Trends in Precipitation and Streamflow and Changes in Stream Morphology in the Fountain Creek Watershed, Colorado, 1939–99

By Robert W. Stogner, Sr.

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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
inch	25.4	millimeters
inch per year (in/yr)	25.4	millimeters per year
mile	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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Abstract

The Fountain Creek watershed, located in and along the eastern slope of the Front Range section of the southern Rocky Mountains, drains approximately 930 square miles of parts of Teller, El Paso, and Pueblo Counties in eastern Colorado. Streamflow in the watershed is dominated by spring snowmelt runoff and storm runoff during the summer monsoon season. Flooding during the 1990's has resulted in increased streambank erosion. Property loss and damage associated with flooding and bank erosion has cost area residents, businesses, utilities, municipalities, and State and Federal agencies millions of dollars. Precipitation (4 stations) and streamflow (6 stations) data, aerial photographs, and channel reconnaissance were used to evaluate trends in precipitation and streamflow and changes in channel morphology. Trends were evaluated for pre-1977, post-1976, and period-of-record time periods.

Analysis revealed the lack of trend in total annual and seasonal precipitation during the pre-1977 time period. In general, the analysis also revealed the lack of trend in seasonal precipitation for all except the spring season during the post-1976 time period. Trend analysis revealed a significant upward trend in long-term (period of record) total annual and spring precipitation data, apparently due to a change in total annual precipitation throughout the Fountain Creek watershed. During the pre-1977 time period, precipitation was generally below average; during the post-1976 time period, total annual precipitation was generally above average. During the post-1976 time period, an upward trend in total annual and spring precipitation was indicated at two stations. Because two of four stations evaluated had upward trends for the post-1976 period and storms that produce the most precipitation are isolated convection storms, it is plausible that other parts of the watershed had upward precipitation trends that could affect trends in streamflow. Also, because of the isolated nature of convection storms that hit some areas of the watershed and not others, it is difficult to draw strong conclusions on relations between streamflow and precipitation.

Trends in annual instantaneous peak streamflow, 70th percentile, 90th percentile, maximum daily-mean streamflow (100th percentile), 7-, 14-, and 30-day high daily-mean streamflow duration, minimum daily-mean streamflow (0th percentile), 10th percentile, 30th percentile, and 7-, 14-, 30-day low daily-mean streamflow duration were evaluated. In general, instantaneous peak streamflow has not changed significantly at most of the stations evaluated. Trend analysis revealed the lack of a significant upward trend in streamflow at all stations for the pre-1977 time period. Trend tests indicated a significant upward trend in high and low daily-mean streamflow statistics for the post-1976 period. Upward trends in high daily-mean streamflow statistics may be an indication that changes in land use within the watershed have increased the rate and magnitude of runoff. Upward trends in low daily-mean

streamflow statistics may be related to changes in water use and management. An analysis of the relation between streamflow and precipitation indicated that changes in water management have had a marked effect on streamflow.

Observable change in channel morphology and changes in distribution and density of vegetation varied with magnitude, duration, and frequency of large streamflow events, and increases in the magnitude and duration of low streamflows. Although more subtle, low streamflows were an important component of day-to-day channel erosion. Substantial changes in channel morphology were most often associated with infrequent large or catastrophic streamflow events that erode streambed and banks, alter stream course, and deposit large amounts of sediment in the flood plain.

INTRODUCTION

The Fountain Creek watershed, in and along the eastern slope of the Front Range section of the southern Rocky Mountains, drains approximately 930 mi^2 of parts of Teller, El Paso, and Pueblo Counties in eastern Colorado (fig. 1). Land-surface elevation varies from 14,110 ft at the summit of Pike's Peak to 4,640 ft at the confluence of Fountain Creek and the Arkansas River.

Over the past several years, landowners, farmers, resource managers, municipal, county, local, and Federal agencies have expressed concern that possible increases in streamflow have adversely affected channel stability, resulting in substantial bank erosion along Fountain Creek. Bank erosion has resulted in property losses and damage to roads, bridges, and other structures along the creek. Damages associated with floods are costing property owners and local and State governments millions of dollars to reclaim, replace, and (or) repair affected property and structures (National Oceanographic and Atmospheric Administration, 1999).

In 1999, the U.S. Geological Survey (USGS), in cooperation with the Turkey Creek Soil Conservation District, El Paso County Soil Conservation District, Central Colorado Soil Conservation District, and Pueblo County, began a study to evaluate precipitation and streamflow trends and changes in stream morphology in the Fountain Creek watershed.

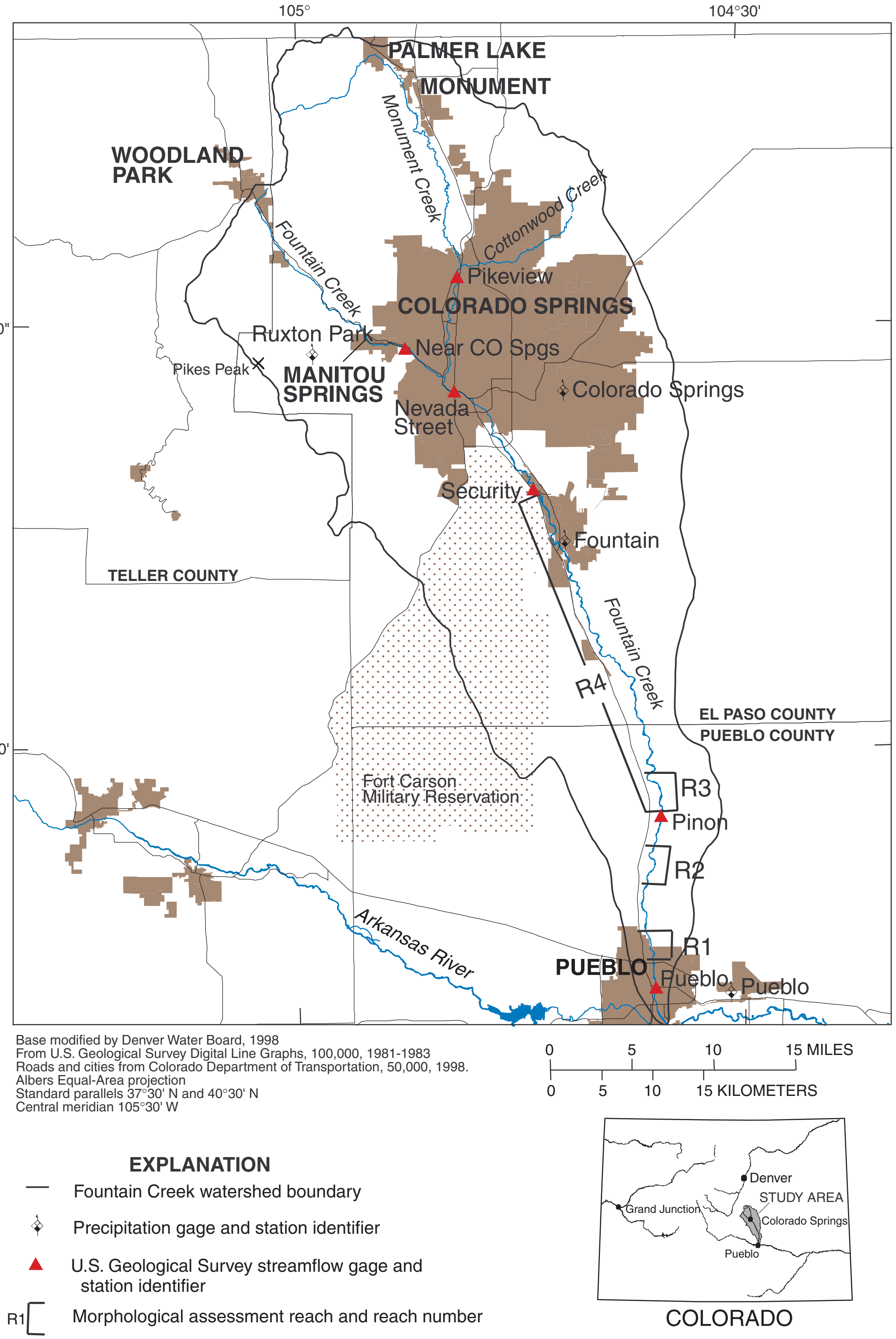
Purpose and Scope

This report describes trends in precipitation and trends in streamflow in the Fountain Creek watershed and presents a qualitative assessment of changes in channel morphology of selected reaches of Fountain Creek downstream from Colorado Springs, Colorado. Trends in precipitation were evaluated for four stations in or near the Fountain Creek drainage basin for the period of record (fig. 1, table 1). Selection of these stations was based on length of record and location in or near the Fountain Creek watershed. Trends in streamflow were evaluated for the period of record at six streamflow-gaging stations (fig. 1, table 2). The six streamflow-gaging stations were selected on the basis of length of streamflow record and location. The length of continuous record varied from 23 to 40 years. In addition to continuous record, several stations had historical data, pre-dating the period of continuous record, which also were included in the evaluation of trends in streamflow. Changes in channel morphology were evaluated using aerial photographs of Fountain Creek downstream from Colorado Springs taken between 1947 and 1999 and field reconnaissance during 1999.

For the purpose of this study, the existence or lack of trend was determined by the reported significance level as determined by the statistical test used. Statistical significance was defined as highly significant, significant, and moderately significant, with corresponding p-values of less than 0.01, 0.05, and 0.1, respectively. A nonsignificant trend was indicated when the p-value was greater than 0.1. The estimated slope of the trend, or rate of change per unit time (trend slope estimate), was compared to trend slope estimates of other stations.

Approach

Daily, seasonal, and annual precipitation data from four stations in and near the Fountain Creek watershed (fig. 1) were used to evaluate spatial and temporal variations and trends in precipitation. Annual precipitation statistics were computed for each water year. A water year extends from October 1 through September 30 of the following year and is identified by the year in which it ends. Complete streamflow records at some stations were not available until 1977; therefore, precipitation data were divided into pre-1977 and post-1976 time periods to (1) evaluate



Base modified by Denver Water Board, 1998
From U.S. Geological Survey Digital Line Graphs, 100,000, 1981-1983
Roads and cities from Colorado Department of Transportation, 50,000, 1998.
Albers Equal-Area projection
Standard parallels 37°30' N and 40°30' N
Central meridian 105°30' W

Figure 1. Location of Fountain Creek watershed, streamflow and precipitation monitoring stations, and river reaches.

Table 1. Precipitation stations in and near the Fountain Creek watershed and period of record

[AP, airport; WSO, Weather Service Office; mm, month; yy, year]

Colorado Climate Center station number	Station name	Station identifier used in this report	Period of record mm/yy to mm/yy	Elevation above sea level (in feet)
51778	Colorado Springs WSO	Colorado Springs	08/48 to 09/99	6,170
53063	Fountain	Fountain	08/48 to 09/97	5,550
56704	Pueblo WSO AP	Pueblo	07/54 to 09/99	4,640
57309	Ruxton Park	Ruxton Park	09/59 to 09/99	9,050

Table 2. Streamflow-gaging stations with 23 or more years of continuous record, period of record for each station, and drainage area

[mi^2, square miles; mm, month; yy, year]

U.S. Geological Survey station number	Station name	Station identifier used in this report	Period of record (mm/yy to mm/yy)	Drainage area (mi^2)
07104000	Monument Creek at Pikeview, CO	Pikeview	10/38 to 09/49, 01/76 to 09/99	204
07103700	Fountain Creek near Colorado Springs, CO	Near CO Spgs	04/58 to 09/99	103
07105500	Fountain Creek at Nevada Street at Colorado Springs, CO	Nevada Street	10/21 to 09/24, 01/76 to 09/99	392
07105800	Fountain Creek at Security, CO	Security	10/64 to 09/99	495
07106300	Fountain Creek at Pinon, CO	Pinon	04/73 to 09/99	849
07106500	Fountain Creek at Pueblo, CO	Pueblo	01/22 to 09/25, 10/40 to 09/65, 02/71 to 09/99	926

whether changes in precipitation occurred within or between these two time periods, and (2) make general comparisons between trends in precipitation and trends in streamflow. Kendall trend and Wilcoxon rank sum tests were used to evaluate temporal trends for the period of record and compare precipitation characteristics for pre-1977 and post-1976 periods. The Kendall trend test is a nonparametric test used to evaluate the significance of a monotonic trend in a variable over time; a monotonic trend exists if variable x generally increases or decreases as variable y (time) increases (Helsel and Hirsch, 1995). It was used to evaluate trends in total annual precipitation for the period of record and for the pre-1977 and post-1976 time periods. The Wilcoxon rank sum test is also a nonparametric test and is used to compare the distribution of two populations (Ott, 1993). In this report, the Wilcoxon rank sum test was used to compare total annual and seasonal precipitation during the pre-1977 period to total annual and seasonal precipitation during the post-1976 period. In addition, precipitation data were evaluated to determine long-term mean, annual departure from mean, and cumulative departure from mean.

Streamflow at gaging stations is computed after developing the relation of stage to streamflow for a particular location (Buchanan and Somers, 1968; Carter and Davidian, 1968; Kennedy, 1983, 1984). At a typical USGS streamflow-gaging station, stream stage, or the level of water in the stream, is recorded at periodic intervals. Based on the defined relation between stage and streamflow, recorded stream stage is converted to streamflow.

Trends in streamflow were evaluated using the Kendall trend test. Streamflow data from six gaging stations in the Fountain Creek watershed (table 1, fig. 1) were evaluated for trends in the following streamflow statistics: annual instantaneous peak streamflow; annual maximum (100th percentile), 90th, 70th, 30th, 10th, and annual minimum (0th percentile) daily-mean streamflow; and annual 7-, 14-, and 30-day high daily-mean streamflow duration and annual 7-, 14-, and 30-day low daily-mean streamflow duration. The annual instantaneous peak streamflows were derived from the single highest recorded stream stage during a given water year. Daily-mean streamflow was computed by averaging all the periodic computed instantaneous streamflows over a day. Mean-daily streamflow was computed by averaging daily-mean streamflow for days of consecutive years of data (for example, October 1, 1978, October 1, 1979, and so on). Annual streamflow statistics were computed by sorting and ranking the daily-mean streamflows. The annual minimum (0th percentile) equals the minimum computed daily-mean streamflow during a year; the annual maximum (100th percentile) equals the maximum computed daily-mean streamflow during a year. Intermediate percentiles, 10th, 30th, 70th, and 90th, are equivalent to the 36th, 109th, 255th, and 328th annual daily-mean streamflow values when sorted from smallest to largest. The *n*-percentile indicates that *n* percent of the annual daily-mean streamflow is below a given streamflow, or (100 minus *n*) percent is above it. The 7-, 14-, and 30-day high and low daily-mean streamflow duration statistics were computed by averaging daily mean streamflow for 7, 14, and 30 consecutive days. This procedure, termed moving average (Helsel and Hirsch, 1995), was used for every day of the water year, meaning that, the average daily-mean streamflow for 7, 14, and 30 consecutive days was computed for October 1st, and then for October 2d, 3d, and so on.

Time periods for the streamflow trend analyses varied because of differences in data requirements and availability for some of the various streamflow statistics evaluated. Trends in annual instantaneous peak streamflow were evaluated for the period of record at each station and for pre-1976 and post-1975 time periods. This break point was selected because some stations were not operational until January of 1976 and annual instantaneous peak streamflow data were not available until the spring of 1976. Computation of streamflow percentiles and streamflow-duration statistics required continuous annual record; therefore, trend analyses of streamflow percentiles and flow duration were evaluated for respective periods of continuous record at each station and for pre-1977 and post-1976 time periods. Annual streamflow statistics were computed for each water year.

Spatial trends in selected streamflow statistics were evaluated for the post-1976 time period. Differences in streamflow for five river reaches were normalized by the contributing drainage area. Evaluation of trends in normalized differences in high daily-mean streamflow statistics identify reaches within which hydrologic responses (such as rainfall runoff) may be different, may have changed as a result of changes in precipitation, or may have been altered as a result of human activities. Human activities that may alter the hydrologic response of a reach include changing land use from natural, pervious or semi-pervious surface to an impervious surface; changing vegetative cover; or concentrating and (or) rerouting surface runoff by constructing storm drains. Additionally, evaluation of trends in normalized differences in low streamflow statistics provide information related to changes in water management such as changes in discharge from wastewater-treatment plants, changes in irrigation return flows, and changes in tributary flow that occur within the stream reaches.

The relation between streamflow and precipitation was evaluated using a double-mass curve (Searcy and Hardison, 1960). In a double-mass curve, the cumulation of one variable plotted against the cumulation of another variable will result in a straight line so long as the data are proportional (Searcy and Hardison, 1960). A change in the slope of the double-mass curve indicates that the relation between the two variables has changed. This analysis compared cumulative average daily precipitation from four precipitation gages to cumulative daily-mean streamflow at the Pueblo station (fig. 1). The average precipitation was used to smooth out spatial variation in precipitation.

Aerial photography from different time periods, field reconnaissance, and topographic maps were used to determine geomorphic characteristics and evaluate changes in channel morphology along selected reaches of Fountain Creek (fig. 1). Periodic aerial photographs were used to characterize flood-plain vegetation patterns, estimate channel width, and determine channel location and sinuosity. This information was used to relate large streamflow events to changes in flood-plain characteristics and channel location as a result of streambed and bank erosion. Photographs selected for the analysis of changes in channel morphology were taken in 1947, 1955, 1965, 1970, 1980, 1991, and 1999.

Field reconnaissance was used to characterize erosion patterns, which may be causing the changes observed in channel location and flood-plain vegetation characteristics. Field reconnaissance was conducted during April and May of 1999, prior to and during the 1999 flood, and during September and October 1999, when streambanks were visible.

DESCRIPTION OF STUDY AREA AND GENERAL LAND USE

Land use within the Fountain Creek watershed includes forests, urban areas, military reservations, agriculture, and rangeland. Forested lands are located predominantly in the northwestern mountainous part of the watershed. The major urban center in the watershed is the Colorado Springs metropolitan area that includes Colorado Springs and several smaller communities in El Paso County. This metropolitan area is located in the north-central part of the watershed. Of the three counties encompassing the watershed, El Paso County had the greatest economic growth and population increase (fig. 2). Between 1890 and 1950, the population of Pueblo and El Paso Counties increased at similar rates of about 900 people per year. Between 1950 and 1990, the population of El Paso County increased at a rate of about 8,000 people per year. Population projections for the year 2000 indicate this rate has increased to about 11,000 people per year during the 1990’s. Between 1960 and 1990, population growth in Pueblo County was relatively flat. Population projections for the year 2000 indicate the rate of growth during the 1990’s has increased to about 1,600 people per year. From 1900 through 1930, the population of Teller County decreased at an annual rate of about 600 people per year. The population of Teller County increased during the 1930’s, but declined during the 1940’s and 1950’s. Since 1970, the population of Teller County has increased at a rate of about 300 people per year. This information is available at http://www.ancestry.com/free/censtats/cocens.htm (accessed 07/18/00). A small portion of the watershed at and upstream from the confluence of Fountain Creek and the Arkansas River is within the urban area of the city of Pueblo. Agriculture and rangeland are located predominantly south and east of Colorado Springs. Agriculture is common along the alluvial valley from Fountain to Pueblo and relies heavily on water diverted from Fountain Creek. A large expanse of rangeland is included within the boundaries of the military reservation at Fort Carson located just south of Colorado Springs, west of Interstate 25 and Fountain Creek to just northwest of Pueblo (fig. 1).

