575	9.02
WRE4	58	03/14/1990	23.55	1.42
WRE4	59	03/29/1990	23.675	0.49
WRE4	60	04/16/1990	59.125	3.04
WRE4	61	04/18/1990	10.45	0.24
WRE4	62	05/02/1990	73.375	5.3
WRE4	63	06/02/1990	19.225	0.07
WRE4	64	06/13/1991	34.725	0.04
WRE4	65	11/24/1992	36.5	2.46
WRE4	66	12/09/1992	13.775	0.99
WRE4	67	12/13/1992	21	1.85

Table 4.18. Rainfall and Runoff data collected at WRE Grazinglands Research Laboratory in El Reno, Oklahoma (Nelson et al. 2020b).

WRE5

SiteID	Event Number	Date	Rainfall (mm)		Runoff (cm)
WRE5	1	05/20/1977	109.85	109.85	1.29
WRE5	2	05/26/1977	41.9	41.9	0.26
WRE5	3	05/27/1978	100.275	100.275	0.84
WRE5	4	04/10/1979	55.3	55.3	0.35
WRE5	5	05/20/1979	41.85	41.85	1.24
WRE5	6	05/21/1979	24.725	24.725	0.35
WRE5	7	06/23/1979	59.25	59.25	2.24
WRE5	8	06/24/1979	18.975	18.975	0.7
WRE5	9	07/17/1979	41	41	0.16
WRE5	10	04/25/1980	39.125	39.125	0.14
WRE5	11	05/01/1980	11.025	11.025	0.13
WRE5	12	05/15/1980	81.6	81.6	0.13
WRE5	13	05/17/1980	28.325	28.325	0.69
WRE5	14	05/29/1980	35.375	35.375	0.06
WRE5	15	12/07/1980	33.775	33.775	0.071
WRE5	16	03/28/1981	14.475	14.475	0.019
WRE5	17	06/30/1981	55.125	55.125	0.027
WRE5	18	08/06/1981	48.975	48.975	0.103
WRE5	19	08/16/1981	23.75	23.75	0.171
WRE5	20	10/11/1981	51.875	51.875	1.013
WRE5	21	10/15/1981	19.6	19.6	0.749
WRE5	22	10/31/1981	29.2	29.2	0.866
WRE5	23	05/30/1982	19.1	19.1	0.234
WRE5	24	06/24/1982	18.85	18.85	0.053
WRE5	25	07/06/1982	44.825	44.825	1.72
WRE5	26	03/25/1983	33.75	33.75	0.096
WRE5	27	04/05/1983	12.775	12.775	0.101
WRE5		05/12/1983	0		1.557
WRE5	28	05/14/1983	24	24	1.442
WRE5	29	05/17/1983	12.75	12.75	0.401
WRE5	30	05/20/1983	42.95	42.95	3.06
WRE5	31	05/22/1983	11.875	11.875	0.659
WRE5	32	06/10/1983	43.875	43.875	4.198
WRE5	33	06/11/1983	3.15	3.15	0.008
WRE5		06/27/1983	20.825	20.825	0.015
WRE5		06/27/1983	20.825	20.825	0.231
WRE5	34	06/28/1983	42.05	42.05	3.086
WRE5	35	08/20/1983	110.125	110.125	3.004
WRE5	36	09/11/1983	37.925	37.925	0.124
WRE5	37	10/19/1983	119.975	119.975	4.231
WRE5	38	03/22/1984	35.75	35.75	0.422
WRE5	39	03/27/1984	11.5	11.5	0.23
WRE5	40	04/07/1984	36.45	36.45	1.809
WRE5		04/30/1984	0		0.035
WRE5		05/29/1984	0		0.338
WRE5	41	06/09/1984	101.1	101.1	6.085
WRE5	42	12/31/1984	40.7	40.7	0.225

