Published as:
Garbrecht, J. D., M. W. Van Liew, and G. O. Brown. 2004. Trends in Precipitation, Streamflow and ET in the Great Plains. Journal of Hydrologic Engineering, 9(5):360-367.

Trends in Precipitation, Streamflow and ET in the Great Plains of the United States

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Abstract

Planning and strategic management of water resources are contingent on trends in water availability. In this study, the impact of decade-scale variations in annual and seasonal precipitation on streamflow and evapotranspiration (ET) were identified for 10 watersheds in Nebraska, Kansas, and Oklahoma. In the Great Plains, an upward trend in precipitation over the last two decades of the 20th century had a strong impact on streamflow and a comparatively weaker impact on ET. Even though precipitation, streamflow and ET amount differed between watersheds, the trend resulting from the precipitation increase was similar for all watersheds. Increased precipitation led to a disproportionately large increase in streamflow and comparatively smaller increase in ET. On average, a 12% increase in annual precipitation led to a 64% increase in streamflow, but only a 5% increase in ET. The seasonal partitioning of the annual precipitation increase was, in most cases, biased toward the fall, winter and spring, with little or no change during the hot summer months. The strong streamflow response indicated that planning and management of surface water storage and supply can be critically impacted by decade-long trends in precipitation. The lack of significant increase in precipitation and streamflow during summer suggests that any existing shortages will likely remain despite the observed annual precipitation increase. The ET response suggests that dryland farming and ecosystem vitality could benefit from the increased precipitation in fall, winter and spring, but the impacts are more modest compared to the streamflow response and do not occur during summer when potential ET is greatest. Finally, since the mid 1990's precipitation and streamflow in a number of Oklahoma watersheds have shown a gradual decline from peak values in the late 1980's towards more average conditions. This declining trend may be important for planning and management of water resources systems that must meet an increasing demand for water by a growing society while at the same time considering environmental and recreational needs.

Key words: Climatic changes; Precipitation; Streamflow; Water Resources; Surface waters, Watersheds, Regional analysis, Nebraska, Kansas; and Oklahoma.

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Introduction

Streamflow and evapotranspiration (ET) often reflect changes in precipitation at time scales from seasons to centuries and longer (NRC, 1998). Seasonal and inter-annual climate variations are common occurrences, and society has built resilience to these variations. Water storage reservoirs are designed to bridge seasonal shortfalls of water, crop insurance programs help in the recovery from typical crop failures, and an elaborate transportation system allows the rapid movement of relief supplies to areas stricken by unusual weather patterns. On the other hand, precipitation variations lasting decades or longer (decade-scale) have the potential to greatly surpass short-term variations in their societal, economic and political impacts (Mantua et al., 1997; Woodhouse and Overpeck, 1998). Even though decade-scale precipitation variations are subtler, it is the cumulative effects of sustained departures from average conditions that may lead to the greater impacts. For example, the 1987-1992 drought in California slowly depleted state water reserves and ultimately affected irrigated agriculture, urban water supply, reservoir operations and natural ecosystems. Also, the decade-long wet period during the 1990's resulted in the substantial growth of Devils Lake near the Fort Totten Indian Reservation in north-eastern North Dakota, flooded agricultural land, water-logged soils, and made low-lying farm roads increasingly impassable.

In many parts of the Unites States annual precipitation is undergoing a slow change towards higher values (Karl at al., 1996; Karl and Knight, 1998; Easterling et al., 2000). A similar trend has been observed in the Canadian Prairies where precipitation has increased over the last 75 years (Akinremi et al., 1999). Hu et al. (1998) detected a gradual increase in precipitation since the mid-1960s in the Central United States, and Garbrecht and Rossel (2002) identified a marked increase over the last two decades of the 20th century for many regions of the Great Plains. The importance of such decade-scale variations in precipitation on the hydrologic system and on various weather dependent segments of our society has been recognized in numerous studies (Mantua et al., 1997; Miles et al., 2000; Hotchkiss et al., 2000; Morehouse, 2000). Lins and Slack (1999) found that streamflow trends in the contiguous United States were consistent with precipitation changes described by Karl and Knight (1998). Miles et al. (2000) successfully correlated seasonal streamflow responses of the Columbia River Basin with corresponding El Nino Southern Oscillation and Pacific Decadal Oscillation phases. Such continental and basin scale investigations are important for the development of climate variation indices, identification of global change signals, determination of regional impacts, and assessment of changing risk of flood or drought conditions. However, the broad-scale findings of these studies are not easily transferable to identify hydrologic impacts at the watershed scale, where many local water resources planning and management decisions are made. Also, the majority of watersheds in the US have undergone modifications (land use change, water conservation measures, dams, irrigation and urban water withdrawals, urbanization, river regulation, and flood control structures), which have undoubtedly affected streamflow regimes to an unknown degree (Changnon and Demissie, 1996). Even if a trend in streamflow were observed, it is difficult, under these conditions, to conclusively attribute the trend to land use or to long term precipitation variations.

In this study the hydrologic impacts of decade-scale variations in precipitation are examined in more detail at the watershed scale. The objectives are to identify the sensitivity, magnitude and range of changes in annual and seasonal streamflow and ET resulting from observed decade-scale precipitation variations. Mid-sized agricultural watersheds in the Great Plains with geographic and physiographic features well suited for this study were selected for investigation. First, the selected watersheds have undergone little land use change, regulation and urbanization over the last half century. As a result, trends in watershed response can be more reliably tied to climate variations. Second, the east-west gradient of annual precipitation in the Great Plains is steep. This provides the opportunity to identify precipitation, streamflow and ET relationships over a range of annual precipitation values. Third, in sub-humid climates, watershed response, particularly streamflow, has been recognized to react sensitively to variations in precipitation (Garbrecht et al., 2001; IPCC Working Group II, 2001), thus providing favorable conditions to establish streamflow-precipitation relationships. Finally and most importantly, water in sub-humid regions is often a limited resource and any sustained change in precipitation could result in tangible impacts on society, thus requiring a reassessment of water availability and utilization strategies. Findings of this study can provide insights and guidance to the effects of precipitation variations on surface water resources and provide useful information for long-term planning and management of those water resources. On the agricultural sector, the magnitude and range of changes in ET as a result of precipitation variations can point to opportunities for increased productivity and potential for diversification, or the need for mitigating agronomic practices and developing supplemental water conservation measures.

