GEOHYDROLOGY, WATER QUALITY, AND PRELIMINARY SIMULATIONS OF GROUND-WATER FLOW OF THE ALLUVIAL AQUIFER IN THE UPPER BLACK SQUIRREL CREEK BASIN, EL PASO COUNTY, COLORADO

By David R. Buckles and Kenneth R. Watts

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ABSTRACT

The upper Black Squirrel Creek basin in eastern El Paso County, Colorado, is underlain by an alluvial aquifer and four bedrock aquifers. The climate of the area is semiarid, and streamflow is irregular. The alluvial aquifer has supplied water to wells since the late 1800's when ranchers first pumped water from shallow wells to grow grass hay for livestock. Ground-water pumpage from the alluvial aquifer has increased since the mid-1950's, and water-level declines have been substantial; the bedrock aquifers virtually are undeveloped. Ground-water pumpage for domestic, stock, agricultural, and municipal uses has exceeded recharge for the past 25 years. The present extent of the effect of pumpage on the alluvial aquifer was evaluated, and a ground-water flow model was used to simulate the future effect of continued pumpage on the aquifer.

Measured water-level declines from 1974 through 1984 were as much as 30 feet in an area north of Ellicott, Colorado. On the basis of the simulations, water-level declines from October 1984 to April 1999 north of Ellicott might be as much as 20 to 30 feet and as much as 1 to 10 feet in most of the aquifer. Flow from the bedrock aquifers to the alluvial aquifer may account for a substantial volume of the recharge to the alluvial aquifer.

The ground-water flow models provided a means of evaluating the importance of ground-water evapotranspiration at various stages of aquifer development. Simulated ground-water evapotranspiration decreased from 1949 to 1984; prior to 1950 ground-water evapotranspiration was about 43.5 percent of the total outflow, but in 1984 it was less than 3 percent.

Thirty-six ground-water samples were collected during 1984. Chemical analyses indicated that concentrations of dissolved nitrite plus nitrate as nitrogen generally were large. Samples from 5 of the 36 wells had concentrations of dissolved nitrite plus nitrate as nitrogen that exceeded drinking-water standards; these concentrations could pose a health threat to infants. Water from the alluvial aquifer generally is of suitable quality for other uses.

INTRODUCTION

The upper Black Squirrel Creek basin is located about 25 mi east of Colorado Springs (fig. 1) and has an area of about 353 mi^2. Streams in the area flow in response to thunderstorms, snowmelt, and prolonged rainfall. All streams are ephemeral and do not provide a dependable source of water. The upper Black Squirrel Creek basin is underlain by an alluvial aquifer and four bedrock aquifers. Most of the water used in the basin is pumped from the alluvial aquifer; the bedrock aquifers virtually are undeveloped.

Since the late 1800's, the alluvial aquifer has provided a dependable source of suitable quality water for domestic, agricultural, and municipal uses. Water from the alluvial aquifer is exported to suburbs east of Colorado Springs and to the Falcon Air Force Station by the Cherokee Water District and the Pikes Peak Water Company. Water from the alluvial aquifer also is used extensively within the basin for irrigation and other agricultural purposes. The study area shown in figure 1 approximately corresponds to the part of the upper Black Squirrel Creek basin underlain by the alluvial aquifer. Since the mid-1950's, after extensive development of the alluvial aquifer, pumpage of water from storage in the aquifer has resulted in large declines of the water table. Because of the declining water levels and increasing demand for ground water in the basin and adjacent areas, the U.S. Geological Survey in cooperation with the Cherokee Water District began a study to: (1) Define the geohydrologic system in the upper Black Squirrel Creek basin, emphasizing the alluvial aquifer; and (2) determine the quality of water in the alluvial aquifer.

Purpose and Scope

This report describes the results of a study of the geohydrologic system of the upper Black Squirrel Creek basin. Because almost all ground water pumped in the basin is from the alluvial aquifer, this aquifer is the focus of the report. Effects of water withdrawals from the alluvial aquifer on water levels during spring 1964 to spring 1984 and from October 1984 to April 1999 are discussed. A ground-water flow model of the alluvial aquifer was used to estimate effects of continued pumpage on water levels in the alluvial aquifer. The chemical quality of water from the alluvial aquifer, based on analyses of samples from 36 wells, also is described. Data collected during the study (water-level measurements and water-quality analyses of chemical constituents in ground-water samples) are included in the report.

Methods of Study

A literature search of reports pertaining to the geohydrology and water quality of the upper Black Squirrel Creek basin was made early in this study; selected references at the end of the report include most of the published information about the area. Many of the data used to evaluate the aquifer were collected during previous investigations and as part of ongoing data-collection programs. Water-level measurements were made and used to define the configuration and altitude of the spring 1984 water table. Development of a ground-water flow model involved the use of independent estimates of model parameters, such as the thickness of the alluvial aquifer, altitude of the water table, aquifer boundaries, hydraulic properties, rates, sources, and distribution of recharge, and rates of ground-water underflow, ground-water evapotranspiration, and ground-water pumpage. These estimates were developed using precipitation data, geologic maps, drillers logs of wells and other existing information on the area.

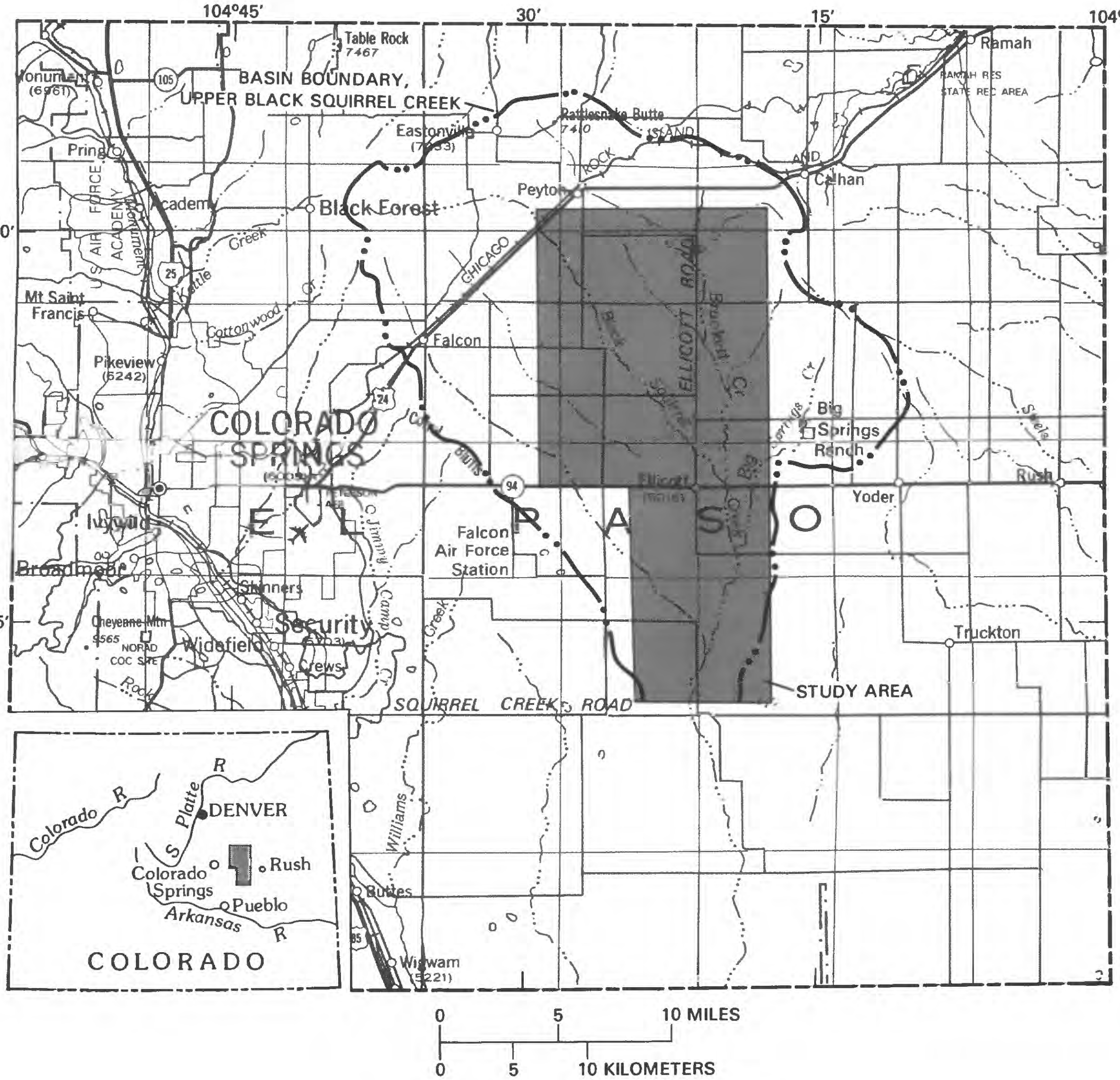


Figure 1.--Location of study area.

Various parameters had different levels of certainty. For example, municipal pumpage is metered; therefore, it has a large degree of certainty. Agricultural pumpage is not metered so it was estimated using crop-consumptive-use methods. The model was calibrated by adjusting parameters within selected limits until an acceptable relation between measured and simulated water-level changes was achieved. After model calibration, sensitivity analyses were made to evaluate the sensitivity of the model to changes of parameter values. Finally, the calibrated model was used to project the response of the hydrologic system to continued ground-water pumpage.

Acknowledgments

The authors wish to thank the employees of the Cherokee Water District and the Pikes Peak Water Company for their support and cooperation in all phases of the study and for supplying vital data to the study. Special thanks are extended to the residents of the upper Black Squirrel Creek basin who allowed access to their property for the collection of data.

UPPER BLACK SQUIRREL CREEK GEOHYDROLOGIC SYSTEM

Prior to development of the ground-water flow model, an independent conceptual model of the upper Black Squirrel Creek hydrologic system was developed (fig. 2). The conceptual model was developed using measured and estimated climatologic, land-use, geologic, and hydrologic data.

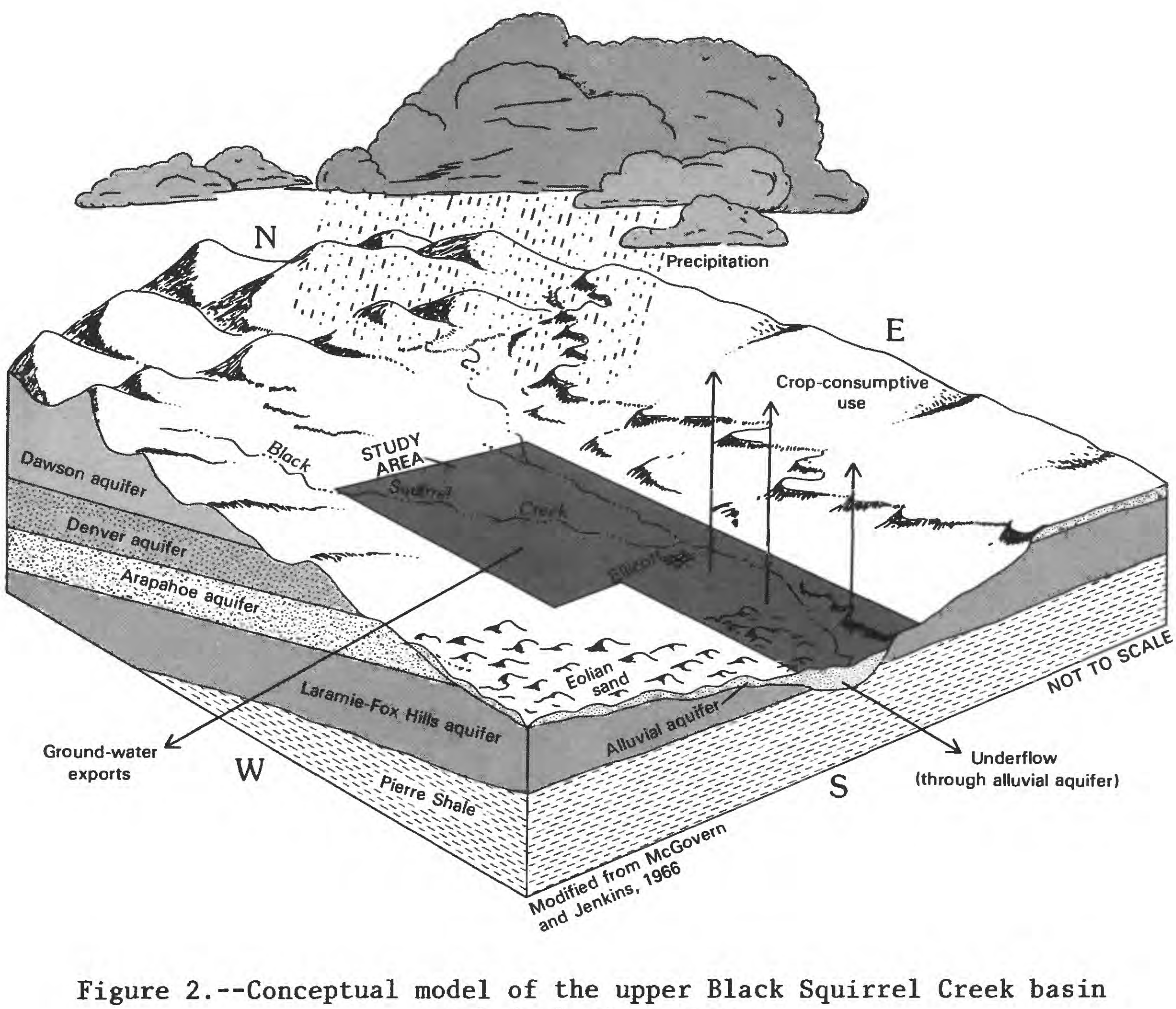


Figure 2.--Conceptual model of the upper Black Squirrel Creek basin geohydrologic system.

Climate

Climate of the upper Black Squirrel Creek basin is semiarid. Precipitation is greatest in the northern part of the study area where the altitude is the highest. Livingston and others (1976) determined a relation between altitude and mean annual precipitation in El Paso County. Mean annual precipitation in the study area is estimated to range from 12.5 in. at altitudes of about 5,700 ft to 13.7 in. at altitudes of about 6,500 ft.

Precipitation data have been collected at two locations in the basin (Big Springs Ranch and Ellicott) and at two locations near the basin (Rush and Colorado Springs). The location that has the longest period of record (representing the climatography in the upper Black Squirrel Creek basin) is Rush (about 16 mi east of Ellicott). Variation of annual precipitation at Rush during 1964-71 and 1975-84 is shown in figure 3*A*. During the period of record at Rush, 2.20 in. or 17 percent of the mean annual precipitation (13.04 in.) fell during October through March, whereas 10.84 in. or 83 percent of the mean annual precipitation fell during April through September (fig. 3*B*). During the months of larger precipitation, the evaporation rate also was large. Mean annual evaporation in the study area from free-water surfaces ranged from 50 to 70 in. (Hansen and others, 1978). The mean January air temperature ranged between 28 and 30 °F, and the mean July air temperature ranged from 65 to 75 °F (Hansen and others, 1978).

Land Use

The principal land uses in the study area include: irrigated cropland, pastureland, and hayland, and nonirrigated cropland, and rangeland. Urban and suburban land use is increasing in the study area. Ranching and farming in the area date back to the 19th century. Ranchers practiced irrigation as early as 1885 to grow grass hay for livestock. Between 1920 and 1940, several irrigation wells were drilled (Larsen, 1981, p. 2). The acreage of irrigated land increased rapidly during the 1950's when many irrigation wells were drilled. Before the early 1960's, water also was pumped from sumps in areas where depth to the water table was less than 10 ft. During 1984, most irrigated land was used to grow alfalfa and pasture grass. Other irrigated land was used to grow small grains, corn, sod (blue grass), and potatoes. Some crops, such as field corn, have been grown successfully in the area using dryland-farming methods.

Surface Water

The upper Black Squirrel Creek basin is drained by Black Squirrel Creek and its tributaries, Brackett Creek and Big Springs Creek. Currently (1986), all streams are ephemeral and flow only in direct response to precipitation; streambeds in most areas are many feet above the water table (Langbein and Iseri, 1960, p. 18). Because of the ephemeral nature of streams in the basin, streamflow does not provide a dependable source of water. Few records of streamflow are available for any of the streams in the basin. Prior to large water-level declines caused by ground-water pumpage beginning during the 1950's and 1960's, segments of the streams were intermittent.

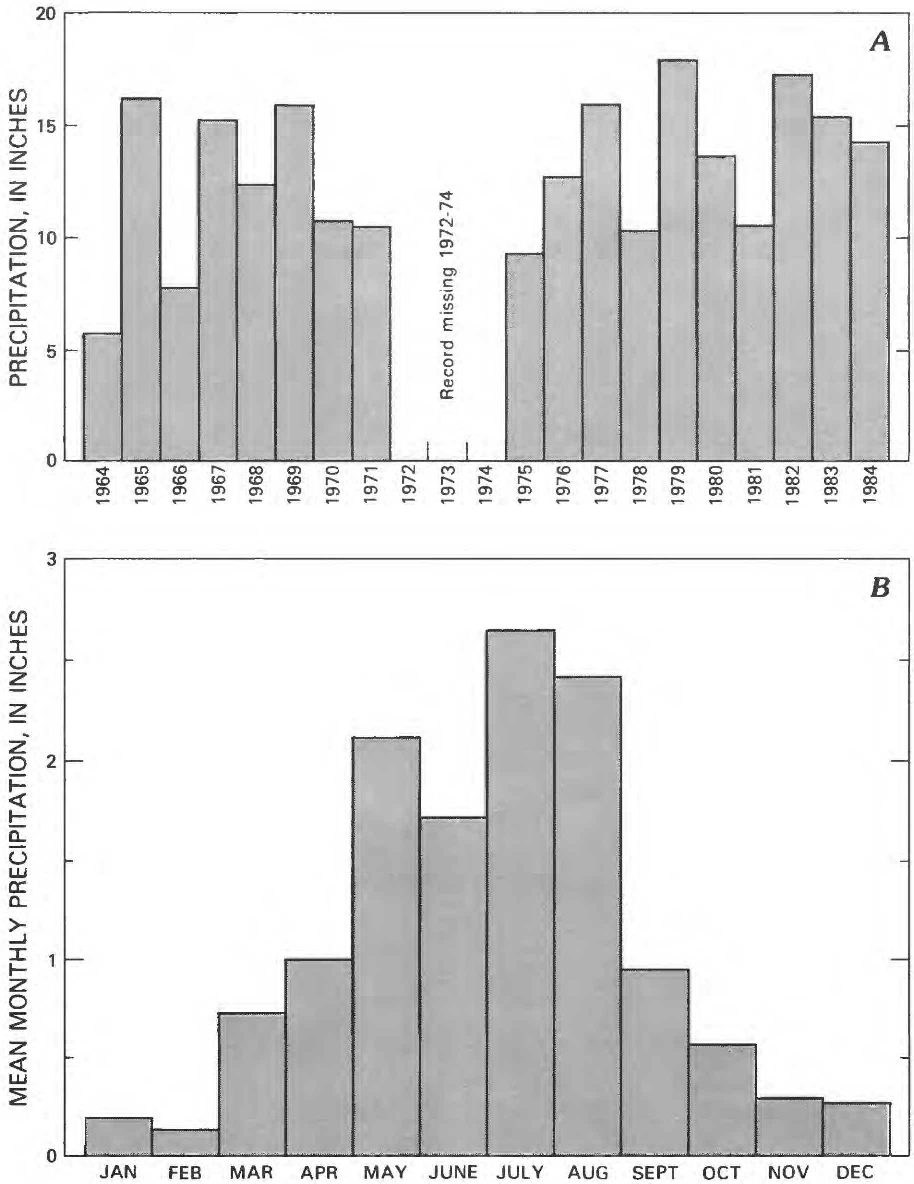


Figure 3.--Annual precipitation (*A*) and mean monthly precipitation (*B*) at Rush, 1964-71 and 1975-84.

