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EFFECTS OF REGIONAL GROUND-WATER LEVEL DECLINES ON STREAMFLOW IN THE OKLAHOMA PANHANDLE

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ABSTRACT: Increased pumping from the High Plains aquifer has resulted in widespread water-level declines in the aquifer. Declines of 25 to 50 feet are common in western Oklahoma; south of Guymon, water levels have declined about 100 feet. The number of large-capacity wells (primarily irrigation wells) in the Oklahoma Panhandle increased from about 450 in 1963 to about 2,500 in 1984.

The Beaver River drains most of the Oklahoma Panhandle and has been gaged near Guymon since 1937. Although changes in the use of surface water have been minimal during this period, trend tests confirm that the discharge of the river has decreased substantially. There has been no corresponding change in precipitation. Average annual discharge at Guymon for 23 years through 1960 was 32.2 cubic feet per second; the average annual discharge for the last 10 years (1977-86) has been about 7 cubic feet per second. Prior to the mid-1960's, the river at Guymon was generally perennial; flow ceased only during droughts and then never for more than 60 days in any given year. Since 1968, the river at Guymon has been dry for extended periods every year and presently (1988) averages about 300 days of no flow every year.

KEY TERMS: Streamflow trends; ground-water levels; base flow

INTRODUCTION

The Ogallala Formation underlying most of the Oklahoma Panhandle is part of the High Plains regional aquifer system extending from southern South Dakota to northwestern Texas. The aquifer is primarily a water-table aquifer deriving input from recharge due to precipitation. The High Plains aquifer underlies a land area of about 174,000 mi^2, with the saturated thickness varying from 0 to about 1,000 ft. In the Panhandle, the aquifer consists of hydraulically connected interbedded siltstone, sand, clay, gravel, thin limestone, and caliche in the Ogallala Formation. In the vicinity of Guymon, Oklahoma, the saturated thickness varies from 0 to about 450 ft, and the measured water table elevation (1980) was about 3,000 ft above sea level (Havens and Christenson, 1984).

Prior to the start of large-scale pumping for irrigation in the 1960's, the aquifer was in equilibrium. The estimated recharge rate for the Ogallala Formation in the Beaver River basin upstream from Guymon is 0.056 in per year (Luckey and others, 1986, p. 29); this represents less than 1 percent of the mean annual precipitation. With the start of extensive irrigation pumping, and no increase in natural recharge, the water table in the southern part of the High Plains aquifer began to decline (Havens and Christenson, 1984). This decline in ground-water levels in combination with changes in land-use practices has been recognized to be a primary cause of decreases in stream discharge in the Solomon and Republican River basins in Kansas (U.S. Bureau of Reclamation, 1984, 1985). Boyle Engineering Corp. (1987) attributed decreases in stream discharge in the western Panhandle of Oklahoma to these same factors. Their conclusions were based on mass-diagram analyses.

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The purpose of this paper is to evaluate the effects of regional ground-water level declines on streamflow in the Oklahoma Panhandle using statistical methods to test for trends in streamflow. Factors that may have produced any identified changes also will be examined. The study will concentrate on the Beaver River near Guymon.

DESCRIPTION OF STUDY AREA

The study area (Figure 1) includes drainages of both the Beaver (headwaters of the North Canadian River) and Cimarron Rivers. These rivers drain the Oklahoma Panhandle, along with parts of northeastern New Mexico, northern Texas, southeastern Colorado, and southwestern Kansas. The Beaver River drains most of the Panhandle and has been gaged near Guymon since 1937. During this period, the use of surface water for irrigation in the Beaver River basin upstream from Guymon has been minimal. The storage capacity in the basin upstream from Guymon in reservoirs of more than 100 acre-ft capacity has been estimated to be 5,425 acre-ft, 5,165 acre-ft of which is in New Mexico (Canadian River Commission, 1987).

