Evaluation of Possible Alternatives to Lower the High Water Table of St. Charles Mesa, Pueblo County, Colorado

By Daniel L. Brendle

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CONVERSION FACTORS

Multiply	By	To obtain
inch	25.4	millimeter
foot (ft)	0.3048	meter
square foot (ft^2)	0.09290	square meter
foot per day (ft/d)	0.3048	meter per day
mile	1.69	kilometer
gallons per day (gal/d)	0.003785	cubic meter per day (m^3/d)
square mile (mi^2)	2.590	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
square foot per second (ft^2/s)	929,664	square meter per day
inch per year (in/yr)	2.590	millimeter per year
gallon per minute (gal/min)	0.06309	liter per second
gallon	7.48	cubic foot
cubic foot per second (ft^3/s)	378,432,000	inches per year per square foot

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

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Abstract

St. Charles Mesa, an upland terrace southeast of Pueblo, Colorado, has become increasingly urbanized as cultivated fields have been subdivided and converted to residential areas. In some areas, the water table in the terrace alluvial aquifer underlying St. Charles Mesa is very shallow. Bessemer Ditch, which delivers irrigation water to farms on the mesa and other areas of the lower Arkansas River Valley, traverses St. Charles Mesa along its southern side and is the principal source of recharge to the terrace alluvial aquifer. The ground-water flow system was assumed to be in a state of dynamic equilibrium (steady-state condition) for this study. A steady-state ground-water flow model of the terrace alluvial aquifer was constructed and calibrated. The model was run in transient state to evaluate possible alternatives of lowering the water table. The possible alternatives evaluated were (1) reducing areal recharge by reducing recharge to irrigated areas by 25 percent, (2) lining Bessemer Ditch from (a) Aspen Street to 21st Lane; (b) Aspen Street to 23rd Lane; (c) Aspen Street to 25th Lane; and (d) Aspen Street to Nicholson Road, (3) installing two drains at a depth of 10 feet below land surface upgradient from the high water table areas, and (4) installing 22 dewatering wells within the high water table areas, each pumping at 80 gallons per minute. All alternatives evaluated were at least partly effective in lowering the water table. As the simulated extent of Bessemer Ditch lining was increased, the extent and magnitude of simulated water-table declines also increased. The maximum simulated declines in the water table were 3 feet when simulated areal recharge to irrigated areas was reduced by 25 percent, 29 feet when lining of Bessemer Ditch was simulated from Aspen Street to Nicholson Road, 6.8 feet when two drains were simulated at 10-foot depth, and 14.4 feet when 22 dewatering wells, each pumping at 80 gallons per minute, were simulated. Lining Bessemer Ditch from Aspen Street to 25th Lane and from Aspen Street to Nicholson Road both resulted in water-table declines of at least 5 feet throughout most of the area. Except for reducing recharge to irrigated areas and installation of the two drains, all the alternatives evaluated probably would lower the water table enough to diminish the ground-water supply available for at least some existing wells.

INTRODUCTION

St. Charles Mesa (hereinafter, the Mesa), an upland terrace southeast of Pueblo, Colorado, has an area of about 10 mi^2 (fig. 1). During the last 35 years, the Mesa has become increasingly urbanized as cultivated fields have been subdivided and converted to residential areas. The U.S. Geological Survey (USGS), in cooperation with Pueblo County, began a two-phase study in 1997 to define the extent of the area in which the water table is high and to evaluate possible alternatives to lower the high water table.

During the first phase of the study, the extent of the high water table in November 1997 and water-table

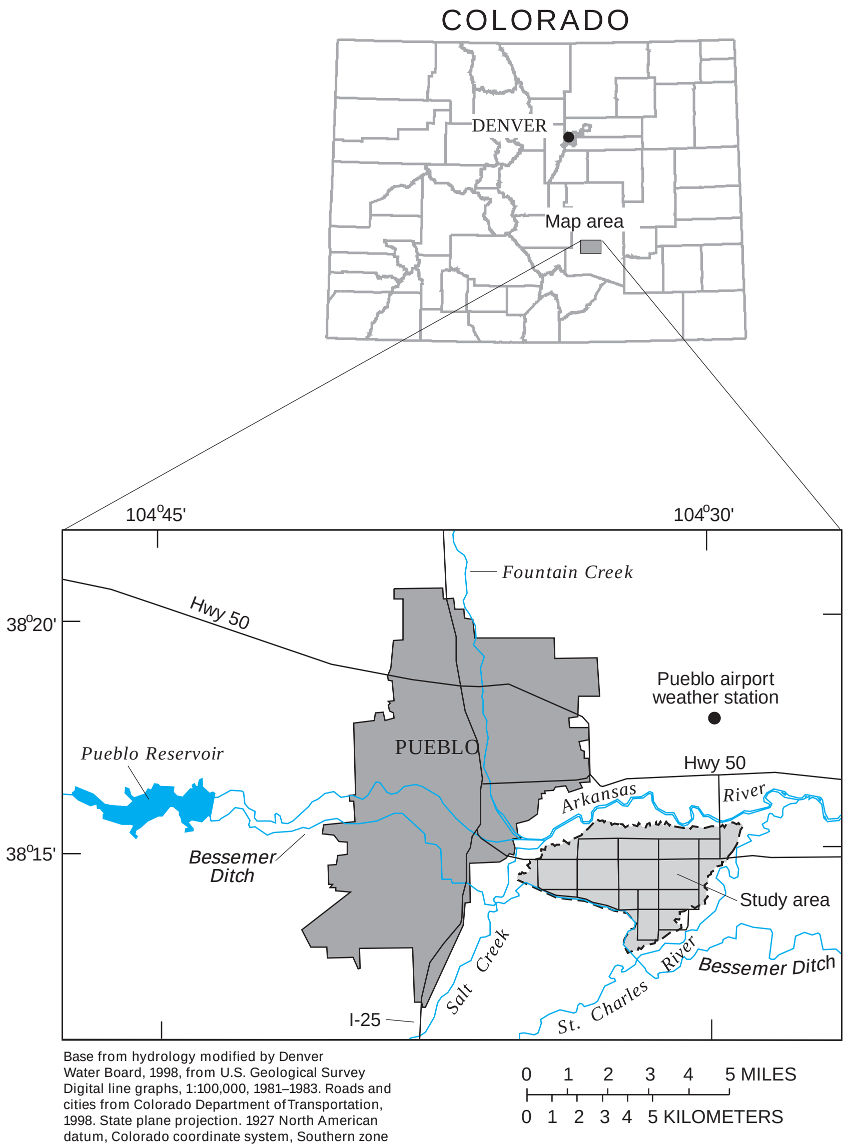


Figure 1. Location of study area.

fluctuations from April 1997 to October 1998 were determined (Brendle, 1999) and a preliminary ground-water flow model was developed. The preliminary model was developed to determine which characteristics of the hydrologic system needed better definition to improve model accuracy. In the second phase of the study, the ground-water flow model was refined to evaluate possible alternatives to lower the high water table in problem areas. Possible alternatives evaluated to lower the water table are (1) reducing areal recharge by reducing recharge to irrigated areas by 25 percent, (2) lining Bessemer Ditch from (a) Aspen Street to 21st Lane; (b) Aspen Street to 23rd Lane; (c) Aspen Street to 25th Lane; and (d) Aspen Street to Nicholson Road, (3) installing two drains at a depth of 10 feet below land surface upgradient from the high water table areas, and (4) installing 22 dewatering wells within the high water table areas, each pumping at 80 gallons per minute.

Purpose and Scope

This report presents the results of simulations of ground-water flow in the terrace alluvial aquifer of the Mesa. The ground-water flow system of the Mesa, the development of the digital ground-water flow model, and the use of the model to evaluate possible alternatives for lowering the water table are described. Areas of the Mesa having a high water table are defined in this report by November 1997 depth-to-water measurements.

Description of Study Area

The study area covers about 10 mi^2 on the Mesa in southern Colorado (fig. 1). The Mesa is bounded by the Salt Creek Valley below its northwestern slope, the Arkansas River Valley below its northern slope, the St. Charles River Valley below its southeastern slope, and by shale-dominated hillocks southwest of the Bessemer Ditch (hereinafter, the Ditch). The Mesa was originally developed in the late 1800's for use as an agricultural area with farm residences (Dumeyer, 1975). Currently (2000), crops are grown on about 4 mi^2 of the Mesa. The Ditch was constructed during the late 1800's on the southern side of the Mesa in part to deliver water to agricultural fields. Because the owners of the Ditch, the Bessemer Irrigation Ditch Company, have several relatively high priority water rights, water is conveyed through the Ditch every year. The Ditch is not lined where it traverses the Mesa, and the inflow of water from seepage from the Ditch and from irrigation has contributed to the water table becoming artificially high relative to the water table that probably existed before development of the Ditch and the start of irrigation on the Mesa. Twenty-two lateral ditches branch off the Ditch and are used to convey water to agricultural fields on the Mesa. Some lateral ditches are lined, others are unlined. The study area hereinafter will be referred to as "the modeled area."

Acknowledgments

Data needed for the development of the ground-water flow model were provided by Dan Henrichs, Bessemer Irrigation Ditch Company; Dave Simpson, St. Charles Mesa Water District; Ina Bernard, Division of Water Resources; and 57 private well owners who allowed the USGS to measure water levels in their wells.

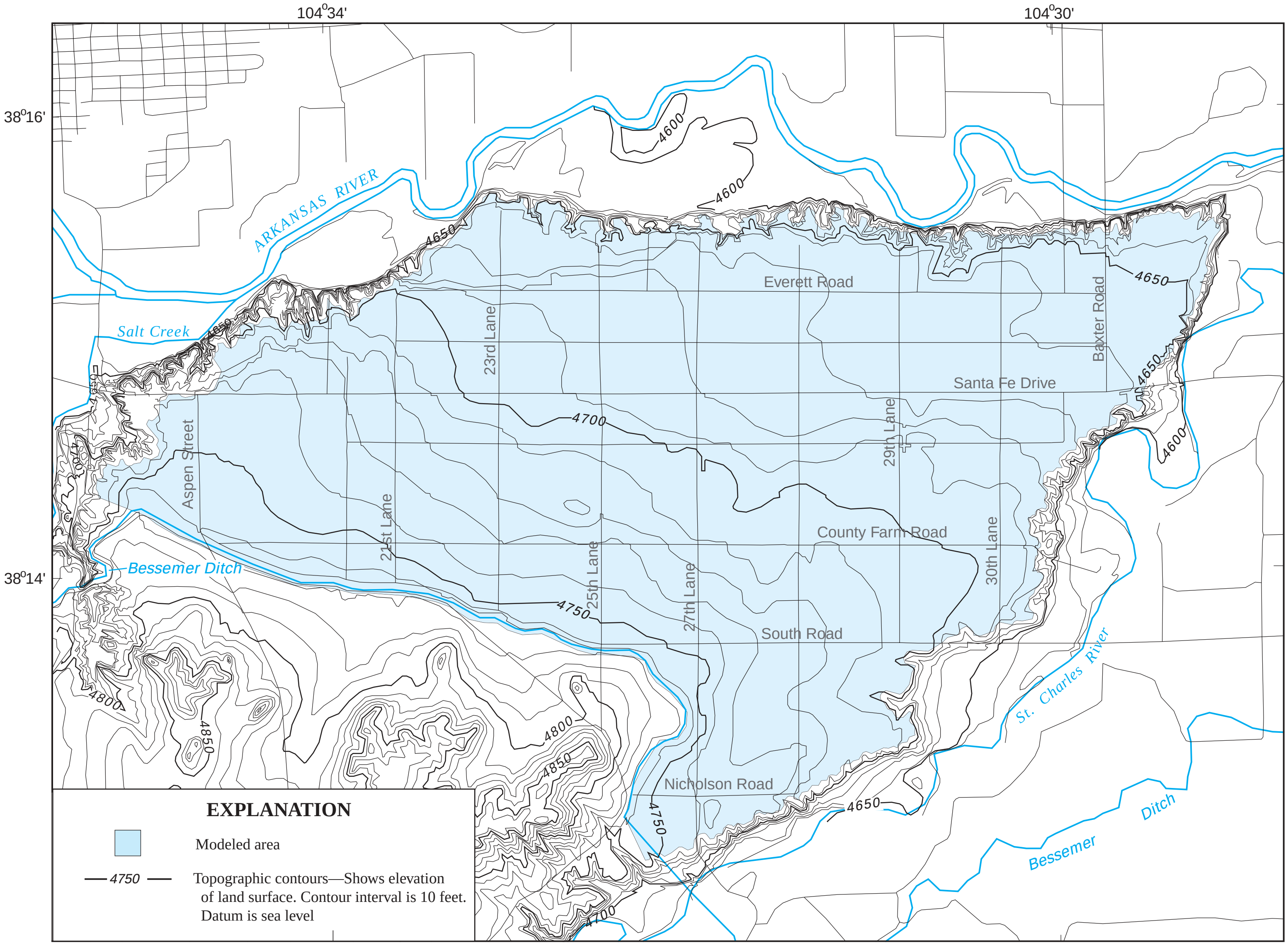
GEOHYDROLOGIC SETTING OF ST. CHARLES MESA

The Mesa is a remnant of a previously more extensive alluvial terrace that was deposited by the ancestral Arkansas River during the Pleistocene Epoch (Scott, 1969b). The alluvial deposits that compose the terrace alluvial aquifer on the Mesa include the Slocum Alluvium, generally south of Santa Fe Drive (fig. 2), and the Louviers Alluvium, generally north of Santa Fe Drive and in a narrow band along the southeastern side of the Mesa. These alluvial deposits generally consist of sand and gravel and range in thickness from about 7 to more than 38 ft (Scott, 1969a). The alluvial deposits are overlain by approximately 5 to 32 ft of eolian sand of late Holocene age (Scott, 1969b).

Erosion of the alluvial terrace produced the current physiographic feature that resembles a mesa. The Mesa is bounded by fairly high-angle scarps on its northwestern and northern sides, a gradually descending slope on its southeastern side, and a topographic rise underlain by bedrock on its southwestern side. The land surface of the Mesa slopes downward to the north-northeast toward the Arkansas River Valley (fig. 2). The topographic contours east of Salt Creek, south of the Arkansas River, and west of the St. Charles River illustrate the relief in the vicinity of the Mesa (fig. 2).

The northwestern, northern, and southeastern sides of the Mesa are dissected by numerous washes that convey stormwater flow off the Mesa and commonly contain springs and seeps. These washes generally are less than one-fourth mile in length and have a central axis perpendicular to the trend of the scarp or slope. Due to the ground-water discharge from springs and seeps, these washes usually contain water-loving vegetation (phreatophytes) in their upper ends.

Rocks of Cretaceous age form the bedrock underlying the Mesa. The Pierre Shale directly underlies the terrace alluvial aquifer throughout most of the Mesa. The Niobrara Formation is exposed on the Mesa's northwestern scarp and the southeastern slope (Scott, 1964; 1969b). Deformation of the Cretaceous rocks in the vicinity of the Mesa has caused the contact between the overlying Pierre Shale and the underlying Niobrara Formation to become exposed along the sides of the Mesa. The Pierre Shale that underlies the terrace alluvial aquifer acts as an impermeable lower boundary to the ground-water flow

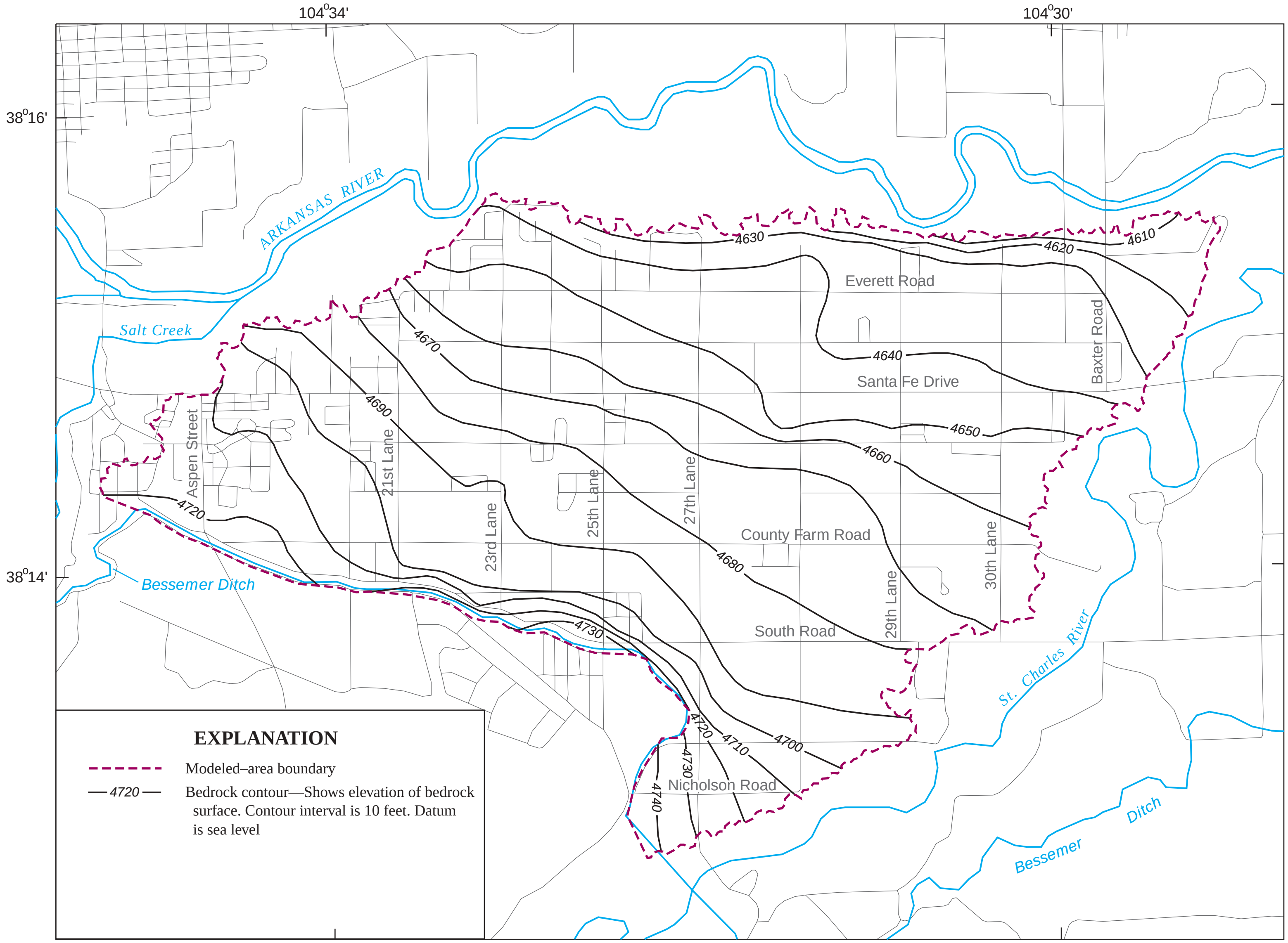


Base from hypsography from U.S. Geological Survey Digital Raster Graphics, 1998. From U.S. Geological Survey 1:24,000 quadrangles: Devine, Northeast Pueblo, Southeast Pueblo, Vineland, 1974. Hydrology modified by Denver Water Board, 1998, from U.S. Geological Survey Digital Line Graphs, 1:100,000, 1981–1983. Roads and cities from Colorado Department of Transportation, 1998. State plane projection. 1927 North American datum, Colorado coordinate system, Southern zone

0 1/2 1 1-1/2 2 MILES

0 0.5 1 1.5 2 KILOMETERS

Figure 2. Topographic contours on and near St. Charles Mesa.