WRE5	43	02/22/1985	27.925	27.925	1.56
WRE5	44	03/03/1985	57.675	57.675	4.35
WRE5	45	03/20/1985	34.625	34.625	1.47
WRE5	46	03/26/1985	8.95	8.95	0.321
WRE5	47	03/30/1985	7.825	7.825	0.897
WRE5	48	04/13/1985	12.7	12.7	0.166
WRE5		04/22/1985	36.575	36.575	0.184
WRE5		04/22/1985	36.575	36.575	
WRE5		04/22/1985	36.575		0.142
WRE5	49	04/27/1985	23.5	23.5	0.528
WRE5	50	04/29/1985	35.85	35.85	0.983
WRE5	51	06/04/1985	55.6	55.6	0.128
WRE5	52	06/06/1985	12.375	12.375	0.185
WRE5	53	06/11/1985	8.175	8.175	0.016
WRE5	54	09/22/1985	49.175	49.175	1.45
WRE5	55	09/29/1985	31.875	31.875	0.76
WRE5	56	10/17/1985	18.1	18.1	0.63
WRE5	57	04/27/1986	12.75	12.75	0.13
WRE5	58	05/08/1986	36.575	36.575	1.11
WRE5	59	05/09/1986	13.975	13.975	0.11
WRE5	60	05/14/1986	57.425	57.425	2.61
WRE5	61	05/16/1986	64.775	64.775	5.26
WRE5	62	06/14/1986	29.2	29.2	0.17
WRE5	63	06/16/1986	50.3	50.3	2.95
WRE5	64	06/23/1986	29.4	29.4	0.76
WRE5	65	08/05/1986	78.45	78.45	1.39
WRE5		09/29/1986	177.85	177.85	6.74
WRE5		09/29/1986	177.85		
WRE5		09/30/1986	12.05		
WRE5	66	10/02/1986	58.875	58.875	4.05
WRE5	67	10/21/1986	50.775	50.775	0.82
WRE5		11/04/1986	49.025	49.025	1.04
WRE5		11/04/1986	49.025		
WRE5		11/04/1986	49.025		
WRE5	68	11/25/1986	23.875	23.875	0.13
WRE5	69	02/14/1987	22.6	22.6	0.86
WRE5	70	02/26/1987	11.825	11.825	0.5
WRE5	71	03/16/1987	24.9	24.9	1
WRE5		03/23/1987	19.7	19.7	0.14
WRE5		03/23/1987	19.7	19.7	0.05
WRE5		03/23/1987	19.7	19.7	0.2
WRE5	72	05/21/1987	41.525	41.525	1.34
WRE5	73	05/23/1987	29.55	29.55	1.65
WRE5	74	05/25/1987	13.9	13.9	0.41
WRE5	75	05/26/1987	10.3	10.3	0.06
WRE5	76	05/27/1987	112.2	112.2	7.24
WRE5	77	05/28/1987	32.525	32.525	1.94
WRE5	78	06/02/1987	15.225	15.225	0.21
WRE5	79	06/19/1987	26.775	26.775	0.09
WRE5	80	07/02/1987	29.8	29.8	0.25