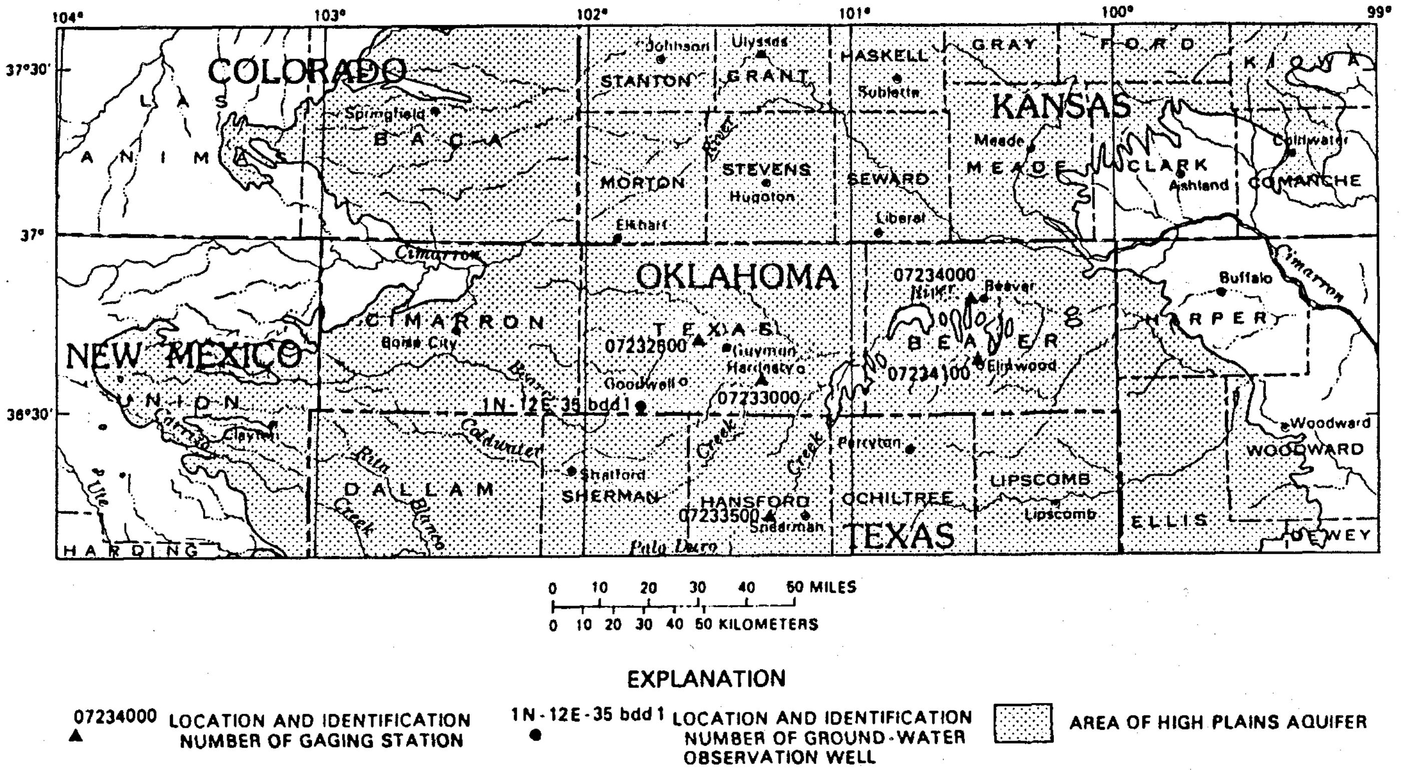

Figure 1. Location of Study Area (Modified from Gutentag and others, 1984).

Average annual precipitation near Guymon is about 17 in, about 10 percent of which falls as snow, with the majority occurring from winter through early summer. Mean daily air temperatures range from 30 °F in January to 78 °F in July. Average annual lake evaporation is about 62 in, and average annual evapotranspiration is about 16 in (Pettyjohn and others, 1983). Average annual runoff is about 0.2 inches. Historically, most runoff generally occurs between April and August, whereas the smallest steamflows usually occur from December through February.

The principal industry in the Panhandle is agriculture, with the land area about evenly divided between farming and ranching. In 1978, about 42 percent of the area of both Beaver and Cimarron Counties and about 59 percent of Texas County was cropland (U.S. Department of Agriculture, 1978). Terracing of cropland in Beaver County increased from about 20,000 acres in 1960 to about 200,000 acres (approximately 40 percent of the total cropland) in 1985 (Boyle Engineering Corp., 1987, p. 3-22). Terracing in Texas and Cimarron Counties, however, is estimated to be less than 1 percent of the cropland area (Robert Griswald and Jerry Allan, U.S. Soil Conservation Service, oral commun., 1988).

Irrigation and municipal ground-water use in Texas County during 1979 totaled 269,199 acre-ft; Cimarron County, upstream of Guymon, recorded total ground-water use of 68,121 acre-ft (Pettyjohn and others, 1983, p. 61). In aggregate, the Panhandle counties accounted for 49 percent of the ground water and only 3 percent of the surface water use in Oklahoma during 1979.

GROUND-WATER LEVELS

The introduction of the center-pivot sprinkler system in the early 1960's resulted in a rapid increase in the use of ground water for irrigation. As late as about 1963, there were only about 450 wells with capacities of greater than 100 gal/min in the Oklahoma Panhandle; by 1984, the number of such wells had increased to almost 2,500 (Oklahoma Water Resources Board, 1984). The increase in numbers of large-capacity wells for the individual counties of the Oklahoma Panhandle is shown in Figure 2A.

