LONG–TERM PRECIPITATION ANALYSES FOR THE CENTRAL TEXAS BLACKLAND PRAIRIE

R. D. Harmel, K. W. King, C. W. Richardson, J. R. Williams

ABSTRACT. *Continuous records of intensively monitored precipitation data are rare, but where available they provide valuable regional information on hydrologic structure design and on other water supply and water quality management and modeling issues. One such long–term precipitation record exists for the Texas Blackland Prairie region. Beginning in 1937 and continuing to the present, hydrologic data have been collected at the USDA–ARS Grassland Soil and Water Research Laboratory watershed facility near Riesel, Texas. The objectives of this article are to present long–term analyses and to publicize the availability of that precipitation database. Long–term analyses included examination of general precipitation properties, depth–duration–frequency relationships, and trends in rainfall amount and occurrence. Annual rainfall for the region averages about 890 mm, with relatively wet springs and falls and drier summer and winter months. Depth–duration–frequency results emphasize the need for engineers to use the most current and extensive data sets and/or proven relationships in the design of hydrologic structures. Several significant temporal trends that can affect water resource management were also determined. These trends include increases in October rainfall, non–spring rainfall, and the number of summer, fall, and annual rainy days. These increases, however, are offset to some degree by decreases in April rainfall, in the number of extreme events in the spring, and in the magnitude of extreme fall rain events.*

Keywords. *Precipitation characteristics, Rain gauges, Weather data.*

Historical data on precipitation occurrence, amount, intensity, and spatial and temporal variability are vital in water resource manage–ment. These data are beneficial in adapting agricultural, industrial, ecological, and domestic water supply management strategies to best utilize the occurrence of natural rainfall events because rainfall ultimately determines surface and groundwater supplies. Therefore, knowledge of historical rainfall patterns is necessary to make informed decisions and predictions about future water supplies. In the Texas Blackland Prairie, an important agricultural region with a large and increasing urban popula–tion, drought and excess rainfall can be experienced throughout the year. With the diverse demands placed on water resources in this region and an increasing demand resulting from an increasing population, water resource management will be an even more important issue in the future. Faced with these demands, the continuous precipita–tion record from the USDA–ARS Grassland Soil and Water Research Laboratory watersheds near Riesel, Texas, should prove valuable in regional water resource planning and management by providing information on long–term trends in rainfall intensity, frequency, and seasonal amount.

Article was submitted for review in March 2003; approved for publication by the Soil & Water Division of ASAE in July 2003.

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HISTORY OF THE HYDROLOGIC DATA COLLECTION NETWORK

In the mid–1930s, the Soil Conservation Service (SCS), now the Natural Resources Conservation Service (NRCS), realized a need to analyze and understand hydrologic processes on agricultural fields and watersheds because of their impact on soil erosion, flood events, water resources, and the agricultural economy. As part of the SCS research program, the Hydrologic Division was created and a number of experimental watersheds were established across the U.S. The primary functions of the facilities were to collect hydrologic data (precipitation, percolation, evaporation, runoff, etc.) and to evaluate the hydrologic response from watersheds influenced by various agricultural land manage-ment practices (USDA–SCS, 1942). One of those three original facilities, the Blackland Experimental Watershed, was established in 1937 in the heart of the Blackland Prairie near Riesel, Texas (fig. 1). This experimental watershed facility later became part of the USDA–ARS Grassland Soil and Water Research Laboratory with headquarters in Tem-ple, Texas.

Hydrologic data have been collected from 1937 to the present at the Riesel watershed, making it one of the longest continuous, intensively monitored hydrological research sites in the U.S. These continuous hydrologic records are particularly valuable for studies designed to identify trends or changes caused by climate shift or other factors. These data have been used for numerous purposes such as water quality studies (Richardson and King, 1995; Kissel et al.,