Data and Methodology

Ten watersheds in Oklahoma, Kansas and Nebraska that have mostly natural unregulated streamflow (Tortorelli, 2002; Slack and Landwehr, 1992; and Personal Communications with various State Water Agencies, 2002) were selected for analysis. Existing unregulated small dams and flood retarding structures exist in many watersheds, however these structures only attenuate flood peaks and have little impact on annual and longer streamflow amount which is the focus of this study. Also, the selected watersheds are not subjected to extensive groundwater pumping for irrigation that could have altered the streamflow and ET characteristics. The locations of the watersheds are shown in Figure 1 and selected watershed attributes are listed in Table 1. The size of the watersheds range from about 800 km^2 (300 sq. mi.) to about 12500 km^2 (4900 sq. mi.), and cover an east-west precipitation gradient ranging from about 1220 mm (48 in) in the east to about 700 mm (28 in) in the west. Land use information was provided by the state office of the National Resources Conservation Service (NRCS) in Oklahoma, Kansas and Nebraska (Table 1). The predominant land use was grassland and pasture, followed by cropland and forest. Exceptions were the Deep Red Creek watershed with predominantly cropland, and the Illinois and Baron Fork watersheds with a high percentage of forest. The NRCS also provided the hydrologic soil group for each watershed, a qualitative parameter that identifies a watershed's runoff production potential. Hydrologic soil groups A and D have low and high runoff potential, respectively; and B and C are representative of moderate runoff production potential. Most watersheds in this study were classified as having moderate to high runoff production potential.

Streamflow data were obtained from the U.S. Geological Survey web site (USGS, 2001). For the Oklahoma and Kansas watersheds, records of registered surface and ground water withdrawal for urban, industrial and agricultural purposes was obtained from the Oklahoma Water Resources Board and the Division of Water Resources of the Kansas Department of Agriculture, respectively. The reported surface and ground water withdrawals were less that 2% of the total streamflow for most watersheds, and for all practical purposes had little impact on streamflow. The Blue River is the exception with withdrawals of about 8% for the City of Durant and the Oklahoma State Fish Hatchery, primarily from surface flow. For the Oklahoma and Kansas watersheds, the reported amount of water withdrawn was added back to the streamflow to better approximate natural streamflow conditions. In the two Nebraska watersheds, most water withdrawals were from groundwater, i.e. the High Plains aquifer. However, only water rights have been recorded by the State, not actual withdrawal amounts (G. Lindeman, State of Nebraska, Dept. of Natural Resources, Personal Communication, 2002). Given this lack of information, no adjustments could be made to the streamflow for the Nebraska watersheds. The limitations of this approximation will be taken into consideration for results interpretation. Finally, streamflow values were standardized in terms of runoff depth to facilitate comparison with precipitation depth.

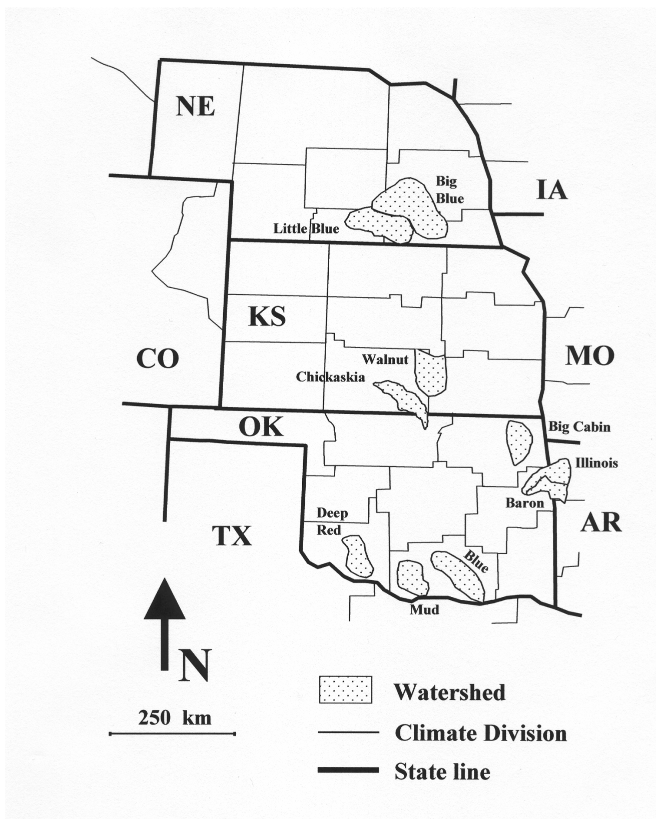

Fig. 1. Location map of the watersheds.

As for many rural areas in the Great Plains, the density of raingages with long-term records is low, and gages are usually situated near towns where they are conveniently accessed for daily recording. Only a few gages with long-term records were found within or in the immediate vicinity of the ten watersheds selected for analysis. Furthermore, precipitation between climate stations that 30 or more km apart often show poor correlation. Hence, a regionally averaged precipitation index was chosen to better represent regional and decade-long climate trends over each watershed. State divisional precipitation data were used estimate seasonal and annual precipitation. State divisional precipitation data are spatially averaged monthly precipitation over a climate division and were obtained from the National Climatic Data Center (NCDC, 1994; NCDC, 2001). The historical origin and the calculation of divisional data can be found in Guttman and Quayle (1996). Climate divisions in Oklahoma, Kansas and Nebraska cover an area of about 15,000 to 26,000 km^2. The divisional precipitation data are well suited for this study because they bring out temporal, decade-long precipitation trends and variations that affect the entire region. The effects of spatial precipitation gradients and watershed location within a climate division are minimized by interpolation of neighboring climate division precipitation values to the center of the watersheds.