The combination of low rates of natural recharge and the increase in number of large-capacity wells has produced substantial declines in water levels throughout large areas of the Ogallala Formation. Havens (1983) reported that, for the period before development to 1980, water-level declines of 25 to 50 ft are common in western Oklahoma; south of Guymon, water levels have declined more than 100 ft. Recent data based on 52 wells in Cimarron County and 104 wells in Texas County show that the median water level changed little in Cimarron County between 1982 and 1987, but declined an additional 4.3 ft in Texas County. End-of-month readings are presented in Figure 2B for water levels in a long-term observation well completed in the Ogallala Formation in Texas County. The water level in the well began to decline rapidly about 1964 and appears to have reached a relatively steady rate of decline in the early 1970's that continues to the present (1988). A digital simulation model of the High Plains aquifer in Oklahoma was used by Havens and Christenson (1984) to predict future water levels through 2020. They predict that the aquifer will continue to be an important water source after 2000, but, as water levels continue to decline, ground-water discharge to streams will decrease, and, in some cases, may cease.

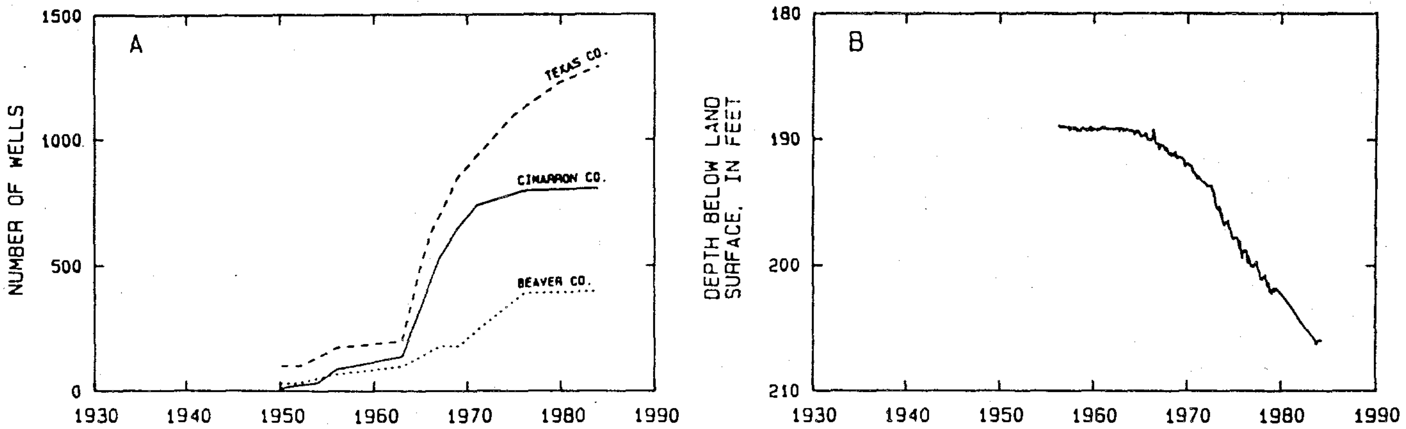

Figure 2. Changes with Time in: A) Numbers of Large-Capacity Wells in Beaver, Texas, and Cimarron Counties, Oklahoma, 1950-84 (from Oklahoma Water Resources Board, 1984, p. 16); B) Water Levels in a Long-Term Observation Well in Texas County (1956-85).

PRECIPITATION

Climatic records in the area do not show evidence of long-term changes in precipitation. Precipitation records for Boise City, Guymon, and Goodwell and pan-evaporation data for Goodwell were examined. The annual precipitation at Goodwell is representative of the Panhandle and is shown in Figure 3A; a trace of the 5-year moving average of the annual precipitation also is shown. The 5-year moving average was used because Marine (1963) suggested that hydrographs of water levels in the Oklahoma Panhandle correlate with graphs of the 5-year moving average of precipitation. Marine's work was, of course, prior to the effect of drawdown produced by large-scale pumping. The annual precipitation amounts for Goodwell range from about 9 to 27 in and averages 17 in. The 5-year moving average oscillates between about 12 to 25 in and shows definite high and low periods. For example, the droughts of the 1930's and 1950's are quite evident on the moving-average trace. However, there is no discernable long-term trend shown by the moving average. This indicates that changes in the rate of precipitation have not been a major factor in either declines of ground-water levels or decreases of streamflows from the Panhandle.