  ISSN 0001–2351

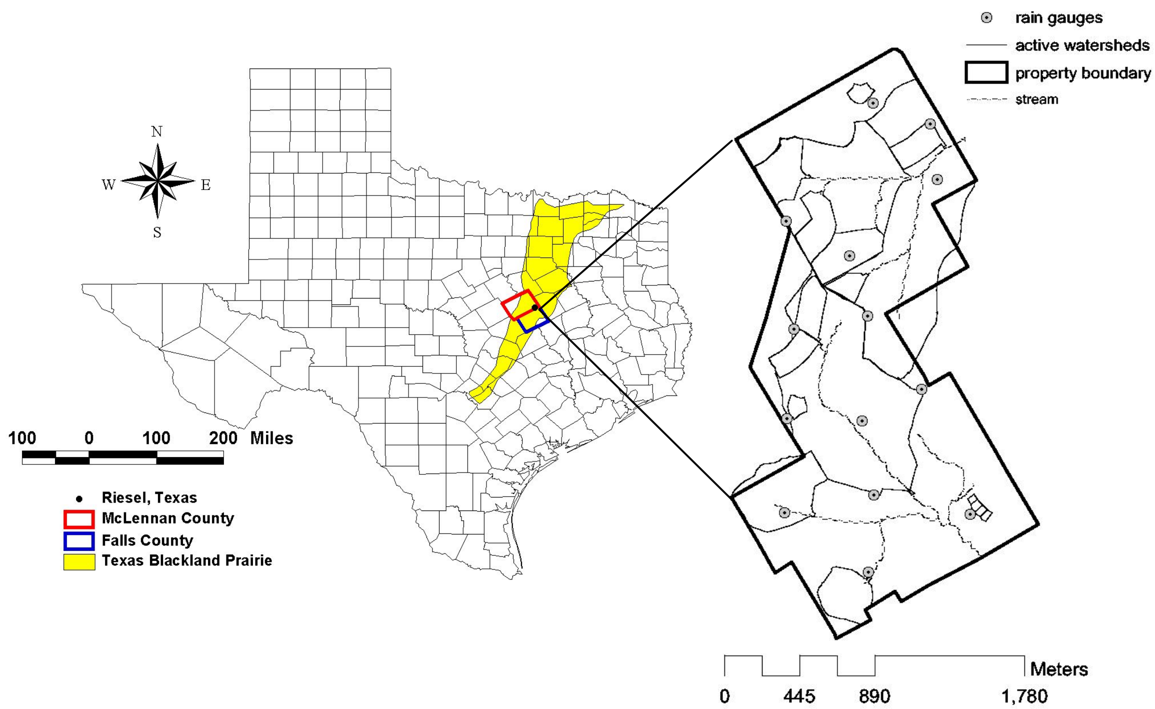

Figure 1. USDA–ARS Grassland Soil and Water Research Laboratory, Riesel, Texas.

1976; Williams et al., 1971), farming practice evaluations (Baird et al., 1970; Baird and Knisel, 1971), and natural resource modeling (King et al., 1996; Arnold and Williams, 1987; Harmel et al., 2000).

Our objective in this article is to present the results of long–term analyses (1939–1999) of precipitation data for the central Texas Blackland Prairie. These results should provide useful information to projects involving design of hydrologic structures such as dams, culverts, and detention basins; water supply and water quality modeling; and other hydrologic and water quality issues relevant to the region. The lack of adequate hydrologic data has been recognized for some time as a cause of failure of hydrologic structures but more commonly as contributing to unnecessarily conservative safety factors in structure design (USDA–SCS, 1942). More recently, the importance of precipitation data in hydrologic modeling has been demonstrated (Chaubey et al., 1999; Harmel et al., 2000; Favis–Mortlock, 1995).

In addition to presenting results from the precipitation analyses, this article publicizes the availability of the precipitation data from Riesel. Recent publications by Hanson (2001) and Nichols et al. (2002) provide valuable regional precipitation analyses based on USDA–ARS experimental watershed data from Reynolds Creek, Idaho (35–year length of record) and Walnut Gulch, Arizona (43–year length of record). This publication will provide similar regional precipitation analyses (64–year length of record) within the Texas Blackland Prairie. These regional studies are important supplements to nationwide analyses such as Karl and Knight (1998), which are reviewed in Groisman et al. (2001).

Site Description

The USDA–ARS Grassland Soil and Water Research Laboratory watershed facility was established near Riesel, Texas, because of its central location in the Blackland Prairie region. The Texas Blackland Prairie encompasses 4.45 million ha and is a major agricultural region extending from San Antonio 480 km north to the Red River. The area also contains the major metropolitan areas of Dallas, Fort Worth, Waco, Temple/Belton/Killeen, Austin, and San Antonio. Houston Black clays are the most extensive soils in the region and are noted for their strong shrink/swell potential.

Long, hot summers and short, mild winters characterize the climate in the region. The growing season lasts on average from mid–March to mid–November. A majority of rainfall occurs associated with the passage of Canadian continental and Pacific maritime fronts (Knisel and Baird, 1971). Convective thunderstorms during the warmer months also contribute intense, short–duration rainfall events. Tropical hurricanes can contribute substantial rainfall, but their occurrence is rare. Freezing rain, sleet, and snow occur occasionally but do not contribute significant moisture.

Riesel Precipitation Network

Collection of rainfall data at the Riesel facility began in 1937 with a total of 57 rain gauges used at some time during the period of record. Several rain gauges have been operated continuously since 1937, but others were closed during World War II. Some gauges were opened and closed for specific project needs. Many of the rain gauges were only open for a few years in the late 1930s and early 1940s. Historical data from 57 rain gauges (approximately 1400 rain gauge years) are available on the USDA–ARS Grassland Soil and Water Research Laboratory internet site (http://ars-serv0.tamu.edu/hydata.htm). Rainfall estimates for individual watersheds and runoff stations can be calculated from Thiessen polygon weights, which are also available. This internet site lists the stations and the years for which daily and

Table 1. Currently active rain gauges at Riesel.

Rain Gauge	Precipitation Record	Number of Complete Years
Continuous Records		
rgW2A	1938–2001	64
rgW6	1938–2001	64
rg75A	1939–2001	63
rg69	1939–2001	63
rgW4	1941–2001	61
rg69B	1958–2001	44
rgW5A	1961–2001	41
rgW1B	1970–2001	32
Discontinuous Records		
rg84A	1939–1942, 1947–2001	59
rg70	1939–1942, 1948–2001	58
rg89	1939–1942, 1948–2001	58
rgW2	1939–1941, 1961–2001	44
rgW3	1940–1941, 1969–2001	35
rg70A	1940–1941, 1969–2001	35
rgW9	1938–1941, 1960–1967, 1991–2001	23

sub–daily rainfall data are available. Currently, 15 rain gauges are in operation within the 340 ha watershed area (table 1). These operational gauges are instrumented with a tipping bucket rain gauge and datalogger to measure and record sub–daily precipitation. A standard non–recording rain gauge is also used at each site as a backup and calibration device.