For the annual and longer time periods considered in this study, evapotranspiration (ET) was calculated as the difference between precipitation and streamflow. Streamflow includes direct surface runoff, subsurface seepage return flow (interflow) and groundwater channel recharge. Since long term groundwater and ET monitoring was not available for the selected watersheds, the net change in water storage within the watershed was assumed to average over a long period. In most cases this is a realistic assumption, because water storage, either in the soil profile or in the groundwater, fluctuates about a mean value, and the net change over the years remains confined and small compared to cumulative precipitation, streamflow and ET amounts over the same period. For example, a 2.0 m increase in average groundwater level over a 10 year period requires 160 mm of water (assuming an aquifer specific yield of 8%). In a 700 mm precipitation zone and over a 10 year period, this 160 mm water depth corresponds to 2.3% of the total precipitation over the same period. Thus, the net change in water storage at decade-long time scales can be assumed negligible compared to precipitation, streamflow and ET. Similarly, lag effects between precipitation and streamflow, while important at daily and monthly time scales, are less important at annual and decadal time scales. Finally, groundwater leaving the watershed as lateral subsurface flow was assumed to be small compared to streamflow and ET amounts and was neglected. These simplifying assumptions are consistent with the moderate to high runoff producing soils in the watersheds. These soils have low infiltration, slow percolation, and rapid surface runoff response, thus limiting storage and lag effects. With this simplified framework for long-term water budget considerations, all precipitation entering the watershed control-volume leaves as either streamflow or ET. For seasonal water budget considerations, the assumptions are somewhat less applicable and their shortcomings and implications are discussed in conjunction with the result interpretation.

Year-to-year variations in precipitation and streamflow are filtered and decade-scale variations are brought out by applying an 11-year moving average (11-yr MA) to the annual time series. For the five years on each end of the series, averages were computed for available years only. Visual inspection of the time series of the 11-yr MA's and plots of cumulative departure of annual precipitation from the mean are used to identify decade long wet and dry periods. For the identified decade-long wet and dry periods, the mean annual and seasonal precipitation, streamflow and ET are calculated and compared to determine the magnitude, sensitivity and range of change between the dry and wet periods. For the purpose of this study, winter is 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.

Table 1. Streamflow, climate division and precipitation characteristics by watershed.

Watershed and USGS gage #	Drainage Area [km^2]	Period of Streamflow	Mean Precipitation[1] [mm]	Land Use [2] [%] F G C O	Hydrologic Soil Group [3] A B C D
Blue Creek, OK 07332500	1232	1937-2001	1021	08 / 82 / 07 / 03	02 / 44 / 18 / 36
Mud Creek, OK 07315700	1480	1961-2001	856	10 / 73 / 16 / 01	07 / 74 / 04 / 15
Deep Red Creek, OK 07311500	1597	1950-2001	733	01 / 35 / 63 / 01	00 / 18 / 03 / 79
Baron Fork, OK 07197000	795	1949-2001	1124	47 / 49 / 02 / 02	00 / 77 / 16 / 07
Illinois River, OK 07196500	2483	1936-2001	1112	52 / 39 / 01 / 08	00 / 65 / 09 / 26
Big Cabin Creek, OK 07191000	1165	1948-2001	1014	08 / 72 / 15 / 05	00 / 30 / 36 / 34
Chickaskia River, OK 07152000	4813	1937-2001	753	01 / 67 / 30 / 02	05 / 57 / 14 / 24
Walnut River, KS 07147800	4867	1922-2001	814	02 / 75 / 20 / 03	00 / 16 / 37 / 47
Big Blue River, NE 06882000	11513	1932-2001	736	02 / 10 / 86 / 02	00 / 58 / 18 / 24
Little Blue River, NE 06884000	6084	1930-2001	690	02 / 21 / 75 / 02	02 / 71 / 22/ /05

1- Mean precipitation over 1895-2001 period.
2- F=: forest; G=: grassland; C=: cropland; O=: other
3- A=: high infiltration, low runoff potential; B=: moderate infiltration;
C=: slow infiltration; D=: very slow infiltration; high runoff potential.

Results

The 11-yr MA of the annual precipitation and streamflow shows a surprisingly high level of correlation. This is illustrated in Figure 2 for Baron Fork, Mud Creek, Chickaskia River, and Walnut River, which are representative of the precipitation-streamflow behavior of the other seven watersheds. The coefficients of determination (R^2) of the precipitation-streamflow regressions range from 0.6 to 0.95. Both precipitation and streamflow show depressed values in the 1950's, 1960's and 1970's and elevated values in the 1980's and 1990's. The 1961-1980 period, termed the relative "dry period", and the 1981-2001 period, termed the relative "wet period", are used to illustrate differences in streamflow and ET. The beginning and ending years of the two periods are intentionally selected to be the same for all watersheds to provide an unbiased comparison between watersheds. While a number of years during the 1950's could have been included for many of the watersheds, it was preferred to keep the length of the wet and dry period the same for all watersheds. The average annual precipitation, streamflow and ET for each of the periods are given in Table 2.

