Estimated Predevelopment Discharge to Streams From the High Plains Aquifer in Northwestern Oklahoma, Southwestern Kansas, and Northwestern Texas

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CONVERSION FACTORS AND VERTICAL DAT

Multiply	By	To obtain
	Length	
inch	2.54	centimeter
mile	1.609	kilometer
acre	4,047	square meter
	Flow rate	
acre-foot	1,233	cubic meter
foot per day	0.3048	meter per day
cubic foot per second	0.02832	cubic meter per second
cubic foot per second per mile	0.04557	cubic meter per second per kilometer

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ABSTRACT

A study of the High Plains aquifer in Oklahoma was initiated in 1996 to: (1) provide the information needed by the Oklahoma Water Resources Board to manage the quantity of water produced from the aquifer; and (2) provide baseline water-chemistry data. The approach used to meet the first objective is to develop a digital ground-water flow model. The model will be calibrated, in part, by comparing simulated and estimated predevelopment discharge from the aquifer to streams and cross-boundary flow. This report presents the estimated predevelopment discharge to streams from the High Plains aquifer.

Streamflow data were the primary source of information used to estimate predevelopment discharge from the High Plains aquifer. Data from 30 streamflow stations between the Arkansas and Canadian Rivers were considered in the analysis, and winter low-flow frequencies for 7-, 14-, and 30-day periods were determined for 25 stations. The 14-day low flow with a recurrence interval of 2 years was the primary value used to estimate predevelopment discharge from the aquifer.

The streams that drain the eastern part of the High Plains aquifer in Kansas (generally east of 99.5 longitude) are estimated to have had large predevelopment discharge from the aquifer, and most of them received discharge from near their headwaters. For streams with more than one streamflow gage, the upper perennial reaches appeared to have gained more discharge from the aquifer than the lower reaches. The total predevelopment discharge from the aquifer in this area to several streams is estimated to have been about 312 cubic feet per second, not including discharge that probably went directly to the Arkansas River. The Cimarron River and its tributaries are estimated to have gained about 78 cubic feet per second, but nearly one-half that amount was lost in the lower reaches of the river. The cause of the loss in the lower reaches is unknown. The Beaver River and its tributaries are estimated to have gained a net of about 10 cubic feet per second above Wolf Creek with the upper reaches gaining more than the lower reaches. Wolf Creek is estimated to have gained 30 cubic feet per second over its total length.

INTRODUCTION

The High Plains is a major agricultural area, supported in large part by water from the High Plains aquifer. The aquifer underlies about 174,000 square miles in parts of eight states (Weeks and others, 1988) including 7,350 square miles in northwestern Oklahoma (fig. 1). The aquifer is recharged by infiltration of precipitation that falls on the High Plains, either directly where it falls or after it has moved some distance overland. To a lesser degree, the aquifer also is recharged by infiltration of streamflow that originates west of the High Plains. Water in the aquifer generally flows from west to east although locally flow is towards streams that are incised onto the aquifer. Gutentag and others (1984, p. 28) estimated the average velocity of water in the aquifer under natural conditions is approximately 1 foot per day. Water discharges naturally to streams and small springs and seeps in the eastern part of the High Plains aquifer where the water level in the aquifer rises to near or above land surface. Additional water leaves the aquifer naturally by moving across the eastern boundary, by discharging to the atmosphere by evapotranspiration where the depth to water is shallow, or by flowing into underlying aquifers. Streamflow is the largest natural discharge from the aquifer. Most discharge to springs and seeps and most cross-boundary flow becomes streamflow in a relatively short distance. When evapotranspiration decreases during the winter, streamflow and seepage increase correspondingly. During the last few decades, pumpage has become a major artificial discharge from the aquifer and has caused water-level declines and streamflow reductions.

The Oklahoma High Plains are semiarid. Normal precipitation (1961-90) ranges from about 16 to 26 inches per year with the panhandle receiving less than 22 inches per year (Dugan and Sharpe, 1996, fig. 2). Mean annual evaporation from Class-A pans exceeds 90 inches over most of the area (Thelin and Heimes, 1987, fig. 2). Much of the precipitation occurs during summer thunderstorms with the winters generally being cold and dry (fig. 2). All references to precipitation in this report are based on data found in the annual climate summaries for the various states (National Oceanic and Atmospheric Administration).

In 1995, about 17.9 million acre-feet of water were pumped from the eight-state High Plains aquifer; about 95 percent of the water was used of irrigation (data from U.S. Geological Survey National Data Storage and Retrieval System). This is up somewhat from 1990 when about 16.5 million acre-feet of water were pumped from the aquifer (Dugan and Cox, 1994, table 3). In the Oklahoma High Plains, about 540,000 acre-feet of water were pumped in 1980 to irrigate about 389,000 acres (Thelin and Heimes, 1987, table 7). Pumpage in the Oklahoma High Plains decreased to 406,000 acre-feet in 1990 (Dugan and Cox, 1994, table 3), a particularly wet year, and increased to about 750,000 acre-feet in 1995 (1995 data from U.S. Geological Survey National Data Storage and Retrieval System). Most of the pumpage from the High Plains aquifer in Oklahoma occurs in Beaver, Cimarron, and Texas Counties.

Oklahoma High Plains agricultural practices have changed dramatically in the last 50 years. In 1950 less than 10,000 acres of the Oklahoma High Plains were irrigated, based on U.S. Census of Agriculture data. By 1960 irrigated acreage increased to more than 50,000 acres and by 1965 was more than 100,000 acres. Irrigated acreage, as reported by the census, reached a high of more than 300,000 acres in 1978 and has since declined somewhat to about 270,000 acres in 1992, the last year in which census data are available. While some crops can be grown in the Oklahoma High Plains without irrigation, many crops require irrigation, and irrigation can increase yields from virtually all crops.

The U.S. Geological Survey, in cooperation with the Oklahoma Water Resources Board, initiated a study of the High Plains aquifer in Oklahoma in 1996 to: (1) provide the Water Resources Board with the information needed to manage the quantity of water produced from the aquifer; and (2) provide baseline water-chemistry data that could be used to determine if the quality of water in the aquifer is becoming degraded. The approach used to meet the first objective of the study is to develop a digital ground-water flow model. The model will concentrate on the Oklahoma portion of the aquifer, but its boundaries will extend from the Canadian River in Texas to the Arkansas River in Kansas. The ground-water flow model will be calibrated against observed conditions, including both water levels in the aquifer and natural outflow from the aquifer. Natural outflow from the High Plains aquifer includes discharge to streams, flow across the eastern boundary, discharge by evapotranspiration, and discharge to springs and seeps. This report contains information about natural outflows from the aquifer and, the ground-water flow model of the area will be calibrated, in part, using the information in this report.

Purpose and Scope

The purpose of this report is to present estimates of the predevelopment discharge to streams from the High Plains aquifer (fig. 1). The discharges were estimated for the area of the High Plains aquifer between the Arkansas and Canadian Rivers and the areas immediately east of the aquifer where cross- boundary flow may be collected by streams. Because of the season used in the analysis in this report, the discharge to streams includes flow across the eastern boundary of the aquifer, discharge by evapotranspiration, and discharge to springs and seeps. Predevelopment refers to the period prior to major development of the aquifer for irrigation. Development of the aquifer in Oklahoma began in the 1950's and accelerated in the late 1960's. However, most streams did not see the effect of development until the 1970's.

Streamflow gaging network

Streamflow data were the primary source of information used to estimate predevelopment discharge from the High Plains aquifer. All daily-value streamflow gaging stations between the

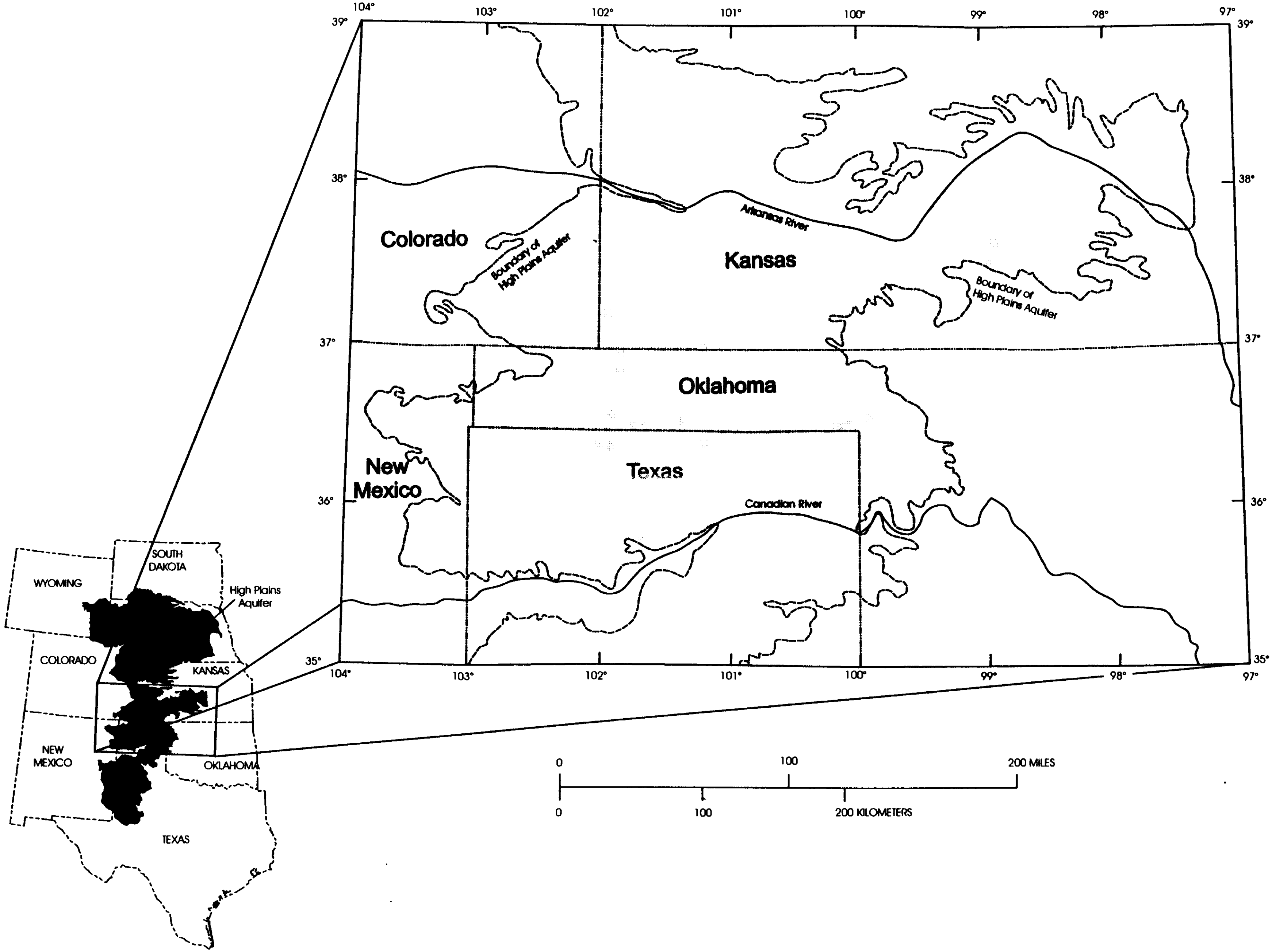

Figure 1. Location of study area.

