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# Runoff and soil loss relationships for the Texas Blackland Prairies ecoregion ☆

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**Summary** Hydrological and soil loss data have been collected since 1937 at the USDA-ARS Grassland Soil and Water Research Laboratory near Riesel, TX. Data from the site, originally named the Blacklands Experimental Watershed, have played a vital role in the evaluation of conservation management practices to limit soil erosion and offsite herbicide transport and in the development of several watershed models used worldwide. The entire record of precipitation, runoff, sediment loss, management practices, and limited meteorological information is publicly available (http://www.ars.usda.gov/spa/hydro-data). The data represent a valuable regional resource for use in water supply modeling, rural land development, and agricultural land management. Results of the present analyses confirmed the importance of soil–water phases to temporal runoff patterns in the Texas Blackland Prairies ecoregion. Little runoff occurs in the ''dry'' soil–water phase (avg. = 2–9 mm/month), but substantial surface runoff and lateral subsurface return flow occurs in the ''saturated'' phase (avg. = 19–28 mm/month). Strong linear relationships ($P < 0.0001$) were determined between watershed size and annual peak flow rates for return intervals from 2 to 100 yr. Long-term data indicate a drastic reduction in soil loss from small grain production compared to row crop production due to the presence of soil cover in both the spring and fall high precipitation periods. Thus, utilization of a winter cover crop in row crop production or conversion from row crop to small grain production can be effective in reducing offsite transport of sediment and associated contaminants, which may be important in watersheds with substantial agricultural contribution to water quality impairment.
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## Introduction

Historical hydrologic and sediment transport data are valuable in many applications including agricultural conservation practice design, urban development guidance, water resource planning, flood control, and ecological management. In the absence of regional data, relationships often are used that were established for areas with different hydrologic and climatic regimes. When extrapolated data are used in such applications, substantial uncertainty is added to already uncertain situations. Therefore, when long-term records are available they should be relied upon to guide water resource management and planning.

Baseline studies on local runoff processes are needed to guide development design and to adequately address land conversion issues and urban sprawl (Marsh and Marsh, 1995). Flow data are necessary for calibration and validation of water supply and water quality models, which are used to explore water resource scenarios. These data are also needed for the optimal design of hydraulic structures (e.g. dams, culverts, and detention basins). The lack of adequate data has been recognized for some time as a cause for failure of hydrologic structures but more commonly as contributing to unnecessarily conservative safety factors in structure design (USDA-SCS, 1942). Additionally, soil erosion and sediment transport data are valuable in estimating detention basin and water supply reservoir design factors. Historical region-specific soil erosion and sediment data in conjunction with modeled rates under future scenarios can provide the most accurate design life estimates. Simon et al. (2004) highlighted the need for ecoregion-specific sediment transport data because of the effect of sediment on stream channel stability and aquatic ecosystem health.

In many areas in Texas and other states, the diverse demands of agricultural water requirements and rapidly increasing urban populations stress available water supplies. One such area is Texas Blackland Prairies ecoregion (Omernik, 1987). This region contains Austin-San Marcos, one of the top ten fastest growing metropolitan areas in the US, and Dallas-Fort Worth, the fastest growing metropolitan area containing over 5 million people (US Census Bureau, 2001). Expensive and litigious water quality projects involving total maximum daily loads (TMDLs) are also underway. In this and other regions with intense water resource conflicts, measured flow and sediment transport data are especially valuable because cities, industry, legal interests, and regulatory agencies are hesitant to make decisions with estimates or information extrapolated from other regions.

It was in this Texas Blackland Prairies ecoregion that the Blacklands Experimental Watershed was established in 1937 (Fig. 1). The experimental watershed facility near Riesel, TX, is now part of the USDA-ARS Grassland Soil and Water Research Laboratory with headquarters in Temple, TX. In the mid-1930s, the United States Department of Agriculture

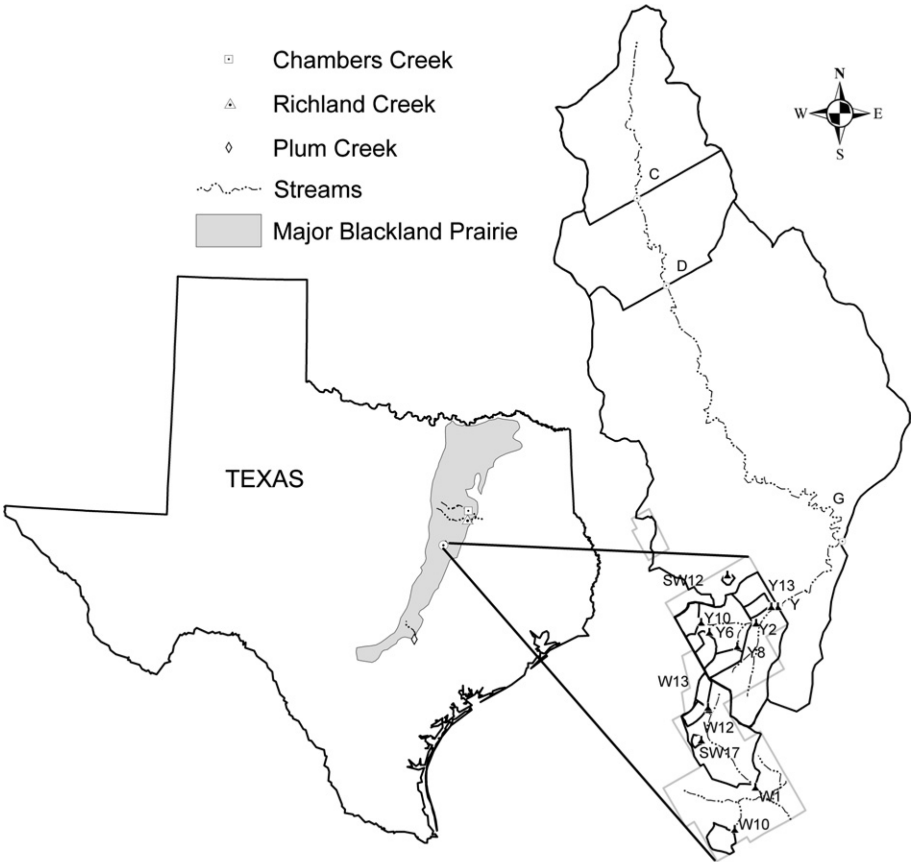

**Figure 1** USDA-ARS Grassland Soil and Water Research Laboratory watersheds and selected USGS gauged watersheds located in the Texas Blackland Prairies.

Soil Conservation Service (USDA-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. The research program of the Hydrologic Division of the SCS established a number of experimental watersheds across the US. Riesel was one of the three original watersheds, which were designed to collect hydrologic data (precipitation, percolation, evaporation, runoff) and to evaluate the hydrologic and soil loss response as influenced by various agricultural land management practices (USDA-SCS, 1942).