Geology

The upper Black Squirrel Creek basin contains consolidated and unconsolidated deposits. Consolidated deposits in ascending stratigraphic order include the Cretaceous Fox Hills Sandstone, Laramie, and Arapahoe Formations, and the Cretaceous and Tertiary Denver Formation and the Dawson Arkose, all of which are important aquifers. In addition, the Cretaceous Pierre Shale subcrops beneath the alluvial aquifer in the extreme southern part of the study area; however, the Pierre Shale does not yield any water to wells in the area. The Fox Hills Sandstone and the Laramie Formation are exposed in the southeastern part of the study area (fig. 4). The Dawson Arkose is exposed in the north-central and northeastern parts of the study area. The Arapahoe and Denver Formations are covered by eolian sand and alluvium in most areas. The consolidated water-bearing formations (Fox Hills Sandstone, Laramie, Arapahoe, and Denver Formations, and Dawson Arkose) generally dip to the north at angles of 10 degrees or less. Maximum thickness of these formations is about 1,700 ft at the northern boundary of the alluvial aquifer (Major and others, 1983, p. 204). The altitude and configuration of the top of the bedrock surface are shown in figure 5.

Alluvium, mapped as undifferentiated (fig. 4), includes the valley-fill alluvium, Piney Creek Alluvium, and alluvium occupying present stream channels. Soister (1968) described the valley-fill alluvium as the oldest and thickest alluvial deposit in the upper Black Squirrel Creek basin. The valley-fill alluvium, consisting mostly of gravely sand, was deposited during the late Pleistocene in stream channels. It ranges from 0 to 200 ft in thickness and consists mostly of granite, quartz, and feldspar sand and gravel and occupies an area of about 100 mi^2. The valley-fill alluvium weathers to a light yellowish gray or grayish orange. Eolian sand of Holocene age overlies the valley-fill alluvium. It consists of fine- to very coarse-grained sand that ranges from 10- to 40-ft thick, although large dunes are as much as 140-ft thick (Soister, 1968). In some areas, the Piney Creek Alluvium overlies the eolian sand; in other areas, it overlies the valley-fill alluvium. The Piney Creek Alluvium (Holocene) consists of clayey sandy silt and silty sand and ranges from 5 to 15 ft in thickness. The most recent alluvium is less than 15 ft thick and consists of clay, silt, and gravel deposits that occupy stream channels. Where alluvium and eolian sand are saturated with water, they form the alluvial aquifer.

Ground Water

The alluvial aquifer contains sufficient water to supply domestic, stock, irrigation, and municipal wells, and it is the principal aquifer in the study area. Water pumped from municipal wells is exported to areas west of the basin by the Cherokee Water District and the Pikes Peak Water Company. Domestic water supply within the study area is obtained from the aquifer by individual domestic wells.

The extent of the alluvial aquifer, altitude of the water table, direction of ground-water movement, and thickness of saturated alluvium for March 1984 are shown in figure 6. The approximate area of the alluvial aquifer is

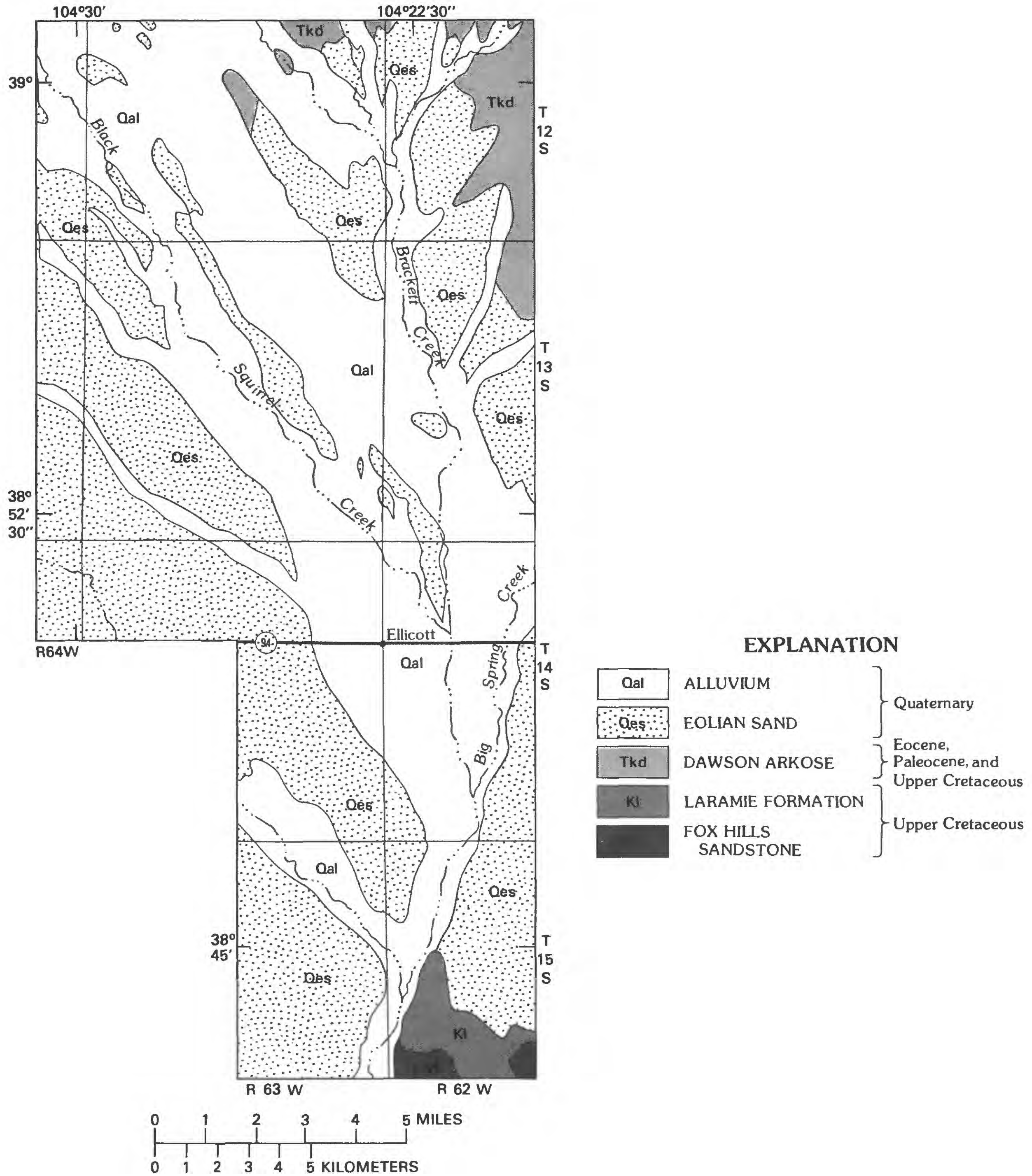


Figure 4.--Generalized surficial geology.

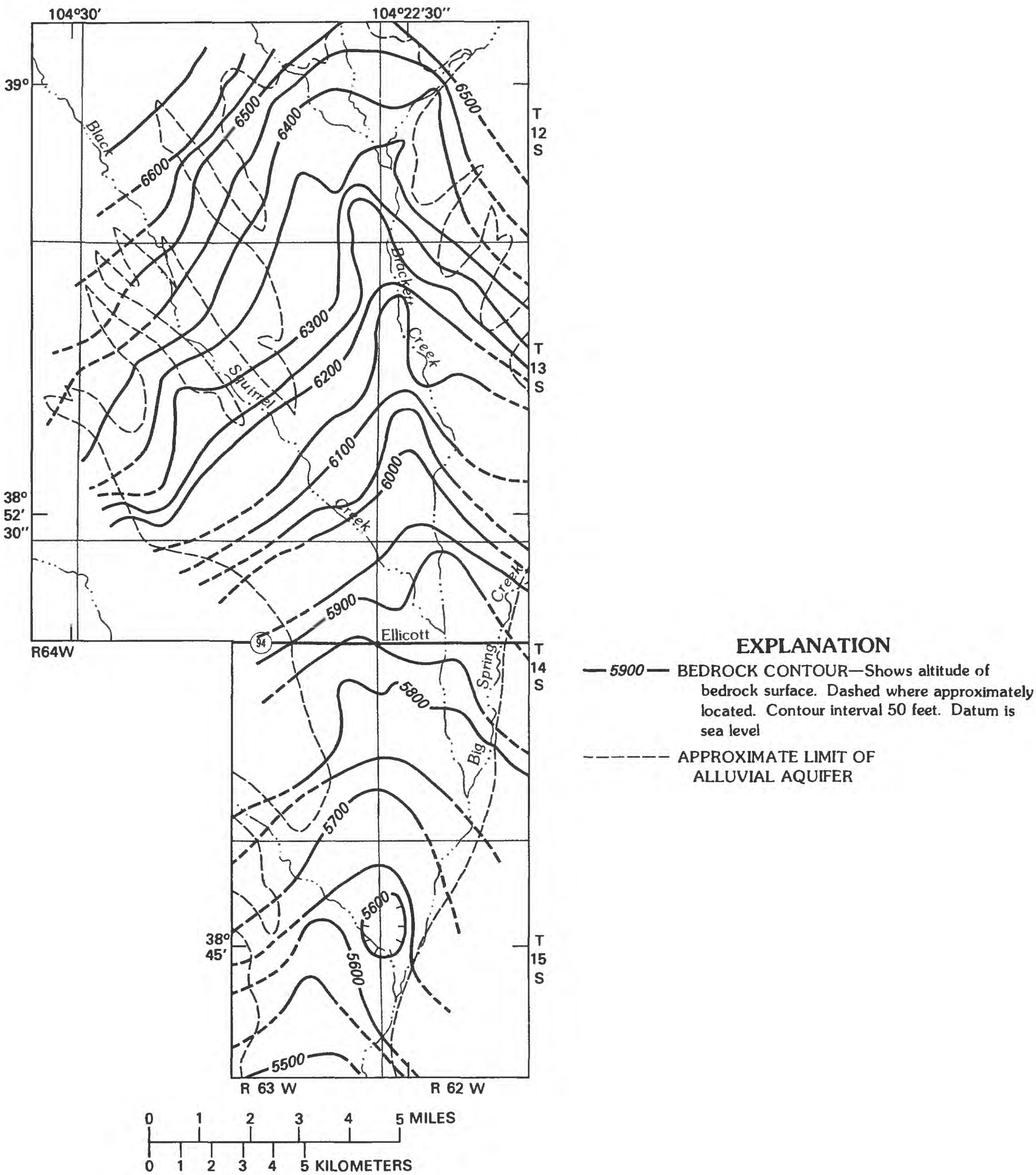


Figure 5.--Altitude and configuration of bedrock surface.

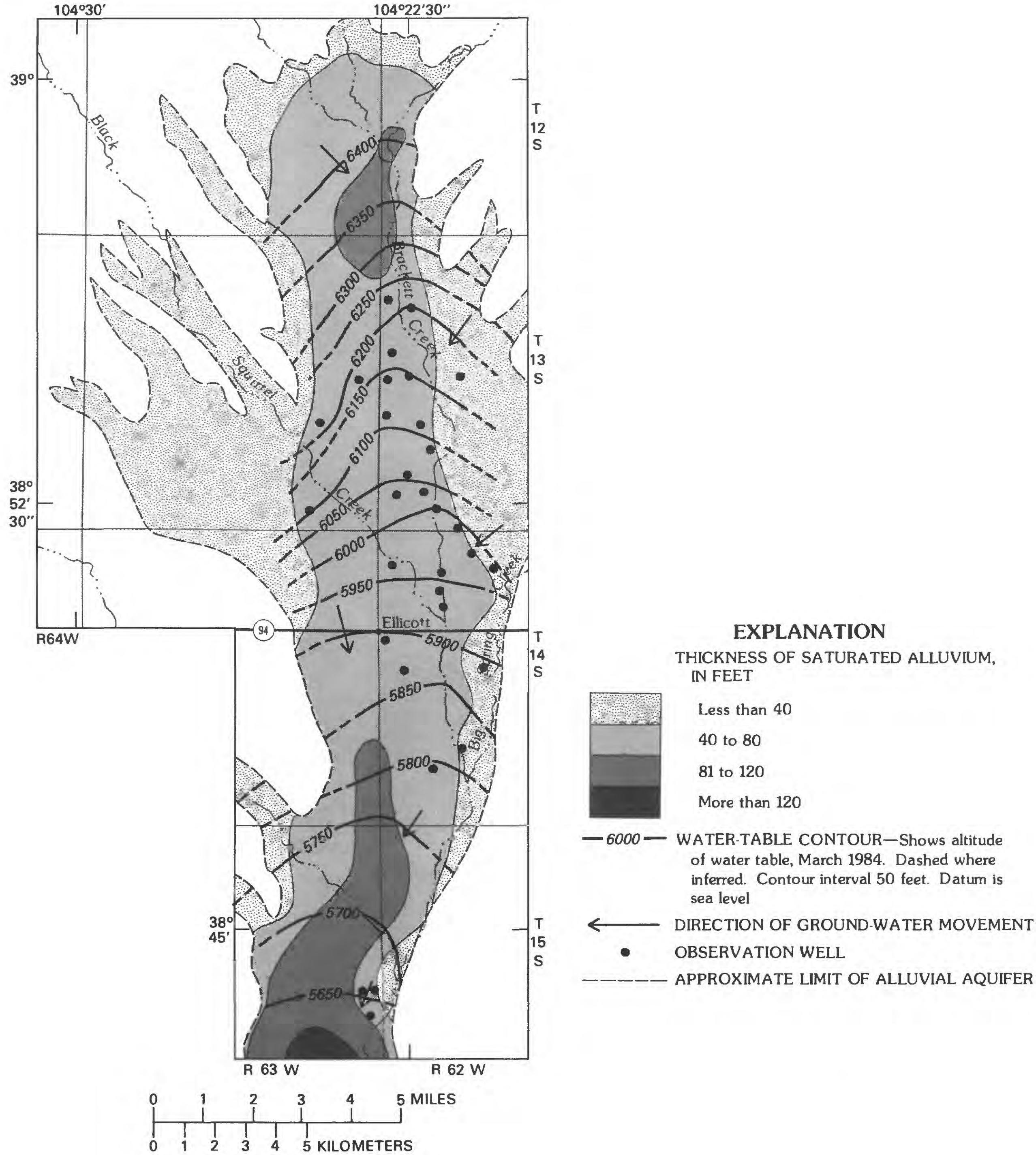


Figure 6.--Extent of the alluvial aquifer, altitude of the water table, direction of ground-water movement, and thickness of saturated alluvium, March 1984.

101.3 mi^2 (Emmons, 1977, p. 7). Horizontal ground-water movement occurs approximately perpendicular to water-table contours. Water in the alluvial aquifer generally flows to the south out of the study area. Thickness of saturated alluvium during March 1984 ranged from less than 40 ft to more than 120 ft. The greatest thickness of saturated alluvium was at the southern boundary of the study area (fig. 6).

Yields from wells generally range from about 10 gal/min for stock and domestic wells to 1,500 gal/min for irrigation and municipal wells. Yields greater than 2,000 gal/min have been reported where the saturated thickness is greater than 100 ft. Because of the decline of the water table, many well yields have decreased; some wells near the boundaries of the aquifer are now dry.

Recharge to the aquifer is from deep percolation of precipitation, irrigation-return flow, infiltration of streamflow, and inflow from underlying bedrock aquifers. Natural discharge from the aquifer is by evapotranspiration and underflow, which accounts for ground water that leaves the basin at the southern end of the study area. During 1964, underflow was estimated to have been about 10,000 acre-ft (McGovern and Jenkins, 1966).

Before the 1950's, prior to development of the alluvial aquifer, evapotranspiration probably was a substantial form of discharge from the aquifer. When depth to the water table became larger than 10 ft because of pumpage, evapotranspiration of ground water by native vegetation and phreatophytes became insubstantial (McGovern and Jenkins, 1966).

Pumpage for irrigation and municipal use is the largest discharge from the aquifer. None of the ground water exported out of the basin for municipal use is returned to the Black Squirrel Creek hydrologic system. Part of the water pumped for irrigation is returned to the aquifer through deep percolation. Return of water to the aquifer from irrigation application is estimated to be less than 25 percent when gravity methods of irrigation are used (McGovern and Jenkins, 1966). Since 1970, sprinkler irrigation has increased; during 1984, sprinkler irrigation was the predominant irrigation method used in the study area. Because of its greater efficiency, sprinkler irrigation returns a smaller percentage of the water pumped, although the volume pumped usually is less.