WRE5	81	08/13/1987	87.575	87.575	1.75
WRE5	82	09/20/1987	21.225	21.225	0.05
WRE5	83	11/15/1987	25.5	25.5	0.38
WRE5	84	03/02/1988	57.5	57.5	0.71
WRE5	85	04/01/1988	48.375	48.375	3.3
WRE5	86	09/18/1988	151.7	151.7	0.74
WRE5	87	03/27/1989	69.025	69.025	2.04
WRE5	88	06/03/1989	86.375	86.375	2.45
WRE5	89	06/06/1989	35.1	35.1	1.98
WRE5	90	06/13/1989	33.55	33.55	1.42
WRE5	91	06/23/1989	24.2	24.2	1.11
WRE5	92	08/14/1989	57.475	57.475	0.23
WRE5	93	09/01/1989	24.7	24.7	0.05
WRE5	94	09/12/1989	72.375	72.375	4.21
WRE5	95	10/05/1989	19.925	19.925	0.17
WRE5	96	02/22/1990	14.175	14.175	0.34
WRE5	97	02/28/1990	28.125	28.125	1.95
WRE5	98	03/10/1990	105.575	105.575	8.8
WRE5	99	03/14/1990	23.55	23.55	1.33
WRE5	100	04/16/1990	59.125	59.125	3.1
WRE5	101	05/26/1990	32.2	32.2	3.4
WRE5	102	05/27/1990	11.925	11.925	1.04
WRE5	103	06/02/1990	19.225	19.225	0.6
WRE5					0.01
WRE5					0.056
WRE5					0.042
WRE5	104	07/13/1992	26.025	26.025	0.04
WRE5	105	10/28/1992	31.1	31.1	1.24
WRE5	106	11/24/1992	36.5	36.5	2.28
WRE5	107	12/09/1992	13.775	13.775	0.57

Table 4.19. Rainfall and Runoff data collected at WRE Grazinglands Research Laboratory in El Reno, Oklahoma (Nelson et al. 2020b).

WRE6

SiteID	Event number	Date	Rainfall (mm)	Runoff (cm)
WRE6	1	05/27/1978	100.275	1.3
WRE6	2	04/10/1979	55.3	0.17
WRE6	3	05/04/1979	2.45	0.04
WRE6	4	05/21/1979	24.725	0.15
WRE6	5	06/23/1979	59.25	2.23
WRE6	6	06/24/1979	18.975	0.73
WRE6	7	07/17/1979	41	0.09
WRE6	8	05/15/1980	81.6	0.1
WRE6	9	05/29/1980	35.375	0.13
WRE6	10	08/06/1981	48.975	0.075
WRE6	11	10/11/1981	51.875	0.98
WRE6	12	10/31/1981	29.2	0.769
WRE6	13	05/23/1982	30.725	0.318
WRE6	14	05/27/1982	13.85	0.271
WRE6	15	05/30/1982	19.1	0.597
WRE6	16	06/24/1982	18.85	0.123
WRE6	17	07/06/1982	44.825	1.599
WRE6	18	03/25/1983	33.75	0.181
WRE6	19	04/05/1983	12.775	0.231
WRE6		05/12/1983	0	0.022
WRE6	20	05/14/1983	24	0.058
WRE6	21	05/22/1983	11.875	0.523
WRE6	22	05/22/1983	11.875	0.015
WRE6	23	06/10/1983	43.875	0.175
WRE6	24	06/28/1983	42.05	0.187
WRE6	25	08/20/1983	110.125	1.948
WRE6	26	10/19/1983	119.975	14.701
WRE6		13/22/84	NA	1.963
WRE6		04/27/1984	0	0.037
WRE6		04/30/1984	0	0.122
WRE6	27	06/09/1984	101.1	0.459
WRE6	28	02/22/1985	27.925	2.21
WRE6	29	03/03/1985	57.675	5.08
WRE6	30	03/20/1985	34.625	1.96
WRE6	31	03/26/1985	8.95	0.406
WRE6	32	03/30/1985	7.825	1.06
WRE6	33	04/13/1985	12.7	0.162
WRE6	34	04/22/1985	36.575	0.166
WRE6	35	04/22/1985	36.575	0.18
WRE6	36	04/27/1985	23.5	0.584
WRE6	37	04/29/1985	35.85	1.5
WRE6	38	09/22/1985	49.175	0.551
WRE6	39	09/29/1985	31.875	0.817
WRE6	40	10/14/1985	11.325	0.026
WRE6	41	10/17/1985	18.1	0.744
WRE6	42	05/16/1986	64.775	2.7
WRE6	43	06/16/1986	50.3	1.31