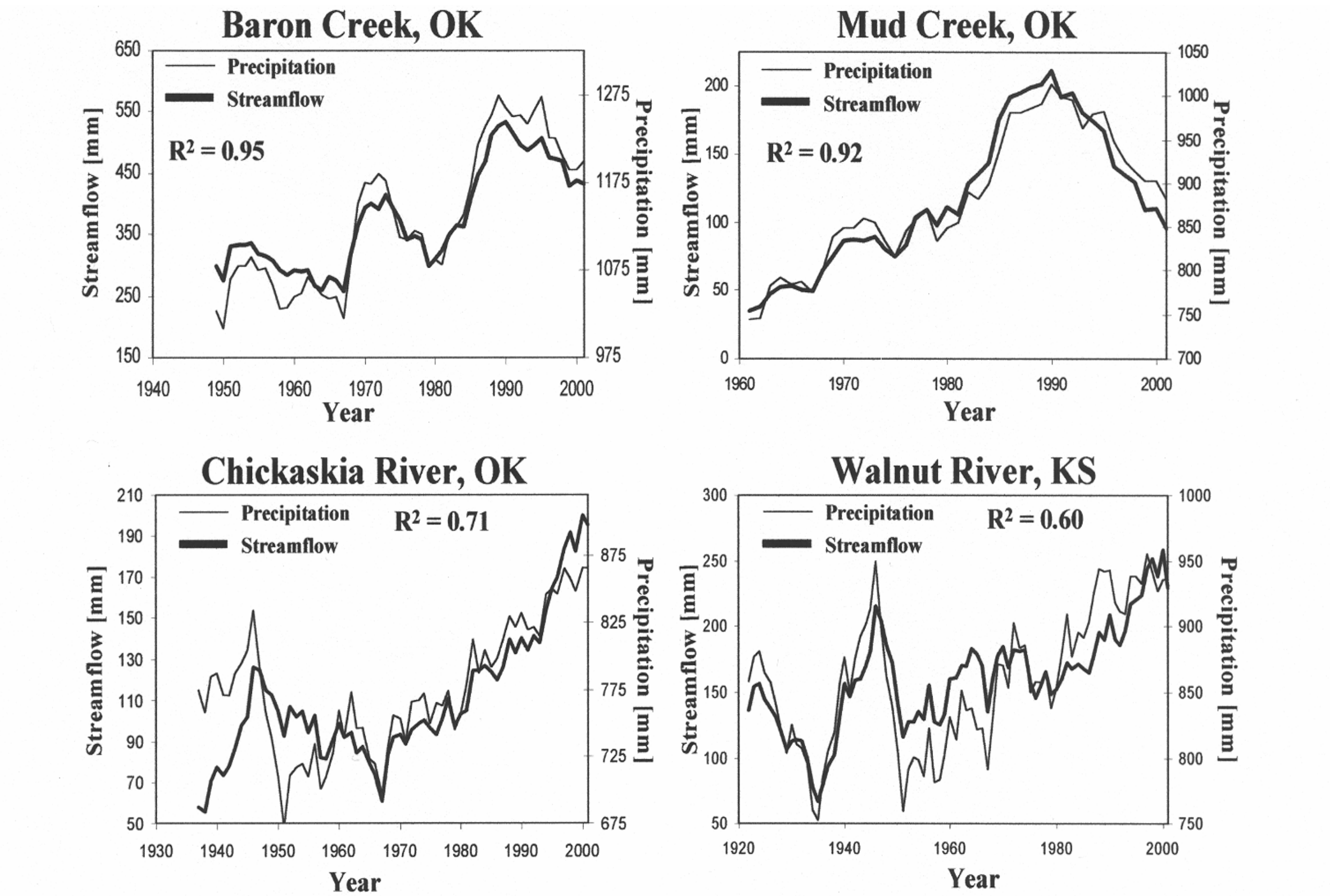

Fig. 2. 11-yr MA of annual precipitation and streamflow for Mud Creek, Baron Fork, Chickaskia River and Walnut River, and coefficient of determination between precipitation and streamflow values.

Precipitation

The regional precipitation trend for each watershed is evaluated in this section. Precipitation increased for all watersheds during the 1981-2001 wet period. Mud Creek and Deep Red Creek in south-central and southwestern Oklahoma experienced the greatest annual precipitation increase of about 19% over the dry period. The other five Oklahoma watersheds in northern and eastern Oklahoma experienced an increase around 12%over the dry period, whereas the watershed in Kansas experienced a 9% increase, and the two Nebraska watersheds an increase just under 6%. The average precipitation increase over all watersheds was about 12%. With the exception of the two Nebraska watersheds, the precipitation increase in all watersheds was statistically significant (single-tailed t-test with unequal variance and significance level of 0.1). The consistency of the precipitation increase over such a large geographical area attests to the regional character of the precipitation trend. It is also noted that since the mid 1990's the 11-yr MA precipitation trend for Baron Creek and Mud Creek (Figure 2) is showing a gradual decline from the high values observed in the late 1980's. This decline is typical for many watersheds in southern and eastern Oklahoma.

Table 2. Average annual precipitation, streamflow and ET for the dry (1961-1980) and wet period (1981-2001) as a result of decade-long climate variations and difference between the dry and wet period in percent.

Watershed	Average Annual Precipitation[1] [mm] Dry	Wet	Average Annual Streamflow[1] [mm] Dry	Wet	Average Annual ET[1] [mm] Dry	Wet	Average Runoff and Retention Ratio [-]		Streamflow to Precip Sensitivity [-]	ET to Precip. Sensitivity [-]
Blue Creek, OK	972	1124	210	302	762	822	0.24	0.76	3.3	0.5
	Δ152	5.6%	Δ92	43.8%	Δ60	7.9%				
Mud Creek, OK	806	955	65	165	741	790	0.13	0.87	8.3	0.4
	Δ149	18.5%	Δ100	153.8%	Δ49	6.6%				
Deep Red Creek, OK	693	831	53	151	640	680	0.13	0.87	9.3	0.3
	Δ138	19.9%	Δ98	184.9%	Δ40	6.3%				
Baron Fork, OK	1072	1220	315	458	757	762	0.34	0.66	3.3	0.0
	Δ148	13.8%	Δ143	45.4%	Δ5	0.6%				
Illinois River, OK	1068	1196	310	394	758	802	0.31	0.69	2.1	0.4
	Δ128	12.9%	Δ84	27.1%	Δ44	5.8%				
Big Cabin Creek, OK	981	1101	245	330	736	771	0.28	0.72	2.8	0.4
	Δ120	12.2%	Δ85	34.7%	Δ35	4.8%				
Chickaskia River, OK	739	830	88	151	651	679	0.15	0.85	5.8	0.3
	Δ91	12.3%	Δ63	71.6%	Δ28	4.3%				
Walnut River, KS	812	882	162	203	650	679	0.22	0.78	2.9	0.5
	Δ70	8.6%	Δ41	25.3%	Δ29	4.5%				
Big Blue River, NE	732	775	61	84	671	691	0.10	0.90	6.4	0.5
	Δ43	5.9%	Δ23	37.7%	Δ20	3.0%				
Little Blue River, NE	687	727	53	63	634	664	0.08	0.92	3.3	0.8
	Δ40	5.7%	Δ10	18.9%	Δ30	4.7%				
Mean change	Δ108	12%	Δ74	64%	Δ36	5%	0.20	0.80	4.8	0.4

1- Precipitation, streamflow and ET values are given on the first line; difference between wet and dry periods and percent change referenced to the dry period are given on the second line.

