ASSESSING IMPACTS OF CLIMATE CHANGE ON KANSAS WATER RESOURCES: RAINFALL TRENDS AND RISK ANALYSIS OF WATER CONTROL STRUCTURES

by

VAHID RAHMANI

B.S., Amirkabir University of Technology, 2007
M.S., Shiraz University, 2009

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Biological and Agricultural Engineering
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Abstract

Precipitation impacts water resources management, hydrologic structures, agricultural production, and recreational activities, all of which significantly affect a state's economy. Water control structure design is based on the maximum runoff rate resulting from storms with a specific return period and duration. The Rainfall Frequency Atlas (National Weather Service Technical Paper 40, 1961) (TP-40) provided statistical rainfall analysis as the basis for hydrologic structure design until the information was updated for Kansas in February 2013 (National Oceanic and Atmospheric Administration Atlas 14, volume 8) (Atlas-14). With growing concern about the effects of global climate change and predictions of more precipitation and extreme weather events, it is necessary to explore rainfall distribution patterns using the most current and complete data available. In this work, the changes in rainfall patterns were studied using the daily rainfall data from 23 stations in Kansas and 15 stations from adjacent states with daily rainfall data of 1890 through 2012. Analysis showed an increase in extreme precipitation events in Kansas with increase in magnitude from the northwest to southeast part of the state. A comparison of results of the TP-40 analysis to period 1980–2009, showed that approximately 84% of the state had an increase in short-term rainfall event magnitudes. In addition, trend analyzes on the total annual rainfall indicated a gradual increase at 21 out of 23 stations, including eight statistically significant trends. A change-point analysis detected a significant sudden change at twelve stations as early as 1940 and as recently as 1980. The increasing trend, particularly after the significant change-points, is useful in updating water management plans and can assist with agricultural production decisions such as crop selection and new plant variety development. A comparison between 10-yr, 24-hr storms from TP-40 and Atlas-14 indicated a change of -12% to 5% in Kansas. However, the number of exceedances from the 10-yr, 1-, 2-, 3-, 4-, 7-, and 10-day storms demonstrated a tendency towards more exceedances, particularly in the last five decades. Results of this study are useful for hydrologic structure design and water resources management in order to prevent accepting additional risk of failure because of the current changing climate.

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Dedication

To all of those who have helped me in my life, especially my wife Sogand, and my family.

Chapter 1 - Introduction

The Intergovernmental Panel on Climate Change, has reported changes in global average temperature and precipitation. An increasing temperature trend of 0.74 ºC has been estimated for 1906 to 2005, with a slope approximately twice as steep in the last 50 years. In addition, statistically significant precipitation increase has been observed in portions of eastern North and South America, northern Europe, and northern and central Asia. In Sahel, the Mediterranean, southern Africa, and areas of southern Asia, precipitation decrease has been observed (Solomon, 2007).

Climate change impacts have been studied on hydrological processes and water resources (Bates et al., 2008; Vörösmarty et al., 2000), natural systems (Parmesan and Yohe, 2003), ecological environments (Walther et al., 2002), human behavior and health (Hughes et al., 2003; Patz et al., 2005), cultures (DeMenocal, 2001), economy (Stern, 2007), and food supply (Rosenzweig and Parry, 1994) since the early 1900s (Langbein and Schumm, 1958; Thiessen, 1911). Adams et al. (1990) discussed impacts of global climate change on US agriculture production and economy and concluded that agricultural production is sensitive to climate change. Precipitation and temperature changes reduce crop yields and increase crop water demands. The price of US agricultural production would increase based on outputs of a global climate change model, developed by the Princeton Geophysical Fluid Dynamics Laboratory prediction.

Many disasters, such as flooding and crop failure, and their societal and behavioral aspects are connected to climate fluctuations. The World Health Organization reports a significant number of deaths (27.82 deaths/million population) attributed to climate change annually (McMichael and Woodruff, 2005). McMichael et al. (2004) studied impacts of global climate change on human health. They indicated that climate variability, thermal extremes, and weather disasters such as floods, increase human deaths and injuries. Climate change can result in decreased cold mortalities or increased crop yields in temperate zones, but these impacts are negligible compared to increase in infectious disease and malnutrition in developing countries.

The National Academy of Engineering listed access to clean water as a Global Grand Challenge for the 21st century (Gleick, 2006; Watkins, 2009; WHO/UNICEF Joint Water Supply and Sanitation Monitoring Programme, 2005). Dependable access to clean water requires understanding global and regional climate impact on water resources in order to more effectively manage water and protect against flooding and structural damage.

Changes in precipitation and temperature impact runoff generation rate. Solomon et al. (2007) predicted a greater rate of runoff for higher latitudes and wet tropical regions and a decline in runoff rate for drier parts of the world. In addition, an increase in extreme rainfall trends have been estimated (Klein Tank and Können, 2003; Rahmstorf and Coumou, 2011). Increased runoff and heavy rainfall events augment flood risk which can have social, economic, environmental, and hydrological consequences.

In the current changing climate, can water resources be adapted with new climate conditions? How vulnerable are existing water resources and hydrologic structures to climate change? A solid understanding of climate change and its impact on water resources allows for effective management of problems associated with worldwide water availability. Research in this study was conducted on estimated changes in precipitation patterns in Kansas, including magnitude, intensity, and frequency, with a long-term goal of understanding the impact of climate change on water resource changes and water control structure design.

Some general points should be noted for the whole project. In Kansas, precipitation occurs as fog, drizzle, rain, snow, and hail, classified based on the precipitation drop sizes and characteristics, however rain has the highest percentage of precipitation (Barnett et al., 2008; Huffman et al., 2011; Lull, 1959). In the literature, "precipitation" and "rainfall" have been used alternatively. In this study all the analysis were completed on rain. In the third chapter I used 24 stations in the study area, however, more data quality exploration dictated to remove one station (Lawrence) from the analysis in chapter four and five. Each chapter has accomplished with the longest available data at the time of doing the analysis.

Research Objectives

Historical precipitation trend analysis builds a strong foundation for understanding changes of climate. One goal of this research was to analyze historical precipitation data and determine trends of total annual rainfall in the state of Kansas.

Precipitation trends of different sub-periods (1891-1920, 1921-1950, 1951-1980, and 1981-2010) were compared with trends over a longer period (1890-2011) in order to determine shifts in precipitation patterns within a changing climate. Annual rainfall impacts agricultural production (Piao et al., 2010), antecedent moisture condition (Adamson et al., 2010), underground water (Xavier et al., 2010), and river discharge (Bookhagen and Burbank, 2010).

Water control structure design is based on maximum runoff resulting from a storm with a specific return period and duration. Currently, design storm values for Kansas are obtained from the rainfall frequency atlas (National Weather Service Technical Paper 40: TP-40) from 1961 which utilizes data from 1911 to 1958 (Hershfield, 1961). The second goal of this research was to calculate design storm values using data from as early as 1890 and as late as 2009, and compare these results with Hershfield's 1961 results.

Rainfall duration impacts antecedent moisture condition and runoff generation. During a continuous rain, soil absorbs water until the saturation point and then excess water flows as runoff (Betson, 1964; Chen and Wong, 1993; Lange and Bronstert, 2013; Ogden and Julien, 1993). The third goal of this research was to analyze trend of annual daily and longer duration (2-, 3-, 4-, 7-, and 10-day) maximum rainfall events and assess shifts in failure risk of hydrologic structures due to changing antecedent moisture.

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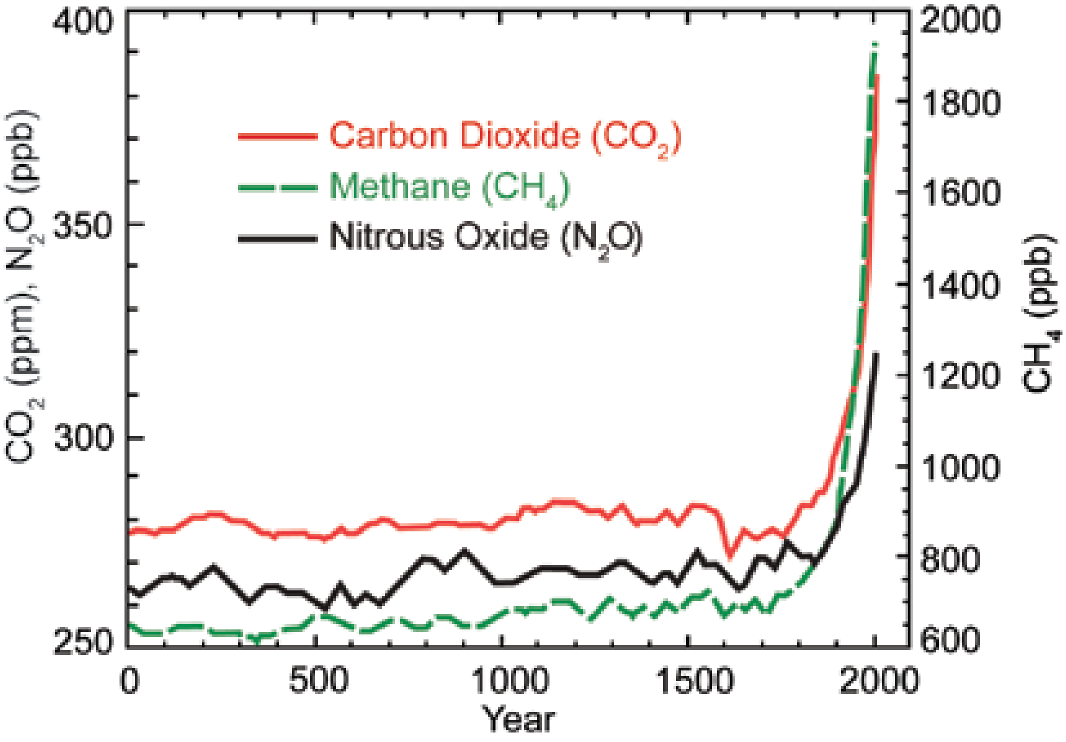
Chapter 2 - Literature Review

Climate Change

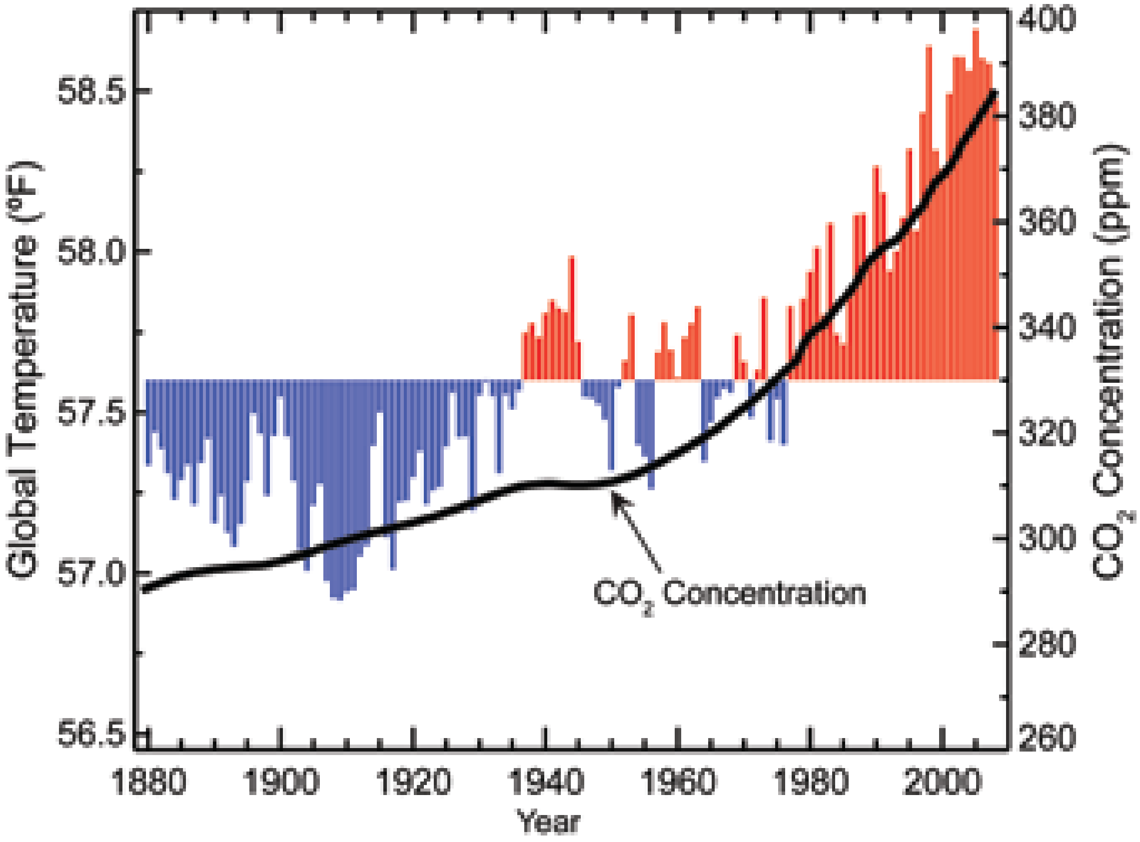
Climate change has been studied widely over the past century. Several scientists have discovered that greenhouse gas emission resulting from human activities plays important role in global climate change (Allan, 2011; Christidis et al., 2011; Gleick, 1989; Ma et al., 2010). Karl and Trenberth (2003) observed that, by affecting the energy balance of the atmosphere, human-based activities cause global climate variability and change more than natural events. Carbon dioxide emission from burning fossil fuels and deforestation, and methane and nitrous emission from industrial production and agriculture can change the atmospheric chemical composition. Fig. 2-1 demonstrates changes in greenhouse gas concentration throughout the last 2000 years. Carbon dioxide concentration has been increasing since the Industrial Revolution (since 1750), and this trend is expected to continue (Blasing and Smith, 2006; Forster et al., 2007; Xie et al., 2010).

Fig. 2-1- Greenhouse gas concentration (Karl et al., 2009)



Composition change of materials in the earth's surface and atmosphere reduces radiation from Earth to space, thus accelerating global warming. Jones et al. (1999) indicated global temperature increases of 0.37 ºC and 0.32 ºC for two twenty-year periods, 1925-1944 and 1978-1997. Fig. 2-2 indicates increasing global temperature and carbon dioxide since 1880. Global warming affects agriculture and ecosystems, natural habitats, human health, water resources, and sea level (Justus and Fletcher, 2001). For example, an increase of approximately 4 to 10 inches of sea level has been observed over the last century: An increase of 0.8 to 3 inches because of the thermal expansion of the ocean and a 0.8 to 2 inches rise because of ice melting (Justus and Fletcher, 2001).

Fig. 2-2- Global temperature and carbon dioxide (Karl et al., 2009)



Climate change and precipitation

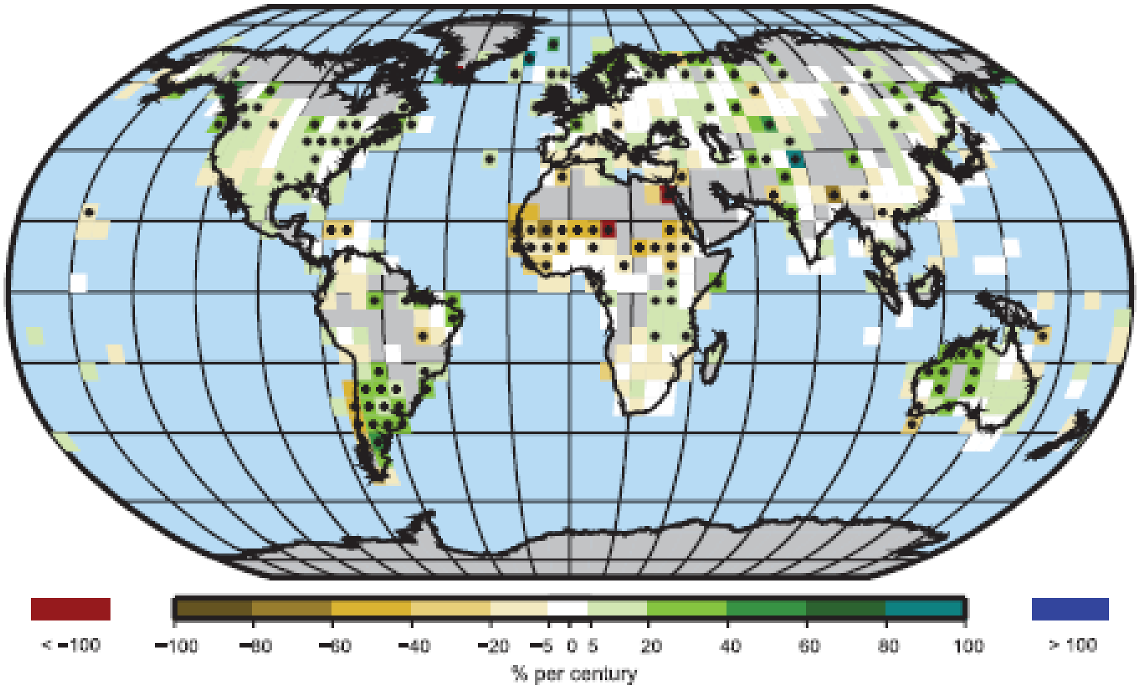
Precipitation intensity, frequency, and magnitude change because of global warming (Held and Soden, 2006; Zhang et al., 2013). Temperature changes are linked to precipitation patterns by changing atmospheric circulation patterns and moisture availability (Karl et al., 2009). In addition, inter-annual and inter-decadal global and regional climate variability are linked to natural global phenomena such as El Nino and La Nina (Kug and Ham, 2011; McGregor et al., 2013), Pacific Decadal Oscillation (PDO) (Mills and Walsh, 2013), and North Atlantic Oscillation (NAO) (Hurrell and

Deser, 2009). Seasonal to inter-annual global climate variability is predominantly occurring because of the El Niño-Southern Oscillation (ENSO) phenomenon (Dore, 2005; Rasmusson and Wallace, 1983), and the ENSO by the PDO can cause regional inter-annual climate variability for instance in the Pacific Northwest (Mantua et al., 1997; Zhang et al., 1997). Air temperature and sea surface temperature are significantly correlated with NAO in the northern hemisphere. The air and sea surface temperature changes impact precipitation by changing weather and storm patterns (Alexandersson et al., 1998; Hanssen-Bauer and Førland, 2000). For example, higher storm frequency and intensity were observed in relation to NAO in winter (Serreze et al., 1997).

Total precipitation

Global precipitation indicated a non-uniform significant increase of 2% over the period 1900-1994 (Doherty et al., 1999; Hulme et al., 1998; Jones and Hulme, 1996). Regionally, the precipitation increase was 7-12% in the northern hemisphere and 2% in the southern hemisphere (Dore, 2005). Groisman et al. (2005) summarized total annual precipitation trends in portions of the former Union of Soviet Socialist Republics (USSR), Europe, United States of America (USA), Australia, Africa, Brazil, and Mexico: an increase of 10-15% was observed in the former USSR during the period 1936-1997. In northern Europe, a significant increase of 16%/50-yr was demonstrated during 1951-2002. In the northwestern coast of North America, total annual precipitation increased significantly, approximately 10.3%/50-yr. In Australia, annual precipitation totals increased 16%/100-yr in the northern portion of the continent and decreased by the same rate in the southwestern part. In the South Africa, total annual precipitation did not change during 1906-1997, and in eastern Brazil and Uruguay, the increasing trend was not statistically significant. In central Mexico, trends showed a statistically significant decrease of 20%/30-yr. Other researchers also studied regional change in total annual precipitation. In Canada, a 10% increase was found from 1900 to 1996 (Mekis and Hogg, 1999), and Akinremi et al. (1999) indicated a significant increase from 1956 through 1995. In China, total annual precipitation showed a decreasing trend of -0.9%/decade from 1951 through 1995 (Zhai et al., 1999). Fig. 2-3 presents global observed precipitation changes for two periods, 1901-2010 and 1951-2010.

Fig. 2-3- Global trend of annual precipitation, 1901 to 2005 (%/century) (Solomon, 2007)



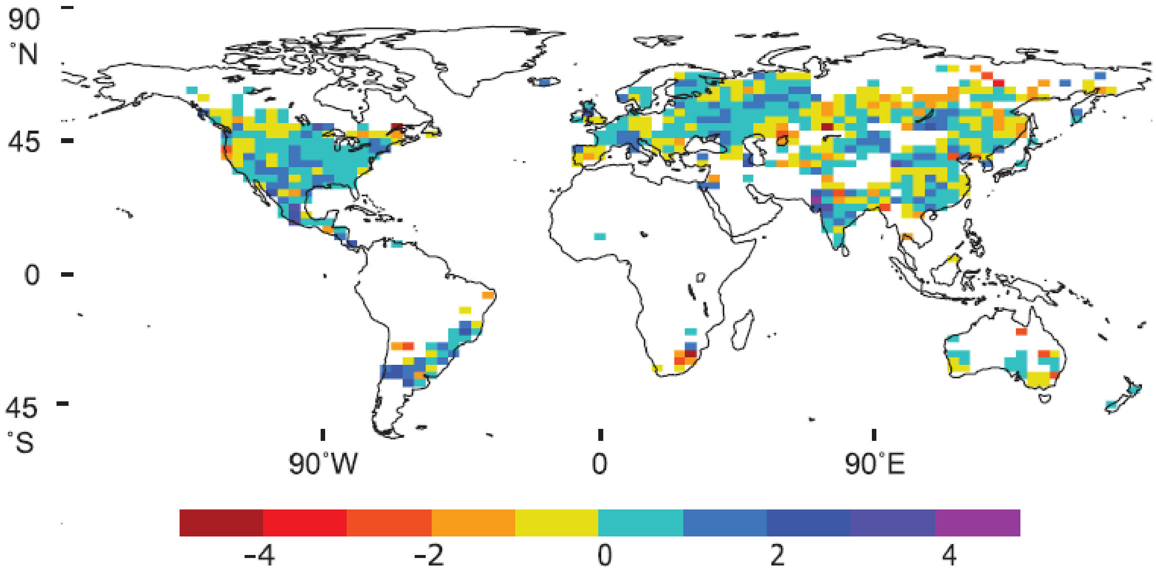
In the United States (US), total precipitation has increased approximately 7% over the past century, including regional varieties (Karl et al., 2009). Diaz and Quayle (1980) indicated general eastern and northwestern increase and southwestern decrease in total annual precipitation when comparing 1955-1977 and 1921-1925. Annual precipitation increase was significant in the northwestern and southeastern and no significant decrease occurred, based on 90% confidence interval. Sharratt and Spoden (2001) discovered an upward trend in annual precipitation from 1898 to 1997 throughout Minnesota, South Dakota, Iowa, and Wisconsin, with an increasing trend from northwest to southeast of the studied area. Many studies showed increasing trend in total annual precipitation.in regions including the study area of this research (Kansas). Martino et al. (2013) found an increasing trend in annual precipitation over the US with significant trends primarily in the central and northeastern portions, including Kansas, Nebraska, Oklahoma, South Dakota, and from Minnesota to Maine. Garbrecht et al. (2004) indicated an average of 12% increase of precipitation in 10 selected watersheds in Oklahoma (12%-19%), Nebraska (6%), and Kansas (9%). Eight watersheds, including all Kansas watersheds, showed significant trends based on a significance level of 0.1. In addition, future precipitation projections predict wetter conditions for northern areas and drier conditions for southwestern regions (Alexander et al., 2013).