Methods

General Rainfall Characteristics

Descriptive statistics for measured monthly, seasonal, and annual rainfall were calculated for the 61–year period 1939 to 1999 for rain gauges rg69, rg75A, rgW2A, and rgW6, which are the longest continually active gauges. Data from these four stations were also used to compare the spatial variability of daily rainfall. Based on these results, analyses of long–term rainfall characteristics such as occurrence, amount, and variability were conducted for rgW2A, a representative rain gauge.

Depth–Duration–Frequency Relationships

The relationships between rainfall amounts, event durations, and event frequencies were determined. These depth–duration–frequency relationships are important in hydro–logic structure design, water supply modeling, and flood prediction. Annual maximum 0.25, 0.5, 1, 2, 3, 6, 24, 48, and 72 h rainfall amounts were calculated for rain gauges rg75A, rgW2A, and rgW6. The return frequency for each of these depths and durations was then calculated, as indicated by Haan (1977). The mean depth for each of these durations was then plotted for 1, 2, 5, 10, 25, and 50 year return frequencies for comparison with results calculated with the USGS depth–duration–frequency procedure for Texas (Asquith, 1998) and estimates from the Rainfall Frequency Atlas of the United States, or "TP–40" (Hershfield, 1961). With the calculated depth–duration–frequency relationships for measured data, estimates were made for 100–year rainfall depths and for return periods for the largest measured events. Return frequencies for seasonal and annual rainfall totals were also calculated, as indicated by Haan (1977).

Trend Analysis

The final task in this study was to analyze possible changes in rainfall properties over time. Linear regression over time was conducted with data from rgW2A to evaluate long–term trends in monthly, seasonal, and annual rainfall totals. Trends in rainfall variability were examined with regression analyses on the absolute value of the residuals (value minus monthly mean). Selected rainfall properties were also calculated for each decade. These properties include: mean, median, standard deviation, skew, number of rainy days, number of days with greater than 25.4 and 50.8 mm, extreme amount percentiles (75th, 90th, and 95th), and gamma distribution parameters. Linear regression was then used to detect trends in decadal rainfall properties.

Table 2. Annual, seasonal, and monthly rainfall (mm) for selected gauges for 1939 to 1999 (mean ±1 standard deviation).

	rgw2a		rgw6		rg75A		rg69	
Period	Mean	Std Dev.	Mean	Std Dev.	Mean	Std Dev.	Mean	Std Dev.
Annual	894.3	±228.4	884.0	±224.1	898.4	±234.6	889.9	±229.4
Winter	199.2	±88.9	194.2	±87.5	199.6	±87.7	198.5	±88.0
Spring	293.8	±120.5	291.2	±119.2	299.2	±123.1	293.4	±119.9
Summer	170.0	±95.3	170.8	±94.9	167.1	±90.3	168.9	±93.7
Fall	231.3	±108.8	227.8	±108.0	232.5	±112.0	229.1	±107.3
January	55.9	±39.6	54.5	±40.4	54.3	±37.2	56.1	±38.1
February	71.0	±41.4	69.6	±40.2	71.3	±41.7	70.6	±42.7
March	72.3	±43.4	70.1	±42.0	74.0	±44.7	71.8	±44.1
April	90.4	±61.4	89.1	±62.7	92.0	±62.2	91.2	±62.8
May	115.1	±71.8	114.6	±72.5	117.7	±70.8	114.2	±67.1
June	88.3	±61.3	87.5	±62.3	89.5	±61.8	88.0	±61.3
July	48.2	±48.6	48.2	±49.0	47.3	±48.9	46.5	±49.6
August	54.8	±53.6	56.4	±53.6	54.0	±53.5	54.6	±54.6
September	67.0	±50.3	66.3	±47.8	65.8	±47.4	67.8	±49.3
October	85.2	±67.1	84.0	±66.7	87.0	±70.8	85.6	±68.2
November	74.2	±50.7	73.3	±49.9	73.6	±49.6	72.7	±48.1
December	72.0	±50.5	70.5	±50.2	71.9	±49.7	70.7	±49.3

Results and Discussion

General Rainfall Characteristics

Mean annual rainfall for the four continuously active rain gauges (rg69, rg75A, rgW2A, rgW6) was approximately 880 to 900 mm (table 2). Typically, spring (defined as April, May, and June) is the wettest period, with average rain of 294 mm; fall (October, November, and December) is also relatively wet, averaging more than 230 mm. Winter (January, February, and March) and summer (July, August, and September) are relatively dry, with less than 200 mm of rainfall occurring each season. Average monthly rainfall ranges from 115 mm in May to less than 50 mm in July. An average of 90 days per year had measurable rain (greater than 0.25 mm), 72 days per year had rain amounts greater than 0.76 mm, and 11 days had rain amounts greater than 25 mm.