Hydrologic data collection at the Riesel experimental watersheds began in 1937 and continues to the present. It is one of the most intensively monitored small watershed research sites in the US. The continuous hydrologic records are particularly valuable for studies designed to identify trends or changes caused by climate shift or other factors and are necessary to determine the influence of extreme, rare events (Edwards and Owens, 1991). These data have been used for numerous purposes such as water quality studies (Kissel et al., 1976; Sharpley, 1995; Harmel et al., 2004), farming practice evaluations (Baird et al., 1970; Baird and Knisel, 1971; Chichester and Richardson, 1992), and natural resource model application and development (Williams et al., 1971; Arnold and Williams, 1987; Richardson and King, 1995; King et al., 1996; Ramanarayanan et al., 1998; Harmel et al., 2000).

The USDA-ARS experimental watershed databases are particularly valuable for field- to farm-scale research and design because of their long-term, detailed, continuous record on multiple watersheds. These small watershed data are vital to properly evaluate runoff and sediment transport processes from single land use, relatively homogeneous watersheds and to differentiate mechanisms for various land use conditions. Sediment transport and flow data collected at larger scales are often influenced by dams, channel processes, and variable land management, which alter sediment and discharge routing and generally confounds interpretation of smaller-scale land management. However, small watershed data are available only for limited regions of the US because of the resource commitment necessary to implement and maintain such data collection networks. In contrast, the United States Geologic Survey (USGS) operates a nationwide hydrologic monitoring network that has historically provided larger-scale data, which are needed to evaluate integrated effects and downstream routing processes. For years, the USGS hydrology database has provided valuable information such as peak flows, return intervals, and low flow durations, which have led to knowledgeable decisions that made without hydrologic data would have resulted in high costs to the US.

In a review of the importance of hydrometeorological data, Slaughter (2000) points to the need for the collection and preservation of long-term, spatially diverse data. These data are vital for research and planning related to water resources, climate change, ecological preservation, and the global food supply. The value of these data should not be disregarded in decisions made concerning budgets for monitoring programs. The USDA-ARS in cooperation with other federal agencies and programs (such as: USGS, USDA Forest Service, and National Science Foundation) has a unique opportunity and responsibility to provide continuous, watershed-based information to state and local governments, universities, and private organizations that will continue to need these data (Slaughter and Richardson, 2000). With these needs in mind, personnel at several USDA-ARS watershed networks have recently published long-term data and analyses on precipitation (Hanson, 2001; Nichols et al., 2002; Harmel et al., 2003) and discharge and sediment transport (Pierson et al., 2001; Van Liew and Garbrecht, 2003).

The specific objective of this study is to provide a summary and analysis of hydrologic and sediment loss data for the Texas Blackland Prairies ecoregion. The selected analyses, along with the publicly available data, should provide valuable information on water resource and erosion control management in the Texas Blackland Prairies ecoregion and in other Vertisol-dominated areas. When used in conjunction with regional USGS relationships for larger watersheds (e.g. Lanning-Rush, 2000; Raines, 1998), the analyses should support policy decisions in this region with rapidly growing population, increasing urban development, and intense debates over urban and agricultural contribution to water quality concerns.

## Methods and materials

### Site description

The USDA-ARS Grassland Soil and Water Research Laboratory experimental watershed was established near Riesel, TX, because of its central location in the Texas Blackland Prairies. This ecoregion, which encompasses 4.45 million ha, is a productive 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, Austin, and San Antonio. Houston Black clay soils (fine, smectitic, thermic, udic Haplustert), recognized throughout the world as the classic Vertisol, dominate the watershed site. These highly expansive clays, which shrink and swell with changes in moisture content, have a typical particle size distribution of 17% sand, 28% silt, and 55% clay. This soil series consists of very deep, moderately well-drained soils formed from weakly consolidated calcareous clays and marls and generally occurs on 1–3% slopes in upland areas. This soil is very slowly permeable when wet (approximate saturated hydraulic conductivity of 1.5 mm/h); however, preferential flow associated with soil cracks contributes to high infiltration rates when the soil is dry (Arnold et al., 2005; Allen et al., 2005).

Long, hot summers and short, mild winters characterize the climate in the region. The average growing season lasts from mid-March to mid-November. A majority of the annual precipitation occurs 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. Tropical hurricanes can contribute substantial precipitation, but their occurrence is rare. Freezing rain, sleet, and snow occur occasionally but do not contribute significant moisture.

## Data collection

The historical record of hydrology and soil loss from Riesel is extensive with approximately 1400, 1300, and 700 gauge years respectively of daily and sub-daily precipitation, runoff, and soil loss data. All data are available on the internet at: http://www.ars.usda.gov/spa/hydro-data. A description of the rain gauge network and long-term analyses of precipitation appears in Harmel et al. (2003). Forty watersheds have been used to provide runoff and soil loss data at some time within the historical record. For the present study, data were used from 12 of the 18 currently active watersheds and three inactive watersheds (Table 1, Fig. 1).

At the outlet of each of the 18 currently active watersheds at Riesel, a runoff structure is instrumented with three stage recording devices: (1) pressure transducer and datalogger; (2) float gauge with chart recorder; and (3) bubbler associated with ISCO 6700 automated sampler. Currently, bubblers are used as the primary stage measurement devices, and the transducers and float gauges serve as back up devices. Historically, float gauges served as the primary stage measurement devices. Discharge measurements are made by continuously recording flow levels in a stilling well located in each calibrated flume or weir structure. Flow depth data are converted to flow rate with established stage discharge relationships.

In 2001, ISCO 6700 samplers were installed at each site to automatically collect water quality samples in each runoff event. From the 1970s to 2001, runoff water samples were taken with Chickasha samplers (Chichester and Richardson, 1992). These automated, mechanical samplers were turned on with a float-activated water level switch. Discrete samples were taken on variable time intervals with more frequent samples taken on the rising limb of the hydrograph. Prior to the 1970s, runoff water samples were collected by hand during runoff events (Knisel and Baird, 1970). On-call personnel collected discrete samples on variable time intervals similar to the collection frequency of the automated samplers. To quantify soil loss and sediment concentrations in runoff, collected sediment was dried, weighed, and recorded with the corresponding flow rate.

## Data analysis

Selected hydrologic and sediment loss analyses are presented because of their broad applicability. All statistical analyses were conducted with Minitab statistical software (Minitab, 2000) with an a priori $\alpha = 0.05$ probability level and methods described by Helsel and Hirsch (1993) and Haan (2002). The non-parametric Mann–Whitney test was used instead of parametric alternatives to evaluate possible differences in median values because differences were typically not normally distributed as determined by the Kolmogorov–Smirnof test (Haan, 2002).

