HYDROLOGIC EFFECTS OF PUMPAGE FROM THE DENVER BASIN BEDROCK AQUIFERS OF NORTHERN EL PASO COUNTY, COLORADO

By Edward R. Banta

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 88-4033

Prepared in cooperation with the
CITY OF COLORADO SPRINGS

Denver, Colorado
1989

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
Box 25046, Mail Stop 415
Federal Center
Denver, CO 80225-0046

Copies of this report can be purchased from:

U.S. Geological Survey
Books and Open-File Reports Section
Box 25425
Federal Center
Denver, CO 80225-0425
[Telephone: (303) 236-7476]

CONTENTS

	Page
Abstract	1
Introduction	3
Purpose and scope	3
Location of the study area	3
Acknowledgments	5
Geohydrology	5
Aquifers and confining units	5
Hydraulic characteristics of aquifers	7
Recharge and discharge	12
Water levels	15
Simulated geohydrologic system of the study area	15
Model description	19
Limitations of model results	21
Steady-state (predevelopment) model and calibration	22
Transient-state model and calibration	27
Simulated effects of future pumpage	32
Simulation SIMBASE	35
Simulation SIMGRO	46
Simulation SIMGWELL	53
Simulation SIMGWSUB	59
Simulation SIMGCITY	63
Model sensitivity	65
Summary and conclusions	77
References cited	80
Supplemental information	82

PLATES
[In pocket]

Plate 1. Maps showing altitude and configuration of the base and top of the Laramie-Fox Hills aquifer and the bases of the Arapahoe aquifer and lower Denver confining unit in the Denver basin, Colorado.

2. Maps showing altitude and configuration of the base of the Dawson aquifer, model grid and locations of features simulated, areas where aquifers are initially (1985) simulated as unconfined, differences between model-calculated steady-state hydraulic heads and measured hydraulic heads used for model calibration, and model-derived recharge from precipitation to the bedrock aquifers in the Denver basin, Colorado.

3. Maps showing simulated 1985 potentiometric surfaces for the bedrock aquifers in the Denver basin, Colorado.

4. Maps showing simulated 2085 potentiometric surfaces and 1985-2085 drawdowns for the bedrock aquifers for model simulation SIMBASE in the Denver basin, Colorado.

5. Maps showing simulated 2085 potentiometric surfaces and 1985-2085 drawdowns for the bedrock aquifers for model simulation SIMGRO in the Denver basin, Colorado.

FIGURES

Page

Figures 1-7. Maps showing:
1. Location of study area------------------------------------ 4
2. Transmissivity of the Laramie-Fox Hills aquifer in the southern part of the Denver basin---------------------- 8
3. Transmissivity of the Arapahoe aquifer in the southern part of the Denver basin---------------------------------- 10
4. Potentiometric surface for the Laramie-Fox Hills aquifer in the southern part of the Denver basin, 1985--------- 14
5. Potentiometric surface for the Arapahoe aquifer in the southern part of the Denver basin, 1985---------------- 16
6. Potentiometric surface for the Denver aquifer in the southern part of the Denver basin, 1985---------------- 18
7. Potentiometric surface for the Dawson aquifer in the southern part of the Denver basin, 1985---------------- 20

8. Graph showing mean square error for eight sequential steady-state model runs---------------------------------- 24

9-28. Hydrographs showing model-calculated heads for simulations SIMBASE and SIMGRO at:
9. Model node (46,14,1)------------------------------------ 36
10. Model node (46,31,1)------------------------------------ 36
11. Model node (54,15,1)------------------------------------ 37
12. Model node (58,14,1)------------------------------------ 37
13. Model node (59,22,1)------------------------------------ 38
14. Model node (49,14,2)------------------------------------ 38
15. Model node (49,26,2)------------------------------------ 39
16. Model node (52,15,2)------------------------------------ 39
17. Model node (57,15,2)------------------------------------ 40
18. Model node (58,19,2)------------------------------------ 40
19. Model node (46,23,3)------------------------------------ 41
20. Model node (47,13,3)------------------------------------ 41
21. Model node (52,16,3)------------------------------------ 42
22. Model node (55,19,3)------------------------------------ 42
23. Model node (58,16,3)------------------------------------ 43
24. Model node (46,13,4)------------------------------------ 43
25. Model node (46,19,4)------------------------------------ 44
26. Model node (50,24,4)------------------------------------ 44
27. Model node (51,17,4)------------------------------------ 45
28. Model node (53,16,4)------------------------------------ 45