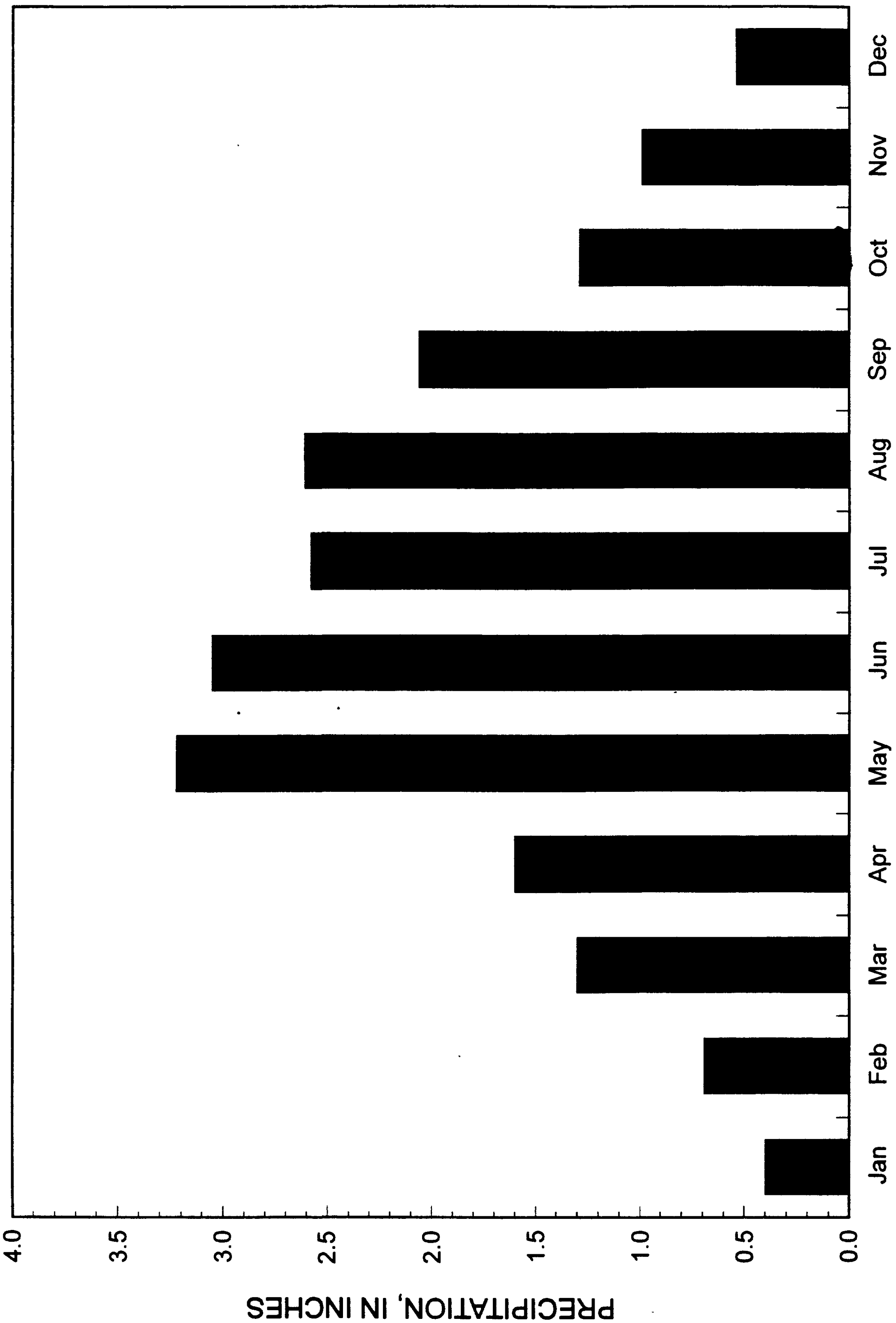

Figure 2. Average monthly precipitation for the Oklahoma panhandle (Oklahoma Climate Division 1) from 1961 through 1990.

Arkansas and Canadian Rivers that were on the High Plains or east of the boundary of the High Plains and potentially received a major part of their flow during nonrunoff periods from the High Plains aquifer were considered for analysis (table 1, fig. 3). Some study-area stations in the western part of the High Plains flow only after runoff events, do not receive discharge from the aquifer, and are not listed in table 1. Streamflows at some stations were found to be influenced by human activity; when estimating discharge from the aquifer at these stations, the likely effects of human activity were taken into account.

Stations on the Arkansas and Canadian Rivers were not used to estimate discharge from the aquifer. These rivers may be the northern and southern boundaries of the flow model, and even if the contribution of the High Plains aquifer to the flow of these streams could be determined, a major part of the contribution may be coming from areas outside of the flow model. More importantly, these rivers are so highly regulated by human activity that the streamflow record is not likely to yield reliable information about discharge from the aquifer. A major reservoir regulates the Canadian River just before it enters the High Plains, and this reservoir dominates downstream flow. In addition, only one streamflow station is on the Canadian River on the High Plains, and the next downstream station is far east of the High Plains. The Arkansas River has a number of streamflow stations on the High Plains. However, this river also is very heavily regulated by upstream reservoirs and irrigation diversions, and both reservoir operations and irrigation diversions have changed substantially with time.

The station number, described in the next paragraph, is the unique identifier for streamflow gaging stations. The station name is a more commonly recognized identifier. The station name identifies the stream name and a nearby geographic feature, generally a town. However, some of the towns used in the station names are quite small and may not be shown on many maps. The stations are shown on figure 3, but neither figure 3 nor any other figure in this report includes all of the towns used in the stations names. The exact location of the streamflow stations can be determined from the information in table 1.

U.S. Geological Survey streamflow gaging stations are numbered in a downstream direction along the main stem (Blazs and others, 1994). Stations on tributaries are numbered between stations on the main stem where the tributary enters the main stem. Gaps are left in the numbering system to allow for additional stations. Each station number contains eight digits (table 1). The first two digits designate the major river basin; all stations in this report begin with 07 for the Lower Mississippi River Basin. Stations in this report beginning with 0714 are tributary to the Salt Fork of the Arkansas River or the Arkansas River below the Salt Fork, while stations beginning with 0715 are on or tributary to the Cimarron River. Stations in this report beginning with 0723 are on or tributary to the North Canadian River. For example, Wolf Creek near Fargo, Oklahoma, is assigned the number 07236000, which means it is downstream from the station near Shattuck, Oklahoma, (station 07235500) and upstream from the station near Fort Supply, Oklahoma, (station 07237000).

LOW-FLOW ANALYSIS

Low flow in natural streams generally represents the contribution of the ground-water system to streamflow. In the far western part of the High Plains, the aquifer does not contribute flow to streams because the water level in the aquifer is below the bottom of the stream channel. Further east, the stream channel intersects the aquifer and the aquifer contributes flow to streams.

Most of the streamflow on the High Plains during the winter is discharge from the aquifer. During the summer, discharge from the aquifer can be masked by runoff from precipitation, release of water from bank storage that occurred during prior runoff periods, and evapotranspiration along the stream. Seventy five percent of the total annual precipitation on the High Plains falls during April through September (fig. 2). The least precipitation occurs in December through February when only 8 percent of the annual total occurs, usually in the form of snow. There is generally little runoff from December through February period, and bank storage from previous runoff periods probably has essentially drained by the early part of December. Evapotranspiration during this period is at an annual minimum, and residual effects from evapotranspiration during the previous summer probably are minimal. By only considering the lowest flows that occur during the winter, the possibility of including the effects of runoff or releases from bank storage in the analysis is further reduced. Evapotranspiration could affect the analysis during

Table 1. Streamflow stations used in the analysis of predevelopment discharge from the High Plains aquifer

Station number	Station name	County	Latitude	Longitude	Starting winter for analysis	Ending winter for analysis
07142300	Rattlesnake Creek near Macksville, Kansas	Stafford	37° 52′ 20″	98° 52′ 30″	1959-60	1992-93
07142575	Rattlesnake Creek near Zenith, Kansas	Stafford	38° 05′ 37″	98° 32′ 45″	1973-74	1992-93
07142620	Rattlesnake Creek near Raymond, Kansas	Rice	38° 13′ 50″	98° 25′ 00″	1960-61	1992-93
07144780	North Fork Ninnescah River above Cheney Reservoir, Kansas	Reno	37° 50′ 41″	97° 56′ 09″	1965-66	1992-93
07144800	North Fork Ninnescah River near Cheney, Kansas	Sedgwick	37° 40′ 00″	97° 46′ 00″	1950-51	1963-64
07144910	South Fork Ninnescah River near Pratt, Kansas	Pratt	37° 38′ 16″	98° 43′ 14″	1980-81	1992-93
07145200	South Fork Ninnescah River near Murdock, Kansas	Kingman	37° 33 ′51″	97° 51′ 10″	1950-51 1964-65	1958-59 1992-93
07149000	Medicine Lodge River near Kiowa, Kansas	Barber	37° 02′ 17″	98° 28′ 04″	1937-38 1954-55 1959-60	1949-50 1954-55 1992-93
07151500	Chikaskia River near Corbin, Kansas	Summer	37° 07′ 44″	97° 36′ 04″	1950-51 1975-76	1964-65 1992-93
07156800	Cimarron River near Liberal, Kansas	Seward	37° 08′ 55″	100° 44′ 57″	1938-39	1941-42
07156900	Cimarron River near Forgan, Oklahoma	Meade, KS	37° 00′ 40″	100° 29′ 29″	1965-66 1987-88	1985-86 1992-93
07157000	Cimarron River near Mocane, Oklahoma	Beaver	36° 58′ 33″	100° 18′ 50″	1942-43	1964-65
07157500	Crooked Creek near Englewood, Kansas	Meade	37° 01′ 54″	100° 12′ 29″	1942-43	1992-93
07157580	Cimarron River near Englewood, Kansas	Harper, OK	36° 58′ 38″	99° 58′ 32″	1981-82	1986-87
07157740	Cimarron River near Buttermilk, Kansas	Comanche	37° 01′ 36″	99° 28′ 04″	1972-73	1978-79
07157940	Bluff Creek near Buttermilk, Kansas	Comanche	37° 01′ 55″	99° 28′ 45″	1973-74	1978-79
07157950	Cimarron River near Buffalo, Oklahoma	Harper	36° 51′ 07″	99° 18′ 54″	1960-61	1992-93
07157960	Buffalo Creek near Lovedale, Oklahoma	Harper	36° 46′ 14″	99° 22′ 00 "	1966-67	1992-93
07232500	Beaver River near Guymon, Oklahoma	Texas	36° 43′ 17″	101° 29′ 21″	1937-38	1992-93
07232900	Coldwater Creek near Guymon, Oklahoma	Texas	36° 34′ 19″	101° 22′ 52″	1980-81	1992-93
07233000	Coldwater Creek near Hardesty, Oklahoma	Texas	36° 38′ 38″	101° 12′ 38″	1939-40	1963-64
07233500	Palo Duro Creek near Spearman, Texas	Hansford	36° 12′ 08″	101° 18′ 20″	1945-46	1978-79
07233650	Palo Duro Creek at Range, Oklahoma	Texas	36° 32′ 38″	101° 04′ 50″	1991-92	1992-93
07234000	Beaver River at Beaver, Oklahoma	Beaver	36° 49′ 20″	100° 31′ 08″	1937-38	1977-78
07234100	Clear Creek near Elmwood, Oklahoma	Beaver	36° 38′ 42″	100° 30′ 07″	1965-66	1992-93
07235000	Wolf Creek at Lipscomb, Texas	Lipscomb	36° 14′ 19″	100° 16′ 31″	1961-62	1992-93
07235500	Wolf Creek near Shattuck, Oklahoma	Ellis	36° 17′ 10″	99° 54′ 45″	1937-38	1945-46
07236000	Wolf Creek near Fargo, Oklahoma	Ellis	36° 23′ 57″	99° 37′ 22″	1942-43	1975-76
07237000	Wolf Creek near Fort Supply, Oklahoma	Woodward	36° 34′ 00″	99° 33′ 05″	1942-43	1977-78
07237500	North Canadian River at Woodward, Oklahoma	Woodward	36° 26′ 12″	99° 16′ 41″	1942-43	1977-78