Base from hydrology modified by Denver Water Board, 1998, from U.S. Geological Survey Digital line graphs, 1:100,000, 1981–1983. Roads and cities from Colorado Department of Transportation, 1998. State plane projection. 1927 North American datum, Colorado coordinate system, Southern zone

0 1/2 1 1-1/2 2 MILES

0 0.5 1 1.5 2 KILOMETERS

Figure 3. Bedrock surface underlying St. Charles Mesa.

system. Figure 3 shows the configuration and elevation of the bedrock surface. The contact between the terrace alluvial aquifer and the underlying bedrock on the steep sides of the Mesa generally lies between the top and the bottom of the scarp forming the sides of the Mesa. Because the contact between the bedrock and the overlying terrace alluvial aquifer is physiographically higher than the Arkansas River and St. Charles River alluvial aquifers, the shallow, unconfined ground-water flow system on the Mesa is perched and does not receive flow from adjacent aquifers.

Ground-water flow in the terrace alluvial aquifer is generally from the southwest to the northeast, with the highest water-table elevations in the vicinity of the Ditch near the southwestern corner of the study area. The water table for May 1998 (fig. 4) represents nearly average hydrologic conditions. The terrace alluvial aquifer of the Mesa is very permeable and receives recharge as seepage from the Ditch when water is being conveyed in the Ditch. Water levels in well SCM–28, which is near the Ditch (fig. 4), fluctuated about 14 ft during April 1997 through October 1998 and increased relatively rapidly when water was diverted into the Ditch beginning in mid-February 1998 (fig. 5). Water levels in well SCM–02 (fig. 5), which is farther away from the Ditch (fig. 4), fluctuated about 3 ft during this period. The Ditch conveys water beginning in mid-February to mid-March until mid-November. Recharge to the terrace alluvial aquifer occurs as seepage through the unlined bottom of the Ditch, as seepage from lateral ditches as water is delivered to irrigated fields, and by deep percolation of irrigation water, precipitation, and septic-system effluent.

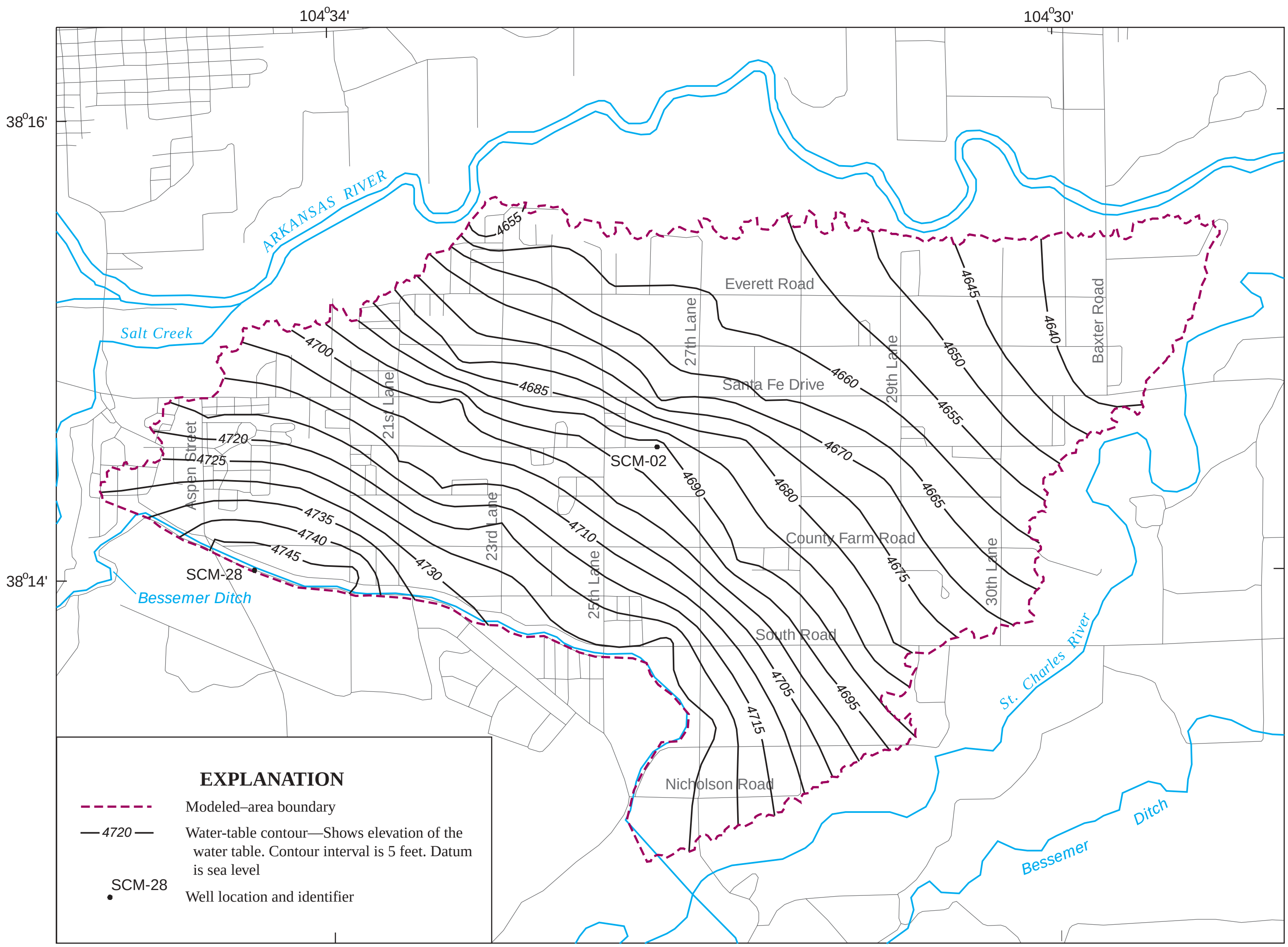
Hydrographs of water levels measured in wells during April 1997 through October 1998 indicated that the ground-water levels in the terrace alluvial aquifer varied by less than 1 ft to more than 15 ft (Brendle, 1999) (fig. 5). The ground-water flow system was assumed to be in a state of dynamic equilibrium (steady-state condition) for this study. Thus, average monthly water levels and pumpage, and Ditch diversions and precipitation for June 1, 1997, through May 31, 1998, were used in model construction and calibration.

The hydrologic components that affect ground-water flow and storage in the terrace alluvial aquifer of the Mesa (fig. 6) are recharge by infiltration of water that seeps from the Ditch and lateral ditches as irrigation water is conveyed; recharge by infiltration of water from lawn and crop irrigation and septic-system effluent; recharge by infiltration of precipitation; discharge of ground water through springs and seeps on the northwestern, northern, and southeastern sides of the Mesa; discharge of water by evaporation or transpiration (evapotranspiration); and discharge of water by well pumpage, some of which results in discharge off the Mesa through lined drainage ditches. Seepage from the Ditch is the main source of inflow to the terrace alluvial aquifer (Dumeyer, 1975).

Infiltration of water from lawn and crop irrigation, septic-system effluent, and precipitation; discharge of ground water by evaporation or transpiration; and flow from springs and seeps on the northwestern, northern, and southeastern sides of the Mesa were not measured during this study.

Bedrock Surface

The map of the bedrock surface (fig. 3) was developed from well-construction reports obtained from the Colorado Division of Water Resources (DWR) in Denver; the bedrock/alluvium contact along the Mesa scarp, which is shown on the geologic maps of the Pueblo area (Scott, 1964; 1969b); and depths to bedrock from test holes shown on the geologic maps and in a previous USGS study (Major and others, 1970). Most wells on the Mesa were drilled and installed to the top of the bedrock and fully penetrate the saturated thickness of the terrace alluvial aquifer. The depths to bedrock from lithologic logs for 118 wells were used in constructing a contour map of the bedrock surface (fig. 3). Locations of the 118 wells obtained from DWR were plotted on a USGS topographic map using the reported distances from the north or south and the east or west section lines. The elevation of the land surface at each well was interpolated from the topographic contours. These points and 15 data points from the geologic maps and from Major and others (1970) were used to calculate the elevation of the bedrock surface (bedrock elevation equals land-surface elevation minus depth to bedrock). Bedrock-surface elevations were machine contoured using the TOPOGRID and LATTICECONTOUR commands in the geographic information system (GIS) program ArcInfo (Environmental Systems Research Institute, 1992). The resulting calculated contours of the bedrock surface were checked for validity and edited to more accurately represent the data points where



Base from hydrology modified by Denver Water Board, 1998, from U.S. Geological Survey Digital line graphs, 1:100,000, 1981–1983. Roads and cities from Colorado Department of Transportation, 1998. State plane projection. 1927 North American datum, Colorado coordinate system, Southern zone

0 1/2 1 1-1/2 2 MILES
0 0.5 1 1.5 2 KILOMETERS

Figure 4. Water table in May 1998, and the location of wells SCM–02 and SCM–28, St. Charles Mesa.

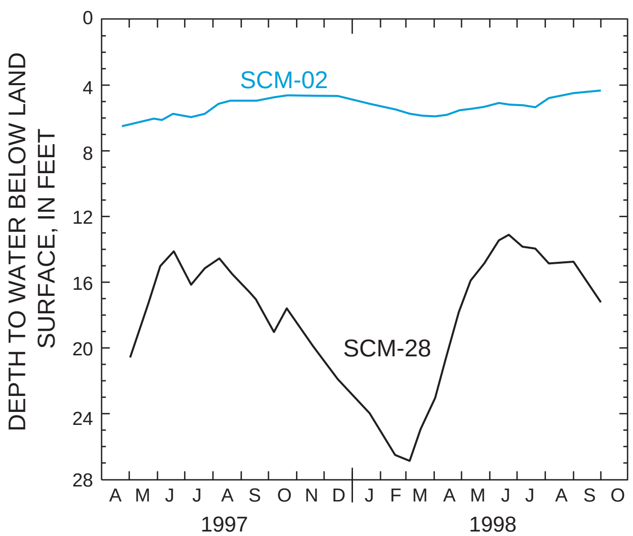


Figure 5. Depth to water in wells SCM–02 and SCM–28, April 1997–September 1998.

necessary. Some calculated contours were smoothed to reduce what appeared to be unreasonable sinuosity.

Hydraulic Conductivity

Results from six specific-capacity tests were used to estimate the horizontal hydraulic conductivity of the terrace alluvial aquifer. One test completed by the USGS (Wilson, 1965) on the north side of the Mesa yielded a horizontal hydraulic conductivity of 490 ft/d. Analysis of five specific-capacity tests completed by private well drillers in the vicinity of South Road and 25th Lane (fig. 4) yielded a range of estimated horizontal hydraulic-conductivity values of 250 to 750 ft/d.

Water-Table Surface

Depth-to-water (water-level) measurements were obtained in 54 privately owned wells from April 1997 through October 1998. Although measurements were obtained at varying intervals (weekly, biweekly, and monthly) depending on the well's proximity to the Ditch and to areas where the high water table exists, only the monthly measurements were used in mapping the average monthly water table (fig. 7). The average monthly water-table surface was selected to represent the water table under the assumption of a steady-state condition.

Monthly depth-to-water measurements from June 1, 1997, through May 31, 1998, were averaged for the 54 wells. The average depth-to-water values were converted to water-table elevations above sea level and were machine contoured using the TOPOGRID and LATTICECONTOUR commands of

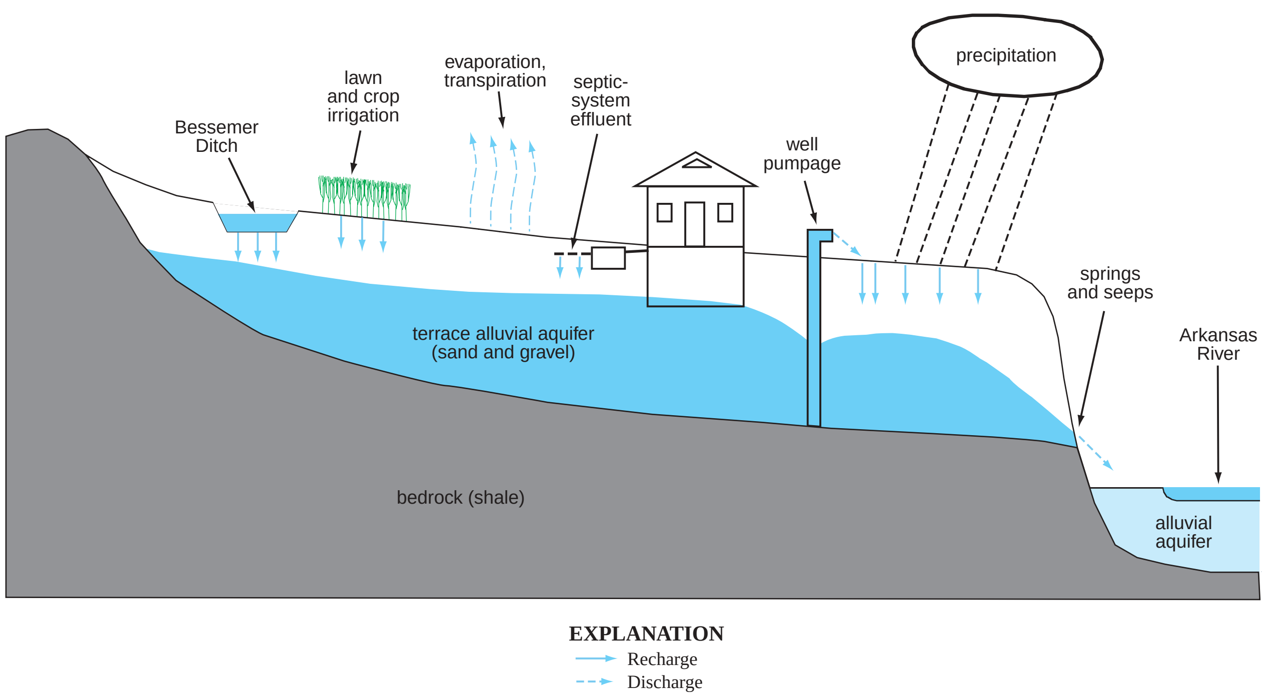
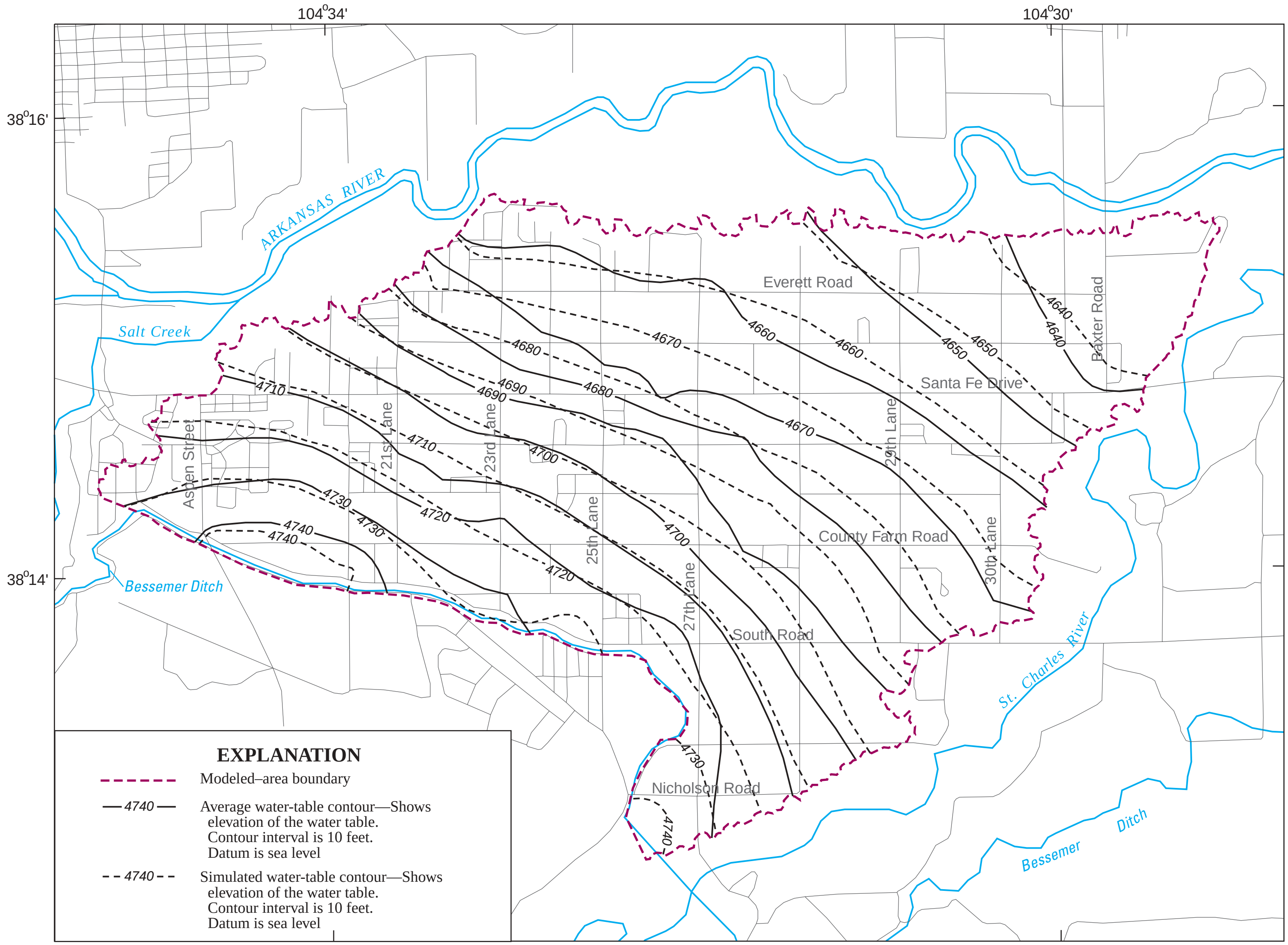