STREAMFLOW

There has been a general recognition since the mid-1970's that flows of the Beaver River near Guymon, Oklahoma, were declining. By about 1980, even casual observers recognized that the flow patterns of the Beaver River had changed. Prior to about 1970, the Beaver River occasionally ceased to flow, but only for short periods. For example, between 1939 and 1945 the river flowed continually throughout the year only in 1942; however, the total number of days without flow never exceeded 60 in a year. This pattern is repeated from 1956 through 1969 with sustained flow in the river throughout the year only in 1957, 1958, and 1967. Again, however, the total number of days per year without flow never exceeded 60. Beginning in 1970, the pattern changed; since then, the river has been dry at Guymon for more than 60 days in all years but 1971. The percentage of days without flow for each year is shown in Figure 3B. Since about 1970, the number of days without flow appears to have increased steadily, and presently (1988) the river at Guymon flows for only about 60 days in a year. In other words, the river is now dry about 85 percent of the year; prior to 1971, the river was dry generally less than about 15 percent of the year.

The average annual discharge of the river has undergone similar changes. The average annual discharge reported in 1960 for 23 years of record (water years 1938-60) was 32.2 ft^3/s (U.S. Geological Survey, 1964). By 1985, the average discharge based on 48 years of record (water years 1938-85) was only 21.9 ft^3/s (Hauth and others, 1985). The annual average discharge for the period of record at Guymon is shown in Figure 3C; the 10-year moving average of those discharges also is shown. The moving average damps the year-to-year variation that is normal in this region and is helpful in detecting trends. The 10-year moving average was relatively stable from about 1950 to about 1965, fluctuating within a range of about 25 to 30 ft^3/s; by 1986, however, the average discharge for the past 10 years (water years 1977-86), had decreased to about 7 ft^3/s.

Possible changes in the peak flows of the Beaver River have been less pronounced, but plots of annual peak discharge versus time (Figure 3D) indicate that peak flows also may be decreasing with time. Although certainly not definitive, even the largest peaks that have occurred since 1970 would be among the smallest peaks in the record had they occurred prior to 1970. Also, annual peaks have traditionally occurred between April and November with about 60 percent occurring in June, July, or August (Figure 4A).

Analysis of daily-duration hydrographs provides an alternative way of examining changes in the flow patterns of a stream. In such an analysis, each day of the year is subjected to an individual flow-duration analysis. The result of the analysis is a frequency distribution for discharges for each day of the year. Daily-duration analysis