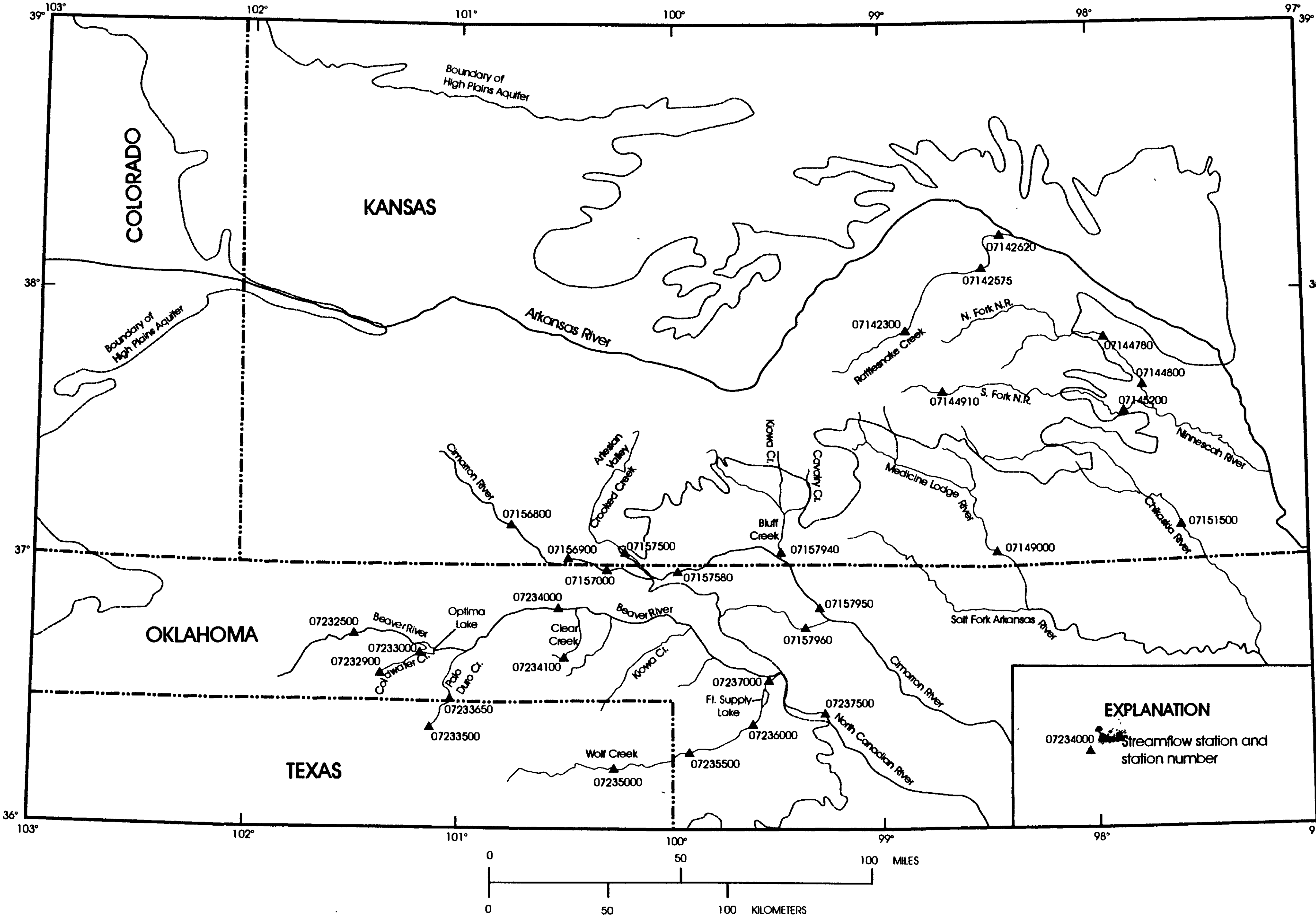

Figure 3. Streamflow stations used in the analysis of discharge from the High Plains aquifer.

unusually warm winter periods, but this effect is reduced by considering flow periods ranging from a week to a month, at least part of which should not include substantial evapotranspiration.

The lowest mean streamflow for 7, 14, and 30 consecutive days for each December-February period was determined. The 7-, 14-, or 30-day winter low flows were ranked from smallest to largest for the period of analysis. The period of analysis generally was the period of the streamflow record, but in some cases where the winter low flow appeared to change with time the period of record was subdivided. The probability that lowest mean flow was not exceeded was calculated using the formula (Riggs, 1968, p. 7)

$$P\{nonexceedence\}=K \div (N+1) \qquad (1)$$

where

P{nonexceedence} is the probability that the flow is not exceeded in any one winter;

K is the rank number of the winter with the year with lowest flow ranked 1 and the year with highest flow ranked N; and

N is the number of winters in the period of analysis.

The recurrence interval, which is simply the reciprocal of the probability of nonexceedence, was calculated using the formula:

$$T=1 \div P\{nonexceedence\}=(N+1) \div K \qquad (2)$$

where

T is the recurrence interval, in years; and the other variables are as defined in equation 1.

The logarithm of the 7-, 14-, or 30-day lowest mean winter flow was plotted against the recurrence interval and a smooth curve was fitted to the points using a Pearson Type III distribution (Riggs, 1968, p. 4-6). The curve was then used to estimate the long-term recurrence intervals for the 7-, 14-, or 30-day lowest mean winter flow. Figure 4 illustrates this process for the Beaver River near Guymon, Oklahoma, for data through the winter of 1974-75. The 7-day winter low flow with a recurrence interval of 2 years is 4.0 cubic feet per second. This means that the probability that the lowest mean flow for a 7-day period will not exceed 4.0 cubic feet per second in any one winter is 0.5, or that, on a long-term average, the lowest winter mean flow for a 7-day period will be less than 4.0 cubic feet per second for one year out of two. The 30-day winter low flow with a recurrence interval of 5 years is 4.4 cubic feet per second. This means on a long-term average, the lowest mean winter flow for a 30-day period will be less than 4.4 cubic feet per second for one year out of five, and the probability that the lowest mean flow for a 30-day period in any one winter will not exceed 4.4 cubic feet per second is 0.2. The lowest mean winter flow increases as the number of days in the flow period increases or as the recurrence interval decreases. For example, for the Beaver River near Guymon, Oklahoma, the winter low flow with a recurrence interval of 2 years is 4.0 cubic feet per second for a 7-day period whereas it is 6.0 cubic feet per second for a 30- day period. The 14-day winter low flow is 3.4 cubic feet per second for a 5-year recurrence interval whereas it is 4.9 cubic feet per second for a 2-year recurrence interval.

If the lowest mean winter flow does not change much as the period or the recurrence interval changes, the stream has very stable low flow. Stable winter low flow indicates that the streamflow likely is ground-water discharge from a large area of the aquifer that integrates recharge over a long period of time and that little else influences winter streamflow. Less stable winter low flow may indicate that ground-water discharge may be occurring from a more local area of the aquifer that does not integrate recharge over a long period of time, evapotranspiration may not be minimal in some years, or something other than ground-water discharge may be influencing winter streamflow.

PREDEVELOPMENT DISCHARGE FROM THE HIGH PLAINS AQUIFER

The 7-, 14-, and 30-day low flows for December through February were characterized for those stations where a sufficient number of years of record were available to estimate winter low-flow frequency characteristics. No fixed period of record was required for low-flow frequencies to be characterized; shorter periods of record were accepted for stations with stable winter flows while longer periods were required if winter flows were more variable. The estimated winter low-flow frequencies are shown in table 2. No single low-flow characteristic was chosen to estimate predevelopment discharge from the aquifer, but estimated predevelopment discharges tended to frequently rely on the 14-day winter low flow with a recurrence interval of 2 years. This value is referred to as the "2-year, 14-day winter low flow" in the remainder of this report. The 30-day low flows contained some possible runoff events for some years and may tend to

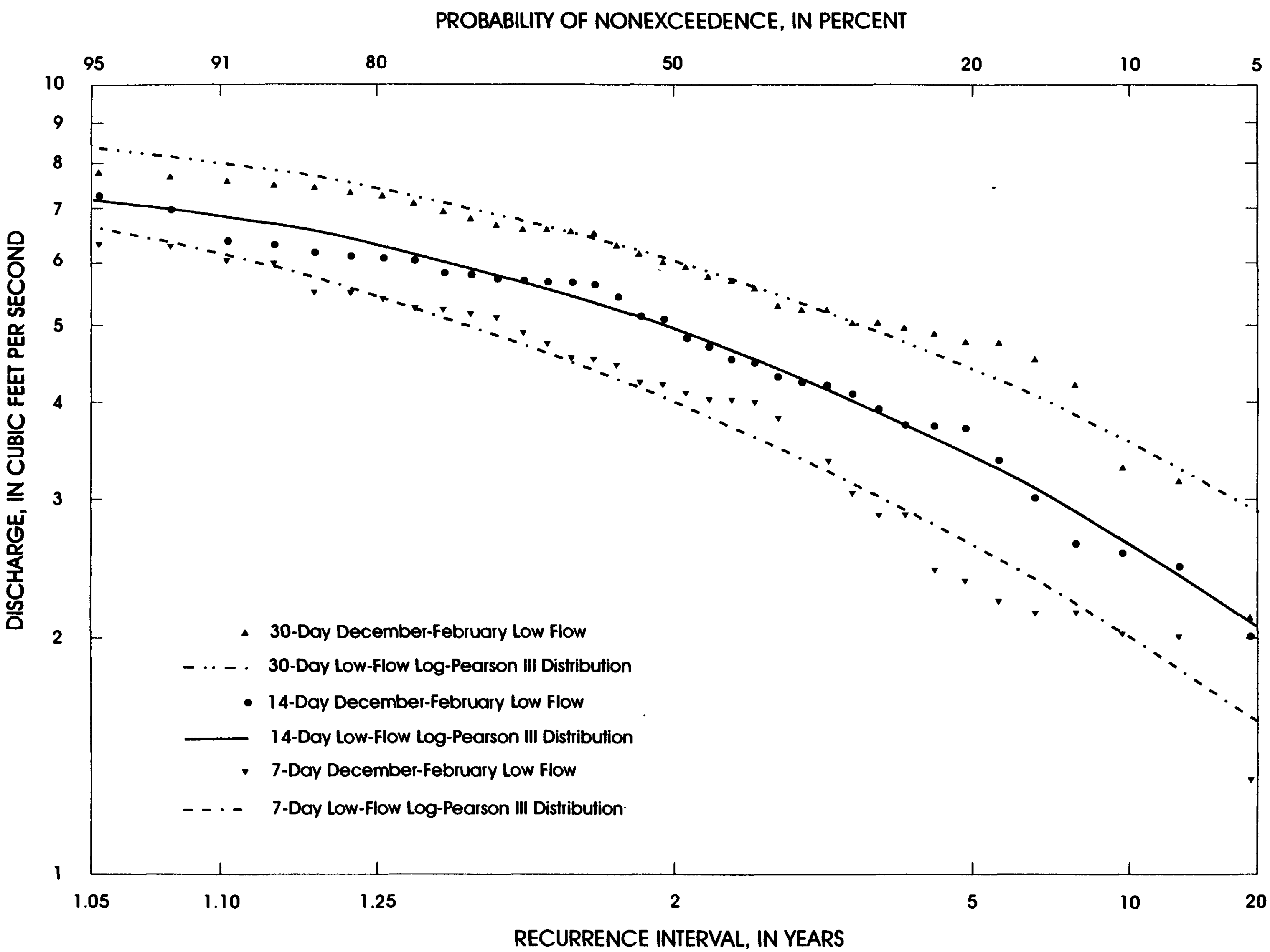

Figure 4. Frequency curves for 7-, 14-, and 30-day December-February low flows for Beaver River near Guymon, Oklahoma, (station 07232500) for winters of 1937-38 through 1974-75.

overestimate discharge from the aquifer. The 7-day low flows may give too much weight to periods of unusually low streamflow that may be the result of either evapotranspiration or, in rare cases, temporary reduction of streamflow due to ice conditions. However, for many stations, the choice of the low-flow period would not substantially alter the estimate of predevelopment discharge from the aquifer. The 2-year recurrence interval was used because it represents a median value; on the average, about one half of the years would have more low flow than the 2-year value and one-half of the years would have less low flow.

Some, but not all, winter low flows changed with time. They frequently appeared to decrease due to development of the aquifer, so the predevelopment discharge was estimated to be greater than the 2-year, 14-day winter low flow. In many cases, the predevelopment discharge was estimated based on the median 14-day winter low flow for the earlier part of the record that did not appear to be affected by development. If the period of record was too short to calculate winter low-flow characteristics, the record was examined and, in a few cases, the predevelopment discharge from the aquifer was estimated. However, estimates not based on low-flow frequencies probably are less reliable and certainly are less reproducible than those based on low-flow frequencies.

Some measurements of low flows made at places other than streamflow stations were used to estimate predevelopment discharge from the High Plains aquifer. These measurements generally represent only a single point in time and estimates of discharge from the aquifer based on these are considered poor. Observations of the stream itself or discussions with people familiar with the stream also were used in a few cases to estimate predevelopment discharge. These estimates of discharge from the aquifer also are considered poor.

Topographic maps were used to estimate the point at which the streams began to receive discharge from the aquifer prior to major development of the aquifer for irrigation. This point might be indicated by the stream becoming perennial, by springs along the stream, or by woodland vegetation indicated on the map.

The following sections are arranged roughly from north to south and generally follow the station number order used in tables 1 and 2. The stations or other information usually are discussed in downstream order within a section. The downstream ordering allows the reader to note whether a stream is receiving additional discharge from or losing water to the aquifer in the reach.