### Temporal relationship between precipitation and runoff

The relationship between precipitation amount and runoff depth was analyzed with measured data from watershed Y2 for the period 1939–2002. Measured runoff for the USGS base period, 1961–1990, was compared to annual runoff estimated by the procedure of Lanning-Rush (2000). The temporal (intra-annual) distributions of measured monthly and annual precipitation, runoff, and runoff to precipitation ratio ($Q/P$) values were also evaluated as were the differences in monthly medians.

### Relationship between peak discharge and watershed area

Annual peak flows were determined for 14 Riesel watersheds (1.2–1773 ha) and for three larger USGS gauged watersheds (80,000–250,000 ha) to encompass the size range of watersheds located entirely within the Texas Black-

**Table 1** Selected characteristics of study watersheds; watershed names and responsible agency are indicated

| Agency | ARS | ARS | ARS | ARS | ARS | ARS |
|---|---|---|---|---|---|---|
| Watershed | SW12 | SW17 | W12 | Y13 | W13 | Y6 |
| Area (ha) | 1.2 | 1.2 | 4.0 | 4.6 | 4.6 | 6.6 |
| Slope (%) | 3.8 | 1.8 | 2.0 | 2.3 | 1.1 | 3.2 |
| Latitude | 31°28′48″ | 31°27′45″ | 31°27′56″ | 31°28′36″ | 31°27′57″ | 31°28′26″ |
| Longitude | 96°52′59″ | 96°53′14″ | 96°53′07″ | 96°52′39″ | 96°53′08″ | 96°53′09″ |
| Agency | ARS | ARS | ARS | ARS | ARS | ARS |
| Watershed | Y10 | W10 | Y8 | Y2 | W1 | Y |
| Area (ha) | 7.5 | 8.0 | 8.4 | 53 | 71 | 125 |
| Slope (%) | 1.9 | 2.6 | 2.2 | 2.6 | 2.2 | 2.4 |
| Latitude | 31°28′31″ | 31°27′12″ | 31°28′22″ | 31°28′30″ | 31°27′27″ | 31°28′36″ |
| Longitude | 96°53′10″ | 96°52′48″ | 96°52′54″ | 96°52′46″ | 96°52′48″ | 96°52′36″ |
| Agency | ARS | ARS | ARS | USGS | USGS | USGS |
| Watershed | C | D | G | Plum Creek | Richland Creek | Chambers Creek |
| Area (ha) | 234 | 449 | 1773 | 80032 | 190109 | 249421 |
| Slope (%) | 2.1 | 2.1 | 2.1 | 2.7 | 2.2 | 2.6 |
| Latitude | 31°31′12″ | 31°31′38″ | 31°29′33″ | 29°41′58″ | 31°57′02″ | 32°06′29″ |
| Longitude | 96°53′35″ | 96°53′23″ | 96°52′37″ | 97°36′12″ | 96°25′16″ | 96°22′14″ |

land Prairies (Table 1, Fig. 1). The Riesel watersheds have continuous annual peak flow records in excess of 35 yr, and the USGS watersheds have records of more than 20 yr. Baird (1950) used 13 of the same watersheds to conduct a similar analysis but with a shorter data set.

For each watershed, peak flows for 2, 5, 10, 25, 50, and 100 yr return frequencies were calculated with the Weibull method presented in Haan (2002). For watersheds with less than a 50 or 100 yr record, peak flows for 50 and 100 yr return intervals were determined by extrapolation with a natural logarithmic trend line unless the estimated flow was less than the highest recorded flow. As recommended by Baird (1950), the watersheds were divided into two size categories (<54 ha, >54 ha). Linear regression analyses were performed on the log-transformed watershed area and peak flow data for each return period in the two watershed size categories. A SAS constrained curve fitting procedure was utilized to insure the lines intersected at the 54 ha delineation (SAS, 1999). Then, 2–100 yr peak flow estimates for Richland Creek and Chambers creek were compared for this annual peak flow relationship based only on watershed size and a regional USGS peak flow relationship based on watershed size and stream slope (Raines, 1998).

### Relationship between land use and runoff

Three small watersheds (Y8, W10, SW12) were chosen to evaluate the impact of land use on hydrologic parameters including annual runoff volume, peak flow rate (normalized by area), and the runoff to precipitation ratio ($Q/P$). These three watersheds are similar in terms of size and slope (Table 1). From 1949 to 2002, Y8 was cultivated with conservation management practices such as contour terraces and grassed waterways. From 1949 to 1963, W10 was cultivated with no conservation practices. In March 1963, W10 was converted to coastal bermuda grass pasture and has been used for grazing and hay production since 1964. The third watershed, SW12, is a native prairie reference site. Potential differences in median runoff volume, $Q/P$, normalized peak flow, and precipitation for differing land uses were evaluated. Conventional and conservation agronomic practices were compared to native conditions for 1949–1963, and conservation agronomic practices were compared to native and improved pasture management for 1982–2002.

### Relationship between land use and soil loss

Measured monthly and annual soil loss was calculated for six cultivated watersheds (Y6, Y8, Y10, Y13, W12, W13) with conservation practices (Table 1). Soil loss for 1982–2002 was compared to historical soil loss estimates prior to conservation management. Also, data for two watersheds (Y6, Y13) were combined and used to analyze the intra-annual temporal distribution of monthly soil loss in comparison to temporal patterns in precipitation and runoff. Potential differences in monthly median soil loss with data grouped for the six cultivated watersheds for 1982–2002 were evaluated.

To evaluate the influence of cropping pattern on sediment loss from cultivated watersheds, soil loss differences were analyzed for the two dominant cropping patterns. Specifically, erosion rates were compared for small grain (wheat, oats) production, which typically occurs between October and June, and row crop (corn and sorghum) production, which typically occurs between February and August.

### Trends in runoff

Potential trends in annual and seasonal runoff volumes and annual peak flow rates were analyzed because of their importance to water resource planning. For the seasonal analysis, winter was defined as January, February, and March; spring as April, May, and June; summer as July, August, and September; and fall as October, November, and December. The native prairie watershed (SW12) had consistent management from the beginning of its hydrologic record in 1948. The mixed land use watershed (Y2), which has a hydrologic record dating from 1939, had minimal land use change between 1948 and 2002. However, several substantial land use changes occurred prior to 1948 (Baird, 1964). Conventional management was used from 1939 to 1942, and conservation management with additional areas converted to grass occurred from 1943 to 1947. It was important to selected watersheds with long periods of consistent land use to minimize the influence of land use change on runoff characteristics, so only data from 1948 to 2002 were analyzed. Runoff trends were also analyzed for Y2 for 1939–1999, which is the same period that precipitation trends were examined in Harmel et al. (2003), to determine whether precipitation trends translated into similar runoff trends. Linear regression analysis was used to detect the presence of linear trends in annual and seasonal runoff volume and annual peak flows (Haan, 2002). Analysis of residuals for runoff volume and peak flow showed that they are not all normally distributed; however, with these relatively large data sets, the central limit theorem justifies an assumption of normality, which even if violated results in decreased power of hypothesis tests (Haan, 2002; Helsel and Hirsch, 1993). The non-parametric rank correlation test was also used to evaluate potential trends in runoff (Helsel and Hirsch, 1993).