PRECIPITATION

Analysis of spatial distribution and temporal trends in precipitation is constrained by the sparse distribution of long-term precipitation-monitoring stations in the watershed. Variations in the frequency of daily precipitation, seasonal distribution, seasonal and annual precipitation at four stations were evaluated. Seasonal and annual precipitation data were evaluated for the entire period of record to evaluate long-term trends and were divided into pre-1977 and post-1976 time periods to be consistent with existing streamflow record.

General Precipitation Characteristics

Climate within the watershed is broadly characterized as semiarid temperate continental. However, it can vary from alpine arctic to semiarid, depending on elevation and proximity to the Front Range (Hansen and others, 1978). Depending on the precipitation station, between about 40 and 60 percent of daily precipitation that occurs is 0.1 inch or less in magnitude. Between about 70 and 80 percent of daily precipitation that occurs in the region is less than or equal to 0.25 inch (table 3). Daily precipitation of magnitude 0.25 inch or greater occurs most frequently between July and September (table 4). Of the total number of daily precipitation events that occurred during July through September, between 25.2 and 34.1 percent were greater than 0.25 inch in magnitude. Many of the precipitation events during the summer are convection storms driven by the inflow of monsoon moisture from the southwest (Giannasca, 1999). Convection storms are generally strong, isolated events that occur during the late afternoon and early evening.

Annual precipitation generally decreases with distance from the headwaters of the watershed and as elevation decreases. The Ruxton Park station (fig. 1) receives more precipitation than the Colorado Springs station. Total annual precipitation at the Colorado Springs station (fig. 3) generally is equivalent to total annual precipitation at the Fountain station (fig. 4).

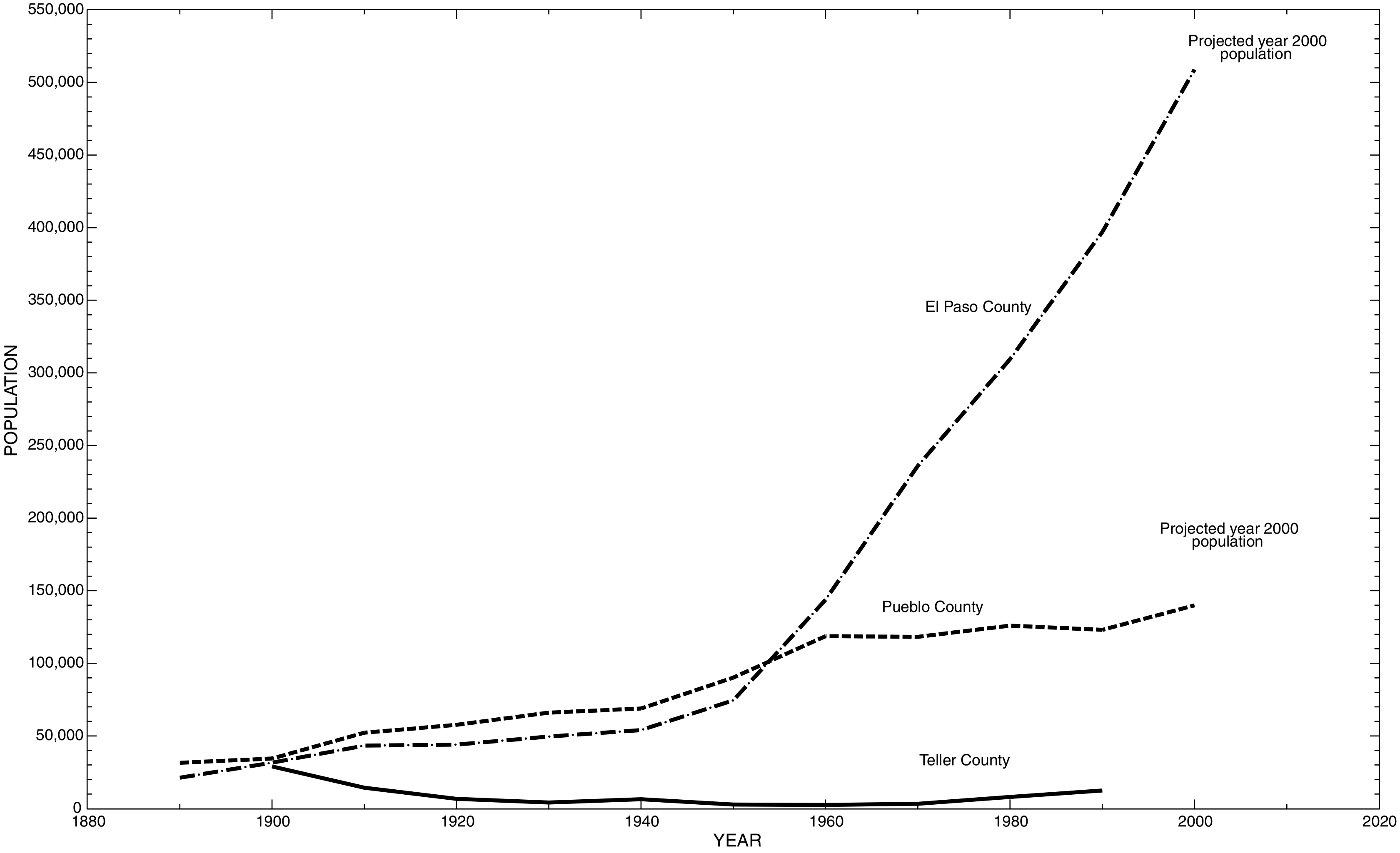


Figure 2. Population of El Paso, Pueblo, and Teller Counties, 1890–1990, with projected year 2000 population.

Table 3. Range in magnitude of daily precipitation at precipitation-monitoring stations in and near the Fountain Creek watershed

Magnitude	Colorado Springs	Fountain	Pueblo	Ruxton Park
	Precipitation monitoring station name			
	Percentage of daily precipitation values less than or equal to indicated magnitude			
0.10	57.2	42.9	57.5	40.6
0.25	78.7	69.0	79.1	70.7
0.50	90.9	86.4	91.9	87.6
0.75	95.3	92.6	95.6	94.1
1.00	97.3	95.7	98.3	96.8
2.00	99.5	99.3	99.8	99.4
3.00	99.9	99.8	100.0	99.9
4.00	100.0	99.9	100.0	100.0
5.00	100.0	100.0	100.0	100.0
6.00	100.0	100.0	100.0	100.0

Table 4. Seasonal distribution of daily precipitation of indicated magnitude at precipitation-monitoring stations in and near the Fountain Creek watershed

[≤, less than or equal to; >, greater than]

Magnitude (inches)	October–March		April–June		July–September	
	Number of events during period of record	Percentage of events	Number of events during period of record	Percentage of events	Number of events during period of record	Percentage of events
			Colorado Springs			
≤0.25	1,342	29.2	736	16.0	1,535	33.4
>0.25	176	3.8	264	5.8	540	11.8
			Fountain			
≤0.25	688	22.4	658	21.4	819	26.7
>0.25	165	5.4	316	10.3	424	13.8
			Pueblo			
≤0.25	1,005	31.8	709	22.4	809	25.6
>0.25	156	4.9	209	6.6	273	8.6
			Ruxton Park			
≤0.25	1,071	25.7	785	18.9	1,084	26.1
>0.25	315	7.6	386	9.3	520	12.5

Total annual precipitation at the Colorado Springs and Fountain stations generally are greater than total annual precipitation at the Pueblo station.

During the respective periods of record, recorded annual precipitation was variable from year to year at all stations (figs. 3 and 4). The Ruxton Park station consistently received the most precipitation annually, reporting a mean annual precipitation of 24.5 inches. The reporting station at the Pueblo station received the least rainfall annually, reporting a mean annual precipitation of 11.9 inches.

Temporal Trends in Precipitation

Temporal changes in precipitation characteristics were analyzed. The analysis revealed no appreciable difference in the percentage of days with precipitation greater than or equal to 0.01 inch (table 5) during the post-1976 time period compared to the pre-1977 time period. Differences in the frequency distribution of daily precipitation between the pre-1977 and post-1976 time periods compared to the entire period of record were slight (fig. 5).

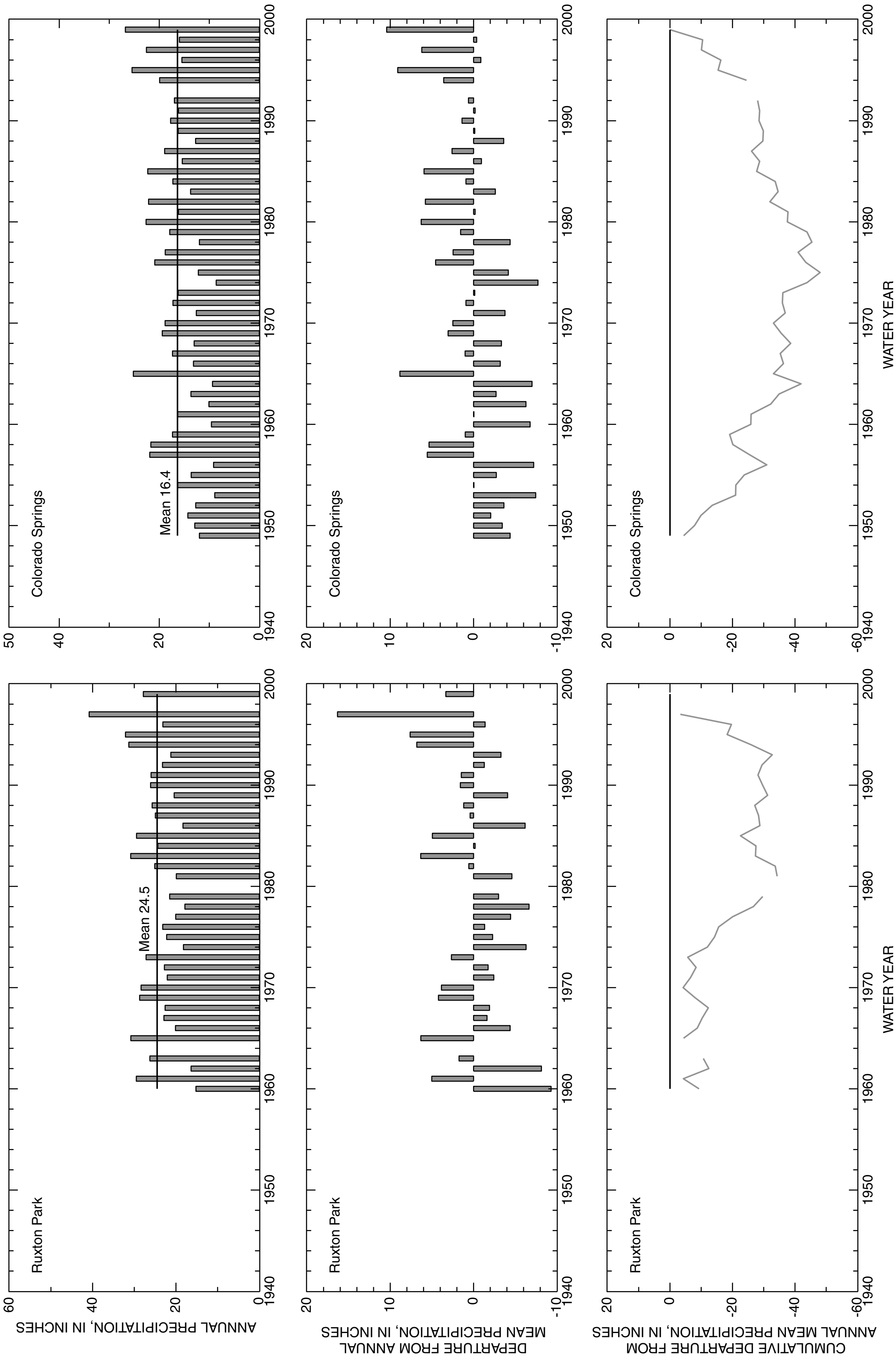


Figure 3. Annual precipitation, departure from annual mean precipitation, and cumulative departures from annual mean precipitation at Ruxton Park and Colorado Springs.

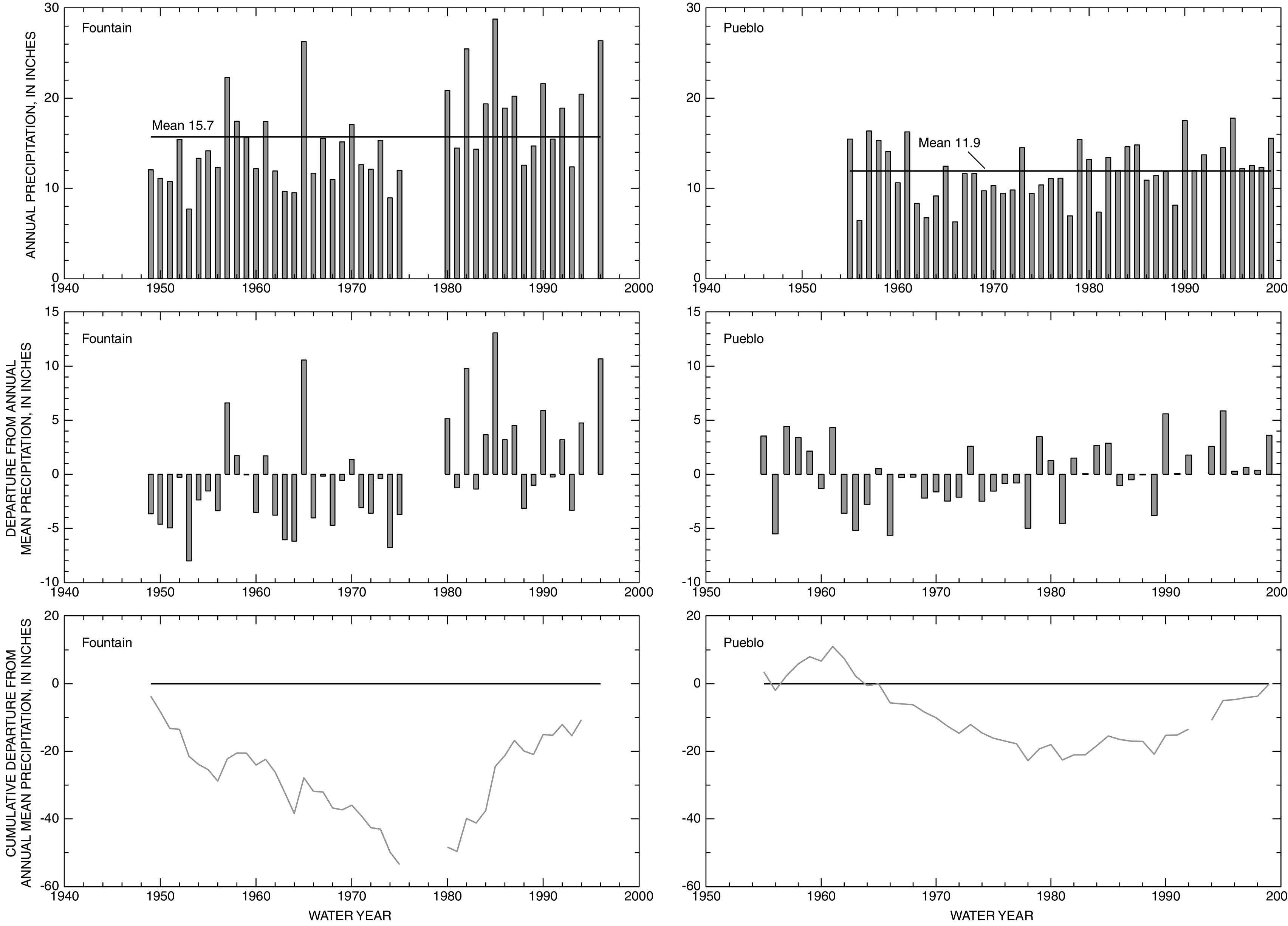


Figure 4. Annual precipitation, departure from annual mean precipitation, and cumulative departures from annual mean precipitation at Fountain and Pueblo.

Table 5. Frequency of receiving precipitation of 0.01 inch or greater during a 24-hour period at locations in the Fountain Creek watershed for water year 1960 through the end of record, 1960 through water year 1976 and 1977 through the end of record

[<, less than; ≥, greater than or equal to]

Precipitation	Colorado Springs		Fountain		Pueblo		Ruxton Park	
	Number of precipitation events	Percentage of the total number of precipitation events	Number of precipitation events	Percentage of the total number of precipitation events	Number of precipitation events	Percentage of the total number of precipitation events	Number of precipitation events	Percentage of the total number of precipitation events
Water year 1960–end of record								
<0.01	10,237	74	10,903	79	11,051	80	9,797	71
≥0.01	3,451	25	2,334	17	2,615	19	4,003	29
Missing	191	1	642	5	213	2	79	1
Water years 1960–76								
<0.01	4,741	76	5,124	83	5,078	82	4,449	72
≥0.01	1,465	24	949	15	1,132	18	1,749	28
Missing	4	0	137	2	0	0	12	0
1977–end of record								
<0.01	6,047	72	5,779	75	6,543	78	5,861	70
≥0.01	2,167	26	1,385	18	1,643	20	2,420	29
Missing	187	2	505	7	213	2	119	1

Trend estimates for the period of record were computed for all stations (fig. 6). Trend tests indicated statistically significant ($p < 0.05$) upward trends in total annual precipitation over the total period of record at the Colorado Springs and Fountain stations (fig. 6, table 6), and moderately significant upward trends in total annual precipitation at the Ruxton Park and Pueblo stations (fig. 6, table 6).

Trend analysis was also done on the precipitation data for the pre-1977 and post-1976 time periods. During the pre-1977 period, all stations generally recorded below-average total annual precipitation and cumulative departures from the mean annual precipitation generally were increasingly negative (figs. 3 and 4). During the post-1976 period, all stations generally recorded above-average total annual precipitation (figs. 3 and 4). Kendall trend analysis revealed no significant trends in total annual precipitation at any station for the pre-1977 time period, and the Colorado Springs and Fountain stations for the post-76 time period. Kendall trend analysis revealed a moderately significant upward trend at the Pueblo station, and significant upward trend in total annual precipitation at the Ruxton Park station for the post-1976 period (fig. 6, table 6). The indication of significant trends at some stations and not others is probably a result of storms that hit some areas but not others, which makes it difficult to draw strong conclusions on relations between precipitation and streamflow at different stations.