Rattlesnake Creek

Rattlesnake Creek drains the eastern part of the High Plains in Kansas south of the Arkansas River between approximately 98.5 and 99.5 longitude (fig. 3). This area had rapid ground-water development for irrigation in 1973-74 (Fader and Stullken, 1978). Pumpage of ground water has caused water-table declines and decreased ground-water discharge to streams.

The uppermost station on Rattlesnake Creek is near Macksville, Kansas, (station 07142300). The record at this station began just prior to the winter of 1959-60. The 2-year, 14-day winter low flow for the winters of 1959-60 through 1992-93 is 13 cubic feet per second (table 2). The winter low flows appear to have decreased substantially with time (fig. 5). The median 14-day winter low flow for the 1960's (ending in February 1969) is 23 cubic feet per second; for the 1970's is 18 cubic feet per second; and for the 1980's is 6 cubic feet per second. The high winter flow in 1973-74 was the result of precipitation in September and October 1973, which exceeded 14 inches (National Oceanic and Atmospheric Administration). The effect of this unusually large precipitation on winter low flows persisted for several years. The flow in the 1960's appeared to decrease with time, although this was prior to major irrigation development and probably represented a return to more normal conditions following the wet years 1957-61 (National Oceanic and Atmospheric Administration). The predevelopment discharge from the High Plains aquifer upstream from this point on the stream is estimated to have been about 23 cubic feet per second (table 2), based on the median 14-day winter low flow for the first decade of record.

The next downstream station on Rattlesnake Creek is near Zenith, Kansas, (station 07142575). The record at this station, which began before the winter of 1973-74, also appears to show decreased winter flow with time. The 2-year, 14-day winter low flow for the winters of 1973-74 through 1992-93 is 18 cubic feet per second (table 2). The median 14-day winter low flow for 1974-79 (ending in February 1979) was 44 cubic feet per second; for 1980-89 was 19 cubic feet

Table 2. Streamflow stations with December-February low-flow analysis and estimated predevelopment discharge from the High Plains aquifer

[--, value not computed or estimated; ≈,approximately]

Station number	Station name	Discharge for indicated recurrence interval and flow period (cubic feet per second)					Estimated predevelopment discharge (cubic feet per second)	Remarks
		Recurrence interval (years)	Nonexceedence probability	Flow period (consecutive days)				
				7 days	14 days	30 days		
07142300	Rattlesnake Creek near Macksville, Kansas	1.25 2.0 5.0	0.8 0.5 0.2	29 12 3.0	30 13 3.2	30 14 3.8	23	Low-flow frequency characteristics are based on winters of 1959-60 through 1992-93. Predevelopment discharge is based on the median 14-day winter low flow for the winters of 1959-60 through 1968-69 because winter low flow appears to have decreased substantially with time.
07142575	Rattlesnake Creek near Zenith, Kansas	1.25 2.0 5.0	0.8 0.5 0.2	38 16 6.9	40 18 7.9	45 21 9.9	30	Low-flow frequency characteristics are based on winters of 1973-74 through 1992-93. Predevelopment discharge is based primarily on comparison of estimates at upstream and downstream stations.
07142620	Rattlesnake Creek near Raymond, Kansas	1.25 2.0 5.0	0.8 0.5 0.2	36 12 3.8	40 14 4.2	49 17 5.3	32	Low-flow frequency characteristics are based on winters of 1960-61 through 1992-93. Predevelopment discharge is based on the median 14-day winter low flow for the winters of 1960-61 through 1968-69 because winter low flow appears to have decreased substantially with time.
07144780	North Fork Ninnescah River above Cheney Reservoir, Kansas	1.25 2.0 5.0	0.8 0.5 0.2	84 57 41	90 62 46	110 76 55	52	Low-flow frequency characteristics are based on winters of 1965-66 through 1992-93. Predevelopment discharge is based on the median 14-day winter low flow for the entire period of record except for five winters of unusually high flows.
07144800	North Fork Ninnescah River near Cheney, Kansas	1.25 2.0 5.0	0.8 0.5 0.2	83 50 28	100 66 37	120 81 46	52	Low-flow frequency characteristics are based on winters of 1950-51 through 1963-64, prior to filling of Cheney Reservoir. Predevelopment discharge is based on the median 14-day winter low flow for the entire period of record, estimate at upstream station, and adjustment for local discharge.
7144910	South Fork Ninnescah River near Pratt, Kansas	1.25 2.0 5.0	0.8 0.5 0.2	11 9.7 8.5	11 10 8.9	12 11 9.4	10	Low-flow frequency characteristics are based on winters of 1980-81 through 1992-93. Predevelopment discharge is based on the 2-year, 14-day winter low flow for the entire period of record.
07145200	South Fork Ninnescah River near Murdock, Kansas	1.25 2.0 5.0	0.8 0.5 0.2	130 100 78	140 110 91	160 130 100	100	Low-flow frequency characteristics are based on winters of 1950-51 through 1958-59 and 1964-65 through 1992-93. Predevelopment discharge is based on the 2-year, 14-day winter low flow for the entire period of record with adjustment for discharge that comes from areas off the High Plains.

Table 2. Streamflow stations with December-February low-flow analysis and estimated predevelopment discharge from the High Plains aquifer —Continued

Station number	Station name	Discharge for indicated recurrence interval and flow period (cubic feet per second)					Estimated predevelopment discharge (cubic feet per second)	Remarks
		Recurrence interval (years)	Nonexceedence probability	Flow period (consecutive days) 7 days	14 days	30 days		
07149000	Medicine Lodge River near Kiowa, Kansas	1.25 2.0 5.0	0.8 0.5 0.2	87 60 31	93 65 38	100 76 51	65	Low-flow frequency characteristics are based on winters of 1937-38 through 1992-93 except much of the 1950's. Predevelopment discharge is based on the 2-year, 14-day winter low flow for the entire period of record.
07151500	Chikaskia River near Corbin, Kansas	1.25 2.0 5.0	0.8 0.5 0.2	100 56 25	110 63 30	120 74 40	63	Low-flow frequency characteristics are based on winters of 1950-51 through 1992-93 except much of period 1966-75. Predevelopment discharge is based on the 2-year, 14-day winter low flow for the entire period of record.
07156800	Cimarron River near Liberal, Kansas	--	--	--	--	--	20	Period of record is too short to calculate low-flow frequency characteristics. Predevelopment discharge is based on low flows during the winters of 1938-39 through 1941-42.
07156900	Cimarron River near Forgan, Okla-homa	1.25 2.0 5.0	0.8 0.5 0.2	48 37 28	53 42 33	61 49 40	45	Low-flow frequency characteristics are based on winters of 1965-66 through 1992-93 (except 1986-87). Predevelopment discharge is based on the median 14-day winter low flows for the winters of 1965-66 through 1984-85 because winter low flow appears to have decreased substantially with time.
07157000	Cimarron River near Mocane, Oklahoma	1.25 2.0 5.0	0.8 0.5 0.2	49 36 23	58 48 35	69 59 47	48	Low-flow frequency characteristics are based on winters of 1942-43 through 1964-65. Predevelopment discharge is based on the 2-year, 14-day winter low flow for the entire period of record.
07157500	Crooked Creek near Englewood, Kansas	1.25 2.0 5.0	0.8 0.5 0.2	11 8.2 5.8	13 10 7.2	16 12 8.9	10	Low-flow frequency characteristics are based on winters of 1942-43 through 1992-93. Predevelopment discharge is based on the 2-year, 14-day winter low flow for the entire period of record; estimate may be low.
07157580	Cimarron River near Englewood, Kansas	--	--	--	--	--	40	Period of record is too short to calculate low-flow frequency characteristics. Predevelopment discharge is based on the median 14-day winter low flow for the winters of 1981-82 through 1986-87 with adjustment because of the assumption that winter low flow has decreased with time. Estimate of predevelopment discharge is poor.
07157740	Cimarron River near Buttermilk, Kansas	--	--	--	--	--	--	Period of record is too short to calculate low-flow frequency characteristics. Record is too poor to estimate predevelopment discharge.

Table 2. Streamflow stations with December-February low-flow analysis and estimated predevelopment discharge from the High Plains aquifer —Continued

Station number	Station name	Discharge for indicated recurrence interval and flow period (cubic feet per second)					Estimated predevelopment discharge (cubic feet per second)	Remarks
		Recurrence interval (years)	Nonexceedence probability	Flow period (consecutive days)				
				7 days	14 days	30 days		
07157940	Bluff Creek near Buttermilk, Kansas	1.25 2.0 5.0	0.8 0.5 0.2	26 12 5.2	30 15 6.8	33 17 9.4	20	Low-flow frequency characteristics are based on winters of 1973-74 through 1978-79. Predevelopment discharge is based on the 2-year, 14-day winter low flow for the entire period of record with adjustment because of the assumption that winter low flow has decreased with time. Because of the short period of record, the estimate may be poor.
07157950	Cimarron River near Buffalo, Oklahoma	1.25 2.0 5.0	0.8 0.5 0.2	58 28 8.8	67 33 14	94 60 33	40	Low-flow frequency characteristics are based on winters of 1960-61 through 1992-93. Predevelopment discharge is based on the 2-year, 14-day winter low flow for the entire period of record with adjustment because of the assumption that winter low flow has decreased with time.
07157960	Buffalo Creek near Lovedale, Oklahoma	1.25 2.0 5.0	0.8 0.5 0.2	4.2 1.3 0.2	5.2 1.5 0.2	5.6 2.0 0.7	1.5	Low-flow frequency characteristics are based on winters of 1966-67 through 1992-93. Predevelopment discharge is based on entire period of record but considering only winters with lower flows. Estimate of predevelopment discharge is poor.
07232500	Beaver River near Guymon, Oklahoma	1.25 2.0 5.0	0.8 0.5 0.2	5.4 4.0 2.6	6.3 4.9 3.4	7.4 6.0 4.4	5	Low-flow frequency characteristics are based on winters of 1937-38 through 1974-75. Predevelopment discharge is based on rounded value of the 2-year, 14-day winter low flow for the winters of 1937-38 through 1974-75.
		1.25 2.0 5.0	0.8 0.5 0.2	0 0 0	0.1 0 0	0.8 0 0	--	Low-flow frequency characteristics are based on winters of 1975-76 through 1992-93. Predevelopment discharge is given above.
07232900	Coldwater Creek near Guymon, Oklahoma	--	--	--	--	--	≈ 1	Period of record is too short to calculate low-flow frequency characteristics. Estimated predevelopment discharge, based on downstream station, is approximate and poor.
07233000	Coldwater Creek near Hardesty, Oklahoma	1.25 2.0 5.0	0.8 0.5 0.2	2.7 1.4 0	3.8 2.2 0	5.2 3.0 0.9	2.5	Low-flow frequency characteristics are based on winters of 1939-40 through 1963-64. Predevelopment discharge is based on the 2-year, 14-day winter low flow for the winters of 1939-40 through 1958-59 with adjustment because of the assumption that winter low flows have decreased with time.