Extreme precipitation

Climate change impacts precipitation patterns by varying time, location, amount, and intensity of precipitation events, and result in an increasing trend of extreme events (Gutowski et al., 2008). Flood and droughts are expected to occur more frequently with precipitation pattern changes (Karl et al., 2009). Groisman et al. (2005) reviewed heavy precipitation trends in many parts of the world which will be explained shortly. They defined various thresholds of heavy and very heavy rainfalls for regions based on average rainfall, climate conditions, and empirical distribution function and found an increase for greater than 15% of very heavy rainfalls (upper 1% of daily rainfall) in the former USSR. In northern Europe, a significant increase of 40%/50-yr in annual frequency of very heavy rainfall (higher than 0.5 mm) was observed in high latitudes, and, in the northwestern coast of North America, heavy rainfalls (95 percentile of daily rainfall) significantly increased, 18%/50-yr. In Australia, the frequency of very heavy precipitation (upper 0.3% of daily rainfall) increased 52%/100-yr in the southeastern portion of the continent and decreased 43%/100-yr in the southwestern portion. In South Africa, the frequency of very heavy precipitation (upper 0.3% of daily rainfall) increased significantly (44%/100-yr) during 1906-1997. In eastern Brazil and Uruguay, very heavy precipitation (upper 0.3% of daily rainfall) indicated a statistically significant increase of greater than 40%/100-yr, and the central United States showed a statistically significant increase of 18%/100-yr for very heavy precipitation (upper 0.3% of daily rainfall). In central Mexico, the annual frequency of very heavy precipitation (upper 0.3% of daily rainfall) showed a statistically significant increase of 200%/30-yr. Zhai et al. (1999) found significant increase in the upper 10% of precipitation from 1951 through 1995. Fig. 2-4 indicates global trends of very wet days, defined as the top 95th percentile of observations.

Fig. 2-4- Global trends of very wet days (95th percentile and above) (%/decade)

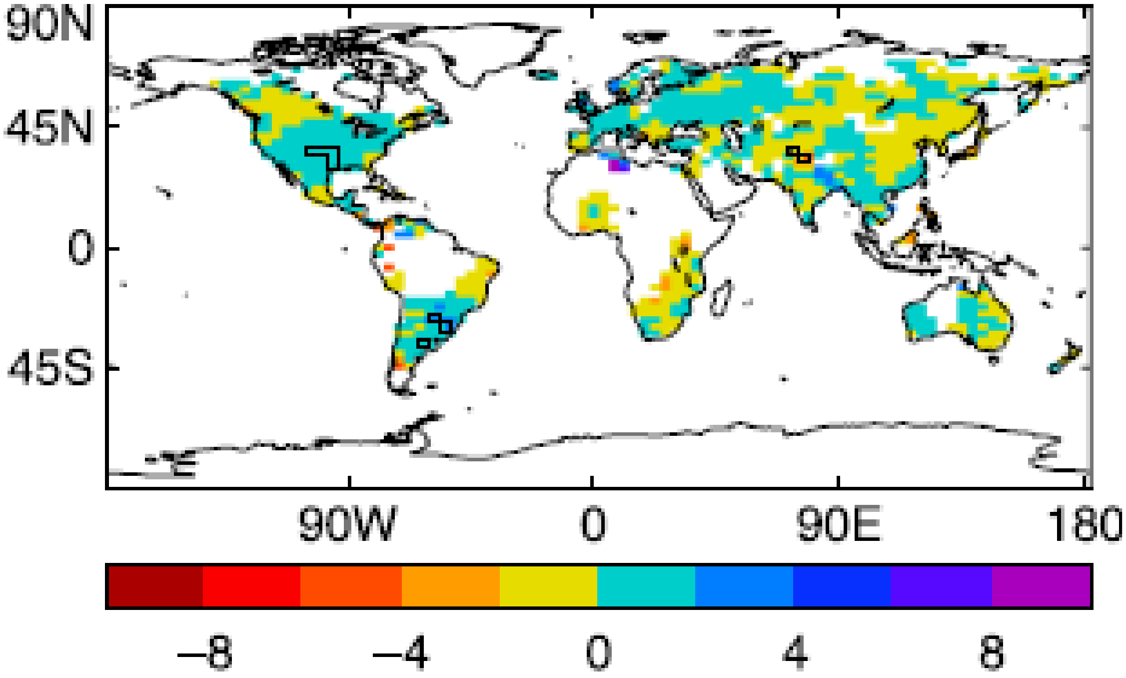
(Solomon, 2007)



In the United States, the heaviest rainfall events increased approximately 20% during the last century with the greatest increases occurring in wet places such as the Northeast and the Midwest (Backlund, 2009; Groisman et al., 2004; Kunkel et al., 2008). The annual number of days with heavy precipitation (rain higher than 10 mm) has increased up to two days per decade in south-central USA (Alexander et al., 2006). Saunders et al. (2012) indicated that the annual frequency of heavy storms have increased since 1961, with the highest increase occurring in the last decade (2001-2010). The frequency of storms 1) less than one inch, 2) between one and two inches, 3) between two and three inches, and 4) larger than three inches were calculated for 1961-2010. Results indicated a greater increase in frequency for larger events, with the smallest increase of 8% for Group 1 and the highest increase of 103% for Group 4. Villarini et al. (2011)

found a slight increase in annual maximum daily rainfalls in the midwestern United States, with the greatest 100-yr, daily rainfalls occurring in eastern Kansas, Iowa, and Missouri. Fig. 2-5 indicates the global trend for days experiencing heavy precipitation (higher than 10 mm) from 1951-2003.

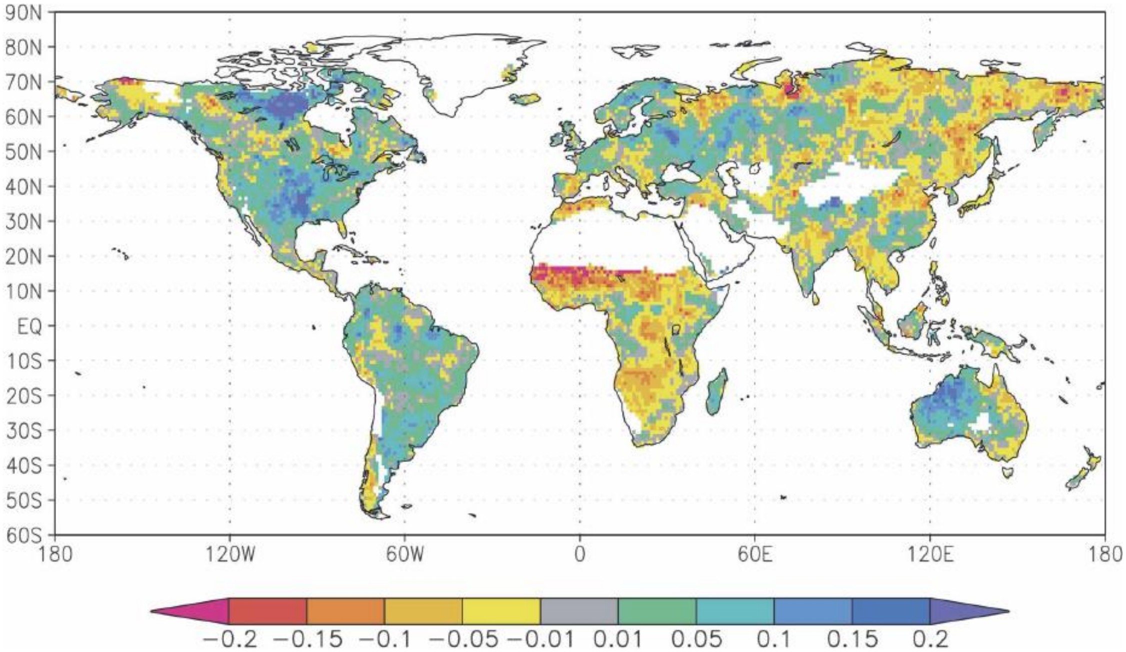
Fig. 2-5- Global trends in heavy precipitation days (higher that 10 mm rainfall) in days/decade for 1951-2003 (Alexander et al., 2006)



Relation between antecedent soil moisture, rainfall duration and runoff

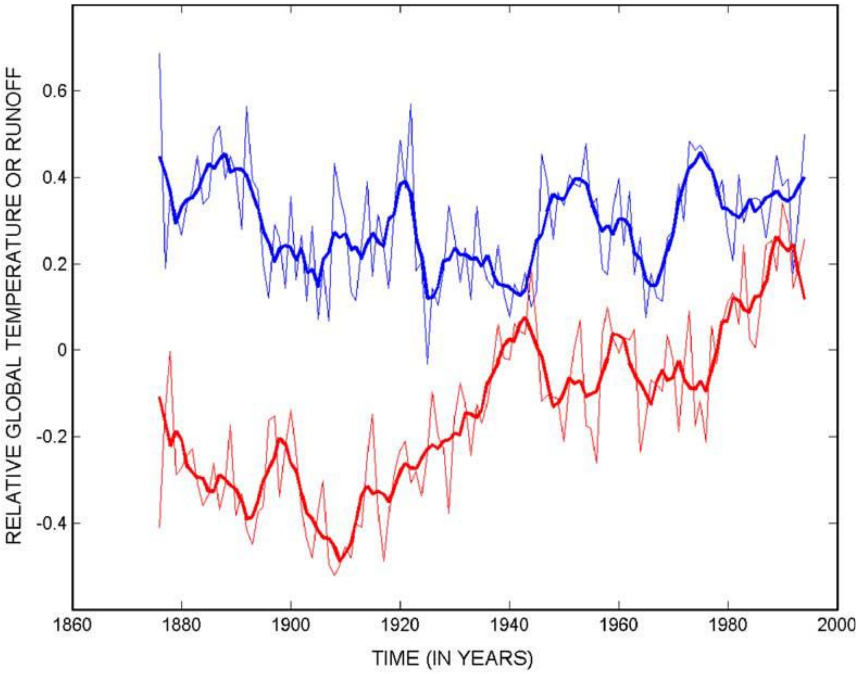
Soil water availability is a crucial factor affecting runoff generation. When rain begins, soil absorbs water until the saturation point. Excess water after saturation flows as runoff. Hence, longer precipitation events result in higher runoff generation. Soil water availability also impacts agricultural production and groundwater (McCarthy, 2001). Climate change influences soil water content by impacting soil properties such as infiltration rate and soil water capacity (Boix-Fayos et al., 1998). Fig. 2-6 demonstrates the global trend of annual mean volumetric soil moisture.

Fig. 2-6- Global trend of annual mean volumetric soil moisture (%/yr) (Sheffield and Wood, 2008)



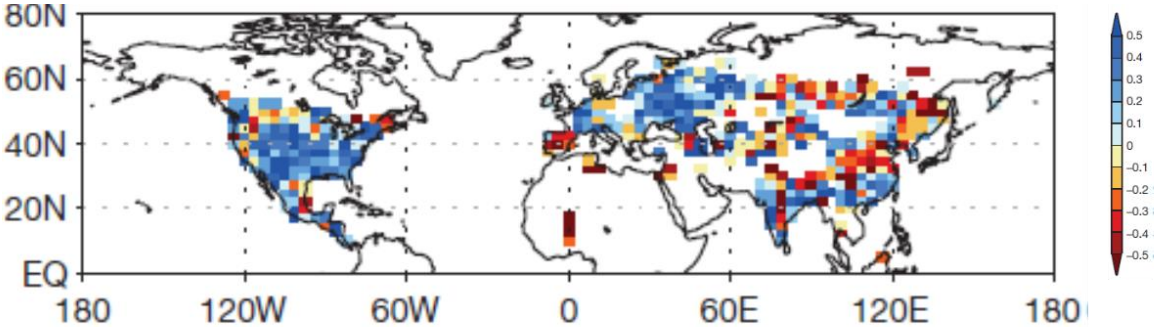
Global warming is also correlated to runoff. For example, Labat et al. (2004) indicated that global runoff increased 4% because of 1 ºC rise in global temperature using data period 1875-1994 (Fig. 2-7).

Fig. 2-7- Annual global runoff (blue) and temperature (red) for 1875-1994 (Labat et al., 2004)



Mishra et al. (2008) found that runoff generation rate is strongly correlated with rainfall duration. Many scientists analyzed precipitation data to determine trends of annual maximum 5-day rainfall magnitude. Globally, an increasing trend was observed in maximum 5-day precipitation, with a significant trend in south-central and southeastern United States (Alexander et al., 2006). Fig. 2-8 demonstrates the global trend of 5-day precipitation.

Fig. 2-8- Global trends of 5-day consecutive precipitation amount for 1951-1999 (%/yr) (Min et al., 2011)



Nandintsetseg et al. (2007) showed an increasing trend in the 5-day precipitation total in Mongolia. In western Germany, Hundecha and Bardossy (2005) indicated a significant winter increasing trend for 5-day precipitation for average magnitude and number of stations and a decreasing trend in summer from 1958 to 2001. In the United States, Kunkel et al. (1999) presented a statistically significant (5% confidence level) upward trend for 7-day events with 1-yr and 5-yr return period for 1931-1996. Regionally, the southwest and central United States indicated the greatest statistically significant increasing trend at 5% confidence level. They repeated the analysis on 1 and 3-day events and found similar results. Kunkel (2003) found lower frequency of 5-day extreme events in early 20th century and higher than average frequencies in late 20th century.

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Chapter 3 - Extreme Daily Rainfall Event Distribution Patterns in Kansas

This chapter is a published paper in the Journal of Hydrologic Engineering: Rahmani, V., S. L. Hutchinson, J. M. S. Hutchinson, and A. Anandhi (2013), Extreme Daily Rainfall Event Distribution Patterns in Kansas, Journal of Hydrologic Engineering, 19(4), 707-716. "With permission from ASCE".

The Rainfall Frequency Atlas (TP-40) was last updated for Kansas in 1961 using weather data from 1911 to 1958. Rainfall information contained in the atlas is the basis for important engineering and hydrologic design decisions in the state. With growing concern about the effects of global climate change and predictions of more extreme weather events, it is necessary to explore rainfall distribution patterns using the most current and complete data available. In this study, extreme rainfall frequency was analyzed using daily precipitation data (1920 through 2009) from 24 stations in Kansas and 15 stations from adjacent states. The Weibull distribution was used to calculate the precipitation probability distribution frequency at each station. Weather station point data were spatially interpolated using kriging. The overall analysis showed an increase in extreme precipitation events in Kansas with extreme event values tending to increase in magnitude from the northwest to southeast part of the state. Comparing results of the original TP-40 analysis to the last of three study periods (1980–2009) showed that approximately 84% of the state had an increase in short-term rainfall event magnitudes.

Long-term event magnitudes were predicted to be less than those reported in the earlier, but have increased over time, most likely due to the short data period used to calculate the TP-40 precipitation probability distribution frequency. Results show a shift in rainfall distribution patterns in Kansas across both time and space. This shift changes the design criteria for water management systems, both in runoff control and storage structures.

Introduction

Rainfall patterns are expected to change significantly as a result of climate change (Kyoung et al., 2011). Floods are the most widely publicized events caused by extreme rainfall because of the threat to human life and the great expense required to construct and maintain hydraulic flood control structures (Cuevas, 2011; Mehrotra and Sharma, 2011). Improved understanding of the frequency and magnitude of rainfall events is necessary to help inform the design of effective and economical hydraulic control structures to reduce the risk of property damage and loss of life.

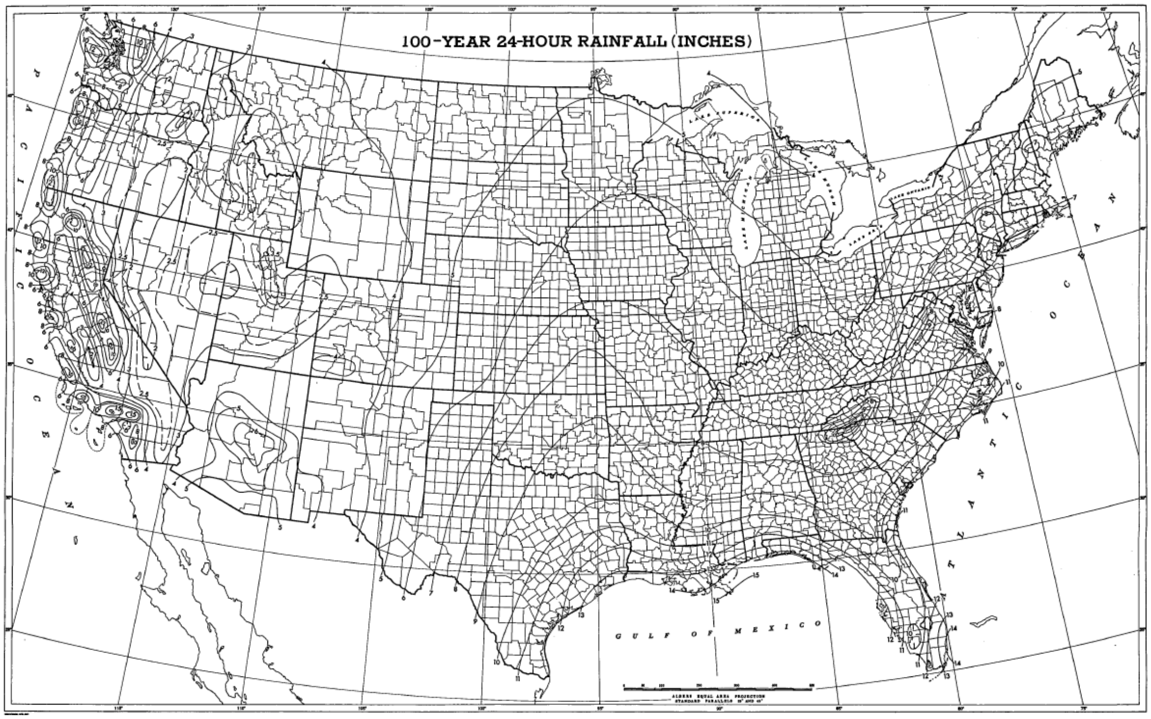
Many rainfall frequency distribution studies have been completed worldwide, highlighting significant changes in Canada (Waters et al., 2003), the United Kingdom (Rodda et al., 2010), Africa (Ngongondo et al., 2011), China (Yang et al., 2010), Korea (Kyoung et al., 2011), Argentina (Lucero, 1998), and Turkey (Haktanir et al., 2010). In addition, studies in the United States have documented changes in the frequency distribution of extreme rainfall events (Huff and Angel, 1989; Kelly et al., 2009) by showing the increasing magnitude of change in the Midwest, including parts of Kansas, Missouri, Nebraska, Iowa, Illinois, Minnesota, Wisconsin, and North and South Dakota

(Faiers et al., 1997; Huff and Angel, 1992; Huff and Changnon, 1987; Villarini et al., 2011).

In 2003, the Hydrometeorological Design Studies Center (HDSC) of the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) began updating the precipitation frequency estimates for the United States in NOAA Atlas 14 [http://hdsc.nws.noaa.gov/hdsc/pfds/]. However, the majority of the midwestern U.S. has not yet been updated, resulting in the continued use of "Technical Paper 40: Rainfall Frequency Atlas for the United States" (TP-40) (Hershfield, 1961) to estimate rainfall frequency and amount for hydraulic structure design. The TP-40 includes results of rainfall frequency analysis for storm durations from 30 minutes to 24 hours and return periods from 1 to 100 years.

Hershfield (1961) developed the rainfall frequency analysis in TP-40 for the entire U.S. using rainfall data from climatological record books dating from approximately 1911 through 1958, depending on the availability of data at specific weather stations (Kansas data ranged from 1911 through 1958). Fig. 3-1 indicates the TP-40 results for 100-yr, 24-hr rainfall in inches. Results from TP-40 were updated by the U.S. Department of Commerce Weather Bureau in "Two- to Ten-day Precipitation for Return Periods of 2- to 100-years in the Contiguous United States" (TP-49) (Miller, 1964) and NOAA Technical Memorandum NWS HYDRO-35, "Five- to 60-Minute Precipitation Frequency for the Eastern and Central United States" (Frederick et al., 1977).

Figure 3-1- TP-40: 100-yr, 24-hr rainfall (inches)



Important engineering and hydrologic design decisions (*e.g.,* small headwater runoff control dams, stormwater sewer systems, and agricultural runoff control systems) are based on the TP-40 analysis. However, prior research has shown that the 24-hour, 100-yr values from TP-40 were exceeded more than 3 times more often than expected in Michigan (Sorrell and Hamilton, 1990) and nearly twice as often in Illinois and Wisconsin (Huff and Angel, 1992).

To develop a better understanding of precipitation event frequency and magnitude in Kansas, a long-term (1920–2009) precipitation frequency analysis was conducted using daily rainfall data from across Kansas and bordering states to assess precipitation distribution shifts over the last century. This analysis provides a more comprehensive and updated design tool for local engineers and hydrologists. By improving our understanding of historic precipitation distributions in Kansas, scientists and engineers will be better prepared to assess the effects of future climate change on water resources across the state.