## Results and discussion

### Temporal relationship between precipitation and runoff

For the period 1939–2002, annual rainfall measured for watershed Y2 averaged 907 mm with a median of 928 mm but was quite variable from year to year with a standard deviation of 234 mm. Annual runoff was even more variable with a mean of 159 mm, median of 136 mm, and standard deviation of 132 mm. When applied to runoff measured at Riesel for the USGS base period (1961–1990), the USGS regional relationship developed by Lanning-Rush (2000) under-predicted mean annual runoff by 11%. This performance at 11 Riesel watersheds (1.3–449 ha) is actually quite good considering that the regional USGS relationships were developed for large watersheds (6700–148,000 ha).

In terms of intra-annual variability, May is the wettest month with mean monthly precipitation of more than 117 mm (median = 102 mm); April, June, and October are also quite wet with mean monthly precipitation of 89–91 mm (medians = 76 mm). These months, however, are not necessarily the months with the greatest amount of runoff (Figs. 2–4). April and May contribute 10% and 13% of annual precipitation and contribute similar amounts of annual runoff (12% and 17%). In contrast, October contributes 10%

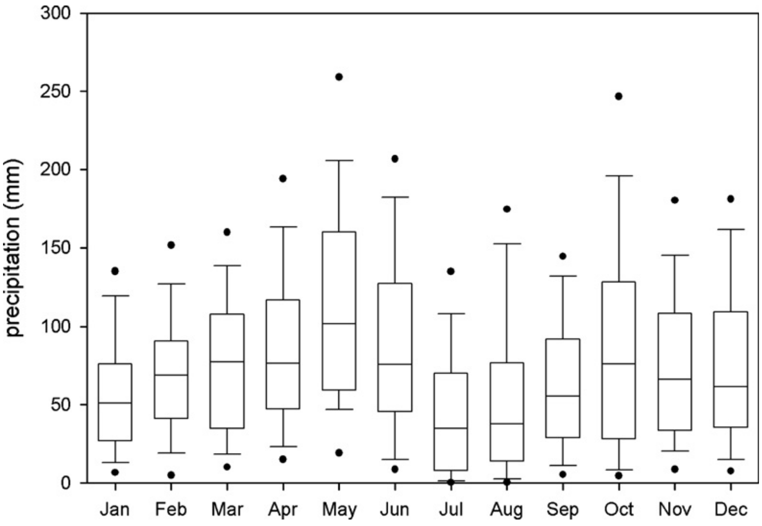

**Figure 2** Distribution of monthly precipitation for rain gauge 75A within watershed Y2 (points indicate the 5th and 95th percentile; whiskers indicate the 10th and 90th; box boundaries indicate the 25th and 75th; the line within each box indicates the median value).

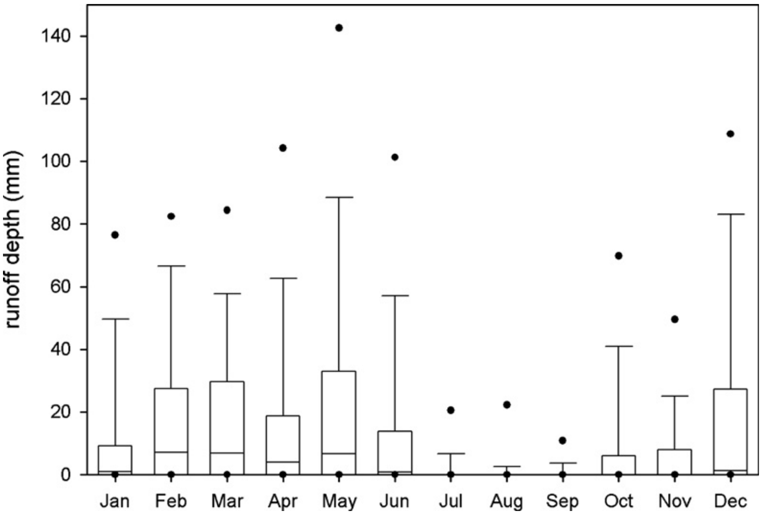

**Figure 3** Distribution of monthly runoff for watershed Y2 (points indicate the 5th and 95th percentile; whiskers indicate the 10th and 90th; box boundaries indicate the 25th and 75th; the line within each box indicates the median value).

of annual rain but only 6% of annual runoff. Also, the months of June, July, August, and September contribute a combined 28% of annual rain but only 14% of annual runoff.

The Mann—Whitney test revealed several statistically significant differences in median monthly precipitation amount; however, few of these differences exhibited a consistent temporal pattern. The exceptions are that May precipitation exceeded all other months; July precipitation was less then all other months except August; and January precipitation was less than all other months except August and September. In contrast, statistically significant differences in median monthly $Q/P$ (Table 2) and runoff (not shown) exhibited a consistent intra-annual pattern. Runoff and $Q/P$ for February through May consistently exceeded corresponding values for July through October (Table 3).

The intra-annual temporal differences in runoff are driven by the changing interaction of precipitation and soil—water status. The differences in measured monthly runoff over the 64 yr record correspond to the four soil—water phases described for the site by Allen et al. (2005), which were based on data from one annual recharge cycle. Runoff exhibits clear differences throughout the year as shown in Table 3. For the ''dry phase'' of July through November, soils are typically dry and cracked and runoff is rare. In the ''field capacity phase'' of December through January, decreases in soil crack volume are observed due to increased rain and decreased evapotranspiration, and surface runoff and lateral subsurface flow commence. In the ''saturated phase'' of February through May, substantially more precipitation exits the watershed as surface runoff and lateral subsurface return flow. Then in the June

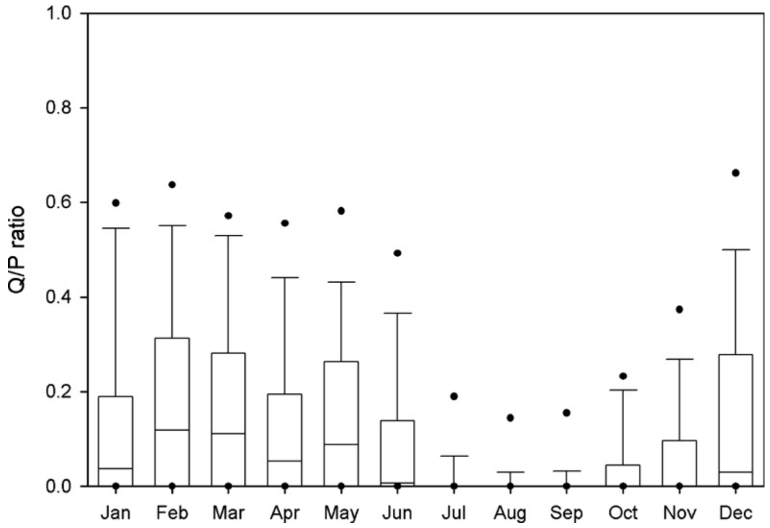

**Figure 4** Distribution of monthly *Q*/*P* ratio values for watershed Y2 (points indicate the 5th and 95th percentile; whiskers indicate the 10th and 90th; box boundaries indicate the 25th and 75th; the line within each box indicates the median value).