Table 2. Streamflow stations with December-February low-flow analysis and estimated predevelopment discharge from the High Plains aquifer —Continued

Station number	Station name	Discharge for indicated recurrence interval and flow period (cubic feet per second)					Estimated predevelopment discharge (cubic feet per second)	Remarks
		Recurrence interval (years)	Nonexceedence probability	Flow period (consecutive days) 7 days	14 days	30 days		
07233500	Palo Duro Creek near Spearman, Texas	1.25	0.8	0.5	0.7	1.0	0.5	Low-flow frequency characteristics are based on winters of 1945-46 through 1978-79. Predevelopment discharge is based on the median 14-day winter low flow for the early part of record and assumption that winter low flow has decreased with time.
		2.0	0.5	0.1	0.2	0.3		
		5.0	0.2	0	0	0		
07233650	Palo Duro Creek at Range, Oklahoma	--	--	--	--	--	≈ 3	Period of record is too short to calculate low-flow frequency characteristics. Estimated predevelopment discharge is approximate and poor.
07234000	Beaver River at Beaver, Oklahoma	1.25	0.8	14	20	30	12	Low-flow frequency characteristics are based on winters of 1937-38 through 1977-78, prior to filling of Optima Lake. Predevelopment discharge is based on estimates at upstream and downstream stations and work of Wahl and Tortorelli (1997). Estimate of predevelopment discharge is poor.
		2.0	0.5	2.8	4.5	6.9		
		5.0	0.2	0	0	0.1		
07234100	Clear Creek near Elmwood, Oklahoma	1.25	0.8	2.5	2.6	2.6	2.4	Low-flow frequency characteristics are based on winters of 1965-66 through 1992-93. Predevelopment discharge is based on the 14-day winter low flows for the entire period of record with more weight given to the first decade of record because winter low flow appears to have decreased with time.
		2.0	0.5	2.0	2.1	2.2		
		5.0	0.2	1.6	1.7	1.8		
07235000	Wolf Creek at Lipscomb, Texas	1.25	0.8	3.3	3.7	4.4	3	Low-flow frequency characteristics are based on winters of 1961-62 through 1992-93. Predevelopment discharge is based on the median 14-day winter low flow for the winters of 1961-62 through 1976-77 because winter low flows appear to have decreased with time.
		2.0	0.5	1.7	1.9	2.4		
		5.0	0.2	0.7	0.9	1.2		
07235500	Wolf Creek near Shattuck, Oklahoma	1.25	0.8	19	21	24	10	Low-flow frequency characteristics, which are based on winters of 1937-38 through 1945-46, have potential for substantial error because of short period of record. Estimate of predevelopment discharge, which is based on the 2-year, 14-day winter low flow for the entire period of record, is poor.
		2.0	0.5	8.9	10	13		
		5.0	0.2	3.1	3.8	5.7		
07236000	Wolf Creek near Fargo, Oklahoma	1.25	0.8	35	38	41	28	Low-flow frequency characteristics are based on winters of 1942-43 through 1975-76. Predevelopment discharge is based on the 2-year, 14-day winter low flow for the entire period of record.
		2.0	0.5	26	28	32		
		5.0	0.2	14	16	19		
07237000	Wolf Creek near Fort Supply, Oklahoma	1.25	0.8	10	17	39	--	Completely regulated by Fort Supply Lake since May 1942. Low-flow analysis done only to estimate predevelopment discharge to the Beaver River. Low-flow frequency characteristics are based on winters of 1942-43 through 1977-78.
		2.0	0.5	2.4	4.2	11		
		5.0	0.2	0.5	0.8	2.0		

Table 2. Streamflow stations with December-February low-flow analysis and estimated predevelopment discharge from the High Plains aquifer —Continued

Station number	Station name	Discharge for indicated recurrence interval and flow period (cubic feet per second)					Estimated predevelopment discharge (cubic feet per second)	Remarks
		Recurrence interval (years)	Nonexceedence probability	Flow period (consecutive days)				
				7 days	14 days	30 days		
(estimation point only)	Beaver River at confluence with Wolf Creek						10	Estimated predevelopment discharge, based on difference between the 2-year, 14-day winter low flow at stations 07237500 and 07237000 for winters of 1942-43 through 1977-78 (14-4.2), is poor.
(estimation point only)	Wolf Creek at confluence with Beaver River						30	Predevelopment discharge is based on estimate at upstream station and assumption that stream received some additional discharge in its lower reaches.
(estimation point only)	North Canadian River below Wolf Creek						40	Predevelopment discharge is sum of estimates for Beaver River and Wolf Creek at confluence (10 + 30).
07237500	North Canadian River at Woodward, Oklahoma	1.25 2.0 5.0	0.8 0.5 0.2	45 11 1.4	52 14 2.3	79 24 3.9	--	Partially regulated by Fort Supply Lake since May 1942. Low-flow analysis done only to estimate predevelopment discharge to the Beaver River. Low-flow frequency characteristics are based on winters of 1942-43 through 1977-78.

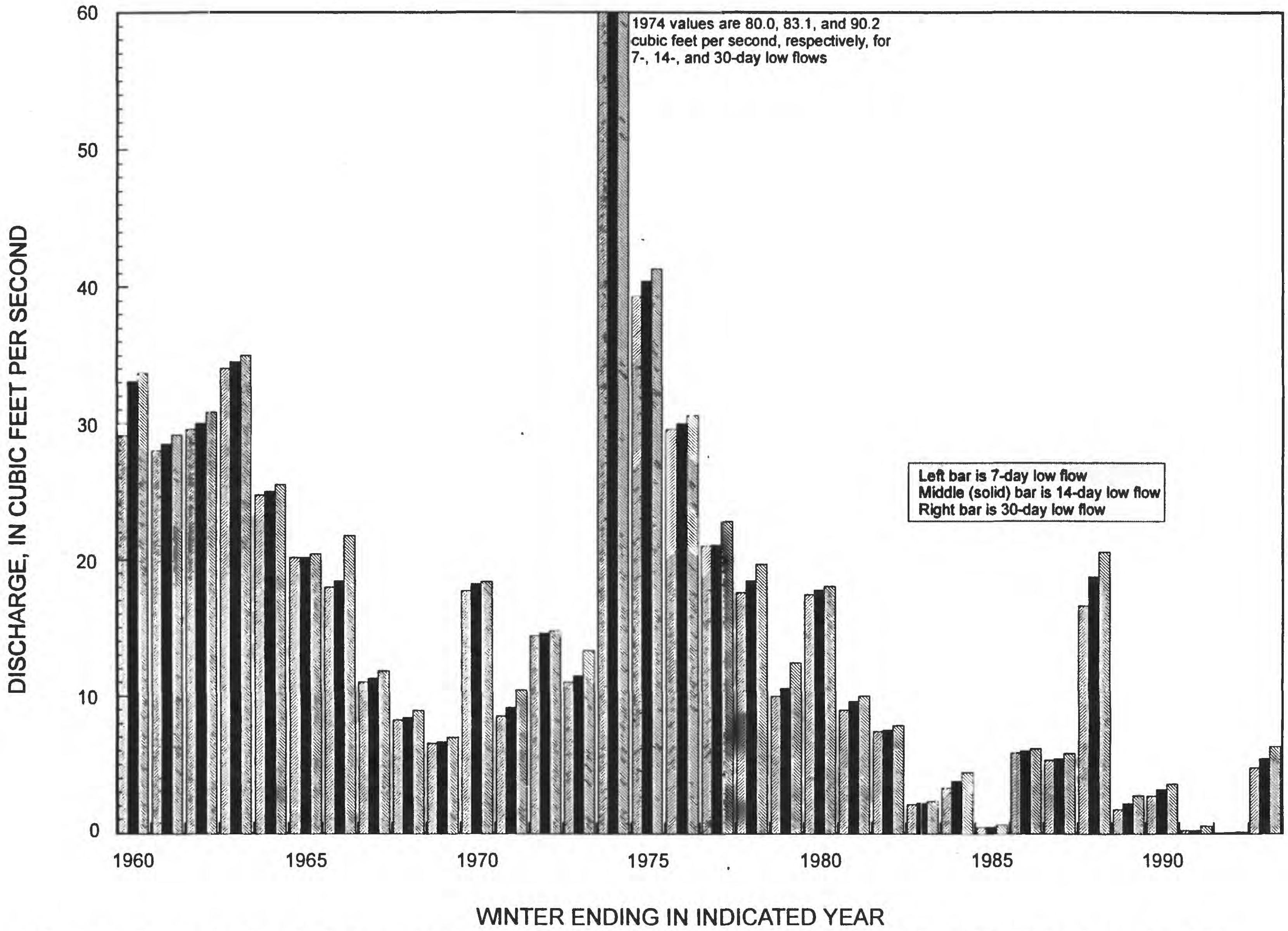

Figure 5. December-February low flows for 7-, 14-, and 30-days for the Beaver River near Guymon, Oklahoma, (station 07232500) for winters of 1959-60 through 1992-93. Left bar is 7-day low flow, middle bar is 14-day low flow, and right bar is 30-day low flow.

per second; and for 1990-93 was 7 cubic feet per second. Based primarily on the estimates at the upstream and downstream stations, the predevelopment discharge from the High Plains aquifer is estimated to have been about 30 cubic feet per second (table 2); this estimate is consistent with the early part of the record.

Rattlesnake Creek near Raymond, Kansas, (station 07142620) is near the mouth of the stream. The record at this station began before the winter of 1960-61. Fader and Stullken (1978) estimated mean discharge from the aquifer at this station for 1960-71 to have been 22 cubic feet per second from a ground-water drainage area of 960 square miles. The 2-year, 14-day winter low flow for the winters of 1960-61 through 1992-93 is 14 cubic feet per second (table 2). The winter low flows at this station are quite variable, but still appear to have decreased substantially with time. However, the decrease may have occurred later than at upstream stations. The median 14-day winter low flow for the 1960's (ending February 1969) was 32 cubic feet per second; for the 1970's was 36 cubic feet per second; and for the 1980's was 6 cubic feet per second. The median 14-day winter low flow for 1990-93 was 3 cubic feet per second. Based on the median 14-day winter low flow for the first decade of record, the predevelopment discharge from the High Plains aquifer upstream from this point on the stream is estimated to have been 32 cubic feet per second (table 2). During the summer, much of this discharge probably was consumed by evapotranspiration and only during the winter did it become streamflow.

The estimated predevelopment discharge from the High Plains aquifer to Rattlesnake Creek is summarized in figure 6. U.S. Geological Survey topographic maps show that the stream becomes perennial more than 20 miles upstream from the station near Macksville, Kansas, (station 07142300). In the reach upstream from the first station, the stream is estimated to have gained more than 23 cubic feet per second prior to development, which is about 1 cubic foot per second per mile. The stream is estimated to have gained an additional 7 cubic feet per second to the next station (station 07142575) and an additional 2 cubic feet per second to the last station (station 07142620). Most of the gain in discharge from the aquifer occurred in the upper reaches of the stream; the lower reaches of the stream gained little additional discharge from the aquifer. The aquifer is thicker beneath the upper reaches, and as a result, probably transmits more water. This may explain why the upper reaches gain more water. The decrease in winter flow with time probably is due to large pumpage for irrigation in the upper reaches; the pumpage has caused the water table to decline and has reduced ground-water flow to the stream. The area around the lower reaches has had little ground-water development for irrigation (Thelin and Heimes, 1987).

Ninnescah River Tributaries

The North and South Forks of the Ninnescah River drain the extreme eastern part of the High Plains aquifer south of the Arkansas River in Kansas (fig. 3). Both forks originate on the High Plains and are perennial almost from their headwaters. The stations on these two tributaries record discharge that comes directly from the High Plains aquifer and discharge that crosses the eastern boundary of the aquifer before reaching the tributaries. The areas drained by the tributaries have some ground-water development for irrigation, but not sufficient development to cause water-level declines (Gutentag and others, 1984, fig. 23; Dugan and Sharpe, 1996, fig. 6).

The record for the North Fork of the Ninnescah River above Cheney Reservoir, Kansas, (station 07144780) began before the winter of 1965-66. The 2-year, 14-day winter low flow for the winters of 1965-66 through 1992-93 is 62 cubic feet per second (table 2). Five of the 28 winters have 14-day low flows of more than 100 cubic feet per second; these flows probably represent both local and regional discharge from the High Plains aquifer following unusually wet periods. Local discharge means water that was recharged in the local area whereas regional discharge means water that was recharged over a much larger area. Regional discharge integrates recharge over a large area, and hence a long period of time, whereas local discharge does not. The area drained by this river contains many sand dunes that are nearby recharge areas for the aquifer. The median 14-day low flow for the remaining 23 winters is 52 cubic feet per second and probably is a reasonable estimate of more regional predevelopment discharge from the High Plains aquifer (table 2).