Daily precipitation data were divided into seasons to evaluate seasonal trends; October to December – fall, January to March – winter, April to June – spring, and July to September – summer. With the exception of summer precipitation for the period 1949 – 97 at the Fountain station ($p = 0.0018$), trend test revealed no significant trend in seasonal precipitation during the fall, winter, and summer for the period of record, the pre-1977 period, or the post-1976 period. Kendall trend tests revealed highly significant to significant upward trends in spring precipitation at the Ruxton Park, Colorado Springs, and Pueblo stations for the period of record and moderately significant trends in spring precipitation at the Ruxton Park and Pueblo stations in the post-1976 time period (table 7). Trends in annual precipitation at the Ruxton Park and Pueblo stations (table 6) are a function of trends in springtime precipitation.

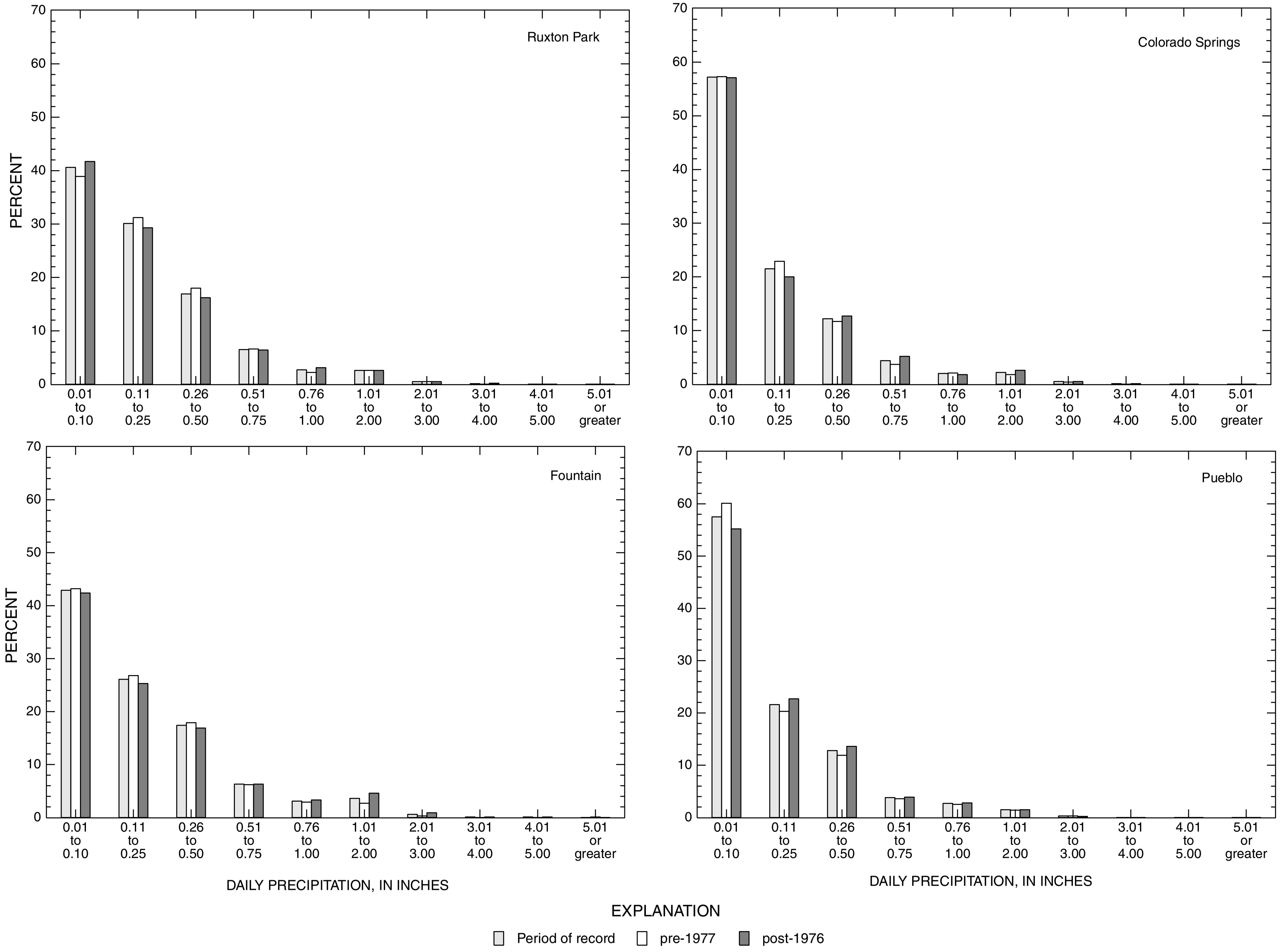


Figure 5. Distribution of precipitation at stations in and near the Fountain Creek watershed for period of record, pre-1977, and post-1976 time periods.

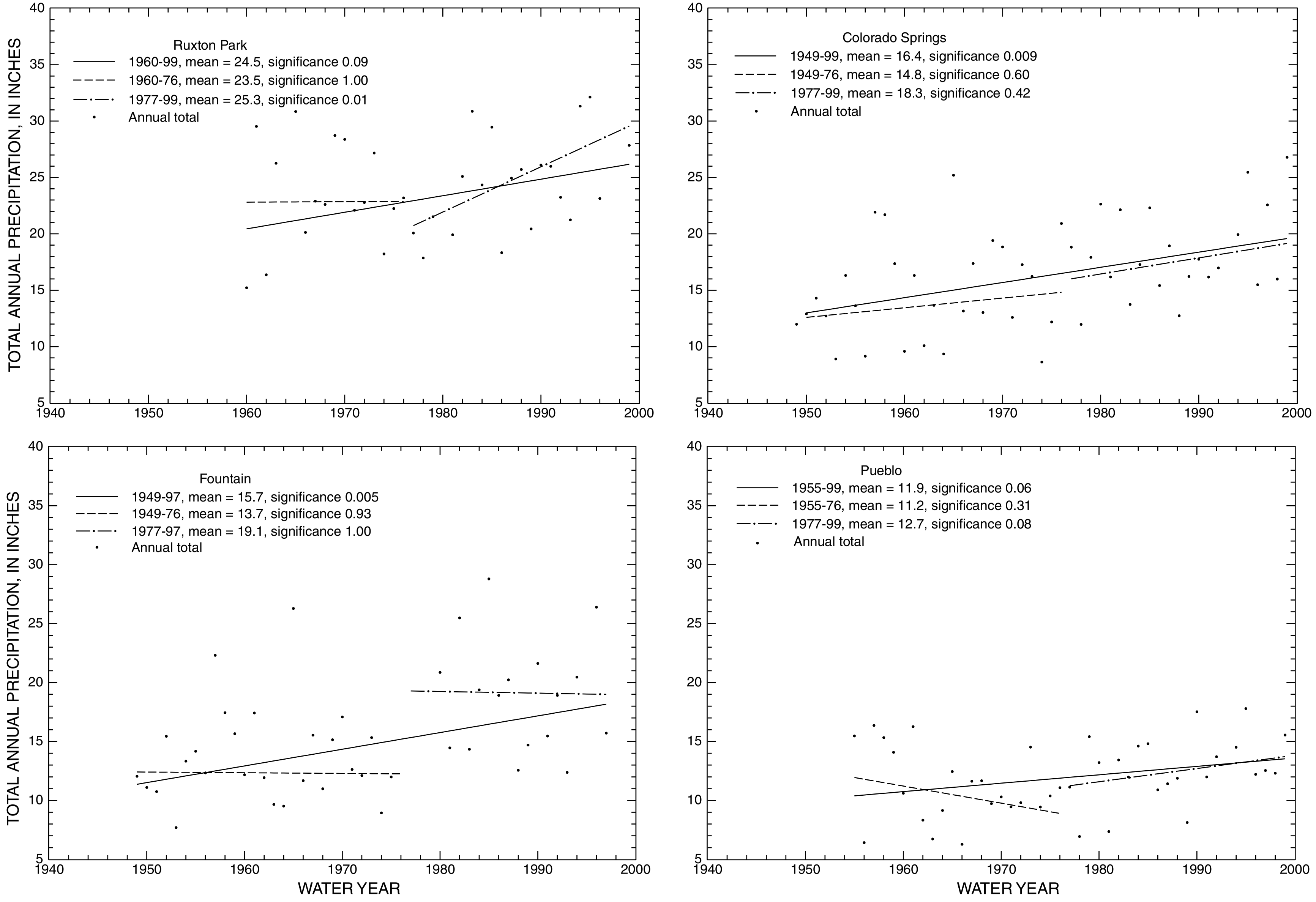


Figure 6. Total annual precipitation with estimated trend line for the period prior to 1977, 1977 to 1999, and period of record.

Table 6. Kendall trend analysis of annual precipitation for the period of record, and pre-1977 and post-1976 time periods

[Shaded p-value indicates period with significant trend; see table 1, fig. 1 for station location]

Station identifier	Time period	Time period (water years)	Kendall tau	Two-side p-value	Trend slope (inches/year)
Colorado Springs	Pre-1977	1950–76	0.07	0.6022	0.0855
	Post-1976	1977–99	0.13	0.4298	0.1429
	Period of record	1950–99	0.26	0.0086	0.1346
Fountain	Pre-1977	1949–76	–0.01	0.9335	–0.0058
	Post-1976	1977–97	–0.01	1.0000	–0.0143
	Period of record	1949–97	0.30	0.0049	0.1415
Pueblo	Pre-1977	1955–76	–0.16	0.3100	–0.1450
	Post-1976	1977–99	0.27	0.0804	0.1120
	Period of record	1955–99	0.20	0.0613	0.0714
Ruxton Park	Pre-1977	1960–76	0.00	1.0000	0.0041
	Post-1976	1977–99	0.39	0.0144	0.4012
	Period of record	1960–99	0.20	0.0916	0.1468

Table 7. Summary of Kendall trend analysis of spring precipitation

[Shaded p-value indicates period with significant trend; see table 1, fig. 1 for location]

Station identifier	Time period	Time period (water year)	Kendall tau	Two-side p-value	Trend slope (inches/year)
Colorado Springs	Pre-1977	1950–76	0.07	0.6168	0.0257
	Post-1976	1977–99	0.04	0.8215	0.0277
	Period of record	1950–99	0.22	0.0279	0.0596
Fountain	Pre-1977	1949–76	–0.08	0.5878	–0.0336
	Post-1976	1977–97	0.06	0.7619	0.0700
	Period of record	1949–97	0.16	0.1175	0.0312
Pueblo	Pre-1977	1955–76	–0.14	0.3819	–0.0500
	Post-1976	1977–99	0.28	0.0711	0.0693
	Period of record	1955–99	0.22	0.0354	0.0376
Ruxton Park	Pre-1977	1960–76	0.24	0.2016	0.1478
	Post-1976	1977–99	0.27	0.0907	0.1329
	Period of record	1960–99	0.32	0.0047	0.1000

The Wilcoxon rank-sum test was used to evaluate whether the mean precipitation during the periods prior to 1977 and after 1976 were different. The Wilcoxon rank-sum test revealed moderately significant differences in mean precipitation between the two periods at the Pueblo station and highly significant differences between the two periods at the Colorado Springs and Fountain stations (table 8). This test also indicated no significant differences in mean precipitation between the two periods at the Ruxton Park station. Although tests revealed differences in the mean precipitation for the periods prior to and since the mid-1970's, the distribution in the magnitude of precipitation events during these time periods was similar (fig. 5). Therefore, differences between the two periods are not a result of more rain during any given day but more days with "typical" rainfall.

The Wilcoxon rank-sum test was also used to evaluate differences in seasonal precipitation during the pre-1977 and post-1976 periods. The Wilcoxon rank-sum test revealed no significant differences between mean precipitation during the fall, winter, and summer seasons, except for summer precipitation at the Fountain station. The Wilcoxon rank-sum test

Table 8. Wilcoxon rank sum test of differences between mean annual precipitation during the pre-1977 and post-1976 time periods

[Shaded values indicate significant differences in mean precipitation between the pre-1977 and post-1976 time periods; N, number of complete years of record in period]

Station identifier	Time period	Time period (water years)	N	Mean score	p-value
Colorado Springs	Pre-1977	1950–76	28	20.7	0.0083
	Post-1976	1977–99	22	31.7	
Fountain	Pre-1977	1949–76	27	16.9	0.0006
	Post-1976	1977–97	16	30.6	
Pueblo	Pre-1977	1955–76	22	18.9	0.0620
	Post-1976	1977–99	22	26.1	
Ruxton Park	Pre-1977	1960–76	16	17.5	0.4713
	Post-1976	1977–99	21	20.1	

revealed highly significant differences in summer precipitation at the Fountain station (p = 0.0048) between the pre-1977 and post-1976 periods. The Wilcoxon rank-sum test also revealed significant differences in spring precipitation between the pre-1977 and post-1976 periods at the Fountain (p = 0.0454) and Ruxton Park (p = 0.0459) stations, and moderately significant differences at the Colorado Springs (p = 0.0622) and Pueblo stations (p = 0.0747).

Synthesis of Precipitation Analysis

Precipitation data from four stations were used to characterize and evaluate changes and trends in precipitation in the Fountain Creek watershed. Trend analysis revealed significant increases in annual precipitation at the Colorado Springs and Fountain stations since the late 1940's and moderate increases at Ruxton Park and Pueblo stations since the mid- to late 1950's. An analysis of the pre-1977 period indicates that annual precipitation was generally below average and no trends were detected in annual precipitation. An analysis of the post-1976 period indicates that annual precipitation was generally above average and upward trends were detected at the Ruxton Park and Pueblo stations. In addition, the post-1976 annual precipitation at the Colorado Springs, Fountain, and Pueblo stations were significantly greater than the pre-1977 annual precipitation. However, there has been no change in the distribution or magnitude of rainfall occurring during a 24-hour period. Therefore, the differences between the two periods result from more days with rainfall rather than more rain during any given day. Also, because two of the four stations evaluated had upward trends for the post-1976 period and storms that produce most of the precipitation are isolated convection storms, it is plausible that other parts of the watershed had increasing precipitation that could affect trends in streamflow.

An analysis of seasonal trends indicated that significant increases in spring precipitation have occurred at the Ruxton Park, Colorado Springs, and Pueblo stations since the 1940's and 1950's. An analysis of the pre-1977 period indicated no significant trend during any season. An analysis of the post-1976 period indicated moderately significant upward trends in spring precipitation at the Ruxton Park and Pueblo stations. The upward trends in annual precipitation for the post-1976 period at the Ruxton Park and Pueblo stations are likely a result of the upward trends in spring precipitation at these stations.

STREAMFLOW

Streamflow in the Fountain Creek watershed varies seasonally and has three distinct flow regimes: base flow, spring snowmelt and storm runoff that occurs during the summer monsoon season (fig. 7). The base-flow period begins in late September or early October and extends until the following April. During the base-flow period, streamflow is fairly uniform. Depending on temperature and winter snowfall amounts, the snowmelt period begins about mid-April and extends until about mid-June. Early in the snowmelt period, streamflow increases substantially from

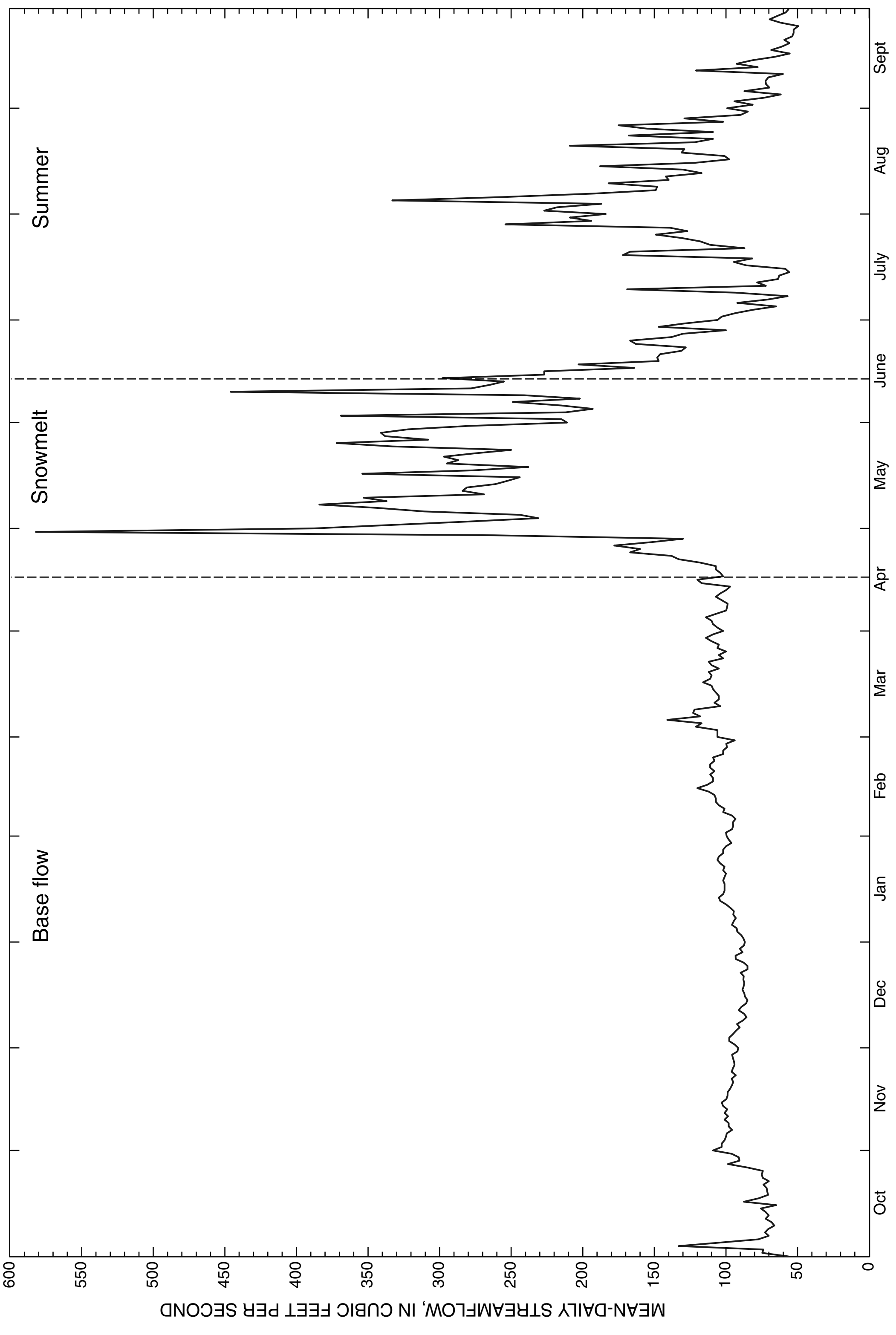


Figure 7. Annual hydrograph of average mean-daily streamflow at Pinon, 1973 through 1999.

base-flow conditions. Streamflow decreases fairly quickly after peaking in early to mid-May. The summer flow period follows the snowmelt period and generally begins about mid-June and extends through September, sometimes into October. Streamflow during the summer period is highly variable. Changes in streamflow during the summer are primarily driven by afternoon and evening storms.