**Table 2** *P* values for Mann–Whitney tests of differences between median monthly *Q*/*P* ratios; statistically significant values ($P < 0.05$ for $\alpha = 0.05$) are italicized

| | February | March | April | May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|---|
| January | 0.199 | 0.193 | 0.756 | 0.341 | 0.261 | *0.000* | *0.000* | *0.000* | *0.001* | *0.029* | 0.837 |
| February | | 0.988 | 0.220 | 0.649 | *0.014* | *0.000* | *0.000* | *0.000* | *0.000* | *0.001* | 0.347 |
| March | | | 0.196 | 0.632 | *0.010* | *0.000* | *0.000* | *0.000* | *0.000* | *0.000* | 0.326 |
| April | | | | 0.377 | 0.150 | *0.000* | *0.000* | *0.000* | *0.000* | *0.010* | 0.998 |
| May | | | | | 0.998 | *0.029* | *0.000* | *0.000* | *0.000* | *0.001* | 0.573 |
| June | | | | | | *0.000* | *0.000* | *0.000* | *0.022* | 0.264 | 0.173 |
| July | | | | | | | 0.459 | 0.269 | 0.104 | *0.004* | *0.000* |
| August | | | | | | | | 0.679 | *0.020* | *0.000* | *0.000* |
| September | | | | | | | | | *0.009* | *0.000* | *0.000* |
| October | | | | | | | | | | 0.211 | *0.001* |
| November | | | | | | | | | | | *0.017* |

**Table 3** Monthly runoff volumes and runoff to precipitation ratios (*Q*/*P*) for corresponding soil–water phases

| Month | Soil–water phase | Median runoff (mm) | Mean runoff (mm) | *Q*/*P* |
|---|---|---|---|---|
| January | Field capacity | 1.0 | 12.3 | 0.04 |
| February | Saturated | 6.9 | 18.8 | 0.12 |
| March | Saturated | 6.7 | 19.2 | 0.11 |
| April | Saturated | 4.1 | 19.5 | 0.05 |
| May | Saturated | 7.4 | 27.6 | 0.09 |
| June | Transition | 0.7 | 15.2 | 0.01 |
| July | Dry | 0.0 | 2.5 | 0.00 |
| August | Dry | 0.0 | 2.0 | 0.00 |
| September | Dry | 0.0 | 2.6 | 0.00 |
| October | Dry | 0.0 | 8.9 | 0.00 |
| November | Dry | 0.0 | 9.1 | 0.00 |
| December | Field capacity | 1.4 | 21.1 | 0.03 |
| Annual | | 136.1 | 158.7 | 0.16 |

''transition phase,'' evapotranspiration begins to dominate and crack volume increases, thus runoff and lateral subsurface flow is reduced.

## Relationship between peak discharge and watershed area

The log-transformed watershed size and peak flow data for 17 watersheds exhibited statistically significant relationships ($P < 0.0001$) with little scatter for 2, 5, 10, 25, 50, and 100 yr return intervals (Table 4, Fig. 5). The relationships were improved by dividing the watersheds into two size categories (<54 ha, >54 ha), as recommended by Baird (1950) because peak flows were over-predicted on small watersheds without this division. Results of the constrained curve fitting procedure support the appropriateness of the 54 ha delineation. Baird (1950) gave two explanations of this watershed size phenomenon. One is that lack of well-defined drainage channels in small watersheds leads to a higher percentage of flow reaching the outlet after the flow peak. The other factor,

**Table 4** Regression relationships between annual peak flows ($Qp$, m$^3$/s) and watershed size (area, ha)

| Return period (yr) | Watersheds <54 ha | Watersheds >54 ha | $P$ |
|---|---|---|---|
| 2 | $\log(Qp) = -1.054 + 0.918 \times \log(\text{area})$ | $\log(Qp) = -0.487 + 0.591 \times \log(\text{area})$ | <0.0001 |
| 5 | $\log(Qp) = -0.738 + 0.916 \times \log(\text{area})$ | $\log(Qp) = -0.196 + 0.603 \times \log(\text{area})$ | <0.0001 |
| 10 | $\log(Qp) = -0.601 + 0.909 \times \log(\text{area})$ | $\log(Qp) = -0.080 + 0.608 \times \log(\text{area})$ | <0.0001 |
| 25 | $\log(Qp) = -0.410 + 0.860 \times \log(\text{area})$ | $\log(Qp) = 0.018 + 0.613 \times \log(\text{area})$ | <0.0001 |
| 50 | $\log(Qp) = -0.293 + 0.860 \times \log(\text{area})$ | $\log(Qp) = 0.147 + 0.606 \times \log(\text{area})$ | <0.0001 |
| 100 | $\log(Qp) = -0.202 + 0.860 \times \log(\text{area})$ | $\log(Qp) = 0.258 + 0.594 \times \log(\text{area})$ | <0.0001 |

specific to watersheds in the Texas Blackland Prairies ecosystem and other areas dominated by cracking clay soils, is the loss of appreciable precipitation excess to cracks. This effect is most pronounced for small watersheds (small time of concentration) because runoff into cracks can be proportionally large during the short time period when cracks are open at the soil surface. The influence of cracks on surface runoff decreases as watershed size increases and is negligible in larger watersheds.

In a recent USGS report, Raines (1998) emphasized the value of accurate estimates of the frequency and magnitude of peak discharges and noted that regional studies should produce more accurate results than statewide studies. Raines (1998) produced peak discharge frequency relationships with return intervals from 2 to 100 yr ($r^2 > 0.90$) based on watershed size and stream slope for a Blackland-dominated region of the Brazos River basin in Texas. It is important to note that improved estimation may result by including additional parameters, such as stream slope and/or drainage density, but the present study produced strong linear relationships for the same return intervals considering only watershed size (Table 4). Peak flow frequency estimates for Richland Creek and Chambers Creek based on the equations in Table 4 were on average 25% larger than estimates based on the USGS procedure (Raines, 1998). When compared with calculated peak flow frequencies, Table 4 relationships produced an average error of −5% (overestimation). The USGS relationships produced a +22% average error (underestimation); however, either method appears appropriate for predicting peak flow rates and return frequencies in the Texas Blackland Prairie.