The North Fork of the Ninnescah River near Cheney, Kansas, (station 07144800) has data for the winters of 1950-51 through 1963-64, all before an upstream reservoir was completed. The station is off

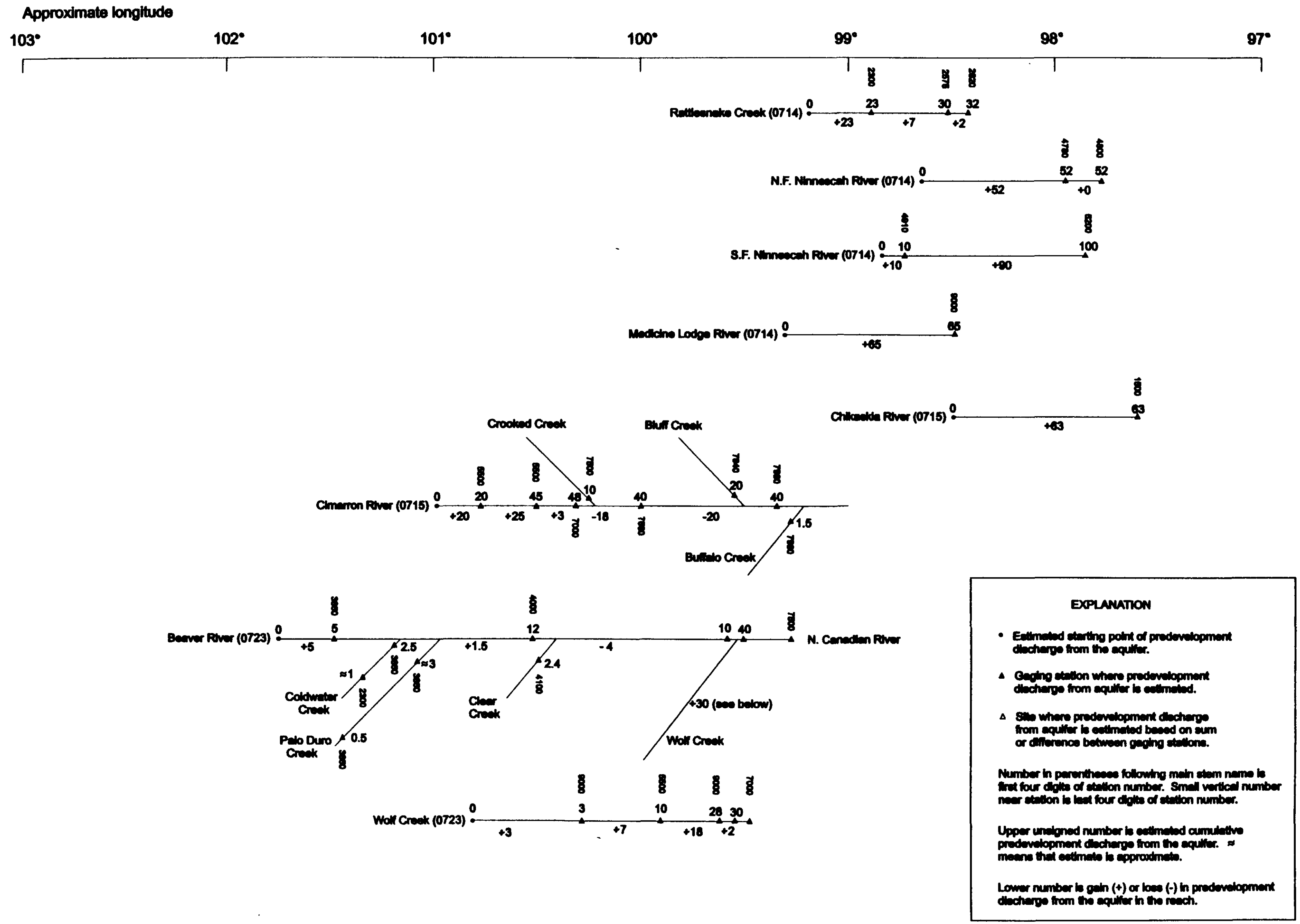

Figure 6. Predevelopment discharge from the High Plains aquifer to streams.

the High Plains, but is useful to extend the record of the station above the reservoir backward in time. The 2-year, 14-day winter low flow is 66 cubic feet per second (table 2). This station, together with the station above the reservoir, indicates that the discharge from the High Plains aquifer to the North Fork has not declined with time and that 52 cubic feet per second (table 2) is a reasonable estimate for regional discharge from the aquifer. The remaining 14 cubic feet per second of water at this station probably is a combination of local discharge from the High Plains aquifer and water that originates east of the High Plains because of recharge to the alluvium along the river.

The South Fork of the Ninnescah River near Pratt, Kansas, (station 07144910) is on the High Plains and is near the headwaters of the stream. The 2-year, 14-day winter low flow for the winters of 1980-81 through 1992-93 is 10 cubic feet per second (table 2). The winter low flows are quite stable and this flow probably is a good estimate of predevelopment discharge from the High Plains aquifer upstream from this point on the stream.

The South Fork of the Ninnescah River near Murdock, Kansas, (station 07145200) is east of the High Plains, but most of the winter low flow in the stream probably is discharge from the High Plains aquifer, either directly or after crossing the eastern boundary of the aquifer. The 2-year, 14-day winter low flow for the winters of 1950-51 through 1958-59 and 1964-65 through 1992-93 is 110 cubic feet per second (table 2). The winter low flows are quite stable and most of this flow probably is from the High Plains aquifer. Based on the 2-year, 14-day winter low flow for the entire period of record, the estimated predevelopment discharge from the aquifer is 100 cubic feet per second (table 2), with the remaining 10 cubic feet per second assumed to originate east of the High Plains along the valley of the river. This assumption is based in part on the length of the valley beyond the High Plains and in part by evaluating the low flow for each individual winter.

The estimated predevelopment discharge from the High Plains aquifer to the North and South Forks of the Ninnescah River is summarized on figure 6. The start of flow on the streams prior to major ground-water development was estimated using U.S. Geological Survey topographic maps. The two forks collectively are estimated to have received 152 cubic feet per second from the aquifer prior to development.

Medicine Lodge River

Medicine Lodge River drains a small part of the High Plains in Kansas. It also collects discharge that crosses the southern boundary of the aquifer in Kansas. Medicine Lodge River near Kiowa, Kansas, (station 07149000) is just north of the Kansas-Oklahoma state line. Some data were collected at this site in 1895-96, but the record used in this analysis began with the winter of 1937-38. Data were not collected at the station during much of the 1950's (table 1).

The 2-year, 14-day winter low flow at the station for 28 winters during the period 1937-38 through 1992-93 is 65 cubic feet per second (table 2). The winter low flows do not appear to have decreased with time, and if anything, may have increased. The winters of 1984-85 through 1987-88 were periods of particularly high flow, with a median 14-day low flow for the four winters of 140 cubic feet per second. The area drained by Medicine Lodge River had above normal precipitation for 1981-87 (National Oceanic and Atmospheric Administration) and the high winter flows may have been the result of higher ground-water discharge from the local area. Based on the 2-year, 14-day winter low flow for the full period of record, 65 cubic feet per second (table 2) seems to be a reasonable estimate of predevelopment discharge from the High Plains aquifer.

Chikaskia River

The Chikaskia River drains a small part of the High Plains aquifer near the southeastern boundary of the aquifer in Kansas. The river also collects water that flows across the boundary of the aquifer. Chikaskia River near Corbin, Kansas, (station 07151500) has 33 years of record beginning with the winter of 1950-51. The record was interrupted during the period 1966-75 (table 1). The 2-year, 14-day winter low flow for 33 winters during the period 1950-51 through 1992-93 is 63 cubic feet per second (table 2). The record appears to be relatively stable with time, and 63 cubic feet per second (table 2) probably is a reasonable estimate of predevelopment discharge from the aquifer.

Cimarron River and Tributaries West of 99° Longitude

The Cimarron River originates in New Mexico and enters the High Plains in northern Cimarron County, Oklahoma. The river has some perennial flow before it enters the High Plains, but this flow is not associated with the High Plains aquifer and quickly disappears after the river enters the High Plains. Prior to major ground-water irrigation development, the Cimarron River began to flow on the High Plains just east of 101° longitude (Gutentag and others, 1981, p. 43-45) and over the next few tens of miles received substantial discharge from the High Plains aquifer. A brief period of record exists for the Cimarron River near Liberal, Kansas, (station 07156800). The record at this station is too short to determine winter low-flow characteristics, but based on the low flows of the winters of 1938-39 through 1941-42, the predevelopment discharge from the aquifer upstream from this point on the river appears to be about 20 cubic feet per second (table 2). This is consistent with data reported by Gutentag and others (1981) for November 1974. In March 1997, the river at this point was observed to have almost continuous pools but little, if any, flow, so discharge from the aquifer has decreased substantially with time.

The next downstream station on the Cimarron River is near Forgan, Oklahoma, (station 07156900). This station is in Kansas just before the river re-enters Oklahoma. The 2-year, 14-day winter low flow for the winters of 1965-66 through 1992-93 (except 1986-87 when no data were collected) is 42 cubic feet per second (table 2). The winter low flows at this station have decreased somewhat with time, probably because of pumpage, so discharge from the aquifer is estimated to have been 45 cubic feet per second (table 2) prior to ground-water development, based on the median 14-day winter low flow for the first two decades of record.

The next downstream station is near Mocane, Oklahoma, (station 07157000). The 2-year, 14-day winter low flow for the winters of 1942-43 through 1964-65 is 48 cubic feet per second (table 2). This probably is a good estimate of the predevelopment discharge from the aquifer because the record predates major development of the aquifer.

Crooked Creek, a tributary from the north, enters the Cimarron River downstream from the Mocane station. Crooked Creek near Englewood, Kansas, (station 07157500; formerly called Crooked Creek near Nye, Kansas) has a 2-year, 14-day winter low flow for the winters of 1942-43 through 1992-93 of 10 cubic feet per second (table 2). This station is on the eastern boundary of the aquifer. Despite the heavy development of the aquifer for irrigation in the area drained by Crooked Creek (Gutentag and others, 1981, plate 2), the winter low flow of the stream appears to only have decreased a few cubic feet per second over the period of record. The predevelopment discharge from the High Plains aquifer to Crooked Creek is estimated to have been 10 cubic feet per second (table 2) based on the 2-year, 14-day winter low flow for the entire period of record, although this may be a low estimate. In March 1997, after a relatively dry period, Crooked Creek was observed to flow as far north as 37° 17′ latitude where U.S. Geological Survey topographic maps show it as perennial. North of this point, the stream had little flow. The topographic maps show an area near where the stream makes a sharp turn to the south (fig. 3) called "Artesian Valley." Many small wetlands and seeps were observed in this area in March 1997. These probably represented discharge from the High Plains aquifer. Two residents from the area reported that the stream had once flowed, except during the very driest summers, as far north as where the stream makes the sharp turn to the south. This verbal report also indicates that the flow of the stream may have decreased with time.

Cimarron River near Englewood, Kansas, (station 07157580) has only a few years of record in the 1980's and the record is too variable to make a good estimate of discharge from the aquifer. The median 14-day winter low flow for the winters of 1981-82 through 1986-87 is 30 cubic feet per second. This probably is much less than the predevelopment discharge from the aquifer. Predevelopment discharge is estimated to have been 40 cubic feet per second (table 2) with a wide margin of error associated with the estimate, based on the winter low flows for the period of record and the assumption that discharge must have been more prior to the 1980's.

A station on the Cimarron River just above where Bluff Creek enters the river, Cimarron River near Buttermilk, Kansas, (station 07157740), had only 7 years of record. The record was generally poor and was not adequate to estimate predevelopment discharge from the aquifer upstream from this point on the river.

Bluff Creek drains the High Plains aquifer and the area south of it between 99° and 100° longitude. Bluff Creek near Buttermilk, Kansas, (station 07157940) has record for the winters of 1973-74 through 1978-79. The 2-year, 14-day winter low flow based on only 6 years of record is 15 cubic feet per second (table 2). The record is too brief to make a good estimate of discharge from the aquifer and covers a period after major irrigation development took place. However, based on winter low flows of the period of record and the assumption that flow had already started to decrease in the 1970's, the predevelopment discharge from the High Plains aquifer to Bluff Creek is estimated to have been approximately 20 cubic feet per second (table 2). Because of the short period of record, the estimate could have a considerable margin of error associated with it. Bluff Creek was visited in March 1997 during a dry period, and based on observations during the visit, the estimate of discharge from the aquifer appeared reasonable. Above the streamflow station, the stream has three branches (from west to east): Bluff Creek, Kiowa Creek, and Cavalry Creek. Kiowa Creek carried the most flow in March 1997, followed by Bluff Creek, with Cavalry Creek carrying very little flow. Bluff Creek and Kiowa Creek drain a much longer length of aquifer boundary than does Cavalry Creek.

The last station on the main stem considered in this report is the Cimarron River near Buffalo, Oklahoma, (station 07157950). The 2-year, 14-day winter low flow for the winters of 1960-61 through 1992-93 is 33 cubic feet per second (table 2). The winter low flows are quite variable, ranging from less than 10 cubic feet per second to more than 100 cubic feet per second, so any trend in the data would be difficult to recognize. However, 3-, 5-, and 7-year moving averages of winter low flows show an apparent downward trend. Predevelopment discharge from the aquifer at this site is estimated to have been about 40 cubic feet per second (table 2). This estimate is based on the 2-year, 14-day winter low flow and the assumption that winter low flows in more recent years are less than they were prior to development of the aquifer.