Methods and Materials

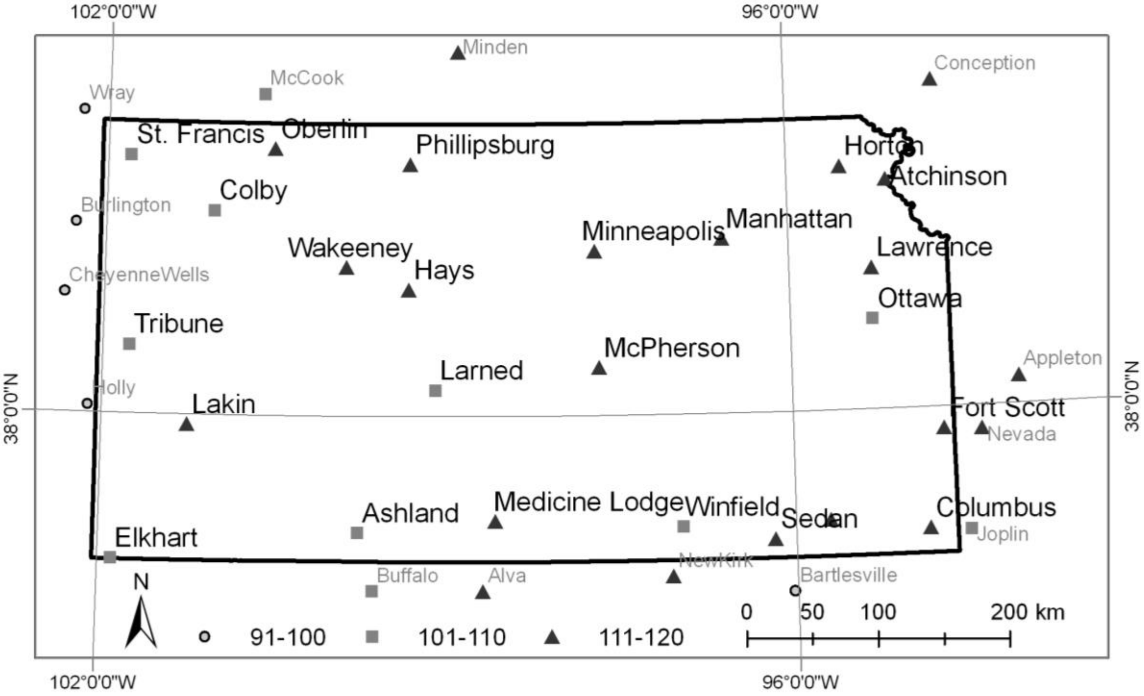
Study area

Kansas is located in the midwestern U.S. between 37° to 40° N latitude and 94.58 to 102.05° W longitude containing an area of approximately 213,100 km^2 (82,227 mi^2). Kansas is a mid-continental temperate climate that is hot during the summer and cold in the winter with humidity ranging from humid in the east to arid in the southwest. The average temperature ranges from a low of 0°C in January to a high of 26°C in July. On average Kansas receives 720 mm/yr precipitation, but there is a strong gradient from east (1220 mm/yr) to west (440 mm/yr). Kansas weather can be unpredictable due to weather fronts moving from west to east out of the Pacific or southwest to northeast from the Gulf of Mexico. These frontal systems result in frequent high winds, significant temperature fluctuations, and provide most of the state's moisture. These sources strongly affect the state's climate and precipitation amounts, causing less precipitation in the winter than the summer months. The dominant wind directions during the winter are from the west and northwest, originating from the Pacific Ocean and decreasing in power as it crosses the Rocky Mountains. By the time the wind reaches Kansas, only a small amount of moisture remains. During summers, southern winds from the Gulf of Mexico, unaffected by orographic features, cause high humidity. Because the Gulf of Mexico is much closer to the southern and eastern parts of Kansas, precipitation amounts are higher in these regions (Goodin et al., 1995).

Data sources

Daily rainfall data were extracted from the High Plains Regional Climate Center (HPRCC) and the United States Historical Climatology Network (U.S. HCN). High quality weather stations with at least 100 years of data, known as century stations, were selected for the state of Kansas (24 stations), with 16 stations reporting 111–120 years of data and 8 stations with 101–110 years of data. Fifteen stations were selected from the adjacent states of Missouri, Nebraska, Colorado, and Oklahoma to improved estimates near the Kansas border (Fig. 3-2). Of these, seven documented 111–120 years of data, three 101–110 years, and five 91–100 years of data. Because maximum 24-hour rainfall values may differ from observational daily data, a conversion factor of 1.13 was used to transform daily data to 24- hour data. This factor was chosen since it was used in NWS HYDRO-35 and TP-40 to convert an observational day (constrained observation) to 24 hours (unconstrained). The relationship was an empirical one developed by comparing 1140-minute periods containing the maximum rainfall and daily rainfall. Additionally, Bonnin et al. (2006) used the same factor in Atlas 14, Volume 2.

Fig. 3-2- Location of rainfall stations within Kansas and border states. Circle, square and triangle signs show the stations with 91–100, 101–110, and 111–120 years of data respectively.



Methods

Maximum daily precipitation

Daily precipitation data was analyzed using the annual series method, which considers the maximum value of daily rainfall in each year, as opposed to the partial duration series, which considers all events over a certain threshold for each year of record. The results of both methods are considered the same for return periods equal to or greater than 10 years (Huffman et al., 2011; Langbein, 1949). The partial duration series will yield a higher value for shorter return period events. Because the major focus of this study was to assess trends across the state, the annual series was considered appropriate. Additionally, the TP-40 results are based on the annual series method; however, the final documents were transformed to partial duration series statistics. Hence, two factors of 1.086 and 1.004 were applied to convert the annual series method outputs to partial duration series statistics (Bonnin et al., 2006). These factors are applied only to create Figs. 3-13 and 3-14, all other results are the annual series method statistics.

For precipitation, a data record length of at least 20 years is recommended to provide a statistically representative sample of events (Houghton et al., 2001; Serrano, 1997). Because the data record length varied across the stations, three sequential periods (1920–1949, 1950–1979, and 1980–2009) covering 90 years of data were selected for the analysis. A period of 30 years was selected based on the World Meteorological Organization’s definition of a climate period (WMO, 1989).

Weibull Distribution model

The Weibull distribution was used to calculate the rainfall distribution function for each weather station and time period. Gumbel and Generalized Extreme Value (GEV) distributions are other functions that have been used in previous studies (Beirlant et al., 2004; Rao and Hamed, 2000; Singh et al., 2007). Gumbel is a type I extreme value distribution and GEV is a combination of Gumbel, Frechet and Weibull. The Weibull distribution was selected because of its simplicity, versatility and ability to approximate exponential, normal, and/or skewed distributions (Reeve, 1996; Schönwiese et al., 2003;

Van den Brink and Können, 2011; Weibull, 1951; Wilson and Toumi, 2005). In addition, the Weibull method is emphasized by the American Society of Agriculture and Biological Engineers (ASABE) in Huffman et al. (2011) as the primary method for calculating design storm magnitudes, making it the most common distribution used by practicing engineers and students.

To achieve a simple equation for calculating probability a manipulated version of the two-parameter Weibull cumulative distribution function (CDF) was used (Eq. (3-1), (Huffman et al., 2011)).

$$P(x) = \exp[-(x/\alpha)^{\beta}] \qquad (3\text{-}1)$$

where ***P(x)*** is the Weibull cumulative distribution function, ***x*** is rainfall depth (L), α is characteristic depth (L), and β is shape parameter (dimensionless). The parameters α and β were determined by linear regression of the distribution function with Eq. (3-2).

$$\ln[\ln(1/P(x))] = \beta \ln x - \beta \ln \alpha \qquad (3\text{-}2)$$

For the annual series method, the single maximum daily rainfall event was selected for each year of analysis. These values were arranged in order from largest to smallest and a plotting position, or relative frequency, was assigned to each value (Eq. (3-3)).

$$P = (m - d)/(N + 1 - 2d) \qquad (3\text{-}3)$$

where ***P*** is the plotting position, *d* is a parameter that depends on the distribution (*e.g.,* normal, exponential, etc.) and ranges from 0 to 0.44, *N* is the number of observations, and ***m*** is the numeric rank of each observation. Bedient and Huber (2002) recommend using d = 0.4 in calculating the plotting position when the distribution is unknown.

The α and β coefficients were computed by conducting a linear regression of the left side of Eq. (3-2) and the natural logarithm of the precipitation. The slope of this line is equivalent to the shape parameter, β, and the characteristic depth, α, was computed using the y-intercept of the regression line (b) and the slope (β) with Eq. (3-4).

$$\alpha = \exp(-b/\beta) \qquad (3\text{-}4)$$

After calculating α and β for each location and time period, Eq. (3-1) can be rewritten and used to determine rainfall depth (x) for any frequency (probability of occurrence) (Eq. 3-5).

$$x = \alpha[-\ln(P(x))]^{(1/\beta)} \qquad (3\text{-}5)$$

The frequency of occurrence is the reciprocal of the return period, ***T***; for example, a 2-yr event has a 0.5 frequency (1/2), or a 50% likelihood of occurrence in any given year, and a 100-yr event has a 0.01 frequency (1/100), or a 1% likelihood of occurrence in any given year. For this study, the 2-yr, 24-hr and 100-yr, 24-hr events are compared.

Interpolation method

For each weather station location and study period, Weibull distribution parameters α and β and the 2-yr, 24-hr and 100-yr, 24-hr return period values were spatially interpolated using ordinary kriging in a geographic information system (GIS) to produce isoline maps for the state of Kansas. Kriging is a multistep process based on geostatistical principles that includes exploratory statistical analysis of these data, variogram modeling, and surface creation (Chilès and Delfiner, 2012). The continuous prediction surface is based on the semivariogram and the spatial arrangement of the closest measured values, but does not require the predicted surface to be fitted to each station value. Using this more complex analysis allowed for the creation of smoother prediction surfaces.

Comparison between TP-40 and Interpolated Results

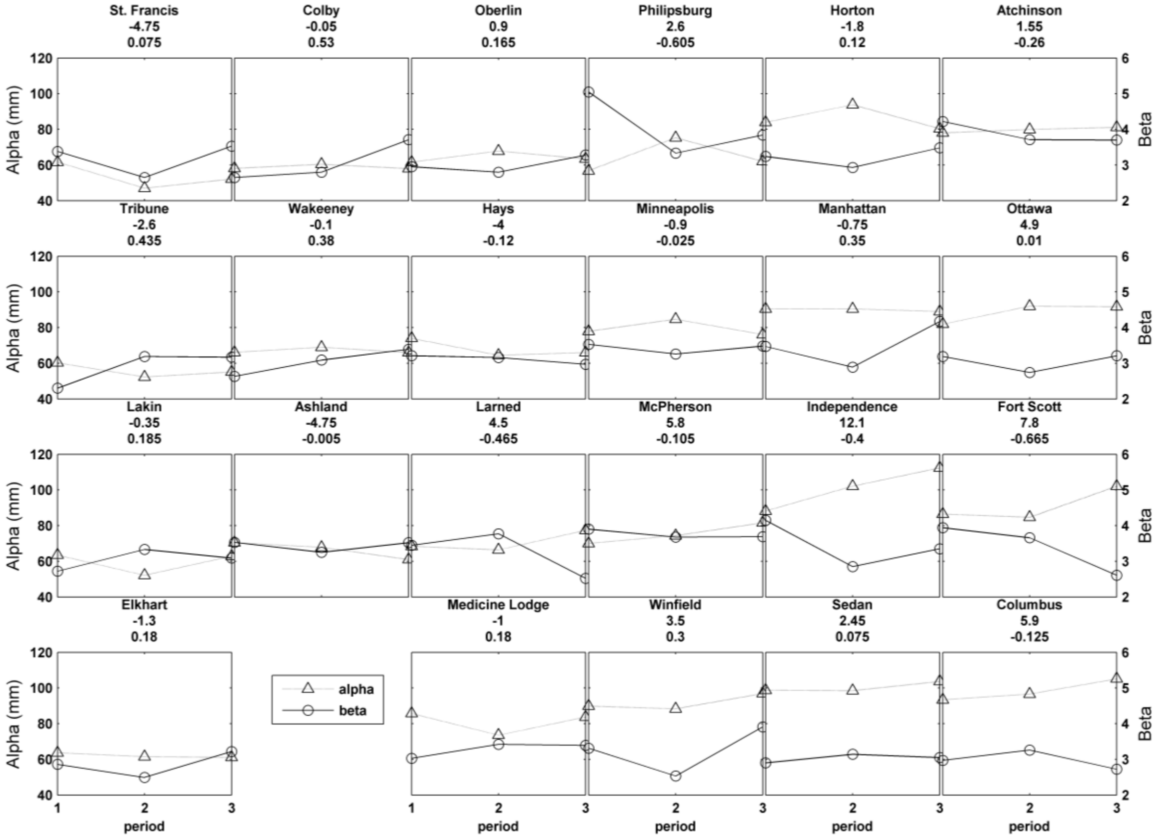
Hershfield's (TP-40, 1961) original rainfall distribution maps were scanned and geo-referenced in a GIS. A "heads-up" digitizing technique was then used to create digital copies of the original isolines. An additional interpolation method, based on the ANUDEM program by Hutchinson (1989), was used to convert the digitized contour line maps into continuous raster surfaces for direct comparison with the kriged map products described above. Difference maps between the published TP-40 maps and the new return period maps were created by subtracting one raster surface from the other.

Results and discussion

The scale (α) and shape (β) parameters for all stations and all periods are plotted in Fig. 3-3. The squared correlation coefficient, r^2, ranged from 0.74 to 0.98 for Eq. 3-2. Higher r^2 values show better goodness of fit. The scale parameter (α – mm) is plotted on the primary vertical axis, and β (dimensionless) is plotted on the secondary axis. The trend line slope of the entire period (1920–2009) for α and β are noted on the top of each subplot.

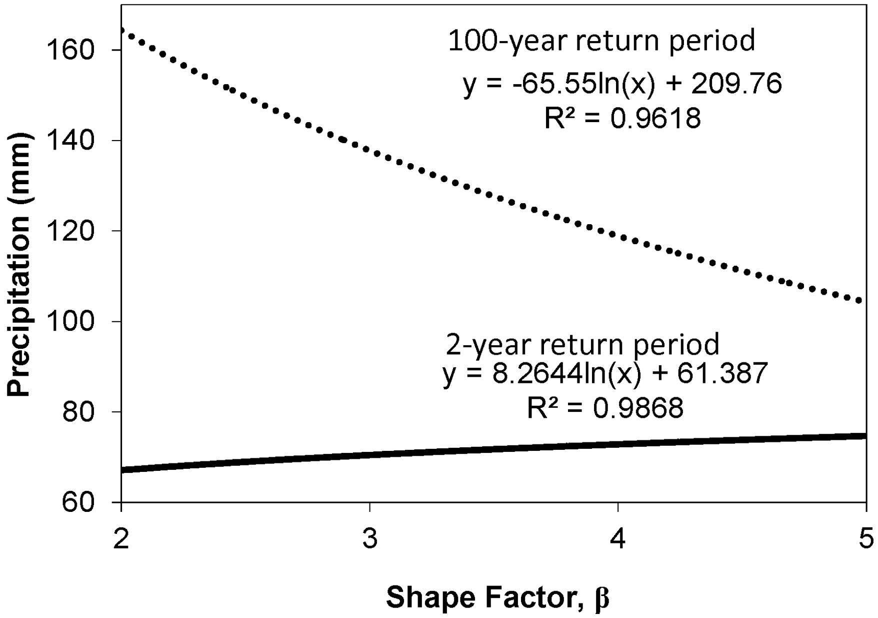
The shape parameter, β, ranged from 1.96 to 5.05 with no clear trend across the state, and the majority of the values fell within the range of a normal data distribution ($2.6 < \beta < 3.7$) as defined by Rinne (2009) and available from ReliaSoft Corporation (http://www.weibull.com/; http://reliawiki.org/index.php/The_Weibull_Distribution).

Fig. 3-3- Variation in parameters of the Weibull distribution (α (mm) and β) for three time-periods (Period 1 = 1920–1949, Period 2 = 1950–1979, and Period 3 = 1980–2009). The two values below station's name represent the overall (1920–2009) trend slope for α (top) and β (bottom). The subplots in the figure are arranged in their approximate geographical location.



Because the relationship between shape factor, (*β*), and rainfall amount is not linear, it is more difficult to assess how shifts in *β* influence the rainfall amount. Fig. 3-4 shows the change in *β* (ranging from 2 through 5) when holding *α* constant on an average value of 80 mm (the approximate average value for Kansas). In general, for frequent rainfall events (*e.g.*, return period (T) <= 2.7 yrs), an increase in β means an increase in rainfall depth and for return periods greater than 2.7 years, an increase in β means a reduction in rainfall depth. Lower β shrinks the storm range and results in enlarging the smaller events and reduce the larger events.

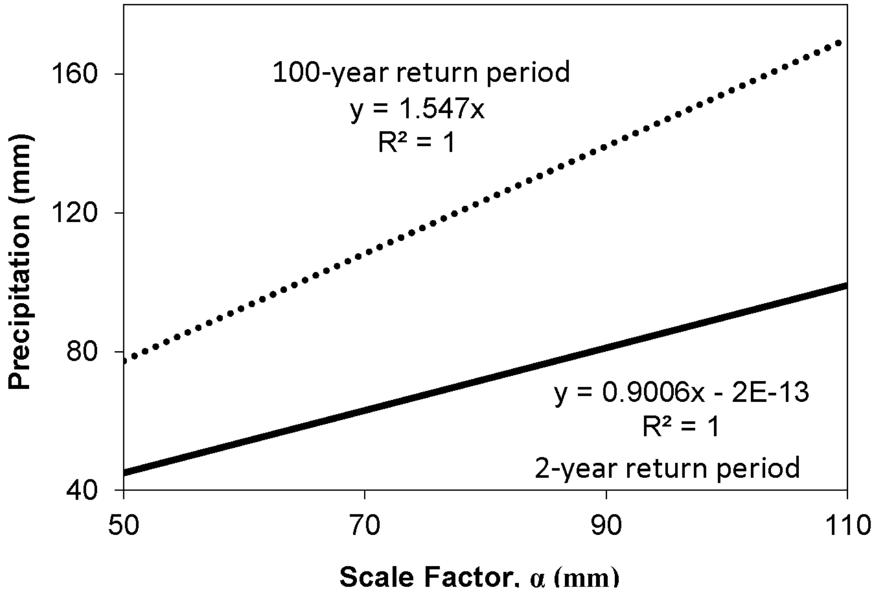
Fig. 3-4- Precipitation vs. shape factor (β) for a constant average α of 80 mm.



The scale factor, α, ranged from 47 mm to 112 mm with the lowest values occurring primarily in the western part of the state. In general, higher α values mean higher variability and more extreme rainfall events. The shift in α over the 90-yr period was not consistent, however a majority of stations had a relatively constant α across all periods. Only three stations (Independence, McPherson, and Columbus) showed a strong positive trend (increasing alpha) and two stations (St. Francis and Ashland) a negative (decreasing alpha) trend. However, 12 of 23 sites (52%) have a positive trend across the entire time period, suggesting rainfall events are likely to become more extreme.

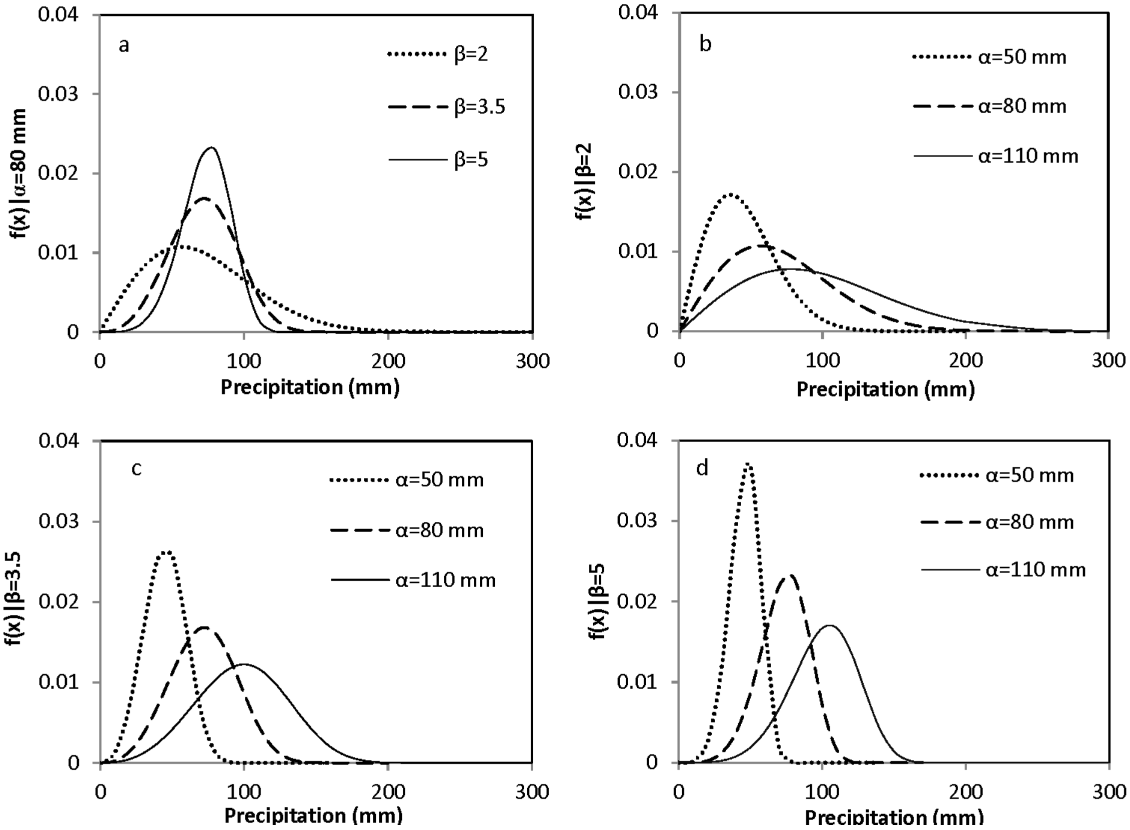
Fig. 3-5 shows that when holding *β* at a constant value (β = 3.5) and increasing *α* through the range calculated for Kansas, the increase in rainfall amount is sharper for larger return year period events (slope = 1.55) compared with the increase in rainfall for more frequent events (slope = 0.90).

Fig. 3-5- Precipitation vs. scale factor, α (mm) for a constant average β of 3.5.