Figure 6. Components of the St. Charles Mesa hydrologic system.



Base from hydrology modified by Denver Water Board, 1998, from U.S. Geological Survey Digital line graphs, 1:100,000, 1981–1983. Roads and cities from Colorado Department of Transportation, 1998. State plane projection. 1927 North American datum, Colorado coordinate system, Southern zone

0 1/2 1 1-1/2 2 MILES
0 0.5 1 1.5 2 KILOMETERS

Figure 7. Average monthly water table, June 1997–May 1998, and the simulated water table for the calibrated steady-state model.

ArcInfo (Environmental Systems Research Institute, 1992). The resulting machine contours of the water-table surface were checked for validity and edited to more accurately represent the data points where necessary, but the contours were not smoothed.

Recharge

Water that recharges the terrace alluvial aquifer of the Mesa comes from seepage from the Ditch and lateral ditches, precipitation, water used for lawn and crop irrigation (surface and ground water), and septic system effluent. Estimates of recharge to the terrace alluvial aquifer were made separately for Ditch seepage and for areal recharge (seepage from lateral ditches, precipitation, water used for lawn and crop irrigation, and septic-system effluent).

Areal recharge was estimated for agricultural (irrigated) areas and residential (nonirrigated) areas. The percentages of precipitation, applied lawn or crop irrigation water, and septic-system effluent on which the estimates were based were obtained from reports of previous studies in similar hydrologic or climatic settings (Watts and Lindner-Lunsford, 1992; Goodell, 1988; Weist, 1965). The locations of irrigated parcels (fig. 8) were obtained from a digital coverage of the Mesa obtained from the DWR. Areas not indicated as irrigated were considered nonirrigated, even though the application of water in those areas was not necessarily uniform between discreet nonirrigated areas. Some nonirrigated parcels are residential lots, whereas others are vacant lots that receive no lawn watering.

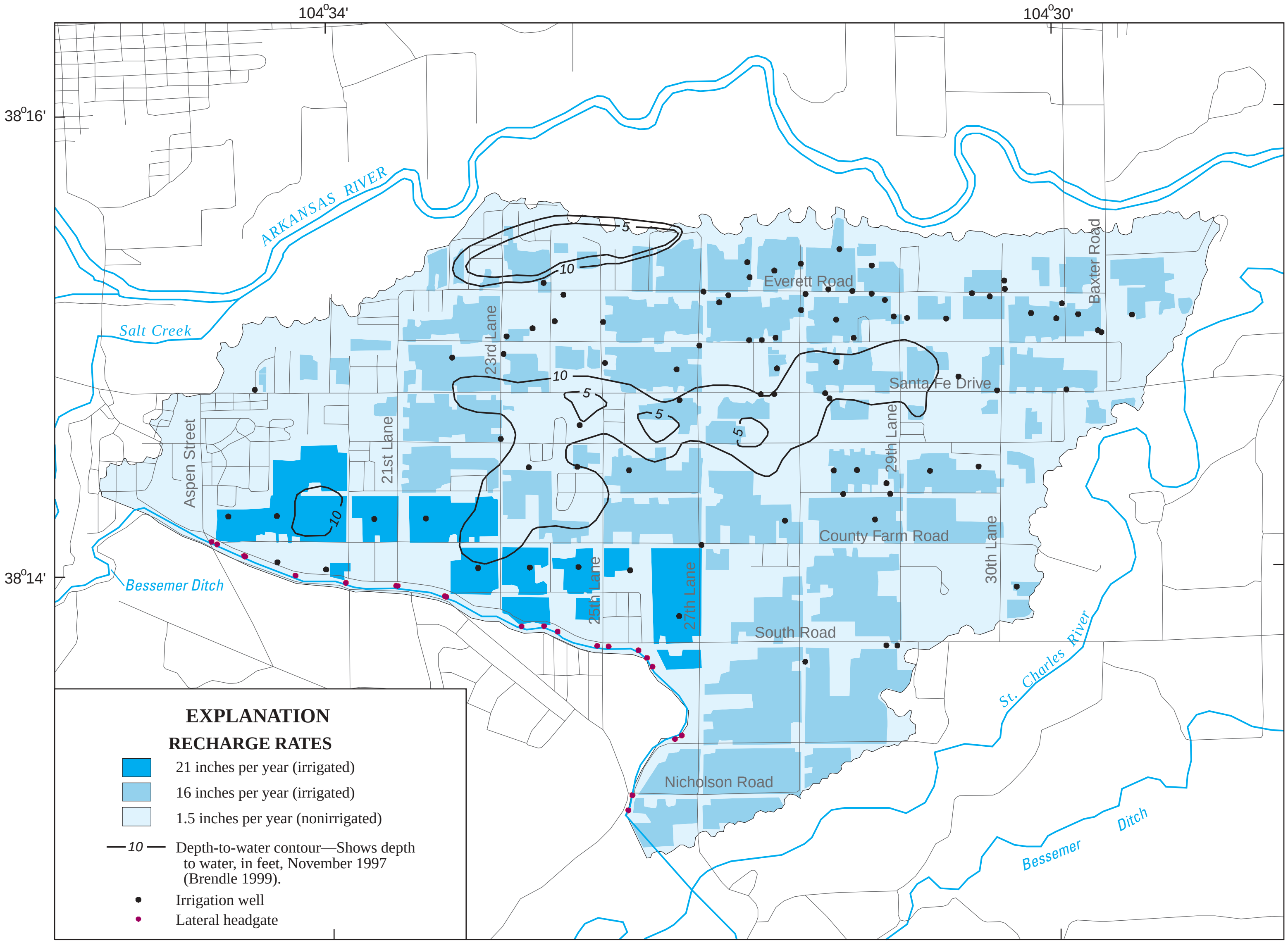
Ditch Seepage

Although the Ditch through Pueblo is lined to limit seepage, the lining ends at Aspen Street on the Mesa. Where the Ditch is not lined, water seeps through the bottom and sides of the Ditch and recharges the terrace alluvial aquifer. Because the water table near the Ditch is approximately 4 ft below the bottom of the Ditch, the water table does not contribute flow back into the Ditch. The amount of seepage from the Ditch was estimated on the basis of measurements made during May 1999 and March and April 2000.

Because the Ditch had been flowing for about 3 months in May 1999, steady seepage through the Ditch's bottom and sides was assumed. Discharge measurements were made during one day at the Aspen Street bridge (upstream site), upstream from the 25th Lane bridge over the Ditch, the overflow structure at Nicholson Road (downstream site), and at all the lateral ditches where a measurement was possible. Five measurements were made at the Aspen Street bridge and at the overflow structure at Nicholson Road, and three measurements were made upstream from the 25th Lane bridge over the Ditch. Flow into lateral ditches that were inaccessible for a measurement was estimated from the Bessemer Irrigation Ditch Company's settings for the lateral headgates (Dan Henrichs, Bessemer Irrigation Ditch Company, oral commun., 1999).

The difference between the average of five flow measurements obtained at the upstream (258.4 ft^3/s) and downstream (191.0 ft^3/s) ends of the Ditch was 67.4 ft^3/s. A total seepage of 22.1 ft^3/s from the Ditch to the terrace alluvial aquifer was calculated by subtracting lateral diversions from the difference between the upstream and downstream flows. The estimated seepage is greater than the presumed 5-percent error in the discharge measurements.

The relation between the rate of flow in the Ditch and the height of water in the Ditch for each flow rate (rating) was used to estimate the amount of seepage associated with each average monthly rate of flow. Additional flow measurements at the Aspen Street bridge were obtained in March 2000 (79.2 ft^3/s) and in April 2000 (174 ft^3/s) and were used to develop a rating curve for the Ditch. Because a plot of the logarithm of discharge (flow) against the logarithm of stage (height of water above the bottom of a stream or ditch) is approximately linear, it is possible to estimate the stage for a known (measured) flow rate (Kennedy, 1984). Because the shape of the Ditch is approximately trapezoid, the stage is approximately the average height of water above the horizontal bottom of the Ditch. Monthly flow in the Ditch, which was provided by the Bessemer Irrigation Ditch Company (Dan Henrichs, Bessemer Irrigation Ditch Company, oral commun., 1999), was used to estimate average monthly stage. The average monthly stage in the Ditch at Aspen Street was assumed to approximate the average monthly stage in the reach of the Ditch traversing the Mesa.



Base from hydrology modified by Denver Water Board, 1998, from U.S. Geological Survey Digital line graphs, 1:100,000, 1981–1983. Roads and cities from Colorado Department of Transportation, 1998. Irrigated areas from the Colorado Division of Water Resources, 1998. State plane projection. 1927 North American datum, Colorado coordinate system, Southern zone

0 1/2 1 1-1/2 2 MILES
0 0.5 1 1.5 2 KILOMETERS

Figure 8. Calibrated recharge rates for irrigated and nonirrigated areas, and the locations of irrigation wells and lateral headgates on the Mesa.

Average monthly seepage from the Ditch (*Q*) was calculated using Darcy's Law (eq. 1),

$$Q = -K\ A\ dh/dx \qquad (1)$$

where

- Q is the discharge (vertical flow) through the Ditch bottom (seepage), in cubic feet per second;
- K is the hydraulic conductivity of the Ditch bottom materials through which flow occurs, in feet per day;
- A is the area through which flow occurs (area of Ditch bottom), in square feet;
- dh is the change in head across the materials through which flow occurs ($h_2 - h_1$), in feet, where h_1 is the initial height of water (average monthly stage in the Ditch) and h_2 is the final height of water above the bottom of the Ditch, assumed to be 0 ($h_1 = dh$ when $h_2 = 0$); and
- dx is the distance over which flow occurs perpendicular to the area through which flow occurs ($x_2 - x_1$), or the thickness of the Ditch bottom, in feet.

Because the hydraulic conductivity of the Ditch bottom (*K*) and the flow-path length (*dx*) are unknown and the area of the ditch bottom (*A*) is only approximate, the factor *KA*/*dx* was calculated. Equation 1 was rearranged to solve for the constant *KA*/*dx* by using the seepage from the Ditch (*Q*) estimated from the May 1999 flow measurements and the stage (*dh*) at the time the seepage was estimated.

For *Q* of 22.1 ft^3/s and *dh* of 4.17 ft (estimated stage for *Q* of 22.1 ft^3/s), the factor *KA*/*dx* is 5.30 ft^2/s (22.1 $ft^3/s \div 4.17$ ft = 5.30 ft^2/s). The average monthly seepage rates (*Q*) were estimated as the product of *KA*/*dx* and the estimated average monthly stage (h_1). The average of the monthly seepage rates was 13.2 ft^3/s (table 1).

Areal Recharge

The term "areal recharge" refers to recharge that is not focused at a point but that occurs over a larger area, such as agricultural fields or residential areas. Initially, two different areal recharge rates were estimated, one for irrigated areas and one for residential areas.

Seepage from lateral ditches was expected to contribute to recharge to the terrace alluvial aquifer. Lateral ditch seepage was not measured but was assumed to be accounted for in the overall areal recharge term.

Table 1. Average monthly flow and stage in Bessemer Ditch, average monthly seepage from Bessemer Ditch, and total diversions from Bessemer Ditch to lateral ditches for June 1997 through May 1998

	Average monthly flow in Bessemer Ditch (cubic feet per second)	Average monthly stage (h_1) in Bessemer Ditch (feet)	Average monthly seepage from Bessemer Ditch (cubic feet per second)	Total of diversions to lateral ditches (cubic feet per second)
June 1997	263.54	4.22	22.36	55.66
July	276.63	4.34	23.00	56.65
August	263.55	4.22	22.37	52.96
September	167.67	3.27	17.33	38.82
October	115.66	2.73	14.47	35.69
November	52.37	2.02	10.71	11.72
December	0	0	0	0
January 1998	0	0	0	0
February	0	0	0	0
March	62.55	2.14	11.34	28.75
April	143.30	3.02	16.01	42.43
May	232.53	3.92	20.78	51.84
AVERAGE	131.48	2.49	13.20	31.21

There is no continuous-recording rain gage on the Mesa, but precipitation measurements obtained at the weather station at Pueblo Airport are considered representative of precipitation on the Mesa because neither the airport nor the Mesa is affected by orographic effects (Viessman and others, 1977). Precipitation measured at the weather station at Pueblo Airport (fig. 1), which lies about 5 miles north from the center of the Mesa, was 15.8 inches (4.18×10^{-8} ft^3/s) from June 1, 1997, through May 31, 1998.

In agricultural areas, recharge to the terrace alluvial aquifer includes precipitation and ground water and surface water used for irrigation. Twenty-two percent of precipitation was assumed to recharge the terrace alluvial aquifer in the agricultural areas (Goodell, 1988). Goodell's estimates are used for this study because the climatic conditions, precipitation, and soils on the Mesa are similar to areas of the Snake River Plain. Twenty-five percent of applied irrigation water was assumed to recharge the terrace alluvial aquifer (Weist, 1965). The average total diversion into lateral ditches was 31.2 ft^3/s (Dan Henrichs, Bessemer Irrigation Ditch Company, written commun., 1999), the average pumpage used for irrigation was 985 gal/min (2.19 ft^3/s) (Colorado Division of Water Resources, Pueblo), and the precipitation was 15.8 in/yr (4.18×10^{-8} ft/s). The recharge rate in irrigated areas was calculated using equation 2:

$$RA = \frac{(E + F) \times 0.25}{G} + H \times 0.22 \qquad (2)$$

where

RA is the recharge rate in agricultural areas, in feet per second;

E is the average diversions into lateral ditches, in cubic feet per second;

F is the average pumpage, in cubic feet per second;

G is the total irrigated area, in square feet; and

H is the average annual precipitation, in feet per second.

In the residential area, 5 percent of precipitation was assumed to recharge the terrace alluvial aquifer based on a study by Watts and Lindner-Lunsford (1992) near La Junta, Colorado. Average household water use was 265 gal/d (4.10×10^{-4} ft^3/s) for the 2,100 households receiving municipal water from St. Charles Mesa Water District (David Simpson, St. Charles Mesa Water District, oral commun., February 2000). Seventy percent of household water use was assumed to recharge the terrace alluvial aquifer, based on Goodell's (1988) study in the Snake River Plain in Idaho. Household water use includes infiltration of water used for lawn irrigation and septic-system effluent. Septic systems were assumed to be uniformly distributed throughout the residential area. Recharge due to septic system effluent was accounted for by assuming a certain rate of infiltration of household water used. Equation 3 was used to estimate the recharge rate in residential areas:

$$RR = \frac{A \times B \times 0.7}{C} + D \times 0.05 \qquad (3)$$

where

RR is the recharge rate for residential area, in feet per second;

A is the number of households receiving municipal water;

B is the average water use per household, in cubic feet per second;

C is the total residential area, in square feet; and

D is the average annual precipitation, in feet per second.