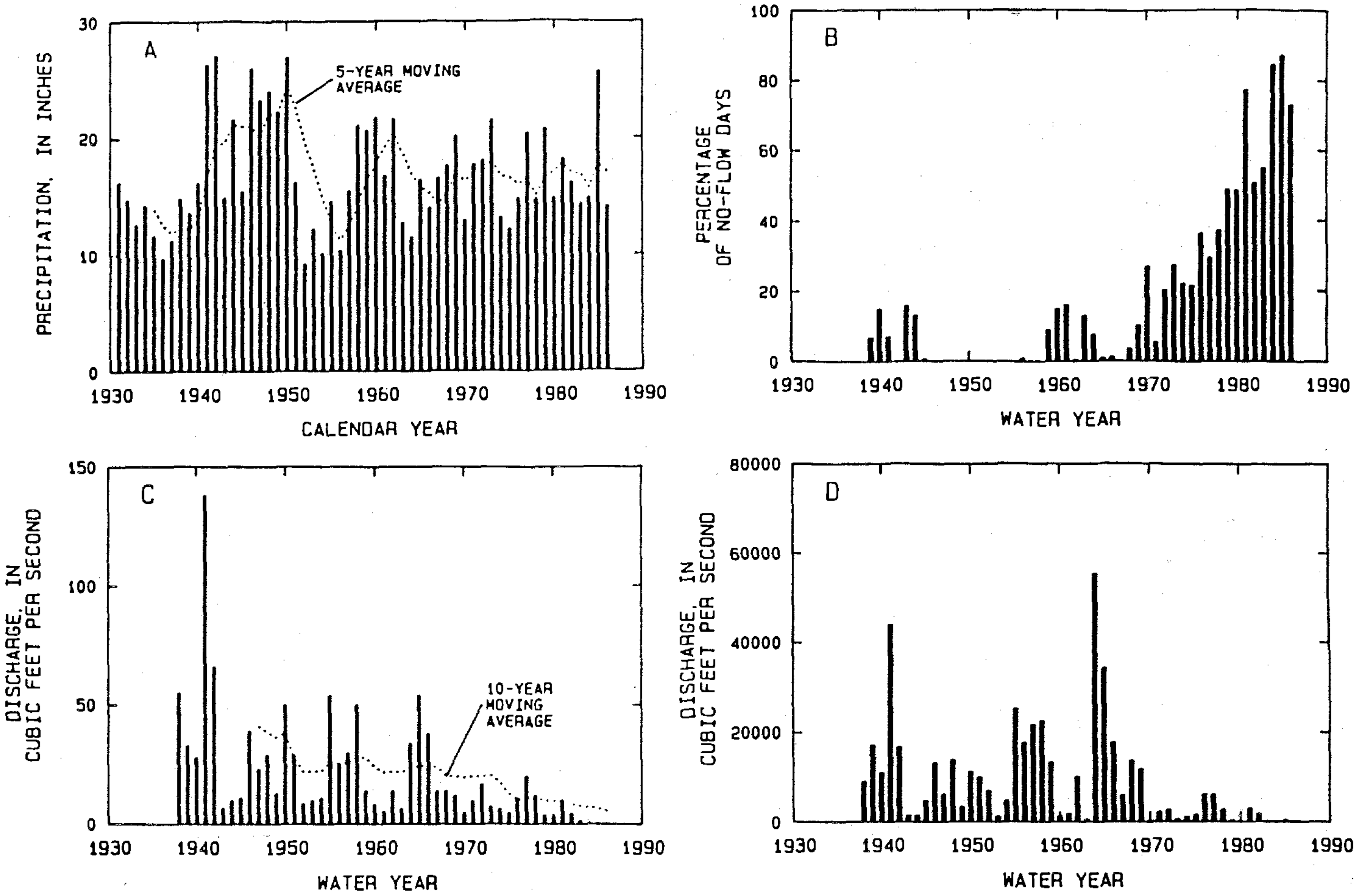

Figure 3. Relation with Time of: A) Annual Precipitation and 5-Year Moving Average at Goodwell, 1931-86; B) Percentage of No-Flow Days for the Beaver River near Guymon, Water Years 1939-86; C) Annual Average Discharge and 10-Year Moving Average for Beaver River near Guymon, Water Years 1938-86; and D) Annual Peak Discharges for the Beaver River near Guymon, Water Years 1938-86,

was done for flows of the Beaver River near Guymon. Because of strong evidence that changes were occurring in the flow sometime in the late 1960's, a recent period of record (water years 1978-86) was analyzed separately from an early period of record (water years 1944-62). (The computer program used requires the use of either 9, 19, 29, 39, or 49 years of data.) The median daily discharges resulting from that analysis are presented for each day of the year in Figure 4B. The median flows portrayed, while not necessarily equal to base flow, are indicative of base-flow conditions of the Beaver River during the two periods. Median discharges for water years 1944-62 were greater than zero for all days of the year, and generally exceeded 5 ft^3/s from about the first of November until about the first of June. Median daily discharges for the remaining months of the year were generally greater than 1 ft^3/s. By contrast, the median daily discharge during water years 1978-86 was zero for almost 6 months of the year, October through mid-December and mid-June through September; median daily flows during the remainder of the year rarely exceeded 3 ft^3/s and never exceeded 5 ft^3/s. The annual runoff represented by these median discharges is 3,810 acre-ft for water years 1944-62 and 530 acre-ft for water years 1978-86.