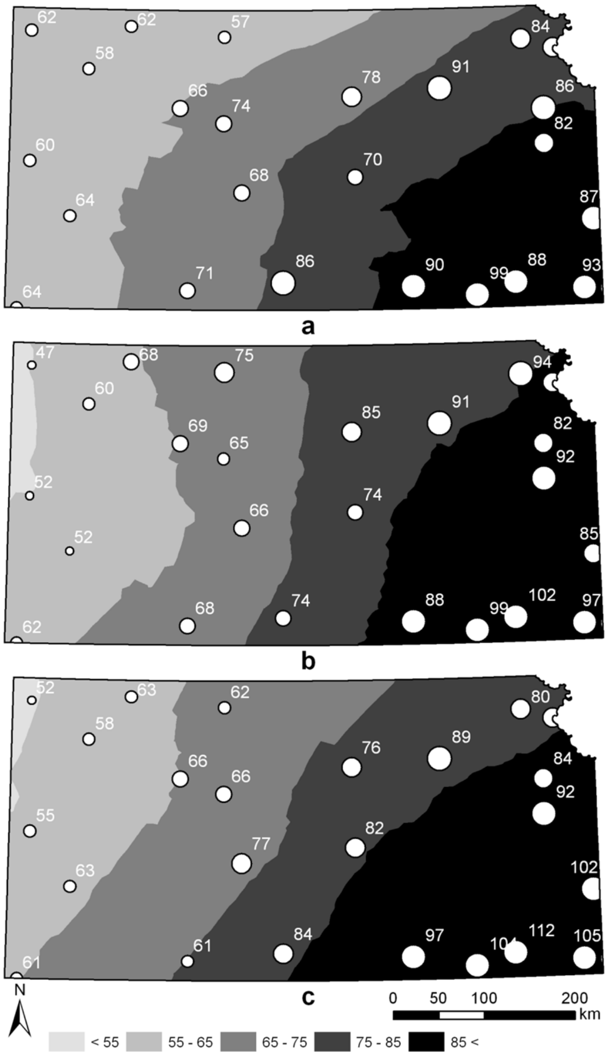
Predicting changes in rainfall amounts is much more complicated when considering changes in both *α* and *β*. The Weibull PDF curves (Fig. 3-6(a–d)) expand on the interaction between α and *β* parameters when modified within the range of values calculated for Kansas. When *α* is held constant at 80 mm (Fig. 3-6(a)), increasing *β* from 2 (Kansas minimum value) to 3.5 (Kansas average) to 5 (Kansas maximum value) shifts the mean value to the right (increases the mean rainfall amount within the distribution). For the low β value (β = 2), the distribution is skewed to the left with a right tail showing a wider range of rainfall events with higher probability of both extreme low and extreme high events. When the β value is 3.5, the distribution is normal. The Weibull PDF curves are shown for scenarios where β are held constant and range from low (β = 2; Fig. 3-6(b)) to average (β = 3.5; Fig. 3-6(c)) to high (β = 5; Fig. 3-6(d)), and α changes from low (α = 50 mm) to average (α = 80 mm) to high (α = 110 mm). Increasing α for a constant β, affects the variability range. As α increases, the spread in the distribution increases, illustrating an increase in rainfall variability.

Fig. 3-6- Effect of different α and β on Weibull PDF function vs. precipitation a) α = 80 mm for β = 2, 3.5, or 5, b) β = 2 for α = 50, 80, or 110 mm, c) β = 3.5 for α = 50, 80, or 110 mm, and d) β = 5 for α = 50, 80, or 110 mm.



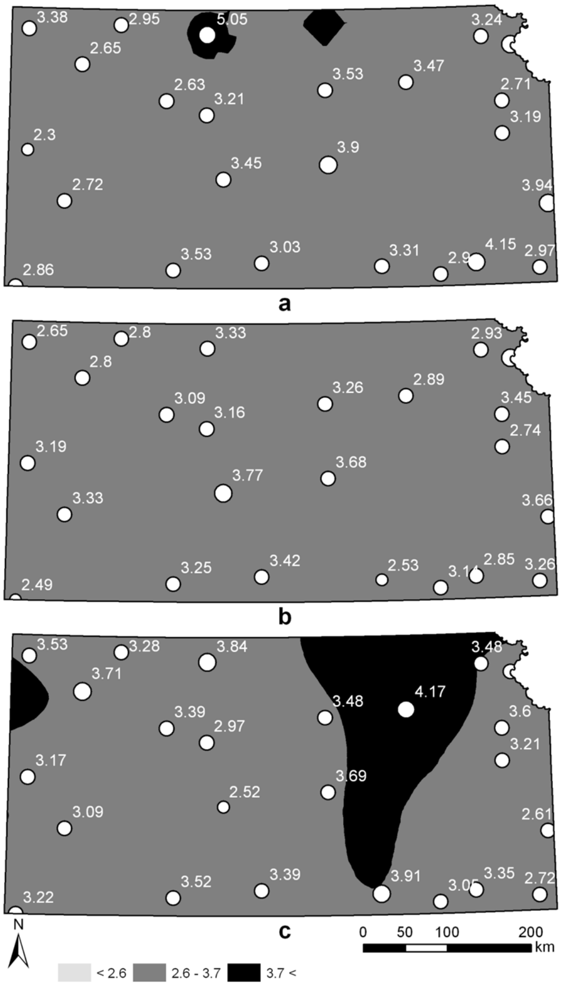
When looking at the relationships of the scale (*α*) (Fig. 3-7) and shape (*β*) (Fig. 3-8) parameters across time and space, some interesting trends were found. First, *α* shows a pattern similar to the moisture gradient across Kansas, with values increasing from the northwest to southeast part of the state.

Fig. 3-7- Scale parameter, α (mm), trend for a) 1920–1949, b) 1950–1979, and c) 1980–2009. The numbers on points show the calculated value for all stations with a graduated circle size.



The maps for β show that the rainfall distribution was normal for the majority of the state across all time periods. The most notable exception was the right-skewed region ($\beta > 3.7$) spanning Kansas from north to south along the eastern third of the state during the last climate period, which indicates this area experienced more extreme events. This result may be due to frontal boundary phenomena that occur in areas where warm southern winds from the Gulf of Mexico confront colder northern winds.

Fig. 3-8- Shape parameter (β) trend for a) 1920–1949, b) 1950–1979, and c) 1980–2009. The numbers on points show the calculated value for all stations with a graduated circle size.



Using several diagnostic statistics, kriging results for the 2-yr and 100-yr return period events were found to be valid and optimal (Table 3-1). Mean prediction errors close to 0 indicate unbiased predictions. With the exception of the first climate period for the 100-yr event, the mean prediction error was near 0. A root-mean-square standardized prediction error close to 1 indicates that the standard errors are accurate and the predictions do not deviate significantly from the measured values, indicated by small root-mean-square error and average standard error. When the average estimated prediction standard errors are close to the root-mean-squared prediction errors, the prediction standard errors are appropriate (Picard and Cook, 1984; Snee, 1977). For the 100-yr return period and the data of 1920–1949, the mean prediction error is high, but the average standard error and root mean square error are so close, and the root mean square standardized error is so close to 1, that the validity of the interpolated result is confirmed.

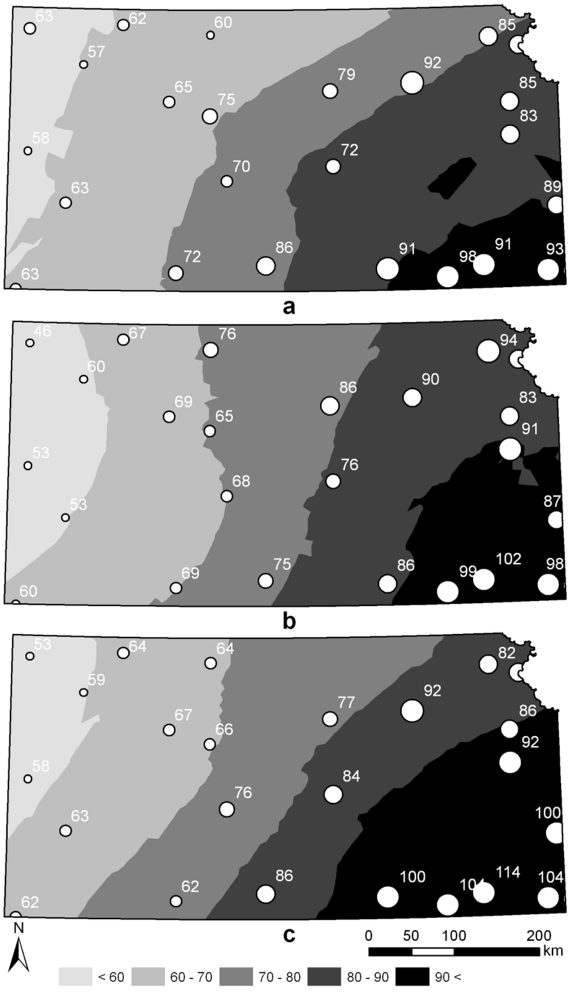
Table 3-1- **Kriging prediction errors**

Return year period	Period	Mean prediction error	Root-mean-square	Mean standardized	Root-mean-square standardized	Average standard error
2	1920–1949	-0.0164	7.2531	0.0029	1.7135	4.1615
	1950–1979	0.0333	6.8341	0.0050	1.1502	5.9791
	1980–2009	-0.1030	8.4083	-0.0156	1.0117	8.2545
100	1920–1949	1.0681	18.1726	0.0481	0.9744	18.7310
	1950–1979	0.0539	18.7689	-0.0010	1.0337	18.3830
	1980–2009	-0.3935	16.8677	-0.0235	1.0550	15.9607

The statewide predicted return periods for the 2-yr, 24-hr and 100-yr, 24-hr rainfall events are presented in Figs. 3-9 and 3-10, respectively. When comparing the 2-yr, 24-hr event across the three climate periods (1920–1949, 1950–1979, and 1980–2009)

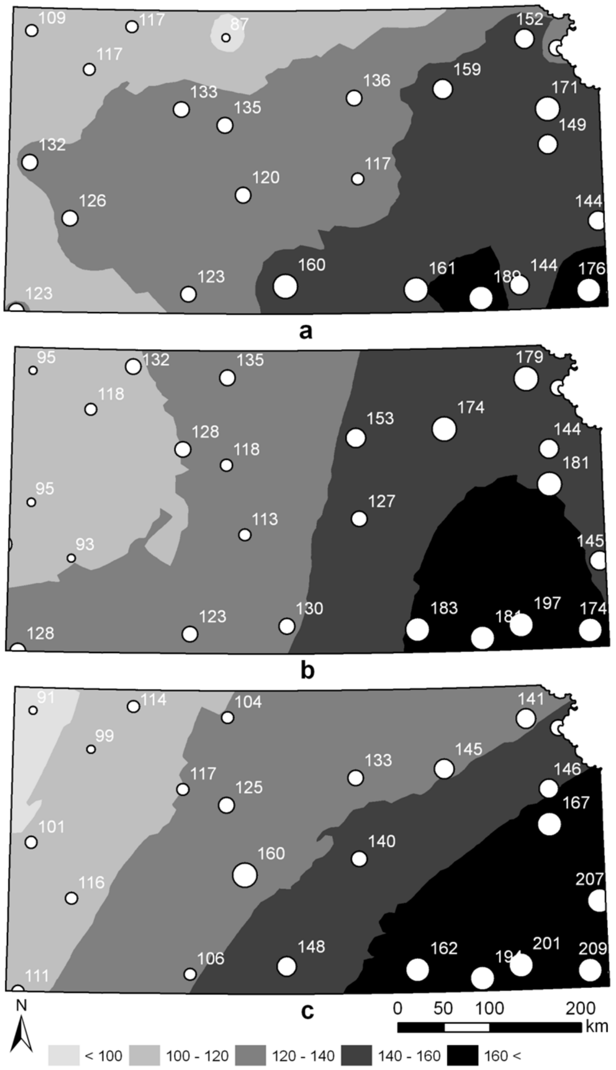
(Fig. 3-9), it is clear that larger magnitude events have increased, extending the region of storms greater than 90 mm toward the northwest from the far southeast corner of the state. The increase in rainfall expected at least once every two years is interesting when considering the design of stormwater management systems; the plotted trends indicate larger stormwater systems may be needed to control runoff, particularly in the southeast.

Fig. 3-9- Precipitation trend (mm) of 2-yr, 24-hr rainfall events for the period of a) 1920–1949, b) 1950–1979, and c) 1980–2009. The numbers on points show the calculated value for all stations with a graduated circle size.



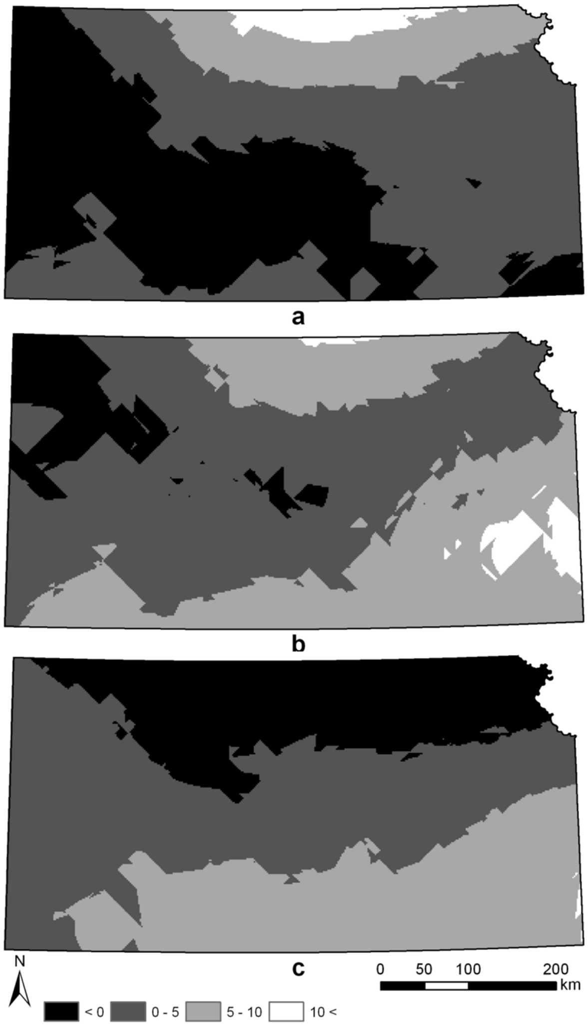
The 100-yr, 24-hr event maps display a similar trend to the shorter return period events with the magnitude of storms increasing in the southeast, and the portion of the state predicted to have events of greater than 160 mm much greater during the last period compared with previous periods (Fig. 3-10).

Fig. 3-10- Precipitation trend (mm) of 100-yr, 24-hr rainfall events for the period of a)1920–1949, b)1950–1979, and c)1980–2009. The numbers on points show the calculated value for all stations with a graduated circle size.



The differences between different climate periods for the 2-yr and 100-yr return period maps are shown in Figs. 3-11 and 3-12, respectively. For 2-yr, 24-hr return period events (Fig. 3-11), 64% of the state was predicted to have an increase in rainfall from the first (1920-1949) to second (1950-1979) climate period (Fig. 3-11(a)) and over 90% of the state showed an increase from the last period (1980-2009) to the first period (1920-1949), with 9% of the state along the east and north boundaries showing an increase of more than 10 mm (Fig. 3-11(b)). The change between the last two climate periods showed that 68% of the state was expected to have larger 2-yr rainfall events with the northern boundary remaining relatively constant over the last two periods (Fig. 3-11(c)).

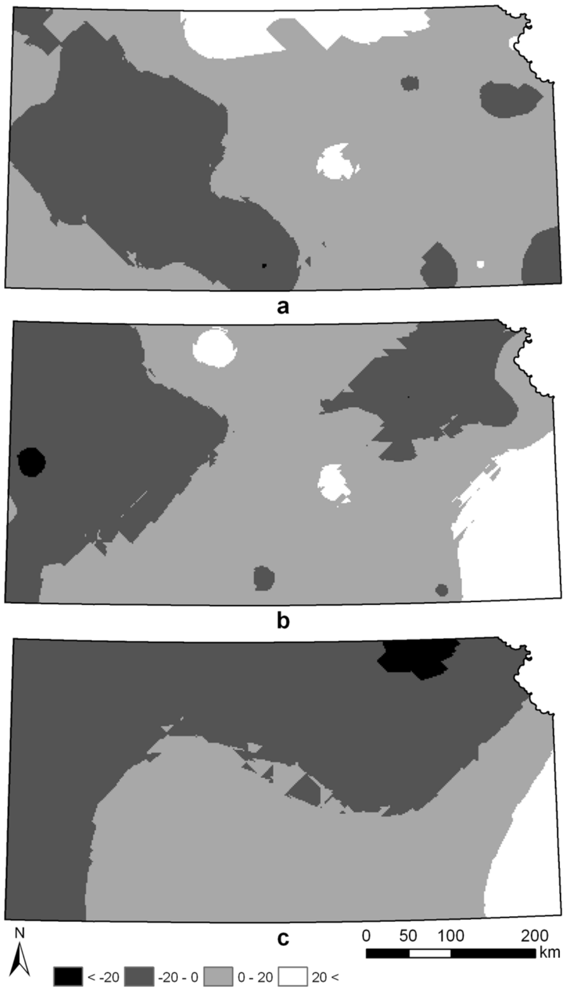
Fig. 3-11- Rainfall distribution shift (mm) of 2-yr, 24-hr rainfall events for the period of a) 1950–1979 vs. 1920–1949, and b) 1980–2009 vs. 1920–1949, and c) 1980–2009 vs. 1950–1979.



For the 100-yr, 24-hr return period (Fig. 3-12), storm magnitudes increased for most of the eastern and southern portions of the state across all time periods. Comparing time period 2 with time period 1 (Fig. 3-12(a)) shows 69% of the state was expected to experience larger 100-yr events, and comparing time period 3 with time period 1 (Fig. 3-

12(b)) shows 66% of the state should expect larger storm events. The change between the last 2 climate periods shows that 42% of the state was receiving larger rainfall events in the south and east, with the rest Kansas expected to have lower magnitude events including a small portion of the northeast expected to see long-term events decline by more than 20 mm (Fig. 3-12(c)).

Fig. 3-12- Rainfall distribution shift (mm) of 100-yr, 24-hr rainfall events for the period of a)1950–1979 vs. 1920–1949, and b)1980–2009 vs. 1920–1949, and c)1980–2009 vs. 1950–1979.



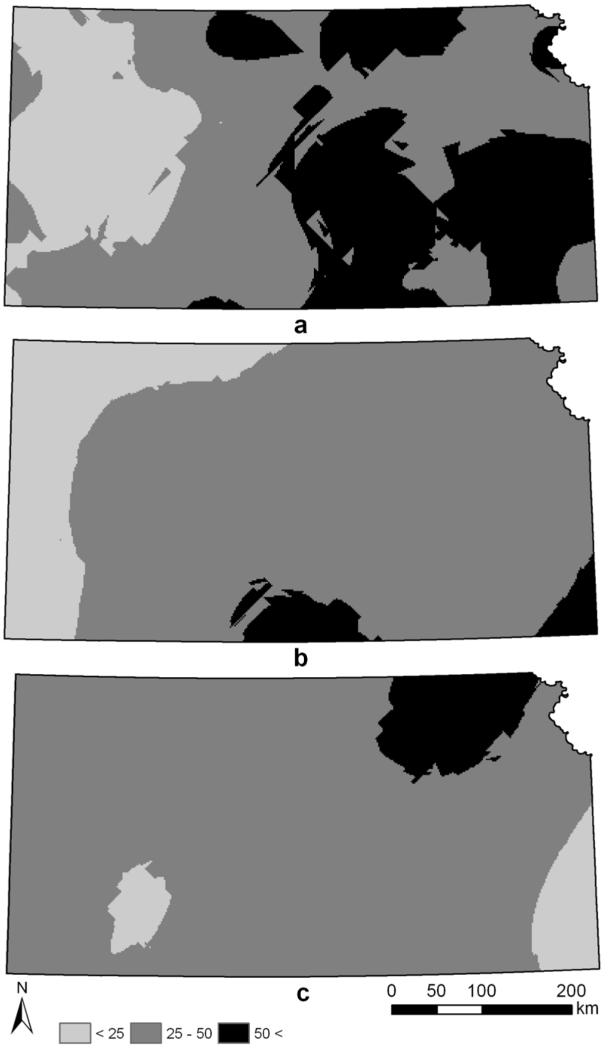
Compared with the new return period estimates, the TP-40 maps, underestimate the 2-yr, 24-hr storm events (Fig. 3-13) and overestimate the 100-yr, 24-hr events (Fig. 3-14). Using the TP-40 maps as the baseline and subtracting the new estimates from each climate period, 81% of the state was predicted to have larger 2-yr events during 1920–1949, 98% during 1950–1979, and 100% during 1980–2009.

Fig. 3-13- Rainfall distribution shift (mm) of Hershfield (1961) vs. the period of a)1920–1949, b)1950–1979, and c)1980–2009 for 2-yr, 24-hr rainfall events.

For 100-yr, 24-hr events, the TP-40 maps predicted larger storms for the entire state across all time periods (Fig. 3-14). During the first climate period (1920–1949), new estimates for western Kansas were more similar to the TP-40 predictions while the eastern portion of the state was over predicted by more than 50 mm (28% of the state gained more than 50 mm of rainfall, 53% between 25 and 50 mm, and 19% gained less than 25 mm of rainfall). The majority of the state was over-predicted by 25–50 mm during the second period (69%) and third period (84%).

These results highlight one of the greatest weaknesses in using a 30-yr period of record to predict long-term event magnitude. As shown earlier, this study indicates that predicted 2-yr, 24-hr rainfall magnitudes have increased over time. By including data from a severe drought period (1930's dust bowl era), Hershfield's (TP-40, 1961) results under predicted the more frequent events, generating a steeper slope on the probability plot that, when extrapolated beyond 30 years, resulted in overprediction of long-term events. However, given that the majority of Kansas was predicted to have 100-yr, 24-hr events comparable to those published in TP-40, the magnitude of long-term events likely has also increased over time. This is difficult to confirm, though, based on the difficulty of finding the exact data used in the original TP-40 analysis.

Fig. 3-14- Rainfall distribution shift (mm) of Hershfield (1961) vs. the period of a)1920–1949, b)1950–1979, and c)1980–2009 for 100-yr, 24-hr rainfall events.