In contrast to the extensive development of the alluvial aquifer, development of the four bedrock aquifers in the upper Black Squirrel Creek basin has been minimal. Because the alluvial and bedrock aquifers are hydraulically connected, development of the bedrock aquifers (the Laramie-Fox Hills, Arapahoe, Denver, and Dawson aquifers) could have an adverse effect on the water supply in the alluvial aquifer.

Hydraulic Characteristics

Hydraulic characteristics describe an aquifer's physical capability to transmit and store water. Hydraulic characteristics affect the rate of ground-water movement, the volume of water in storage, and the rate and extent of water-level declines. Specific yield, transmissivity, and hydraulic conductivity were measured or estimated for the alluvial aquifer.

Specific yield, a dimensionless hydraulic property of an aquifer is the quantity of water the aquifer will release from storage by gravity drainage per unit volume of saturated aquifer. Specific yield may be measured using several techniques, including long-duration aquifer tests. Because no aquifer tests of sufficient duration have been made in the upper Black Squirrel Creek basin, specific yield was estimated based on specific yield of similar alluvial materials. Size and sorting of the aquifer sediments affect the specific yield. Grain sizes of the aquifer material range from clay to gravel, and sorting of sediments also is variable. The degree of sorting ranges from poorly to well sorted. Sorting commonly changes rapidly within short distances, both vertically and horizontally. Johnson (1967, p. 70) estimated several values of specific yield for aquifer materials ranging in size from clay to coarse gravel; average specific-yield values ranged from 2 percent (clay) to as much as 22 percent (coarse gravel).

A well may penetrate many types of sediments, which have various degrees of sorting and grain sizes. Specific-yield values of 15 to 20 percent commonly are estimated for alluvial aquifers. Locally, specific yield may deviate from this range; basinwide, these estimates were considered representative of the aquifer. A specific yield of 18 percent was used during this study.

Transmissivity is the rate water is transmitted through a unit width of the aquifer under a unit hydraulic gradient (Lohman and others, 1972). Transmissivity (in feet squared per day) is the product of hydraulic conductivity (in feet per day) and saturated thickness (in feet). In homogenous aquifers, transmissivity is directly proportional to the saturated thickness. Hydraulic conductivity is a measure of an aquifer's capability to transmit water and is independent of the saturated thickness. Results from three aquifer tests made during 1954 and 1955 in the study area were presented by Wilson (1965) and by McGovern and Jenkins (1966). During 1954 and 1955, transmissivity values estimated from aquifer tests ranged from 4,700 to 9,400 ft^2/d, and hydraulic-conductivity values ranged from 84 to 147 ft/d. The average transmissivity from these three aquifer tests was 7,800 ft^2/d, and the average hydraulic conductivity was 113 ft/d.

Ground-Water Budget

A ground-water budget accounts for inflows to and outflows from an aquifer. Changes in the volume of water in storage are assumed to be equal to the difference between inflows and outflows. Transient conditions exist when a long-term change in the volume of water in storage occurs. The alluvial aquifer has been losing water from storage since the mid-1950's. The ground-water budget presented here represents average conditions for 1964-84. This is a period during which pumpage exceeded inflow and during which ground water was being removed from storage.

Inflows

Principal inflows to the alluvial aquifer include deep percolation of precipitation, infiltration of streamflow, infiltration of irrigation-return flow, and inflow from the bedrock aquifers. Deep percolation of precipitation and inflow from the bedrock aquifers represent the major sources of recharge to the aquifer.

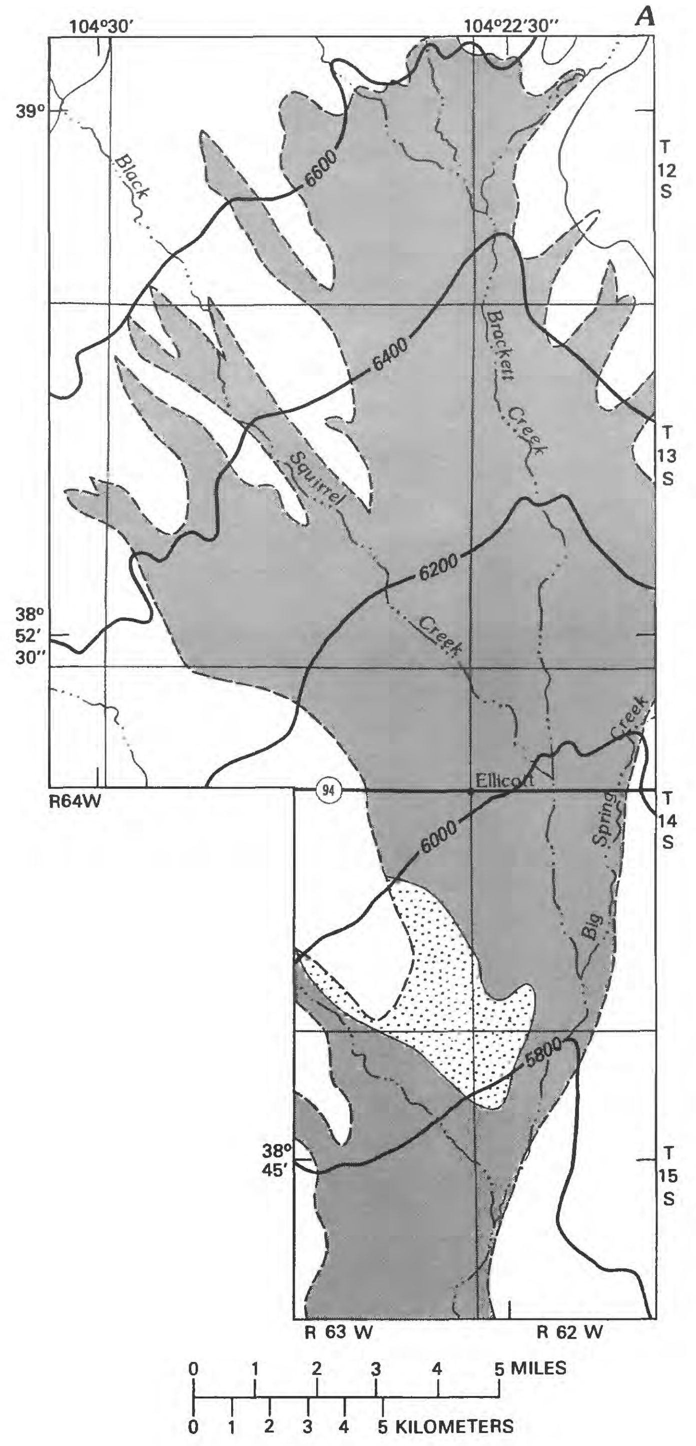
Infiltration rates in the study area are rapid. Major soil types in the study area include arkosic, well-drained soils and sandy, noncalcareous, excessively drained soils (Larsen, 1981). Rates of infiltration range from about 2 to 20 in/h; however, not all precipitation that infiltrates the soil recharges the aquifer (Larsen, 1981).

Annual recharge from precipitation was estimated as a function of total precipitation and major soil type. Total precipitation in the study area increases with increasing land-surface altitude (Livingston and others, 1976). Topography and major soil types are shown in figure *7A*. Goeke (1970, p. 31) estimated that 5 percent of the precipitation that fell on alluvial sediments recharged the aquifer and that 15 percent of the precipitation that fell on eolian sand recharged the aquifer. J.W. Patterson and Associates, Inc. (1980, p. 14) estimated that between 0 and 6.4 percent of the precipitation that fell on the alluvial aquifer entered the ground-water system. Recharge rates used during this study ranged from 0.62 in/yr (5 percent of precipitation) for arkosic soils to 1.29 in/yr (10 percent of precipitation) for eolian soils (fig. *7B*). Estimated recharge from precipitation ranged from 1,700 acre-ft during 1964 to 5,100 acre-ft during 1979 and averaged 3,700 acre-ft/yr for 1964-84.

The ephemeral nature of the streams and the lack of streamflow data for the basin makes estimation of the rate of recharge to the aquifer from streamflow uncertain. Infiltration of streamflow generally takes place only in the northern part of the study area because all streamflow generally infiltrates before reaching the southern part of the study area. Streamflow is irregular, and it occurs in response to snowmelt during early spring and in response to thunderstorms during the summer and fall in the headwaters of Black Squirrel Creek, northwest of the study area. Based on a statistical relation between altitude and annual streamflow for adjacent areas of El Paso County (Livingston and others, 1976, p. 18) and infiltration rates from artificial-recharge tests in the study area (Emmons, 1977), recharge from streamflow for the study area was estimated to range from 400 acre-ft during 1964 to 1,100 acre-ft during 1979 and averaged 800 acre-ft/yr for 1964-84.

Some irrigation water is returned to the aquifer through deep percolation. McGovern and Jenkins (1966) estimated that less than 25 percent of the applied irrigation water returned to the aquifer (less than 2,000 acre-ft during 1964). Before 1970, gravity methods of irrigation were the most common; however, since 1970, a mixture of sprinkler and gravity methods have been used. Irrigation-return flow to the aquifer was not estimated during this study because irrigation pumpage was estimated as crop consumptive use.

The rate and direction of flow between the alluvial and bedrock aquifers are dependent on the vertical conductance (the quotient of flow-path length and vertical hydraulic conductivity) and on the vertical-head gradients between the aquifers. The potentiometric surfaces of the bedrock aquifers are poorly defined; therefore, the vertical-head gradient between the alluvial aquifer and the bedrock aquifers are not well defined in most of the study area. As a result, the rate of flow between the alluvial aquifer and the bedrock aquifers could not be estimated except on a regional basis. Robson (1984, p. 60), using a regional steady-state model, estimated that the alluvial aquifer



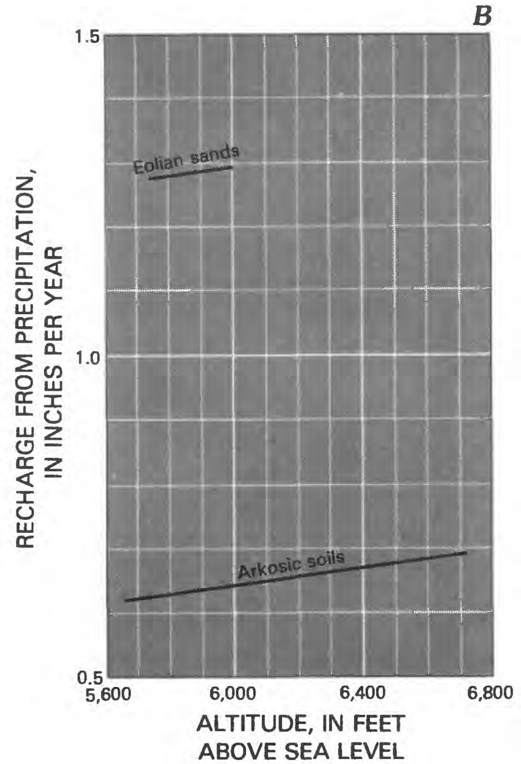


Figure 7.--Topography and major soil types (*A*) and relation between altitude and recharge from precipitation for major soil types (*B*).

received recharge from the underlying bedrock aquifers at the rate of about 1,300 acre-ft/yr; most of the flow comes from the Denver and Arapahoe aquifers. Because the vertical-head gradient and the direction of flow are subject to change as the aquifers are developed, the magnitude and direction of flow will change with time.

Outflows

Outflows from the alluvial aquifer consist of underflow at the southern end of the study area and pumpage by wells. Outflow also occurs by evapotranspiration of ground water by native vegetation and phreatophytes in swampy areas; however, evapotranspiration has been small in most areas since 1964 because the depth to water generally is greater than 10 ft. However, alfalfa, one of the major crop types in the area, is capable of sending its roots to depths greater than 10 ft to utilize ground water. Evapotranspiration of ground water by alfalfa was included in the crop-consumptive-use estimates, and it was not necessary to estimate this flow component separately.

Underflow is a major outflow from the alluvial aquifer and is calculated using the Darcy equation:

$$Q = -KIA \tag{1}$$

where Q = underflow (discharge), in cubic feet per day;
K = hydraulic conductivity, in feet per day;
I = hydraulic gradient (dimensionless); and
A = cross-sectional area of flow, in square feet.

The estimated underflow (Q) is directly proportional to hydraulic conductivity (K), hydraulic gradient (I), and cross-sectional area of flow (A). Therefore, errors in these parameters will produce proportional errors in the estimate of underflow. Because hydraulic conductivity is poorly defined by the available data, the estimated underflow also may be poorly defined. Based on an average hydraulic conductivity of 117 ft/d, a hydraulic gradient of 0.006, and a cross-sectional area of about 1,645,000 ft^2, the underflow during 1964 through 1987 was calculated to average 1,155,000 ft^3/d or about 9,700 acre-ft/yr. Using a hydraulic conductivity of 113 ft/d, McGovern and Jenkins (1966) estimated underflow at 10,000 acre-ft/yr during 1964.

Since 1964, discharge from wells has been the largest outflow from the alluvial aquifer. Water pumped from wells meets agricultural, municipal, stock, and domestic needs. Irrigation is the principal use of ground water. Based on fuel and electric-power records, McGovern and Jenkins (1966) estimated that irrigation pumpage from 95 wells and sumps was 8,000 acre-ft during 1964. Of the ground water pumped for irrigation during 1964, an estimated 6,000 acre-ft was consumptively used (McGovern and Jenkins, 1966).

The volume of water transpired to the atmosphere by the growth of plants and the volume of water evaporated from the plant foliage and surrounding soil is the crop-consumptive use. The crop-consumptive-use method of estimating pumpage for irrigation as described by Frenzel (1984) was used in this study. All water pumped for irrigation, which was not consumptively used by crops, was assumed to be returned to the aquifer through deep percolation. This assumption is reasonable because of the rapid infiltration rates of the soils.

In areas where the water table is at or near land surface, ground water discharges by evaporation from the soil and is transpired by phreatophytes, plants whose roots tap the water table. Both processes often occur concurrently and are referred to as ground-water evapotranspiration. Crop-consumptive use also involves the process of evapotranspiration; however, it is distinguished from ground-water evapotranspiration in this report.

The maximum depth to which plant roots may draw directly from the water table varies with the species of plant and the type of soil. A maximum depth (extinction depth) of 5 ft was assumed for ground-water evapotranspiration by native grasses, which are the predominant phreatophyte in the study area. Ground-water evapotranspiration probably was a major outflow from the alluvial aquifer prior to extensive development of the aquifer, which increased the depth to water in most areas. Ground-water evapotranspiration during this study was estimated to be less than 2 percent of the total outflow from the aquifer for 1964-84. The importance of ground-water evapotranspiration was evaluated using ground-water flow models and is discussed in the section entitled "Importance of Ground-Water Evapotranspiration."

An onsite field survey of the study area was done during March 1985 to determine the major crop types grown during 1964 through 1984; these crops included alfalfa, pasture grass, corn, small grains, sod (blue grass), sorghum grains, and potatoes. Growth of sod in the area requires about 3 ft of water per year; of that requirement, less than 1 ft is supplied by precipitation. Corn requires the smallest quantity of water (about 1.5 ft/yr); corn has been grown successfully using dryland farming methods. Using the results of the onsite survey and aerial photographs taken during 1953, 1954, 1975, and 1983, the consumptive use from 1964 through 1984 was estimated; it ranged from 6,400 acre-ft during 1964 to 8,700 acre-ft during 1975 and 1976. A summary of agricultural and municipal consumptive use of ground water from 1964 through 1984 is shown in figure 8.

Municipal use is ground water that is exported out of the basin by the Cherokee Water District and the Pikes Peak Water Company. The Cherokee Water District has exported ground water from the basin to satisfy domestic and industrial needs in the Colorado Springs area since 1964. Pumpage by the Cherokee Water District ranged from 830 acre-ft during 1975 to 5,300 acre-ft during 1964 and averaged 2,400 acre-ft/yr from 1964 through 1984. The Pikes Peak Water Company has exported water since 1975. Pumpage by the Pikes Peak Water Company ranged from 660 acre-ft during 1975 to 850 acre-ft during 1977 and averaged 740 acre-ft/yr from 1975 through 1984. A summary of ground-water pumpage for municipal use is listed in table 1. Consumptive use of all water pumped for municipal purposes is considered to be 100 percent because no water is returned to the aquifer in the study area. Pumpage of ground water for domestic and stock purposes in the study area is small (less than 2 percent of the total pumpage) compared to irrigation and municipal pumpage.

<u>Changes in storage</u>

Changes in the volume of water in storage in an aquifer are the result of unequal quantities of inflow and outflow. Since the mid-1950's, inflows to the alluvial aquifer have been less than outflows. Long-term decreases in

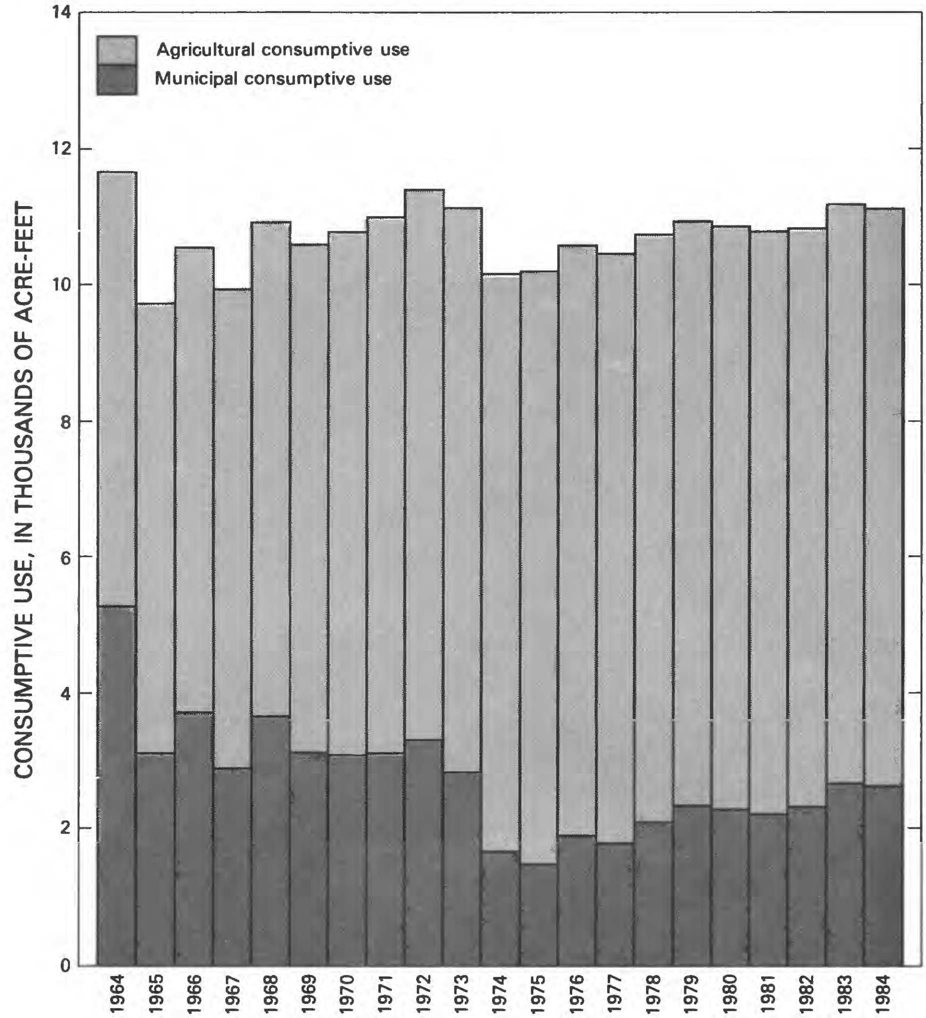


Figure 8.--Agricultural and municipal consumptive use of ground water, 1964-84.