Temporal Trends

Temporal trends in streamflow were evaluated for the following streamflow statistics: annual instantaneous peak streamflow, high daily-mean streamflow percentiles (70th, 90th, 100th percentile), high daily-mean streamflow duration (7-, 14-, 30-day), low daily-mean streamflow percentiles (0th, 10th, 30th percentile), and low daily-mean streamflow duration (7-, 14-, 30-day). The instantaneous peak streamflow statistic was evaluated for the period of record, pre-1976, and post-1975 time periods; all other statistics were evaluated for the period of record, pre-1977, and post-1976 time periods. The mismatch in the time periods is due to the fact that two of the selected gaging stations were not operational until January 1976 (water year). The result was an incomplete year of record, which prevented the evaluation of streamflow percentiles and streamflow duration statistics. Instantaneous peak streamflow data were available for the partial year of record. Cumulative streamflow data were compared to cumulative precipitation data to evaluate the relation between streamflow and precipitation.

Trends in High Streamflow Statistics

Trends in annual instantaneous peak streamflow; 70th, 90th, and 100th daily-mean streamflow percentiles; and 7-, 14-, and 30-day daily-mean streamflow statistics were evaluated. Annual instantaneous peak streamflows were derived from the single highest recorded stage during a given water year. Streamflow percentiles, 70th, 90th, and 100th, are equivalent to the 255th, 328th and annual maximum daily-mean streamflow values when sorted from smallest to largest. Flow-duration statistics, 7-, 14-, and 30-day, were computed by averaging daily-mean streamflows for n-days.

Instantaneous Peak Streamflow

Variations in annual instantaneous peak streamflow for the six gaging stations are shown in figure 8. Kendall trend analysis indicated significant upward trend in annual instantaneous peak streamflow at the Pikeview station for the post-1975 period and highly significant upward trend in annual instantaneous peak streamflow at Security (table 9) for the period of record (1967–99). However, significant trends in annual instantaneous peak streamflow were not detected during the pre-1976 period at any station and post-1975 time period at any station except the Pikeview station.

Evaluation of long-term streamflow data at Pueblo (1941–65, 1971–99) indicates instantaneous streamflow peaks of 10,000 ft^3/s or greater magnitude occurred more frequently during the 1990’s than any decade since the 1940’s (fig. 8). Annual instantaneous peak streamflow during 1994–97 and 1999 ranked in the top 16 of 59 (27 percent) all-time recorded maximum streamflow events. Although large streamflow events occurred more frequently during the 1990’s than during previous decades since the 1940’s, no significant trend was detected in the magnitude of peak streamflow events. The magnitudes of streamflow events that occurred during the 1990’s were not atypical of historical peaks.

Examination of streamflow data and historical accounts of the period (Colorado Climate Center, 1999; National Oceanographic and Atmospheric Administration, 1999; Snipes, 1974) indicates that the four largest streamflow events at Pueblo occurred during the spring snowmelt period, mid-April to mid-June (table 10). Each of these events was caused by several inches of rainfall that fell during intense storms over large areas of the Fountain Creek watershed and southeastern Colorado during a short period of time. In some areas, rainfall amounts received during a couple of days approached or exceeded the average total annual rainfall in the Colorado Springs area (table 10) (National Oceanographic and Atmospheric Administration, 1999; Hansen and others, 1978; Snipes, 1974). Also significant is the fact that the most recent event, the flood of April 30, 1999, was estimated to be about a 15-year flood for this station. A 15-year flood is a streamflow event of a given magnitude with a probability of recurring once every 15 years. This estimate is based on available record, not including the 1935 peak streamflow. The peak streamflow of 1935 is an estimate and considered

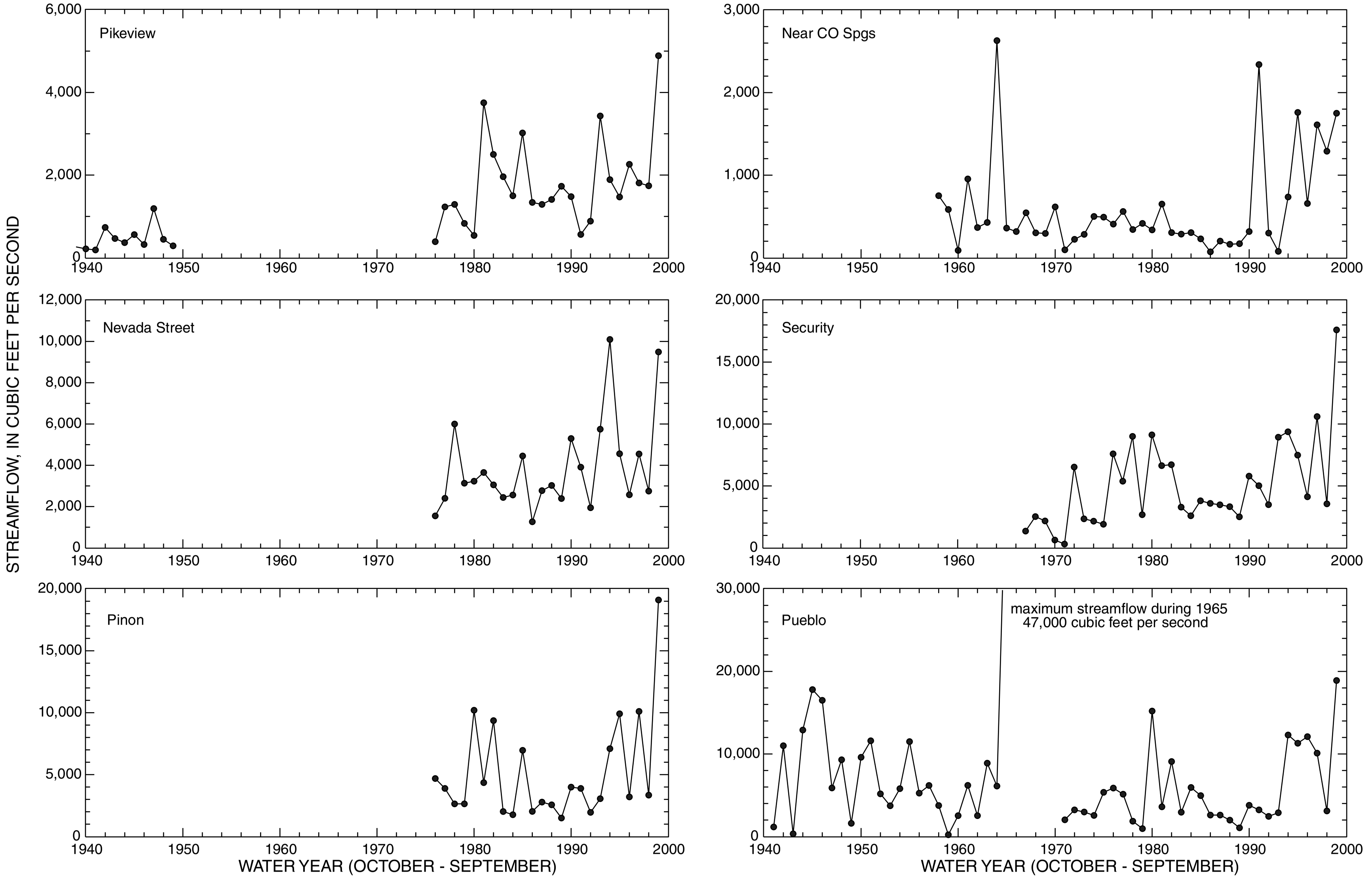


Figure 8. Annual instantaneous peak streamflow at gaging stations in the Fountain Creek watershed, 1940–99.

questionable. The flood of April 30, 1999, caused millions of dollars of damage and resulted in Presidential declaration of several counties in the Fountain Creek watershed as well as other downstream counties as a Federal flood disaster area.

High Streamflow Percentiles

The 70th percentile (Q_{70}), 90th percentile (Q_{90}), and 100th percentile (Q_{100}) daily-mean streamflows were computed for each year. The *n*-percentile indicates that *n* percent of the annual daily-mean streamflow is below a given streamflow, or (100 minus *n*) percent is above it. Results of analysis of trends in streamflow percentiles are summarized in table 11.

Two stations, Near CO Spgs and Security, had continuous streamflow record dating back to the late 1950's and mid 1960's. Two other stations, Pikeview and Pueblo, had historical streamflow record dating back to the early 1920's and early 1940's; however, this record was not continuous. Significant upward trends ($p<0.05$) were evident in the Q_{70}, Q_{90}, and Q_{100} percentiles at the Security station and the Q_{70} and Q_{90} percentiles at the Near CO Spgs station for the respective periods of record. At the Near CO Spgs station, estimated annual changes in the Q_{70} and Q_{90} streamflow regimes were small, with trend slopes of 0.22 and 0.49 ft^3/s per year. At the Security station, estimated annual changes in the Q_{70}, Q_{90}, and Q_{100} streamflow

Table 9. Kendall trend analysis of annual instantaneous peak streamflow for the indicated period of record, and pre-1976 and post-1975 time periods

[Shaded p-value indicates period with a significant trend; ft^3/s/yr, cubic feet per second per year; see table 1, figure 1 for location]

Station identifier	Time period	Time period (water years)	Kendall tau	Two-side p-value	Trend slope (ft^3/s/yr)
Pikeview	pre-1976	1939–49	0.20	0.4363	20.0
	post-1975	1976–99	0.29	0.0471	40.0
Near CO Spgs	period of record	1958–99	–0.01	0.9051	–0.65
	pre-1976	1958–75	–0.27	0.1297	–14.5
	post-1975	1976–99	0.13	0.3989	18.6
Nevada Street	post-1975	1976–99	0.22	0.1303	97.8
Security	period of record	1967–99	0.41	0.0009	130
	pre-1976	1967–75	–0.06	0.9170	–20.0
	post-1975	1976–99	0.12	0.4419	60.0
Pinon	post-1975	1976–99	0.13	0.3850	50.5
Pueblo	pre-1976	1941–65	–0.07	0.6238	–114
	post-1975	1976–99	0.14	0.3334	111

Table 10. Summary of five largest streamflow events on Fountain Creek at Pueblo, Colorado, and magnitude and general location of precipitation

[ft^3/s, cubic feet per second; na, not available; NE, northeast; yr, year]

Date	Peak instantaneous streamflow (in ft^3/s)	Recurrence interval exceeded	Streamflow at recurrence interval (in ft^3/s)	Flow period	General storm location within watershed	Reported precipitation (in inches)
06/17/1965	47,000	200 yr	45,750	Snowmelt	NE Colorado Springs	14
05/30/1935	35,000	50 yr	30,060	Snowmelt	NE Colorado Springs	18
06/04/1921	34,000	50 yr	30,060	Snowmelt	na	na
04/30/1999	18,900	10 yr	15,750	Snowmelt	Colorado Springs	10
07/10/1945	17,800	10 yr	15,750	Summer	na	na

regimes were larger than the Near CO Spgs station, with trend slopes of about 3.5, 5.2, and 26.7 ft^3/s per year. Analysis of trends for the period of record at Pikeview and Pueblo was not conducted due to the hiatus of continuous record prior to 1976.

Streamflow records were divided into pre-1977 and post-1976 time periods. Streamflow record from four stations—Pikeview, Near CO Spgs, Security, and Pueblo, as noted above—were used to evaluate trends in the pre-1977 period. Significant trends were not

Table 11. Kendall trend analysis of 70th, 90th, and 100th percentiles of streamflow for the respective periods of record, pre-1977, and post-1976 time periods

[Shaded p-values indicate periods with a significant trend; ft^3/s/yr, cubic feet per second per year]

Station identifier	Time period	Time period (water years)	Kendall tau	Two-side p-value	Trend slope (ft^3/s/yr)
		Annual 70th percentile of daily streamflow (Q_{70})			
Pikeview	pre-1977	1939–49	–0.04	0.9372	0.00
	post-1976	1977–99	0.39	0.0096	1.21
Near CO Spgs	period of record	1959–99	0.30	0.0052	0.22
	pre-1977	1959–76	–0.07	0.7316	–0.02
	post-1976	1977–99	0.34	0.0262	0.55
Nevada Street	post-1976	1977–99	0.36	0.0187	2.40
Security	period of record	1965–99	0.60	0.0000	3.53
	pre-1977	1965–76	0.02	1.0000	0.17
	post-1976	1977–99	0.48	0.0014	5.00
Pinon	post-1976	1977–99	0.51	0.0008	6.78
Pueblo	pre-1977	1941–65	–0.16	0.2721	–0.94
	post-1976	1977–99	0.49	0.0011	6.57
		Annual 90th percentile of daily streamflow (Q_{90})			
Pikeview	pre-1977	1939–49	–0.02	1.0000	–0.20
	post-1976	1977–99	0.29	0.0571	1.55
Near CO Spgs	period of record	1959–99	0.27	0.0125	0.49
	pre-1977	1959–76	0.00	1.0000	0.00
	post-1976	1977–99	0.26	0.0905	1.30
Nevada Street	post-1976	1977–99	0.24	0.1191	5.00
Security	period of record	1965–99	0.43	0.0003	5.25
	pre-1977	1965–76	–0.29	0.2160	–2.67
	post-1976	1977–99	0.31	0.0419	7.62
Pinon	post-1976	1977–99	0.29	0.0571	7.75
Pueblo	pre-1977	1941–65	–0.20	0.1803	–4.77
	post-1976	1977–99	0.29	0.0538	8.13
		Annual 100th percentile of daily streamflow (Q_{100})			
Pikeview	pre-1977	1939–49	0.13	0.6404	4.33
	post-1976	1977–99	0.42	0.0055	13.07
Near CO Spgs	period of record	1959–99	0.13	0.2293	1.00
	pre-1977	1959–76	0.01	1.0000	0.14
	post-1976	1977–99	0.16	0.2908	3.35
Nevada Street	post-1976	1977–99	0.28	0.0645	22.75
Security	period of record	1965–99	0.36	0.0025	26.70
	pre-1977	1965–76	0.12	0.6312	28.00
	post-1976	1977–99	0.32	0.0324	25.18
Pinon	post-1976	1977–99	0.33	0.0302	50.88
Pueblo	pre-1977	1941–65	–0.07	0.6238	–11.47
	post-1976	1977–99	0.41	0.0071	54.00

detected in the Q_{70}, Q_{90}, and Q_{100} streamflow regimes at the Pikeview, Near CO Spgs, Security, and Pueblo stations during the pre-1977 time period.

For the post-1976 time period, streamflow records from all six stations were evaluated. Analyses indicated significant upward trends in the Q_{70} streamflow regime at all stations. Trend-slope estimates indicated that changes in the Q_{70} streamflow regime generally increased from upstream to downstream and ranged from 0.6 ft^3/s per year at the Near CO Spgs station to about 6.8 ft^3/s per year at the Pinon station and 6.6 ft^3/s per year at the Pueblo station. Moderately significant to significant trends were detected in the post-1976 Q_{90} streamflow regime at the Pikeview, Near CO Spgs, Security, Pinon, and Pueblo stations. A significant trend was not detected in the Q_{90} streamflow regime at Nevada Street during the post-1976 period. Trend-slope estimates indicate that changes in the Q_{90} streamflow regime increased from upstream to downstream stations and ranged from 1.3 $ft^3/s/yr$ at Near CO Spgs to 8.1 $ft^3/s/yr$ at Pueblo. Moderate to highly significant trends were detected in the Q_{100} steamflow regimes at the Pikeview, Nevada Street, Security, Pinon, and Pueblo stations. Trend-slope estimates indicated that changes in the Q_{100} streamflow regime generally increased from upstream to downstream and ranged from about 13.1 ft^3/s per year at the Pikeview station to 54.0 ft^3/s per year at the Pueblo station. A significant trend in the Q_{100} streamflow regime was not detected in the post-1976 streamflow record for the Near CO Spgs station.

The significant upward trend in precipitation at the Ruxton Park station during the post-1976 period (fig. 6) could possibly explain the upward trends in Q_{70} and Q_{90} streamflow at the Near CO Spgs station. In the absence of significant changes over time in post-1976 precipitation at the Colorado Springs and Fountain stations (fig. 6), upward trends in the high streamflow regimes at the Nevada Street, Security, and Pinon stations that were detected in the post-1976 period could be explained by changes in land use and (or) water use and resultant rate of runoff in the watershed. However, it is plausible that precipitation has increased over time in other parts of the watershed but went undetected because of the sparse spatial distribution of fairly long-term precipitation stations and the scattered spatial distribution of convection storms. Additionally, changes in high-flow regimes at upstream locations generally would be transferred to downstream locations.

Streamflow Duration

The 7-, 14-, and 30-day high daily-mean streamflow statistics were evaluated. The *n*-day high streamflow duration indicates the highest average daily-mean streamflow for *n*-consecutive days during a year. Time series of annual 7-, 14-, and 30-day high-flow magnitude are shown in figure 9.

Analysis of 7-, 14-, and 30-day high daily-mean streamflow magnitudes at the Pikeview station did not indicate trends during the 1939 through 1949 period (table 12). However, moderately significant to significant upward trends were detected in the 7- and 14-day daily-mean streamflow magnitudes during the 1977 through 1999 period. Although analysis indicated upward trends in 7- and 14-day high daily-mean streamflow since 1977, it is important to note that the magnitudes of the high daily-mean streamflow durations since 1977 generally have been similar to, or slightly less than, daily-mean streamflows of the same durations during the 1939 through 1949 time period (fig. 9).

At the Near CO Spgs station, analysis indicated moderately significant upward trend in the high 7-day daily-mean streamflow and significant upward trends in the 14- and 30-day daily-mean streamflow statistics for the period of record (1959–99). Significant trends were not indicated in the 7- and 14-day high daily-mean streamflow during the pre-1977 and post-1976 time periods; however, moderately significant upward trends were indicated in the 30-day high daily-mean streamflow statistic for the post-1976 period. Figure 9 illustrates that the 7-, 14-, and 30-day daily-mean streamflow in the mid- to late 1990's have been greater than those of most of the historical record. Therefore, the indicated upward significant trend in 14- and 30-day high daily-mean streamflow for the period of record was affected by the high streamflows that occurred in the mid- to late 1990's.

At the Security station, highly significant upward trends were indicated in the 7-, 14-, and 30-day high daily-mean streamflows for the period of record, and moderately significant to significant upward trends were indicated in the 7-, 14-, and 30-day high daily-mean streamflow for the post-1976 period. Similar to the Near CO Spgs station, no significant trends were indicated for the pre-1977 period at the Security station. Again, the upward significant trends in 7-, 14- and 30-day high daily-mean streamflows for the period of record were affected by the high streamflows that occurred in the mid- to late 1990's.