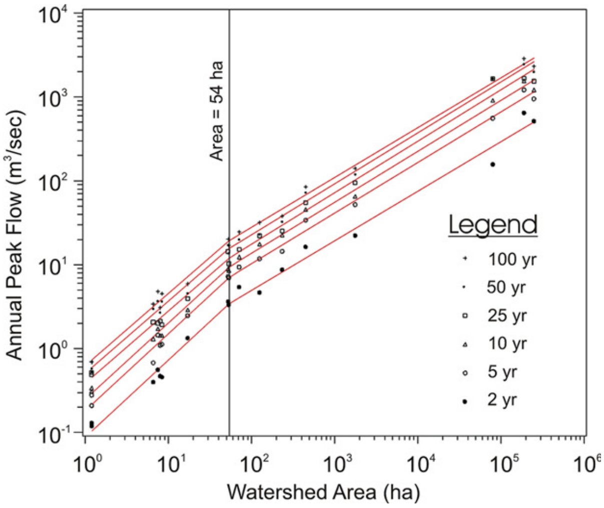

**Figure 5** Relationship between annual peak flow and watershed area.

## Relationship between land use and runoff

From 1939 to 1942, the two larger watersheds (Y2, W1) that contain the smaller watersheds (Y8, W10) were managed the same to evaluate pre-treatment (conservation practice) conditions. In this period, no inherent differences were determined between the watersheds, but the importance of spatial variation in precipitation was noted even in small areas (Baird, 1950; Baird et al., 1970).

For the period 1949–1963, the hydrologic effects of conventional and conservation agronomic practices and native prairie were compared. Results of Mann–Whitney tests indicated that annual runoff volume, $Q/P$, and area-normalized peak flow rate were all statistically greater for the conventionally managed watershed than for the native prairie watershed; however, no differences were observed between the conservation watershed and the native prairie (Table 5). The observed differences were confidently attributed to land use effects, as no statistically significant differences in annual precipitation existed between the watersheds. Compared with native prairie conditions, conventional management increased average values of runoff (+56%), $Q/P$ (+83%), and normalized peak flow (+100%); and conservation management increased runoff (+19%), $Q/P$ (+33%), and normalized peak flow (+20%). The ability of conservation practices, and more recently minimum tillage, to minimize the impact of cultivated agriculture on hydrology is an important and well-documented accomplishment (Baird, 1948, 1964; Baird et al., 1970; Chichester and Richardson, 1992; Richardson and King, 1995; Smith et al., 1954). Much credit is due to early scientists, engineers, and landowners who developed and utilized these practices.

From 1982 to 2002, land use effects on hydrologic characteristics were evaluated under native prairie, improved pasture, and conservation management. During this period, which again had no significant difference in precipitation between watersheds, differences in hydrology were less profound. No significant difference in median annual runoff volume or $Q/P$ occurred between the watersheds, but the area-normalized peak flow rate for the native prairie exceeded that from the conservation management and improved pasture watersheds. Two possible reasons for the reduced impact of land use in this period are less drastic differences in land use management and above average precipitation. In the period 1949–1963, drastically different land

**Table 5** Hydrologic effects of land use differences measured in two periods (for each row, median values with the same letter indicate no significant difference at $\alpha = 0.05$)

| 1949–1963 | Native prairie (SW12) | | Conservation management (Y8) | | Conventional management (W10) | |
|---|---|---|---|---|---|---|
| | Mean (stdev) | Median | Mean (stdev) | Median | Mean (stdev) | Median |
| Runoff volume (mm) | 65.4 (123.1) | a<br>10.5 | 77.8 (122.0) | ab<br>43.4 | 102.3 (117.3) | b<br>57.2 |
| *Q*/*P* | 0.06 (0.09) | a<br>0.02 | 0.08 (0.09) | ab<br>0.06 | 0.11 (0.09) | b<br>0.08 |
| Normalized peak *Q* ($m^3 s^{-1} ha^{-1}$) | 0.05 (0.07) | a<br>0.02 | 0.06 (0.06) | ab<br>0.05 | 0.10 (0.08) | b<br>0.10 |
| Rain (mm) | 779.8 (253.2) | a<br>795.3 | 772.6 (252.0) | a<br>791.5 | 788.4 (253.0) | a<br>766.8 |
| 1982–2002 | Native prairie (SW12) | | Conservation management (Y8) | | Improved pasture (W10) | |
| | Mean (stdev) | Median | Mean (stdev) | Median | Mean (stdev) | Median |
| Runoff volume (mm) | 166.8 (113.8) | a<br>175.3 | 152.0 (101.2) | a<br>162.8 | 138.2 (89.6) | a<br>126.3 |
| Q/P | 0.16 (0.10) | a<br>0.17 | 0.15 (0.09) | a<br>0.17 | 0.14 (0.08) | a<br>0.14 |
| Normalized peak *Q* ($m^3 s^{-1} ha^{-1}$) | 0.16 (0.12) | a<br>0.13 | 0.06 (0.05) | b<br>0.05 | 0.06 (0.06) | b<br>0.04 |
| Rain (mm) | 935.7 (197.3) | a<br>1005.1 | 956.3 (194.5) | a<br>971.8 | 933.5 (195.1) | a<br>978.4 |

uses (from native conditions to intensive crop production with no conservation practices) were compared; however, the conversion of the conventionally-managed watershed to improved pasture reduced this difference. Also, mean annual precipitation for 1982–2002 exceeded the long-term annual average and the annual average for 1949–1963 (Table 5). Baird (1948) concluded that little difference in runoff due to land use type occurs in the Texas Blackland Prairies during prolonged wet periods in which soil moisture deficiencies are satisfied. Because of the differences in precipitation, comparisons of land use impacts across the two periods were not conducted.

## Relationship between land use and soil loss

In many aspects, differences in soil erosion from differing land use and management have been well established for a number of years (Smith et al., 1954; Wischmeier and Smith, 1965). For example, it is well accepted that forested and grassed sites experience a fraction of the erosion as sites disturbed by cultivation or construction and that sites with steeper, longer slopes erode more than less steep, shorter slopes. Historical annual average erosion rates measured at Riesel from 1939 to 1947 under conventional tillage with no conservation practices ranged from 35,800 to 41,700 kg/ha (Baird, 1948, 1964). Baird (1964) reported that watershed W1 with limited grassed areas and conventional tillage experienced a mean annual soil loss of 22,900 kg/ha from 1939 to 1961 compared with 2700 kg/ha for watershed Y2 with additional grassed areas, contour tillage, and terraces. These studies formed the basis of now well-accepted relationships of tillage and conservation practices on soil loss in the Texas Blackland Prairies. In the last 60 yr, improved ''conservation'' agronomic practices have replaced conventional practices that did little to reduce extreme erosion rates. For 1982–2002, average annual soil loss ranged from 552 to 2381 kg/ha for the six cultivated watersheds at Riesel, which is acceptable according to NRCS ''*t* value'' guidelines. Annual soil losses for individual fields ranged from 0 to 13,000 kg/ha in this period.