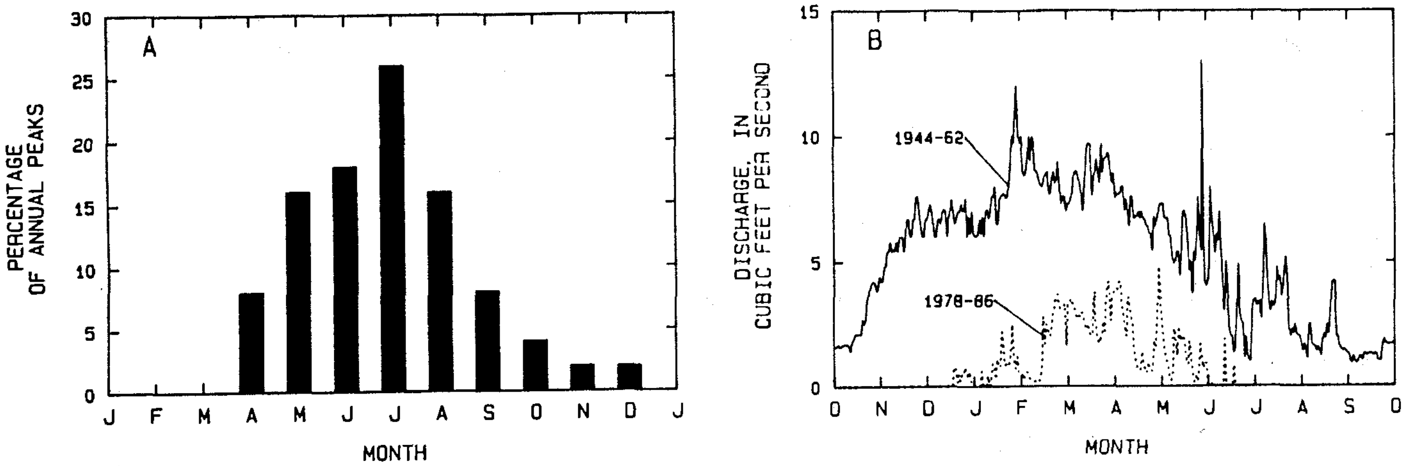

Figure 4. A) Distribution of Annual Peaks by Month for the Beaver River near Guymon, Water Years 1938-86; B) Comparison between Median Daily Mean Discharges for Water Years 1944-62 and 1978-86 for the Beaver River near Guymon.

Contributions to total streamflow from base flow also were analyzed using a method proposed by the Institute of Hydrology (1980a,b). The days of the water year are divided into 5-day increments and the minimum flow for each 5-day increment is identified. Minimums that are less than 111% (1/0.9) of adjacent minimums are labeled as turning points of the base-flow hydrograph. Straight lines are drawn between turning points (on semilogarithmic paper); the area beneath this line is an estimate of the volume of base-flow for the period. The ratio of this volume to the actual volume of streamflow for the period is defined as the base-flow index. A computer program was written and used to estimate the base flow for selected streams. The method may not yield the true base flow of the stream, but tests in Great Britain and Canada (Institute of Hydrology, 1980b, Swan and Condie, 1983) suggest that it yields consistent numbers that are indicative of the base flow of the stream. Although traditional methods of hydrograph separation may be more precise, they are tedious, time consuming, and are subjective, relying on the judgment of the analyst. The method used in this paper has the advantage that it is computer based, permitting many years to be evaluated, and the method is objective.

The average base flow of the Beaver River near Guymon for 28 years (water years 1938-65) was 2,700 acre-ft, and the average for 21 years (water years 1966-86) was 1,600 acre-ft. The average base flow for the last 10 years (water years 1977-86) was only 470 acre-ft; the range for the 10-year period is from 20 to 1,300 acre-ft. Prior to 1966, the computed range was from 1,300 to 5,100 acre-ft.

Table 1. Gaging Stations and Periods of Record Available for Analysis.

Gaging Station		Drainage Area (mi^2)		Period Available, Water Years
Number	Name	Total	Contributing	
07232500	Beaver River near Guymon, OK	2,139	1,175	1938-86
07233000	Coldwater Creek near Hardesty, OK	1,967	767	1940-64
07233500	Palo Duro Creek near Spearman, TX	960	440	1945-79
07234000	Beaver River at Beaver, OK	7,955	3,685	1938-78
07234100	Clear Creek near Elmwood, OK	170	170	1966-86

Although the focus of this analysis is on the Beaver River near Guymon, other streams in the study area also were analyzed. The gaging stations considered and the period of record evaluated are listed in Table 1. Tests for trend were conducted for annual average flow, annual base flow, and annual peak discharge on these stations; those tests are described in the next section. All the streams shown are underlain by the Ogallala Formation (Figure 1).

TESTS FOR TREND

Two related procedures were used in this paper to test for trends. A form of a procedure commonly called Kendall's tau (Kendall, 1938, 1975) was used to test for the presence of trends. In addition, a Kendall slope estimator (Sen, 1968) was used to estimate trend magnitude. The slope estimator was modified by Hirsch and others (1982) to allow its use to account for seasonality. The procedures are designed to identify whether monotonic changes are occurring with time and to estimate the rate of change. They are not intended for testing a hypothesis that a change occurred at a specific time. However, if such a change is suspected, the data for the entire period can be tested and, if a trend is detected, the data can be subdivided at the point the trend is believed to have begun. The individual periods can then be tested independently, assuming of course that the subdivided record lengths are sufficiently long to permit testing. Although the methods are exploratory, they can be used in this manner in combination with other techniques (such as graphical exploration) to test hypotheses of timing and cause. The power of the Kendall tau and the seasonal Kendall slope estimator is that they are nonparametric; they do not require that the test variable be normally distributed. The tests are relatively insensitive to the presence of individual outliers and are applicable even when the record under test has values missing.