WRE6	44	06/23/1986	29.4	0.09
WRE6	45	09/29/1986	177.85	8.59
WRE6	46	09/30/1986	12.05	0.36
WRE6		10/02/1986	58.875	
WRE6	47	10/11/1986	13.125	0.12
WRE6	48	10/21/1986	50.775	2.77
WRE6		11/04/1986	49.025	2.97
WRE6		11/04/1986	49.025	
WRE6		11/04/1986	49.025	
WRE6	49	02/01/1987	7.45	0.07
WRE6	50	02/14/1987	22.6	1.01
WRE6	51	02/26/1987	11.825	0.44
WRE6	52	03/16/1987	24.9	1.97
WRE6	53	03/23/1987	19.7	0.12
WRE6	54	03/23/1987	19.7	0.27
WRE6	55	05/23/1987	29.55	0.33
WRE6	56	05/27/1987	112.2	7.6
WRE6	57	05/28/1987	32.525	2.39
WRE6	58	06/02/1987	15.225	0.22
WRE6	59	06/19/1987	26.775	0.43
WRE6	60	06/22/1987	9.725	0.03
WRE6	61	07/02/1987	29.8	0.2
WRE6	62	08/13/1987	87.575	2.59
WRE6	63	08/13/1987	87.575	0.17
WRE6	64	09/12/1987	23.775	0.02
WRE6	65	09/18/1987	22.05	0.08
WRE6	66	09/20/1987	21.225	0.62
WRE6	67	09/28/1987	17.325	0.21
WRE6	68	11/15/1987	25.5	0.28
WRE6	69	03/02/1988	57.5	1.04
WRE6	70	04/01/1988	48.375	4.63
WRE6	71	09/18/1988	151.7	0.53
WRE6	72	03/27/1989	69.025	2.59
WRE6	73	06/03/1989	86.375	1.16
WRE6	74	06/06/1989	35.1	2.73
WRE6	75	06/13/1989	33.55	1.61
WRE6	76	06/23/1989	24.2	0.59
WRE6	77	09/12/1989	72.375	4.52
WRE6	78	10/06/1989	11.275	0.05
WRE6	79	02/28/1990	28.125	0.73
WRE6	80	03/10/1990	105.575	8.42
WRE6	81	03/14/1990	23.55	1.4
WRE6	82	04/16/1990	59.125	3.36
WRE6	83	04/18/1990	10.45	0.09
WRE6	84	05/02/1990	73.375	4.67
WRE6	85	05/29/1990	21.25	0.04
WRE6	86	06/02/1990	19.225	0.41
WRE6	87	09/21/1990	37.45	0.8
WRE6	88	04/03/1991	25.6	0.006
WRE6	89	09/18/1991	33.45	0.364
WRE6	90	10/28/1991	32.75	0.874

WRE6	91	11/16/1991	17.325	0.118
WRE6	92	11/19/1991	10.425	0.165
WRE6	93	03/04/1992	12.3	0.1
WRE6	94	08/26/1992	39.625	0.6
WRE6	95	10/28/1992	31.1	1.46
WRE6	96	11/11/1992	44.95	1.26
WRE6	97	11/22/1992	3.05	2.68
WRE6	98	11/24/1992	36.5	1.81
WRE6	99	12/09/1992	13.775	1.08
WRE6	100	12/13/1992	21	1.64

Table 4.20. Rainfall and Runoff data collected at WRE Grazinglands Research Laboratory in El Reno, Oklahoma (Nelson et al. 2020b).