The estimates of recharge rates for residential and irrigated areas are listed in table 2. The distribution of areal recharge is shown in figure 8.

Discharge

Water that discharges from the terrace alluvial aquifer of the Mesa occurs as spring and seep discharge, evapotranspiration, and ground-water pumpage. Ground water that is pumped from the terrace alluvial aquifer can recharge the ground-water system, can flow off the Mesa through drainage ditches, or can be lost through evaporation.

Spring and Seep Discharge

Previously, spring and seep discharge from the Mesa was estimated by Dumeyer (1975) to be 13 ft^3/s. Cain and others (1980) made several discharge measurements in the Arkansas River in the reach north of the Mesa. No measurable tributary inflows were observed in this reach, and spring and seep discharge from the Mesa of 21 ft^3/s was calculated. The current (2000) spring and seep discharge from the Mesa was assumed to be between 13 and 21 ft^3/s for this study.

Table 2. Land-use areas and estimated recharge rates

[Ditch, Bessemer Ditch in fig. 2]

Area classifications	Area (square feet)	Percentage of precipitation, household wastewater, or irrigation water recharging the terrace alluvial aquifer	Estimated recharge rate (cubic feet per second per square foot)	Rate used in calibrated model (cubic feet per second per square foot)
Residential (nonirrigated) area	158,748,125	5[a] precipitation; 70[b] household wastewater	5.81×10^{-9}	4.00×10^{-9}
Irrigated parcels less than 0.5 mile from the Ditch between Aspen Street and South Road	18,438,410	22[c] precipitation; 25[c] irrigation water	8.59×10^{-8}	5.54×10^{-8}
Irrigated parcels greater than 0.5 mile from the Ditch, or parcels within 0.5 mile of the Ditch from South Road to Nicholson Road	90,326,016	22[c] precipitation; 25[c] irrigation water	8.59×10^{-8}	4.23×10^{-8}

[a]Watts and Lindner-Lunsford, 1992.
[b]Goodell, 1988.
[c]Weist, 1965.

Evapotranspiration

An evapotranspiration (ET) rate of 47 in/yr and an extinction depth of 5 ft was estimated for the Mesa area. This estimate was based on a curve of ET relative to depth to water developed for a study in the San Luis Valley in Colorado (Emery, 1970, fig. 3), and is lower than the pan evaporation rate for this area of 60 in/yr. The extinction depth is the depth below which the ET rate is zero. Above the extinction depth, the ET rate increases linearly to the maximum rate at the ground surface. The area of the Mesa within which ET is expected to occur occupies about one-fifth of a square mile. This area corresponds with the areas defined in November 1997 as having a depth to water less than 5 ft (fig. 8).

Pumpage

Monthly pumpage from 86 irrigation wells (rates ranged from 11.41 to 531 gal/min (2.54×10^{-2} to 1.18 ft^3/s)) obtained from DWR was used in the model. Figure 8 shows the locations of the irrigation wells. Pumpage from household wells was not included in the pumpage estimates. Most water for domestic use is provided by the St. Charles Mesa Water District. Pumpage from household wells is used mostly to supplement water provided by the St. Charles Mesa Water District.

Conceptual Model

The terrace alluvial aquifer of the Mesa is a shallow, unconfined, ground-water system perched on impermeable shale. The terrace alluvial aquifer does not receive water discharged from neighboring ground-water systems because it is perched above both the Arkansas and St. Charles alluvial aquifers. Water-table elevations are highest near the southwest corner of the Mesa. Ground water generally flows toward the northeast. Recharge to the aquifer occurs primarily as seepage from the Ditch and lateral ditches, and infiltration of lawn and crop irrigation water, septic-system effluent, and precipitation. Discharge from the aquifer occurs primarily as outflow from springs and seeps, evapotranspiration, and pumpage. Springs and seeps are intermittently dispersed along the northwestern, northern, and southeastern sides of the Mesa.

SIMULATION OF GROUND-WATER FLOW

The numerical model of ground-water flow, MODFLOW–96 (Harbaugh and McDonald, 1996), which uses a finite-difference approximation method, was used to simulate ground-water flow in the terrace alluvial aquifer of the Mesa. The terrace alluvial aquifer of the Mesa was simulated as a one-layer system with an underlying impermeable boundary (bedrock). A grid, consisting of 98 columns by 58 rows, was used to divide the modeled area into 300-ft by 300-ft cells (fig. 9). Each cell represents an area of 90,000 ft^2 within which characteristics of the flow system are assumed to be uniform.

Hydrologic characteristics of the flow system were measured (seepage from the Ditch at relatively high flow and water levels in wells) or estimated (hydraulic conductivity of the aquifer, ET rate and extinction depth, recharge rates for irrigated and nonirrigated areas of the Mesa, and the extent of areas through which spring and seep discharge occurs) for input into the model.

Data that define the geometry and hydraulic properties of the terrace alluvial aquifer, and the locations of hydrologic flows (such as spring and seep discharge) and stresses (such as ground-water pumpage) were developed as digital coverages in ArcInfo (Environmental Systems Research Institute, 1992) for input to a graphical user interface (GUI), developed by the USGS and Argus Interware, which runs on the GIS program ArgusONE (Argus) (Shapiro and others, 1997). Argus creates the model grid and populates each model cell with the flow-system parameters (land-surface elevation, bedrock elevation, water-table elevation, recharge rate, and so forth) that are later used as input files for MODFLOW–96.

Model Description

The terrace alluvial aquifer has real physical boundaries, such as the impermeable bedrock, which acts as a lower boundary to limit flow in a downward direction. The model boundaries simulate hydrologic boundaries that control the amount and rate of water entering and leaving the simulated terrace alluvial aquifer of the Mesa. Boundaries of the model are the horizontal-flow boundaries, a lower no-flow boundary at the bottom of the model's active cells, and an upper, specified-flow boundary.

The horizontal-flow boundaries are no-flow cells surrounding most of the lateral extent of active cells, cells containing injection wells to simulate Ditch seepage, and drain cells used to simulate spring and seep discharge (fig. 9). The lateral extent of the model corresponds to the Ditch on the southwestern side and the bedrock-alluvium contact on the northwestern, northern, and southeastern sides of the Mesa (Scott, 1964; 1969b). The drain cells on the sides of the Mesa are used to simulate ground-water discharge from springs and seeps. The drain cells generally are located at the head of the washes that dissect the steep sides of the Mesa. No-flow cells were simulated between these washes because there is negligible ground-water discharge along the scarp between the washes. A no-flow boundary was used upgradient from the Ditch because the small area of alluvium southwest of the Ditch does not contribute significantly to flow in the system.

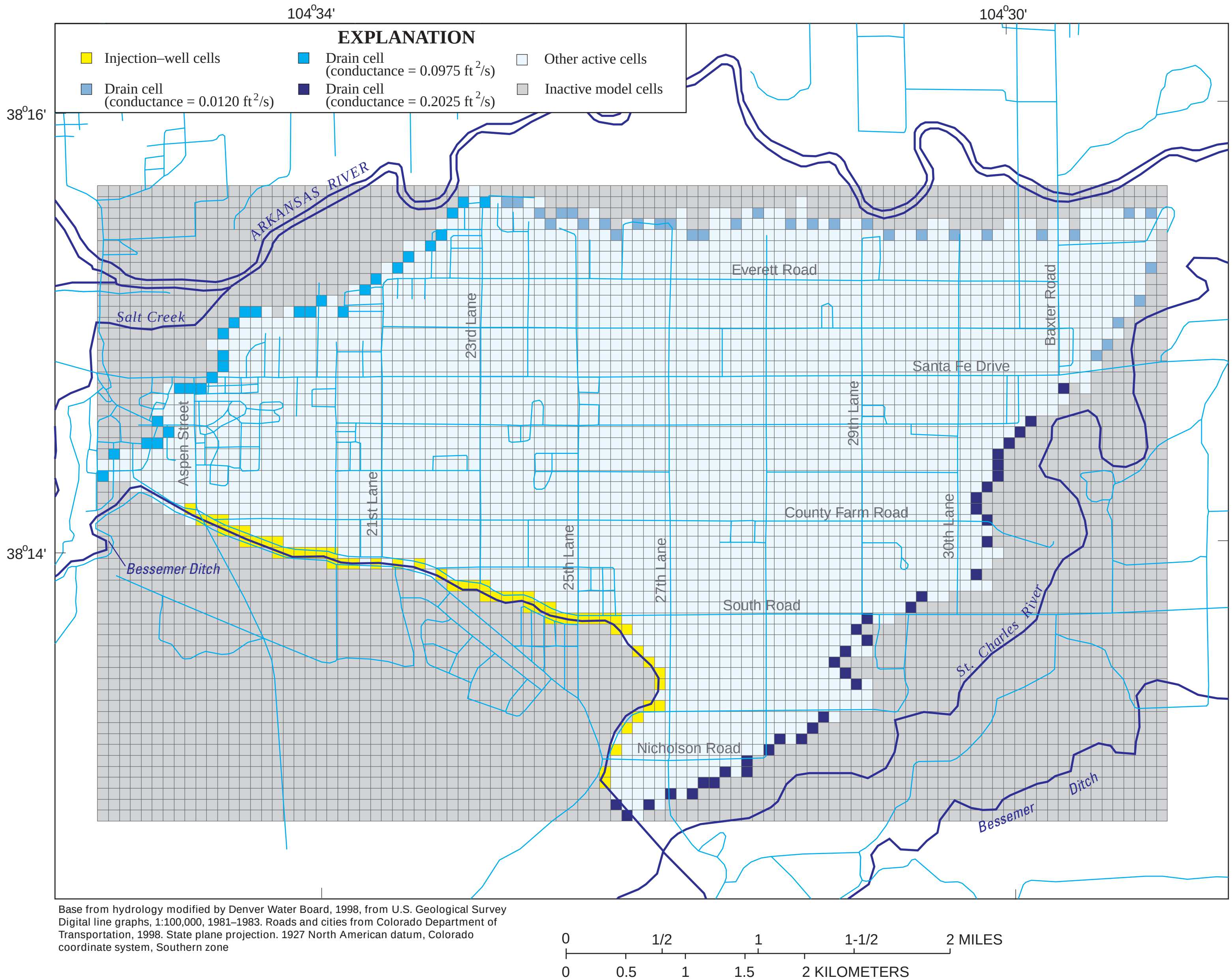
The bottom of the active model cells is a no-flow boundary that represents the bedrock surface, which directly underlies the alluvial deposits that compose the terrace alluvial aquifer of the Mesa.

The water table is the upper boundary of the model. This boundary is a specified-flow boundary, whose level may move vertically in response to recharge and discharge conditions.

The preliminary model developed during the first phase of this study indicated that better definitions were needed on the amount of Ditch seepage and the hydraulic conductivity of the terrace alluvial aquifer. Based on three flow measurements made in the Ditch, an average Ditch seepage of 13.2 ft^3/s was calculated and used in the model. A value of hydraulic conductivity of 500 ft/d (5.78×10^{-3} ft/s) for the terrace alluvial aquifer was used initially in the model. Estimates of initial recharge to residential areas was 2.2 in/yr (5.81×10^{-9} ft/s), and in irrigated areas initial recharge was 32.5 in/yr (8.59×10^{-8} ft/s). Monthly pumpage from 86 wells (rates ranged from 11.41 to 531 gal/min [2.54×10^{-2} to 1.18 ft^3/s]) obtained from DWR was used in the model. The pumpage was simulated both as discharge from the ground-water flow system and as a component in estimating the amount of simulated recharge to irrigated fields.

Model Calibration

The model input layers were entered into the Argus GUI (Shapiro and others, 1997) and the model was calibrated to the average monthly water table for June 1, 1997, through May 31, 1998. Figure 7 shows the average monthly water table for June 1, 1997, through May 31, 1998, and the simulated water table for the calibrated steady-state model. The spring and seep discharge of 13 ft^3/s estimated by Dumeyer (1975) and 21 ft^3/s calculated from measurements made by Cain and others (1980) were used to define a



Base from hydrology modified by Denver Water Board, 1998, from U.S. Geological Survey Digital line graphs, 1:100,000, 1981–1983. Roads and cities from Colorado Department of Transportation, 1998. State plane projection. 1927 North American datum, Colorado coordinate system, Southern zone

Figure 9. Model grid and simulated boundary conditions.

calibration range. The values and spatial distributions of hydraulic conductivity, recharge, drain conductance, and Ditch seepage were adjusted during calibration to minimize the difference between simulated and average water-table elevations and to match the estimated spring and seep discharge. Adjustments to the values were made within limits considered likely for the hydrologic system. For example, hydraulic conductivities for valley-fill deposits in the Arkansas River Valley determined by Wilson (1965) ranged from 32 to 2,045 ft/d (3.70×10^{-4} to 2.37×10^{-2} ft/s). Thus, the calibrated values for hydraulic conductivity were kept within these limits.

During model calibration, the distribution of hydraulic conductivity (fig. 10) was changed from a single value for the entire aquifer to one that was based on the distribution of the Slocum Alluvium and Louviers Alluvium that form the terrace alluvial aquifer. The revised distribution of hydraulic conductivity resulted in a better match between average measured and simulated water levels. Hydraulic conductivity was also adjusted, alternately with drain conductance, to better match the estimated discharge through seeps and springs. Simulated Ditch seepage was adjusted during calibration by redistributing injection wells from cells in areas where simulated heads along the Ditch were too high to cells in areas along the Ditch where the simulated heads were too low. Table 3 lists the distribution of simulated Ditch seepage and the length of the Ditch through which the simulation occurs in the calibrated model.

The distribution of recharge from irrigated fields was adjusted to account for the expected seepage losses from lateral ditches delivering water to fields by assigning higher recharge rates to irrigated fields near the Ditch (table 2). Because water delivered to irrigated fields farther from the Ditch must flow through lateral ditches adjacent to fields near the Ditch, seepage losses from laterals nearer the Ditch likely would be greater.

The model was considered calibrated when the root mean squared error (RMSE) and the mean of the differences were minimized between the average water-table elevations and the simulated water-table elevations at points corresponding to the 54 water-table-measurement locations. The RMSE is a measure of the magnitude of differences (errors) between average measured and simulated water levels over the entire modeled area (Lucey and others, 1995). The mean of the differences is a measure of the systematic error; it approaches zero when the sum of the differences between average measured and simulated water levels that are greater than zero equals the sum of the differences that are less than zero (Lucey and others, 1995). The RMSE is calculated as shown in equation 4 (Anderson and Woessner, 1992):

$$RMSE = \sqrt{\frac{\sum (M - S)^2}{N}} \quad (4)$$

where

M is the average measured water level, in feet;
S is the simulated water level, in feet; and
N is the number of comparisons.

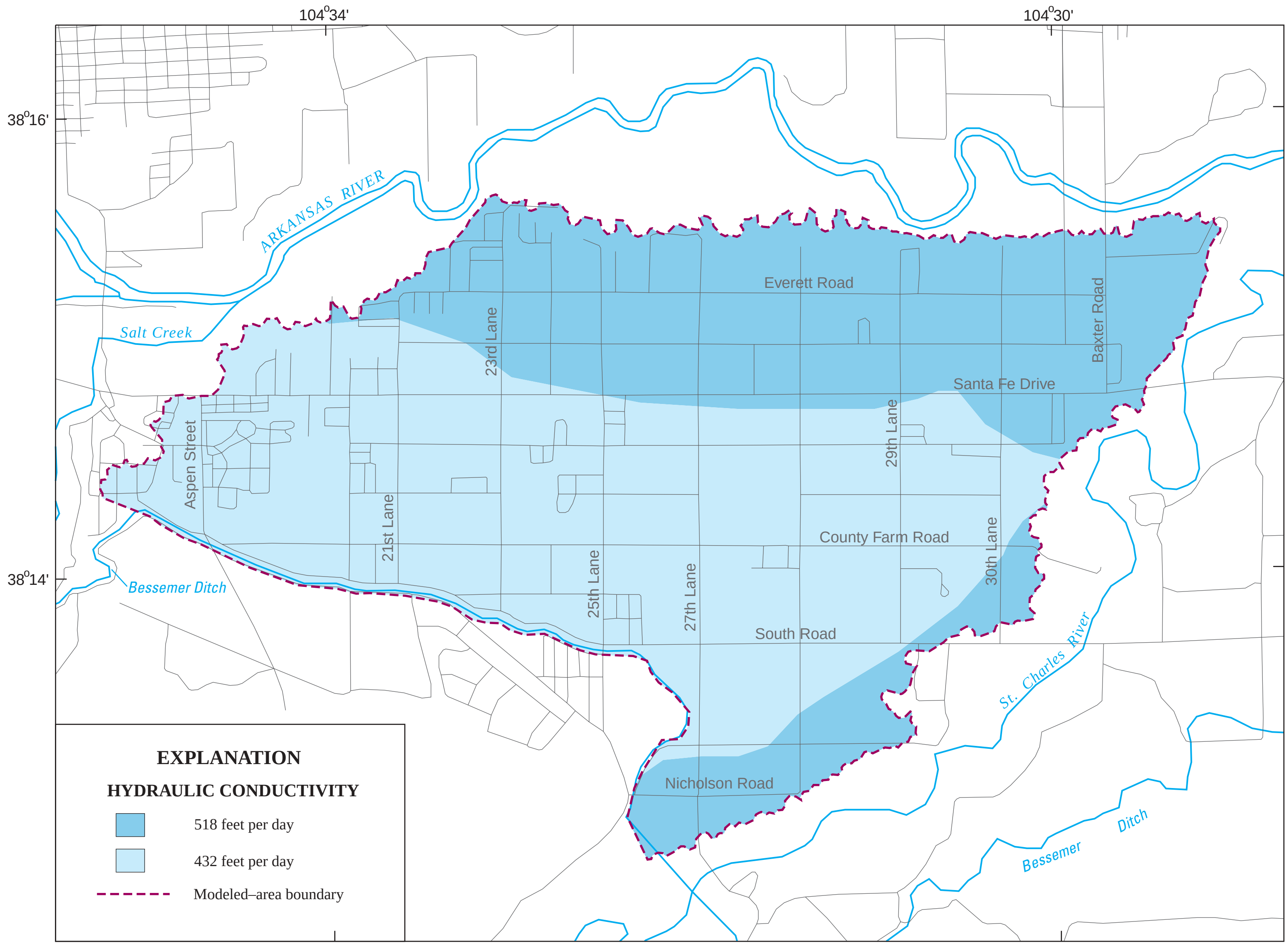
The RMSE and the mean of the differences for the calibrated model were, respectively, 3.85 ft and –0.44 ft. The –0.44 ft mean of the differences indicates that the simulated heads are on average 0.44 ft higher than the mean of the average measured water levels in the wells used for comparison.