Conclusions

The Rainfall Frequency Atlas (TP-40), which is the basis for important engineering and hydrologic design decisions in many parts of the U.S., needs to be updated for Kansas. Results showed that storm magnitudes have increased over time in the southeast portion of Kansas, while the northwest portion of the state has remained more consistent with earlier predictions. This shift in rainfall distribution will affect the function of runoff control structures such as dams, culverts, terraces, grassed waterways, and channels.

This analysis indicates that structures designed to handle large events with longer return periods may have been overdesigned if design information was based on the Hershfield (1961) analysis with data from 1911–1958; however, with the continued increase in magnitude of the frequent storms across the entire state over the last 90 years, small conservation structures such as grassed waterways, terraces, and infiltration practices likely were underdesigned when using the TP-40 information. Understanding the change in rainfall patterns across the state is critical to designing runoff control structures that are adequately sized and cost-effective.

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Chapter 4 - Analysis of temporal and spatial distribution and change-points for annual precipitation in Kansas, USA

Precipitation directly impacts agricultural production, water resources management, and recreational activities, all of which significantly affect a state’s economy. As the human population increases, demand for water escalates due to its crucial role in human health and food production. The question then becomes, can current water management strategies ensure sustainable access to clean water, maintain food supplies, and permit industrial uses given a changing climate? Developing a solid understanding of rainfall patterns and trends is vital, particularly for regions like Kansas with high spatial and temporal climate variability. In this study, three statistical methods were used to analyze annual rainfall trends in Kansas using daily rainfall data from 1890 through 2011: 1) a linear regression model, 2) the Mann-Kendall test, and 3) the Spearman test. A gradual increase in total annual rainfall was noted for 21 out of 23 stations, including eight statistically significant upward trends. The 23 station period of record average slope for Kansas was 6.8 mm/10yr with a minimum value of -8.5 mm/10yr for Saint Francis in the northwest and a maximum value of 20.1 mm/10yr for Independence in the southeast. In addition, sudden change analyses were conducted using cumulative sum and Pettitt tests. At twelve stations, significant change-points were detected as early as 1940 and as recently as 1980. The increasing trend, particularly after the significant change-points, is useful in updating water management plans. Total annual rainfall correlates with available water in soil, lakes, streams, and reservoirs and can assist with agricultural production decisions such as crop selection and new plant variety development when combined with rainfall distribution analysis throughout the year.

Introduction

The climate of Kansas is highly variable. While temperature variation has been important, Kansas is notorious for inter-annual fluctuations in precipitation. Precipitation variation influences water availability, water resources management, agricultural production and recreational activities. Understanding rainfall trends is useful in planning/operating water management systems as conditions vary and/or change. Knowledge of precipitation variations in space and time is especially vital for Kansas, which experienced the Dust Bowl of the 1930s, droughts of the 1950s and 1980s, and the 1951 Kansas River and 1993 Missouri River floods resulting in agricultural and property damage, loss of life, and economic turmoil (Brooks, 2006; Flora, 1934; Karl, 1983; Kolva, 1993; Woodhouse and Overpeck, 1998).

Studies throughout the United States have documented changes in precipitation (Changnon and Demissie, 1996; Karl et al., 1996; Lettenmaier et al., 1994), with an increasing trend for Central U.S. and Kansas (Garbrecht et al., 2004; Hu et al., 1998; Rahmani et al., 2013). Flora (1934) stated that over a 20-year period in early twentieth century, the number of 30 consecutive day periods with rainfall lower than 6.35 mm (0.25 inch) during crop-growing seasons, April-September, was 9 periods for the eastern portion of the state and 33 periods for the western portion. The smaller number of dry spells in eastern Kansas indicated fewer crop stress periods compared to western Kansas. Garbrecht and Rossel (2002) found a trend of increasing rainfall in Central Great Plains and Kansas during the late 20th century, 1980-2000, resulting from a diminishing number of dry years and an increasing number of wet years. However, the number of very wet years did not increase significantly.

The precipitation-frequency atlas of the United States, which provides the statistical analysis of data for water control structure designs, was released for Kansas in February 2013 (Perica et al., 2013). Stations with different data ranges were used in the analysis. The earliest record goes back to 1836 and the most recent to 1985. Using the overall trend of the entire data record (1836-2011) can be a source of inaccuracy if there is a sudden change at some point during the period of record. In addition, a sudden change over time might impact the trend analysis results. A step-change in a series of data might affect the mean, median, variance, and dependency (Kundzewicz and Robson, 2004). In this study, the annual rainfall trend and change-point analysis were completed using daily rainfall data from 1890 through 2011 for 23 stations across Kansas. Better understanding of changing precipitation patterns will enhance water management for agricultural production, irrigation and water management, and stormwater structural design.

Methods

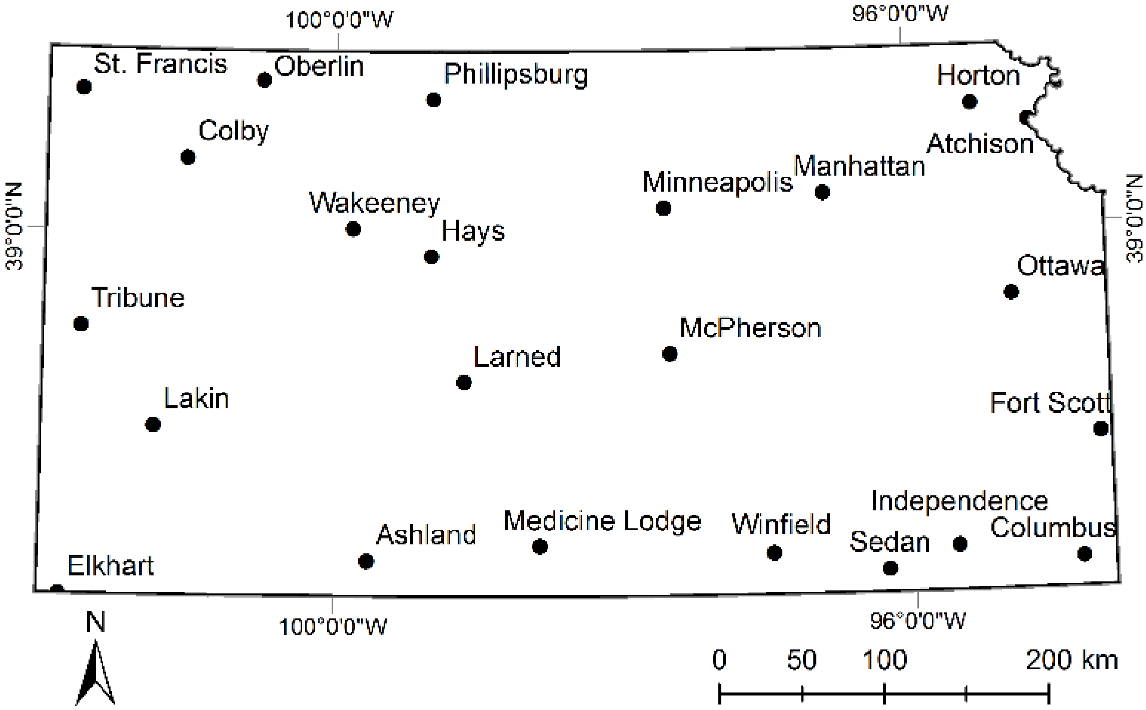
Study area

Kansas, located in the Midwestern U.S., experiences a typical mid-continental climate with hot summers and cold winters, and humidity levels ranging from humid in the East to arid in the Southwest. Average temperatures ranges from a low of 0°C in January to a high of 26°C in July. On average, Kansas receives 700 mm/yr rainfall, but a strong gradient exists from east (950 mm/yr) to center (650 mm/yr) to west (500 mm/yr). The weather is extremely variable in this area due to cold fronts moving from the north and northwest, warm fronts from the south, the dryline moving in from the southwest, and the low-level jet advecting moisture from the western Gulf of Mexico. Seasonal changes in the dominant processes driving precipitation produce climate conditions in Kansas so that the most rain falls in summer and late-spring, with a pronounced drier season in fall and winter (Goodin, 1995).

Data Source

Daily data were extracted for 23 high-quality weather stations with more than 100 years of data from the High Plains Regional Climate Center (HPRCC) (Table 4-1). Station locations have not been moved since establishment and these data were collected by HPRCC using acceptable protocols to ensure both accuracy and precision. Data for 22 stations continued through 2011, with the exception of Larned (1903 to 2010) which was discontinued in November 2011. Fig. 4-1 shows the location of rainfall stations across Kansas.

Fig. 4-1- Location of rainfall stations within Kansas



Total annual rainfall

Daily rainfall was summed to calculate the total annual rainfall at each station. The high variability of total annual rainfall must be analyzed for each station instead of averaged across the state, which can weaken extreme event effects (Powell, 1977). The Minneapolis station was selected to demonstrate the details of the trend analysis process. This station is located in the north central part of Kansas with a data record length of 120 years (1892 through 2011).

Statistical methods: gradual change

Trend analysis was completed using parametric and non-parametric tests to detect the presence of change in the annual rainfall. Parametric methods are the most powerful trend analysis for data sets with normally-distributed residuals. However, parametric methods are less powerful than non-parametric methods when data deviates from a normal distribution (Helsel and Hirsch, 2002). Mann-Kendall and Spearman tests are two non-parametric methods which are widely used to find gradual monotonic trends in annual rainfall data (Folland et al., 2001; Groisman et al., 2004; Haylock and Nicholls, 2000; Karpouzos et al., 2010; Modarres and de Paulo Rodrigues da Silva, V., 2007; Nikhil Raj and Azeez, 2012; Partal and Kahya, 2006; Qin et al., 2010). The advantage of the non-parametric tests is their rank-based procedure (Press et al., 1992). These methods can handle nonnormal, censored and missing data (Gan, 1998). The power of these non-parametric tests are almost equal in trend analysis and depends on the significance level, trend magnitude, sample size, and variation in the range of data (Yue et al., 2002). In this study, results of linear regression parametric method and Mann-Kendall and Spearman non-parametric methods were compared. A two-tailed test with 95% confidence interval (significance level of 0.05) was used in all methods. All these methods assume that errors in data are serially independent. When the errors related to a specific time period occurs in other time periods, serial correlation exist. Serial correlation does not impact the unbiasedness and consistency of the analysis but can increase the probability of trend detection, which may cause invalid results (von Storch and Navarra, 1999). Lag one autocorrelation estimates and Durbin-Watson statistics were used in order to assess the independence assumption.

Parametric method: **linear regression-** Linear regression is the most common method to measure correlation (Helsel and Hirsch, 2002). Least square regression assumes that the residuals are independent. Durbin-Watson statistics were used to evaluate the dependence of the residuals (Durbin and Watson, 1951; Pindyck and Rubinfeld, 1991).

$$d = \frac{\sum_{i=2}^{n}[\varepsilon_i - \varepsilon_{(i-1)}]^2}{\sum_{i=1}^{n}\varepsilon_i^2} \tag{4-1}$$

where d is the Durbin-Watson statistic, $\varepsilon_i = y_i - \bar{y}$ is the residual of i-*th* observation, y_i is the i-*th* observation and $\bar{y}$ is the observations mean. If *d* was smaller than the critical value (d_L), the null hypothesis was rejected and the interpretation was that the residuals were correlated. The significance level was set at 0.05.

Non-parametric method: Spearman- Spearman is a distribution-free rank-based method to measure the statistical monotonic relationship between two variables (Kendall and Gibbons, 1990; Maritz, 1995). To calculate the Spearman rank correlation coefficient (ρ), first the independent (*x*) variable was ordered from smallest to largest and given a rank of 1 to *n* (Rx_i). Then an appropriate rank (Ry_i) was assigned to each observation (*y*). Then ρ was determined by:

$$\rho = \frac{\sum_{i=1}^{n}(Rx_i.Ry_i) - n(\frac{n+1}{2})^2}{n(n^2-1)/12} \qquad (4\text{-}2)$$

Where n is the number of observations. In that case, (n+1)/2 is the mean rank of both *x* and *y*. If all observations increase as x increases, ρ is equal to 1; if all observations decrease as x increases, ρ is equal to -1, both indicating a strong correlation between y and x. In the case of no correlation, ρ is close to zero (Helsel and Hirsch, 2002).

Non-parametric method: Mann-Kendall- Mann-Kendall is a distribution-free rank-based method that provides the Kendall's τ as the monotonic relationship between x and y (Bradley, 1968; Kendall, 1975; Mann, 1945). Because ranked-based methods are based on the rank of the observation and not the observation (*y*) itself, τ is not sensitive to outliers. Observations were sorted in ascending order based on the independent parameter (x). The test statistic *S*, measures the relationship between observations (y) based on their occurrence time (x ranks):

$$S = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} sgn(y_j - y_i) \qquad (4\text{-}3)$$

and:

$$sgn(y_j - y_i) = \begin{cases} 1, & y_j - y_i > 0 \\ 0, & y_j - y_i = 0 \\ -1, & y_j - y_i < 0 \end{cases} \qquad (4\text{-}4)$$

where y_i and y_j are the *i*-th and *j*-th observation. When all y values increase as x increases, S is the maximum possible comparison between n data points:

$$S_{max} = \frac{n(n-1)}{2} \qquad \textbf{(4-5)}$$

thus, Kendall's τ is the ratio of S to the S_{max} or:

$$\tau = \frac{S}{n(n-1)/2} \qquad \textbf{(4-6)}$$

which can be between -1 and 1. Then S is compared to the expected value when the null hypothesis is true to test for significance of τ. The null and alternative hypotheses are:

$H_0: \tau = 0 \ (no\ significant\ trend)$

$H_a: \tau \neq 0 \ (significant\ trend)$

For large sample sizes (*n* > 20), S follows a normal distribution, and Z test statistics are:

$$Z_s = \begin{cases} \frac{S-1}{\sigma_s}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sigma_s}, & S < 0 \end{cases} \tag{4-7}$$

where

$$\sigma_s = \sqrt{\left[\left(\frac{n}{18}\right)(n-1)(2n+5) - \sum_{k=1}^{n} t_k(k)(k-1)(2k+5)\right]/18} \tag{4-8}$$

where t_k is the number of ties ($y_i = y_j$) of extent k. A two-tailed test was selected at the 0.05 or higher significance level for all methods; therefore, the H_0 is rejected at significance level of α if $|Z_s| > Z_{1-\alpha/2}$.

This method was used because it accurately accounts for threshold data, censoring, and non-normality. Computing Kendall's τ requires simple calculations and because Mann-Kendall is a ranked-based method, it is resistant to anomalous values. In addition, it works for linear and nonlinear correlations (Berryman, 1988; Helsel and Hirsch, 2002). In addition, it has a high (0.985) asymptotic efficiency relative to student t-test statistic for normal distribution and at least 0.95 for other distributions (Noether, 1958; Stuart, 1954; Stuart, 1956). The Mann-Kendall method has a few advantages compared to the Spearman method: 1) performs better with a large number of ties in the ranks, 2) is simpler to interpret, and 3) exhibits better results for small sample sizes (n < 20) (Anandhi et al., 2008; Bhattacharyya and Johnson, 1977; Leach, 1979).

Mann-Kendall and Spearman tests are correct when the indepence assumption is valid. Lag autocorrelation coefficient was used to test the serial correlation of the time series.

$$\boldsymbol{r_k} = \frac{\sum_{i=1}^{n-k} \varepsilon_i \cdot \varepsilon_{(i+1)}}{\sum_{i=1}^{n} \varepsilon_i^2} \quad \textbf{(4-9)}$$

where r_k is the lag k autocorrelation, n is the number of observations and $\varepsilon_i = y_i - \bar{y}$, is the residual of i-*th* observation. The first autocorrelation (k=1) is usually measured for randomness assumption test (Box et al., 2011; Chatfield, 2003). The value of r is between -1 and 1 with larger absolute r showing the presence of correlation in the time series.

Statistical methods: abrupt change

Change-point analysis helps detect any possible abrupt changes in data series. Pettitt and cumulative sum (CUSUM) are two widely used methods to detect a change-point (Karpouzos et al., 2010; Smadi and Zghoul, 2006; Villarini et al., 2011). These rank-based methods are non-parametric, distribution-free and resistant to outliers.

CUSUM method- The cumulative sums were calculated as (Taylor, 2000):

$$\boldsymbol{S_i = S_{i-1} + (y_i - \bar{y}), \qquad i = 1,\ 2,\ \ldots,\ n} \quad \textbf{(4-10)}$$

where, $S_0 = 0$, y_i is the i-th observation, and $\bar{y}$ is the mean of the observations. A sudden turn in CUSUM curve direction shows a sudden change in the data average. A confidence interval was calculated for the step-change running a bootstrap analysis. Before doing the bootstrapping, an initial magnitude of change was required to be able to compare bootstrapping results with the initial data arrangement result. The initial change was determined by:

$$\mathbf{S_{diff} = S_{max} - S_{min}} \tag{4-11}$$

where $S_{max} = \max(S_i)$ and $S_{min} = \min(S_i)$.

The bootstrapping process steps were: 1) generate a bootstrap sample from the original data (n observations) with replacement, 2) based on the new data order, generate the CUSUM values, denoted as S_i^o, 3) calculate the S_{diff}^o for each new bootstrapped sample, 4) determine if the new S_{diff}^o is less than the original S_{diff}. Then repeat all the four steps, N times to have accurate results (N was set on 1000 times in this paper). Finally, calculate the confidence interval as:

$$CL = 100 * \frac{X}{N} \% \tag{4-12}$$

where X is the number of times that $S^{o}_{diff} < S_{diff}$. The location of the change-point is the year when the $\max|S_i|$ occurred.

Pettitt test- First, the variable U_k was calculated (Pettitt, 1979; Smadi and Zghoul, 2006):

$$U_k = 2\sum_{i=1}^{k} Ry_i - k(n+1) \qquad (4\text{-}13)$$

where Ry_i is the rank of the *i*-th observation when the values $y_1, y_2, \ldots, y_n$ in the series are arranged in ascending order. Then the statistical change-point test statistic was defined as:

$$K = \max_{1 \le k \le n} |U_k| \qquad (4\text{-}14)$$

where a change-point in the series occurs at which U_k achieves a maximum value of K. The change-point is statistically significant if $K > K_\alpha$. The critical value (K_α) is given by:

$$K_\alpha = [-ln\alpha(n^3 + n^2)/6]^{1/2} \qquad (4\text{-}15)$$

then the approximate significance probability, *p(t)*, of a change-point can be calculated from (Fealy and Sweeney, 2005):

$$p(t) = 1 - \exp\left(\frac{-6K^2}{n^3 + n^2}\right) \qquad (4\text{-}16)$$

All these analyses were accomplished in Matlab version R2012a.

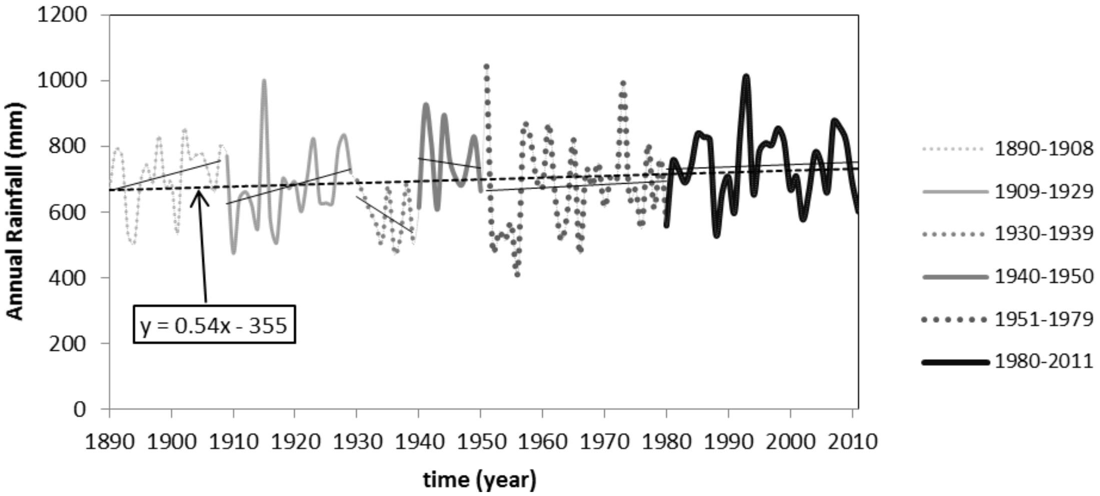
Results and discussion

Annual trend

Fig. 4-2 shows the mean of total annual rainfall trend in Kansas (1890-2011) averaged for 23 stations across the state. The Dust Bowl years are clear around the 1930s, which corresponds with Garbrecht and Rossel (2002) for the Central Great Plains based on data from 1895 through 1999. After the 1930s drought years, a sharp increase occurred in the mean annual rainfall for the wet decade of the 1940s and the 1951 Kansas River flood. After the drought years of 1952-1955 and an increase in the mean of total annual rainfall, a gradual precipitation increase emerged from 1956 through 2011. The increase in precipitation since 1956 of interest due to potential impact on Midwestern region (Garbrecht et al., 2001). However, a deeper analysis of the rainfall trend demonstrates the high variability in the state since 1890. There was an increasing trend in total annual rainfall from 1890 to 1908. A similar trend was observed in the 1909 through 1929 time period; however, the mean of this increase was lower than the previous time period. The drought of the 1930s more significantly decreased the mean and caused a decreasing trend in data for 1930-1939. In the 1940s, the mean increased dramatically, followed by another decrease from 1951 through 1979, and a small increase for 1980-2011. Finally, these data displayed an increasing trend from 1951 through 2011.

Combining all these subperiod trends, the overall trend shows a positive slope in total annual rainfall mean from 1890 to 2011.

Fig. 4-2- Total annual rainfall trend in Kansas based on data from 1890 to 2011 averaged for 23 stations



Serial correlation

Comparing the lag one autocorrelation (r1) with the critical value based on the 0.05 significance level, two stations (Lakin and Independence) exhibited significant serial correlation in the residuals, which was negligible in the analysis. Additionally, Durbin-Watson statistics diagnosed a significant correlation at the same stations.