Rainfall variability exhibited a seasonal pattern similar to mean rainfall amount (fig. 2). The wetter months exhibit greater rainfall variability, as shown by the height of the interquartile box, the distribution from the 25th to 75th percentile. The four months with the highest average rainfall (April, May, June, October) also have the highest variability, as measured by the standard deviation. Figure 2 also illustrates that average monthly rainfall typically exceeds median monthly rainfall and is therefore positively skewed. This same property occurs in daily rainfall amounts on rainy days. Because of this skew and a lower bound at zero, monthly and daily rainfall totals are best represented by non–symmetrical distributions such as the gamma or mixed–exponential (Wilks, 1999; Haan, 1977; Yevjevich, 1972; Richardson, 1982).

Monthly, seasonal, and annual rainfall amounts and variability did not differ substantially between the four rain gauges (table 2). This result was expected as the gauges are within 2500 m with little change in topography. In terms of the maximum difference between the four rain gauges for each rainy day, relatively small differences were observed. On days with rain, spatial variability ranged from 0 to 54 mm, with an average difference of 2.8 mm. However, 75% of values were within 3.3 mm, and 90% were within 7.1 mm. Because of the small difference between these four rain gauges, rainfall characteristics and trends analyses are presented for the representative rain gauge rgW2A.

Average monthly rain data for three different periods between 1940 and 1999 are presented in figure 3, which illustrates that substantial changes in rainfall are evident from records of various lengths or in different time periods

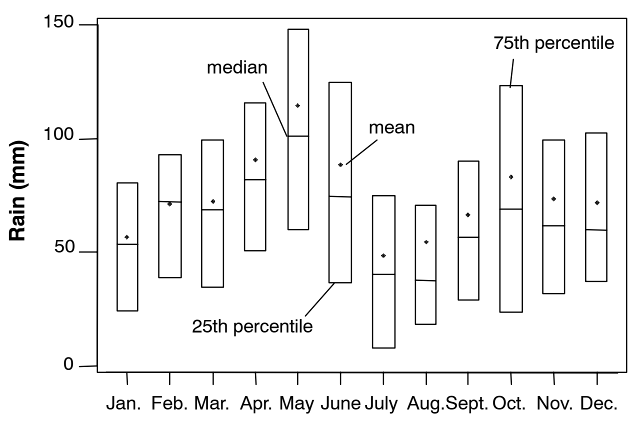

Figure 2. Monthly distribution of rainfall and rainfall variability.

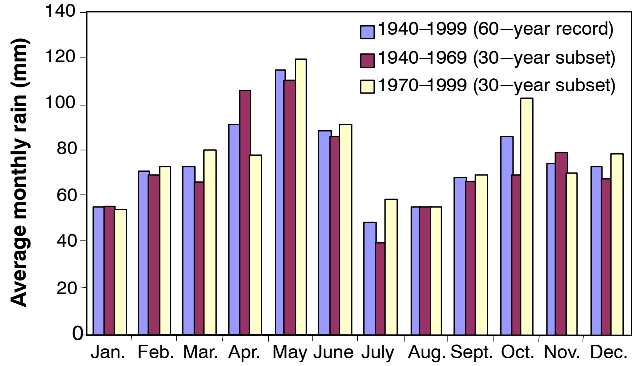

Figure 3. Monthly average rainfall for rain gauge rgW2A from different time periods.

(notice April, July, and October). These data emphasize the importance of using the longest available rainfall record in planning efforts, but also that rainfall patterns may change or appear to change based on the available record. Care should be used not to assume that historical patterns will adequately represent future events, especially since each year nature produces events of "never before seen" magnitude with extreme variability. Therefore, whenever measured rainfall data are used to model or predict future water resource availability, the variability and uncertainty of future rainfall events must be considered.

These precipitation characteristics and their temporal relationships are valuable for many applications because rainfall directly affects nonpoint–source water pollution, domestic water supply, agricultural production, and aquatic organisms. Although these general rainfall parameters are valuable, examining possible changes in rainfall patterns may be of even greater importance as plans and decisions are made with respect to increasing future water resource demands.

Depth–Duration–Frequency Relationships

To evaluate the accuracy of two common depth–duration–frequency relationships, measured rainfall depths for durations from 0.25 to 72 h and 1 to 50 year return frequencies were compared to a USGS depth–duration–frequency procedure for Texas (Asquith, 1998) and TP–40 (Hershfield, 1961) in figure 4. Measured data and estimates derived from the USGS depth–duration–frequency procedure were similar at return frequencies greater than one year for all durations. Although TP–40 results were similar to measured data for most durations for return frequencies greater than one year, TP–40 depths for the commonly used 24 h design duration were considerably larger (approximately 25 mm). This difference represents a significant volume in hydrologic design and emphasizes the need for engineers to use the most up–to–date and extensive data sets and/or proven relationships when designing hydrologic structures.