The differences between the average water-table elevations and the simulated water-table elevations at points are shown in figure 11. Differences greater than zero indicate simulated water levels are lower than the average water-table elevations, and differences less than zero indicate simulated water levels are higher than the average water-table elevations.

The water budget for the model (table 4) is useful in evaluating whether the calibrated model adequately represents the hydrologic system of the Mesa. Discharge from springs and seeps was cali-

Table 3. Description of Bessemer Ditch segments, the segment length, and the amount of simulated seepage for each Ditch segment

Description (see fig. 10)	Length of ditch segment (miles)	Amount of simulated seepage (cubic feet/second)
From Aspen Street to Nicholson Road	3.31	13.2
From 21st Lane to Nicholson Road	2.28	7.4
From 23rd Lane to Nicholson Road	1.74	6.3
From 25th Lane to Nicholson Road	1.19	3.7
From Aspen Street to 21st Lane	1.03	5.8
From 21st Lane to 23rd Lane	0.54	1.1
From 23rd Lane to 25th Lane	0.55	2.6

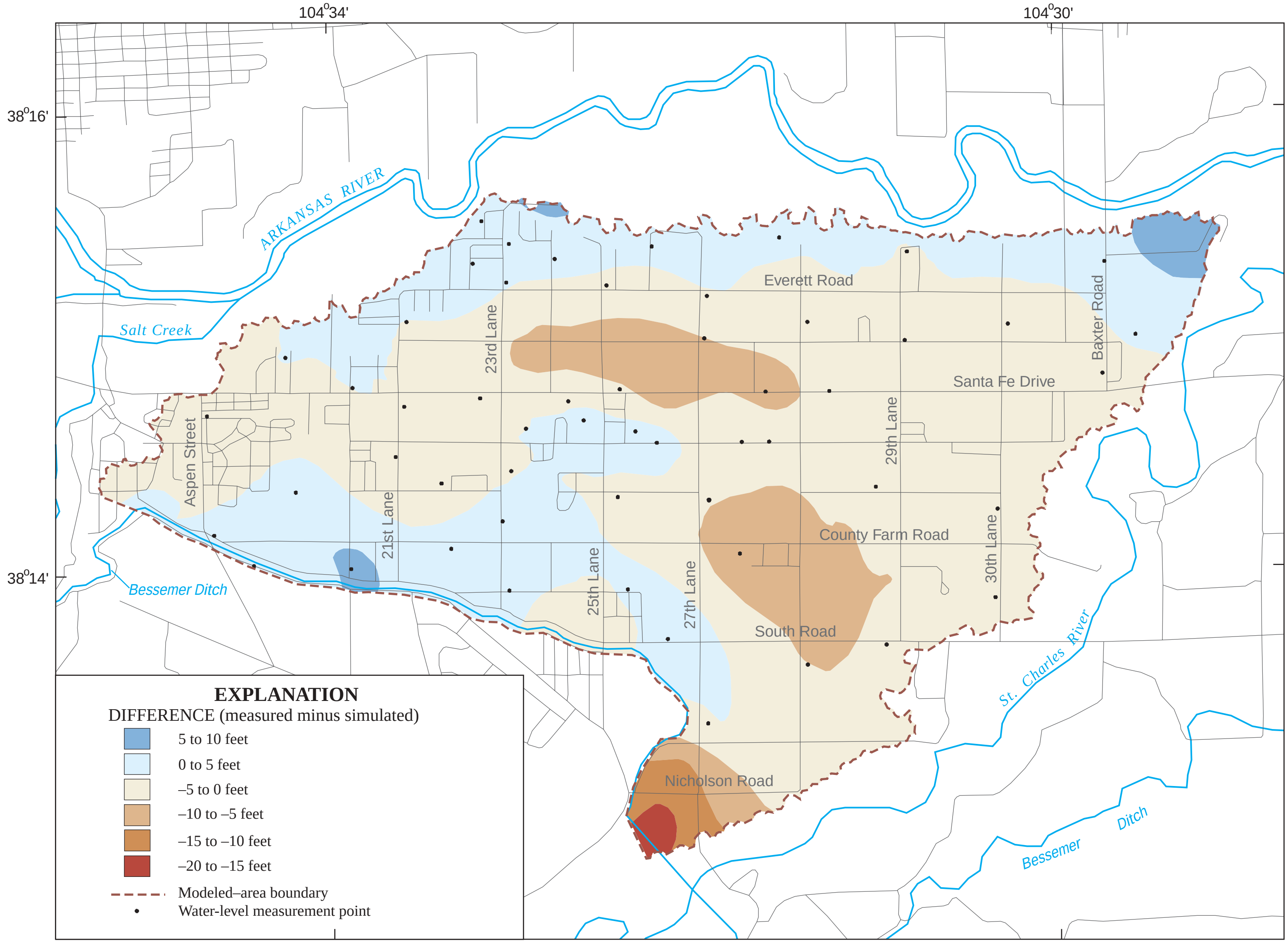


Base from hydrology modified by Denver Water Board, 1998, from U.S. Geological Survey Digital line graphs, 1:100,000, 1981–1983. Roads and cities from Colorado Department of Transportation, 1998. State plane projection. 1927 North American datum, Colorado coordinate system, Southern zone

0 1/2 1 1-1/2 2 MILES

0 0.5 1 1.5 2 KILOMETERS

Figure 10. Hydraulic-conductivity zones used in the calibrated steady-state model.



Base from hydrology modified by Denver Water Board, 1998, from U.S. Geological Survey Digital line graphs, 1:100,000, 1981–1983. Roads and cities from Colorado Department of Transportation, 1998. State plane projection. 1927 North American datum, Colorado coordinate system, Southern zone

0 1/2 1 1-1/2 2 MILES
0 0.5 1 1.5 2 KILOMETERS

Figure 11. Difference between the measured and simulated water levels, and the locations of water-level measurement points.

Table 4. Water budget for the calibrated model

[Ditch, Bessemer Ditch in fig. 2]

Inflow	Rate of simulated inflow (cubic feet per second)	Percentage of total inflow	Outflow	Rate of simulated outflow (cubic feet per second)	Percentage of total outflow
Injection wells to simulate Ditch seepage	13.18	70.4	Withdrawal wells	2.20	11.8
Areal recharge	5.53	29.6	Drains to simulate springs and seeps	15.86	84.7
			Evapotranspiration	0.66	3.5
TOTAL INFLOW	18.71	100	TOTAL OUTFLOW	18.72	100

brated to be between the discharge estimated from previous studies (13 to 21 ft^3/s). The primary inflow simulated by the model is Ditch seepage (70.4 percent of total inflow), and the primary outflow is spring and seep discharge (84.7 percent of total outflow). The water budget indicates the significant effect of seepage from the Ditch on the terrace alluvial aquifer. The discrepancy of 0.01 ft^3/s between the inflow to the model and the outflow from the model is due to rounding errors when calculating the budget terms.

Sensitivity Analysis

Sensitivity testing of a model is performed to determine uncertainties in the calibrated model which are caused by uncertainties in parameter values (Anderson and Woessner, 1992). The model is considered to be more sensitive to a particular parameter if a change in the parameter results in a relatively large increase in the RMSE. Parameters to which a model is very sensitive need to be defined as well as possible to improve model accuracy.

An analysis of model sensitivity was performed by changing parameter values incrementally to determine the effect of those changes on the RMSE. Drain conductance, hydraulic conductivity, areal recharge rate, and Ditch seepage were individually changed to 50, 75, 95, 110, 125, and 150 percent of their calibrated values to determine the associated change in RMSE for the model (fig. 12). The model did not converge on a solution when Ditch seepage was reduced below 95 percent of the calibrated value. When the seepage was reduced to below 95 percent of its calibrated value, cells near the Ditch were completely dewatered. The model also failed to converge when hydraulic conductivity was increased to greater than 110 percent of the calibrated value. Large increases in hydraulic conductivity allowed too much discharge of water from the model, thus simulating complete dewatering of local portions of the terrace alluvial aquifer. The order of decreasing sensitivities for the remaining parameters was as follows: decreased hydraulic conductivity, increased ditch seepage, decreased drain conductance, increased areal recharge rate, increased drain conductance, and decreased areal recharge rate.

The model was relatively insensitive to decreases in the areal recharge rate. The model yielded lower RMSE values for decreases in recharge rate to 75 and 95 percent of the calibrated value. These lower values of recharge were not used in the calibrated model because they were lower than values considered reasonable.

EVALUATION OF POSSIBLE ALTERNATIVES TO LOWER THE HIGH WATER TABLE

Possible alternatives to lower the high water table of the Mesa were tested by running transient-state simulations using the hydraulic parameters from the calibrated steady-state model. The alternatives were simulated in transient-state mode because the model would not converge in steady-state mode when the Ditch seepage was entirely cut off. In steady-state mode, model cells were simulated to become prematurely dry when the Ditch seepage was decreased to simulate each of the Ditch-lining alternatives. In transient-state mode, the model approaches a solution in smaller increments, and fewer model cells were simulated to become dry. Steady-state results can be approximated by running a steady-state model in transient mode until subsequent model runs induce only relatively small changes in storage in the aquifer.

Several model simulations were run to evaluate various possible alternatives for lowering the water table of the Mesa. The possible alternatives simulated were (1) reducing areal recharge by reducing recharge to irrigated areas by 25 percent, (2) lining Bessemer Ditch from (a) Aspen Street to 21st Lane; (b) Aspen Street to 23rd Lane; (c) Aspen Street to 25th Lane; and (d) Aspen Street to Nicholson Road, (3) installing two drains at a depth of 10 feet below land surface upgradient from the high water table areas, and (4) installing 22 dewatering wells within the high water table areas, each pumping at 80 gallons per minute.

The calibrated steady-state water levels were used as the starting water-table elevations in the transient simulations to calculate the effectiveness of the alternatives in lowering the water table. The effectiveness of the alternatives for lowering the high water table was based on the amount and extent of simulated water-level decline associated with each alternative. The model calculates the amount of decline for each alternative relative to the starting heads in the system. The saturated thickness simulated to be remaining in the terrace alluvial aquifer for each of the alternatives was calculated by subtracting the simulated water-table declines and the bedrock-surface elevations from the simulated initial water-table surface elevations.

Maps showing the amount and extent of water-table declines were generated for each of the six alternatives that were at least partially effective in lowering the water table in the areas defined in November 1997 as having a high water table. The November 1997 water-level measurements were selected to represent the high water table because the highest water table in most wells occurs in autumn. November 1997 depth-to-water contours (Brendle, 1999) were superimposed on the maps for comparison with the mapped, simulated water-level declines for each alternative. A simulation was considered effective in alleviating the high water table if water-table declines were at least 5 ft in the areas where a high water table existed in November 1997.

Reducing Areal Recharge

The alternative of reducing areal recharge in irrigated areas by 25 percent resulted in a maximum decline in the water table of about 3 ft near the northeast corner of the Mesa. The water-table declines resulting from this alternative were only about 1 ft in the areas defined as having a high water table in

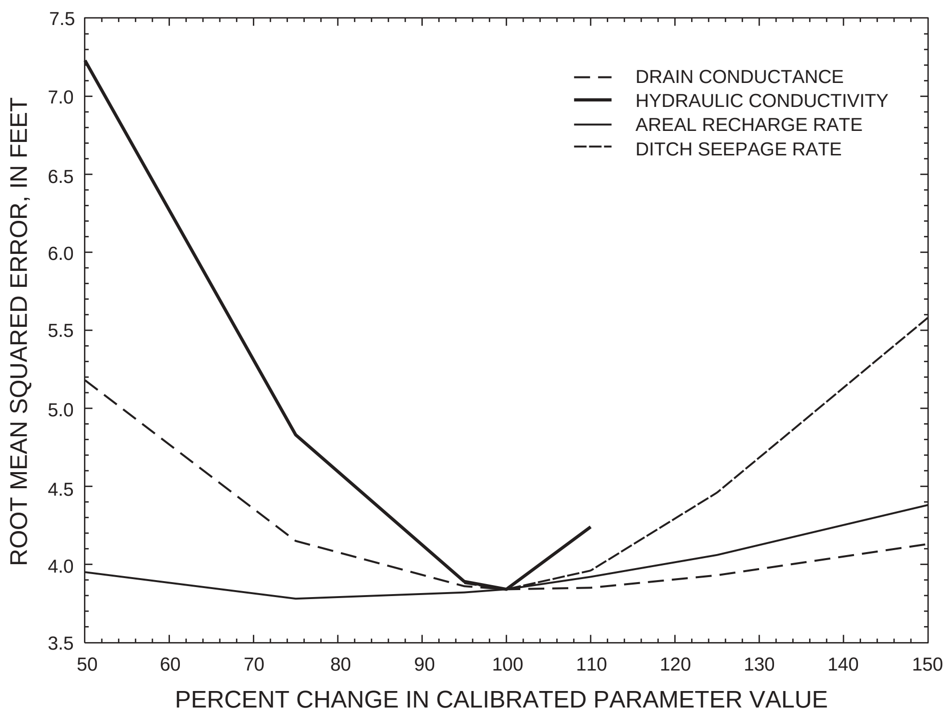


Figure 12. Root mean squared error between measured and simulated water levels as a result of varying model input-parameter values.

November 1997 and were, thus, considered ineffective in lowering the high water table in those areas. For these reasons, no map is shown of the resulting water-table declines or the saturated thickness in the terrace alluvial aquifer for this alternative. Larger reductions in the rate of areal recharge to irrigated areas were not evaluated because they were considered to be too large to be reasonably implemented.

Lining Various Portions of the Ditch

The effects of lining various portions of the Ditch along its reach across the Mesa were simulated by removing injection wells used to simulate seepage of Ditch water into the ground-water flow system. Four alternatives simulated lining the Ditch: from Aspen Street to 21st Lane; from Aspen Street to 23rd Lane; from Aspen Street to 25th Lane; and from Aspen St. to Nicholson Road (the entire Ditch across the Mesa).

The three alternatives that simulated partial lining of the Ditch resulted in partial dewatering of the terrace alluvial aquifer. All the Ditch-lining alternatives resulted in simulated maximum water-table declines of about 27 to 29 ft (figs. 13–16).

Based on the November 1997 depth-to-water contours, as the length of the simulated Ditch lining increased, the extent of the area in which the water table was simulated as being lowered also increased. Simulation of lining the Ditch from Aspen Street to 21st Lane resulted in water-table declines of slightly less than 5 ft to 27 ft in the area west of 25th Lane and south of Everett Road (fig. 13). Increases in the extent of Ditch lining caused increasingly greater simulated areas with at least 5 ft of decline in the water table (figs. 14–16). Lining the entire Ditch resulted in simulated declines in the water table of at least 5 ft in most of the modeled area (fig. 16). However, none of the Ditch-lining alternatives appear to have been effective in lowering the water table at least 5 ft throughout the entire area having a high water table north of Everett Road.

The saturated thickness of the terrace alluvial aquifer resulting from each of the Ditch-lining alternatives was compared with the initial saturated thickness of the aquifer (fig. 17). As the extent of simulated Ditch lining increased, the simulated saturated thickness in the aquifer decreased (figs. 18–20). A simulated saturated thickness map is not shown for lining the entire Ditch because model results indicate almost complete dewatering of the aquifer.

All the Ditch lining alternatives likely would result in water-table declines that could cause at least some private wells to become unusable because of aquifer dewatering, with the more extensive Ditch lining resulting in the largest number of wells becoming unusable. Wells could stop producing water if implementation of an alternative lowered the water table to a position lower than the pump intake (fig. 21).

Installation of Drains and Dewatering Wells

Alternatives were simulated to evaluate the potential effects of subsurface drains and dewatering wells on water levels in the area of the high water table on the Mesa. One alternative simulated two drains that were 10 ft below land surface (fig. 22) and the other simulated 22 dewatering wells, each pumping at 80 gal/min (0.18 ft^3/s) (fig. 23). Maximum simulated water-table declines for these two alternatives were much smaller than for the alternatives involving lining the Ditch: 6.8 ft for the drain alternative and 14.4 ft for the dewatering-well alternative.