Table 1.--*Summary of ground-water pumpage for municipal use from the alluvial aquifer, 1964-84*

[dashes indicate no pumpage]

Year	Cherokee Water District pumpage[1] (acre-feet)	Pikes Peak Water Company pumpage[2] (acre-feet)
1964	5,300	--
1965	3,100	--
1966	3,700	--
1967	2,900	--
1968	3,700	--
1969	3,100	--
1970	3,100	--
1971	3,100	--
1972	3,300	--
1973	2,900	--
1974	1,700	--
1975	830	[4]660
1976	1,100	[4]780
1977	[3]950	[4]850
1978	1,400	[4]680
1979	1,500	[4]820
1980	1,500	750
1981	1,500	700
1982	1,600	690
1983	2,000	730
1984	1,900	730
TOTAL	50,180	7,390

[1]Source: Cherokee Water District (written commun., yearly).
[2]Source: Rodney Preisser (Pikes Peak Water Company, written commun., 1985).
[3]Source: J.W. Patterson and Associates, Inc. (1980).
[4]Source: Tony Venetucci (local resident, written commun., 1980).

storage are indicated by long-term declines of water levels. From spring 1964 through spring 1984, some wells completed in the alluvial aquifer had water-level declines as much as 44 ft (fig. 9). The hydrograph shown in figure 9 is for well SC-13-62-31ABB which is located about 3 mi due north of Ellicott in an intensely pumped area of the aquifer. (See figure 10 for the system for numbering wells.) In general, depth to water is largest during May, June, July, and August (when agricultural pumpage is largest); depth to water is smallest during December, January, February, and March. Prior to 1981, no municipal wells were located upgradient from well SC-13-62-31ABB. Water levels were affected by changes in natural inflows and outflows and by agricultural pumpage. During 1981, two large-capacity municipal wells began operation upgradient from the well. The hydrograph (fig. 9) shows an increased rate of water-level decline beginning about that time. The relatively slow rate of decline during the 1970's was due to decreased agricultural pumpage in the immediate area around the well. Based on a specific yield of 18 percent, the estimated ground water in storage during 1964 was about 600,000 acre-ft. Between 1964 and the end of 1984, about 100,000 acre-ft had been removed from storage. This represents an average decrease in storage of about 5,000 acre-ft/yr.

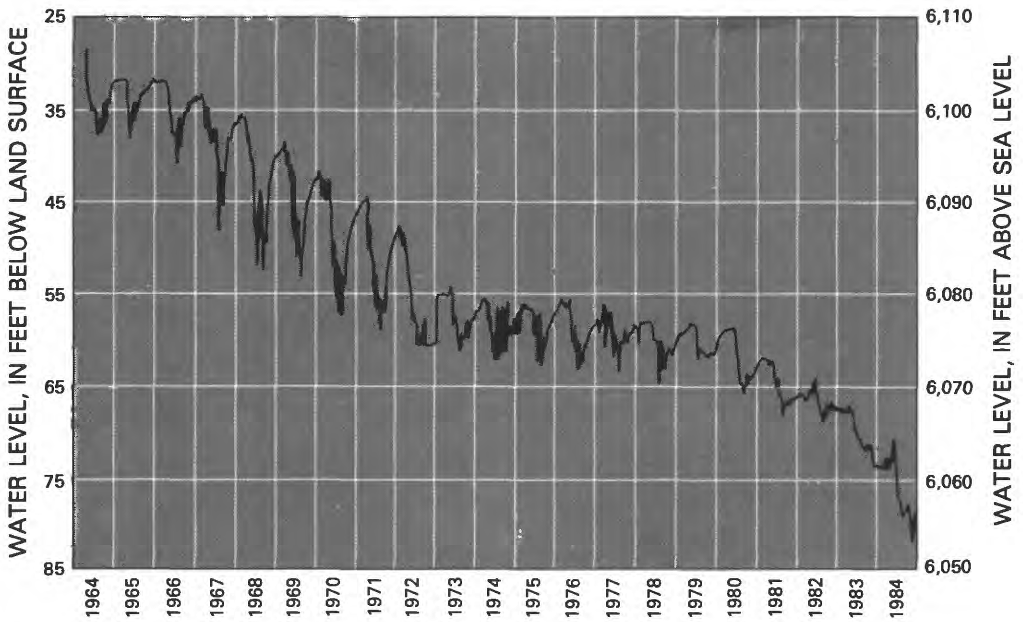


Figure 9.--Long-term decline of water level for well SC-13-62-31ABB.

Bingham and Klein (1974) documented water-level declines of as much as 46 ft in an area east of Ellicott from spring 1964 through spring 1974. Water-level declines from spring 1974 through spring 1984 are shown in figure 11; declines were as much as 30 ft in an area north of Ellicott. The area affected by ground-water pumpage has expanded since 1974; however, the magnitude of the declines has been smaller.

Summary of inflows and outflows

An average annual ground-water budget for the alluvial aquifer for 1964-84 (table 2) indicates that estimated change in storage (inflow minus outflow) averaged 14,850 acre-ft/yr. Comparing this estimate of change in storage with that of 5,000 acre-ft/yr based on historic water-level changes indicates that the ground-water budget may be in error by as much as 9,850 acre-ft/yr. Because pumpage for municipal and irrigation use are the most reliable estimates in the budget, it is likely that the errors result from overestimating underflow and underestimating inflow from recharge from precipitation, infiltration of streamflow, and inflow from bedrock aquifers.

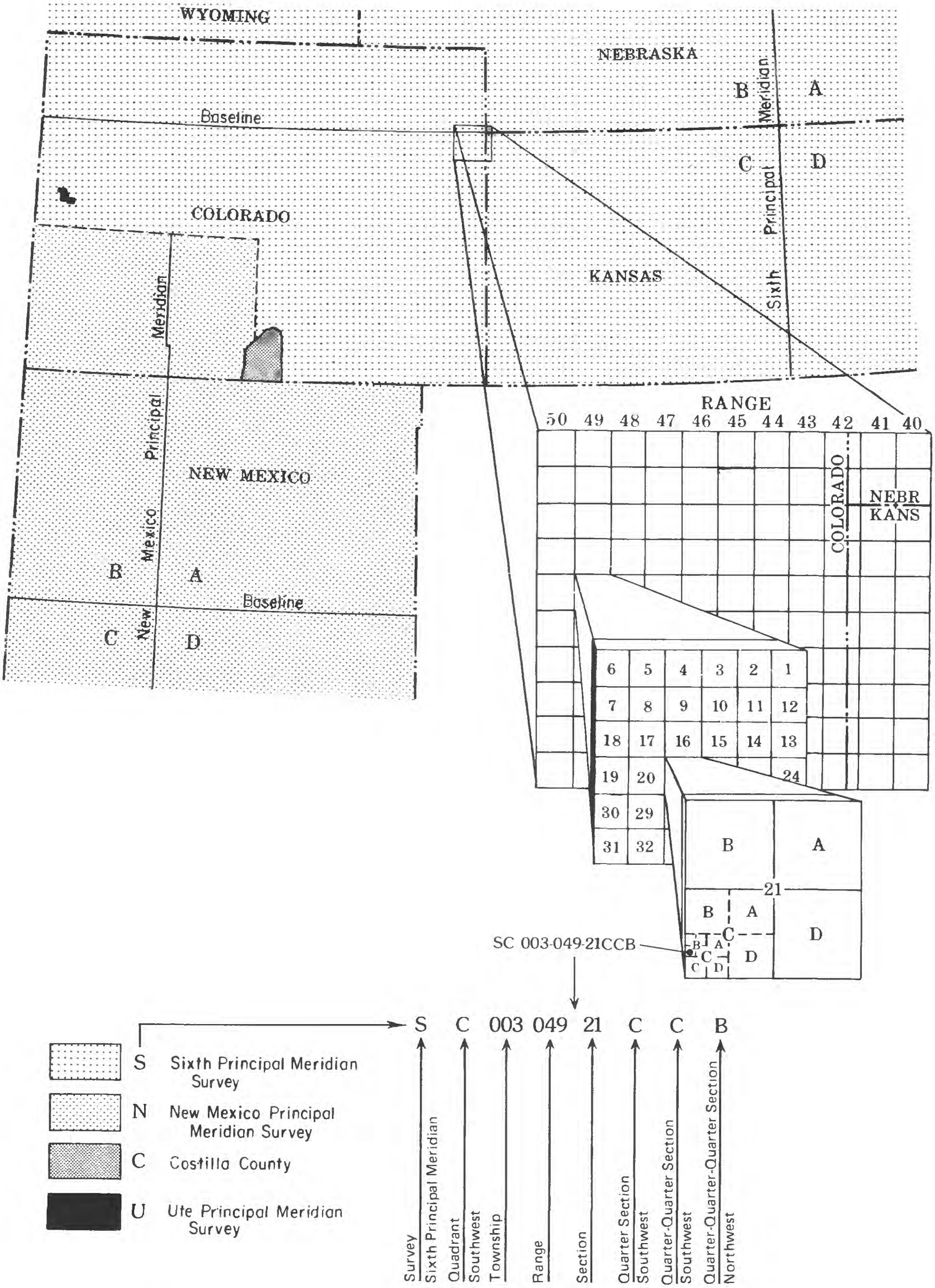


Figure 10.--System of numbering wells to obtain local well number.

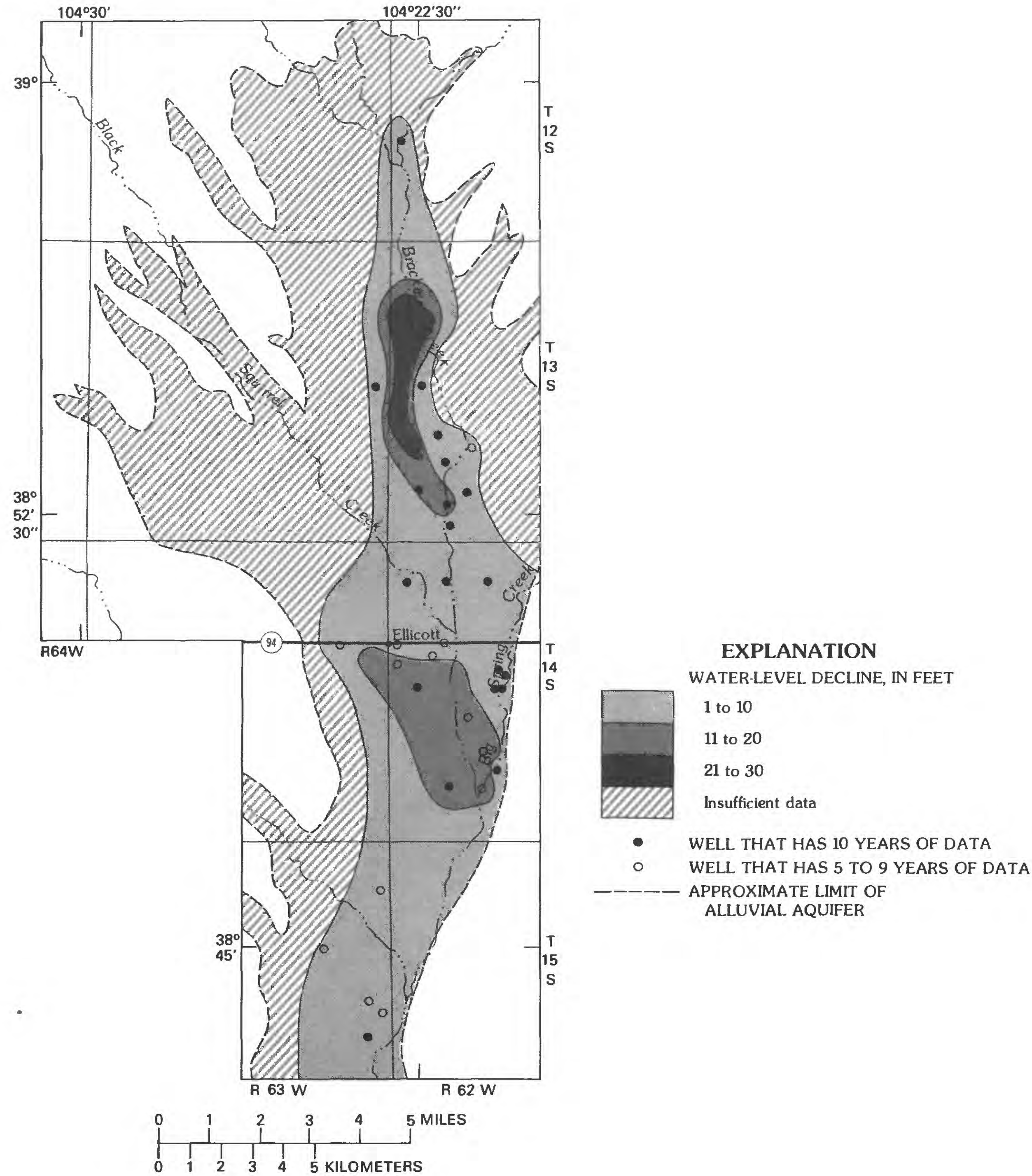


Figure 11.--Water-level declines from spring 1974 through spring 1984.

Table 2.--*Average annual ground-water budget for the alluvial aquifer, 1964-84*

Source		Average annual rate[1] (acre-feet per year)
Inflows:		
Recharge from precipitation		3,700
Infiltration		800
Inflow from bedrock aquifers[2]		1,300
	Total inflows	5,800
Outflows:		
Consumptive use including:		
Municipal pumpage		2,750
Crop-consumptive use (irrigated crops)		8,000
Evapotranspiration		400
Underflow at southern end of the basin		9,500
Surface-water outflow		0
	Total outflows	20,650
Change in storage: (Inflow - outflow)		-14,850

[1]Average annual rates computed for a period of 21 years.
[2]Robson (1984, p. 60).

WATER QUALITY

During this study, water-quality samples were collected from 36 wells completed in the alluvial aquifer. Of these, 24 samples were analyzed for dissolved nitrite plus nitrate as nitrogen (hereafter referred to as nitrite plus nitrate) and dissolved solids; 12 samples were analyzed for major cations and anions. Field measurements were made of pH, temperature, and specific conductance at all sampled wells. Water-quality data for the 24 samples that have nitrite plus nitrate analyses are listed in table 3, and the 12 samples that have major cation and anion analyses are listed in table 4.

Specific conductance, in microsiemens per centimeter at 25 degrees Celsius, is a measure of the ability of a water sample to conduct electricity. Specific conductance of a sample is dependent on the type and concentration of the substances dissolved in the water. The relation between specific conductance and dissolved solids for water from the alluvial aquifer is shown in figure 12. Dissolved solids are a measure of the concentration of dissolved minerals and other substances in the water. Most water in the alluvial aquifer had a dissolved-solids concentration less than 300 mg/L. This relation (fig. 12) can be used to estimate concentrations of dissolved solids in water from the alluvial aquifer from specific-conductance measurements.

Table 3.--*Physical and selected chemical characteristics of water from 24 wells completed in the alluvial aquifer*

[μS/cm, microsiemens per centimeter at 25 °Celsius; °C, degrees Celsius; mg/L, milligrams per liter; --, data not available]

Local well number	Date of sample	Specific conductance, laboratory (μS/cm)	Temperature (°C)	pH, (standard units)	Solids, residue at 180 °C, dissolved (mg/L)	Nitrogen, nitrite + nitrate, dissolved (mg/L as N)
SC-12-62-30BDB	08-09-84	365	14.5	6.8	244	11
SC-12-62-30CDC	08-08-84	356	18.0	6.6	237	11
SC-12-63-22BBB	08-09-84	--	13.0	6.9	316	1.7
SC-13-62-09BBB	08-10-84	1,220	13.0	7.2	842	33
SC-13-62-16AAB	08-10-84	608	13.5	7.5	401	3.6
SC-13-62-21BDD	08-10-84	349	13.5	9.2	210	.16
SC-13-63-01CCC	08-16-84	261	15.0	6.6	171	6.5
SC-13-63-06DAA	08-09-84	515	11.0	7.8	321	<.10
SC-13-63-12CDB	08-09-84	310	12.5	7.5	195	2.8
SC-13-63-14ABB	08-13-84	410	11.5	8.1	257	1.7
SC-13-63-22ADB	08-10-84	561	13.0	7.7	353	2.9
SC-14-62-05ACD	08-16-84	369	14.5	6.7	233	6.0
SC-14-62-08CCB	08-10-84	288	14.5	7.0	193	4.8
SC-14-62-20DBC	08-10-84	825	17.5	7.3	548	8.4
SC-14-62-32BBA	08-07-84	323	15.5	6.6	220	4.1
SC-14-63-03DDC	08-09-84	295	16.0	8.2	179	.69
SC-14-63-12DCD	08-10-84	302	16.0	7.4	200	4.2
SC-14-63-13DAA2	08-10-84	290	13.5	7.1	196	4.4
SC-14-63-36AAB	08-07-84	333	14.5	7.1	222	4.4
SC-15-63-01AAA	08-07-84	309	15.0	7.1	204	5.1
SC-15-63-12DCC	08-07-84	303	16.5	6.9	199	3.5
SC-15-63-24DAB	07-24-84	554	14.0	7.9	349	4.3
SC-15-63-25BBA	07-24-84	341	14.0	8.4	223	4.6
SC-15-63-26BAB	08-08-84	362	14.5	6.9	235	5.5

The average chemical composition of 11 samples analyzed from the alluvial aquifer is shown in figure 13. The predominant cations were sodium and calcium, and the predominant anion was bicarbonate. Although concentrations of various ions varied between samples, the relative proportions were consistent. The water sample collected from well SC-12-63-14DDC (table 4) was not considered representative of the aquifer because of possible point sources of contaminants, as indicated by the large concentration of nitrite plus nitrate as nitrogen (72 mg/L).