Kendall's tau is determined in the following manner: Given a time series x_1, x_2, -------, x_n, of length n, the differences $d_{ij} = x_i - x_j$ are determined for $1 \leq j < i \leq n$. There are n(n-1)/2 of these differences. If P is the number of positive differences and N is the number of negative differences, then:

$$\text{tau} = (P - N) / [n(n-1)/2] \qquad (1)$$

If all differences are positive, tau = +1; if all the differences are negative, tau = -1. However, if the number of positive differences is equal to the number of negative differences (P = N), tau = 0. Tau is, therefore, a measure of the correlation between the series of x_i and time.

Slopes between individual pairs of x_i are computed as $d_{ij}/(i-j)$, and the Kendall slope estimator is defined as the median of the slopes. The slope estimator is based on the same set of differences as tau and, therefore, can be computed concurrently.

In application, the procedure tests the null hypothesis that the data are random samples that are identically distributed and not time dependent. Although the hypothesis is based on the assumption that the data are identically distributed, no assumption is required regarding the underlying distribution. If the test shows tau is not statistically different from 0, the null hypothesis is accepted, and the data are considered to be free from time trends. However, if tau is different from 0 at the specified probability level, the null hypothesis is rejected, and a time trend is confirmed; the sign of tau indicates the direction of the trend.

Results of the tests for trends are presented in Table 2 for selected stations in the study area. For purposes of this study, a trend was considered to be in evidence when the null hypothesis was rejected for a two-tailed test at the 98 percent confidence level (probability of 0.02). Where trends were indicated, an equation that describes the apparent trend is listed in Table 2. The equation is of the form

$$Q = A + St, \qquad (2)$$

where Q is discharge; S is the Kendall slope estimator; t is time, in years (t=0 at the first year of record); and A is a constant. In ordinary least-squares regression, A and S would be determined by minimizing the sum of squared deviations about the regression line. In this study, A is defined as the value that causes the equation to pass through the median value of Q at the midpoint of the time period. Although the equations presented are linear, the procedures do not test whether or not the trends are linear.

DISCUSSION OF RESULTS

The hypothesis was that changes have occurred in the flow of streams draining the Panhandle, and that those changes began to occur in about 1965; furthermore, these changes are not related to changes in precipitation. Trend tests for the annual precipitation at Goodwell for 1936-85 indicated that no trends had occurred. However, when the entire periods of record for both Beaver River gages were evaluated, both records showed that decreases had occurred in annual average discharge and in annual peak discharges. In addition, the data for Beaver River at Guymon (07232500) had a marked downward trend in base flow. The records were then re-analyzed using only those records collected before water year 1966. The null hypothesis could not be rejected (no trends were detected) for any of the three streamflow parameters for either gage. The record for the Beaver River near Guymon (07232500) was then re-evaluated using only water years 1966-86; this again indicated that all three streamflow parameters were decreasing. Records for the gage at Beaver (07234000) are affected by Optima Reservoir after water year 1978 and are, therefore, too short for analysis.

Records are available only before 1965 for Coldwater Creek near Hardesty (07233000). Trend tests of those records are in agreement with the hypothesis; no trends are evident in any of the three streamflow parameters tested.

The records for Clear ~~Water~~ Creek (07234100) are for water years 1966-88 and those for Palo Duro Creek (07233500) are for water years 1945-79. Based only on the period of record available, both would be expected to show trends. However, the record for neither gage shows a trend for any of the three streamflow parameters. Clear Water Creek drains an area where ground-water levels have declined less than 10 ft (Havens, 1983); therefore, any changes in flow have probably been minor. There is little evidence of hydraulic connection between Palo Duro Creek and the aquifer, even in the 1940's. The average base-flow index (ratio of base flow to total flow) for Palo Duro Creek is only about 0.06 whereas the base-flow indices for the other streams studied were greater than 0.16. Changes in ground-water discharge, therefore, would have less effect on Palo Duro Creek than on those streams with larger components of base flow. Also, the record of Palo Duro Creek extends only to 1979.

The link between declines in ground-water levels and both annual and base-flow is fairly obvious, but the relation between ground-water levels and annual peak discharges is not so clear. One possible explanation for the decrease in magnitude of annual peak discharges of the Beaver River is that changes in farming and conservation practices have affected peaks. However, less than 1 percent of the cropland acreage of Texas and Cimarron Counties is terraced. It is, therefore, improbable that terraces have produced significant decreases in direct runoff. The number of stock ponds in Cimarron and Texas Counties, Oklahoma, and Dallam and Sherman Counties, Texas, increased from about 100 in 1940 to almost 1,000 in 1985 (Boyle Engineering Corp., 1987, p.3-21). However, the rate of increase in number of ponds was greatest before 1960; only about 300 ponds were constructed during 1960-85. Although the stock ponds are normally small and are located in the headwater areas, they probably have affected the magnitude of peak discharges. The effects, however, should have been gradual and would have been reflected in discharges before 1965. The trend tests, however, provide no evidence of trends in the pre-1965 record.