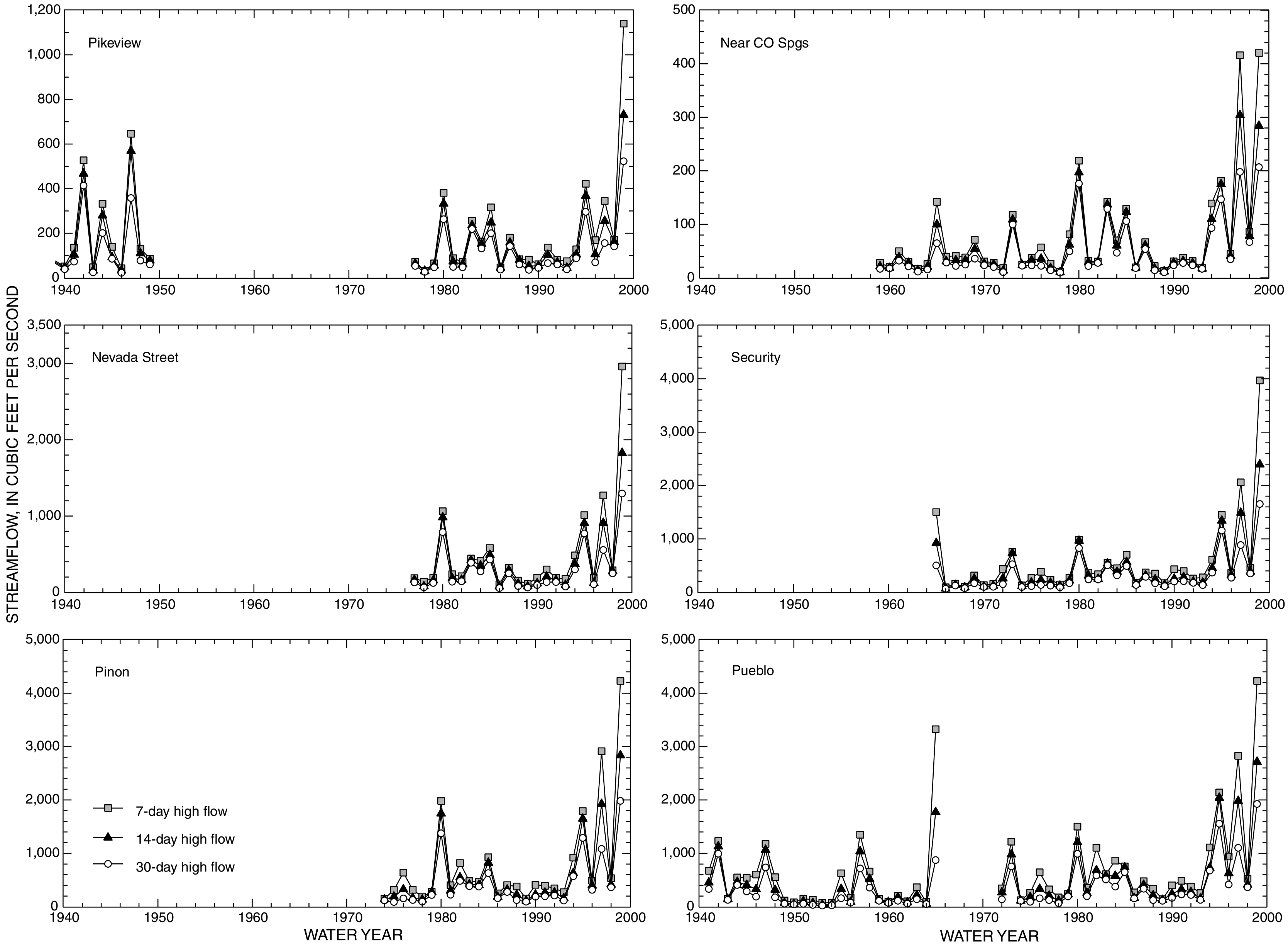


Figure 9. Magnitude of 7-, 14-, and 30-day high flows at gaging stations in the Fountain Creek watershed, 1940–99.

Table 12. Kendall trend analysis of 7-, 14-, and 30-day high daily-mean streamflow duration

[Shaded p-values indicate periods with a significant trend; $ft^3/s/yr$, cubic feet per second per year; see table 1, figure 1 for location]

Station identifier	Time period	Time period (water years)	Kendall tau	Two-side p-value	Trend slope ($ft^3/s/yr$)
7-day					
Pikeview	pre-1977	1939–49	0.05	0.8763	1.0
	post-1976	1977–99	0.30	0.0447	5.4
Near CO Spgs	period of record	1959–99	0.21	0.0506	0.8
	pre-1977	1959–76	0.12	0.4954	0.7
	post-1976	1977–99	0.24	0.1191	2.0
Nevada Street	post-1976	1977–99	0.22	0.1538	8.6
Security	period of record	1965–99	0.35	0.0029	11.4
	pre-1977	1965–76	0.18	0.4507	13.4
	post-1976	1977–99	0.33	0.0303	15.5
Pinon	post-1976	1977–99	0.27	0.0725	15.5
Pueblo	pre-1977	1941–65	–0.16	0.2825	–6.1
	post-1976	1977–99	0.30	0.0447	24.7
14-day					
Pikeview	pre-1977	1939–49	0.09	0.7555	3.4
	post-1976	1977–99	0.28	0.0645	3.3
Near CO Spgs	period of record	1959–99	0.22	0.0398	0.8
	pre-1977	1959–76	0.18	0.3247	0.6
	post-1976	1977–99	0.21	0.1696	2.1
Nevada Street	post-1976	1977–99	0.18	0.2452	5.5
Security	period of record	1965–99	0.37	0.0017	8.5
	pre-1977	1965–76	0.18	0.4507	8.8
	post-1976	1977–99	0.30	0.0447	11.8
Pinon	post-1976	1977–99	0.24	0.1131	12.5
Pueblo	pre-1977	1941–65	–0.17	0.2336	–8.3
	post-1976	1977–99	0.27	0.0725	18.0
30-day					
Pikeview	pre-1977	1939–49	0.02	1.0000	0.6
	post-1976	1977–99	0.23	0.1256	2.1
Near CO Spgs	period of record	1959–99	0.26	0.0157	0.6
	pre-1977	1959–76	0.12	0.4954	0.3
	post-1976	1977–99	0.25	0.0960	1.7
Nevada Street	post-1976	1977–99	0.18	0.2345	6.0
Security	period of record	1965–99	0.39	0.0010	6.8
	pre-1977	1965–76	0.12	0.6312	3.4
	post-1976	1977–99	0.27	0.0725	10.2
Pinon	post-1976	1977–99	0.21	0.1696	10.1
Pueblo	pre-1977	1941–65	–0.21	0.1412	–6.11
	post-1976	1977–99	0.28	0.0683	15.1

High daily-mean streamflow duration analysis at the Pinon station indicated moderately significant upward trend in the magnitude of the 7-day high daily-mean streamflow for the post-1976 period. Significant trends were not detected in the magnitude of 14- or 30-day streamflow statistics.

At the Pueblo station, analysis indicated no significant trends in the magnitude of the 7-, 14-, or 30-day streamflow statistics for the pre-1977 period. Significant to moderately significant upward trend was indicated in the 7-, 14-, and 30-day streamflow statistics for the post-1976 period. As occurred with many of the upstream stations, the streamflow durations in the mid- to late 1990's have generally been greater than most of the historical record.

The relative ranks of streamflow magnitude of the high daily-mean streamflow duration statistics were compared. The evaluation of the rank of the high daily-mean streamflow indicates that the magnitude of streamflow within all the high daily-mean streamflow duration statistics for 1999 were either ranked first or second for the entire period of record at all the stations evaluated. This indicates that high streamflows that occurred during 1999 remained elevated for a longer period of time than any other period of record.

Trends in Low Streamflow Statistics

Trends in 0th, 10th, and 30th daily-mean streamflow percentiles and 7-, 14-, and 30-day low daily-mean streamflow statistics were evaluated. Streamflow percentiles, 0th, 10th, and 30th, are equivalent to the annual minimum, 36th, and 109th annual daily-mean streamflow values when sorted from smallest to largest. Low streamflow duration statistics, 7-, 14-, and 30-day, were computed by averaging daily-mean streamflows for *n*-days.

Low Streamflow Percentiles

Specific streamflow statistics were computed for each year: minimum (Q_0), 10th percentile (Q_{10}), and 30th percentile (Q_{30}) daily-mean streamflow. The *n*-percentile indicates that *n* percent of the annual daily-mean streamflow is below a given streamflow, or (100 minus *n*) percent is above it. Results of analysis of trend in streamflow percentiles are summarized in table 13.

Significant upward trends were detected in the Q_0, Q_{10}, and Q_{30} streamflow regime at the Near CO Spgs station (1959–99). Highly significant upward trends were detected in the Q_0, Q_{10}, and Q_{30} streamflow regimes at the Security station (1965–99). At the Near CO Spgs station, estimated annual changes in the Q_0, Q_{10}, and Q_{30} streamflow regime were small, 0.05, 0.06, and 0.07 ft^3/s per year, respectively. Downstream at the Security station, estimated changes in the Q_0, Q_{10}, and Q_{30} were larger, about 1.7, 2.5, and 2.8 ft^3/s per year, respectively.

Similar to the analysis of trends in the magnitude of high daily-mean streamflow statistics, analysis did not indicate trends in the Q_0, Q_{10}, and Q_{30} streamflow regimes during the pre-1977 time period at the Pikeview, Near CO Spgs, Security, or Pueblo stations.

For the post-1976 time period, analysis indicated highly significant upward trends in the Q_0, Q_{10}, and Q_{30} streamflow regimes at the Pikeview, Nevada Street, Security, Pinon, and Pueblo stations and a moderately significant upward trend in the Q_{30} streamflow regime at the Near CO Spgs station. No significant trends were detected for this period in the Q_0 and Q_{10} flow statistics for the Near CO Spgs station. Trend slope estimates indicate that changes in the Q_0 streamflow regime increased from Pikeview and Nevada, with trend slopes of about 0.5 and 0.7 ft^3/s per year, to Security, with a trend slope of 2.2 ft^3/s per year. The trend slope then decreased at Pinon and Pueblo to about 0.8 ft^3/s per year. Similar changes were indicated by the analysis of the Q_{10} streamflow regime. Trend slope estimates indicate that changes in the Q_{10} streamflow regime increased from Nevada Street (0.9 ft^3/s per year) to Security (about 3.4 ft^3/s per year) and then decreased at Pinon (about 2.7 ft^3/s per year). Trend slope estimates indicate that changes in the Q_{30} streamflow regime increased from Pikeview (about 0.7 ft^3/s per year) and Near CO Spgs (about 0.2 ft^3/s per year) to Nevada Street (about 1.1 ft^3/s per yr), Security (about 3.9 ft^3/s per year), and Pinon (6.1 ft^3/s per year) and then decreased at Pueblo (about 5.3 ft^3/s per year). The upward trends in all three of the low streamflow statistics for the 1977–99 period indicate that low streamflow conditions have significantly increased throughout most of the watershed over the past 23 years.

In the Fountain Creek watershed, streamflow consists of native and imported transbasin water. Transbasin water is used to meet the growing domestic, municipal, and industrial water uses in the Colorado Springs metropolitan area. Return flows associated with lawn watering throughout Colorado Springs and the municipalities along Monument Creek may explain the indicated trends in the low streamflow regimes from the Pikeview to Nevada Street stations. Return flows may explain a portion of the indicated trends in low streamflow downstream from the Nevada Street station. Upstream return flows combined with increases in wastewater effluent and changes in water management downstream from the Nevada Street station result in the indicated increases in the low-flow regimes ($Q_0 - Q_{30}$) downstream from the Nevada Street station.

Table 13. Kendall trend analysis for 0th, 10th, and 30th percentiles of streamflow for the respective periods of record, pre-1977 and post-1976 time periods

[Shaded p-values indicate stations and time periods with a significant trend; ft^3/s/yr, cubic feet per second per year; see table 1, figure 1 for location]

Station identifier	Time period	Time period (water years)	Kendall tau	Two-side p-value	Trend slope (ft^3/s/yr)
		Annual minimum (daily mean) streamflow (Q_0)			
Pikeview	pre-1977	1939–49	0.33	0.1844	0.17
	post-1976	1977–99	0.51	0.0006	0.47
Near CO Spgs	period of record	1959–99	0.28	0.0110	0.05
	pre-1977	1959–76	–0.01	0.9697	0.00
	post-1976	1977–99	0.13	0.4125	0.03
Nevada Street	post-1976	1977–99	0.42	0.0051	0.67
Security	period of record	1965–99	0.66	0.0000	1.69
	pre-1977	1965–76	0.35	0.1305	0.70
	post-1976	1977–99	0.50	0.0010	2.20
Pinon	post-1976	1977–99	0.71	0.0000	0.73
Pueblo	pre-1977	1941–65	0.19	0.1889	0.01
	post-1976	1977–99	0.62	0.0000	0.88
		Annual 10th percentile of daily streamflow (Q_{10})			
Pikeview	pre-1977	1939–49	0.31	0.2101	0.22
	post-1976	1977–99	0.58	0.0001	0.57
Near CO Spgs	period of record	1959–99	0.24	0.0308	0.06
	pre-1977	1959–76	–0.21	0.2377	–0.03
	post-1976	1977–99	0.14	0.3548	0.08
Nevada Street	post-1976	1977–99	0.43	0.0041	0.89
Security	period of record	1965–99	0.66	0.0000	2.53
	pre-1977	1965–76	0.30	0.1905	0.54
	post-1976	1977–99	0.54	0.0004	3.36
Pinon	post-1976	1977–99	0.64	0.0000	2.70
Pueblo	pre-1977	1941–65	0.02	0.9248	0.00
	post-1976	1977–99	0.61	0.0001	3.00
		Annual 30th percentile of daily streamflow (Q_{30})			
Pikeview	pre-1977	1939–49	0.24	0.3502	0.29
	post-1976	1977–99	0.48	0.0014	0.70
Near CO Spgs	period of record	1959–99	0.29	0.0085	0.07
	pre-1977	1959–76	–0.20	0.2535	–0.06
	post-1976	1977–99	0.25	0.0952	0.17
Nevada Street	post-1976	1977–99	0.44	0.0036	1.05
Security	period of record	1965–99	0.72	0.0000	2.84
	pre-1977	1965–76	0.30	0.1905	0.67
	post-1976	1977–99	0.60	0.0001	3.85
Pinon	post-1976	1977–99	0.58	0.0001	6.06
Pueblo	pre-1977	1941–65	–0.15	0.2922	–0.08
	post-1976	1977–99	0.51	0.0007	5.33

Streamflow Duration

The magnitudes of low streamflow with 7-, 14-, and 30-day durations were evaluated. Low *n*-day streamflow duration indicates the lowest average daily-mean streamflow for *n*-consecutive days during a year. Unlike graphical analysis of high daily-mean streamflows (fig. 9 and table 12), trends in the magnitude of 7-, 14-, and 30-day low streamflows were quite obvious for most stations (fig. 10) and are summarized in table 14.

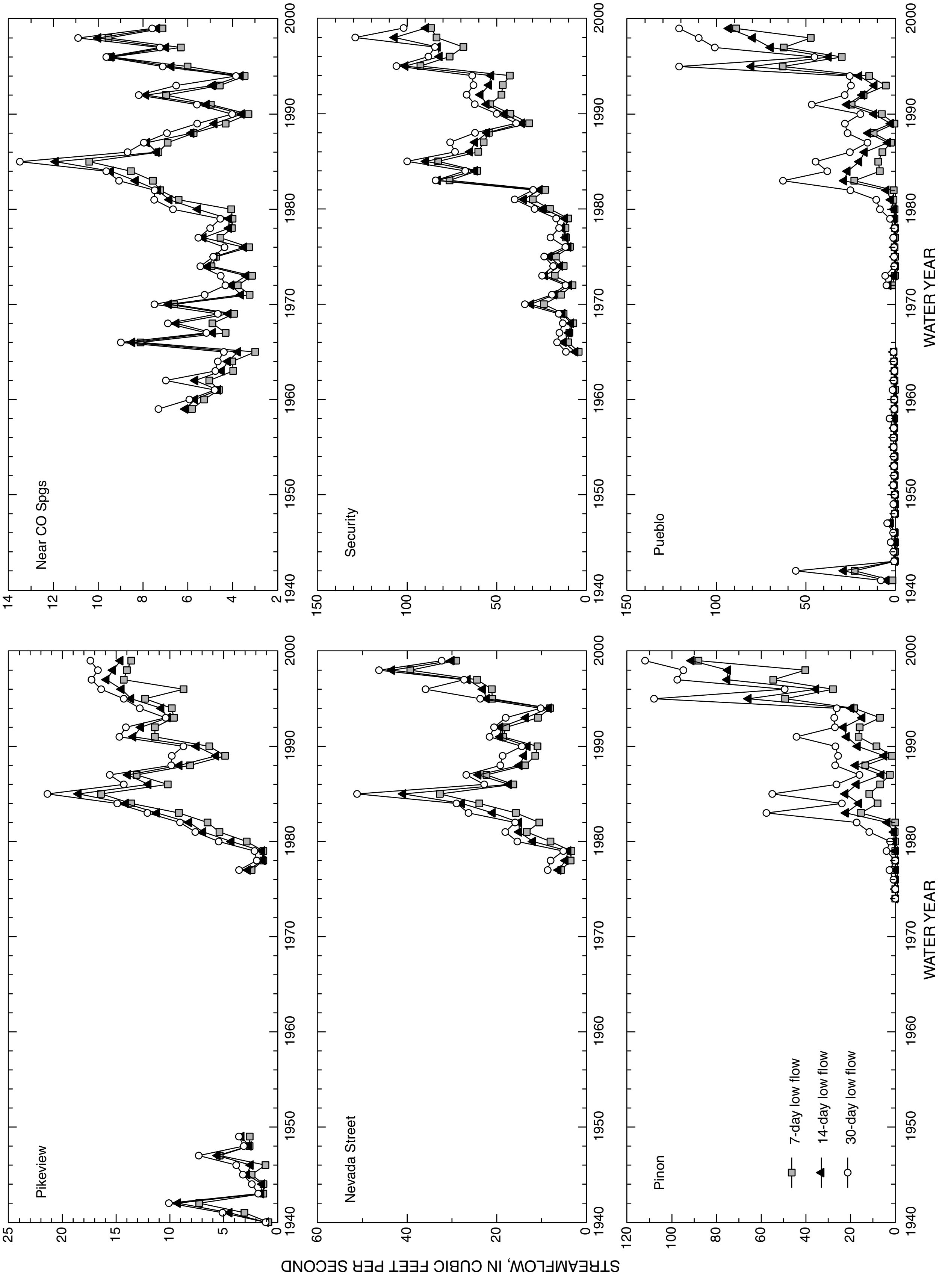


Figure 10. Magnitude of 7-, 14-, and 30-day low flows at gaging stations in the Fountain Creek watershed, 1940–99.