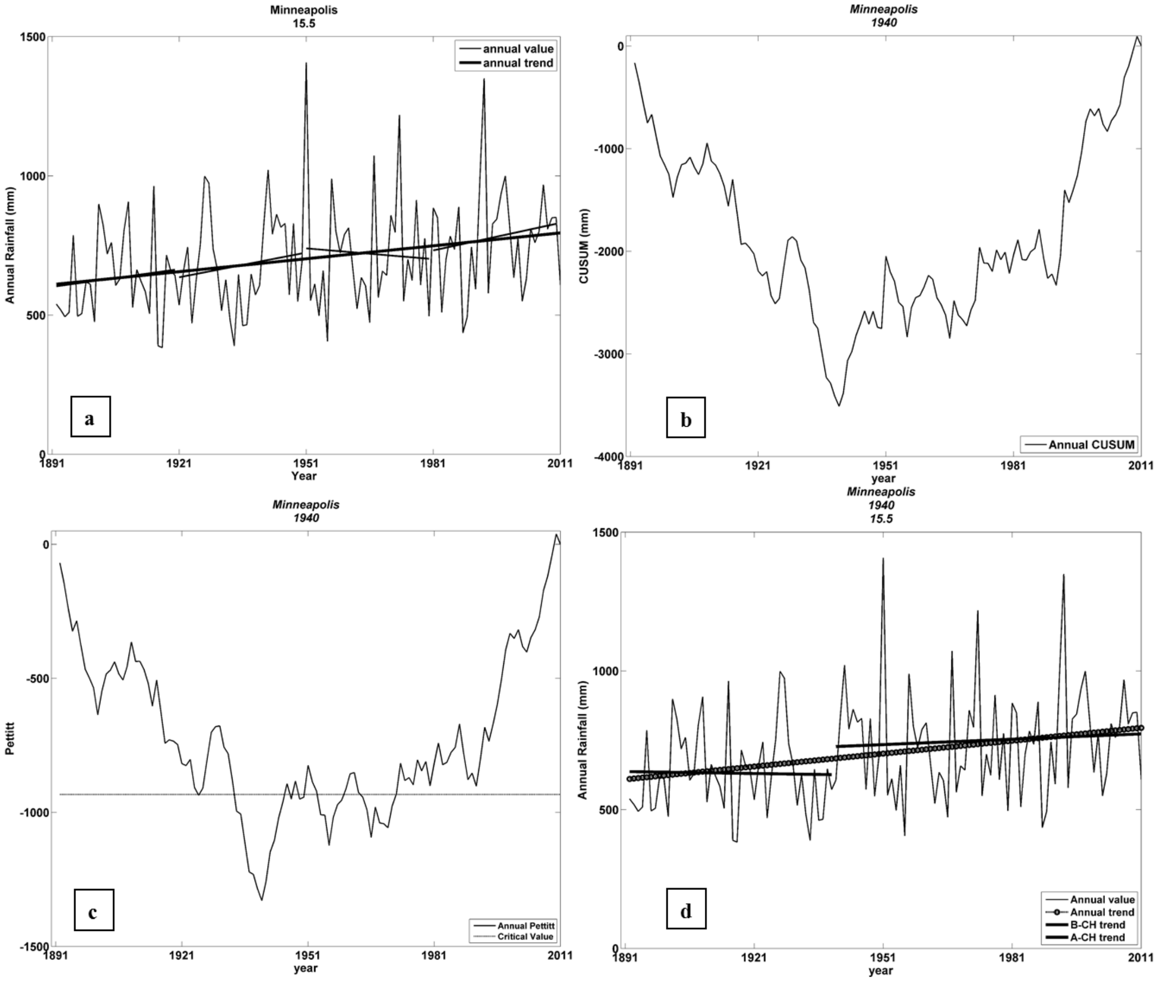
Gradual change: overall data record trend

The results of Minneapolis are shown as an example (Fig. 4-3), but the same process was executed for all 23 stations (Table 4-1). The overall trend is shown by the slope of linear regression fit, which indicates an increasing trend of 15.5 mm/10yr in the total annual rainfall from 1892 to 2011 (Fig. 4-3(a)). In addition, four consecutive periods of 1891-1920, 1921-1950, 1951-1980, and 1981-2010 were analyzed to compare the overall and sub-period trends. The periodic trends varied from a slope similar to the overall trend in the first period, an increase in the second period, a decrease in the third period, and an increase in the most recent period, as compared to overall data. For reference, the periodic trends do not match the overall trend at the other stations with even more deviation at some locations, which highlights the variability across the state over time.

Table 4-1 shows the Mann-Kendall τ, Spearman ρ, and linear regression slope (mm/10yr) for all stations over the entire data record. The trends indicate that the total annual rainfall has increased at a majority of stations (21 of 23) from 1890 to 2011.

In a specific investigation of works closely associated with the study area of this paper, Garbrecht et al. (2004) indicated a 9% increase in the annual rainfall in the Walnut River watershed in Kansas from 1895 to 2001. Winfield, KS, a station used in this study, is located in this watershed and the total annual rainfall indicated a significant increasing trend of 17.4 mm/decade (Table 1) at this station. Hu et al. (1998) analyzed rainfall data from Missouri, Illinois, Iowa, Kansas, and Nebraska, using 168 stations with more than 80 years of data ending in 1996. Data analysis revealed an upward trend in annual rainfall, especially for the last 10 years of data range (1985-1996). In this project, results

Fig. 4-3- a) Total annual rainfall trend using linear regression, b) CUSUM test results; The number below the station name is the change-point year, c) Pettitt test results; The number below the station name is the change-point year, and the horizontal line is the critical value for the significance test, and d) Trend analysis before and after the change-point (year 1940). The line with circle symbol shows the linear fit on overall data and the solid lines show the linear fit before and after 1940 (the change-point); B-CH: before change-point, A-CH: after change-point. All for Minneapolis, KS.



showed that all but two stations (Saint Francis and Ashland) exhibited an increase in rainfall with all three methods. The linear trend fit showed that the total annual rainfall decreased by 5.4 and 8.5 mm/10yr in Ashland and Saint Francis, respectively. Mann-Kendall test results show that eight stations experienced a significant increase based on a significance level of 0.05. Six of these stations are located in the eastern and central part of the state. In addition, the magnitude of the upward trend was found to increase from West to East. Spearman test results confirmed the Mann-Kendall results and linear regression analysis confirmed the results with two exceptions. Linear regression analysis did not show a significant trend in Manhattan based on the significance level of 0.05; however, the trend was significant at the 0.10 significance level. Secondly, linear regression was the only method showing a significant decrease (8.5 mm/10yr) in Saint Francis. Overall, eight stations showed a significant upward trend based on at least two statistical methods. Review of the significant linear regression slopes shows a minimum increase of 8.0 mm/10yr at Lakin (western Kansas) to a maximum increase of 20.1 mm/10yr for independence (eastern Kansas).

Table 4-1- Total annual precipitation trend analysis without change-point

Station	Period	Trend analysis method		
		Kendall τ	Spearman ρ	Linear trend, mm/10yr
Ashland	1900-2011	-0.07	-0.11	-5.4
Atchison	1890-2011	0.05	0.08	4.5
Colby	1900-2011	0.11	0.17	6.0
Columbus	1890-2011	0.02	0.03	1.9
Elkhart	1900-2011	0.03	0.06	1.2
Fort Scott	1895-2011	0.06	0.10	7.7
Hays	1892-2011	0.02	0.03	1.6
Horton	1890-2011	**0.15***	**0.23***	**14.0***
Independence	1893-2011	**0.21***	**0.32***	**20.1***
Lakin	1893-2011	**0.16***	**0.25***	**8.0***
Larned	1903-2010	0.06	0.09	4.5
Manhattan	1890-2011	**0.14***	**0.20***	9.6
McPherson	1890-2011	0.08	0.13	6.9
Medicine Lodge	1891-2011	0.11	0.15	6.3
Minneapolis	1892-2011	**0.20***	**0.30***	**15.5***
Oberlin	1893-2011	0.08	0.13	3.6
Ottawa	1900-2011	0.12	0.17	10.0
Philipsburg	1890-2011	0.09	0.12	5.7
Saint Francis	1908-2011	-0.11	-0.17	**-8.5***
Sedan	1890-2011	**0.13***	**0.19***	**12.9***
Tribune	1900-2011	0.11	0.16	4.2
Wakeeney	1893-2011	**0.15***	**0.24***	**9.8***
Winfield	1900-2011	**0.16***	**0.25***	**17.4***

Bold fonts: statistically significant station/trend, *: statistically significant trend, α = 0.05

Abrupt change: overall data record

These data were analyzed to detect a single abrupt change over the entire data record. Figs. 4-3(b) and 4-3(c) show the CUSUM and Pettitt tests results for Minneapolis. Both tests detected a significant change-point in 1940. For this station, 98% of the CUSUM runs indicated an abrupt change in the average total annual rainfall in the year 1940 (α=0.05). Prior to 1940, the annual CUSUM value followed a decreasing trend, indicating that the general total annual rainfall was declining. After 1940, the CUSUM value increased, indicating an increasing average. In the Pettitt test, the maximum value of the Pettitt parameter was compared to a critical value to detect significant change. Over the data record, twelve stations experienced a significant abrupt change (α=0.05) (Table 4-2).

For the stations where one or both methods detected a significant change-point, these data before and after the change-point were re-analyzed to investigate the gradual change. More than one abrupt change-point may exist in these data, which could be detected on these data before and after the first change-point. For example, McCabe et al. (2007) and Schubert et al. (2004) found a decadal or multidecadal extratropical forcing of climate variations in Great Plains and upper Colorado River Basin. The number of change-points affects the trend analysis, particularly in a region such as Kansas with a high variability. In this study, only one change-point was assumed in these data in which a more reliable trend analysis is feasible based on the length of available data before and after the change-point (Villarini et al., 2011).

The CUSUM and Petitt tests provided very similar results: eight stations had a significant change-point with the CUSUM and 11 stations with the Petitt method (Table 4-2). Four cases occurred: 1) both methods showed the same significant change-point year for a station, and that particular year was selected as the change-point, 2) one method detected a significant abrupt change in these data and the other method didn't, so the significant change-point year was selected as the change-point, 3) the two methods detected two different years in which the significant abrupt change occurred, causing the later year to be selected as the change-point to be more reliable, and 4) no significant change-point were detected for either method. This procedure covered the period, which was intersected in both methods.

Significant change-points occurred in different years across Kansas with the earliest one occurring in 1940 in Horton, Minneapolis, and Ottawa and the most recent one in Winfield in 1980. All but two stations (Saint Francis and Ashland) demonstrated an increase in the mean of total annual rainfall after the change-point as compared to the average before the change-point, meaning that, on average, the annual rainfall has increased after the change-points throughout the state and these stations gained more rain in recent years.

In seven of the eight stations with significant trend over the entire data period, a significant change-point was detected (Table 4-2). Additional analysis of these seven stations showed the average total annual rainfall has increased after the change-point, when compared to before the change point, with the exception of the Saint Francis station. This suggests the overall trend may be influenced strongly by the trend after the change-point and a trend analysis on these data before and after the change-point showed these effects.

Gradual change: before and after the change-point

Fig. 4-3(d) demonstrates the trend analysis results for Minneapolis on the overall data record, including results before and after the change-point. The numbers below the station name are the change-point year and the overall linear fit slope, respectively. The overall data from 1892 to 2011 had a significant positive slope of 15.5 mm/10yr, a nonsignificant negative slope before the change-point on data of 1892 to 1939, and a nonsignificant positive slope after the change-point on data of 1940 to 2011.

Table 4-2- Change-point on mean of the total annual rainfall

Station	Period (yr)	CUSUM Change-point	Pettitt Change-point	Selected Change-point
Ashland	1900-2011	1929	1929	—
Atchison	1890-2011	1956	1956	—
Colby	1900-2011	1940	1972	—
Columbus	1890-2011	1984	1966	—
Elkhart	1900-2011	1939	1939	—
Fort Scott	1895-2011	1980	1980	—
Hays	1892-2011	1991	1991	—
Horton	1890-2011	1940*	1940*	**1940**
Independence	1893-2011	1966*	1966*	**1966**
Lakin	1893-2011	1939	1968*	**1968**
Larned	1903-2010	1991	1991	—
Manhattan	1890-2011	1940	1956*	**1956**
McPherson	1890-2011	1970*	1970	**1970**
Medicine Lodge	1891-2011	1972	1972	—
Minneapolis	1892-2011	1940*	1940*	**1940**
Oberlin	1893-2011	1964*	1970*	**1970**
Ottawa	1900-2011	1940*	1940*	**1940**
Philipsburg	1890-2011	1956	1956	—
Saint Francis	1908-2011	1951*	1951*	**1951**
Sedan	1890-2011	1972	1921	—
Tribune	1900-2011	1977	1977*	**1977**
Wakeeney	1893-2011	1943	1943*	**1943**
Winfield	1900-2011	1980*	1980*	**1980**

Bold fonts: statistically significant station/selected year, *: statistically significant year

Table 4-3 presents the results of trend analysis before and after the change-points with Mann-Kendall, Spearman, and linear regression tests with a significance level of 0.05. Table 4-1 shows that none of the stations had a significant trend after the change point and only Ottawa had a significant trend before the change point. The results emphasize the importance of the trend analysis on the subperiods compared to the entire data set.

Table 4-3- Total annual precipitation trend analysis before and after the change-point

Station	Before the change-point				After the change-point			
		Trend analysis method				Trend analysis method		
	Period	Kendall τ	Spearman ρ	Linear trend, mm/10yr	Period	Kendall τ	Spearman ρ	Linear trend, mm/10yr
Ashland	—	—	—	—	—	—	—	—
Atchison	—	—	—	—	—	—	—	—
Colby	—	—	—	—	—	—	—	—
Columbus	—	—	—	—	—	—	—	—
Elkhart	—	—	—	—	—	—	—	—
Fort Scott	—	—	—	—	—	—	—	—
Hays	—	—	—	—	—	—	—	—
Horton	1890-1939	-0.14	-0.20	-20.0	1940-2011	0.04	0.06	3.0
Independence	1893-1965	-0.01	-0.02	-5.4	1966-2011	0.12	0.19	39.0
Lakin	1893-1967	0.01	0.02	2.6	1968-2011	0.01	0.01	-0.7

Larned	—	—	—	—	—	—	—	—
Manhattan	1890-1955	-0.01	-0.02	3.4	1956-2011	0.08	0.14	18.0
McPherson	1890-1969	-0.10	-0.14	-10.0	1970-2011	0.09	0.17	19.0
Medicine Lodge	—	—	—	—	—	—	—	—
Minneapolis	1892-1939	-0.01	-0.02	-2.3	1940-2011	0.06	0.10	6.4
Oberlin	1893-1969	-0.11	-0.15	-10.0	1970-2011	-0.01	0.01	0.1
Ottawa	1900-1939	-0.25*	-0.35*	-62.0*	1940-2011	0.00	-0.01	-3.2
Philipsburg	—	—	—	—	—	—	—	—
Saint Francis	1908-1950	0.06	0.10	9.2	1951-2011	0.09	0.14	5.0
Sedan	—	—	—	—	—	—	—	—
Tribune	1900-1976	-0.08	-0.13	-6.3	1977-2011	0.08	0.07	7.0
Wakeeney	1893-1942	0.04	0.08	12.5	1943-2011	0.04	0.07	3.3
Winfield	1900-1979	-0.05	-0.06	-4.5	1980-2011	0.09	0.14	35.0

Bold fonts: statistically significant station/trend, *: statistically significant trend

Change-points were detected in more than 50% of the stations (12 out of 23), indicating that hydrologic structures designed based on design storm values calculated using the entire period of record may be inadequate due to disregarding the sudden changes. Neglecting abrupt shifts ignores climate change impacts particularly in recent years.

Summary and conclusions

Long-term trend analysis on the total annual rainfall in Kansas showed an upward trend for 1890 to 2011. The positive slopes tended to increase across the state from west to east, with the steepest slopes (greatest increase) in eastern Kansas. Results for the entire data record indicated an upward trend at 21 out of 23 stations with the slope of seven of these 21 being significant. The maximum significant positive slope was observed at Independence, KS at 20.1 mm/10yr. Two of the 23 stations had a decreasing trendline slope with one being significant and was observed at Saint Francis at -8.5 mm/10yr.

In addition, a change-point analysis on the entire data length detected a significant change-point at 12 stations with the earliest one happening in 1940 and the latest one happening in 1980. Trend analysis for a gradual change before and after the change-points did not show significant trend at the majority of stations, excepting Ottawa which showed a significant decreasing trend of -62 mm/10yr from 1900 to 1939. However, except for two stations (Lakin and Ottawa), the trend was insignificantly increasing after the change-point at other 10 stations. The importance of considering sudden changes is clear when assessing the impact of changing climate on water management and hydraulic control structure design. Comparing the trends of the entire data record with the trends before and after the change points improves the knowledge of climate change impacts and helps to select the best period with the current available data.

These results emphasize the high level of inter-annual variation in Kansas rainfall and an upward trend in the total annual rainfall, particularly throughout the second half of the 20th Century. However the trends are insignificant after the change-points. The implications of the trends after the change-points could be applied to update water management systems and agricultural decisions. The trends after the change-points also influences water control structures such as dams and culverts, therefore necessitating consideration of new rainfall regimes when addressing upgrading or replacing these structures in order to avoid design failure.

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Chapter 5 - Climate Change and Water Control Structures Failure Risk

Water control structure design is based on the maximum runoff rate resulting from storms with a specific return period and duration. The Rainfall Frequency Atlas (National Weather Service Technical Paper 40, 1961) (TP-40) provided statistical rainfall analysis as the basis for hydrologic structure design until the information was updated for Kansas in February 2013 (National Oceanic and Atmospheric Administration Atlas 14, volume 8) (Atlas-14). The current study compares the 10-yr, 24-hr storms from TP-40 and Atlas-14 to determine change in the estimated structural failure risk across Kansas. Analysis on the number of exceedances from the 10-yr, 1-, 2-, 3-, 4-, 7-, and 10-day rainfall events and the annual maximum for 23 stations in Kansas showed higher values in recent years for both the frequency of and the magnitude of longer rainfall events at a majority of the stations. Results of this study are useful for hydrologic structure design in order to prevent accepting additional risk of failure because of the current changing climate.

Introduction

An increasing trend has been observed for annual and extreme rainfall events (Alexander et al., 2006; Frich et al., 2002; Groisman et al., 2005; Villarini et al., 2011), with a shift in extreme rainfall distribution with the changing climate (Karpouzos et al., 2010; Peterson, 2013; Qin et al., 2010; Rahmani et al., 2013; Trenberth et al., 2007). Water control structure design is based on maximum runoff resulting from storms with a specific return period and duration. Structural design return periods for events of different magnitude vary based on many factors, including drainage area size, risk of failure, importance of the structure, and economic balance between the cost of periodic structure repairs and the cost of potential property loss and rebuilding the structure. Hydrologic structures associated with systems with a low risk of injury to humans and loss of property, such as agricultural terraces, grassed waterways, and small water and sediment control basins, are typically designed to control a 10-yr, 24-hr storm (American Society of Agricultural and Biological Engineers, 2006; American Society of Agricultural and Biological Engineers, 2012). Larger, more expensive structures in which higher risk of loss is expected are designed to handle larger events, such as the 100-yr, 24-hr storm events. Runoff generation rate depends on many factors, including but not limited to rainfall intensity and duration, antecedent moisture condition, landcover, topography, watershed size, slope, and soil properties (Brocca et al., 2007; Castillo et al., 2003; Dunne et al., 1991; Woolhiser et al., 1996). In general, runoff increases with increased antecedent soil moisture, rainfall duration, and rainfall intensity (MartõÂnez-Mena et al., 1998; Nettleton et al., 1969; Reynders, 1972). Vahabi and Mahdian (2008) examined the effect of antecedent soil moisture, slope, vegetation cover, clay, sand, and silt soils on runoff rate resulting from two simulated rainfall intensities. They found that for a 24.5 mm/h rain, antecedent soil moisture played the second most effective role (after vegetation cover), on runoff generation. For a rainfall intensity of 32 mm/h, antecedent soil moisture placed third in the effect on runoff generation after vegetation cover and sandy soil. Saghafian et al. (1995) indicated that differences in initial soil moisture cause more diversity in runoff for short duration storms as compared to long duration storms.

Among all factors that affect runoff production, rainfall intensity, rainfall duration and antecedent soil moisture are the factors that have the most effect on runoff generation. Castillo et al. (2003) showed that higher intensity rainfalls (50 mm/h) are less correlated to antecedent soil moisture as compared to lower intensity rainfalls (25-35 mm/h). In urban and large rural areas, the complexity of surface types and continuous change make the determination of important factor in runoff generation difficult. In an agricultural watershed, where soil properties and land use type are more stable over time, rainfall magnitude, by changing the antecedent moisture condition, and rainfall intensity are the main parameter that impact runoff generation (Chen et al., 2009; Choi and Deal, 2008; Niehoff et al., 2002). For this study, agricultural fields were selected to eliminate the effects of spatial changes in landcover, topography, slope, and soil properties.

Updated precipitation frequency data of the United States, National Oceanic and Atmospheric Administration (NOAA) Atlas 14 (Atlas-14) (Perica et al., 2013), was released for Kansas (Volume 8) in February 2013. Hershfield's Technical Paper 40 (TP-40) (Hershfield, 1961), has served as the basis for structural design since 1961; however, Kansas has experienced an increase in annual and intense rainfall particularly in recent years (Brunsell et al., 2010; Garbrecht and Rossel, 2002; Hu et al., 1998; Rahmani et al., 2013; Small and Islam, 2008). In Denmark, Arnbjerg-Nielsen (2012) found an increase of 10-50% within the next 100 years in design precipitation intensities. The new climate patterns should be considered in hydrologic structure design. In this study, the results of Atlas-14 and TP-40 are compared to determine changes in the failure risk of selected hydrologic structures. In addition, the antecedent rainfall condition is examined by calculating the annual daily and multi-day maximum rainfall. The annual maximum rainfall is used to estimate the maximum runoff which is utilized in hydrologic structures design.