WRE7

SiteID	Event Number	Date	Rainfall (mm)	Runoff (cm)
WRE7	1	05/20/1977	109.85	0.61
WRE7	2	05/26/1977	41.9	0.11
WRE7	3	05/27/1978	100.275	1.04
WRE7	4	06/21/1978	51.325	0.01
WRE7	5	04/10/1979	55.3	0.23
WRE7	6	05/04/1979	2.45	0.04
WRE7	7	05/20/1979	41.85	0.42
WRE7	8	05/21/1979	24.725	0.13
WRE7	9	06/23/1979	59.25	1.4
WRE7	10	06/24/1979	18.975	0.94
WRE7	11	07/05/1979	32.425	0.08
WRE7	12	07/17/1979	41	0.31
WRE7	13	07/18/1979	28.975	0.67
WRE7	14	04/25/1980	39.125	0.09
WRE7	15	05/01/1980	11.025	0.1
WRE7	16	05/15/1980	81.6	0.13
WRE7	17	05/17/1980	28.325	0.78
WRE7	18	05/29/1980	35.375	0.08
WRE7	19	08/16/1981	23.75	0.018
WRE7	20	10/11/1981	51.875	0.018
WRE7	21	10/16/1981	20.4	0.007
WRE7	22	10/31/1981	29.2	0.041
WRE7	23	05/12/1982	109.225	0.048
WRE7	24	05/16/1982	72.825	0.775
WRE7	25	05/24/1982	11.3	0.129
WRE7	26	05/30/1982	19.1	0.284
WRE7	27	08/20/1983	110.125	2.964
WRE7	28	10/19/1983	119.975	11.6
WRE7	29	10/19/1983	119.975	0.149
WRE7	30	03/22/1984	35.75	1.248
WRE7	31	03/27/1984	11.5	0.333
WRE7	32	04/07/1984	36.45	2.271
WRE7		04/30/1984	0	0.047
WRE7	33	06/09/1984	101.1	0.357
WRE7	34	02/22/1985	27.925	2.71
WRE7	35	03/03/1985	57.675	4.03
WRE7	36	03/20/1985	34.625	1.01
WRE7	37	03/26/1985	8.95	0.04
WRE7	38	03/30/1985	7.825	0.279
WRE7	39	04/27/1985	23.5	0.045
WRE7	40	04/29/1985	35.85	0.474
WRE7	41	09/29/1985	31.875	0.361
WRE7	42	10/17/1985	18.1	1.16
WRE7	43	05/14/1986	57.425	3.01
WRE7	44	05/16/1986	64.775	0.76
WRE7	45	06/16/1986	50.3	0.94
WRE7	46	06/23/1986	29.4	0.09
WRE7	47	08/05/1986	78.45	1.31

WRE7	48	09/29/1986	177.85	10.83
WRE7	49	09/30/1986	12.05	0.01
WRE7	50	10/02/1986	58.875	7.11
WRE7	51	10/21/1986	50.775	3
WRE7		10/21/1986	50.775	
WRE7		10/22/1986	10.525	
WRE7	52	11/04/1986	49.025	2.86
WRE7		11/04/1986	49.025	
WRE7		11/04/1986	49.025	
WRE7	53	11/25/1986	23.875	0.28
WRE7	54	02/14/1987	22.6	0.66
WRE7	55	02/26/1987	11.825	0.37
WRE7	56	03/16/1987	24.9	1.42
WRE7	57	05/27/1987	112.2	5.42
WRE7	58	05/28/1987	32.525	1.73
WRE7	59	06/19/1987	26.775	0.06
WRE7	60	06/30/1987	3.875	0.14
WRE7	61	07/02/1987	29.8	1.21
WRE7	62	08/13/1987	87.575	2.11
WRE7	63	09/20/1987	21.225	0.72
WRE7	64	11/15/1987	25.5	0.15
WRE7	65	03/02/1988	57.5	1.72
WRE7	66	04/01/1988	48.375	4.93
WRE7	67	09/18/1988	151.7	2.62
WRE7	68	03/27/1989	69.025	3.72
WRE7	69	05/12/1989	79.375	0.51
WRE7	70	05/17/1989	25.125	0.25
WRE7	71	06/03/1989	86.375	5.83
WRE7	72	06/06/1989	35.1	3.44
WRE7	73	06/13/1989	33.55	2.07
WRE7	74	06/23/1989	24.2	0.53
WRE7	75	08/14/1989	57.475	1.91
WRE7	76	09/01/1989	24.7	0.14
WRE7	77	09/12/1989	72.375	6.17
WRE7	78	10/06/1989	11.275	0.14
WRE7	79	02/22/1990	14.175	0.56
WRE7	80	02/28/1990	28.125	2.36
WRE7	81	03/10/1990	105.575	5.86
WRE7	82	03/14/1990	23.55	1.69
WRE7	83	04/16/1990	59.125	2.54
WRE7	84	04/18/1990	10.45	0.1
WRE7	85	05/02/1990	73.375	4.48
WRE7	86	06/02/1990	19.225	0.07
WRE7	87	09/21/1990	37.45	0.51
WRE7	88	04/03/1991	25.6	0.034
WRE7	89	06/13/1991	34.725	0.026
WRE7	90	09/18/1991	33.45	0.23
WRE7	91	11/16/1991	17.325	0.6
WRE7	92	11/19/1991	10.425	0.26
WRE7	93	06/08/1992	5.1	0.03
WRE7	94	07/13/1992	26.025	0.02