Simulated water-table declines for the drain alternative were greatest in the vicinity of Santa Fe Drive and 25th and 27th Lanes and north of Everett Road, between 23rd and 25th Lanes (fig. 22). Existing wells in these areas would stop producing water if water-table declines were sufficient to lower the water table below the pump intakes (fig. 21).

Simulated water-table declines for the dewatering-well alternative were greater than 5 ft between 23rd and 27th Lanes and north of County Farm Road (fig. 23). This alternative for lowering the water table might cause some wells to stop producing water in the areas where the greatest simulated declines occurred: northeast of Everett Road and 23rd Lane and southeast of Santa Fe Drive and 23rd Lane.

The drain and dewatering-well alternatives were more effective in lowering the water table in the high water table areas than lining the Ditch from Aspen Street to either 21st Lane or 23rd Lane. The drain and dewatering-well alternatives were less effective in lowering the water table in the high water table areas than lining the Ditch from Aspen Street to either 25th Lane or to Nicholson Road.

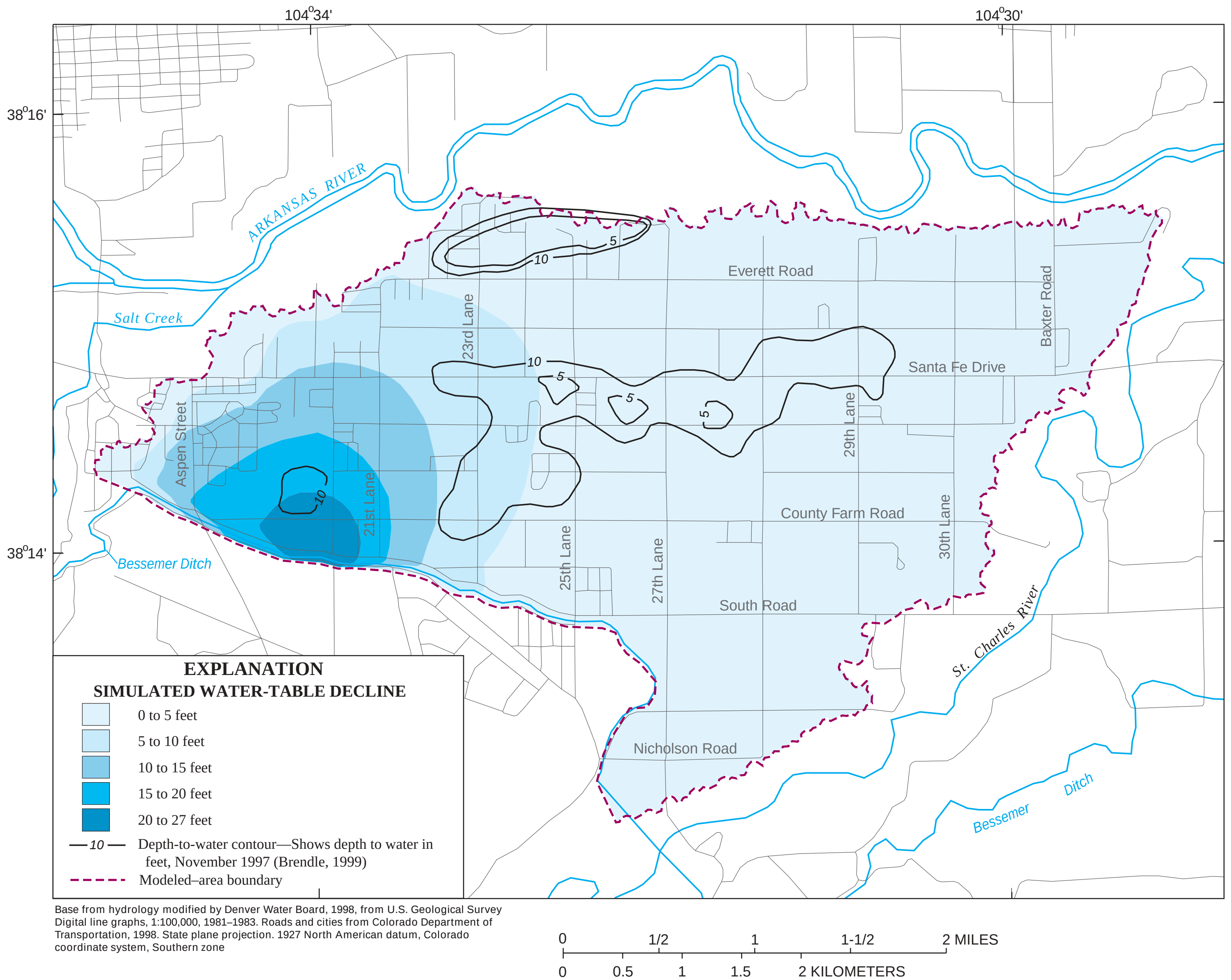
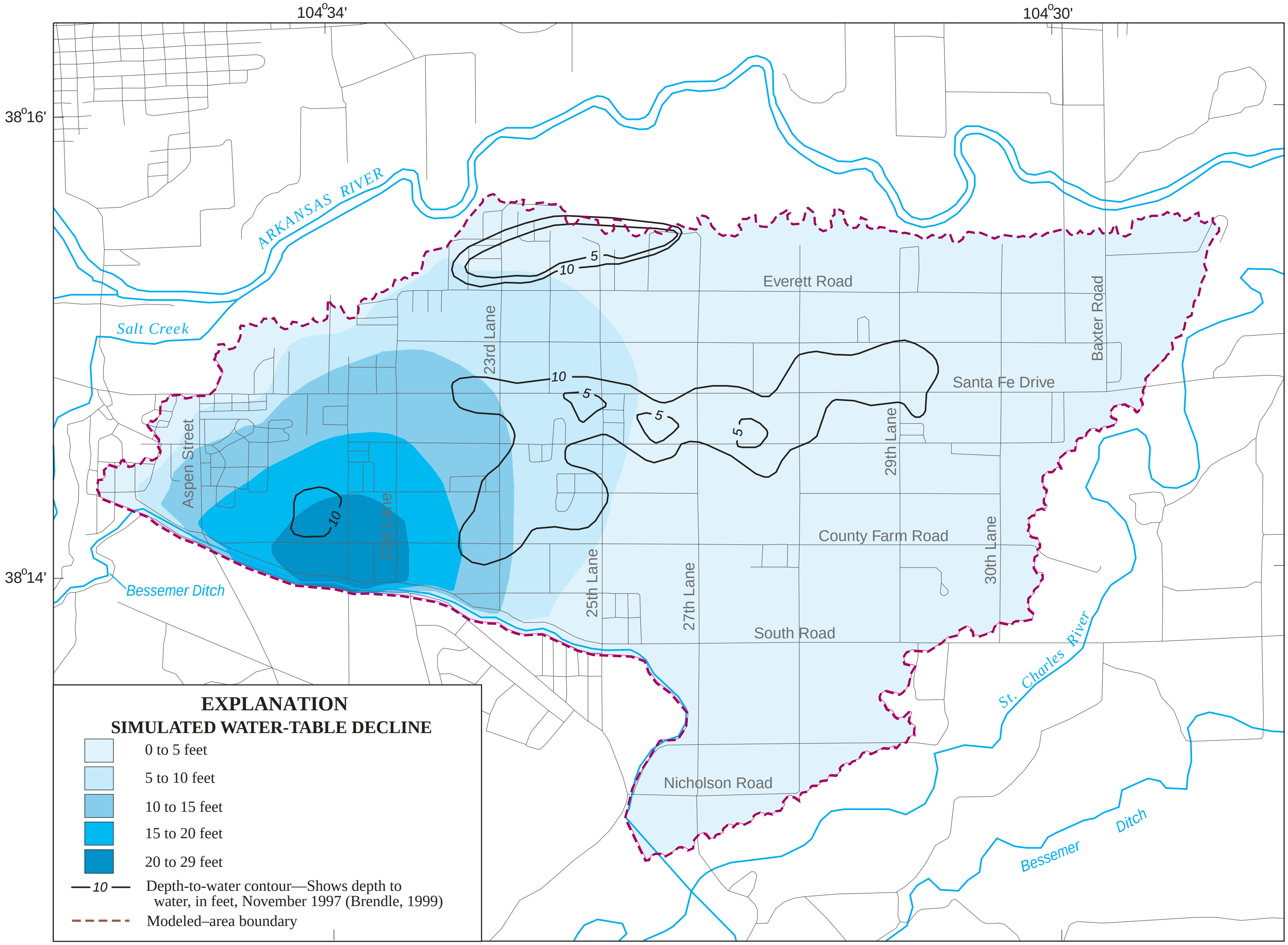


Figure 13. Simulated water-table decline in the St. Charles Mesa terrace alluvial aquifer as a result of lining the Ditch from Aspen Street to 21st Lane.



Base from hydrology modified by Denver Water Board, 1998, from U.S. Geological Survey Digital line graphs, 1:100,000, 1981–1983. Roads and cities from Colorado Department of Transportation, 1998. State plane projection. 1927 North American datum, Colorado coordinate system, Southern zone

0 1/2 1 1-1/2 2 MILES

0 0.5 1 1.5 2 KILOMETERS

Figure 14. Simulated water-table decline in the St. Charles Mesa terrace alluvial aquifer as a result of lining the Ditch from Aspen Street to 23 Lane.

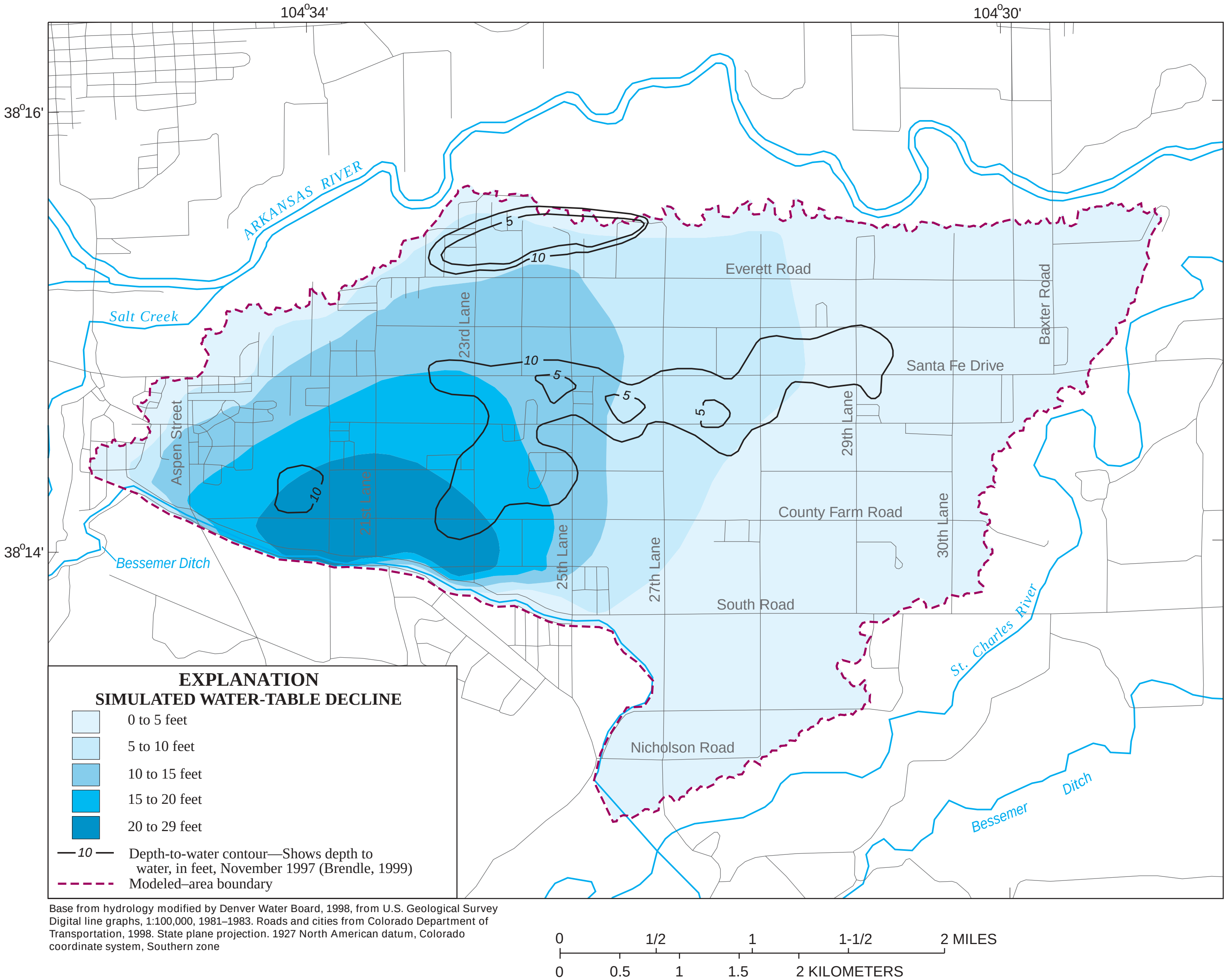
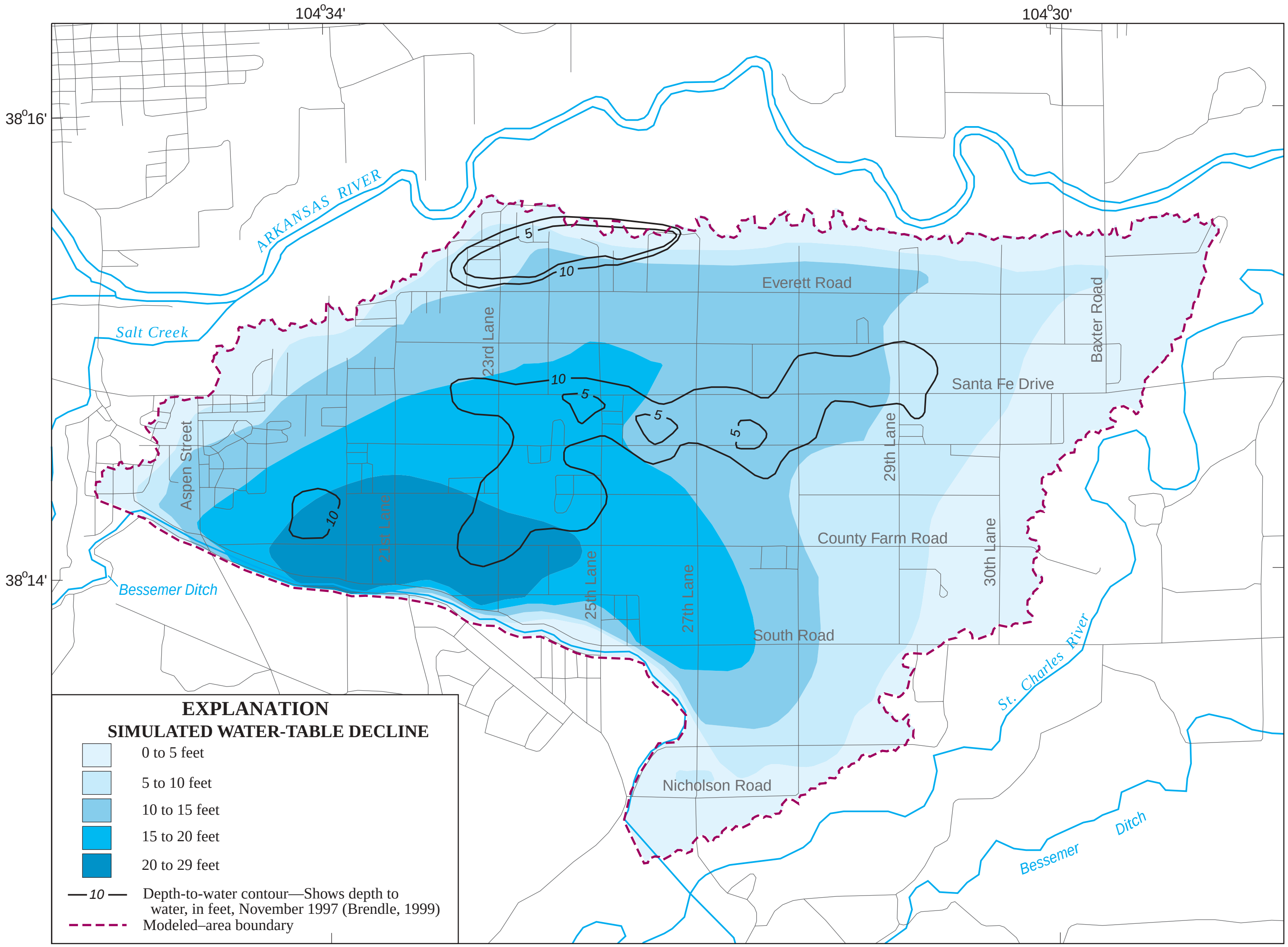


Figure 15. Simulated water-table decline in the St. Charles Mesa terrace alluvial aquifer as a result of lining the Ditch from Aspen Street to 25th Lane.