For 1982 to 2002, the monthly pattern of soil loss (Fig. 6) represented by two selected cultivated watersheds (Y13, Y6) was similar to the temporal runoff pattern (Fig. 7). Three months with average runoff volumes greater than 16 mm (March, May, December) also experienced high soil erosion (>200 kg/ha). Similarly, months with average runoff less than 1 mm (July, September) also experience little erosion (<22 kg/ha). However, several interesting exceptions also occurred due to interactions between rainfall frequency and intensity, crop rotations, and land management. In February, runoff averaged more than 22 mm, but soil loss averaged only 105 kg/ha. In contrast, April and August had low average runoff (<7 mm) but relatively high soil loss (>115 kg/ha).

Many significant differences in median monthly soil loss for the six small watersheds were revealed by the Mann–Whitney tests (Table 6). The most striking was that median July soil loss was 0.0 kg/ha, which is significantly different than for all other months. The median September soil loss (22 kg/ha) was also quite low and significantly lower than eight other months. The temporal patterns in soil loss are driven by the interaction of hydrologic and land conditions; however, the effect of land cover was difficult to distinguish because cropping patterns changed from year

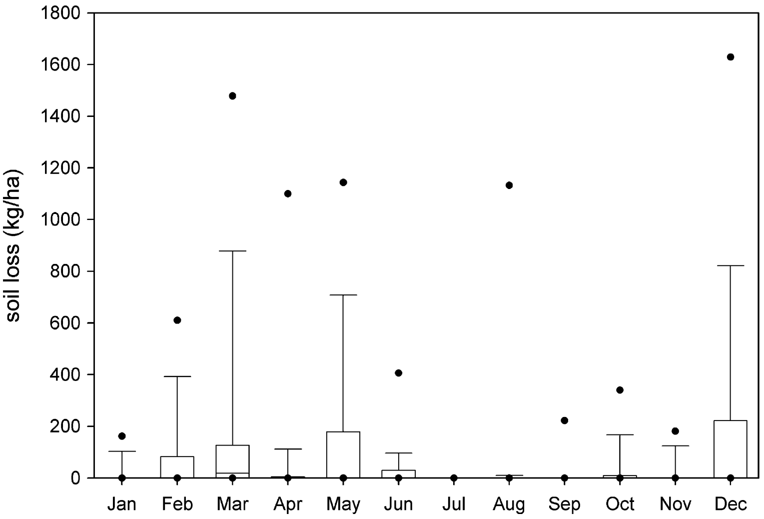

**Figure 6** Distribution of monthly soil loss; data grouped for Y6 and Y13 (points indicate the 5th and 95th percentile; whiskers indicate the 10th and 90th; box boundaries indicate the 25th and 75th; the line within each box indicates the median value).

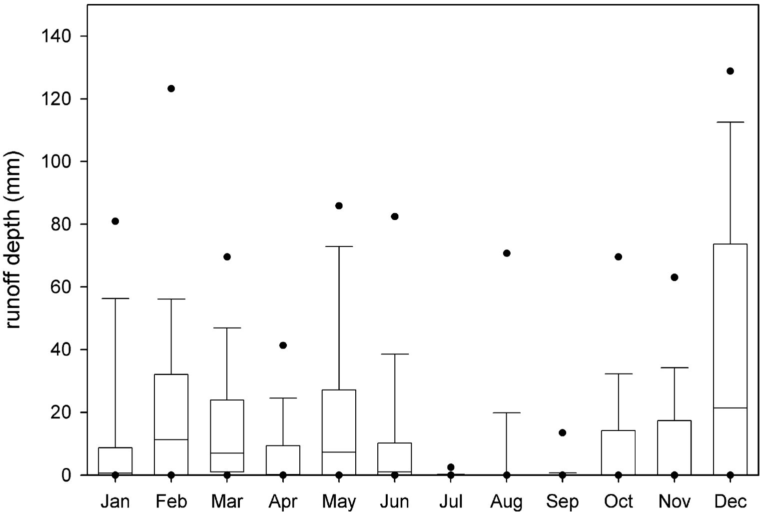

**Figure 7** Distribution of monthly runoff depth; data grouped for Y6 and Y13 (points indicate the 5th and 95th percentile; whiskers indicate the 10th and 90th; box boundaries indicate the 25th and 75th; the line within each box indicates the median value).

**Table 6** *P* values for Mann—Whitney tests of median monthly soil loss from watersheds from 1982 to 2002; statistically significant values ($P < 0.05$ for $\alpha = 0.05$) are italicized

| | February | March | April | May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|---|
| January | 0.471 | *0.045* | 0.128 | 0.066 | 0.575 | *0.005* | 0.379 | 0.298 | 0.810 | 0.379 | *0.020* |
| February | | 0.810 | 0.471 | 0.298 | 0.174 | *0.005* | 0.810 | *0.005* | 0.575 | *0.045* | 0.379 |
| March | | | 0.689 | 0.936 | *0.005* | *0.005* | 0.689 | *0.005* | 0.379 | *0.005* | 0.575 |
| April | | | | 0.689 | *0.008* | *0.005* | 0.471 | *0.005* | 0.379 | *0.005* | 0.689 |
| May | | | | | *0.013* | *0.005* | 0.379 | *0.005* | 0.230 | **0.005** | 0.810 |
| June | | | | | | *0.005* | 0.174 | 0.128 | 0.810 | 0.575 | *0.005* |
| July | | | | | | | *0.005* | *0.005* | *0.005* | *0.005* | *0.005* |
| August | | | | | | | | *0.005* | 0.575 | 0.093 | 0.174 |
| September | | | | | | | | | *0.045* | 0.128 | *0.005* |
| October | | | | | | | | | | 0.471 | 0.279 |
| November | | | | | | | | | | | *0.005* |

to year. Thus, the influence of cropping system was explored further.

When the two major cropping systems used in Texas Blackland Prairies were compared for 1982–2002, the difference in soil loss between small grain and row crop production was striking. Under wheat or oat production, both mean and median annual soil loss were significantly lower than from corn or sorghum production. This same result occurred in the comparison of soil loss between row crop and small grain production for three different scenarios: for all six cultivated watersheds, for a watershed selected to eliminate possible inherent differences between watersheds, and for a pair of watersheds in which cropping system alternated between the two. For these three scenarios, mean annual soil loss for small grains were only 10–48% of losses from row crop production, and median losses were only 8–24% of those from row crop production. These dramatic differences are attributed to the soil cover provided by small grain production, which occurs between October and June and does not leave the soil bare in the high runoff potential times of fall or spring. In contrast, row crop production provides soil coverage only in the spring season. This difference may have little importance in terms of agricultural productivity since erosion levels under conservation management are typically within acceptable NRCS ranges. However, utilizing a winter cover crop in row crop production or converting from row crop to small grain production can be effective in reducing offsite transport of sediment and associated contaminants in watersheds with substantial agricultural contribution to water quality impairment.