Table 14. Kendall trend analysis of 7-, 14-, and 30-day low streamflow duration

[Shaded p-values indicated stations and time periods with significant trend; ft^3/s/yr, cubic feet per second per year; see table 1, figure 1 for location]

Station identifier	Time period	Time period (water years)	Kendall tau	Two-side p-value	Trend slope (ft^3/s/yr)
7-day					
Pikeview	pre-1977	1939–49	0.27	0.2758	0.21
	post-1976	1977–99	0.49	0.0011	0.48
Near CO Spgs	period of record	1959–99	0.24	0.0277	0.06
	pre-1977	1959–76	–0.29	0.0956	–0.09
	post-1976	1977–99	0.16	0.2908	0.07
Nevada Street	post-1976	1977–99	0.46	0.0022	0.86
Security	period of record	1965–99	0.62	0.0000	2.14
	pre-1977	1965–76	0.27	0.2437	0.73
	post-1976	1977–99	0.47	0.0018	2.84
Pinon	post-1976	1977–99	0.73	0.0000	1.66
Pueblo	pre-1977	1941–65	0.11	0.4545	0.01
	post-1976	1977–99	0.67	0.0000	1.74
14-day					
Pikeview	pre-1977	1939–49	0.35	0.1611	0.23
	post-1976	1977–99	0.55	0.0003	0.54
Near CO Spgs	period of record	1959–99	0.24	0.0310	0.06
	pre-1977	1959–76	–0.33	0.0582	–0.10
	post-1976	1977–99	0.17	0.2787	0.08
Nevada Street	post-1976	1977–99	0.40	0.0082	0.84
Security	period of record	1965–99	0.65	0.0000	2.37
	pre-1977	1965–76	0.33	0.1499	0.76
	post-1976	1977–99	0.52	0.0005	3.25
Pinon	post-1976	1977–99	0.71	0.0000	2.28
Pueblo	pre-1977	1941–65	0.08	0.5748	0.01
	post-1976	1977–99	0.62	0.0000	2.30
30-day					
Pikeview	pre-1977	1939–49	0.31	0.2129	0.25
	post-1976	1977–99	0.57	0.0002	0.59
Near CO Spgs	period of record	1959–99	0.25	0.0240	0.06
	pre-1977	1959–76	–0.27	0.1202	–0.05
	post-1976	1977–99	0.15	0.3283	0.07
Nevada Street	post-1976	1977–99	0.39	0.0096	0.84
Security	period of record	1965–99	0.67	0.0000	2.49
	pre-1977	1965–76	0.21	0.3727	0.57
	post-1976	1977–99	0.57	0.0002	3.59
Pinon	post-1976	1977–99	0.66	0.0000	2.95
Pueblo	pre-1977	1941–65	–0.22	0.1288	–0.02
	post-1976	1977–99	0.60	0.0001	2.81

Analysis of 7-, 14-, and 30-day low streamflows at Pikeview did not indicate trends during the 1939 through 1949 time period. Highly significant trends were detected in the 1977 through 1999 time period. Estimated trend slopes in the 7-, 14-, and 30-day low streamflow for the 1977 to 1999 time period were about 0.5 and 0.6 ft^3/s/yr. Increases in low streamflow appear to have begun in the early 1980’s, peaked in the mid-1980’s, and have remained relatively constant since 1985 (fig. 10).

Analysis of 7-, 14-, and 30-day low streamflow at the Near CO Spgs station indicated significant trends for the period of record, 1959–99. However, although the analysis indicated that the trends were significant, the trend slope estimates were generally small (0.06 $ft^3/s/yr$). Moderately significant downward trends were indicated in the 7- and 14-day low streamflows for the pre-1977 period, and trends were not indicated in the 30-day low streamflow for the pre-1977 period or in the 7-, 14-, or 30-day low streamflows for the post-1976 time periods. Figure 10 indicates that long-term trends (1959–99) were affected by relatively recent changes in low streamflow.

Analysis of 7-, 14-, and 30-day low streamflow at the Nevada Street station indicated highly significant upward trends. Trend slope estimates for 7-, 14-, and 30-day low streamflow were about 0.8 ft^3/s per year. The pattern in low streamflow duration at the Nevada Street station is similar to patterns at the Pikeview station for the same time period (1977–99). The similarities indicate that the changes in low streamflow that occurred at the Nevada Street station probably are largely the result of changes in land use and(or) water management in the Monument Creek watershed.

Streamflow data were available for the Security station since 1965. Analysis indicated highly significant upward trends in the 7-, 14-, and 30-day low streamflow duration statistics for the period of record and post-1976 period. Analysis did not indicate a significant trend in the low streamflow duration statistics for the pre-1977 period. Estimates of trend slope indicate about a three- to sevenfold increase in the average annual rate of change between the pre-1977 and post-1976 periods. Figure 10 indicates that increases in low streamflow began in the early 1980's.

Contrary to trends in high daily-mean streamflow, observed trends in low streamflow duration in the upstream stations are observable at the downstream locations at Pinon and Pueblo. At Pinon, analysis indicated highly significant upward trends in 7-day (about 1.7 ft^3/s per year), 14-day (about 2.3 ft^3/s per year), and 30-day (about 3.0 ft^3/s per year) low streamflow during the post-1976 time period. At Pueblo, analysis did not indicate significant trends in low daily-mean streamflow during the 1941 through 1965 time period. Analysis did reveal highly significant trends in 7-, 14-, and 30-day low streamflow during the post-1976 time period, with estimates of trend slopes of about 1.7, 2.3, and 2.8 ft^3/s per year. As with upstream stations, increases in low daily-mean streamflow duration began in the early 1980's and are probably associated with increases in wastewater-treatment plant discharges and management of Colorado Springs' transbasin return-flow exchange decree.

An evaluation of the ranks of the low streamflow duration statistics indicates that the magnitude of low streamflows in 1999 were the largest or near the largest at most of the stations in the watershed for the period of record.

Spatial Trends

Trends in streamflow regimes between upstream and downstream stations were evaluated for the period 1977 through 1999, the period of overlapping continuous record at all stations. Differences in daily-mean streamflow for each river reach were normalized by drainage area:

$$Q_n = \frac{(Q_d - Q_u)}{(A_d - A_u)} \tag{1}$$

where

Q_n = normalized change in daily-mean streamflow for stream reach, in cubic feet per second per square mile;

Q_d = daily-mean streamflow at downstream station, in cubic feet per second;

Q_u = daily-mean streamflow at upstream station, in cubic feet per second;

A_d = drainage area at downstream station, in square miles; and

A_u = drainage area at upstream station, in square miles.

A decrease in streamflow between an upstream and downstream station indicated a decrease in streamflow within the intervening drainage area, and conversely an increase in streamflow between an upstream and downstream station indicated an increase in the amount of streamflow within the intervening drainage area. The change in daily-mean streamflow for a stream reach was normalized by dividing the change in streamflow by the intervening drainage area, which allows for direct comparison between stream reaches.

High Streamflow

Changes in Q_{70} high daily-mean streamflow statistics for five river reaches for 23 years are shown in figure 11. Trend analyses indicated moderately significant to highly significant increases in Q_{70} streamflow regime in four river reaches: Pikeview to Nevada Street, Near CO Spgs to Nevada Street,

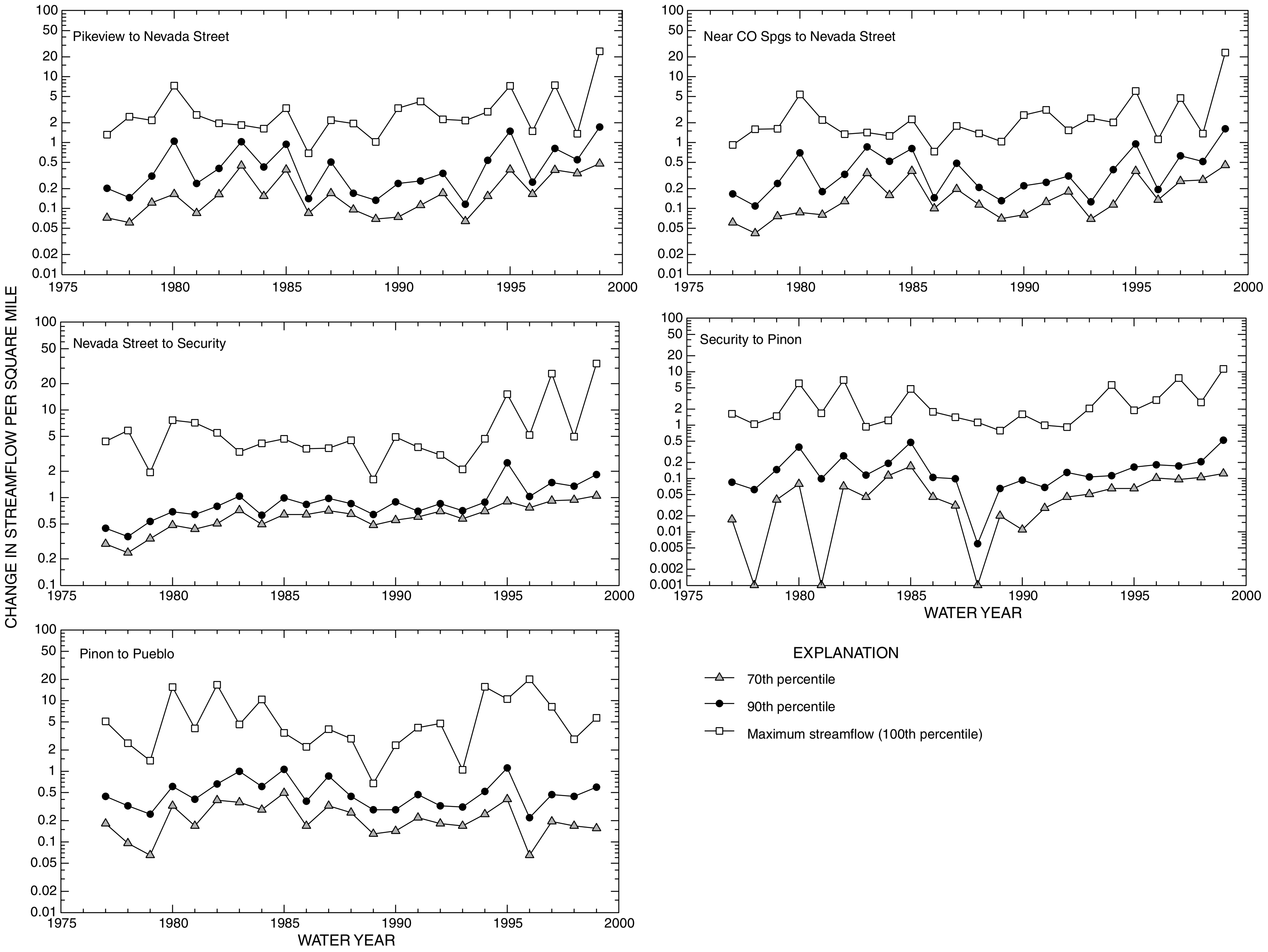


Figure 11. Normalized high flow for selected reaches of Fountain and Monument Creeks, 1977 through 1999.

Nevada Street to Security, and Security to Pinon (table 15). The reach between Nevada Street and Security indicated the greatest and most significant increase in streamflow, with a trend slope of about 0.03 [(ft^3/s)/mi^2/yr] and a significance of 0.0000. Analysis indicated a highly significant trend in the Q_{90} streamflow regime only in the reach between Nevada Street and Security, with an estimated trend slope of about 0.04 [(ft^3/s)/mi^2/yr] and a significance of 0.0001. Analysis indicated there were no significant trends at the Q_{100} streamflow regime within any of the five river reaches.

The changes in Q_{70} high streamflow regime along the reaches between Pikeview and Nevada Street, Near CO Spgs and Nevada Street, Nevada Street and Security, and Security and Pinon may be partially explained by changes in land use, water use, or both.

Changes in the Q_{70} and Q_{90} streamflow regimes within the reach between the Nevada Street and Security stations are probably due to changes in land use within the intervening drainage area. Within the intervening drainage, recent development has resulted in changes in land use from rangeland to urban. Within this drainage, increases in impervious area may have altered the hydrologic response by increasing storm runoff by about 0.03 [(ft^3/s)/mi^2/yr] or about 3.1 ft^3/s per year, which is about 5 times larger than the estimated trend slopes for the other river reaches.

The small but significant changes in the Q_{70} streamflow regime along the reach between Security and Pinon, about 0.004 [(ft^3/s)/mi^2/yr], probably is largely a result of changes in land use within the upper part of the reach.

Low Streamflow

Changes in selected low-streamflow statistics for five river reaches for 23 years are shown in figure 12. Trend analysis indicated that during the period from 1977 through 1999, highly significant to moderately significant upward trends in normalized streamflow in the Q_0 streamflow regime (table 16) were detected in three reaches: Near CO Spgs to Nevada Street, Nevada Street to Security, and Pinon to Pueblo. The trend slopes indicated estimated increases of about 0.003 [(ft^3/s)/mi^2/yr] within the reach from Near CO Spgs to Nevada Street, about 0.03 [(ft^3/s)/mi^2/yr] within the reach between Nevada Street and Security, and about 0.11 [(ft^3/s)/mi^2/yr] within the reach from Pinon to Pueblo.

Table 15. Kendall trend analysis for 70th, 90th, and 100th percentiles of normalized streamflow for the post-1976 time period

[Shaded p-values indicate reaches and time periods with a trend; ft^3/s, cubic feet per second; mi^2, square mile; yr, year; see figure 1 for location]

Stream reach	Time period (water years)	Kendall tau	Two-side p-value	Trend slope [(ft^3/s)/mi^2/yr]
	Annual 70th percentile of daily-mean streamflow (Q_{70})			
Pikeview to Nevada Street	1977–99	0.29	0.0534	0.0058
Near CO Spgs to Nevada Street	1977–99	0.41	0.0065	0.0078
Nevada Street to Security	1977–99	0.69	0.0000	0.0282
Security to Pinon	1977–99	0.36	0.0185	0.0036
Pinon to Pueblo	1977–99	–0.10	0.5074	–0.0022
	Annual 90th percentile of daily-mean streamflow (Q_{90})			
Pikeview to Nevada Street	1977–99	0.20	0.1955	0.0126
Near CO Spgs to Nevada Street	1977–99	0.22	0.1538	0.0117
Nevada Street to Security	1977–99	0.57	0.0001	0.0370
Security to Pinon	1977–99	0.22	0.1462	0.0035
Pinon to Pueblo	1977–99	–0.01	0.9789	0.0000
	Annual 100th percentile of daily-mean streamflow (Q_{100})			
Pikeview to Nevada Street	1977–99	0.17	0.2787	0.0563
Near CO Spgs to Nevada Street	1977–99	0.23	0.1256	0.0516
Nevada Street to Security	1977–99	0.15	0.3417	0.0534
Security to Pinon	1977–99	0.22	0.1538	0.0611
Pinon to Pueblo	1977–99	0.08	0.5974	0.0633

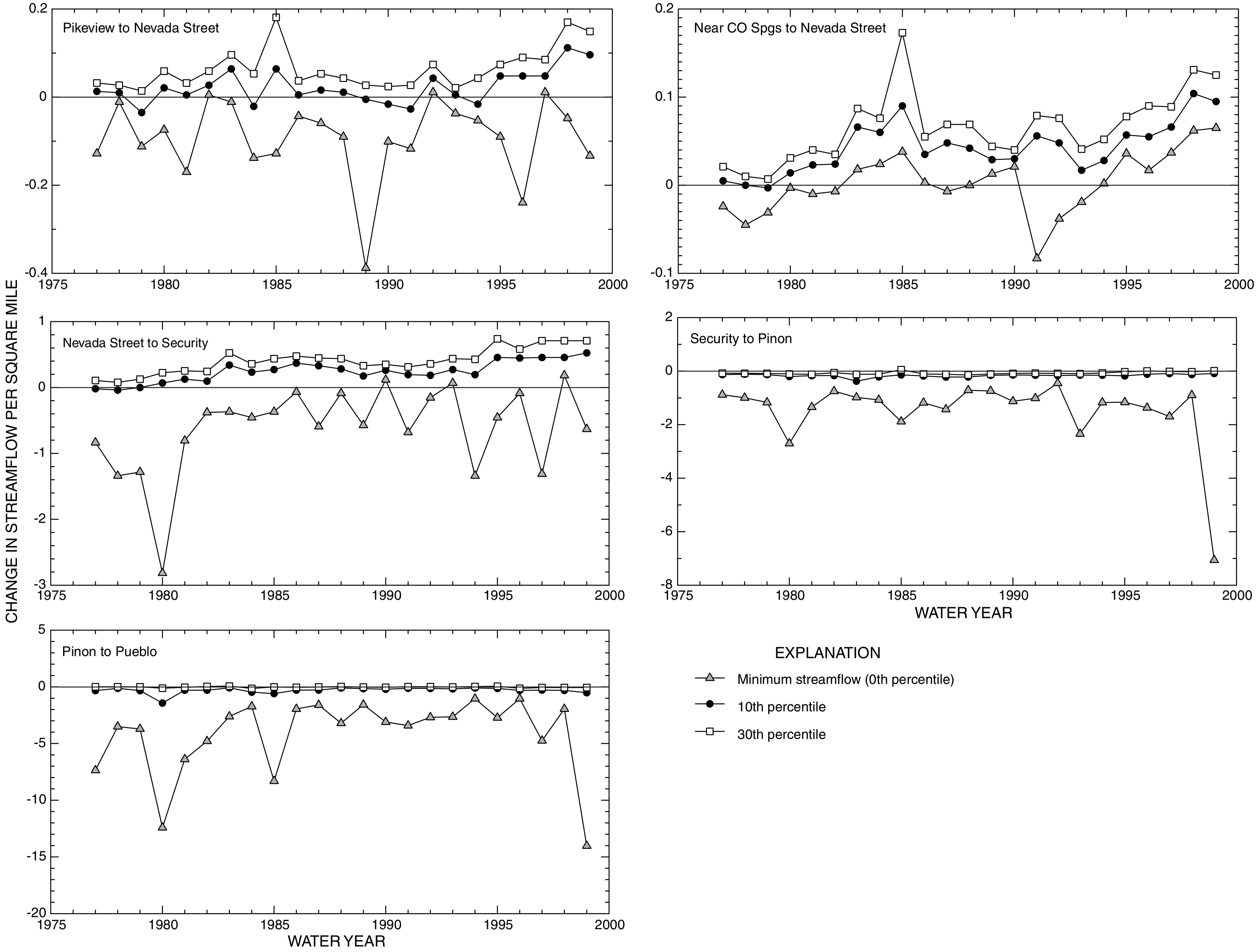


Figure 12. Normalized low flow for selected reaches of Fountain and Monument Creeks, 1977 through 1999.