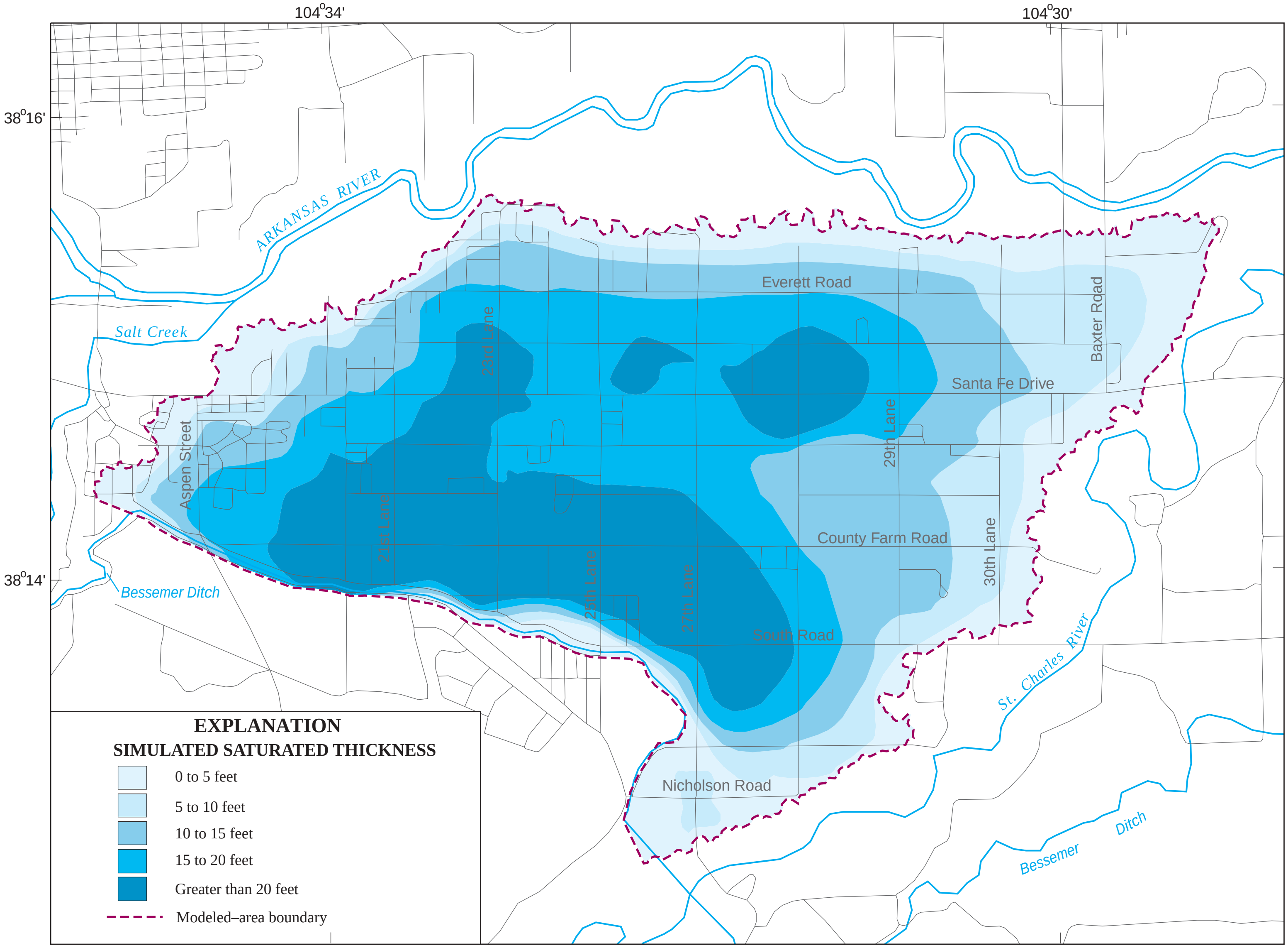


Base from hydrology modified by Denver Water Board, 1998, from U.S. Geological Survey Digital line graphs, 1:100,000, 1981–1983. Roads and cities from Colorado Department of Transportation, 1998. State plane projection. 1927 North American datum, Colorado coordinate system, Southern zone

0 1/2 1 1-1/2 2 MILES

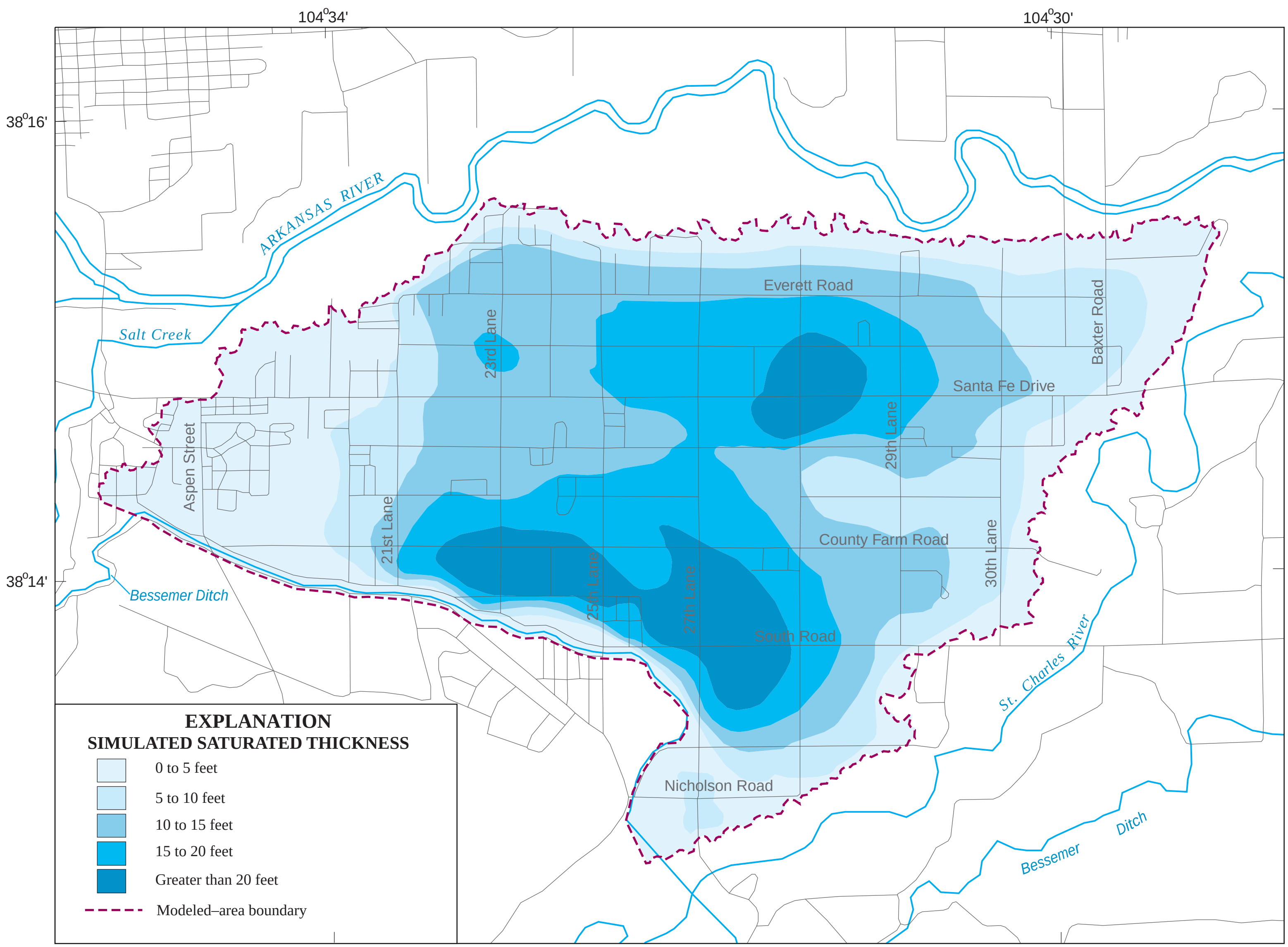
0 0.5 1 1.5 2 KILOMETERS

Figure 16. Simulated water-table decline in the St. Charles Mesa terrace alluvial aquifer as a result of lining the Ditch from Aspen Street to Nicholson Road.



Base from hydrology modified by Denver Water Board, 1998, from U.S. Geological Survey Digital line graphs, 1:100,000, 1981–1983. Roads and cities from Colorado Department of Transportation, 1998. State plane projection. 1927 North American datum, Colorado coordinate system, Southern zone

Figure 17. Simulated saturated thickness of the St. Charles Mesa terrace alluvial aquifer.

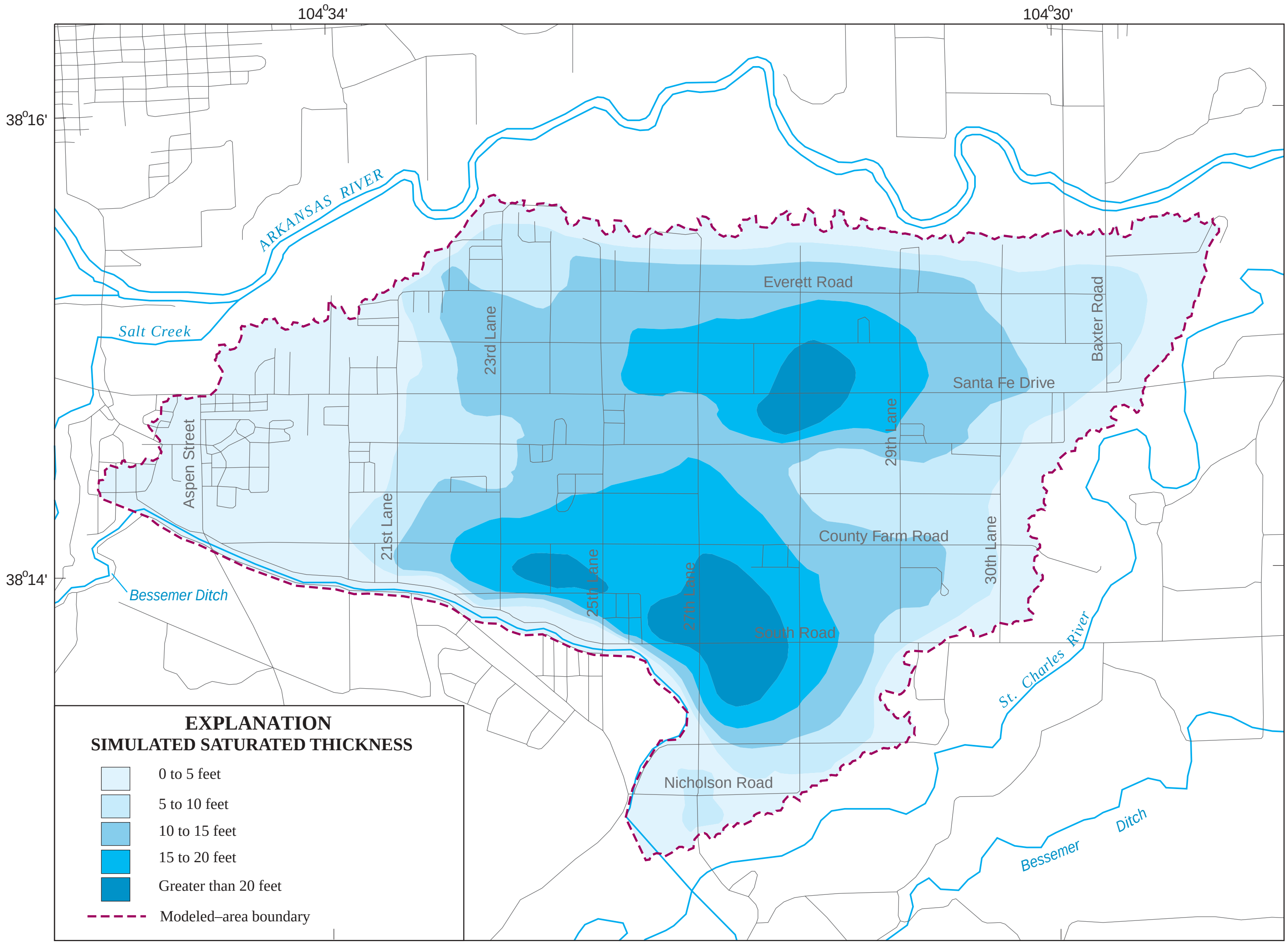


Base from hydrology modified by Denver Water Board, 1998, from U.S. Geological Survey Digital line graphs, 1:100,000, 1981–1983. Roads and cities from Colorado Department of Transportation, 1998. State plane projection. 1927 North American datum, Colorado coordinate system, Southern zone

0 1/2 1 1-1/2 2 MILES

0 0.5 1 1.5 2 KILOMETERS

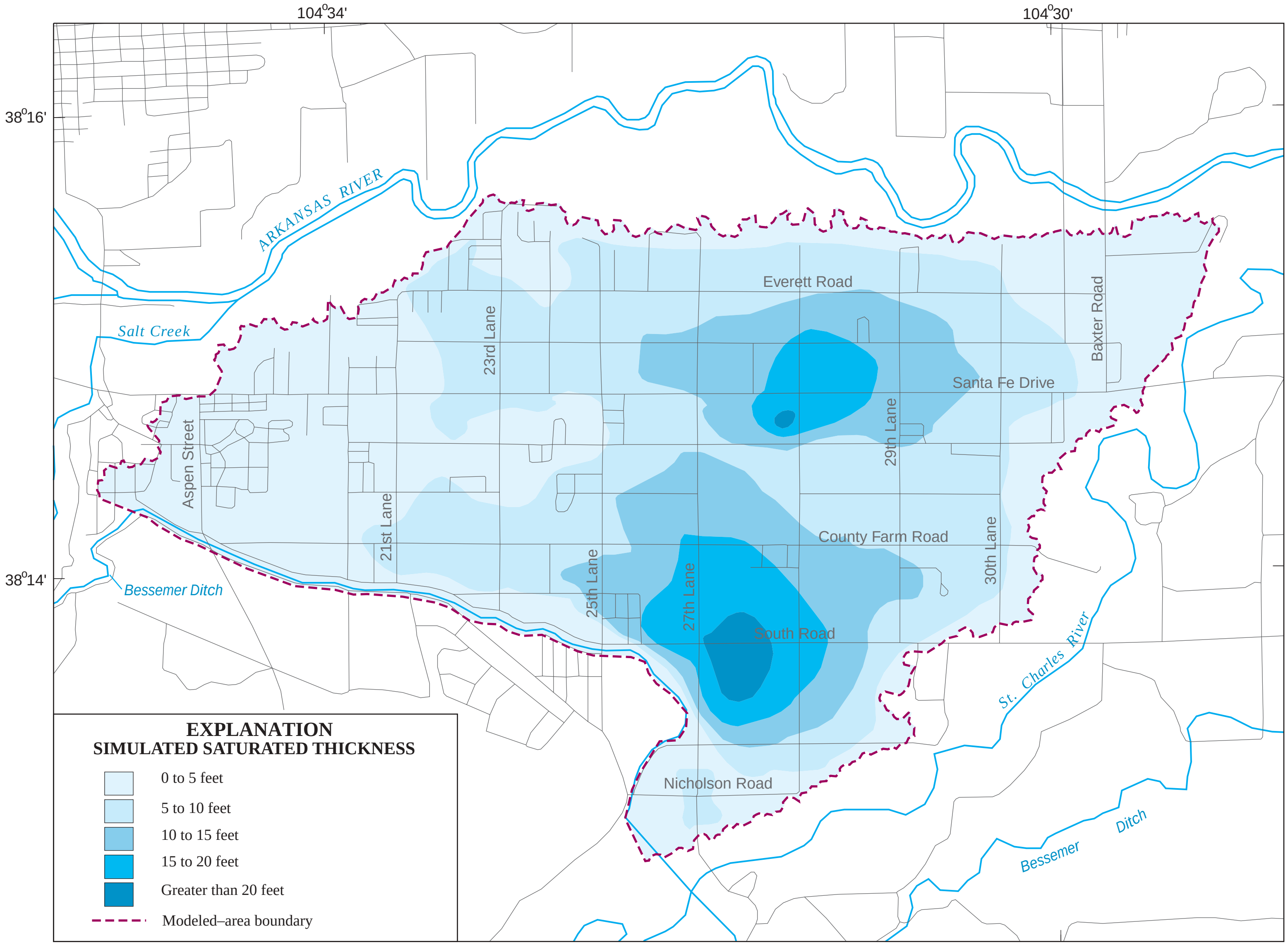
Figure 18. Simulated saturated thickness remaining in the St. Charles Mesa terrace alluvial aquifer as a result of lining the Ditch from Aspen Street to 21st Lane.



Base from hydrology modified by Denver Water Board, 1998, from U.S. Geological Survey Digital line graphs, 1:100,000, 1981–1983. Roads and cities from Colorado Department of Transportation, 1998. State plane projection. 1927 North American datum, Colorado coordinate system, Southern zone

0 1/2 1 1-1/2 2 MILES
0 0.5 1 1.5 2 KILOMETERS

Figure 19. Simulated saturated thickness remaining in the St. Charles Mesa terrace alluvial aquifer as a result of lining the Ditch from Aspen Street to 23rd Lane.



Base from hydrology modified by Denver Water Board, 1998, from U.S. Geological Survey Digital line graphs, 1:100,000, 1981–1983. Roads and cities from Colorado Department of Transportation, 1998. State plane projection. 1927 North American datum, Colorado coordinate system, Southern zone

0 1/2 1 1-1/2 2 MILES

0 0.5 1 1.5 2 KILOMETERS

Figure 20. Simulated saturated thickness remaining in the St. Charles Mesa terrace alluvial aquifer as a result of lining the Ditch from Aspen Street to 25th Lane.