Streamflow

For the geographic region under consideration, annual streamflow volume represents a small portion of the annual precipitation amount, between 8% and 34%. Annual streamflow increased in all watersheds as a result of the decade-scale precipitation trend at the end of the 20th century (Table 2). The magnitude of the streamflow increase was well correlated with the magnitude of the precipitation increase (R^2=0.87), even though streamflow response depends on a combination of factors involving precipitation, land use, hydrologic soil group, ET and other physiographic watershed variables. Also, the relative increase in streamflow from the dry to the wet period was always larger than the corresponding relative increase in precipitation. The two highest relative streamflow increases (150% and above) were observed in two watersheds in south-central and southwestern Oklahoma. The high values for the percentage resulted in part from relating streamflow change to a low annual streamflow reference value. The average relative streamflow increase over all watersheds was 64%. For Baron Creek and Mud Creek, the observed gradual decline in the 11-yr MA precipitation at the end of the 1990's was well reflected in the corresponding streamflow values (Figure 2). These declining streamflow values may be important for planning and management of water resources that must meet increasing municipal, industrial, environmental, and recreations demands.

The sensitivity of streamflow to variations in precipitation was measured by the ratio of the relative increase of streamflow over relative increase of precipitation. The streamflow-precipitation sensitivity for the ten watersheds ranged for 2.1 to 9.3, meaning that a percentage change in precipitation always resulted in a larger percentage change in streamflow. The average streamflow-precipitation sensitivity was 4.8. The increase in streamflow between the dry and wet periods was found to be statistically significant (single-tailed t-test with unequal variance and significance level of p=0.10) for all watersheds in Oklahoma and for the Big Blue River in Nebraska (p-values were 0.02, <0.01, <0.01, <0.01, 0.06, 0.06, <0.01, and 0.06 for the Blue Creek, Mud Creek, Deep Red Creek, Baron Fork, Illinois River, Big Cabin Creek, Chickashia River, and Big Blue River, respectively). The increase was not statistically significant for the Walnut River in Kansas (p-value = 0.17), even though the corresponding precipitation change was significant (p-value = 0.08), and it was not significant for the Little Blue River in Nebraska (p-value = 0.18). The p values are listed here only to provide the reader with a general impression of the level of the significance.

Evapotranspiration

Assuming ET is the complement of runoff, 66% to 90% of the annual precipitation contributed to ET, and the increasing precipitation trend between dry and wet period led to an increased ET for all watersheds (Table 2). For watersheds in the drier precipitation zone (under 900 mm) the average increase in ET was well correlated to average increase in precipitation. However, for watersheds in the higher precipitation zone (above 900 mm) the correlation was lower, mainly because a larger portion of the precipitation increase contributed to streamflow, thus reducing the signal to noise ratio for ET. The average relative increase in ET over all watersheds from the dry to the wet period was about 5% and was found to be statistically significant for only four out of the ten watersheds (single-tailed t-test with unequal variance and significance level of 0.1). The ET-precipitation sensitivity for the ten watersheds ranged for 0.0 to 0.8. These sensitivity values are below 1.0 and imply that an increase in precipitation always resulted in a smaller percent increase in ET. The average ET-precipitation sensitivity was 0.4 and reflected a low sensitivity of ET to changes in precipitation.

Precipitation-Streamflow-ET Relationship

Relative increases in precipitation, streamflow and ET hint at a strong impact of decade-scale precipitation change (12% increase) on streamflow (64% increase) and a weak impact on ET (5% increase). The same holds true when considering actual precipitation, streamflow and ET amounts. On average over all watersheds, precipitation increased by 103 mm, of which the larger share (68 mm) went to streamflow and the smaller share (35 mm) to ET. However, these average values only suggest general tendencies for the region under consideration and do not give justice to the true complexity and range of variations of the precipitation-streamflow-ET relationship at the watershed scale.

The interplay between precipitation, streamflow and ET is best illustrated by considering a plot of 11-year MA annual streamflow and ET versus corresponding annual precipitation for all ten watersheds (Fig. 3). The pattern of the precipitation-streamflow-ET relationship is consistent across all watersheds. Streamflow depth is always less than ET depth. The difference between streamflow and ET depth is large in the low precipitation areas and smaller in areas with higher precipitation. The precipitation-streamflow relationship is flat for low precipitation values, becomes increasingly steeper with increasing precipitation, and approaches a one-to-one slope for annual precipitation values above 900 mm. On the other hand, the pattern of the precipitation-ET relationship is the opposite of the precipitation-streamflow relationship: it is nearly a one-to-one slope for low precipitation values, flattens gradually with increasing precipitation, and approaches a constant 800 mm for annual precipitation above 900 mm. It is also noted that the ET and streamflow values for the two Kansas watersheds are well in line with the data of the Oklahoma and Kansas watersheds. Thus, the previously discussed assumption regarding the accounting of water withdrawals does not appear to have been an important factor in identifying streamflow response to long-term precipitation variations.

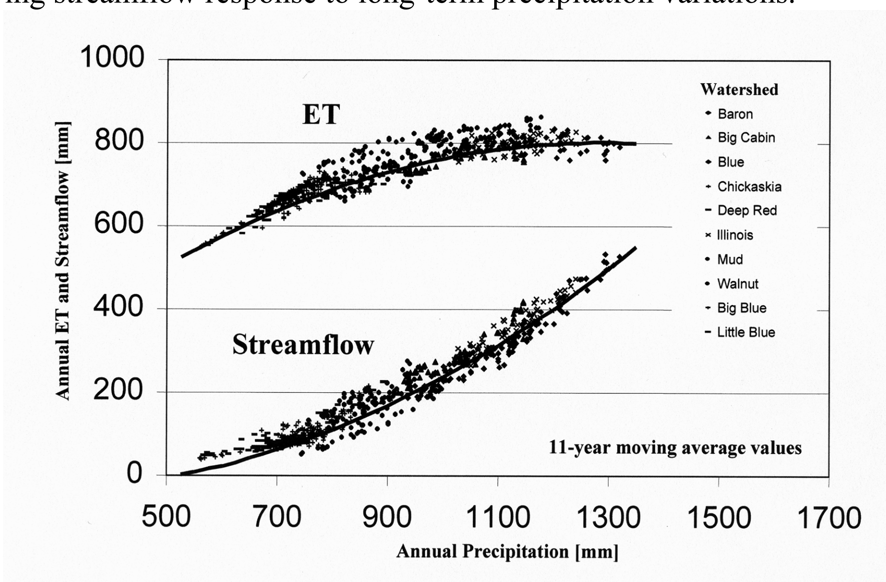

Fig. 3. Precipitation-streamflow-ET relationship for the 10 watersheds and based on 11-year MA annual values.