Hardness is calculated from the concentration of calcium and magnesium in the water and can be used to evaluate the effect of water on soap usage and formation of boiler scale. Hardness of the water from the alluvial aquifer ranged from moderately hard (61-120 mg/L as calcium carbonate) to very hard (more than 180 mg/L as calcium carbonate); however, most ground water in the basin was classified as moderately hard. The hardness classification of Durfor and Becker (1964, p. 27) was used in this study.

Table 4.--*Physical and chemical characteristics of*

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees

Local well number	Date of sample	Specific conductance, laboratory (μS/cm)	Temperature (°C)	pH, standard units)	Solids, sum of constituents, dissolved (mg/L)	Calcium, dissolved (mg/L as Ca)	Sodium, dissolved (mg/L as N)	Potassium, dissolved (mg/L as K)	Magnesium, dissolved (mg/L as Mg)	Manganese, dissolved (μg/L as Mn)	Iron, dissolved (μg/L as Fe)
SC-12-63-14DDC	08-09-84	1,430	11.0	7.0	650	170	85	4.2	21	3	45
SC-12-63-36ACC	08-08-84	388	11.5	6.3	230	35	39	2.4	4.1	3	6
SC-13-62-19CDB	08-07-84	387	13.5	7.7	230	32	44	2.4	3.6	2	8
SC-13-62-30ACC1	08-07-84	415	12.5	7.2	250	38	39	2.3	4.5	1	29
SC-13-62-31ACC	08-07-84	380	13.5	7.2	220	31	41	2.0	3.7	<1	14
SC-13-63-34ABB	08-10-84	405	13.5	7.3	220	36	46	1.9	3.3	<1	4
SC-14-62-05BBB	08-07-84	382	13.0	6.7	230	33	40	2.1	3.9	<1	10
SC-14-62-05CAA	08-07-84	401	13.5	6.7	230	36	41	2.3	4.0	3	10
SC-14-62-16CCC	08-10-84	846	13.0	7.5	510	73	100	2.8	7.2	<1	16
SC-14-62-31BAA	08-07-84	309	14.5	6.8	180	25	36	1.9	2.7	2	14
SC-15-62-18ACB	08-08-84	514	13.5	7.1	320	44	67	2.4	4.7	<1	19
SC-15-63-10DCC	08-07-84	308	14.5	7.2	180	30	32	1.9	2.8	3	22

[1]Bicarbonate was calculated from alkalinity as $CaCO_3$ using the following equation: HCO_3 (mg/L) × 1.2192,

All analyzed chemical constituents, with the exception of nitrite plus nitrate, were present in concentrations less than the limits specified by drinking-water standards (Colorado Department of Health, 1981). Analyses of 36 ground-water samples indicated that concentrations of nitrite plus nitrate generally are large. Areal distribution of concentrations of nitrite plus nitrate in the alluvial aquifer is shown in figure 14. Concentrations ranged from less than 0.1 to 72 mg/L. Of the 36 wells shown in figure 14, 5 wells, or about 14 percent, yielded water containing more than 10 mg/L nitrite plus nitrate, which is the drinking-water standard established by the Colorado Department of Health (1981, p. 27). Wells that have accompanying numbers in figure 14 were not used to define the areal distribution of concentrations of nitrite plus nitrate. The anomalously large concentrations in these three domestic and stock wells (numbered wells in fig. 14) were attributed to point sources of nitrite and nitrate, such as barnyards, septic systems, and nitrogen fertilization, of which one or more may have been the point source. These wells are not considered representative of concentrations of nitrite plus nitrate in the ground-water system.

The health standard for nitrite plus nitrate is based on the possible effects that may occur in infants who drink water containing more than 10 mg/L nitrite plus nitrate as nitrogen (U.S. Environmental Protection Agency, 1976b). Nitrate can be converted to nitrite by certain processes in the gastrointestinal tract of warm-blooded animals. In the bloodstream, nitrate reacts with hemoglobin to produce methemoglobin, resulting in less oxygen transport (U.S. Environmental Protection Agency, 1976a, p. 107-108). This condition, commonly known as "blue baby disease," can be hazardous to infants that are less than 3 months of age. Nitrite poses the same possible health *water from 12 wells completed in the alluvial aquifer*

Celsius; mg/L, milligrams per liter; μg/L, micrograms per liter]

Sulfate, dissolved (mg/L as SO_4)	Nitrogen, nitrite + nitrate, dissolved (mg/L as N)	Fluoride, dissolved (mg/L as F)	Chloride, dissolved (mg/L as Cl)	Silica, dissolved (mg/L as SiO_2)	Phosphorus, dissolved (mg/L as P)	Percent sodium	Sodium adsorption ratio	Hardness (mg/L as $CaCO_3$)	Hardness, noncarbonate (mg/L as $CaCO_3$)	Bicarbonate, calculated (mg/L as HCO_3)[1]
110	72	0.5	76	31	0.02	26	2	510	260	307
65	6.3	.4	10	28	.07	44	2	100	25	96
50	6.5	.4	8.9	30	.04	49	2	95	0	123
62	6.0	.3	12	30	.05	42	2	110	18	117
51	6.0	.4	9.7	29	.05	48	2	93	0	116
33	11	.4	6.1	27	.04	49	2	100	0	130
53	6.5	.4	10	30	.05	46	2	98	10	109
58	7.0	.4	14	30	.05	45	2	110	25	100
140	8.1	.7	48	20	.04	50	3	210	15	240
27	5.1	.5	6.8	30	.08	51	2	74	0	110
61	1.2	1	13	22	.15	52	3	130	0	215
17	5.5	.4	7.0	22	.06	44	2	86	0	127

when $4.5 < pH < 8.3$ (Hem, 1985).

danger as nitrate, although it usually is present in very small concentrations in natural water. Fortunately, nitrite rarely occurs in water in substantial quantities, but water that has concentrations of nitrite as nitrogen concentrations greater than 1 mg/L should not be used for feeding infants (U.S. Environmental Protection Agency, 1976b, p. 81).

SIMULATED HYDROLOGIC SYSTEM

Use of a ground-water flow model aided in understanding the upper Black Squirrel Creek hydrologic system. The ground-water flow model provided a means to evaluate and refine the conceptual geohydrologic model discussed in the section entitled "Upper Black Squirrel Creek Geohydrologic System." The simulation code used to approximate flow of ground water was the modular, three-dimensional, finite-difference, ground-water flow model by McDonald and Harbaugh (1984). No revisions of the simulation code were necessary. Although the model chosen is capable of simulating flow through a vertical sequence of aquifers (three-dimensional flow), it also can be used to simulate flow within a single aquifer (two-dimensional flow), as it was used during this study. Because of the uncertainty in many of the estimates of the aquifer's hydraulic properties and boundary fluxes, this model should be considered as an approximation of the ground-water flow system of the alluvial aquifer.

The process of modeling of ground-water flow requires prior estimates of aquifer properties and boundary conditions. The alluvial aquifer was divided into a series of cells 0.5 mi on each side. The grid, which has 19 columns and 43 rows and was oriented north-south, parallel with the general direction of ground-water movement, is shown in figure 15.

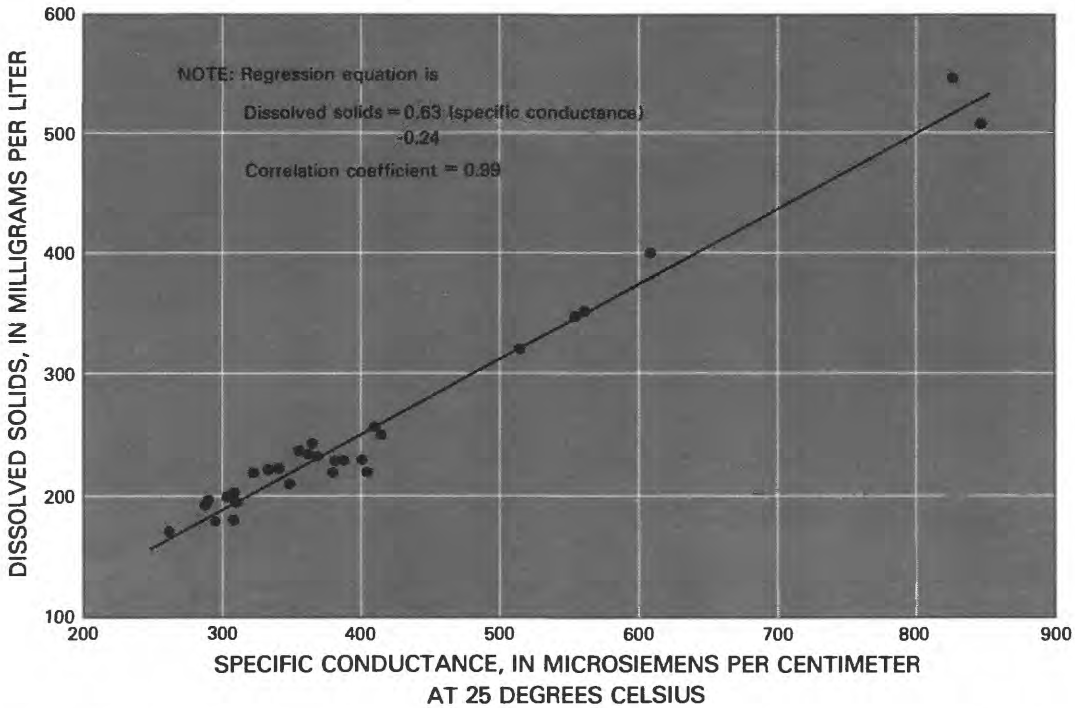


Figure 12.--Relation between specific conductance and dissolved solids.

Steady-State Model

Prior (before 1950) to the development of water supplies using large-capacity wells in the study area, the alluvial aquifer was in steady-state condition. Inflows to the aquifer equaled outflows from the aquifer, and no long-term changes in storage occurred. As part of this study, a steady-state model was developed to simulate ground-water flow for predevelopment conditions.

Model Configuration

Five types of cells were used to represent the alluvial aquifer (fig. 15). Four types of variable-head cell were used to simulate flow in the aquifer where the water-table altitude changed in response to inflows and outflows. Variable-head cells that receive recharge from infiltration of streamflow in the northern part of the study area were assigned larger recharge rates than variable-head cells that only received recharge from precipitation. Areas of the aquifer through which streams previously acted as drains were simulated by variable-head cells that had drains. The drain only simulates outflow from the cell when the water table rises above the altitude of the bottom of the drain. The altitude of the bottom of the drain was the average streambed altitude in the cell. The underflow boundary, at the southern end of the study area (fig. 15), was represented by variable-head cells that had constant flux leaving the cells (simulated as discharging wells).

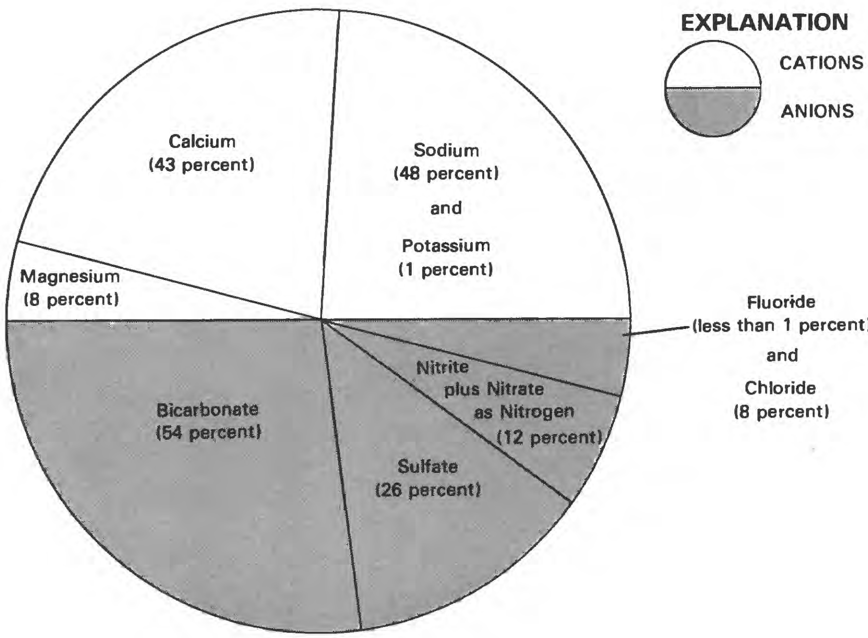


Figure 13.--Average chemical composition of water from the alluvial aquifer.

All other variable-head cells in the model were assigned an areal recharge rate based on soil type (fig. 7*A*) and the relation between altitude and precipitation (fig. 7*B*). Inactive or no-flow cells were assigned where the alluvial aquifer is absent or unsaturated. Lateral inflow of water from adjacent bedrock aquifers was assumed to be negligible. Compared to vertical inflow in subcrop areas, lateral inflow along the valley walls is assumed to be small because of the relatively small area of lateral contact.

Physical characteristics assigned to each variable-head cell included hydraulic conductivity, specific yield, and altitude of the base of the alluvial aquifer. Transmissivity was calculated by the model as the product of hydraulic conductivity and the saturated thickness of the water-table aquifer. A maximum ground-water evapotranspiration rate, a ground-water evapotranspiration extinction depth, and the altitude of the land surface (ground-water evapotranspiration surface) were assigned to each active cell.

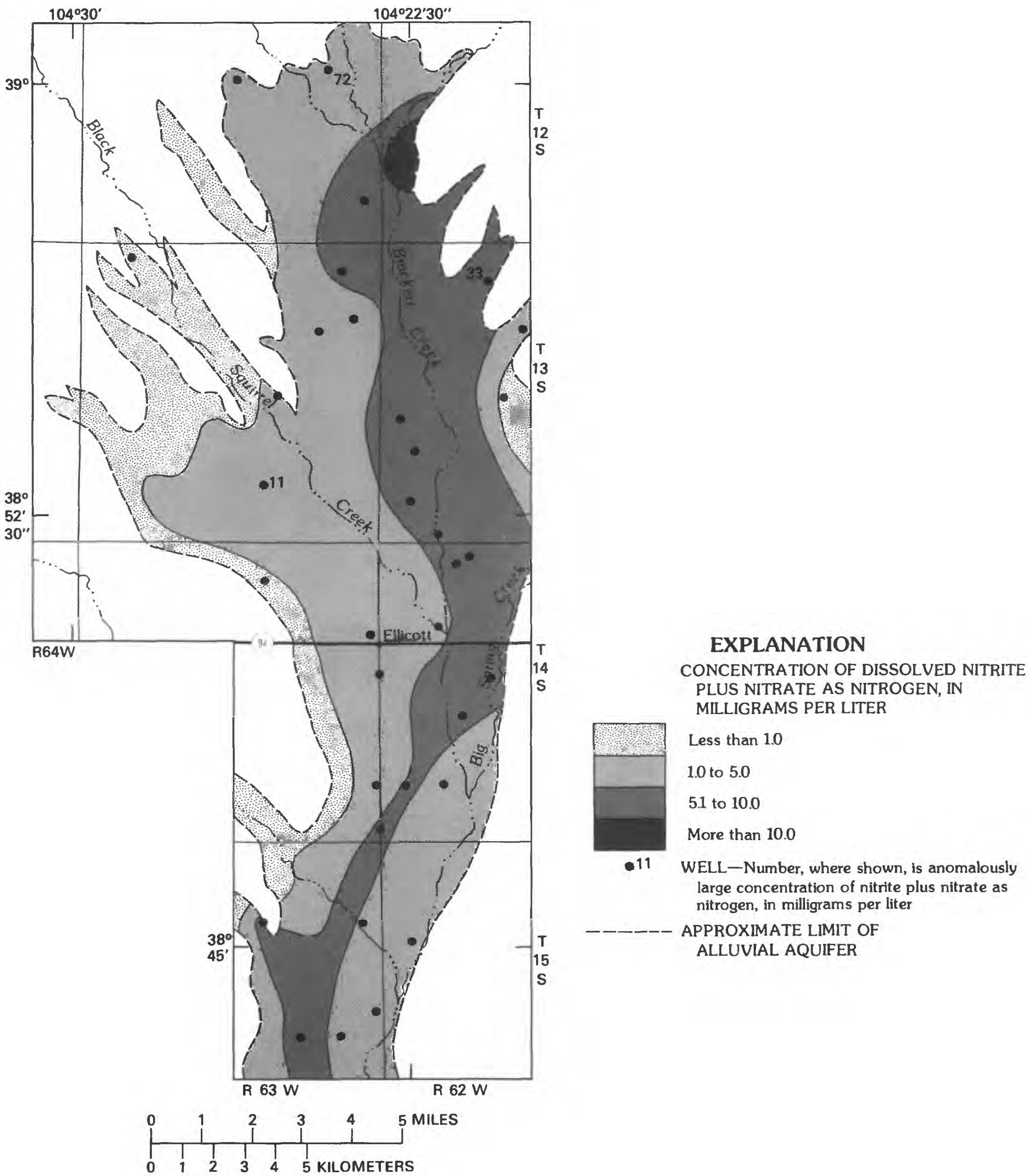


Figure 14.--Areal variations in the concentrations of dissolved nitrite plus nitrate as nitrogen.