WRE7		08/29/1992	0	2.55
WRE7	95	09/05/1992	15.175	0.07
WRE7	96	11/22/1992	3.05	1.36
WRE7	97	11/24/1992	36.5	2.82
WRE7	98	12/13/1992	21	3.58

Table 4.21. Rainfall and Runoff data collected at WRE Grazinglands Research Laboratory in El Reno, Oklahoma (Nelson et al. 2020b).

WRE8

SiteID	Event Number	Date	Rainfall (mm)	Runoff (cm)
WRE8	1	05/20/1977	109.85	0.73
WRE8	2	05/26/1977	41.9	0.17
WRE8	3	05/27/1978	100.275	1.66
WRE8	4	06/21/1978	51.325	0.01
WRE8	5	04/10/1979	55.3	0.09
WRE8	6	05/04/1979	2.45	0.03
WRE8	7	05/20/1979	41.85	0.07
WRE8	8	06/23/1979	59.25	0.58
WRE8	9	06/24/1979	18.975	0.76
WRE8	10	07/17/1979	41	0.12
WRE8	11	07/18/1979	28.975	0.58
WRE8	12	04/25/1980	39.125	0.1
WRE8	13	05/01/1980	11.025	0.12
WRE8	14	05/15/1980	81.6	0.2
WRE8	15	05/17/1980	28.325	1
WRE8	16	05/20/1980	15.875	0.06
WRE8	17	12/07/1980	33.775	0.043
WRE8	18	05/29/1980	35.375	0.16
WRE8	19	03/28/1981	14.475	0.022
WRE8	20	05/29/1981	29.225	0.006
WRE8	21	10/11/1981	51.875	0.072
WRE8	22	10/16/1981	20.4	0.078
WRE8	23	10/31/1981	29.2	0.016
WRE8	24	05/24/1982	11.3	0.178
WRE8	25	05/30/1982	19.1	0.3
WRE8	26	07/06/1982	44.825	1.177
WRE8		05/12/1983	0	0.162
WRE8	27	05/20/1983	42.95	0.713
WRE8	28	05/22/1983	11.875	0.055
WRE8	29	05/30/1983	35.225	0.05
WRE8	30	06/10/1983	43.875	0.228
WRE8	31	08/20/1983	110.125	1.158
WRE8	32	09/11/1983	37.925	0.033
WRE8	33	10/19/1983	119.975	0.086
WRE8	34	10/19/1983	119.975	11.851
WRE8	35	03/22/1984	35.75	1.238
WRE8	36	03/28/1984	2.575	0.353
WRE8	37	04/07/1984	36.45	2.124
WRE8	38	06/09/1984	101.1	0.08
WRE8	39	02/22/1985	27.925	2.47
WRE8	40	03/03/1985	57.675	3.95
WRE8	41	03/20/1985	34.625	1.01
WRE8	42	03/26/1985	8.95	0.067
WRE8	43	03/30/1985	7.825	0.315
WRE8	44	04/13/1985	12.7	0.045
WRE8	45	04/22/1985	36.575	0.065
WRE8	46	04/27/1985	23.5	0.101
WRE8	47	04/29/1985	35.85	0.601