Buffalo Creek is a small tributary to the Cimarron River that collects discharge that crosses the eastern boundary of the High Plains aquifer in Oklahoma. The 2-year, 14-day winter low flow for the winters of 1966-67 through 1992-93 is 1.5 cubic feet per second (table 2) for Buffalo Creek near Lovedale, Oklahoma, (station 07157960). Winter low flows seem to exhibit a bimodal distribution with a few years above 5 cubic feet per second and most years less than 2 cubic feet per second. The winters of 1985-86 through 1989-90, with a median 14-day winter low flow of 11 cubic feet per second, is the most dramatic example of sustained high winter flows. The high winter flows on this stream tend to follow very wet periods, so the higher winter flows at this station may be the result of both local and regional discharge (as defined in Ninnescah River Tributaries section) from the aquifer whereas the lower winter flows are the result of only regional ground-water discharge. The estimated predevelopment discharge from the aquifer at this site is 1.5 cubic feet per second (table 2) based on the smaller winter low flows, but this value is considered poor because of the variability of the data.

The estimated predevelopment discharge to the Cimarron River and its tributaries is summarized on figure 6. The Cimarron River started to receive predevelopment discharge from the High Plains aquifer at approximately 101° longitude. The river is estimated to have received 20 cubic feet per second to the streamflow station near Liberal, Kansas, (station 07156800), and where it reached the streamflow station near Forgan, Oklahoma, (station 07156900), it is estimated to have received 45 cubic feet per second from the aquifer. The station near Mocane, Oklahoma, (station 07157000) is estimated to have a total discharge from the aquifer of 48 cubic feet per second, so the river is estimated to have received only an additional 3 cubic feet per second between the station near Forgan and the station near Mocane. Below the station near Mocane, Crooked Creek, a tributary from the north, added an additional 10 cubic feet per second in predevelopment discharge from the aquifer, but where the Cimarron River reached the station near Englewood, Kansas, (station 07157580), the total predevelopment discharge was only 40 cubic feet per second. A total of 58 cubic feet per second predevelopment discharge had entered the reach but only 40 cubic feet per second left the reach, so 18 cubic feet per second had been lost within this reach. Bluff Creek entered the river from the north between the stations near Englewood, Kansas, and near Buffalo, Oklahoma, (station 07157950), and it contributed an estimated 20 cubic feet per second in predevelopment discharge. However, the river contained only a total of 40 cubic feet per second in predevelopment discharge from the aquifer at the station near Buffalo, so 20 cubic feet per second was lost within the reach between the Englewood and Buffalo stations. The cause of the loss of 38 cubic feet per second of predevelopment discharge in the lower reaches of the Cimarron River is not known. Although some of the estimates of predevelopment discharge are poor, as shown in table 2 and in the discussion for each station, and thus the actual gains and losses may be poorly estimated, the pattern of gains and losses is thought to be valid.

Beaver River and Tributaries above Wolf Creek

The Beaver River originates near the New Mexico-Oklahoma state line and drains much of the Oklahoma panhandle. U.S. Geological Survey topographic maps show the Beaver River as perennial about 15 miles west of the station near Guymon, Oklahoma, (station 07232500). Below Wolf Creek, the name of the Beaver River changes to North Canadian River. Two streamflow stations on the main stem and five stations on tributaries were used in the analysis of predevelopment discharge from the High Plains aquifer. Wahl and Wahl (1988) and Wahl and Tortorelli (1997) looked at changes in both base flow and total flow of the Beaver-North Canadian River system, both on and to the east of the High Plains. Their analyses were much more extensive than those presented here, and were done for purposes other than estimating discharge from the High Plains aquifer. The information presented in this report does not appear to be in conflict with the major conclusions of those two studies.

The most upstream station on the Beaver River used in the analysis is near Guymon, Oklahoma, (station 07232500). This station has data beginning before the winter of 1937-38. The data indicate that the river received discharge from the High Plains aquifer until about the mid-1970's, after which the winter low-flow characteristics changed dramatically (fig. 7). Table 2 uses 1975 as a convenient change point, but the change in conditions on the river probably took place gradually over a number of years. The winter low-flow frequency curves for this station through the winter of 1974-75 are shown in figure 4. The 2-year, 14-day winter low flow for the winters of 1937-38 through 1974-75 is 4.9 cubic feet per second (table 2). Based on this number, predevelopment discharge from the aquifer is estimated to have been about 5 cubic feet per second (table 2). After the winter of 1974-75, the 2-year, 14-day winter low flow is 0 cubic feet per second (table 2).

Coldwater Creek enters the Beaver River below the Guymon streamflow station. U.S. Geological Survey topographic maps show the stream as perennial for a number of miles before it enters the Beaver River, which would imply that it once had discharge from the aquifer. The name itself implies discharge from the aquifer; during the summer, discharge from the aquifer would feel cold. Two stations recorded streamflow in Coldwater Creek. The record for Coldwater Creek near Guymon, Oklahoma, (station 07232900) began before the winter of 1980-81. The record does not indicate any discharge from the High Plains aquifer, but this may be due to the recentness of the period of record. By 1981, the nearby Beaver River (station 07232500) also did not receive any discharge from the aquifer. While Coldwater Creek may have received some predevelopment discharge from the aquifer upstream from this point on the stream, it probably would have been, at most, a few cubic feet per second based on the downstream station (station 07233000). Predevelopment discharge for this station is shown on table 2 and figure 6 as approximately 1 cubic foot per second.

The station on Coldwater Creek near Hardesty, Oklahoma, (station 07233000) had data for the winter of 1939-40 through 1963-64. The 2-year, 14-day winter low flow for the winters of 1939-40 through 1963-64 is 2.2 cubic feet per second (table 2). The median 14-day winter low flow for the winters ending in the 1940's is 2.4 cubic feet per second, for the 1950's is 2.6 cubic feet per second, and for 1960-64 is 1.7 cubic feet per second. The predevelopment discharge from the High Plains aquifer at this station is estimated to have been 2.5 cubic feet per second (table 2), based on the median 14- day winter low flow for the first two decades of record.

Palo Duro Creek is the next major downstream tributary. Two stations recorded streamflow in Palo Duro Creek. Palo Duro Creek near Spearman, Texas, (station 07233500) had data for the winters of 1945-46 through 1978-79. The 2-year, 14-day winter low flow for the winters of 1945-46 through 1978-79 is 0.2 cubic foot per second (table 2). The winter low flows have decreased with time; the median 14-day winter low flow for the first decade of record is 0.5 cubic foot per second while it is 0 cubic feet per second for the last decade. The predevelopment discharge from the High Plains aquifer upstream from this point on the

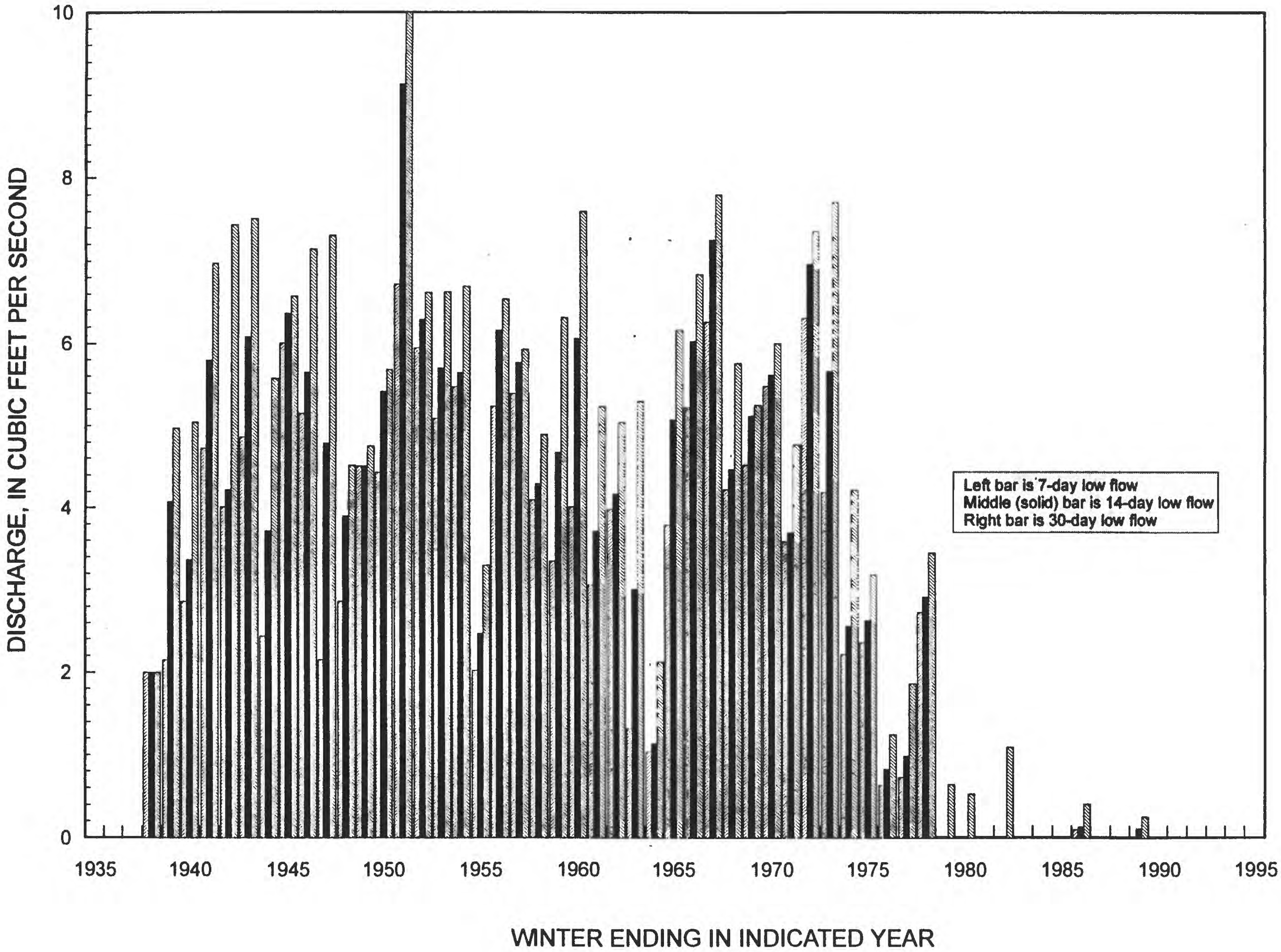

Figure 7. December-February low flows for 7-, 14-, and 30-days for the Beaver River near Guymon, Oklahoma, (station 07232500) for winters of 1937-38 through 1974-75. Left bar is 7-day low flow, middle bar is 14-day low flow, and right bar is 30-day low flow.

stream is estimated to have been 0.5 cubic foot per second (table 2), based on the median 14-day winter low flow for the early part of the record. Wahl and Tortorelli (1997, fig. 14) indicate an average annual base flow of about 1 cubic foot per second for 1945-75 at this point on the stream.

The record for Palo Duro Creek at Range, Oklahoma, (station 07233650) began with the winter of 1991-92. The record indicates a winter low flow of 1-2 cubic feet per second. Flow is regulated by Palo Duro Reservoir 18 miles upstream (Blazs and others, 1994), so the winter low flow could be due to reservoir operation. U.S. Geological Survey topographic maps show both intermittent and perennial segments of the stream and show it as perennial below a spring about a dozen miles upstream from the station, so the winter low flow is thought to be discharge from the aquifer. The predevelopment discharge from the High Plains aquifer to Palo Duro Creek may have been several cubic feet per second, assuming the flow of the stream had decreased by 1991. Predevelopment discharge at this station is shown on table 2 and figure 6 as approximately 3 cubic feet per second; this estimate is poor and may have a wide margin of error associated with it.