Methodology

Study Area

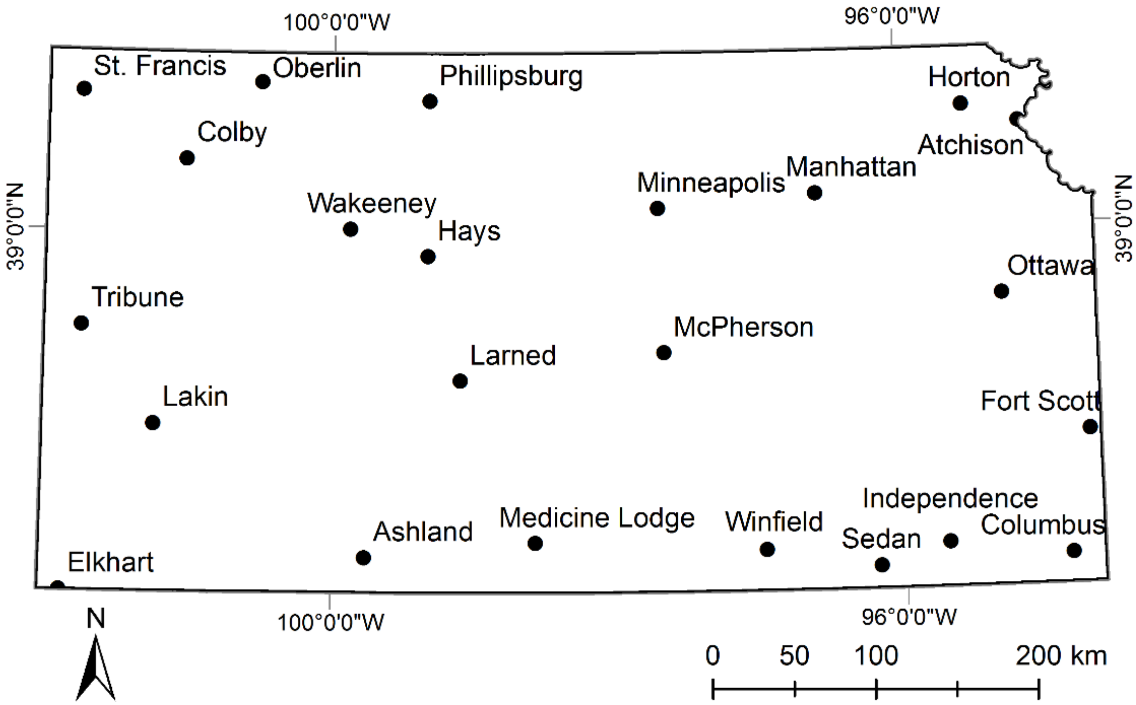
Strong seasonality characterizes the climate of Kansas. With a mid-latitude and continental location, temperature extremes occur in July (26°C) and January (-1.6°C). Over 70% of the precipitation occurs during the warm season, with a peak in June (105 mm) and the minimum in January (18 mm). A pronounced spatial gradient in mean annual precipitation is evident, with places in southeast Kansas averaging over 1000 mm whereas locations in western Kansas average less than 500 mm. This steep east-to-west gradient is related to the location of the primary moisture source, which is the western Gulf of Mexico, and the tendency for wind streams to carry the moisture north and eastward rather than up slope to the west.

Data

Two sets of data were used in the analysis. One set was used to prepare rainfall surface maps for the state of Kansas, and the second set was used for antecedent rainfall condition analysis.

Daily rainfall data were obtained from the High Plains Regional Climate Center for 23 stations with at least 100 years of record in Kansas (Fig. 5-1). In addition, the 10-yr, 24-hr surface maps were extracted from the Atlas-14 and TP-40. The Atlas-14 maps were created using 308 stations in the state of Kansas. The stations reported data records of varying length, with the longest one (Leavenworth) from 1836 to 2011 and the shortest one (St. John) from 1985 to 2009 (Perica et al., 2013). The TP-40 maps were created with fewer stations, and the longest one recorded data from 1911 to 1958. Detailed station information is not available for TP-40.

Fig. 5-1- Kansas stations; stations with more than 100 years of data



Rainfall analysis

10-yr, 24-hr rainfall from Atlas-14 and TP-40

On average, a rainfall event with a specific return period (T) is expected to occur once every T years. Return period is the reciprocal of the probability of occurrence (P) $(T = \frac{1}{P})$, meaning that the probability that a storm could exceed a specific value (T-yr storm) each year is P, i.e., a 10-yr storm has a 10% chance of occurrence in any given year. The values for 10-yr, 24-hr storms were extracted from the Atlas-14 and TP-40.

Annual maximum series (AMS) was the basis for the analysis (Bonnin et al., 2006; Perica et al., 2013). AMS assumes a generalized extreme value distribution and uses annual maximum events in the analysis as compared to partial duration series (PDS) which assumes a generalized Pareto distribution and uses the rainfall events exceeding a threshold value (Madsen et al., 1997). Finally, results were converted to PDS using Langbein's formula to make them comparable with other published materials (Bonnin et al., 2006; Langbein, 1949). Various distribution functions, including 3-parameter Generalized Extreme Value (GEV), Generalized Normal, Generalized Pareto, Generalized Logistic, Pearson Type III distributions, 4-parameter Kappa distribution, and 5-parameter Wakeby distribution, were utilized for different stations with specific characteristics in order to obtain the most accurate results with minimum error. The authors refer readers to NOAA Atlas-14 Volume 8 for the detailed calculation of the 10yr, 24-hr storm values.

Continuous prediction surface maps

The 10-yr, 24-hr rainfall surface maps were extracted from the Atlas-14 for Kansas. The TP-40 isopluvial maps were prepared by hand. The maps were not continuous, and the smoothed contour-lines represented rainfall values at approximately 1-inch (25 mm) intervals. In order to prepare a continuous prediction surface map, the TP-40 maps were scanned and georeferenced in a Geographical Information System (GIS). Additional details of the map digitizing process are explained in Rahmani et al. (2013) (Rahmani et al., 2013). Finally, the raster file version of the TP-40 10-yr, 24-hr surface map was subtracted from the Atlas-14 results to determine any shifts in this metric of rainfall frequency and intensity.

Antecedent Rainfall

In Atlas-14, daily rainfall data were used to calculate the 10-yr, 1-, 2-, 3-, 4-, 7-, and 10-day storms based on the AMS method results. The daily data were recorded at fixed times every day (constrained observations) which resulted in recording lower than true maxima (unconstrained). A conversion factor was used to convert the constrained record values to true values. The conversion factor was 1.12, 1.04, 1.03, 1.02, 1.01 and 1 for 1-, 2-, 3-, 4-, 7- and 10-day storms, respectively. The number of events with 1-, 2-, 3-, 4-, 7-, and 10-day duration that exceeded 10-yr return period thresholds obtained from Atlas-14, were calculated for each year. The results are heavy storms expected to occur once every 10 years. Various definitions of thresholds have been used to calculate rainfall extreme events: Karl et al. (1995) used a fixed daily 50.8 mm rainfall depth as the threshold; Trenderth et al. (2007) used the upper 95th percentile of daily rainfalls. A similar definition of the threshold in this study was used by Kunkel et al. (1999) and Changnon and Kunkel (1995). Kunkel et al. (1999) used a threshold calculated as events with recurrence intervals of one year or longer for 1, 3, and 7-day duration, and Changnon and Kunkel (1995) correlated such events to flooding in small watersheds. In calculating the design storms with the AMS method, annual maximum values are the basis for analysis; therefore, annual maximum events were calculated for all durations.

Finally, trend analysis was accomplished on each duration for the entire data record using a linear regression parametric method and the Mann-Kendall and Spearman nonparametric methods (Bradley, 1968; Kendall and Gibbons, 1990; Kendall, 1975; Mann, 1945; Maritz, 1995). These methods have been widely used in previous studies to detect a possible trend in extreme rainfalls (Crisci et al., 2002), annual, seasonal and monthly rainfall (IPCC, 2002; Modarres and de Paulo Rodrigues da Silva, V., 2007), river flow (Hamed, 2009), number of rainy days (Smadi and Zghoul, 2006; Tarhule and Woo, 1998), and water quality (Yu et al., 1993). A two-tailed test with a 95% confidence interval (significance level of 0.05) was used in all three methods. Because of high spatial variability across the state, analysis was accomplished using individual station data in order to capture rainfall variability.

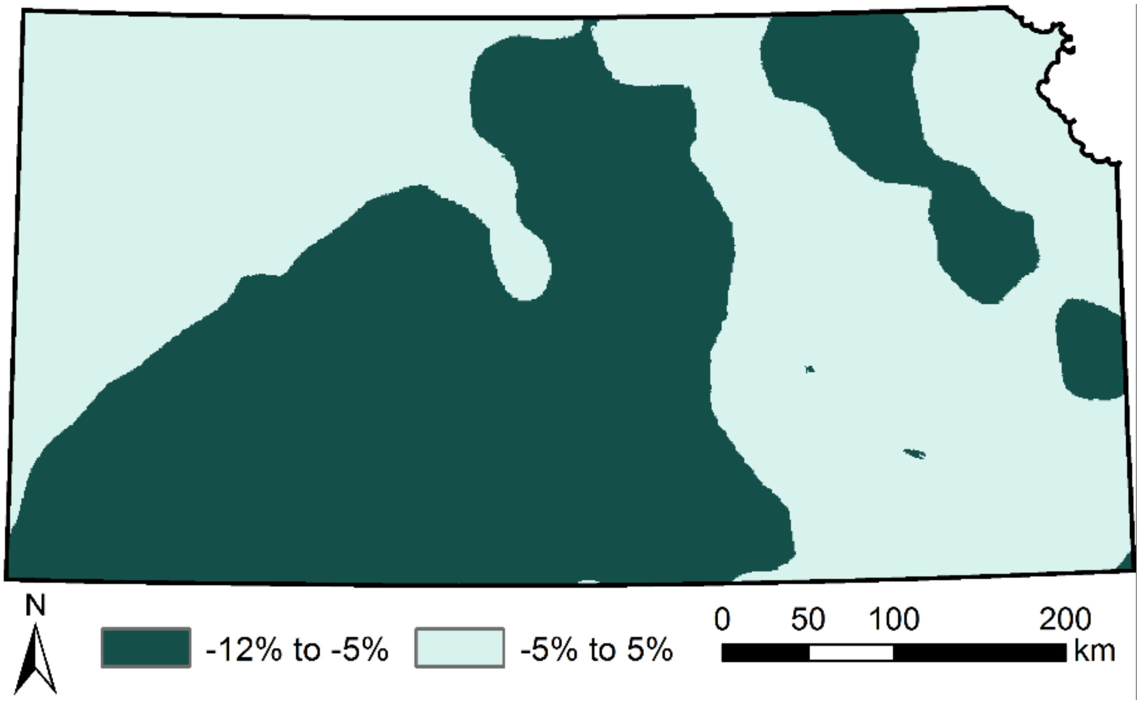
Results and discussion

TP-40 and Atlas-14 comparison

Fig. 5-2 indicates that the 10-yr, 24-hr storms (basis for hydrologic structure design runoff values), have changed in amount by less than 5% for 53% of Kansas, and by greater than 5% for 47% of the state. The maximum difference of the 10-yr, 24-hr storms in Atlas-14 was a -12% primarily in southwestern Kansas compared to TP-40. Young and McEnroe (2006) also found that for return periods of 10 years or less, the older TP-40 values were higher than their results.

Hydrologic structures are designed based on maximum runoff resulting from storms with a specific return period and duration. The 10-yr, 24-hr rain have not changed by more than -12% in regards to areal distribution in Kansas. Conversely, a long duration event can produce greater quantities of runoff. During a continuous light to moderate rain event, soil absorbs water until the point of saturation and then excess water flows as runoff. The antecedent moisture condition is discussed in the following sections.

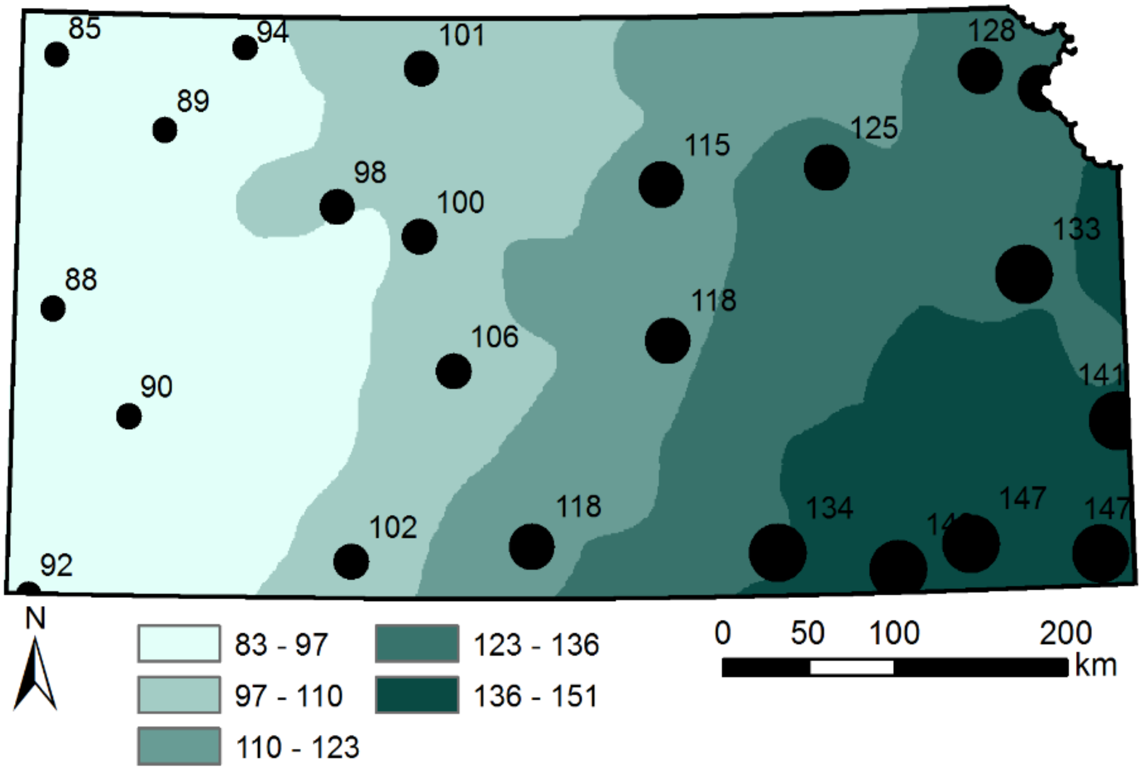
Fig. 5-2- 10-yr, 24-hr surface map difference between Atlas-14 and TP-40 (Atlas-14 - TP-40)



10-yr, 24-hr distribution

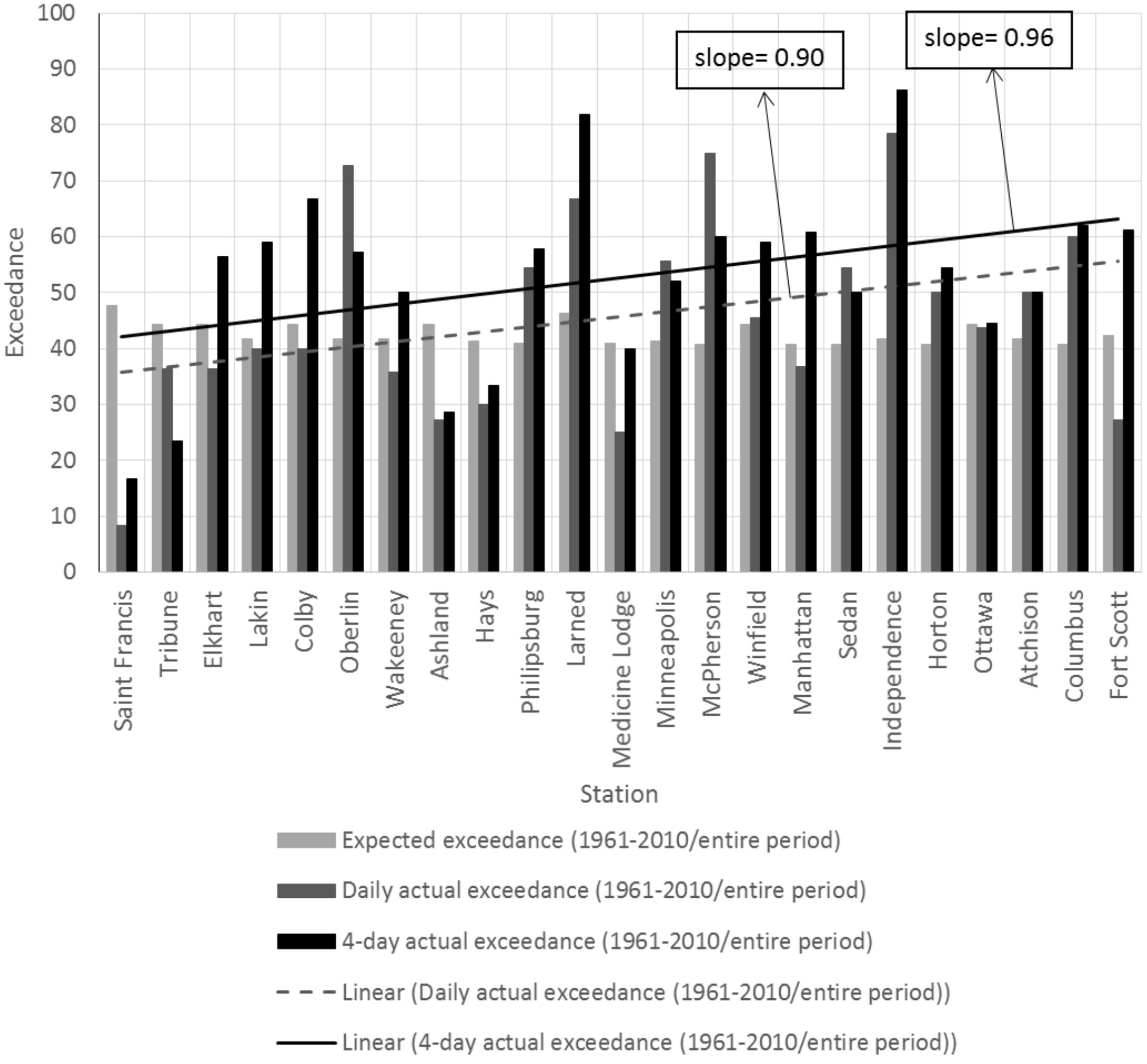
The 10-yr, 24-hr storm map based on Atlas-14 estimates (Fig. 5-3) indicates an increase in values from northwest to southeast. The difference between the lowest (85 mm) and the highest (149 mm) storm value is 64 mm. A structure design based on the highest storm value (149 mm) in eastern Kansas is 75% larger than a structure design based on the lowest storm value (85 mm) in western Kansas. In addition, using an average Kansas storm value of 114 mm for designing hydrologic structures does not meet the minimum requirement criteria for the eastern portion of the state and is 34% higher than the lowest value in the west. The new spatial patterns of extreme and total annual rainfall across the state (Garbrecht and Rossel, 2002; Rahmani et al., 2013; Siebenmorgen et al., 2010; Villarini et al., 2011), helps characterize the failure risk of hydrologic structures and emphasizes the necessity to update design criteria.

Fig. 5-3- 10-yr, 24-hr storm surface map; larger circles shows stations with larger storms



The total annual number of events exceeded the 10-yr, 24-hr storms differed among the stations. No exceedances were observed for several years at all stations since 1890. Manhattan with 19 exceedances of the 10-yr, 24-hr storms and Atchison with 2 exceedances, both located in northeastern Kansas, showed the highest and the lowest exceedance frequencies. An event with 10-yr return period is expected to occur once every 10 years. A weather station was established in Atchison in 1893 and, through 2012, only two events have been recorded that exceeded the 10-yr, 24-hr threshold. However, three nearby stations (Horton, Ottawa, and Manhattan), had 12, 16, and 19 exceedances. Kansas has a warm season precipitation climate that is highly variable in space and time. The differences in these four stations illustrate this variability. TP-40 was prepared using data from 1911 to 1958, so in addition to the entire period of 1890-2012, the data for the period of 1961-2010 was analyzed to determine not only the overall trends but also recent trends. The expected (once every 10 years) and actual number of exceedances were calculated for the entire and 1961-2010 periods. Then the ratio of the exceedances over the recent period of 1961-2010 to the entire data record were examined (Fig. 5-4). Stations are arranged based on their geographical location.

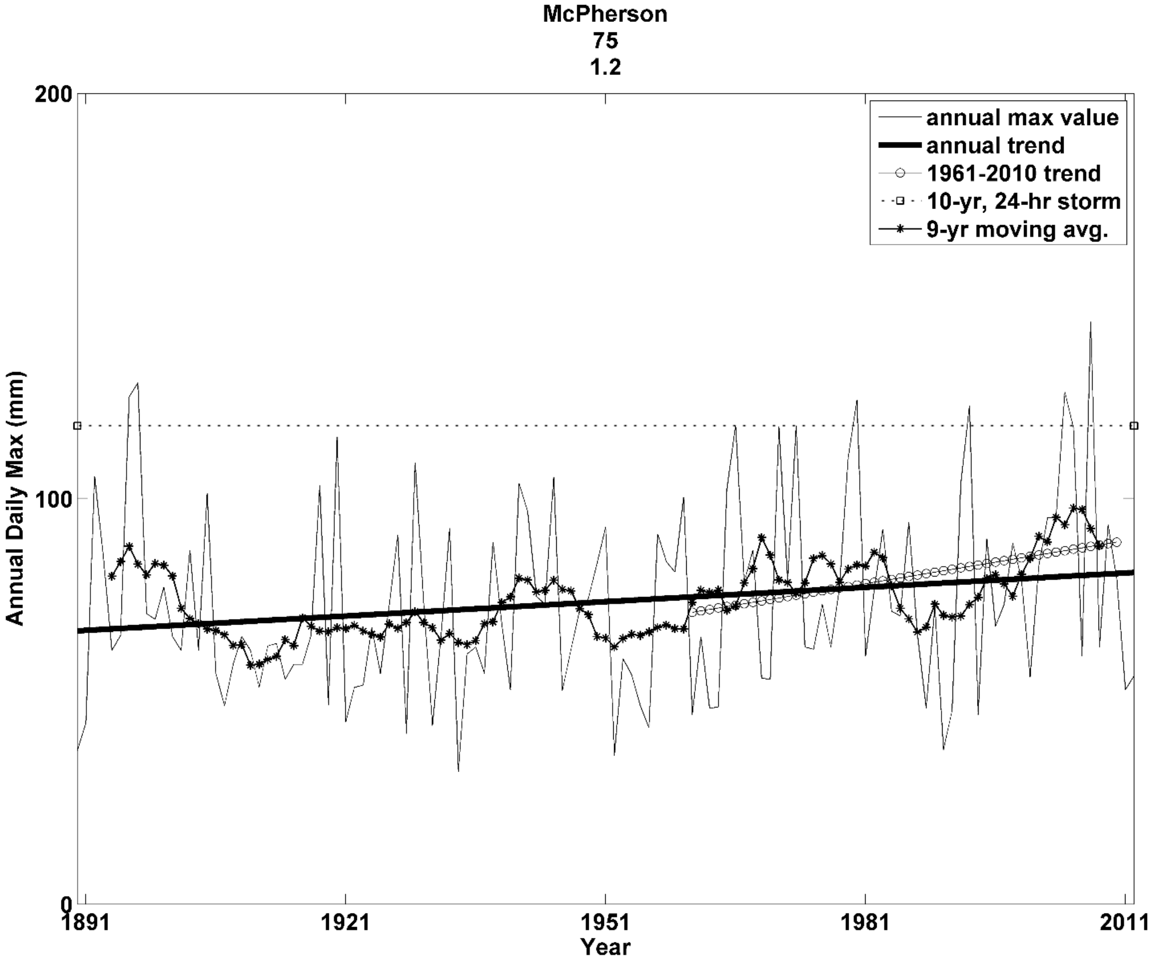
Fig. 5-4- Ratio of the 10-yr, 24-hr and 4-day storm exceedances over the recent period of 1961-2010 to the entire data record. Stations are arranged based on their longitude (western-eastern)



In the cases that this ratio was larger for the actual exceedances compared to expected exceedances, more exceedances occured in the recent years (1961-2010). The linear trend line on the actual exceedances indicates a positive slope indicating that eastern Kansas experiences more exceedances compared to central and western Kansas. From 1961-2010, the actual exceedance values were more than expected values in 48% (11 stations) (Fig. 5-4). Stations with a shorter return period were located in northeast, southeast, central and north central Kansas (Figs. 5-1 and 5-4).