WRE8	48	09/22/1985	49.175	0.013
WRE8	49	09/29/1985	31.875	0.973
WRE8	50	10/17/1985	18.1	0.722
WRE8	51	05/16/1986	64.775	1.89
WRE8	52	06/16/1986	50.3	0.89
WRE8	53	08/05/1986	78.45	0.44
WRE8	54	09/29/1986	177.85	7.72
WRE8	55	10/02/1986	58.875	6.06
WRE8	56	10/21/1986	50.775	1.68
WRE8	57	11/04/1986	49.025	1.41
WRE8		11/04/1986	49.025	
WRE8		11/04/1986	49.025	
WRE8	58	11/25/1986	23.875	0.38
WRE8	59	02/14/1987	22.6	0.89
WRE8	60	03/16/1987	24.9	0.85
WRE8	61	03/23/1987	19.7	0.14
WRE8	62	03/23/1987	19.7	0.3
WRE8	63	05/23/1987	29.55	0.02
WRE8	64	05/27/1987	112.2	4.22
WRE8	65	05/28/1987	32.525	1.54
WRE8	66	06/02/1987	15.225	0.11
WRE8	67	06/19/1987	26.775	0.21
WRE8	68	07/02/1987	29.8	0.04
WRE8	69	08/13/1987	87.575	0.25
WRE8	70	09/12/1987	23.775	0.1
WRE8	71	09/18/1987	22.05	0.1
WRE8	72	09/20/1987	21.225	1.47
WRE8	73	09/28/1987	17.325	0.67
WRE8	74	11/15/1987	25.5	0.01
WRE8	75	03/02/1988	57.5	1.24
WRE8	76	04/01/1988	48.375	4.38
WRE8	77	09/18/1988	151.7	1.68
WRE8	78	06/03/1989	86.375	1.7
WRE8	79	06/06/1989	35.1	1.68
WRE8	80	06/13/1989	33.55	1.46
WRE8	81	06/23/1989	24.2	0.22
WRE8	82	09/12/1989	72.375	4.14
WRE8	83	02/28/1990	28.125	0.18
WRE8	84	03/10/1990	105.575	9.19
WRE8	85	03/14/1990	23.55	1.36
WRE8	86	04/16/1990	59.125	2.07
WRE8	87	05/02/1990	73.375	3.59
WRE8	88	08/26/1992	39.625	0.86
WRE8	89	10/28/1992	31.1	1.17
WRE8	90	11/24/1992	36.5	7.05
WRE8	91	12/09/1992	13.775	4.85

Table 4.22. Rainfall and Runoff data collected at WRE Grazinglands Research Laboratory in El Reno, Oklahoma (Nelson et al. 2020b).

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VITA

Jane Marie Niemeyer grew up in Bowling Green and was raised on a family farm. From a young age, Jane became fascinated by the weather and the effects that it had on her family's business. Jane completed her undergraduate degree at Mizzou in Atmospheric Science in 2007 before deciding to pursue a Master of Science in Learning, Teaching & Curriculum - Secondary Mathematics Education. She completed her master's degree in 2013 and taught high school math for 3 years. While she learned a lot while teaching, Jane happily returned to Atmospheric Science and Mizzou for a PhD in 2016. Her focus was to combine her interest in Atmospheric Science and background of agriculture for a research topic. While finishing that goal, Jane started working at the National Weather Service Training Center in Kansas City, MO. After submitting, the author will continue to work at the Training Center, and excitedly find ways to spend free time without papers, grading, part-time jobs, and assignments.