Depth–duration–frequency relationships for measured data are presented in table 3. With these results, we estimated the return frequency for the largest depth event for each duration. Equations of the form:

$$depth = a \times \ln(freq) + b \qquad (1)$$

were found to fit the 1 to 50 year return frequency data well (eight of nine R^2 values well above 0.95). Each of these equations was then solved to estimate the 100–year rainfall

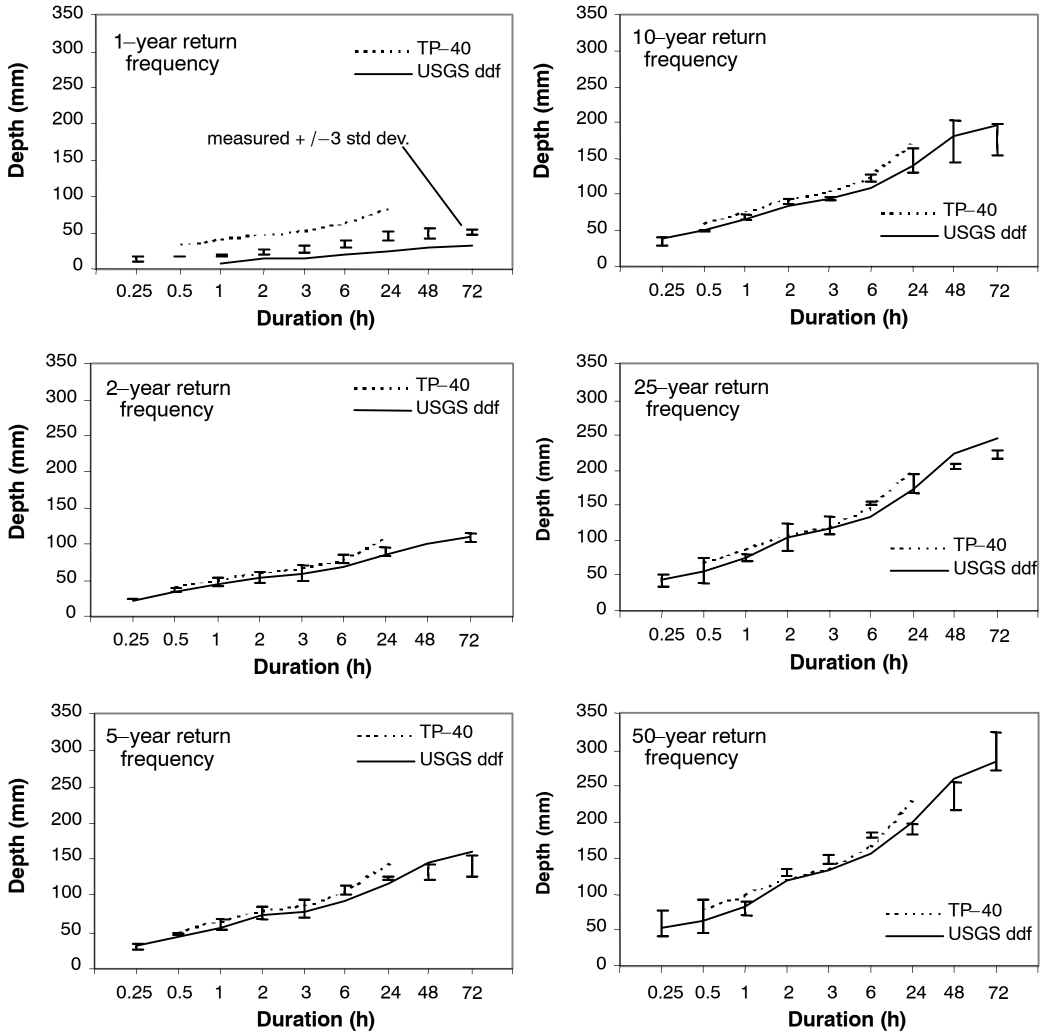

Figure 4. Comparison of measured depth–duration–frequency relationships (presented as mean ±3 standard deviations) to USGS depth–duration–frequency results (Asquith, 1998) and TP–40 estimates (Hershfield, 1961).

Table 3. Results for the depth–duration–frequency analysis (rainfall depths in mm).

Return Frequency	Duration								
	0.25 h	0.5 h	1 h	2 h	3 h	6 h	24 h	48 h	72 h
1 year	13.7	17.2	17.6	22.6	27.0	34.1	44.8	48.9	50.3
2 year	24.6	36.6	47.4	53.6	60.4	79.4	89.1	97.6	110.1
5 year	29.6	45.3	60.7	76.4	82.4	107.9	124.4	133.5	141.1
10 year	34.6	49.0	68.6	90.0	94.1	122.8	146.2	173.7	176.4
25 year	43.9	58.1	77.1	104.2	122.2	153.5	180.8	204.2	221.4
50 year	58.2	68.6	79.7	130.0	148.4	181.5	191.7	235.7	297.7
Max. measured	64.3	72.3	81.2	143.8	157.3	189.6	194.3	255.4	345.7
Estimated freq. (year)	136	66	61	78	69	62	61	67	150
100 year estimated	61.1	77.3	93.4	150.4	168.1	206.2	221.2	274.6	342.3
100 year USGS ddf	59.9	70.1	92.7	137.2	155.7	182.6	233.9	296.9	325.1
100 year TP–40	na	86.6	109.2	134.6	149.9	185.4	254.0	na	na

depth for each duration. For comparison, the estimated 100–year depths from the USGS depth–duration–frequency relationship and TP–40 are also presented. The return frequency of the maximum depth recorded for each duration was also estimated by solving the equations for each recorded maximum rainfall. The estimated 100–year depths were similar to the USGS and TP–40 estimates for all durations.

These depth–duration–frequency results (table 3) are valuable for hydrologic structure design, but seasonal and annual return frequencies are more important for water supply issues. Therefore, we calculated return frequencies of seasonal and annual rainfall estimated from measured rain totals for 1938 to 1999 using the method of Haan (1977). Wet spring and fall seasons are much more frequent than wet summers and winters (table 4). Late fall through early spring rainfall is important because of increased likelihood of runoff into water supply reservoirs due to low evaporation and transpiration losses in this period.