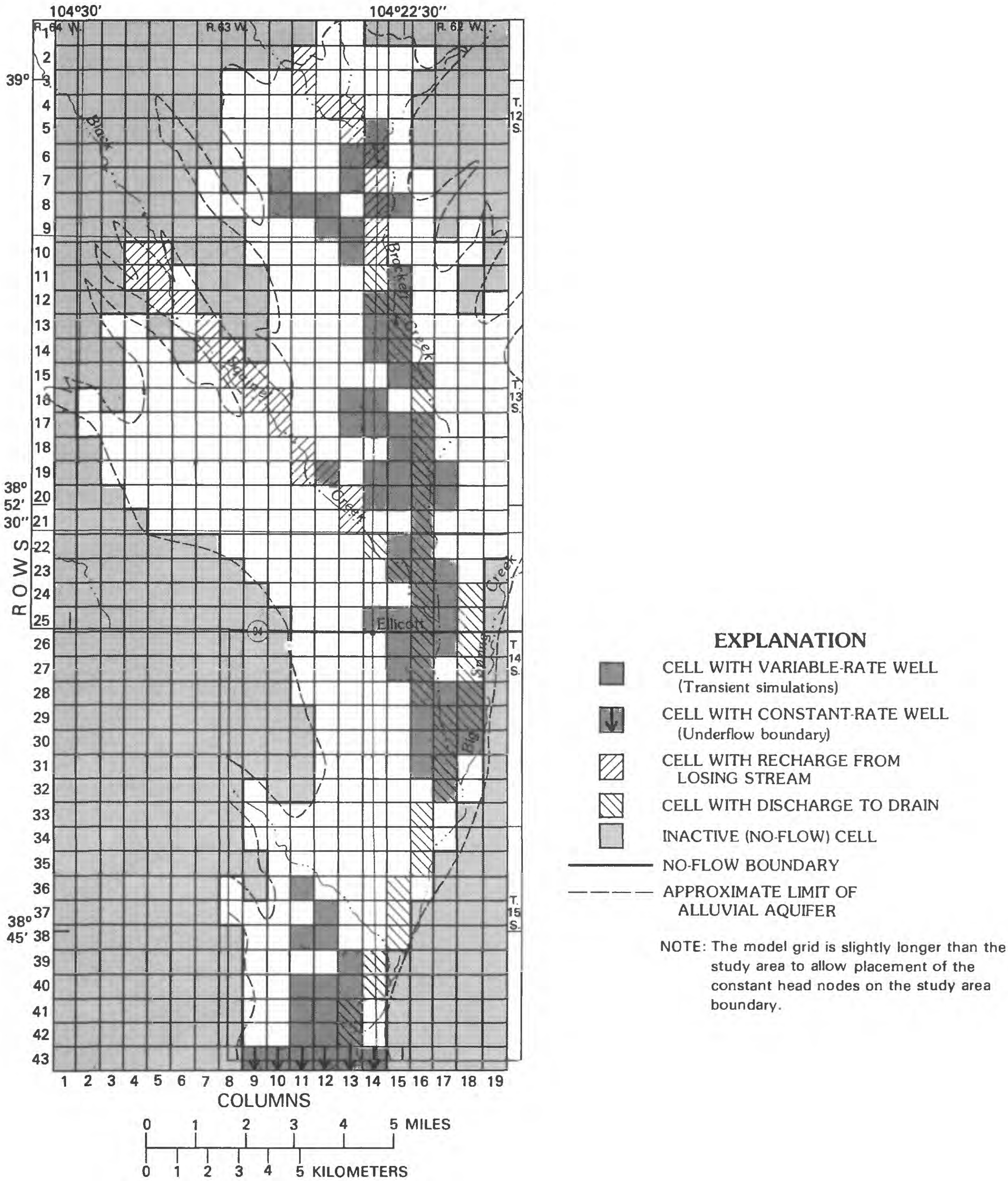


Figure 15.--Model grid, boundaries, and types of cells.

The ground-water evapotranspiration rate of a cell is dependent on the simulated head in the cell. The maximum ground-water evapotranspiration rate occurs when the simulated head in the cell is at land surface, and a rate of zero is assigned when the simulated head in the cell is at or below the ground-water evapotranspiration extinction depth. Intermediate ground-water evapotranspiration rates are determined by a linear relation as described by McDonald and Harbaugh (1984, p. 316-317).

Calibration

A water-level criterion was used to determine the quality of the steady-state calibration. However, few water-level data were available to define the predevelopment altitude of the water table. The predevelopment (pre-1950) altitude of the water table probably was less than the land-surface altitude and greater than the altitude of the water table during spring 1964. Therefore, this was the range of water-level altitudes that was used as the steady-state calibration criterion. Model parameters were adjusted to obtain the best agreement between model-simulated water-table altitudes and predevelopment water-level altitudes. Model parameters adjusted in the calibration of the steady-state model were recharge rates, maximum ground-water evapotranspiration rate, hydraulic conductivity, and underflow (specified flux).

Inflows

One of the least documented components of the flow system in the alluvial aquifer is inflow. Early conceptual models of the aquifer (McGovern and Jenkins, 1966; Erker and Romero, 1967; Goeke, 1970; Waltz and Sunada, 1972) reported areal recharge from infiltration of precipitation as the largest inflow to the alluvial aquifer. Inflows from the bedrock aquifers to the alluvial aquifer were assumed by these studies to be small. J.W. Patterson and Associates, Inc. (1980, p. 7) postulated the possibility of inflow from the bedrock aquifers; however, data were inadequate to quantify the inflow from the bedrock aquifers. Using a regional steady-state water budget of the Denver Basin, Robson (1984, p. 60) estimated that the bedrock aquifers discharged about 1,300 acre-ft/yr to the alluvial aquifer. An inflow of 1,300 acre-ft/yr from the bedrock aquifers comprises a substantial part (about 20 percent) of the total inflow to the alluvial aquifer.

During the initial calibration, total inflow to the alluvial aquifer was assumed to be primarily a function of total precipitation. However, simulations indicated that larger recharge rates were needed in areas where the alluvial aquifer is underlain by the Denver and Arapahoe aquifers, and smaller recharge rates were needed in areas where the alluvial aquifer is underlain by the Laramie-Fox Hills aquifer. Total inflow rates were adjusted using data from Robson (1984, p. 60), which indicated that, of the total water discharged from the bedrock aquifers to the alluvial aquifer, about two-thirds (67 percent) was discharged by the Denver and Arapahoe aquifers, and only 11 percent was discharged by the Laramie-Fox Hills aquifer. Total inflow consists of recharge from precipitation, infiltration of streamflow, and inflow from bedrock aquifers. It was simulated as areal recharge in the models.

The calibrated inflow rates used in this study were less than 1 in/yr where total precipitation was least and the alluvial aquifer was underlain by the Laramie-Fox Hills aquifer in the southern part of the study area. The rates were about 4 in/yr where total precipitation and infiltration of streamflow was greatest and the alluvial aquifer was underlain by the Denver aquifer in the northern part of the study area.

Ground-water evapotranspiration

Initially, the maximum ground-water evapotranspiration rate used in this study was assumed to be 2 ft/yr throughout the study area. Simulations, however, indicated that ground-water evapotranspiration rates were greater at lower altitudes where less precipitation falls and temperatures are warmer. As a result, a maximum ground-water evapotranspiration rate of 1.5 ft/yr was used for land-surface altitudes above 6,500 ft, and a rate as much as 2.5 ft/yr was used for altitudes below 6,500 ft. A maximum ground-water evapotranspiration extinction depth of 5 ft was used throughout the study area. Adjusted calibrated maximum ground-water evapotranspiration rates used in this study are comparable to those used in studies for nearby areas. Weeks and Sorey (1973, p. C23) estimated that "...annual evapotranspiration from ground water was about 18 inches in 1966 and 1968..." in the lower Arkansas River valley in Colorado. Blaney and Criddle (1949) estimated that the total evapotranspiration in the Arkansas River valley ranged from 2.33 to 2.92 ft/yr; however, ground-water evapotranspiration would be less than these estimates because part of the total evapotranspiration is supplied by precipitation.

Hydraulic conductivity and constant flux

Based on values from aquifer tests (Wilson, 1965), the aquifer system initially was simulated using an average hydraulic conductivity of 117 ft/d. The model indicated that this value was too large and resulted in simulated water-table altitudes in the northern part of the study area that were too low when compared to water-table altitudes early in the development period and simulated water-table altitudes in the southern part of the study area that were too high, 20 to 100 ft above land surface. The steady-state calibration was improved by decreasing the hydraulic conductivity to a value of 64 ft/d. Although this value of hydraulic conductivity is about one-half the original estimate, it is well within the range of reasonable hydraulic-conductivity values for alluvial deposits.

The initial specified flux of 9,700 acre-ft/yr in the underflow area in the southern part of the study area was decreased as a result of the adjustment in hydraulic-conductivity values. A constant flux of 4,800 acre-ft/yr was used in the final calibration. This flow is about one-half the underflow value that was calculated by McGovern and Jenkins (1966), but the adjusted hydraulic conductivity used to simulate flow in the alluvial aquifer with the revised model (64 ft/d) also was about one-half that previously used in calculating underflow in this study and that used by McGovern and Jenkins (113 ft/d).

Results

Depth to water in a north-south section through the alluvial aquifer (fig. 16*A*) was used to evaluate the quality of the model calibration. A reasonably accurate calibration was achieved for most areas of the aquifer (fig. 16*B*). Generally, the calibrated steady-state water table was below land surface and at or above the spring 1964 water table. The depth to water (fig. 16*B*) for the spring 1964 water table was obtained from a contoured depth-to-water map that had been discretized (average levels within each model block were estimated by overlaying a model grid on a map of depth to water) to correspond with the steady-state model grid. This process eliminated possible error of comparing point data (measured at wells) with simulated data that are for 0.25-mi^2 areas.

The altitude of the simulated steady-state water table is shown in figure 17. Areas indicated as marshy correspond to areas that reportedly had subirrigation prior to extensive development of the aquifer. An area north of Ellicott in township 13S (fig. 17) was mapped in 1954 as marshy and having numerous springs (U.S. Geological Survey, 1954). Another area southeast of Ellicott (fig. 17) also was marshy prior to extensive development of the aquifer. A long-time resident of the area reported that crops could be grown without irrigation water because of the natural subirrigation provided by the shallow water table (Francis Guthrie, oral commun., 1986). Most of the simulated ground-water evapotranspiration from the alluvial aquifer occurred in these two areas.

Because of inadequacies of the steady-state model to simulate head-dependent inflows from the underlying bedrock aquifers, all inflows for each model cell were added together for the simulation. Total inflow to the alluvial aquifer was simulated at about 9,200 acre-ft/yr (table 5) and included deep percolation of precipitation, infiltration of streamflow, and inflow from the bedrock aquifers. The simulated steady-state ground-water budget (table 5) indicates that prior to 1950 evapotranspiration of ground water was a substantial outflow from the alluvial aquifer (about 43 percent of the total outflow).

Transient-State Model

After calibration of the steady-state model, a transient-state model was developed and calibrated to simulate flow in the alluvial aquifer from 1949 to 1984. An aquifer is in a transient state when inflows and outflows are not equal, resulting in a change in the volume of water stored in the aquifer. The water-table altitudes derived from the calibrated steady-state model were used as the initial condition for the transient simulations. Pumpage from the aquifer and specific yield also were included in transient simulations. Values for aquifer properties and specified boundary fluxes used in the calibrated steady-state model also were used in the transient-state model. The specified flux at the underflow boundary was assumed to remain constant throughout transient simulations. This assumption is reasonable because the hydraulic gradient and the cross-sectional area have remained essentially unchanged. A specific yield of 18 percent was used for transient simulations.

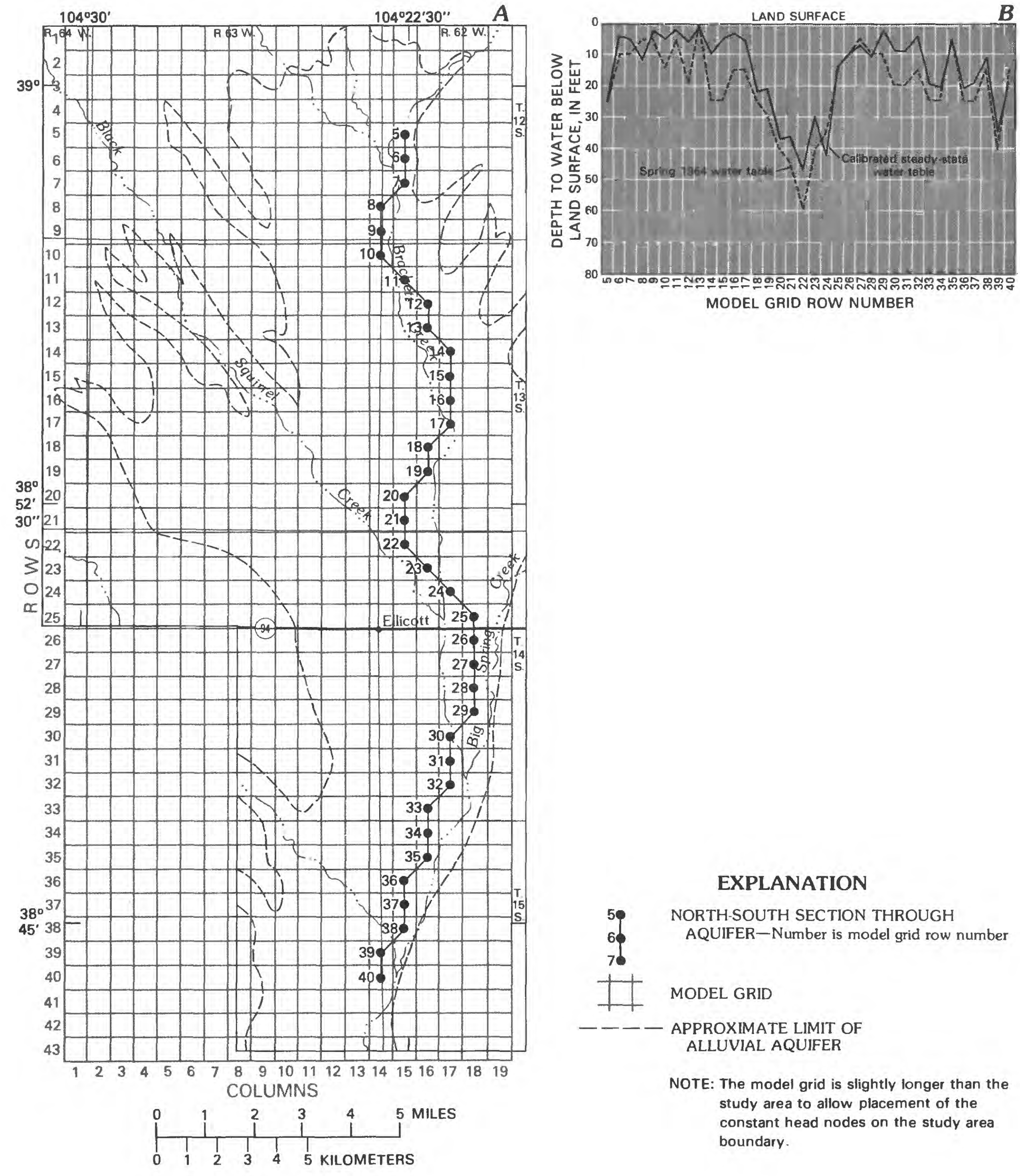


Figure 16.--Location of north-south section through aquifer (*A*), and depth to water for the spring 1964 water table and the calibrated steady-state model (*B*).

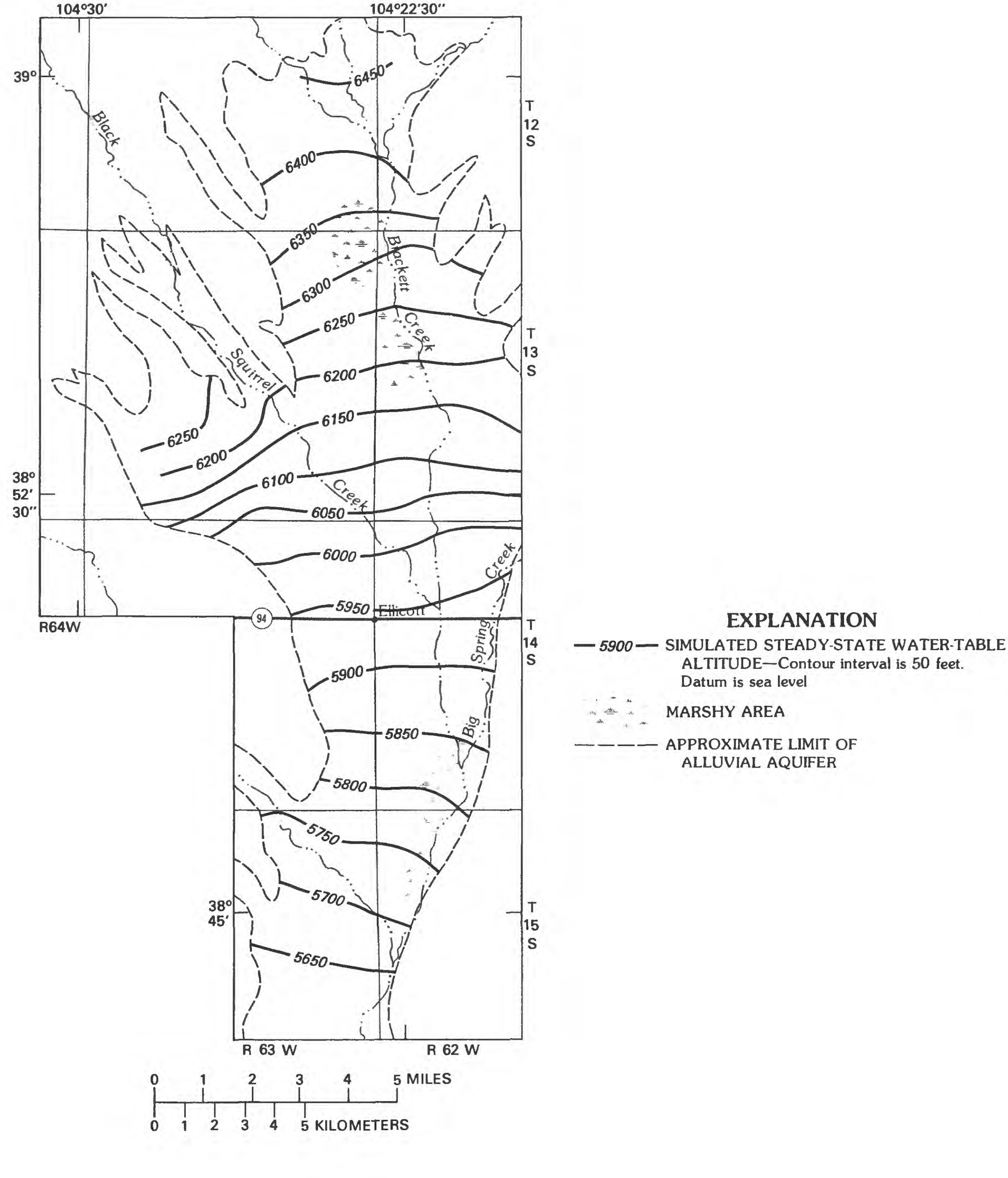


Figure 17.--Simulated steady-state water-table altitudes.