Based on these precipitation-streamflow-ET relationships the following inferences can be drawn. 1) In low precipitation regions and during dry periods (below 750 mm), a large portion of the precipitation variation goes to ET and a small portion to streamflow. However, the small portion of precipitation going to streamflow may be large compared to existing low streamflow and may lead to a large relative increase in streamflow. 2) In high precipitation regions and during wet periods (above 900 mm), the largest portion of the precipitation variation goes to streamflow and a small portion goes to ET. Considering the high initial value of the ET, this small addition only produces a modest relative change in ET. And 3), for the precipitation zone between 750 mm and 900 mm, both streamflow and ET receive roughly an equal fraction of the precipitation. However, because of the comparatively low streamflow and comparatively high ET, the relative change is larger for streamflow than for ET, hence the strong impact of decade-scale precipitation variations on streamflow.

The above analysis was conducted on annual precipitation, streamflow and ET values for all watersheds, and reflects the general behavior of watersheds. For watershed specific relationships, each watershed must be evaluated and interpreted individually. Such an analysis has shown that most watersheds do indeed follow relationships similar to the ones discussed above, even though the trend line for both ET and streamflow may be shifted and more curved than the ones shown in Fig. 3.

Seasonality of Precipitation, Streamflow and ET

Seasonal distribution of decade-scale changes in precipitation, streamflow and ET is as important as annual changes, because seasonal pattern of water availability (precipitation and streamflow) often differ from seasonal water needs, which in turn may require management intervention to balance differences in availability and need. For example, peak urban and agricultural water needs are often during the summer, yet precipitation increases may not occur during that season, and management intervention may be required to use out-of-season water to meet summer needs. For the southern and central Great Plains, seasonal distribution of precipitation varied along a north-south axis. Therefore, the seasonal distribution of changes in precipitation, streamflow and ET for the ten watersheds was reviewed from north to south. Figure 4 shows the seasonal amounts and changes of precipitation, streamflow and ET for the dry (1961-1980) and wet (1981-2001) periods for the Big Blue River, Walnut River, Baron Creek and Mud Creek.

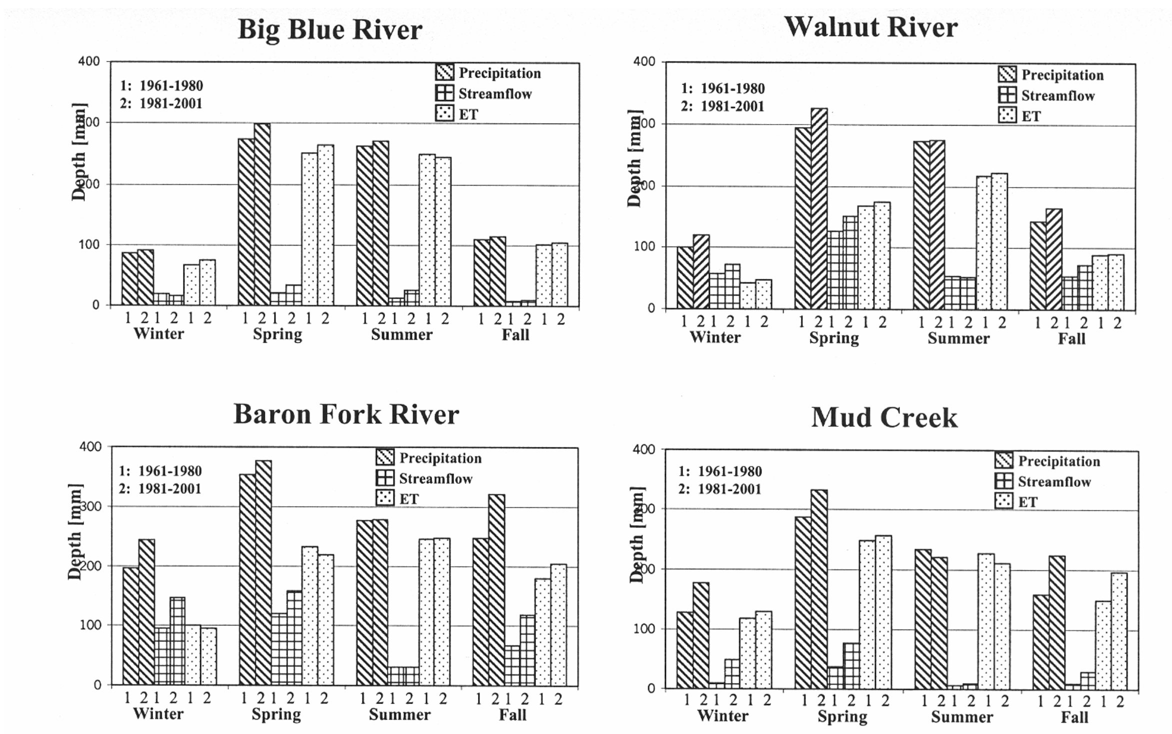

Fig. 4. Differences in the seasonal distribution of precipitation, streamflow and ET between the dry (1961-1980) and wet (1981-2001) dry periods.