Table 4. Seasonal and annual rainfall amounts for several common return periods.

Return Frequency (year)	Greater Than (%)	Rainfall Total (mm)				
		Winter	Spring	Summer	Fall	Annual
50	2	461	672	377	509	1410
25	4	393	597	363	442	1356
10	10	317	416	336	388	1182
5	20	259	354	287	295	1082
2	50	191	262	159	210	883

Table 5. Linear tendencies in rainfall amount from 1938 to 1999.

Period	Average Change (mm/year)
January	0.0
February	0.2
March	0.4
April	–0.7
May	0.1
June	0.0
July	0.3
August	0.2
September	0.0
October	0.9[a]
November	–0.2
December	0.4
Winter	0.6
Spring	–0.6
Summer	0.6
Fall	1.1
Non–Spring	2.2[a]
Annual	1.6

[a] Statistically significant at $\alpha = 0.10$.

Table 6. Mean monthly and annual precipitation (mm) ±1 standard deviation for rgW2A.

Decade	January		February		March	
1940s	55.9	±39.6	67.6	±44.6	79.1	±45.2
1950s	39.5	±15.2	73.0	±24.1	55.1	±41.3
1960s	62.1	±40.6	67.3	±30.8	64.1	±42.2
1970s	51.0	±34.2	59.7	±30.9	77.3	±46.1
1980s	29.6	±15.6	77.7	±46.2	69.4	±22.7
1990s	82.8	50.1	80.2	±51.3	92.7	±36.9
	April		May		June	
1940s	113.7	±43.1	132.9	±83.9	95.2	±59.3
1950s	108.6	±86.0	110.7	±41.3	69.2	±46.2
1960s	93.9	±54.7	87.2	±67.9	94.0	±68.7
1970s	101.8	±53.4	111.5	±84.7	89.0	±59.1
1980s	50.3	±34.9	132.6	±50.2	115.1	±66.4
1990s	80.5	±42.4	114.6	±65.1	69.1	±34.1
	July		August		September	
1940s	52.0	±30.2	42.6	±22.0	59.4	±54.5
1950s	35.6	±30.7	48.5	±47.8	61.5	±44.6
1960s	30.9	±39.7	73.1	±63.0	79.3	±39.0
1970s	70.4	±75.5	58.2	±52.2	104.6	±59.4
1980s	45.4	±26.5	51.8	54.8	49.5	±30.9
1990s	59.0	±46.2	54.3	±54.4	53.6	28.6
	October		November		December	
1940s	61.7	±38.6	86.8	±74.8	85.1	±26.1
1950s	71.6	±72.5	67.5	±49.4	48.7	±39.7
1960s	74.3	±49.8	82.8	±39.8	67.4	±46.3
1970s	106.2	±57.3	67.1	±41.0	62.4	±47.4
1980s	114.6	±86.8	78.5	±38.9	75.0	±49.0
1990s	86.4	±58.8	63.9	±32.0	97.4	±59.8
	Annual					
1940s	942.0	±223.0				
1950s	789.5	±256.8				
1960s	876.3	±188.0				
1970s	959.1	±213.0				
1980s	889.5	±150.2				
1990s	934.5	±217.1				

Trend Analysis

Linear regression over time was conducted to evaluate long–term trends in monthly, seasonal, and annual rainfall totals and rainfall variability. Linear regression was also used to detect possible trends in decadal rainfall properties.

Trends in Amount and Variability Based on 62–Year Record

Linear rainfall trends are presented in table 5 to show the general tendency of rainfall from the late 1930s through 1999. Regression analysis resulted in only one statistically significant change in monthly, seasonal, and annual rainfall at $\alpha = 0.10$. The slope of the regression line (the change in monthly rainfall) for October rainfall was significant. October rainfall increased 0.89 mm (0.035 in) per year, which in terms of water supply is an important increase of more than 50 mm in the 62–year period of record. It is also interesting to note the relatively large increase in rainfall amounts for all seasons except spring and the overall annual increase of more than 1.6 mm. When the influence of decreasing spring rains was removed, a significant increase in non–spring (summer, fall, and winter) rainfall of 2.2 mm per year was detected. The absolute values of the residuals of these monthly values were also evaluated with linear regression ($\alpha = 0.10$). Results indicated significant increases in February and August variability and a significant decrease in November variability.

Trends in Decadal Rainfall Properties

Selected properties were calculated for each decade for a representative rain gauge (rgW2A) and analyzed with linear regression ($\alpha = 0.10$). The rainfall mean and variability for each decade are presented in table 6. Regression of the decadal means resulted in a significant increase for October and decrease for April. Median rainfall for April also decreased for the period. Regression of decadal standard deviations resulted in a significant decrease for November and a significant increase for December.

As stated above, monthly rainfall totals are often represented by a nonsymmetrical distribution such as the gamma; therefore, gamma distribution parameters (defined below) for monthly, seasonal, and annual rainfall were estimated for each decade:

$$f(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \qquad (2)$$

where α = shape parameter and β = scale parameter, with $0 \le x < \infty$, and $f(x) = 0$ for $x < 0$ (Yevjevich, 1972).