Table 16. Kendall trend analyses for the 0th, 10th, and 30th percentiles of normalized streamflow for the post-1976 time period

[Shaded p-values indicate reaches and time periods with significant trend; ft^3/s, cubic feet per second; mi^2, square mile; yr, year; see figure 1 for location]

Stream reach	Time period (water years)	Kendall tau	Two-side p-value	Trend slope $[(ft^3/s)/mi^2/yr]$
		Annual minimum (daily mean) streamflow (Q_0)		
Pikeview to Nevada Street	1977–99	0.02	0.9157	0.0003
Near CO Spgs to Nevada Street	1977–99	0.43	0.0047	0.0030
Nevada Street to Security	1977–99	0.28	0.0641	0.0338
Security to Pinon	1977–99	–0.15	0.3417	–0.0140
Pinon to Pueblo	1977–99	0.26	0.0811	0.1136
		Annual 10th percentile of daily streamflow (Q_{10})		
Pikeview to Nevada Street	1977–99	0.23	0.1243	0.0020
Near CO Spgs to Nevada Street	1977–99	0.48	0.0015	0.0029
Nevada Street to Security	1977–99	0.60	0.0001	0.0203
Security to Pinon	1977–99	0.24	0.1191	0.0024
Pinon to Pueblo	1977–99	0.11	0.4743	0.0026
		Annual 30th percentile of daily streamflow (Q_{30})		
Pikeview to Nevada Street	1977–99	0.27	0.0716	0.0026
Near CO Spgs to Nevada Street	1977–99	0.53	0.0004	0.0035
Nevada Street to Security	1977–99	0.59	0.0001	0.0251
Security to Pinon	1977–99	0.36	0.0184	0.0039
Pinon to Pueblo	1977–99	–0.12	0.4417	–0.0015

Analysis indicated highly significant changes in the Q_{10} streamflow regimes along two reaches, Near CO Spgs to Nevada Street and Nevada Street to Security (table 16). Streamflow increased by an estimated 0.003 $[(ft^3/s)/mi^2/yr]$ in the Near CO Spgs to Nevada Street reach and about 0.02 $[(ft^3/s)/mi^2/yr]$ in the Nevada Street to Security reach.

Analysis indicated moderate to highly significant changes in the Q_{30} streamflow regime within four reaches: Pikeview to Nevada Street, Near CO Spgs to Nevada Street, Nevada Street to Security, and Security to Pinon (table 16). Estimated trend slopes ranged from an estimated 0.003 $[(ft^3/s)/mi^2/yr]$ in the Pikeview to Nevada Street reach to an estimated 0.025 $[(ft^3/s)/mi^2/yr]$ in the Nevada Street to Security reach.

Trends in low streamflow that occurred within selected reaches can be explained by: (1) importation of non-native water, (2) increased return flows, (3) increases in wastewater-treatment-plant discharge, and (4) changes in water management and operations.

Relation between Precipitation and Streamflow

The relation between precipitation and streamflow was evaluated for water years 1960 through 1997, the period when all four precipitation monitoring stations were active. Daily precipitation was summed and average daily precipitation calculated. Average daily precipitation was cumulated and compared to the cumulative daily streamflow at Pueblo using a double-mass plot (fig. 13). The analysis revealed a marked change in the relation between cumulative precipitation and cumulative streamflow between 1980 and 1982. For the period 1960 through about 1980, the relation between precipitation and streamflow was reasonably linear with short-term deviations in the slope, providing a baseline relation. Between 1980 and 1982, cumulative streamflow increased more rapidly than cumulative precipitation, as indicated by the large deviation from the baseline relation (fig. 13). As a result of the deviation, a new relation was established; the new relation continued through the end of water year 1997.

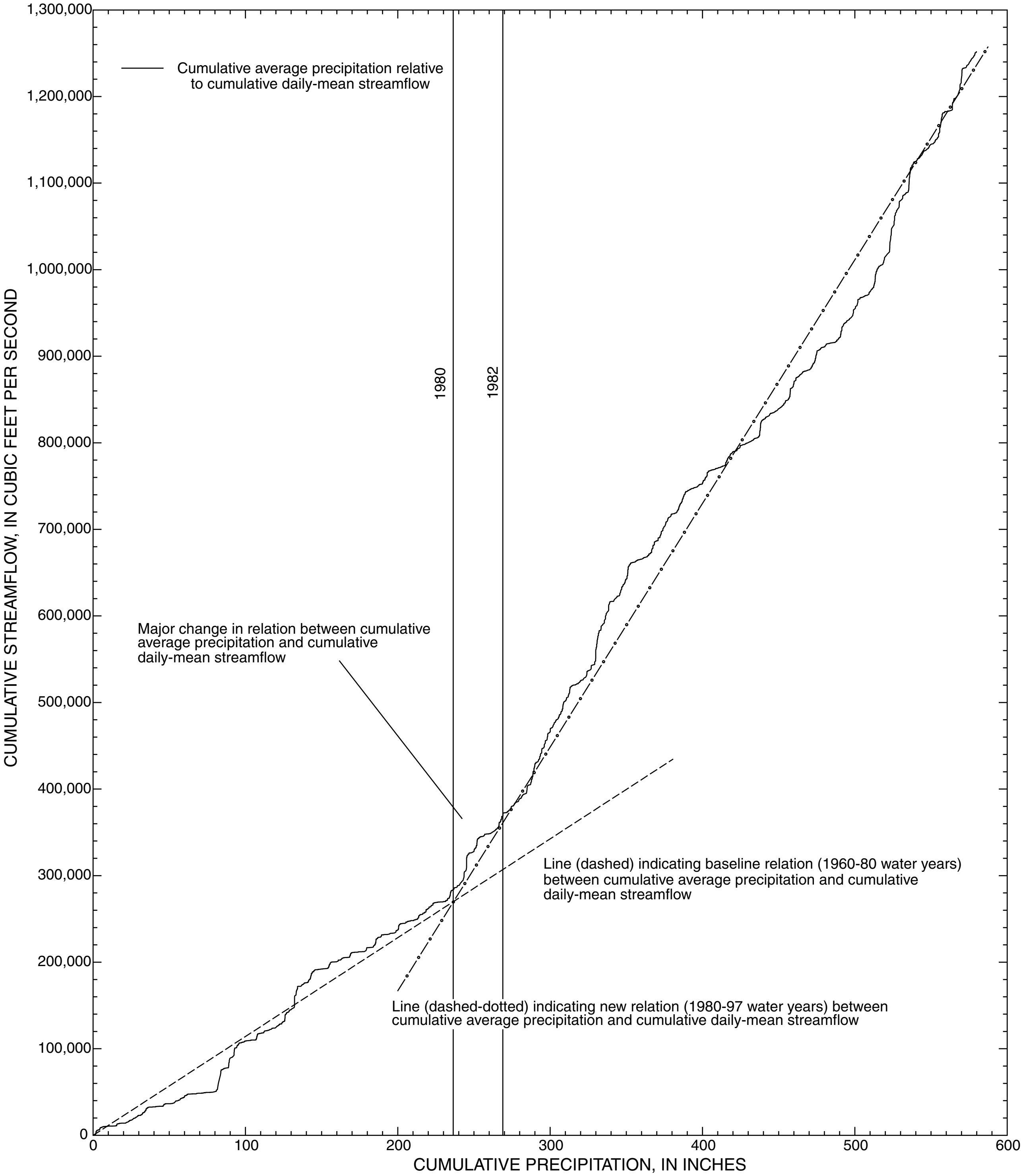


Figure 13. Relation between cumulative average precipitation at four precipitation gages in the Fountain Creek watershed and cumulative daily-mean streamflow at Pueblo, October 1959 through August 1997.

A seasonal evaluation of the relation between precipitation and streamflow was conducted for the typically dry base-flow months of November through February and the wetter snowmelt and summer months of March through October to determine if the influence of spring snowmelt and summer thunderstorms were biasing the interpretation of the relation. Precipitation and streamflow that coincided with dry and wetter periods were summed, averaged, and cumulated as before and compared using a double-mass curve (fig. 14). The analysis indicated that changes in the relation between precipitation and streamflow were nearly identical for the dry months of November through February and the wetter months of April through October. The similarity in the relation between the full year, the wetter months of March through October, and the dry months of November through February, a period which typically receives less than 15 percent of the total annual precipitation, suggests that changes in water management in the watershed had a pronounced effect on streamflow in the watershed, particularly downstream from Colorado Springs.

Several plausible reasons exist for the observed changes between cumulative precipitation and streamflow relation: (1) importation of transbasin water from outside the watershed, increased return flows, or changes in water operations could explain part of the increase in streamflow without a corresponding increase in precipitation; (2) the sparse spatial distribution of precipitation stations may have inadequately measured annual precipitation in the watershed, and therefore the relation between precipitation and streamflow was not accurately defined; (3) changes in land use within the watershed could have altered the hydrologic response of the watershed to precipitation events; or (4) observed changes in the relation between streamflow and precipitation in the watershed are due to a combination of these variables.

Synthesis of Streamflow Analysis

In general, instantaneous peak streamflows have not changed significantly during the periods of available record at most of the stations evaluated. The exceptions are that peak streamflows at Security have changed significantly since 1965 and peak streamflows at Pikeview have changed significantly since 1977.

Significant upward trends were detected in other high daily-mean streamflow statistics (Q_{70}, Q_{90}, Q_{100}, 7-, 14-, 30-day high streamflow duration) at the two stations, Near CO Spgs and Security, that had continuous streamflow record dating back to the mid-1950's and mid-1960's. After the streamflow records were divided into the pre-1977 and post-1976 time periods, no significant trends occurred in these high streamflow statistics for the pre-1977 time period. For the post-1976 period, highly to moderately significant upward trends in some of these high streamflow statistics were detected at most stations. The larger frequencies and high significance level of trends detected in the Q_{70} streamflow regime may be an indication that changes in land use within the watershed have increased the rate and magnitude of runoff for more moderate rainfall events that occur more frequently in the watershed than extreme rainfall events that affect the peak and annual maximum streamflows.

Analysis of low streamflow statistics (Q_0, Q_{10}, Q_{30}, 7-, 14-, 30-day low streamflow duration) generally indicates that the low streamflow regime has significantly increased throughout most of the watershed, particularly since the early 1980's. In addition, the average annual rate of increase in streamflow has tended to be largest at the stations downstream from Nevada Street. The increase in the low streamflow regime may be attributed to changes in water management including management of the Fountain Creek transbasin return-flow exchange decree, increases in wastewater effluent, and return flow from lawn watering and crop irrigation.

Analysis of changes in streamflow for five stream reaches also indicated that significant upward trends in high- and low-flow regimes have occurred within four reaches: Pikeview to Nevada Street, Near CO Spgs to Nevada Street, Nevada Street to Security, and Security to Pinon. Generally, the reach between Nevada Street and Security indicated a greater magnitude in the rate of increase in high streamflows than the other three reaches where significant trends were detected. Within this reach, the estimated annual increase in Q_{70} and Q_{90} streamflow was about 5 times larger than the estimated annual increase in the other three reaches that had significant upward trends. This trend is probably attributable to changes in the land use from rangeland to urban that occurred in the intervening drainage area over the past 23 years, altering the hydrologic response and increasing storm runoff.

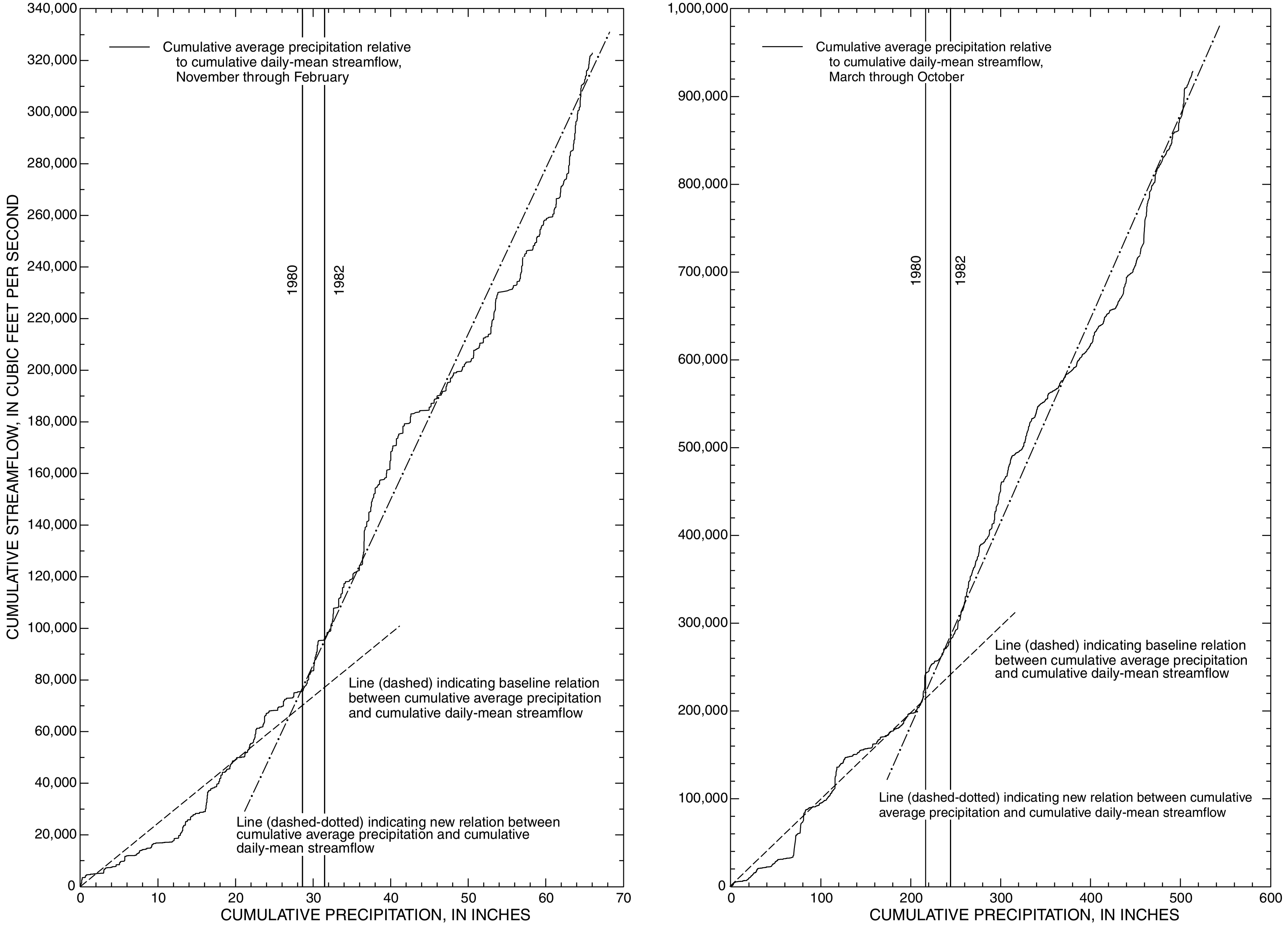


Figure 14. Relation between cumulative average precipitation at four precipitation gages in the Fountain Creek watershed and cumulative daily-mean streamflow at Pueblo, November through March and April through October, 1959–97.

The significant increase and large annual increase in the low streamflow regime in the reach between Nevada Street and Security have resulted from increased wastewater-treatment plant discharge associated with population growth and importation of transbasin water and management of Fountain Creek transbasin return-flow exchange decree.

The relation between streamflow at Pueblo and average precipitation in the watershed was evaluated. A marked change in the relation between streamflow and cumulative precipitation occurred between 1980 and 1982. A seasonal evaluation indicated that similar breaks occurred in the relation of cumulative streamflow and cumulative average precipitation for the base flow and snowmelt/summer flow regimes. This similarity indicates that changes in water management have had a marked effect on streamflow regimes for the entire year and not only during the base-flow period when precipitation is minimal. Other plausible reasons for the observed changes in the relation between precipitation and streamflow are: (1) the sparse spatial distribution of precipitation stations may have inadequately measured annual precipitation in the watershed, and therefore, the relation between precipitation and streamflow was not accurately defined; (2) changes in land use within the watershed could have altered the hydrologic response of the watershed to precipitation events; or (3) observed changes in the relation between streamflow and precipitation in the watershed are due to a combination of these variables.

STREAM MORPHOLOGY

Stream channels naturally change over time in response to streamflow characteristics and sediment delivery from the surrounding watershed (Leopold, and others, 1964; Schumm, 1977; Karlinger and others, 1983). Change in streamflow characteristics and(or) sediment delivery from the surrounding watershed will in turn initiate a series of responses as the channel adjusts to the changes.

Generalized Stream Channel Characteristics

Fountain and Monument Creeks are the primary perennial streams in the watershed. Although detailed morphological characterization of Fountain and Monument Creeks is beyond the scope of this report, in general, morphological characteristics of Fountain and Monument Creeks differ downstream from their origins in the Rampart Range to the confluence of Fountain Creek and the Arkansas River (fig. 1). Channel gradients decrease for both streams from the mountainous regions to the alluvial valley. Channel shape ranges from steep and narrow in the mountainous regions to broad and flat in the alluvial valley. The main sources of streamflow to Fountain and Monument Creeks are snowmelt, runoff from thunderstorms, wastewater-treatment-plant discharge, and irrigation return flows from municipal and agricultural water use.

Fountain Creek originates in the Pike National Forest at an elevation of about 9,200 ft near the community of Woodland Park (fig. 1). Fountain Creek generally flows to the southeast through the communities of Manitou Springs, Colorado Springs, Security, and Fountain and then south to Pueblo and the confluence with the Arkansas River. The stream channel upstream from Manitou Springs is characterized as meandering with a step-pool regime; bed material ranges from sand and gravel to cobbles and boulders. From Manitou Springs to the confluence with Monument Creek, Fountain Creek flows through a series of alluvial terraces into a wide alluvial valley. The stream channel in this valley is characterized as meandering with a pool-and-riffle regime and has bed material composed predominantly of sand, gravel, and cobbles. Downstream from the confluence with Monument Creek to the confluence with the Arkansas River, the channel of Fountain Creek is generally characterized as braided, and bed and bank material is predominantly sand and gravel. In this reach, the alluvial valley can be described as an arroyolike feature bounded on both sides by a steep, scarplike break that separates the active flood plain and high terraces (John Elliott, U.S. Geological Survey, written commun., 1999) upon which county roads, State and Federal highways, and railroad railbeds are located. Active streambank erosion is evident throughout this reach of the channel.

Monument Creek also originates in the Pike National Forest at an elevation of about 9,200 ft and flows east-northeast to the communities of Palmer Lake and Monument, then south to Colorado Springs and the confluence with Fountain Creek. Upstream from the confluence with Cottonwood Creek, the stream channel is characterized as meandering with a riffle-and-pool regime and has bed material consisting of sand, gravel, and cobbles (von Guerard, 1988). Just upstream from the confluence with Cottonwood Creek and continuing through the city limits, the stream-channel banks are lined with concrete and the channel becomes constrained laterally and possibly detached from the flood plain. Bed material is composed predominantly of sand and gravel.

Sediment Transport Capacity

The ability of streamflow to transport sediment (transport capacity) can be described by using the Shields dimensionless shear-stress relation for estimating the particle size of bed material at the threshold of movement (von Guerard, 1989). Maximum particle sizes of bed material that can be transported for various streamflows were estimated by using the following equation (von Guerard, 1989; Elliott and others, 1984):

$$dc = \left(\frac{\bar{D}S}{\left(\left(\left(\frac{\gamma s}{\gamma w}\right)-1\right)\tau^{*}{}_{c}\right)}\right)(308.4) \qquad (2)$$

where

dc = particle size of bed material, in millimeters, at threshold of movement;

$\bar{D}$ = mean channel depth, in feet;

S = water-surface slope;

$\frac{\gamma s}{\gamma w}$ = ratio of specific weights of sediment and water (2.65);

$\tau^{*}{}_{c}$ = dimensionless critical shear stress (the critical shear stress necessary for movement of bed material); and

304.8 = a unit conversion constant, in millimeters per foot.