For the Big Blue River watershed, about 70% of the annual precipitation was in spring and summer. About half of the increase in annual precipitation in the wet period occurred during the spring, while the other half was about evenly distributed between summer, fall and winter

(Figure 4a). Thus, spring, the wettest season of the year, captured the lion's share of the annual precipitation increase, and the warmer summer and drier fall and winter saw smaller increases. Streamflow increased about equally in spring and summer with no increase in fall and winter. The summer increase was attributed in part to a lag in runoff from the spring precipitation increase. Even though the streamflow increase in spring and summer was small in terms of depth (on average 12.5 mm), it represented a sizable relative increase (on average 75%). With respect to ET, half the annual increase occured in spring concurrently with the precipitation increase. The other half occurred in fall and winter. The spring, fall and winter increase in ET was small in terms of depth (on average 7 mm) and in terms of relative size (on average 7 %). The small decrease in ET during the summer was believed to be artificial and related to the spring-to-summer streamflow lag, as well as the simplification in the calculation of ET that assumed no lag. The pattern of seasonal precipitation, streamflow and ET was essentially identical for the neighboring Little Blue River. A more precise accounting of direct runoff, lagged subsurface return flow, and ET requires computer simulation, which is outside the scope of this study.

For the Walnut River watershed, spring and summer received about 65% of the annual precipitation. The precipitation increase due to the wet period was about evenly distributed over the fall, winter and spring, with no relevant change during summer (Figure 4b). The dry fall and winter seasons captured a little over half of the annual precipitation increase, whereas spring captured the remainder and summer saw no change. The seasonal changes for streamflow was distributed similarly to that of precipitation: in winter, spring and fall, streamflow increased by 32%, 18% and 30%, respectively, whereas summer saw a slight decrease (-8%). Increases in ET were minimal, about 9%, 5% and 3% in winter, spring and summer, respectively. For the Chickaskia River, the patterns were also similar for fall, winter and spring. The summer precipitation and ET decreased slightly (-2% and -6%, respectively), while the low summer streamflow increased by about 90%, mostly as a result of runoff lag from higher spring precipitation. The summer decrease in ET was believed to be mostly artificially for reasons given earlier.

For Baron Creek watershed, the low and high precipitation seasons are winter and spring, respectively (Figure 4c). Fall captured about half the annual increase in precipitation from the wet period, while winter captured another third, and spring the remainder. Summer remained unchanged. Hence, fall and winter together captured about 80% of the annual precipitation increase. Streamflow increased about the same amount in winter, spring and fall (on average 46 mm or 52%), with no change during the summer. ET remained somewhat equal during winter and summer and increased during the fall. The slight decrease in ET during spring was again attributed to runoff lag effects and simplified ET calculations. Nevertheless, the overall trend in ET was clear: it increased only in fall by a sizable amount (25 mm or 14%). One reason that ET did not increase during winter and spring even though precipitation increased was that the watershed is in a higher precipitation region (over 1000 mm annual precipitation), the warm season grasses are dormant, and most additional precipitation in the cool winter and spring left the watershed as streamflow. The seasonal patters for the Illinois River, Big Cabin Creek and Blue River were similar, with a slight decrease in precipitation and ET during summer.

Finally, for the Mud Creek watershed, the wet season is spring, and precipitation decreases gradually thereafter from summer to fall to winter. Mud Creek was one of the watersheds that experienced the highest annual increase in precipitation (18%) during the wet period. This increase was evenly distributed over the fall, winter and spring, whereas summer saw a slight decrease. The average precipitation increase during fall, winter and spring was sizable (on average 54 mm or 32%). Thus, the two driest seasons (fall and winter) of the year benefited the most from the precipitation increase. Streamflow displayed a similar seasonal distribution, with fall, winter and spring flows increasing by over 100%, whereas summer low flows remaining essentially unchanged. ET increased mostly in fall (47 mm or 32%) and to a lesser amount in winter and spring. The decrease in ET during the summer is primarily related to the decrease in summer precipitation, with some possible contribution related to the previously discussed lag effect. A similar seasonal distribution pattern for precipitation, streamflow and ET applied to Deep Red Creek.

Conclusions

The central Great Plains experienced a decade-scale precipitation increase at the end of the 20th century. This study examined the annual and seasonal impact of this precipitation trend on streamflow and ET for ten watersheds in Nebraska, Kansas and Oklahoma. Average annual precipitation increased between 6% and 20% with smaller values applying to the northern watersheds and larger values to the southern watersheds. The seasonal partitioning of this increase was in most cases biased towards the fall, winter and spring, with little change during summer. The increase in streamflow amounts resulting from the precipitation trend were mostly modest for watersheds that have annual precipitation less than 700 mm, even though the relative increases in streamflow were substantial, ranging from 50% to over 150%. For those watersheds with annual precipitation above 900 mm, the increase in streamflow amounts was a more substantial portion of the precipitation increase, and the relative increase ranged between 20% and 40%. Evapotranspiration (ET), a large portion of precipitation, increased primarily in the dry western watersheds whereas in the wet eastern watersheds most of the additional precipitation contributed to streamflow. Also, for many Oklahoma watersheds, a recent gradual decline in precipitation trend from the high values of the late 1980's was observed. The seasonal pattern of ET was much less consistent and more difficult to interpret. In general, ET appears to increase in the spring for the northern watersheds and in the fall for southern watersheds. However, the relative increase in ET was modest (generally less than 10%) and sometimes ambiguous due to the simplifying assumption underlying the calculation of ET. The following inferences can be drawn from the findings of this study:

- The high water demand by agricultural and urban areas during the summer months did not directly benefit from the decade-scale trend of precipitation. Water supply shortages during the hot season endured, and available summer water supply remained limited to existing storage capacity.

- In the considered regions, most of the precipitation fueled ET, and fall and winter crops, cool season grasses, and winter wheat grazing opportunities stood to benefit from the precipitation trend. Summer crops and warm season grasses only benefited from additional spring moisture stored in the soil.

- The streamflow and ET impacts of decade-scale precipitation trends in this study could be viewed as an indication of changes one could encounter under climate change scenarios.

Under these conditions, this study suggested that the greatest impact of a wetter or a drier climate in the Great Plains could be expected during fall, winter and spring, but not necessarily during summer, and the most notable impact would be on streamflow.