Over the six–decade period, the α parameter exhibited a significant increase in November, which indicates a possible change in the nature of November rain. The increase in α is

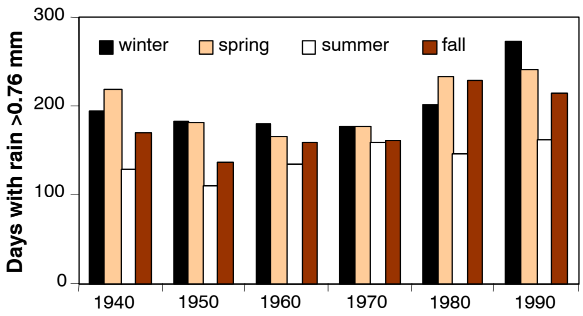

Figure 5. Number of rainy days (>0.76 mm) for each season.

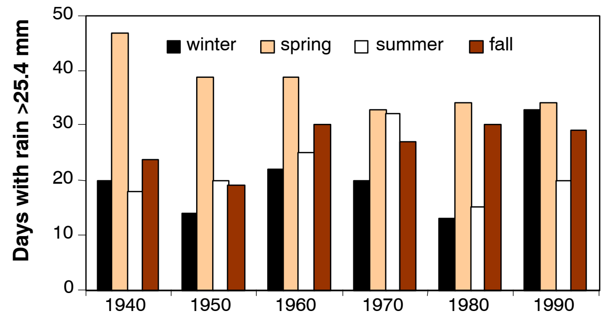

Figure 6. Number of days with rain exceeding 25.4 mm in each season.

particularly interesting because it corresponds to a significant decrease in the skew and variability of November rainfall. The β parameter increased in August but decreased in March, September, and November, which indicates possible changes in rainfall amount for these months.

Because of their impact on the above rainfall trends, changes in rainfall event frequency and magnitude were examined. The number of rainy days (>0.76 mm) for each season is plotted by decade in figure 5. Statistically significant increases were detected in the number of summer, fall, and annual rainy days.

A similar analysis was conducted on the frequency and magnitude of extreme rainfall events (fig. 6). Linear regression resulted in a significant decrease in the number of spring days with rain greater than 25.4 mm. This decrease did not, however, significantly affect the number of days per year with rain greater than 25.4 mm. In addition, no significant change in the number of days with rain greater than 50.8 mm of rain was evident from the 1940s to the 1990s.

In terms of the magnitude of extreme rain events, linear regression for the 75th, 90th, and 95th percentiles showed several changes. These statistically significant changes include decreases in the 75th percentile winter, spring, and fall rainfall events and the 95th percentile fall event.

The interactions of these rainfall properties impact the overall trends presented in table 5. The increases in October rainfall and the number of summer and fall rainy days contribute to increases in summer and fall rainfall. This impact, however, is lessened by a decrease in the magnitude of extreme fall rainfall events and by a decrease in the number of spring days with extreme rainfall. When the influence of decreasing spring rainfall was removed, as was done for summer by Nichols et al. (2002), a significant increase in non–spring rainfall was determined. The lack of a significant trend in annual rainfall, even though non–spring rains are increasing, can be attributed to the decrease in spring rains, which contributed about 30% of the annual rain total.

Conclusions

This article presents results of selected long–term analyses of precipitation data collected at the USDA–ARS Grassland Soil and Water Research Laboratory, Riesel, Texas. Since 1937, annual rainfall has averaged 892 mm. In the wettest months (April, May, June, October) average monthly rainfall exceeds 85 mm, but for July, August, and January rainfall averages less than 55 mm. On average, 72 days per year have rain greater than 0.76 mm, and 11 days per year have rain amounts greater than 25 mm.

The depth–duration–frequency analysis yielded several notable results. The measured 24 h storm depth, which is often used in hydrologic structure design, ranged from 89 mm for a 2–year return period to 192 mm for a 50–year return period. When the measured depth–duration–frequency relationship was compared to a USGS depth–duration–frequency procedure (Asquith, 1998), results were similar for all return periods greater than one year for all durations. Measured depths were also generally similar to TP–40 results (Hershfield, 1961); however, the 24 h TP–40 depths were approximately 25 mm larger than measured depths. This difference can represent a significant volume in hydrologic design and emphasizes the need for engineers to use the most up–to–date and extensive data sets and/or proven relationships in design of hydrologic structures. Based on these results, the USGS depth–duration–frequency procedure (Asquith, 1998) is a recommended alternative to measured data for hydrologic design in the central Texas Blackland Prairie region.

Although the general rainfall characteristics and depth–duration–frequency relationships are important, the analysis of possible changes in precipitation patterns due to possible global climate change has become a topic of intense speculation. In this study, we observed significant increases in October rainfall, non–spring rainfall, and the number of summer, fall, and annual rainy days, all of which contribute to increased rainfall. This impact, however, is lessened by decreases in April rainfall, in the number of extreme spring events, and in the magnitude of extreme fall rain. These changes in rainfall characteristics are different than those of similar studies in other regions. For instance, Nichols et al. (2002) reported increasing annual precipitation due to an increasing frequency in non–summer rains. These differing findings reinforce the need and value of regional, long–term precipitation analyses.

This study included examination of general precipitation properties, depth–duration–frequency relationships, and trends in rainfall amount and occurrence. Results from these selected analyses, as well as from additional analyses that are possible with the extensive, publicly available database, should prove useful in hydrologic structure design, water supply and water quality management and modeling, and other hydrologic and water quality issues relevant to the Texas Blackland Prairie region.