A station in the center of the state (McPherson) was selected to show the detailed results, but the same analysis were executed for all 23 stations. Fig. 5-5 demonstrates the variability of annual daily maxima trend for 1890-2012 for McPherson. The overall trend shows an increase of 1.2 mm/decade for the annual daily maxima. The ratio of actual exceedances over the recent period of 1961-2010 to the entire data record of 1890-2012 is shown below the station name and indicates that 75% of the exceedances occurred in the last five decades at McPherson. The trend over the period of 1961-2010 demonstrates a steeper positive slope comparing to the entire data record trend, indicating that more extreme rainfall events occurred in the last five decades.

Fig. 5-5- Trend of the annual daily maxima and 9-yr moving average. Below the station name; the top number is the percentage of exceedances in the 1961-2010 period, the bottom number is the slope (mm/decade) of the linear fit on the entire data record (solid line), and the dashed circle and square lines are the linear fitted line for 1961-2010 and the 10-yr, 24-hr storm magnitude



Mann-Kendall and Spearman tests and a linear regression model examined an upward trend on the annual daily maximum for 78% of the stations (28% statistically significant) and a downward trend for 22% of the stations (significant at one station, Ashland). Statistical significance may be affected by high interannual or interdecadal variability, indicative of climatic noise in the data. McCabe et al. (2007) and Schubert et al. (2004) discovered decadal or multidecadal climate variations in the Great Plains and upper Colorado River Basin. Based on the linear regression fit, the largest upward trend occurred at Independence in the southeast portion of Kansas (4.2 mm/decade), and the greatest decrease occurred at Ashland in the southwest Kansas (-1.7 mm/decade). Numerous dry and wet periods are notable across the state since 1890 (Fig. 5-5): The Dust Bowl of the 1930s, the wet periods of the 1940s, and a gradual rainfall increase after the 1950s (Brooks, 2006; Flora, 1934; Karl, 1983; Kolva, 1993; Woodhouse and Overpeck, 1998). Sixteen stations experienced a positive slope after 1961, and in 14 stations, the slope was greater as compared to the entire period. These findings highlight the recent increasing trend of the annual daily maximum.

Antecedent Moisture Condition

Trend analysis of 2, 3, 4, 7, and 10-day storms indicated similar trends to daily storms for a majority of stations. The largest change occurred for 4-day duration rainfalls as compared to daily rainfall trends; only results of this duration are presented in order to compare with daily outputs in detail. The 4-day duration is the closest duration to the 5-day antecedent rainfall condition used by well-recognized Curve Number method developed by Soil Conservation Service to estimate runoff (USDA, 1986). Independence, located in southeaster Kansas, with 29 exceedances of the 10-yr, 4-day storms and Atchison, located in northeastern Kansas, with 10 exceedances, indicated the highest and the lowest exceedance frequencies, respectively. All but one station (Colby), experienced greater exceedances frequency from the 10-yr, 4-day storm compared to 10-yr, 24-hr storm, indicating more frequent longer duration events. Fig. 5-4 shows that the ratio of the exceedances over 1961-2010 to the entire period is higher in 70% of the stations for 4-day events as compared to daily events resulting an approximately 5% increase in the trend line level. In addition, the slope of the trend is greater for 4-day rainfall events (0.96) compared to daily rainfall events (0.90), indicating that longer duration events are likely to increase more than shorter duration events.

Fig. 5-6 demonstrates the variability of annual 4-day maxima at McPherson. Trends show that the slope over 1961-2010 is greater than the overall slope (0.5 mm/decade). Trend analysis on the annual 4-day maxima indicated increasing trend at 78% of the stations (17% significant) using Mann-Kendall, Spearman, and linear regression methods. The ratio of actual exceedances over the recent period of 1961-2010 to the entire data record of 1890-2012 indicates that 60% (number below the station name) of the exceedances occurred in the last five decades which is higher than the expected exceedance for this period at McPherson (Fig. 5-6). The slope over 1961-2010 were greater than the slope over the entire period at 61% of the stations. The results show that annual 4-day maximum events are likely to occur more frequently.

In Atlas-14, the storm values are estimated using the longest available data at each station. With the increasing trend for the annual maximum events and steeper positive slopes over the past five decades, the estimated storm values might be higher utilizing more recent data. In addition, many scientists studied the stationary condition of the climate (Bates et al., 2010; Vicente-Serrano and López-Moreno, 2008) and suggested that the stationary should not be assumed valid in water resources engineering due to changes in precipitation patterns (Milly et al., 2007). Using recent periods to calculate the design storm values may decrease failure risk of hydrologic structures particularly for small structures such as grassed waterways, culverts, and channels where storms with shorter return periods (2- or 10-yr) are used for designing. For large structures such as dams, the design criteria is to use storms with 100-yr return period, therefore using at least 100 years of data is recommended.

Fig. 5-6- Trend of the annual 4-day maxima and 9-yr moving average. Below the station name; the top number is the percent of exceedance occurring from 1961-2010, the bottom number is the slope (mm/decade) of the linear fit for the entire data record (solid line), and the dashed lines are the linear fitted line during 1961-2010 and the 10-yr, 4-day storm magnitude

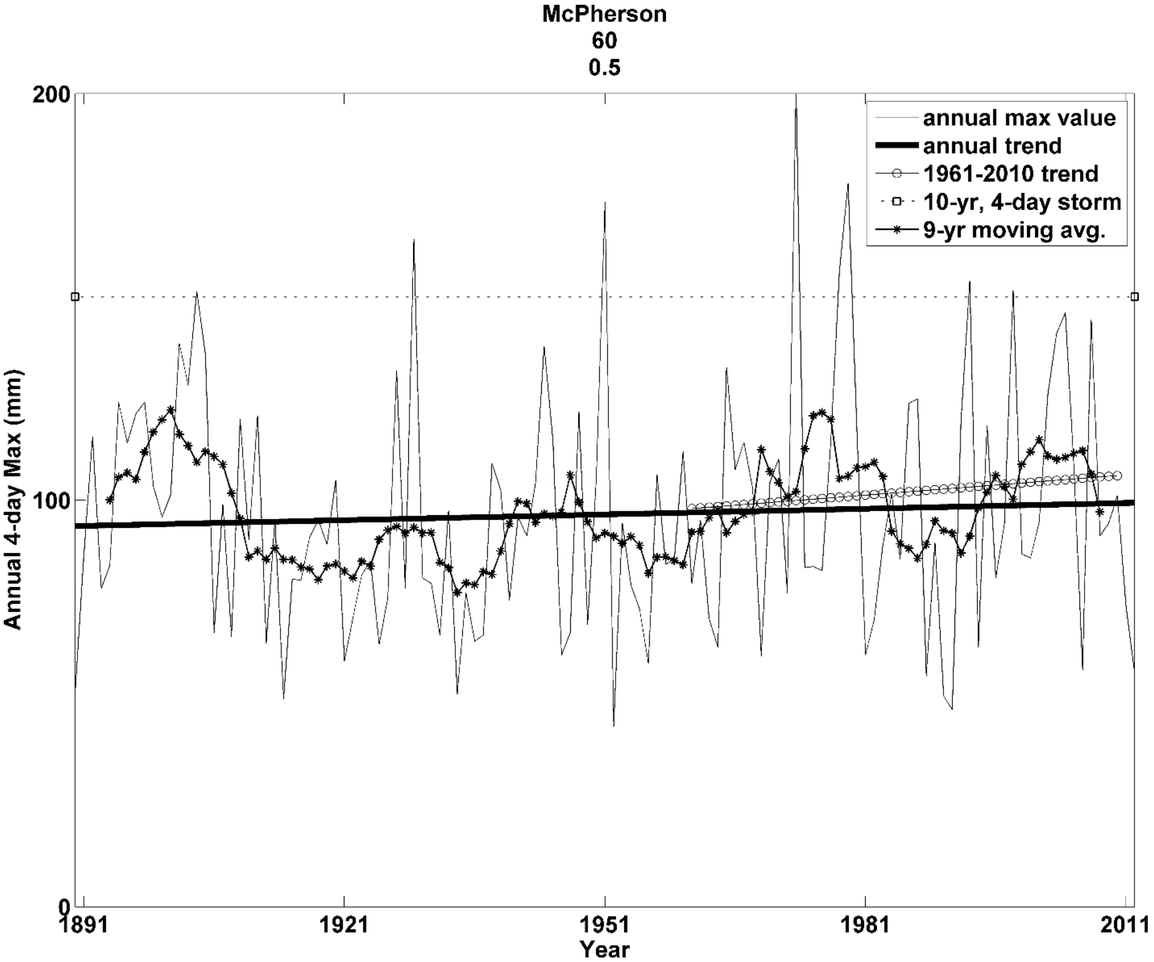


Table 5-1 shows the overall linear trend on the entire period for all rainfall durations at each station. Positivity of the slope increased in 52%, 65%, 65%, 61% and

56% of the stations when comparing the 2-, 3-, 4-, 7-, and 10-day to daily maximum storms, respectively (Table 5-1). Slopes of the annual 4-day maximum events indicate the greatest increase as compared to other storm durations. Independence experienced the steepest positive slope of 5.2 mm/decade in all durations. The greatest change occurred in Ottawa with an increase in slope from 0.2 mm/decade for maximum daily rainfall to 1.4 mm/decade for maximum 4-day rainfall and in 40% of the stations, the increase was higher than 100%. The larger positive slopes for longer events suggest in the likelihood of greater moisture and greater runoff generation caused by decreasing storage capacity. When soil moisture is low, the soil absorbs much of the rainfall until the saturation point and then excess water flows as runoff on ground surface. Hence, increasing rainfall amounts in short periods of rain cause the soil reach saturation condition quicker and result in the potential for greater runoff subsequent rainfall and higher chance of failure risk for hydrologic structures.

Table 5-1- Annual daily and multi-day rainfall trend analysis

Station	Period	Linear trend (mm/decade)					
		1-day (p-value)	2-day	3-day	4-day (p-value)	7-day	10-day
Saint Francis	1908-2012	-0.8	-0.9	-1.0	-0.9	-1.2	-2.4
Tribune	1900-2012	0.4	0.2	0.4	**0.5**	**0.8**	**1.2**
Elkhart	1900-2012	0.0	-0.5	-0.6	-0.2	-0.3	-0.1
Lakin	1893-2012	0.5	**0.7**	**1.1**	**1.4**	**1.8**	**1.9**
Colby	1900-2012	1.0*(0.03)	**1.7**	**1.8**	**2.0***(0.01)	**2.1**	**2.2**
Oberlin	1893-2012	-0.1	**0.5**	**0.7**	**0.3**	**0.4**	**0.8**
Wakeeney	1893-2012	1.0*(0.03)	0.7	0.7	0.6	0.0	0.2
Ashland	1900-2012	-1.7*(0.02)	-2.2	-2.1	-2.0*(0.01)	-2.5	-2.2
Hays	1892-2012	-0.2	-0.3	-0.6	-0.6	-1.0	-1.0
Phillipsburg	1891-2012	0.2	0.2	**0.4**	0.1	0.0	0.2
Larned	1903-2010	0.7	**0.8**	**1.0**	**1.0**	**1.2**	**0.9**
Medicine Lodge	1891-2012	-0.1	**0.8**	**0.7**	**0.4**	**0.1**	-0.3
Minneapolis	1892-2012	1.4*(0.03)	**1.8**	**1.6**	**1.7**	**1.7**	**1.8**
McPherson	1890-2012	1.2	1.0	0.9	0.5	0.7	0.7
Winfield	1900-2012	1.1	**1.2**	**1.2**	**1.7**	**1.2**	0.8
Manhattan	1890-2012	0.8	0.6	0.8	**1.1**	**1.3**	**1.6**
Sedan	1890-2012	2.3*(<0.01)	1.9	2.2	**3.0***(0.02)	**2.8**	**3.1**
Independence	1893-2012	4.2^{+}*(<0.01)	4.2*	4.2*	**5.2^{+}***(<0.01)	**4.9***	4.2*
Horton	1890-2012	0.9	**1.1**	**1.2**	**1.1**	**1.3**	**1.2**
Ottawa	1900-2012	0.2	**0.8**	**1.2**	**1.4**	**0.8**	**0.9**
Atchison	1893-2012	0.6	0.1	-0.5	-0.6	-0.3	-0.8
Columbus	1890-2012	0.9	**2.1**	**1.7**	**1.7**	**1.0**	**1.4**
Fort Scott	1895-2012	0.0	**0.9**	**1.3**	**1.3**	**1.0**	**1.2**

Bold fonts: trend slope increased as compared to daily trend, +: greatest slope for each duration, *: statistically significant trend based on a 5% significance level

Summary and Conclusion

The 10-yr, 24-hr storm values have changed from -12% less to 5% more when compared the new Atlas-14 (Perica et al., 2013) based on data from 1836 to 2011 and the older TP-40 (Hershfield, 1961) based on data from 1911 to 1958. However, a trend analysis on the number of events exceeding the 10-yr, 24-hr storms obtained from Atlas-14, suggests an increasing trend in 65% of the stations. Trend analysis on the 10-yr, 2-, 3-, 4-, 7-, and 10-day rainfall events, generally showed upward trend with a greater increase as the storm duration increased. Analysis on data ranging from 1961-2010 indicated a large positive slope in this period compared to the entire data record (1890-2012) at a majority of the stations. The Dust Bowl of the 1930s and the Missouri River flood of 1993 impacted the analysis with extreme values much higher or lower than the average. These events may be associated with the El Niño or La Niña phenomenon or other teleconnetions with unusual sea surface temperatures (Kolva, 1993; McCabe et al., 2007; Trenberth and Guillemot, 1996; Woodhouse and Overpeck, 1998). Another extreme event or period in Kansas State may likely occur and it is expected to push the trends upward or downward. The general increasing trend, particularly since 1961, highlights the change in rainfall patterns with the changing climate. This shift suggests that new rainfall patterns should be considered in order to avoid under-estimating runoff when designing hydrologic structures and water management systems for runoff control and storage structures, to not accept a great risk of failure than what is already acceptable in general engineering practice.

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Chapter 6 - Summary and Conclusions

Kansas, located in the midwestern United States, has a very variable climate primarily due to movement and contact of cold and warm air streams across the state. The conflict of these air streams create severe thunderstorms with high intensity rainfalls throughout the year with the highest precipitation in summer, followed by spring, fall, and winter, respectively (Goodin et al., 1995; Rahmani et al., 2013). Precipitation variation impacts water resources (Middelkoop et al., 2001), water availability (Milly et al., 2005), agricultural production (Mendelsohn et al., 1994), and economy (Bark, 1978; Parra et al., 2008). In addition, precipitation extremes cause high flooding risk (Büchele et al., 2006) and influence human health (Confalonieri et al., 2007; Haines et al., 2006; Kistemann et al., 2002), food production (Rosenzweig et al., 2001), society (Werritty et al., 2007), ecosystems (FAY et al., 2008; Knapp et al., 2008), and infrastructures (Gersonius et al., 2013; Moran et al., 2010). Understanding precipitation patterns and shifts is crucial for areas such as Kansas with high climate variability in order to investigate consequences and reactions of these shifts. In this work, long-term (from 1890 through 2012) daily rainfall data was analyzed to determine possible trends in extreme daily rainfall events, annual rainfall, and annual daily and multi-day maximum rainfall events in Kansas.

The current rainfall frequency maps of Kansas, used for designing hydrologic structures, was prepared by Hershfield in 1961 (TP-40) with data from 1911 to 1958

(Hershfield, 1961). With a growing attention to climate change, new rainfall patterns should be considered in water control and storage structure design. 2- and 100-yr, 24-hr storms were calculated for each station using data from 1920-2009. Results indicated an increasing trend in daily extreme rainfalls in space and time. Southeastern Kansas experienced greater magnitudes of extreme rainfalls with a decreasing trend towards the northwest portion of the state. From 1920-1949, 1950-1979, and 1980-2009, a larger increase was observed in southeastern Kansas compared to other portions. These temporal and spatial shifts in 2- and 100-yr, 24-hr storms may impact the operation of small structures, such as culverts and channels, and large structures, such as dams. Because of changes in extreme rainfall patterns, an update of the TP-40 rainfall frequency atlas is necessary in order to build well-designed hydrologic structures able to control generated runoff (Hershfield, 1961).

Spatial and temporal increasing trends were observed for total annual rainfalls throughout Kansas. Average total annual rainfall for 23 stations across Kansas indicated an increasing trend for 1890-2011. Impacts of the Dust Bowl in the 1930s, the 1951 Kansas River flood, and the 1993 Missouri River flood are clear on the trends during the analyzed period (1890-2011). Results demonstrated that eastern Kansas experienced more rain than the central and western portions of the state. On average, western Kansas receives approximately 500 mm/yr rain, increasing to 650 mm/yr in the central, and 950 mm/yr in the eastern Kansas, causing difficulties in generalizing rainfall characteristics for the entire state. For example, irrigation strategies currently differ for western, central, and eastern Kansas because of large spatial differences in annual rainfall amounts. In addition to spatial variability, annual rainfall exhibited high interannual and interdecadal temporal variability influenced by global phenomena such as El Nino and La Nina (Johansson et al., 2009; Wolff et al., 2011), Pacific Decadal Oscillation (Cai and Rensch, 2012), and North Atlantic Oscillation (Folland et al., 2009).

Trend analysis of annual rainfalls indicated that all but two stations (St. Francis and Ashland) exhibited an upward trend. Three statistical methods: 1) Linear regression, 2) Man-Kendall, and 3) Spearman, were used to determine significant trends (significance level of 0.05). Eight stations demonstrated significant annual rainfall trend based on results of at least two methods. Linear regression fit indicated the steepest positive slope at Independence in southeastern Kansas with a slope of 20.1 mm/10yr and the greatest negative slope at St. Francis in northwestern Kansas with a slope of -8.5 mm/10yr. The upward rainfall trend in the majority of stations (21 out of 23) can impact agricultural and crop production (Gornall et al., 2010), available moisture (Wang et al., 2011), runoff generation (Chiew et al., 2009), and Kansas economy (Bark, 1978; Barrios et al., 2010; Flora, 1934; Parra et al., 2008).

Using CUSUM and Pettit methods, data were analyzed to detect abrupt change on the mean of annual rainfall for the overall data record. Results indicated that 12 stations experienced a significant change point as early as 1940 (Horton, Minneapolis, and Ottawa) and as recently as 1980 (Winfield), demonstrating the wide spatial and temporal range of sudden changes across the state. Research has been done on the validity of the stationarity assumption (unchanging variability) of climate conditions (Bates et al., 2010; Vicente-Serrano and López-Moreno, 2008). For example, Milly et al. (2007) suggested that the stationarity should no longer be the principal assumption in water resources engineering because of changes in precipitation means and extremes. Therefore, annual rainfall trend analysis for the period after the change-points may be more useful than the overall trend, at least in the station with significant change-point.

Increasing total annual rainfall impacts available soil moisture and runoff generation. Longer rain events help the soil reach the saturation point and if the rain continues, the excess water flows as runoff. Analysis on longer-than-daily rainfalls, including 2, 3, 4, 7, and 10-day duration, showed that as duration increases, positivity of the trend slopes increase. However, annual 4-day maximum rainfalls experienced the greatest upward trend compared to other studied durations. The upward trend of the multi-day duration rainfall events may accelerate flood generation by increasing runoff generation rate.

The most updated rainfall frequency atlas of the United States, Atlas-14, was released in February 2013 for Kansas (Perica et al., 2013). A comparison between the 10-yr, 24-hr rainfall magnitudes from TP-40 and Atlas-14 showed a change of less than 12% since 1961. However, analysis on exceedances from the new thresholds (10-yr, 1, 2, 3, 4, 7, and 10-day storms from Atlas-14 volume 8), illustrated more exceedances than expected, particularly in recent period (1961-2010). Actual exceedances from the 10-yr return period storms were higher than expected exceedances in 48% and 78% of stations for daily and 4-day events, respectively, indicating extreme event occur more frequently with shorter return periods. A storm with a specific return period and duration is used to estimate maximum runoff in hydrologic structures design. With new rainfall patterns and shifts in rainfall duration, design criteria may need to be updated.

Recommendations and limitations

In this study, historical analysis were completed using daily rainfall data on 23 well-distributed centennial stations across Kansas. Adding more stations, particularly in north central Kansas between Horton and Phillipsburg, in the eastern portion of the state between Fort Scott and McPherson, and in the western portion between Larned and Tribune, will enhance the quality of results and output maps.

Daily rainfall data were used in the analysis, however a daily record may not capture the intensity of all events. The use of hourly data allows to analyze high intensity storms with sub-daily durations.

Results of this study such as total annual rainfall, and 2-, 10-, and 100-yr, 24-hr design storms, helps public, farmers, and engineers in regional decision making and water management across Kansas. Developing a data base with the capability of creating various outputs, provides easier access to results.

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