- Long term ET and groundwater measurements are generally not available for watersheds to conduct decade-scale trend analyses. Watershed specific impacts of response-lag and watershed storage, which were assumed negligible in this study because of the year-long sampling time, may be confirmed through numerical watershed modeling, especially at the seasonal time scale.

The strong impact of decade long precipitation variations on streamflow emphasize the importance of including such information in planning and strategic management of water resources. This may be particularly relevant if the recently observed declining trend in decade-scale precipitation and streamflow in the Oklahoma watersheds over the last few years persists because existing management of the water supply system has attuned itself to several decades of prevalently wet conditions.

References

Akinremi, O. O., McGinn, S. M., and Cutfirth, H. W. (1999). Precipitation Trends on the Canadian Prairies. *Journal of Climate*, 12:2996-3003.

Brown, G. O., and Garbrecht, J. D. (2002). Precipitation Trends and Groundwater in the Arbuckle Formation of Oklahoma. In *Proc. of Groundwater/Surface Water Interactions, AWRA 2002 Specialty Conference*, Kenny, J. F. (ed.), American Water Resources Association, Middleburg VA, TPS-02-2, pg. 405-410.

Changnon, S. A., and Demissie, M. (1996). Detection of Changes in Streamflow and Floods Resulting from Climate Fluctuations and Land Use-Drainage Changes. *Climate Change*, 32:411-421.

Easterling, D. R., Evans, J. L., Groisman, P. Ya., Karl, T. R., Kunkel, K. E., and Ambenje, P. (2000). Observed Variability and Trends in Extreme Climate Events: A Brief Review. *Bulletin of the American Meteorological Society*, 81(3):417-425.

Garbrecht, J., and Rossel, F. E. (2002). Decade-Scale Precipitation Increase in Great Plains at End of 20th Century. *Journal of Hydrologic Engineering* 7(1):64-75.

Garbrecht, J., Rossel, F. E., and Schneider, J. M. (2001). Decade-Scale Precipitation and Streamflow Variation in the Kansas-Nebraska Region. In: *Proceedings 12th Symposium on Global Change and Climate Variations*, 81st American Meteorological Society Annual Meeting, Published by AMS, 45 Beacon Street, Boston, MA, 02108-3693, pp. 319-321, January 14-19, 2001, Albuquerque, New Mexico.

Guttman, N. B., and Quayle, R. G. (1996). A Historical Perspective of U.S. Climate Divisions. *Bulletin of the American Meteorological Society*, 77(2):293-303.

Hotchkiss, R. H., Jorgensen, S. F., Stone, M. C., and Fontaine, T. A. (2000). Regulated River Modeling for Climate Change Impact Assessment: The Missouri River. *Journal of the American Water Resources Association*, 36(2):375-386.

Hu Q., Woodruff, C. M., and Mudrick, S. E. (1998). Interdecadal Variations of Annual Precipitation in the Central United States. *Bulletin of the American Meteorological Society*, 79(2):221-229.

McCarthy J. J., Canziani, O. F., Leary, N. A., Dokken, D. J., and White, K. S., Eds. (2001). Climate Change 2001, Impacts, Adaptation and Vulnerability. *Intergovernmental Panel on Climate Change (IPCC) Working Group II.* Published by Cambridge University Press, 40 West 20th Street, New York, NY1001-4211, USA.

Karl, T. R., and Knight, R. W. (1998). Secular Trends of Precipitation Amount, Frequency, and Intensity in the Unites States. *Bulletin of the American Meteorological Society*, 79(2):231-241.

Karl, T. R., Knight, R. W., Easterling, D. R., and Quayle, R. G. (1996). Indices of Climate Change for the United States. *Bulletin of the American Meteorological Society*, 77(2):279-292.

Lins, H. F., and Slack, J. R. (1999). Streamflow Trends in the Unites States. *Geophysical Research Letters*, 26(2):227-230.

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., and Francis, R. C. (1997). A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production. *Bulletin of the American Meteorological Society*, 78(6):1070-1079.

Miles, E. L., Snover, A. K., Hamlet, A. F., Callahan, B., and Fluharty, D. (2000). Pacific Northwest Regional Assessment: The Impacts of Climate Variability and Climate Change on the Water Resources of the Columbia River Basin. *Journal of the American Water Resources Association*, 36(2):399-420.

Morehouse, B. J. (2000). Climate Impacts on Urban Water Resources in the Southwest: The Importance of Context. *Journal of the American Water Resources Association*, 36(2):265-277.

National Climate Data Center (NCDC). (1994). Time Bias Corrected Divisional Temperature-Precipitation-Drought Index. Documentation for Data Set TD-9640. Available from DBMB, NCDC, NOAA, Federal Building, 37 Battery Park Avenue, Asheville, NC 28801-2733. 12 pp.

National Climate Data Center (NCDC). (2001). Climate Division: Temperature-Precipitation-Drought Data. Available from: <http://www.ncdc.noaa.gov/oa/climate/onlineprod/drought/ftppage.html> (June 19, 2002)

National Research Council (NRC). (1998). Decade-to-Century-Scale Climate Variability and Change, A Science Strategy. *Panel on Climate Variability on Decade-to-Century Time Scales; Board on Atmospheric Sciences and Climate; Commission on Geosciences, Environment, and Resources*; National Research Council, pp.141.

Slack, J. R., and Landwehr, J. M. (1992). Hydro-Climatic Data Network: A U.S. Geological Survey Streamflow Data Set for the United States for the Study of Climate Variations, 1874-1988. *USGS Open-File Report* 92-129 <http://water.usgs.gov/pubs/of/ofr92-129/content.html> (July 8, 2002).

Tortorelli, R. L. (2002). Statistical Summaries of Streamflow in Oklahoma through 1999. *U.S. Geological Survey Water-Resources Investigations Report 02-4025*, 510 p.

United States Geological Survey (USGS). (2001). Water Resources of the United States, Historical NWIS-W data. *U.S. Geological Survey*, <http://waterdata.usgs.gov/nwis> (August 6, 2002).

Woodhouse, C. A. and Overpeck, J. T. (1998). 2000 Years of Drought Variability in the Central United States. *Bulletin of the American Meteorological Society*, 79(12):2693-2714.