Acknowledgements

We would like to recognize the efforts of the many employees who have contributed to the collection of data at Riesel. We especially want to recognize current staff members Lynn Grote, Steve Grote, James Haug, and Gary

Hoeft for their outstanding efforts in equipment maintenance, data collection, and record keeping. Without their service, the intensive hydrologic monitoring program at Riesel would not be possible. We are also grateful to Drs. Indrajeet Chaubey (University of Arkansas, Fayetteville, Arkansas), Justin Derner (USDA–ARS, Cheyenne, Wyoming), and Pat Mielnick (Blackland Research and Extension Center, Temple, Texas) for their helpful review of the manuscript.

REFERENCES

Arnold, J. G., and J. R. Williams. 1987. Validation of SWRRB – Simulation for water resources in rural basins. *J. Water Resources Planning and Management* 113(2): 243–256.

Asquith, W. H. 1998. Depth–duration frequency of precipitation for Texas. USGS Water–Resources Investigations Report 98–4044. Washington, D.C.: U.S. Geological Survey.

Baird, R. W., and W. G. Knisel. 1971. Soil conservation practices and crop production in the Blacklands of Texas. Conservation Research Report No. 15. Washington, D.C.: USDA.

Baird, R. W., C. W. Richardson, and W. G. Knisel, Jr. 1970. Effects of conservation practices on storm runoff in the Texas Blackland Prairie. Tech. Bulletin No. 1406. Washington, D.C.: USDA.

Chaubey, I., C. T. Haan, J. M. Salisbury, and S. Grunwald. 1999. Quantifying model output uncertainty due to spatial variability of rainfall. *J. American Water Resources Association* 35(5): 1113–1123.

Favis–Mortlock, D. 1995. The use of synthetic weather for soil erosion modeling. In *Geomorphology and Land Management in a Changing Environment*, 266–282. D. F. M. McGregor and D. A. Thompson, eds. New York, N.Y.: John Wiley and Sons.

Groisman, P. Y., R. W. Knight, and T. R. Karl. 2001. Heavy precipitation and high streamflow in the contiguous United States: Trends in the twentieth century. *Bulletin of the American Meteorology Society* 82(2): 219–246.

Haan, C. T. 1977. *Statistical Methods in Hydrology.* Ames, Iowa: Iowa State Press.

Hanson, C. L. 2001. Long–term precipitation database, Reynolds Creek Experimental Watershed, Idaho, United States. *Water Resources Research* 37(11): 2831–2834.

Harmel, R. D., C. W. Richardson, and K. W. King. 2000. Hydrologic response of a small watershed model to generated precipitation. *Trans. ASAE* 43(6): 1483–1488.

Hershfield, D. M. 1961. Rainfall frequency atlas of the United States: For durations from 30 minutes to 24 hours and return periods from 1 to 100 years. Technical Paper No. 40. Washington, D.C.: U.S. Department of Commerce.

Karl, T. R., and R. W. Knight. 1998. Secular trends of precipitation amount, frequency, and intensity in the United States. *Bulletin of the American Meteorology Society* 79(2): 231–240.

King, K. W., C. W. Richardson, and J. R. Williams. 1996. Simulation of sediment and nitrate loss on a vertisol with conservation tillage practices. *Trans. ASAE* 39(6): 2139–2145.

Kissel, D. W., C. W. Richardson, and E. Burnett. 1976. Losses of nitrogen in surface runoff on the Blackland Prairie of Texas. *J. Environ. Quality* 5(3): 288–293.

Knisel, W. G., and R. W. Baird. 1971. Riesel, Tex. In *Agricultural Research Service Precipitation Facilities and Related Studies*, 97–102. D. M. Hershfield, ed. USDA–ARS 41–176. Washington, D.C.: USDA Agricultural Research Service.

Nichols, M. H., K. G. Renard, and H. B. Osborn. 2002. Precipitation changes from 1956 to 1996 on the Walnut Gulch Experimental Watershed. *J. American Water Resources Association* 38(1): 161–172.

Richardson, C. W. 1982. A comparison of three distributions for the generation of daily rainfall amounts. In *Statistical Analysis of Rainfall and Runoff: Proc. International Symposium on Rainfall–Runoff Modeling*, 67–78. V. P. Singh, ed. Highlands Ranch, Colo.: Water Resources Publications.

Richardson, C. W., and K. W. King. 1995. Erosion and nutrient losses from zero tillage on a clay soil. *J. Agric. Eng. Research* 61(2): 81–86.

USDA–SCS. 1942. The agriculture, soils, geology, and topography of the Blacklands Experimental Watershed, Waco, Texas. Hydrologic Bulletin No. 5. Washington, D.C.: USDA Soil Conservation Service.

Wilks, D. S. 1999. Interannual variability and extreme–value characteristics of several stochastic daily precipitation models. *Agric. and Forest Meteorology* 93(3): 153–169.

Williams, J. R., E. A. Hiler, and R. W. Baird. 1971. Prediction of sediment yields from small watersheds. *Trans. ASAE* 14(6): 1157–1162.

Yevjevich, V. 1972. *Probability and Statistics in Hydrology.* Highlands Ranch, Colo.: Water Resources Publications.