Values of $\tau^{*}{}_{c}$ of 0.045 and 0.060 were used as the upper and lower limits for the transport of coarse materials in Fountain Creek (von Guerard, 1989).

Streamflow and channel morphology data collected during streamflow measurements at the Pueblo station were used to evaluate the capacity of streamflows to transport coarse sand and gravel of 1- to 32-mm size fractions. Analysis indicated that the minimum measured streamflow of 0.97 ft^3/s had the capacity to transport coarse to very coarse sands of 1 to 2 mm. This is consistent with field observations of bed-material transport during low-flow conditions. Analysis also indicated that the transport of bed material of the coarse gravel of 16- to 32-mm-size fractions was possible as streamflows approached and exceeded 2,000 ft^3/s. Analyses conducted by von Guerard (1989) indicated that, in the Colorado Springs area, Fountain and Monument Creeks were capable of transporting bed material of grain sizes similar to bed material at the Pueblo station.

Descriptive Assessment of Changes in Channel Morphology

Dramatic changes in channel morphology are most often associated with infrequent or catastrophic floods that cause rapid changes in channel shape and (or) location and capture the attention of area residents. Peak annual streamflow events greater than 10,000 ft^3/s on Fountain Creek at Pueblo occurred in 1921, 1924, 1935, 1942, 1944–46, 1951, 1955, 1965, 1980, 1994–97, and 1999. However, more frequent conditions associated with bankfull streamflow, while less striking, are considered to be the dominant force in development and maintenance of channel morphology (Leopold and others, 1964; Rosgen, 1996).

Changes in channel morphology along four reaches of Fountain Creek (fig. 1) were investigated using periodic aerial photography and field reconnaissance. River reaches R1, R2, and R3 were two linear miles long and extended north from the Highway 47 bridge (R1), extended 1 mile upstream and 1 mile downstream from the Overton Road bridge (R2), and extended north from the Pinon Road bridge (R3). River reach R4 extended about 20 miles from the town of Widefield to the Pinon Road bridge. Reconnaissance trips were conducted in April, May, September, and October of 1999. The September 1999 reconnaisance of river reach R4 from Widefield to the Pinon Road bridge was conducted by canoeing down Fountain Creek. All other reconnaisance was conducted by driving a motor vehicle to locations in or near the respective reaches and hiking to and along Fountain Creek. Evaluation of these four river reaches was used to make a general descriptive assessment of changes in channel morphology that occurred immediately after and during the interval between large streamflow events.

Analysis of aerial photographs taken in 1947, 1955, 1960, 1970, 1980, 1991, 1993, and 1999 indicated a pattern to changes in vegetation, channel width and length, and location of Fountain Creek within the alluvial valley between the steep scarps of the bounding high terrace. Initial aerial photography taken in 1947 and 1955 indicated sandbars denuded of vegetation. Spatial distribution of vegetation in the flood plain varied and generally was sparse. The sparseness of vegetation along Fountain Creek shown in the 1947 and 1955 aerial photographs represents a period when streamflow in lower Fountain Creek was intermittent, due to diversion of all streamflow for irrigation prior to increased low streamflows in the 1980's and 1990's, as noted earlier. The sparseness is also indicative of changes in vegetation in the alluvial valley following streamflow events of 10,000 ft^3/s or greater, as recorded at Pueblo. Streamflow events of this magnitude occurred in the months or years immediately prior to the 1947 and 1955 aerial photographs. Streamflow events of 10,000 ft^3/s at Pueblo have an annual exceedance probability of 0.2, meaning that flows of this magnitude have a probability of occurring once every 5 years (5-yr flood) and are, hereinafter, referred to as large streamflow events. Aerial photography taken in 1970 and 1991 following extended periods of time during which streamflows at Pueblo did not exceed 10,000 ft^3/s indicated a gradual return of vegetation to the flood plain and sandbars. The increase in vegetation appeared more striking in aerial photographs taken in 1991 and 1993 than 1970 and may be related to the lack of large streamflow events during the 1981 to 1993 time period, or to increased water availability due to increased low flows as noted in previous sections, or both. Aerial photographs taken in May 1999 again show the effects of large streamflow events. Extensive streambank and flood-plain erosion and the subsequent removal of vegetation were noted throughout much of river reaches R1, R2, and R3.

Visible changes in channel width, length, and location between the scarps of the high terrace were only observed in photographs taken after large streamflow events. Morphological changes after large streamflow events included increased channel width as banks and flood plain were scoured of vegetation; altered channel course as floodwaters reoccupied previously abandoned meanders or eroded valley alluvium to create a new channel; straightened channels as streamflow cut off meanders, thus shortening the stream reach; and increased meander amplitude as cutbanks at meander bends were further eroded by the energy of the floodwaters.

Increasing meander amplitude and channel migration were evident at the Overton Road bridge, the centroid of river reach R2 (fig. 15). At the centroid of R2, Fountain Creek flows in a wide meander from the northwest to the base of a high terrace and then southwest. The high terrace at this location is approximately 50 ft above the alluvial valley. Moderate to high streamflows in this meander undercut the high terrace. As the high terrace is undercut, large blocks of overlying material collapse into Fountain Creek. From 1955 to 1999, erosion of the cutbank or outer bank of the meander (fig. 16) resulted in eastward migration of the edge of the high terrace by approximately 280 ft. The eastward migration has occurred at increasing rates since 1970. Despite the historical peak streamflows of 1965, no appreciable changes in the distance between the edge of the high terrace and Overton Road were noted in aerial photographs taken between 1955 and 1970. During the period from 1970 to 1991, one large streamflow event occurred (1980) and the edge of the high terrace moved eastward approximately 100 ft, an average rate of about 5 ft per year. During the period from 1991 to 1999, five large streamflow events occurred and erosion of the cutbank resulted in the migration of the edge of the high terrace eastward about 160 ft, an average rate of about 20 ft per year. Reconnaissance from atop the high terrace prior to and after the April 1999 flood revealed that the edge of the high terrace migrated eastward about 15 ft (fig. 16) as a result of the high streamflows during the spring of 1999. Similar examples of erosion of the high terrace during the 1999 flood were observed or documented throughout the Fountain Creek watershed (Jay Frost, landowner, oral commun., 1999; Mackey and Williamson, written commun., 1999).

Analysis of aerial photography provided other examples of channel migration within river reaches R1, R2, and R3. Between 1955 and 1970, westward channel migration of approximately 1,000 ft occurred along the upper 1-mile stretch of reach R2 and 1,500 ft of a 0.2-mile stretch of reach R3. The apparent cause of channel migration was erosion of streambank and flood-plain sediments during the flood of 1965.

Figure 15. View looking south at the Overton Road bridge and edge of high terrace on April 26, 1999. Following the flood of April 28 through May 5, Overton Road at this location was reduced to one lane due to bank erosion after which the edge of the terrace extended a few feet into the southbound lane from the near foreground to the bridge.

Subsequent aerial photography revealed that high streamflows since 1965 have at times reoccupied all or parts of the abandoned channel.

Reconnaissance of Fountain Creek following the 1999 flood revealed the erosive power of the floodwaters as well as the sediment deposition as floodwaters receded. Structures and property affected by channel erosion and migration during the flood included railway roadbeds, bridges, roadways, and farmland. Extensive areas of the flood plain were also denuded of vegetation. News broadcasts during the flood and aerial photographs taken after the flood documented the loss of mature cottonwood trees, many of which were transported considerable distances downstream.

Observations of flood-plain aggradation prior to the flood of 1999 of about 1-ft at fence posts (Jay Frost, landowner, oral commun., 1999) indicate that flood-plain aggradation occurred at an average rate of about 0.3 in/yr for the period 1965 through 1998. However, it is more likely that flood-plain aggradation occurred during the five large streamflow events of 1980, and 1994 through 1997, depositing an average 2.4 inches of sediment during each of these large streamflow event years. Field reconnaissance of the four river reaches during September and October of 1999 and local accounts (Bill Alt, landowner, oral commun., 1999) revealed flood-plain aggradation as large amounts of sediment were deposited in the flood plain of Fountain Creek (fig. 17) following the 1999 flood.

More subtle changes in the channel occur at lower streamflows. Channel erosion in the form of bank erosion (figs. 17) and transport of bed material was commonly observed in 1999 throughout much of Fountain Creek from Widefield to Pueblo. Undercutting of the streambank occurs during bankfull and lower streamflows. Assuming a large streamflow event does not interrupt the process, bank and flood-plain sediments slough from the roots of the riparian vegetation as streamflow shifts laterally. If these sediments were not redeposited along the bank downstream, bank undercutting and sloughing would be followed by the eventual loss of the riparian vegetation. Channel modifications incurred during low flows generally progress slowly and are not as obvious or striking as those incurred during large streamflow events but are still important.

During periods lacking large streamflow events, 1970–80 and 1980–93, gradual increases in vegetation were noted along the streambank, sandbars, and flood plain. In conjunction with increases in streambank vegetation, mean channel widths decreased, and little if any change in channel location and length was noted. The apparent stability and lack of channel erosion as viewed in aerial photographs does not imply that changes were not occurring, only that they were not visible at the resolution available in the aerial photographs.

Channel aggradation may also be occurring, particularly in reaches within the lower one-half of reach R4. Reconnaissance during September 1999 revealed that the channel width and depth gradually changed from the upper one-half to the lower one-half of reach R4. The channel in the upper one-half of R4 was characterized by a relatively narrow channel with moderate flow depths capable of being canoed. The channel in the lower one-half of R4 was characterized by a broader channel with numerous sandbars and very shallow streamflow that generally was not negotiable by canoe. Based on observations made during the reconnaissance, it appears that sediment transport capabilities diminish in the lower one-half relative to the upper one-half of R4, resulting in the development of broad sandbars. With the diminished transport of stream sediments, streambed elevation increases, streamflow becomes shallower and flows over a broader area, and flow paths tend to move laterally, eroding bank sediments and periodically reworking the bed sediments.

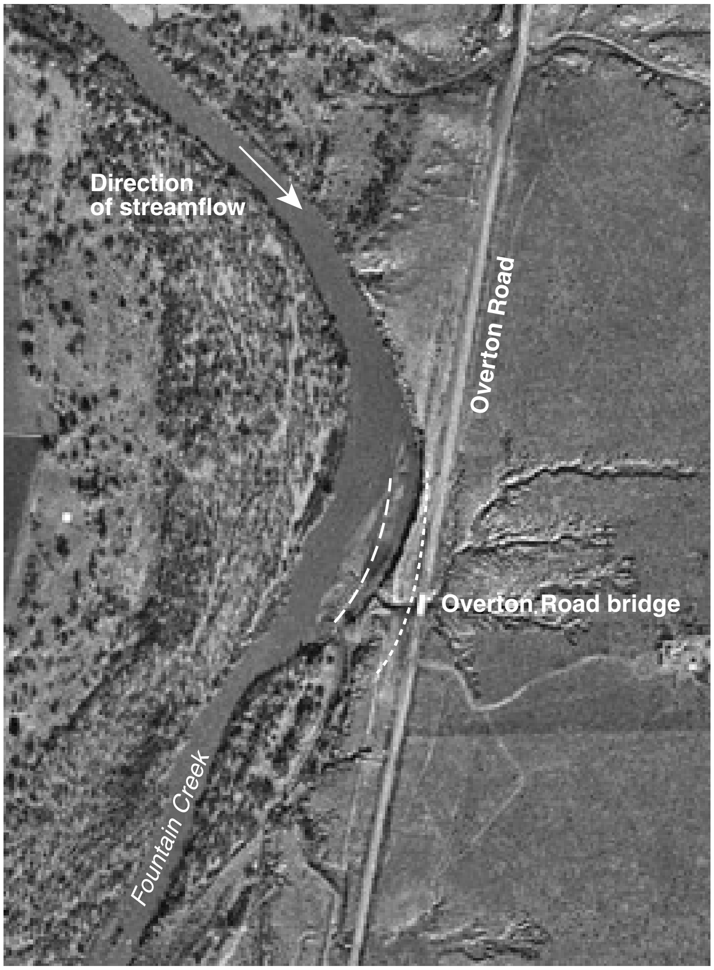


Figure 16. Aerial photograph of Fountain Creek at the Overton Road bridge in September 1991 and periodic changes in the general location of the high terrace from 1955 and 1970 (dashed line) through 1999 (dotted line) after the April 1999 flood.

Figure 17. Streambank erosion and sediment deposition on the flood plain of Fountain Creek.

Several plausible reasons exist for the observed changes in streambank erosion and channel migration. (1) Mass wasting of streambanks and the high terrace has been documented during and following large streamflow events. Accelerated rates of this type of erosion are the direct result of the increased frequency of large storm events and subsequent floods during the mid- to late-1990's and increased low streamflows of the 1980's and 1990's. (2) Differences in sedimentation patterns within selected reaches may be increasing streambed elevation, causing lateral shifts in flow paths. Increasing stage and(or) lateral shifts in the path of streamflow in Fountain Creek would cause erosion and instability of streambank sediments. Even with vegetation cover, coarse to very coarse sand is easily eroded. (3) Bankfull to low flows appear to be laterally eroding streambanks and aiding in the collapse of undercut regions of the high terrace. Estimates of sediment-transport capacity indicate that streamflows as low as 1.0 ft^3/s are capable of reworking the coarse sands to very coarse sands that are the predominant streambed and streambank sediments. Further investigation is needed to evaluate sedimentation characteristics of Fountain Creek and its effects on channel morphology.

SUMMARY AND CONCLUSIONS

Precipitation characteristics and trends in total annual and seasonal precipitation were evaluated for four stations in the Fountain Creek watershed.

1. An analysis of the pre-1977 period indicates that annual precipitation was generally below average, and no trends were detected in annual precipitation. An analysis of the post-1976 period indicates that annual precipitation was generally above average and upward trends were detected at the Ruxton Park and Pueblo stations.
2. There has been no change in the distribution or magnitude of rainfall occurring during a 24-hour period. However, mean annual precipitation was significantly greater during the post-1976 period than the pre-1977 period at Colorado Springs, Fountain, and Pueblo. Therefore, the differences between the two periods result from more days with rainfall rather than more rain during any given day.
3. An analysis of the pre-1977 period indicated no significant trend during any season. An analysis of the post-1976 period indicated moderately significant upward trends in spring precipitation at the Ruxton Park and Pueblo stations. The upward trends in annual precipitation for the

post-1976 period at the Ruxton Park and Pueblo stations are likely a result of the upward trends in spring precipitation at these stations.

Streamflow in the Fountain Creek watershed has three distinct flow regimes: base flow, spring snowmelt and storm runoff during the summer monsoon period. Trends in streamflow were evaluated for six stations in the Fountain Creek watershed. Data were divided into pre-1977, post-1976, and period of record time periods. Trends in annual instantaneous peak streamflow, 70th percentile, 90th percentile, maximum daily-mean streamflow (100th percentile), 7-, 14-, and 30-day high-flow duration, minimum daily-mean streamflow (0th percentile), 10th percentile, 30th percentile, and 7-, 14-, 30-day low-flow duration were evaluated.

1. In general, instantaneous peak streamflows have not changed significantly during the periods of available record at most of the stations evaluated. The exceptions being, peak streamflows at Security have changed significantly since 1965 and peak streamflows at Pikeview have changed significantly since 1977.
2. Significant upward trends were detected in other high streamflow statistics (Q_{70}, Q_{90}, Q_{100}, 7-, 14-, 30-day high daily-mean streamflow duration) at the two stations that had continuous streamflow record dating back to the mid-1950’s and mid-1960’s. After the streamflow records were divided into the pre-1977 and post-1976 time periods, no significant trends occurred in these high streamflow statistics for the pre-1977 time period. For the post-1976 period, highly to moderately significant upward trends in some of these high streamflow statistics were detected at most stations. The larger frequencies and high significance level of trends detected in the Q70 streamflow regime may be an indication that changes in land use within the watershed have increased the rate and magnitude of runoff for more moderate rainfall events that occur more frequently in the watershed than extreme rainfall events that effect the peak and annual maximum streamflows.
3. Analysis of low streamflow statistics (Q_{70}, Q_{90}, Q_{100}, 7-, 14-, 30-day low streamflow duration) generally indicate that the low streamflow regime has significantly increased throughout most of the watershed, particularly since the early 1980’s. The increase in the low streamflow regime may be attributed to changes in water management including management of the Fountain Creek transbasin return-flow exchange decree, increases in wastewater effluent, and return flow from lawn watering and crop irrigation.
4. Analysis of changes in streamflow for five stream reaches also indicated that significant increasing trends in high- and low-flow regimes have occurred. Trends are probably attributable to changes in the land use from rangeland to urban that occurred over the past 23 years altering the hydrologic response and increasing storm runoff, increased wastewater-treatment-plant discharge associated with population growth, and importation of transbasin water and management of Fountain Creek transbasin return-flow exchange decree.
5. The relation between streamflow at Pueblo and average precipitation in the watershed was evaluated. A marked change in the relation between daily-mean streamflow and cumulative average precipitation occurred between 1980 and 1982. A seasonal evaluation indicated that similar breaks occurred in the relation of cumulative streamflow and cumulative average precipitation for the base flow and snowmelt/summer flow regimes. This similarity indicates that changes in water management have had a marked effect on streamflow regimes for the entire year and not only during the base-flow period when precipitation is minimal. Other plausible reasons for the observed changes in the relation between precipitation and streamflow include (1) the sparse spatial distribution of precipitation stations may have inadequately measured annual precipitation in the watershed, and therefore, the relation between precipitation and streamflow was not accurately defined; (2) changes in land use within the watershed could have altered the hydrologic response of the watershed to precipitation events; or (3) observed changes in the relation between streamflow and precipitation in the watershed are due to a combination of these variables.

Bed and bank material of Fountain Creek is composed predominantly of sand and gravel. The capacity of streamflows in Fountain Creek at Pueblo to transport sediment in the sand- and gravel-size fractions was evaluated. Estimates of transport capacity indicate that streamflows less than 1 ft^3/s had the capacity to transport coarse to very coarse sands of the 1- to 2-mm-size fraction, and streamflows of 2,000 ft^3/s or more had the capacity to transport very coarse gravel in the 32-mm-size fraction.

Changes in channel morphology within four reaches of Fountain Creek were evaluated with aerial photography and field reconnaissance.

1. Analysis indicated changes in vegetation and channel characteristics were associated with the frequency of large streamflow events. Sandbars, streambanks, and the flood plain were denuded following large streamflow events, whereas gradual revegetation occurred over extended time periods that lacked large streamflow events.
2. While subtle, erosion caused by low streamflows were an important component of day-to-day channel erosion.
3. Substantial changes in channel morphology were most often associated with infrequent large or catastrophic streamflow events that erode streambed and banks, alter stream course, and deposit large amounts of sediment in the flood plain.

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