Table 5.--*Simulated steady-state ground-water budget*

Component	Average annual rate (acre-feet per year)
Inflows:	
Total inflow (includes deep percolation of precipitation, infiltration of streamflow, and inflow from underlying bedrock aquifers)	9,200
Outflows:	
Ground-water evapotranspiration	4,000
Underflow at southern end of the basin	4,800
Surface-water outflow	400
Total outflow	9,200

Transient simulations were divided into stress periods of several different lengths based on well development and data availability. Based on historic well development, the alluvial aquifer was considered to have been in steady-state conditions prior to 1950.

Predevelopment to April 1964

The first stress period simulated flow in the aquifer from spring 1949 to spring 1954. Pumpage during this period was small compared to later stress periods. Pumpage from six cells was simulated; net pumpage (ground water consumptively used by crops) was estimated at 900 acre-ft/yr from the alluvial aquifer, or about 150 acre-ft/yr per cell.

The second stress period simulated flow in the aquifer from spring 1954 to spring 1964. Most of the wells in the study area were drilled during this period. Pumpage from 35 cells was simulated. Average annual pumpage was about 5,100 acre-ft/yr or about 146 acre-ft/yr per cell.

The quality of the calibration was evaluated at the end of the second stress period (spring 1964) by comparing the simulated water-table altitude with the measured water-table altitude (fig. 18). The measured and simulated contours compared favorably; therefore, the transient-state model was considered calibrated for the early development period of the alluvial aquifer.

April 1964 to September 1984

Ground-water flow was simulated from April 1964 to September 1984 (20.5 yr) using 41 stress periods each lasting 6 months. A simulated year consisted of two stress periods: April through September (irrigation and municipal wells pumped) and October through March (only municipal wells pumped). Municipal pumpage was metered so it was not adjusted during calibration of the transient-state model; irrigation pumpage was estimated so it was adjusted to calibrate the transient-state model. Total calibrated crop-consumptive use

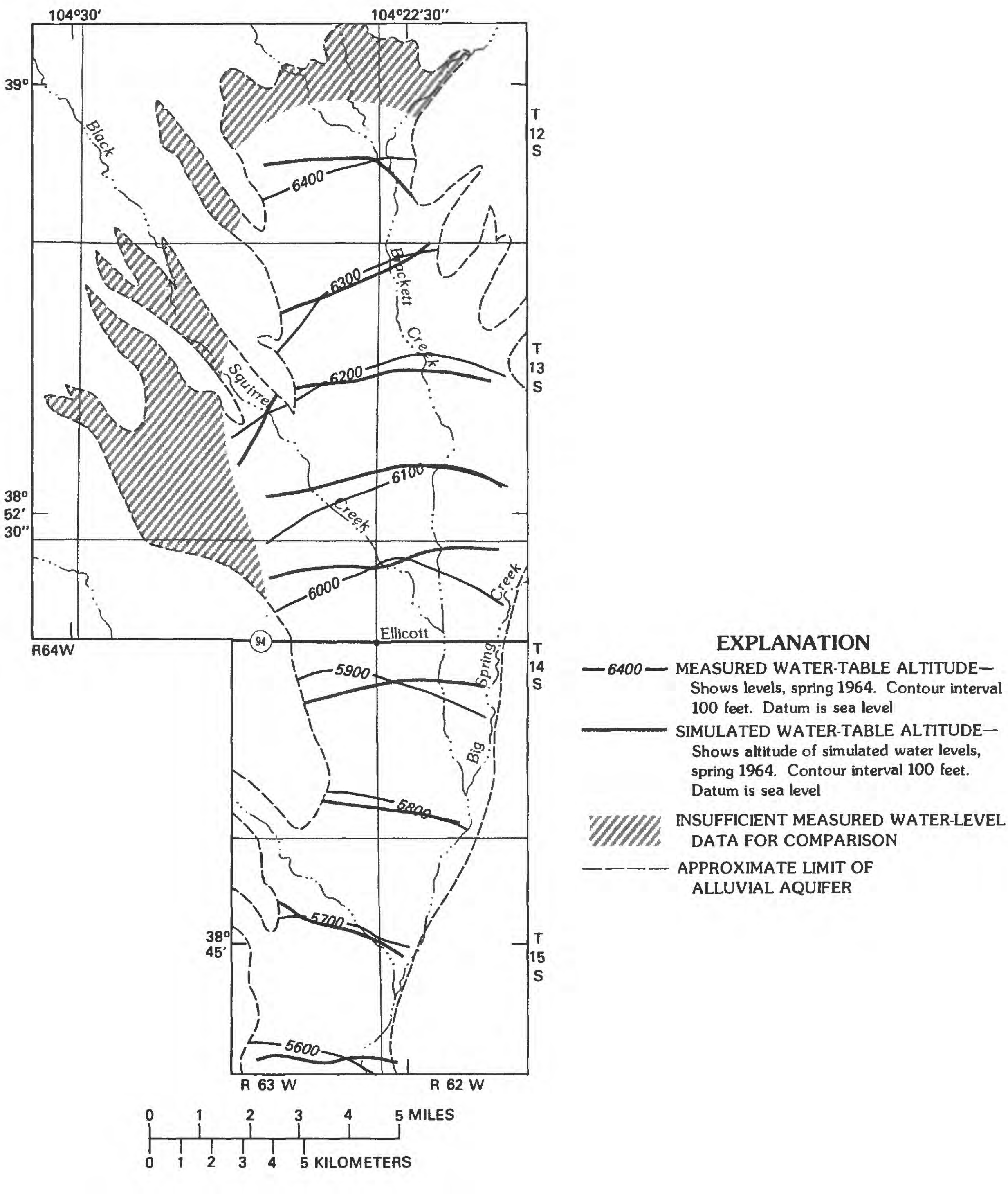


Figure 18.--Measured and simulated water-table altitudes, spring 1964.

was between 10 to 30 percent less than that previously estimated for April 1964 to September 1984 (fig. 8). Cumulative pumpage was simulated at about 184,000 acre-ft for this period.

Two criteria were used to evaluate the quality of the calibration for the simulated period April 1964 to September 1984. The first criterion was the altitude of the spring 1984 water table. The measured and simulated spring 1984 water-table altitudes are shown in figure 19. In most areas, the simulated contours compare favorably with the measured contours. The second calibration criterion was the 1974-84 water-level change. Because most hydrographs indicated long-term declines of water levels, the transient-state model was considered to be calibrated when simulated decline was nearly the same as measured decline. Comparison was made using two statistics: mean error and mean absolute error.

Mean error, in feet, is the summation of the difference between simulated water-level decline and measured water-level decline divided by the number of measurements, n:

$$\text{mean error} = \frac{\sum_{i=1}^{n} \text{simulated decline} - \text{measured decline}}{n}.$$

Mean absolute error, in feet, is the summation of the absolute value of the difference between simulated water-level decline and measured water-level decline divided by the number of measurements, n:

$$\text{mean absolute error} = \frac{\sum_{i=1}^{n} /\text{simulated decline} - \text{measured decline}/}{n}.$$

If simulated and measured declines were the same, the mean error and the mean absolute error would be zero. The mean error should be very nearly zero because of the compensating effect of positive and negative values. The mean absolute error provides a better description of the closeness of fit.

After the first seven of nine simulations, additional adjustments of crop consumptive use produced only small improvements in the mean error (fig. 20*A*) and mean absolute error (fig 20*B*). In addition, simulated water-level declines from spring 1974 to spring 1984 are shown in figure 21. The magnitudes and areal distribution of the simulated water-level declines (fig. 21) are similar to those based on measurements (fig. 11). Discrepancies between figures 11 and 21 generally are the result of discretization errors.

A comparison of the simulated transient ground-water budget (table 6) with the simulated steady-state ground-water budget (table 5) indicates that about 3,300 acre-ft/yr of water was salvaged from evapotranspiration and from surface-water outflow. The average change of storage in the simulated transient ground-water budget of 5,500 acre-ft/yr compares favorably with historical estimated water-level declines of 5,000 acre-ft/yr and is better than conceptual-model estimated water-level declines (table 2) of 14,850 acre-ft/yr.

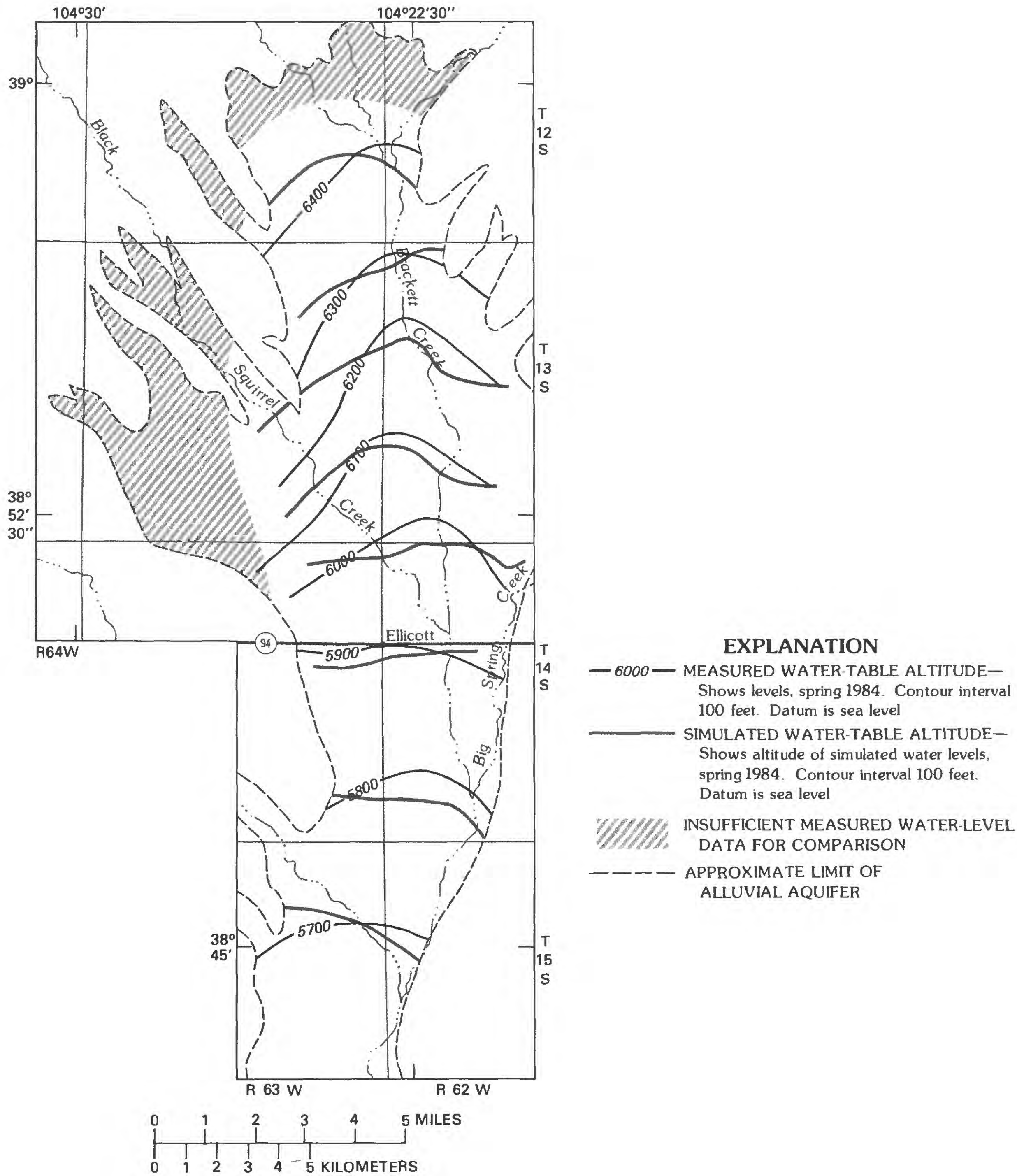


Figure 19.--Measured and simulated water-table altitudes, spring 1984.

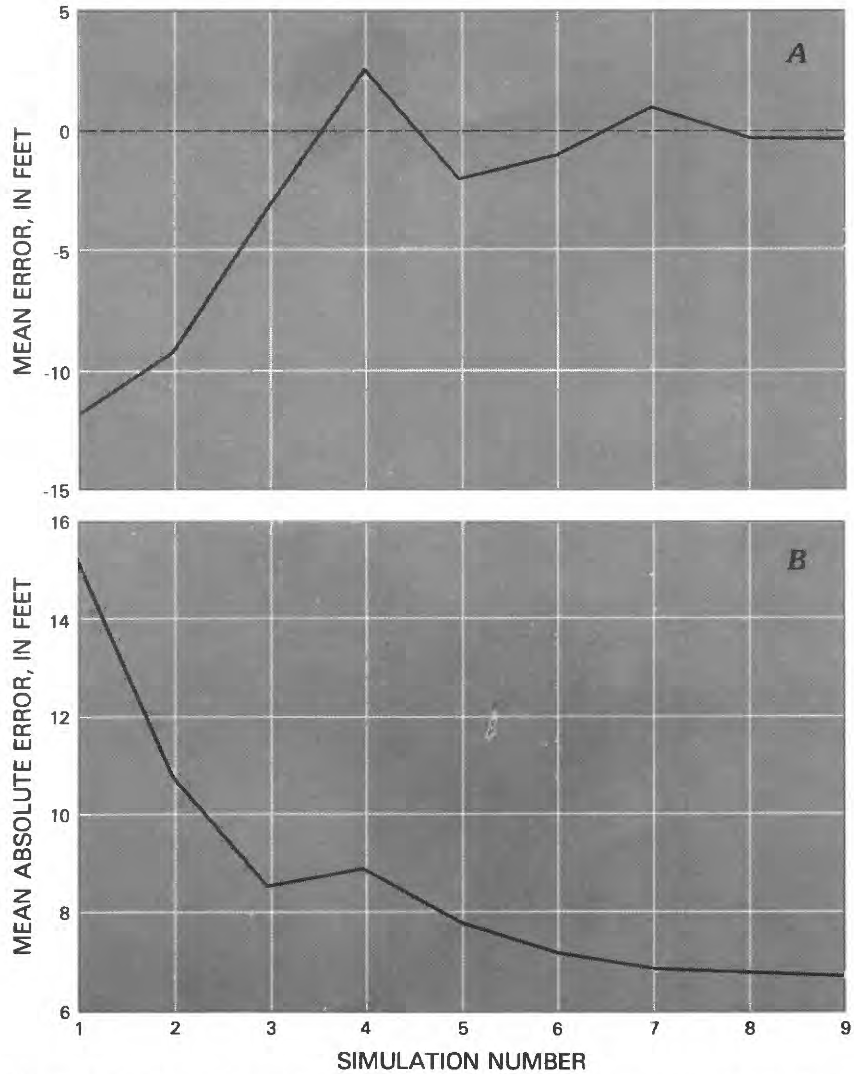


Figure 20.--Change in mean error (*A*) and mean absolute error (*B*) for successive simulations.

Refinements in the conceptual model (table 2) from numerical modeling of ground-water flow include: (1) increasing total inflow, (2) decreasing the hydraulic conductivity and thereby the rate of underflow, and (3) decreasing crop-consumptive-use estimates.

Importance of Ground-Water Evapotranspiration

The ground-water flow models provided a means to evaluate the importance of ground-water evapotranspiration at various stages of aquifer development. Prior to 1950 when conditions in the alluvial aquifer were steady state, simulated ground-water evapotranspiration was about 43 percent of the total outflow (table 5). By 1964, simulated ground-water evapotranspiration represented less than 10 percent of the total outflow, and by 1984, it was less than 3 percent of the total outflow and averaged 7 percent (table 6).