The next downstream station on the Beaver River is at Beaver, Oklahoma, (station 07234000). The record at this station began prior to the winter of 1937-38. Beginning with the winter of 1978-79, flow at this station has been affected by closure of the dam on Optima Lake. Low-flow values given in table 2 are for the winters of 1937-38 through 1977-78 and should represent unregulated conditions. The 2-year, 14-day winter low flow for the winters of 1937-38 through 1977-78 is 4.5 cubic feet per second (table 2). Winter low flows at this station are highly variable from year to year and range from zero during many years to more than 20 cubic feet per second for a few years. The winter low flows seem to be climate related and may lag precipitation by up to a few years. The higher winter low flows tend to occur after wet years, but not all wet years are followed by periods of higher winter flows. The three highest 14-day winter low flows occurred in winters ending in 1947, 1951, and 1969, all following a year of above normal precipitation (National Oceanic and Atmospheric Administration). However, the 14-day winter low flows for winters ending in 1945, 1958, and 1963 were quite small, even though the previous year had comparable above-normal precipitation. Precipitation in the panhandle in 1941 was the highest of the 20th century through 1996, yet the low flows the following winter were not particularly high. The cause of the erratic winter low flows in the river could not be determined, and thus, an estimate of predevelopment discharge is difficult to make. Wahl and Tortorelli (1997, fig. 15) indicate an average annual base flow for this station of about 14 cubic feet per second for 1938-70. Based on upstream and downstream stations (fig. 6) and the work of Wahl and Tortorelli (1997), the estimated predevelopment discharge from the High Plains aquifer is 12 cubic feet per second (table 2), with a large margin of error assigned to the estimate.

Clear Creek enters the Beaver River a few miles downstream from the main-stem streamflow station at Beaver. Clear Creek near Elmwood, Oklahoma, (station 07234100), more than 10 miles upstream from the confluence, has data beginning before the winter of 1965-66. The 2-year, 14-day winter low flow for the winters of 1965-66 through 1992-93 is 2.1 cubic feet per second (table 2). The lowest mean winter flow does not change much as the flow period or recurrence interval changes, so the winter low flow is very stable. This winter flow is certainly regional discharge from the High Plains aquifer. The winter low flows seem to have decreased somewhat with time; the median 14-day winter low flow for the first decade of record is 2.7 cubic feet per second. The estimated predevelopment discharge from the aquifer is 2.4 cubic feet per second (table 2), a value midway between the median for the first decade of record and the 2-year, 14-day winter low flow for the period of record. For about 2 miles downstream from the station, the stream flows over the High Plains aquifer and then it flows over less permeable Permian bedrock until reaching the alluvium along the Beaver River. U.S. Geological Survey topographic maps show the stream becomes intermittent once it reaches the alluvium; the flow of the stream probably is lost into the alluvium associated with the Beaver River. The water lost to the alluvium could re-enter the Beaver River at some point downstream.

Four more tributaries that are shown as perennial on U.S. Geological Survey topographic maps enter the Beaver River from the south before it reaches Wolf Creek. None of these tributaries have streamflow stations on them. However, predevelopment discharge from the aquifer to the Beaver River at its confluence with Wolf Creek can be estimated from stations on the North Canadian River at Woodward, Oklahoma, (station 07237500) and Wolf Creek near Fort Supply, Oklahoma, (station 07237000). Wolf Creek has been completely regulated by Fort Supply Lake since 1942. The North Canadian River has been partially regulated by Fort Supply Lake since 1942, and has been affected by closure of the dam on Optima Lake since 1979. The low flows were determined for winters 1942-43 through 1977-78 at both stations (table 2). The 2-year, 14-day winter low flow for the period on the North Canadian River (station 07237500) was 14 cubic feet per second whereas it was 4.2 cubic feet per second on Wolf Creek (station 07237000). The difference in the 2-year, 14-day winter low flows, 10 cubic feet per second (table 2), is an estimate of discharge from the High Plains aquifer to the Beaver River at its confluence with Wolf Creek. Based on the available data, this is the best estimate that could be obtained, but the estimate is poor.

The estimated predevelopment discharge from the High Plains aquifer to the Beaver River and its tributaries is summarized on figure 6. The Beaver River began to receive predevelopment discharge from the aquifer about 15 miles west of the streamflow station near Guymon, Oklahoma, (station 07232500), and is estimated to have gained 5 cubic feet per second from the aquifer above the station. Coldwater Creek and Palo Duro Creek, both tributaries from the south, probably received some predevelopment discharge from the aquifer. The main stem of the Beaver River gained little additional water before reaching the station near Beaver, Oklahoma, (station 07234000), with estimated cumulative discharge being 12 cubic feet per second. Downstream from the station near Beaver, Clear Creek, a tributary from the south, is estimated to have received about 2 cubic feet per second predevelopment discharge from the aquifer. Estimated cumulative predevelopment discharge from the High Plains aquifer at the confluence with Wolf Creek is 10 cubic feet per second, so the Beaver River is estimated to have lost 4 cubic feet per second predevelopment discharge between Clear Creek and Wolf Creek. Whether this loss is real or is an artifact of errors in the estimation process is unknown.

Wolf Creek

Wolf Creek originates in the northeast part of Texas and joins the Beaver River at about the eastern edge of the High Plains in Oklahoma. Below this junction, the name of the Beaver River changes to the North Canadian River. U.S. Geological Survey topographic maps show Wolf Creek as perennial almost to its headwaters. The same maps show woodland vegetation along parts of Wolf Creek well into Texas. The woodland vegetation indicates that the depth to water probably is shallow along the stream whereas the perennial nature of the stream indicates that the aquifer is discharging into the stream. In March 1997, after a relatively dry period, the stream was flowing as far west as 100° 38′ longitude, although the flow was small until a few miles above the first streamflow station.

The most upstream station on Wolf Creek is at Lipscomb, Texas, (station 07235000). This station had some earlier data, but the record used to estimate predevelopment discharge from the High Plains aquifer is from the winters of 1961-62 through 1992-93. The 2-year, 14-day winter low flow for the period analyzed is 1.9 cubic feet per second (table 2). Although the record was not subdivided for separate analysis, the low flows appear to have decreased since the mid-1970's. Wahl and Tortorelli (1997) also determined that the base flow of Wolf Creek had decreased with time. Based on the apparent reduction in flow and the median winter 14-day low flow for the first half of the period of record, the estimated predevelopment discharge from the High Plains aquifer is 3 cubic feet per second (table 2).

The next downstream station is near Shattuck, Oklahoma, (station 07235500). This station had data for the winters of 1937-38 through 1945-46. The 2-year, 14-day winter low flow is 10 cubic feet per second (table 2), but this estimate has the potential for substantial error because of the short period of record. During the 9 years of record, the 14-day winter low flow is less than 5 cubic feet per second during 3 years and more than 20 cubic feet per second during 3 years. In spite of a large margin of error, 10 cubic feet per second (table 2) seems to be a reasonable estimate of predevelopment discharge from the aquifer upstream from this point on Wolf Creek.

The next downstream station on Wolf Creek is near Fargo, Oklahoma, (station 07236000). This station has data for the winters of 1942-43 through 1975-76. The 2-year, 14-day winter low flow is 28 cubic feet per second (table 2). The differences between the 7-, 14-, and 30-day low flows are small, so 28 cubic feet per second (table 2) probably is a reasonable estimate of regional predevelopment discharge from the aquifer. The last part of the record may have been influenced by ground-water development for irrigation, but not to such an extent as to change the estimated predevelopment discharge.

The last station on Wolf Creek is near Fort Supply, Oklahoma, (station 07237000). The record for this station started in October 1937, but the flow in the stream has been completely regulated by Fort Supply Lake since 1942. Even prior to complete regulation, the flow may have been affected by construction activities. The record at this station cannot be used to estimate predevelopment discharge from the aquifer. The stream may have received some additional predevelopment discharge from the aquifer before it joins the Beaver River a few miles to the northeast, so the total predevelopment discharge to the stream at its confluence with the Beaver River is estimated to have been about 30 cubic feet per second (table 2), based on the upstream station.

Wolf Creek is estimated to have received a total of 30 cubic feet per second in predevelopment discharge between its headwaters in Texas and its confluence with the Beaver River (fig. 6). The majority of the predevelopment discharge to Wolf Creek entered the lower one-third of the perennial reach. In the first 20 miles above the first station at Lipscomb, Texas, (station 07235000), the stream received about 3 cubic feet per second predevelopment discharge while it received about 7 cubic feet per second additional predevelopment discharge in the 20 miles to the next station (station 07235500). In the next 16 miles to the station near Fargo, Oklahoma, (station 07236000), the stream is estimated to have received an additional 18 cubic feet per second in predevelopment discharge from the aquifer. Below the station near Fargo, the stream may have received some additional discharge from the aquifer.

SUMMARY

A study of the High Plains aquifer in Oklahoma was initiated in 1996 to: (1) provide information needed by the Oklahoma Water Resources Board to manage the quantity of water produced from the aquifer; and (2) provide baseline water-chemistry data that could be used to determine if the quality of water in the aquifer is being degraded. The approach used to meet the first objective is to develop a digital ground-water flow model. The modeled area will include the High Plains between the Arkansas and Canadian Rivers. The model will be calibrated by comparing simulated and observed conditions, including predevelopment discharge from the aquifer. This report provides estimates of predevelopment discharge to streams that drain the High Plains aquifer between the Arkansas and Canadian Rivers and streams that collect discharge that crosses the eastern boundary of the aquifer.

Historical data from streamflow stations on and east of the High Plains were the primary source of information used to estimate historical discharge from the High Plains aquifer. Data from 30 streamflow stations between the Arkansas and Canadian Rivers were considered in the analysis (table 1). Winter (December-February) low-flow frequencies were determined for 25 stations that received discharge from the High Plains aquifer; the remaining five stations had too few years of record to permit frequency analysis. Recurrence intervals were determined for 1.25, 2, and 5 years for 7-, 14-, and 30-day winter low-flow periods (table 2). Although all values were examined, the 14-day low flow with a recurrence interval of 2 years was the value most relied upon to estimate predevelopment discharge from the aquifer. The 14-day flow period was thought to be long enough to be representative of nonrunoff periods, and the 2-year recurrence interval represents the median value for the period.

For stations without sufficient record to quantitatively determine the low-flow characteristics, the data were examined and, in some cases, an estimate of predevelopment discharge was made. The estimates made without frequency analysis are considered poor. Topographic maps were used to estimate the point at which the streams began to receive discharge from the aquifer. The analysis, in some cases, relied on personal observations or discussions with others familiar with the stream.

The estimated predevelopment discharge from the High Plains aquifer is summarized on figure 6. The five streams that drain the eastern part of the aquifer in Kansas (generally east of 99.5° longitude) had large predevelopment discharge and most of them received discharge from the aquifer from near their headwaters. For the three streams that had more than one streamflow station, the upper perennial reaches of the streams appear to have received more discharge from the aquifer than did the lower reaches. The North Fork and South Fork of the Ninnescah River collectively are estimated to have received 152 cubic feet per second in predevelopment discharge from the aquifer. Medicine Lodge River is estimated to have received 65 cubic feet per second in predevelopment discharge, Chikaskia River is estimated to have received 63 cubic feet per second, and Rattlesnake Creek is estimated to have received 32 cubic feet per second. The total predevelopment discharge from the aquifer in this area is estimated to have been about 312 cubic feet per second, not including discharge that probably went directly to the Arkansas River.

The Cimarron River began to receive discharge from the High Plains aquifer at approximately 101° longitude prior to major irrigation development. The river is estimated to have received 20 cubic feet per second from the aquifer to the first streamflow station and a total of 45 cubic feet per second to the second station. The cumulative estimated predevelopment discharge to the river reaches a maximum of 48 cubic feet per second at the station near the Kansas-Oklahoma state line. Below this station, Crooked Creek added an additional 10 cubic feet per second predevelopment discharge from the aquifer and Bluff Creek added an additional 20 cubic feet per second, so a total of 78 cubic feet per second entered the reach. However, at the next main-stem station near Buffalo, Oklahoma, the river contained only a total of 40 cubic feet per second predevelopment discharge from the aquifer. The cause of the 38 cubic feet per second decrease in cumulative discharge from the aquifer in the lower reaches is unknown. Although the actual gains and losses may be poorly estimated, the pattern of gains and losses is thought to be valid.

The Beaver River began to receive predevelopment discharge from the High Plains aquifer about 15 miles west of the station near Guymon, Oklahoma. Below the station, two tributaries from the south received some predevelopment discharge while the main stem gained little additional water before reaching the station near Beaver, Oklahoma. Another tributary contributed discharge but the main stem is estimated to have lost 4 cubic feet per second before the confluence with Wolf Creek. Whether this loss is real or an artifact of the estimation process is unknown.

Wolf Creek is estimated to have received a total of 30 cubic feet per second in predevelopment discharge from the High Plains aquifer between it headwaters in Texas and its confluence with the Beaver River. The majority of the predevelopment discharge entered the lower one-third of the perennial part of the stream.

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