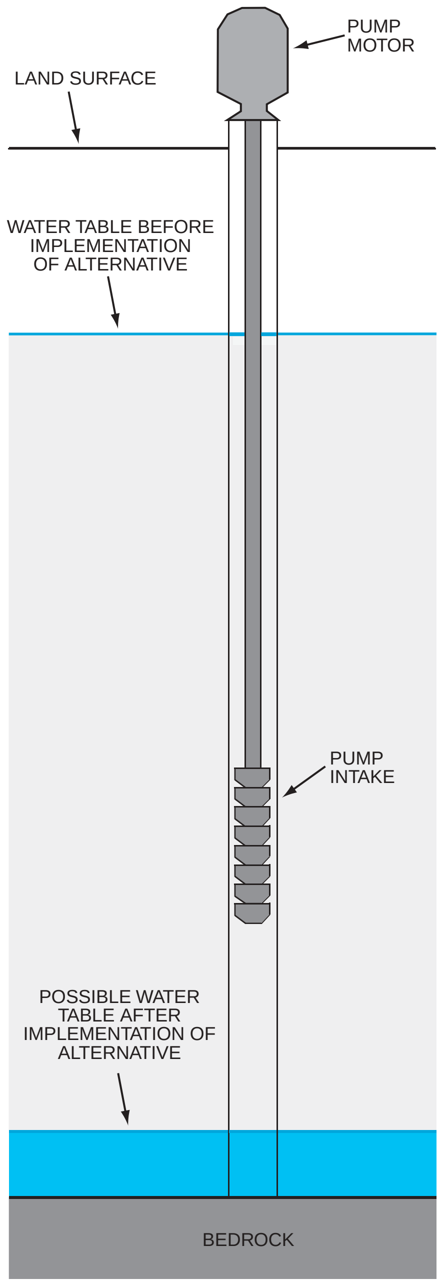


Figure 21. Relation between a pump intake and the position of the water table before and after implementation of an alternative to lower the water table.

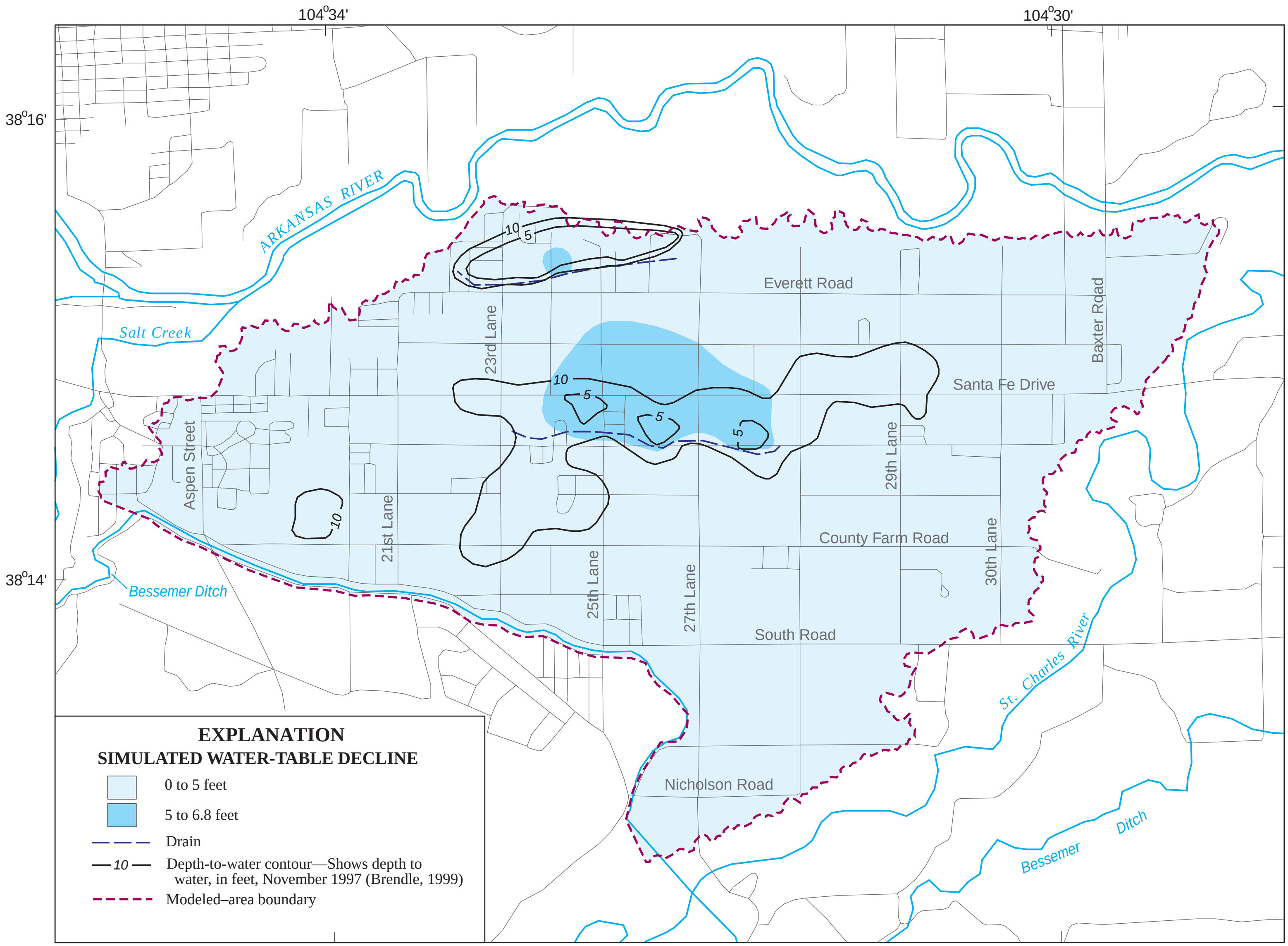
MODEL LIMITATIONS

The ground-water flow model developed for this study is useful for evaluating the ground-water flow system and potential effects of alternatives for lowering the high water table of the Mesa. The model is a simplified mathematical representation of a complex and dynamic physical system. Model cells, which represent areas approximately 300 ft by 300 ft, cannot adequately represent changes in the flow system that occur over distances of less than 300 ft, such as the cones of depression near pumping wells.

The ground-water flow system of the Mesa was modeled as a steady-state system, assuming no change in ground-water storage within a year's seasonal cycle of ground-water-level fluctuations. Calibration of the model to transient conditions would have entailed specifying the temporal variation in rates of inflow and outflow to simulate seasonal water-level fluctuations observed in the terrace alluvial aquifer. The level of detail needed to define temporal variation in inflow and outflow rates is not supported by the available data and is beyond the scope of this study.

The final water-table elevations output by the model reflect the approximate water-table elevation for each model cell that results from a particular alternative of lowering the water table and may not represent the exact water-table elevation that could occur in a small area upon implementation of a particular alternative. Model results near the steep sides of the Mesa may not accurately represent the actual ground-water flow system because water-level measurements were not available in those areas and the accuracy of the calibrated model in those areas is unknown. Because the water-table surface slopes more steeply near the northwestern, northern, and southeastern sides of the Mesa, where ground-water discharge occurs, it is difficult to accurately simulate ground-water flow and water levels in these areas.

If the assumptions used in development of this model are inaccurate—for example, if the distribution and values of hydraulic conductivity are not accurately represented in the model—then the values of other parameters modified during the calibration procedure also may be inaccurate and the model results of the alternatives for lowering the water table could overestimate or underestimate the actual effects of implementing the alternatives.

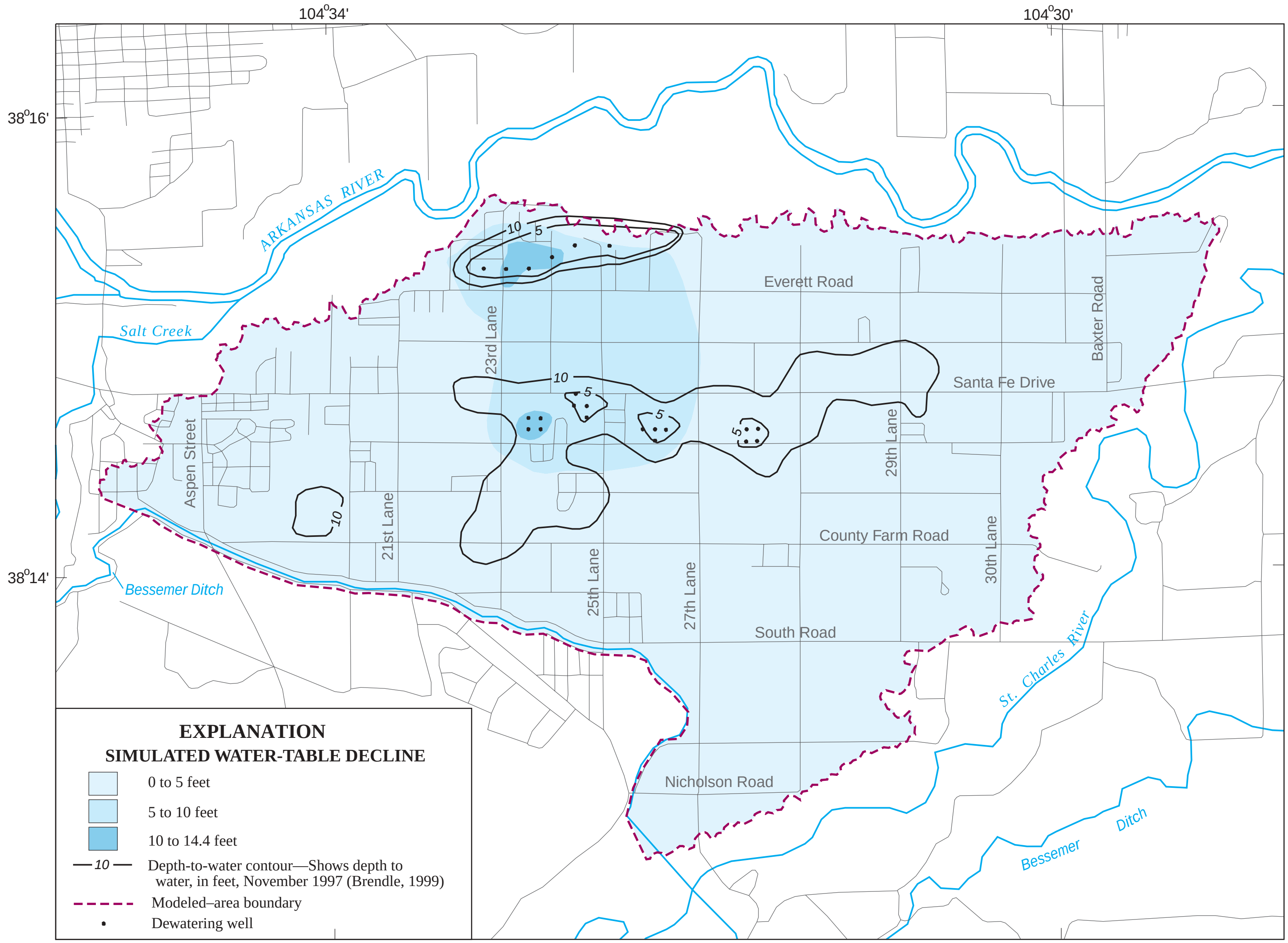


Base from hydrology modified by Denver Water Board, 1998, from U.S. Geological Survey Digital line graphs, 1:100,000, 1981–1983. Roads and cities from Colorado Department of Transportation, 1998. State plane projection. 1927 North American datum, Colorado coordinate system, Southern zone

0 1/2 1 1-1/2 2 MILES

0 0.5 1 1.5 2 KILOMETERS

Figure 22. Simulated water-table decline resulting from installation of two drains at 10 feet below land surface.



Base from hydrology modified by Denver Water Board, 1998, from U.S. Geological Survey Digital line graphs, 1:100,000, 1981–1983. Roads and cities from Colorado Department of Transportation, 1998. State plane projection. 1927 North American datum, Colorado coordinate system, Southern zone

0 1/2 1 1-1/2 2 MILES

0 0.5 1 1.5 2 KILOMETERS

Figure 23. Simulated water-table decline resulting from installation of 22 dewatering wells, each pumping at 80 gallons per minute.

SUMMARY

St. Charles Mesa is an upland terrace southeast of Pueblo, Colorado, with an area of about 10 mi^2. The water table is near the land surface in parts of the Mesa. The U.S. Geological Survey, in cooperation with Pueblo County, began a two-phase study in 1997 to define the extent of the area in which a high water table has occurred (phase 1) and to evaluate possible alternatives to lower the high water table (phase 2).

Alluvial deposits that compose the terrace alluvial aquifer on the Mesa generally are composed of sand and gravel and range in thickness from about 7 to more than 38 ft. The shale bedrock underlying the terrace alluvial aquifer has very low permeability and acts as an impermeable lower boundary to ground-water flow in the terrace alluvial aquifer.

The lateral boundaries of the Mesa are high-angle scarps on its northwestern and northern sides, a gradual slope on its southeastern side, and a topographic rise, underlain by bedrock, on its southwestern side. The northwestern, northern, and southeastern sides of the Mesa are dissected by numerous washes that commonly contain springs and seeps that discharge ground water and convey stormwater flow off the Mesa.

The hydrologic components that affect ground-water flow and storage in the terrace alluvial aquifer of the Mesa are recharge due to seepage from the Ditch and lateral ditches; recharge by infiltration of water from lawn and crop irrigation and septic-system effluent; recharge by infiltration of precipitation; discharge of ground water through springs and seeps on the northwestern, northern, and southeastern sides of the Mesa; discharge of water by evaporation or transpiration; and discharge of water by well pumpage, some of which results in discharge off the Mesa through lined drainage ditches. Seepage from the Ditch is the main source of inflow and discharge from seeps and springs is the main source of outflow from the terrace alluvial aquifer.

The ground-water flow system of the Mesa was assumed to be in a state of dynamic equilibrium (steady-state condition). Average monthly water levels, precipitation, pumpage, and Ditch diversions for June 1, 1997, through May 31, 1998, were used in model construction and calibration. The model was calibrated to the average monthly water table for June 1, 1997, through May 31, 1998, and to estimated spring and seep discharge from previous studies.

Alternatives of lowering the high water table were evaluated using the calibrated steady-state model of the ground-water flow system of the Mesa in transient mode. The modeled area was subdivided into a 98-column by 58-row grid of 300- by 300-ft cells. Several possible alternatives of lowering the water table were evaluated and included: (1) reducing areal recharge by reducing recharge to irrigated areas by 25 percent, (2) lining Bessemer Ditch from (a) Aspen Street to 21st Lane; (b) Aspen Street to 23rd Lane; (c) Aspen Street to 25th Lane; and (d) Aspen Street to Nicholson Road, (3) installing two drains at a depth of 10 feet below land surface upgradient from the high water table areas, and (4) installing 22 dewatering wells within the high water table areas, each pumping at 80 gal/min.

The alternative of reducing areal recharge in irrigated areas by 25 percent resulted in a maximum decline in the water table of about 3 ft near the northeast corner of the Mesa. The water-table declines resulting from this alternative were only about 1 ft in the areas defined as having a high water table in November 1997, and were thus considered ineffective in lowering the high water table.

Based on the November 1997 depth-to-water contours, as the simulated extent of Ditch lining increased, so did the extent of the area throughout which the water table was simulated as being lowered at least 5 ft. All the Ditch-lining alternatives resulted in simulated maximum water-table declines of about 27 to 29 ft. Simulation of lining the Ditch from Aspen Street to 21st Lane resulted in water-table declines of slightly less than 5 ft to 27 ft in the area west of 25th Lane and south of Everett Road. None of the Ditch-lining alternatives were effective in lowering the water table throughout the entire high water table area north of Everett Road. The alternative of lining the Ditch completely resulted in an almost complete dewatering of the aquifer.

All the Ditch-lining alternatives probably would result in water table declines sufficient to cause at least some private wells to become unusable because of aquifer dewatering, with the more extensive Ditch lining resulting in the most wells becoming unusable. Wells could stop producing water if the position of the water table after implementation of an alternative was lower than the pump intake.

Two additional possible alternatives to lower the high water table were evaluated: the installation of two drains at a depth of 10 ft below land surface and instal-

lation of 22 dewatering wells each pumping at 80 gal/min (0.18 ft^3/s). Maximum simulated water-table declines for these two alternatives were much smaller than for the alternatives involving lining the Ditch: 6.8 ft for the drain alternative and 14.4 ft for the dewatering-well alternative.

Simulated water-table declines for the drain alternative were greatest in the vicinity of Santa Fe Drive and 25th and 27th Lanes and north of Everett Road, between 23rd and 25th Lanes. Wells in these areas would stop producing water if water-table declines were sufficient to lower the water table below the pump intake.

Simulated water-table declines for the dewatering-well alternative were greater than 5 ft between 23rd and 27th Lanes and north of County Line Road. This alternative for lowering the water table might cause some wells to stop producing water in the areas northeast of Everett Road and 23rd Lane and southeast of Santa Fe Drive and 23rd Lane, where the greatest simulated declines occurred.

The drain and dewatering-well alternatives were more effective in lowering the water table in the high water table areas than lining the Ditch from Aspen Street to either 21st or 23rd Lanes. The drain and dewatering-well alternatives were less effective in lowering the water table in the high water table areas than lining the Ditch from Aspen Street to either 25th Lane or to Nicholson Road.

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