Table 2. Summary of Results of Tests for Trend.

Station	Period Analyzed	Kendall Statistics			Trend*	Equation of Trend
		Slope	Tau	P*		
		Annual precipitation (in)				
Goodwell	1936-86	-0.004	-0.01	0.927	No	
		Average discharge (ft^3/s)				
07232500	1938-86	-0.62	-0.48	<0.001	Yes	27.5 - 0.62t
	1938-65	-0.44	-0.16	0.244	No	
	1966-86	-0.76	-0.62	<0.001	Yes	15.7 - 0.76t
07233000	1940-64	-0.25	-0.21	0.141	No	
07233500	1945-79	-0.17	-0.13	0.299	No	
07234000	1938-78	-1.98	-0.30	0.005	Yes	103.9 - 1.98t
	1938-65	-1.98	-0.16	0.228	No	
07234100	1966-86	-0.15	-0.29	0.075	No	
		Base flow (acre-ft)				
07232500	1938-86	-64.2	-0.43	<0.001	Yes	3,685 - 64.2t
	1938-65	-21.4	-0.08	0.588	No	
	1966-86	-194	-0.88	<0.001	Yes	3,324 - 194t
07233000	1940-64	+24.4	+0.13	0.388	No	
07233500	1945-79	- 4.70	-0.08	0.505	No	
07234000	1938-78	- 3.56	0.00	0.991	No	
	1938-65	+27.2	+0.04	0.802	No	
07234100	1966-86	-14.8	-0.12	0.450	No	
		Annual peak discharge (ft^3/s)				
07232500	1938-86	-216	-0.33	0.001	Yes	11,050 - 216t
	1938-65	+ 11.8	-0.01	0.957	No	
	1966-86	-350	-0.46	0.007	Yes	5,429 - 350t
07233000	1940-64	-262	-0.30	0.038	No	
07233500	1945-79	- 57.5	-0.15	0.186	No	
07234000	1938-78	-279	-0.25	<0.001	Yes	13,210 - 279t
	1938-65	-304	-0.25	0.060	No	
07234100	1966-84	-167	-0.30	0.064	No	

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*P is the computed probability level of tau. A trend is indicated (the null hypothesis is rejected) at the 98-percent confidence level if P is less than 0.02.

The possible effect of a dry channel on attenuation of peak discharges cannot be discounted. Figure 4 shows that in recent years the streambed has been dry during many days during June through December; traditionally, however, 75 percent of annual peaks have occurred during those months. An examination of flood peaks at Guymon for water years 1944-62 indicates that the median runoff from the annual peaks during the 19 years was about 3,000 acre-ft. The channel at Guymon is about 20 ft wide at low flow, and it is more than 100 mi, measured along the channel, from Guymon to the headwaters of the Beaver River. Durbin and Hardt (1974) noted that initial infiltration rates of 6 in/h were not uncommon in infiltration tests on initially dry material. They also noted that, during a controlled release of 3,100 acre-ft over 20 hours into the dry Mojave River channel in California, none of the flow passed a point 16 river miles downstream; the channel width averaged 200 to 300 ft. Assuming that 50 mi of the Beaver River channel was dry, that the width averaged only 20 ft, and that initial infiltration was 6 in/h, about 1,450 acre-ft/d could be lost to the channel bed. This infiltration loss, combined with channel storage, might be responsible for a substantial proportion of the decrease in peak discharge.

The flow of the Beaver River in the Oklahoma Panhandle has been decreasing since the mid 1960's. Tests for trend confirm that annual average flow, annual base flow, and annual peak discharges have all decreased. The river at Guymon now (1988) averages about 300 days per year without flow, but averaged less than 60 days per year prior to the mid-1960's. Precipitation records for Goodwell, however, show no such changes. The primary mechanism producing these decreased streamflows appears to be the large declines in water levels in the Ogallala Formation that underlies the basin.

The possible future effects of such changes in the interaction between ground water and the discharge of rivers can be seen by examining the history of Optima Reservoir, located on the Beaver River just downstream from Coldwater Creek. Construction of Optima Dam began in 1966; thus, all data available for planning and design was for the period before discharges began to decrease. Storage began in October 1978 after substantial decreases in discharge had occurred. The maximum storage in the reservoir to this time (1988) has been 7,610 acre-ft, only about 6 percent of the capacity of the conservation pool.

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