## Trends in runoff

Linear regression and rank correlation trend tests indicated several statistically significant seasonal and annual trends in runoff volumes for both the native prairie (SW12) and mixed

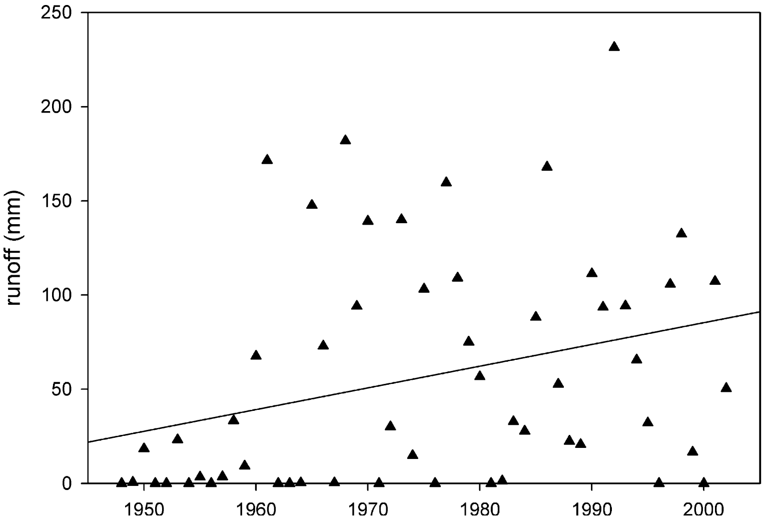

**Figure 8** Winter season runoff depth for watershed SW12 for the period 1948–2002; the linear relationship is shown to illustrate the significant trend.

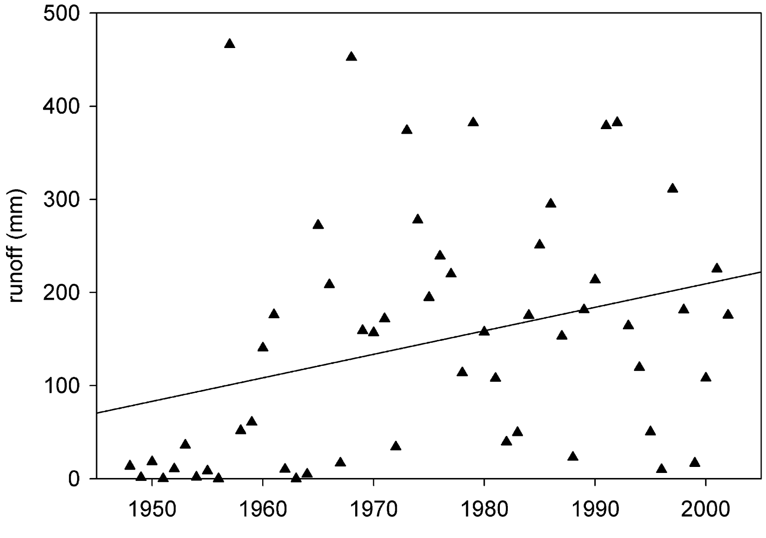

**Figure 9** Annual runoff depth for watershed SW12 for the period 1948–2002; the linear relationship is shown to illustrate the significant trend.

land use (Y2) watersheds in the period 1948–2002, in spite of substantial annual variability. Fall, winter, and annual runoff volumes increased over the period. These increasing trends in winter and annual runoff are illustrated for SW12 in Figs. 8 and 9. The statistical significance of these trends is affected by the extreme drought in the late 1940s and early 1950s. For the native prairie, annual peak flows also exhibited a significant increase over the period.

When precipitation trends for the period 1938–1999 were compared to runoff measured at watershed Y2, several interesting results were noted. Harmel et al. (2003) reported statistically significant decreases in the magnitude of extreme rain events (75–95th percentile) especially in the fall and in the number of extreme rain events (>25.4 mm/day) in the spring. These decreases in extreme precipitation did not translate into a significant decrease in annual peak flows for the period 1940–1999, although the regression slope was negative indicating a possible decrease. Similarly, significant increases in October and ''non-spring'' precipitation did not translate into significant increases in fall or annual runoff for the period 1939–1999, although regression slopes were positive.

The difference in results for trends in runoff for Y2 between the two periods emphasizes some of the difficulty in using historical data to predict future patterns. The runoff record from 1948 to 2002 began with a relatively dry period that strengthened the increasing runoff trends. In contrast, data from 1939 to 1999 began with a wet period that dampened the increasing trend. Therefore, although historical data provide the best estimate possible of future patterns, it is important to remember that historical patterns may not adequately represent future events. When historical runoff data are used to model or predict future water resource availability, the variability and uncertainty of future flow characteristics must be considered.

## Conclusions

This paper provides a summary and selected analyses of runoff and sediment transport data collected from the late 1930s through the present at the USDA-ARS Grassland Soil and Water Research Laboratory watersheds near Riesel, TX. Data collected from these watersheds have contributed to major milestones such as quantification of runoff and erosion control benefits of agriculture conservation practices and development of watershed models currently used worldwide in water resource management. All of these data have been entered into a publicly available database, which provides comprehensive, long-term data on precipitation, runoff, sediment loss, management practices, and climatic conditions for the Texas Blackland Prairies ecosystem.

In the present analyses, several results with immediate practical relevance for water resource management in the Texas Blackland Prairies ecosystem were evident; however, extrapolation to other regions should be performed cautiously, as results could vary substantially for areas with different hydrogeologic conditions.

- The effect of both precipitation and soil–water status to runoff patterns cannot be ignored in this region. Long-term data support the four soil–water phases proposed by Allen et al. (2005). Little surface runoff occurs even with substantial precipitation during in the ''dry phase'' when the soils are dry and cracked, and substantial runoff and lateral subsurface return flow occurs in the ''saturated phase.'' These phases must be adequately represented to appropriately model the region's hydrology.
- Simplified annual peak flow relationships for 2–100 yr return frequencies, based solely on watershed size, were developed and resulted in significant linear relationships. Measured data were also well represented by USGS regional relationships for annual peak flow (Raines, 1998) and runoff volume (Lanning-Rush, 2000). All of these relationships should prove valuable for hydrologic design and planning in the region.
- The data and analyses provided an important reminder of the importance of runoff and erosion control practices related to agriculture and urbanization. Runoff volume, peak flow rate, and soil erosion are much greater from areas with bare soil than from areas with vegetative cover and other appropriate conservation practices.
- For cultivated agriculture, soil erosion was drastically reduced for small grains compared row crops due to the presence of soil cover in both the spring and fall high precipitation periods. Thus, conversion from row crop to small grain production or utilization of winter cover crops in row crop production may be valuable management options to reduce offsite transport of sediment and associated contaminants. This may be especially important in watersheds with substantial agricultural contribution to water quality impairment.

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