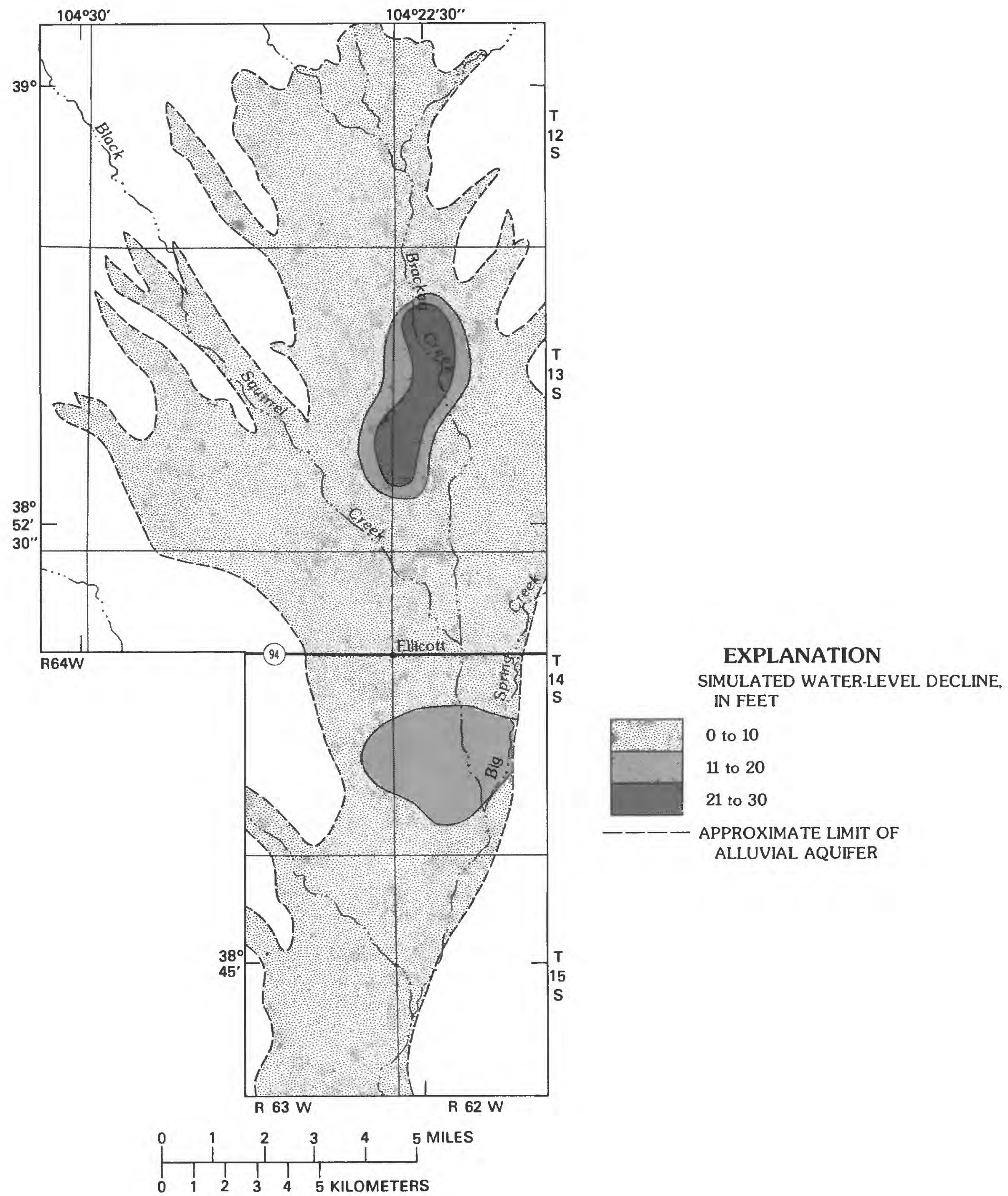


Figure 21.--Simulated water-level declines from spring 1974 to spring 1984.

Table 6.--*Simulated average annual ground-water budget for the alluvial aquifer, April 1964-September 1984*

Component	Average annual rate[1] (acre-feet per year)
Inflows:	
Total inflow includes deep percolation of precipitation, infiltration of streamflow, and inflow from underlying bedrock aquifers	[2]9,450
Outflows:	
Consumptive use including:	
Municipal pumpage	2,750
Crop-consumptive use (irrigated crops)	6,250
Evapotranspiration	1,000
Underflow at southern end of the basin	4,850
Surface-water outflow	100
Total outflow	14,950
Change in storage:	
Inflow-outflow	5,500

[1]Average annual rates computed for a period of 20.5 years.
[2]All values rounded to the nearest 50 acre-feet per year.

A similar decrease in the volume of water leaving the alluvial aquifer from variable-head cells that had drains also was observed. During the early stages of alluvial aquifer development (from spring 1949 to spring 1954), most of the ground water pumped was derived from water that would have been discharged by ground-water evapotranspiration and surface-water outflow. However, as development of the alluvial aquifer increased, more water was pumped from the aquifer than could be supplied by the capture of natural discharge by evapotranspiration and to surface drains (streams). As a result, water was taken from storage and water-level declines occurred.

Sensitivity Analyses

Sensitivity analyses were done to evaluate the sensitivity of the simulation results to variations of model parameters. During each sensitivity analysis, model parameters were the same as those in the calibrated models, except for the model parameter being tested.

Steady-State Model

Sensitivity analyses done on the steady-state model included the effects of changes in the model parameters: inflow, hydraulic conductivity, maximum ground-water evapotranspiration rate, and ground-water evapotranspiration extinction depth. The steady-state model was not sensitive equally to changes in inflow and hydraulic conductivity. Decreasing the inflow by 5 percent from that in the calibrated steady-state model had a greater effect on the volume of simulated ground-water evapotranspiration than did decreasing the hydraulic conductivity by 5 percent (table 7). However, decreasing the inflow by 5 percent from that in the calibrated steady-state model had a lesser effect on the simulated hydraulic heads than did decreasing the hydraulic conductivity by 5 percent. Decreasing the hydraulic conductivity by 5 percent had the greatest effect in the underflow area in the southern part of the study area where simulated hydraulic heads were decreased 5 to 40 ft from that in the calibrated model.

Table 7.--*Summary of selected sensitivity analyses done on the steady-state model*

Model parameter tested	Percentage of change of model parameter[1]	Percentage of change of outflow by ground-water evapotranspiration	Percentage of change of outflow from variable-head cells that had drains	Response of simulated head
Inflow	[2]-5	-15	-1	Within ±2 feet in more than 95 percent of model area; largest effect in northern part of model area where simulated hydraulic heads decreased more than 5 feet.
Hydraulic conductivity.	-5	-2	-9	Within ±2 feet in about 85 percent of model area; largest effect in underflow area where simulated hydraulic heads decreased 5 to 40 feet.
Maximum ground-water evapotranspiration rate.	15	18	-27	Unchanged in most of model area; simulated hydraulic heads in underflow area decreased 15 feet.
Ground-water evapotranspiration extinction depth.	50	14	-21	Unchanged in most of model area; simulated hydraulic heads in underflow area decreased 10 feet.

[1]Percentage of change from calibrated steady-state model.
[2]Negative sign indicates decrease.

In one sensitivity test (table 7), the maximum ground-water evapotranspiration rate was increased by 15 percent. This change increased simulated ground-water evapotranspiration by 18 percent and decreased simulated discharge to drains (streams) by 27 percent. Hydraulic heads in the underflow area also decreased about 15 ft, but hydraulic heads in other areas were relatively unaffected.

When the ground-water evapotranspiration extinction depth was increased 50 percent from 5 to 7.5 ft, ground-water evapotranspiration increased 14 percent and simulated flow to drains decreased 21 percent (table 7). Simulated hydraulic heads remained essentially unchanged in most parts of the study area except for the underflow area where simulated hydraulic heads decreased about 10 ft from those in the calibrated steady-state model. The sensitivity analyses of ground-water evapotranspiration indicate that the steady-state model is more sensitive to the maximum ground-water evapotranspiration rate than to the ground-water evapotranspiration extinction depth. Extending the ground-water evapotranspiration extinction depth by 50 percent did not increase substantially the modeled area in which evapotranspiration of ground water was occurring, because hydraulic heads in most of the study area were still below the ground-water evapotranspiration extinction depth of 7.5 ft.

Transient-State Model

Sensitivity analyses done on the transient-state model included changing net pumpage (irrigation and municipal consumptive use), specific yield, and hydraulic conductivity. These three model parameters were increased and decreased 25 percent from the values used to calibrate the transient-state model. The results of the tests are listed in table 8. The transient-state model was equally sensitive to 25-percent increases in net pumpage and 25-percent decreases in specific yield. Comparing the sensitivity analyses of net pumpage and specific yield indicates that these two model parameters are inversely proportional. Increasing net pumpage has a similar affect as decreasing specific yield; therefore neither model parameter can be determined using a model analysis unless one of these parameters is accurately known. Sensitivity analyses of specific yield indicated that values of 19 to 22 percent would have resulted in nearly the same quality of calibration as did a specific-yield value of 18 percent. The transient-state model was moderately sensitive to a 25-percent change in hydraulic conductivity (table 8). Decreasing the hydraulic conductivity by 25 percent had a lesser effect on the mean absolute error than increasing it 25 percent because of the effects of ground-water evapotranspiration. Decreasing the hydraulic conductivity 25 percent increased hydraulic heads in the northern part of the study area and therefore the volume of ground-water evapotranspiration.

Limitations of the Use of the Models

The steady-state and transient-state models developed as part of this study have limitations on their use, and results from them are preliminary. To prevent misinterpretation of simulation results, the following limitations need to be considered.

Table 8.--*Summary of selected sensitivity analyses done on the transient-state model*

Model parameter tested	Value	Percentage of change of model parameter[1]	Mean absolute error (feet)	Percentage of change of mean absolute error[2]
Net pumpage	[3]--	+25	9.94	+49
	--	0	6.67	0
	--	-25	7.11	+7
Specific yield (dimensionless)	0.225	+25	6.44	-3
	.18	0	6.67	0
	.135	-25	9.44	+42
Hydraulic conductivity (feet per day)	80	+25	8.89	+33
	64	0	6.67	0
	48	-25	7.89	+18

[1]Percentage of change from calibrated value.
[2]Percentage of change from calibrated transient-state model.
[3]Variable from year to year.

The simulation code (McDonald and Harbaugh, 1984) does not allow a variable-head cell that desaturates or goes dry to resaturate if stresses on the variable-head cell decrease or if recharge to the variable-head cell increases. If the simulated hydraulic head in a variable-head cell declines to below the altitude of the base of the aquifer in that cell, the cell becomes inactive for the remainder of the simulation. The transient-state model could not be used to simulate recovery of the alluvial aquifer in areas where variable-head cells have become inactive.

Another limitation of the model is its inability to simulate decreased well yield caused by decreasing saturated thickness. As hydraulic head in a water-table aquifer declines, the transmissivity of the aquifer is decreased, resulting in decreased well yields. The simulation code does not account for this phenomenon, and in stressed areas of the alluvial aquifer, actual water-level declines probably will be smaller than those predicted by the transient model unless more small-capacity wells are drilled to compensate for decreased well yield from large-capacity wells.

Because of the size of the variable-head cells (0.25 mi^2), water-level declines at a well probably will be different than the average water-level declines of the variable-head cell in which a well is located. Caution should be used when comparing values for specific locations with those computed for large areas.

The most important limitation of the models developed is that they do not account for hydraulic-head-dependent flow between the alluvial aquifer and the bedrock aquifers. To simulate the aquifer system adequately, a three-dimensional model needs to be developed that is based on the hydraulic-head distribution, the thicknesses and hydraulic properties, and pumping rates of the bedrock aquifers.

Future Water-Level Declines

The calibrated transient-state model was used to estimate future effects of continued ground-water pumpage on water levels. Ground-water flow was simulated from October 1984 through April 1999, and future water-level declines were estimated for that period.

Prior to simulating future water-level declines, future net pumping rates had to be estimated. Net irrigation pumpage rates for the projection period (October 1984 to April 1999) was assumed to be the same as the 1984 net irrigation pumpage used for the calibrated transient model (8,600 acre-ft/yr). Municipal pumpage during 1984 had increased 55 percent from 1974 rates. Municipal pumpage was estimated to increase at a similar rate in the future because of proposed development in the study area and in adjacent areas.

Initial simulations indicated that estimated future pumpage rates were too large. Before the simulation was complete, many variable-head cells in areas around large-capacity wells (pumping more than 500 gal/min) became desaturated. In subsequent simulations, pumpage rates were decreased until all variable-head cells, which had large-capacity wells, remained active throughout the simulation.

As a result of this adjustment of pumpage estimates, the projections to April 1999 were made using a total annual pumpage (irrigation plus municipal) of about 16 percent less than the 1984 pumpage (9,700 acre-ft/yr). Assuming an average ground-water pumpage of 8,200 acre-ft/yr from October 1984 to April 1999, additional water-level declines of 1 to 10 ft or more were projected in the alluvial aquifer (fig. 22). Near Ellicott, projected water-level declines were 20 to 30 ft; near some municipal wells 4 mi north of Ellicott, projected water-level declines were larger than 30 ft.

Water-level declines in production wells probably will be larger than declines predicted by the transient-state model (fig. 22), because the model predicts the average hydraulic head for a 0.25 mi by 0.25 mi area, not at the well. Well yields in the future could decrease because of smaller saturated thicknesses. Decreases in well yields in many large-capacity wells already have occurred as a result of smaller saturated thickness.

SUMMARY

The upper Black Squirrel Creek basin is underlain by an alluvial aquifer and four bedrock aquifers, in ascending order, the Laramie-Fox Hills, Arapahoe, Denver, and Dawson. Since the late 1880's, the alluvial aquifer has supplied sufficient quantities of water to wells to meet domestic, stock, agricultural, and municipal demands. Water from the alluvial aquifer is exported to suburbs of Colorado Springs and to the Falcon Air Force Station.

Estimated ground-water storage was 600,000 acre-ft during 1964. By 1984, the volume of water in storage had decreased by 100,000 acre-ft. The long-term removal of ground water from storage is indicated by water-level declines. Water-level declines from 1974 to 1984 were as much as 30 ft in an

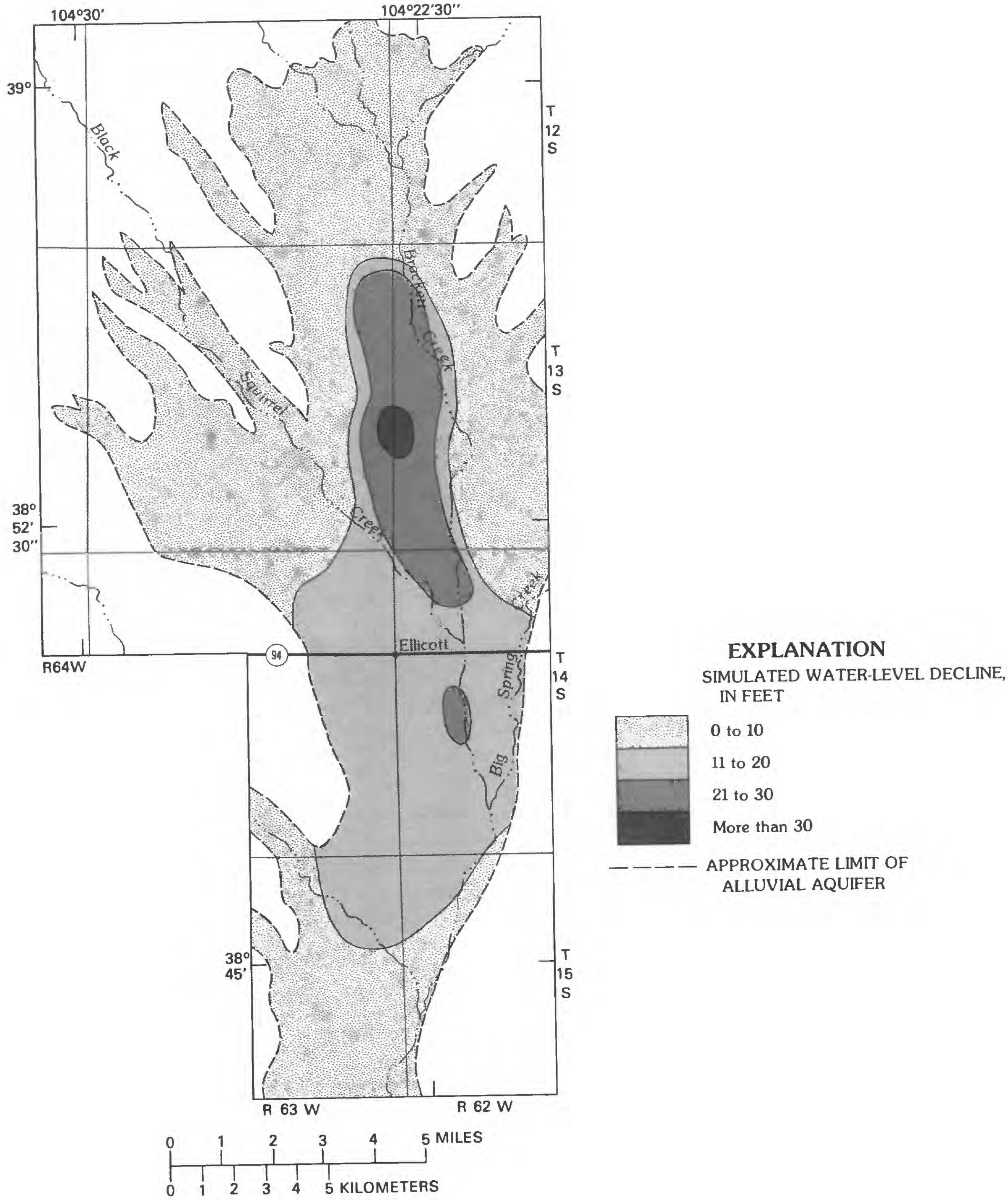


Figure 22.--Simulated water-level declines from October 1984 to April 1999.

area north of Ellicott. From 1964 to 1984, some wells had water-level declines larger than 44 ft. Principal inflows to the alluvial aquifer include infiltration of precipitation, streamflow, and irrigation-return flow. In addition, flow from four underlying bedrock aquifers may provide substantial recharge (10 to 20 percent of total inflow) to the alluvial aquifer. Water is discharged from the aquifer through natural and man-imposed stresses. Ground-water underflow occurs at the southern end of the study area. Irrigation pumpage is the single largest discharge from the aquifer.

Thirty-six ground-water samples were collected during 1984; analyses of the samples indicated that concentrations of nitrite plus nitrate as nitrogen were greater than expected in the ground water. Concentrations of nitrite plus nitrate in 14 percent of the samples exceeded the drinking-water standard and could pose a health threat to infants less than 3 months of age. In general, ground water from the alluvial aquifer is of suitable quality for other uses.

A two-dimensional ground-water flow model was used to simulate the effect of continued pumpage on the alluvial aquifer. Projected declines from October 1984 to April 1999 were from 1 to 10 ft in much of the aquifer. Water-level declines near Ellicott were projected to be 20 to 30 ft. The ground-water flow model also was used to evaluate the importance of ground-water evapotranspiration at various stages of aquifer development. When the aquifer was in steady-state conditions (prior to 1950), ground-water evapotranspiration was a major outflow from the alluvial aquifer. As the alluvial aquifer was developed and depth to water increased, outflow from ground-water evapotranspiration decreased. By 1984, simulated ground-water evapotranspiration was less than 3 percent of the total outflow from the alluvial aquifer. The ground-water flow models developed as part of this study are preliminary because they do not account for hydraulic-head-dependent flow between the alluvial aquifer and the bedrock aquifers. For an adequate simulation of the aquifer system, a three-dimensional ground-water flow model needs to be developed.

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