29. Graph showing simulated discharge to alluvial aquifer and surface water in Monument Creek basin for simulation SIMGRO-- 49

30. Graph showing simulated discharge to alluvial aquifer and surface water in Black Squirrel Creek basin for simulation SIMGRO-- 49

31-39. Maps showing simulated head difference for 2085 between simulations:
31. SIMGWELL and SIMGRO for the Laramie-Fox Hills aquifer---- 50
32. SIMGWELL and SIMGRO for the Arapahoe aquifer------------- 52
33. SIMGWELL and SIMGRO for the Denver aquifer--------------- 54
34. SIMGWSUB and SIMGRO for the Laramie-Fox Hills aquifer---- 56
35. SIMGWSUB and SIMGRO for the Arapahoe aquifer------------- 58

Page

Figures 31-39. Maps showing simulated head difference for 2085 between simulations--Continued:
36. SIMGWSUB and SIMGRO for the Denver aquifer-------------- 60
37. SIMGCITY and SIMGRO for the Laramie-Fox Hills aquifer---- 62
38. SIMGCITY and SIMGRO for the Arapahoe aquifer------------ 64
39. SIMGCITY and SIMGRO for the Denver aquifer-------------- 66
40-42. Graphs showing:
40. Effects of transmissivity variations on mean square error and discharge to Monument Creek and Black Squirrel Creek basins--------------------------------- 68
41. Effects of vertical-conductance variations on mean square error and discharge to Monument Creek and Black Squirrel Creek basins--------------------------- 69
42. Effects of variations in recharge from precipitation on mean square error and discharge to Monument Creek and Black Squirrel Creek basins----------------------- 69
43-48. Hydrographs showing effect of changes in storage property on simulated head at:
43. Model node (46,14,1)------------------------------------ 71
44. Model node (49,14,2)------------------------------------ 71
45. Model node (47,13,3)------------------------------------ 72
46. Model node (46,19,4)------------------------------------ 72
47. Model node (54,15,1)------------------------------------ 73
48. Model node (57,15,2)------------------------------------ 73
49. Hydrograph showing effect of changes in maximum constant-head leakage rate on simulated head at model node (54,15,1)-- 74
50. Hydrograph showing effect of changes in maximum constant-head leakage rate on simulated head at model node (46,19,4)-- 74
51-53. Hydrographs showing effect of changes in simulated pumpage from the northern part of the Denver basin on simulated head at:
51. Model node (46,14,1)------------------------------------ 75
52. Model node (49,14,2)------------------------------------ 75
53. Model node (46,23,3)------------------------------------ 76
54. Hydrograph showing effect of changes in rate of recharge from precipitation on simulated head at model node (47,13,3), where aquifer is deeply buried---------------- 76
55. Hydrograph showing effect of changes in rate of recharge from precipitation on simulated head at model node (46,19,4), where aquifer outcrops------------------------ 77

TABLES

Page

Table 1. Generalized correlation of geologic units, geohydrologic units, and equivalent layers in the Denver basin digital model-- 6
2. Estimated vertical hydraulic conductivity of confining units 25
3. Steady-state (predevelopment) ground-water budget----------- 26

Page

Table 4. Steady-state (predevelopment) flow rates to or from bedrock aquifers in Monument Creek and Black Squirrel Creek basins 26
5. Simulated pumping rates during the three pumping periods of the transient-state calibration, 1958 to 1978---------- 28
6. Simulated 1985 flow rates to or from bedrock aquifers in Monument and Black Squirrel Creeks basins----------------- 30
7. 1985 ground-water budget------------------------------------- 31
8. Summary of predictive simulations--------------------------- 34
9. 2085 ground-water budget for simulation SIMBASE------------- 46
10. 2085 ground-water budget for simulation SIMGRO-------------- 51
11. 2085 ground-water budget for simulation SIMGWELL------------ 57
12. 2085 ground-water budget for simulation SIMGWSUB------------ 61
13. 2085 ground-water budget for simulation SIMGCITY------------ 67

CONVERSION FACTORS

For the convenience of readers who may prefer to use metric (International System) units rather than the inch-pound units in this report, values may be converted by using the following factors:

Multiply inch-pound unit	*By*	*To obtain metric unit*
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
cubic foot per second (ft^3/s)	0.028317	cubic meter per second
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer
foot (ft)	0.3048	meter
foot per day (ft/d)	0.0003528	centimeter per second
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per day (gal/d)	3.785	liter per day
gallon per year (gal/yr)	3.785	liter per year
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer

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

HYDROLOGIC EFFECTS OF PUMPAGE FROM THE DENVER BASIN BEDROCK AQUIFERS OF NORTHERN EL PASO COUNTY, COLORADO

By Edward R. Banta

ABSTRACT

The Denver ground-water basin underlies a 6,700-square-mile area that extends from the Front Range to Limon and from Greeley to Colorado Springs in eastern Colorado. The Laramie-Fox Hills, Arapahoe, Denver, and Dawson aquifers are, in ascending order, the four major bedrock aquifers that yield water to wells in the Denver basin. Water-yielding materials are composed of permeable conglomerate, sandstone, and siltstone of Cretaceous and Tertiary age. The water-yielding materials commonly are interbedded with low permeability shale. Thicker intervals of shale form regional confining units between the aquifers.

Anticipated increases in withdrawals from the bedrock aquifers in the southern part of the Denver basin have created a need for a quantitative geohydrologic appraisal of the current conditions of these bedrock aquifers. In particular, the relation of pumpage to recent and likely future water-level changes and the interactions between the bedrock aquifers and alluvial aquifers and surface water needed to be evaluated. Water levels, streamflow gain and loss, and other data were collected. Ground-water flow was analyzed with the aid of a digital finite-difference model. The model also was used to make predictive, 100-year simulations of the response of the aquifers to several possible future pumping scenarios.

Results of modeling indicated that prior to development, when the system was in a long-term, steady-state condition, recharge to, and discharge from, the bedrock aquifers were each about 59 cubic feet per second. About 90 percent of this flow is estimated to have been supplied by recharge from precipitation; the rest was recharged from streams and alluvial aquifers. In the part of El Paso County underlain by the southern part of the Denver ground-water basin, the drainage basins of two creeks, Monument and Black Squirrel Creeks, are of major hydrologic importance. In the simulated predevelopment condition, net discharge to Monument Creek basin was about 6.1 cubic feet per second, and net discharge to the Black Squirrel Creek basin was about 1.7 cubic feet per second.

Water levels in the bedrock aquifers in El Paso County were measured during 1985. Water-level changes between 1978 and 1985, likely caused by variations in precipitation and in pumping and by lowering of the water table in the overlying Black Squirrel Creek alluvial aquifer, ranged from rises of more than 40 feet to declines of as much as 80 feet.

In 1985, pumping from the bedrock aquifers was about 56 cubic feet per second, or about 94 percent of the simulated total predevelopment inflow and outflow. About 43 percent of the water simulated as pumped came from a decline in volume of ground water in storage; about 37 percent came from induced recharge and captured discharge. The remaining 20 percent came from a transient high rate of recharge from precipitation. Total simulated inflow and outflow were each about 103 cubic feet per second. By 1985, simulated net discharge rates to the Monument Creek and Black Squirrel Creek basins had declined slightly.

Five simulations of possible future aquifer conditions that could result from various pumping scenarios over a 100-year period beginning in 1985 were made. The first of these simulations indicates minimal drawdowns for constant pumping at 1985 rates in the southern part of the basin.

In the other four simulations, increasing pumping, at rates that would supply projected population growth in the vicinity of Colorado Springs with water needs, was simulated. All four simulations indicate that the required pumpage would be accompanied by large drawdowns and large decreases in quantity of ground water in storage in the aquifers; most of the water pumped would be supplied by withdrawal of water in storage. For all the simulations during which pumping was increased at the rate required to supply the projected population growth, net discharge to Monument Creek and Black Squirrel Creek basins greatly declined; eventually net recharge was induced.

If pumpage is distributed as the growing population is projected to be distributed, drawdowns of as much as 1,300 feet after 100 years are predicted by the model; drawdowns would be largest in the lower aquifers in the areas of most intensive pumping. Some dewatering of the aquifers also is predicted.

A hypothetical well field, superimposed on the pattern of increasing pumpage and pumping at about 16 cubic feet per second from the lower three aquifers in north-central El Paso County, would produce incremental drawdowns of as much as 100 feet in the Laramie-Fox Hills aquifer, 150 feet in the Arapahoe aquifer, 200 feet in the Denver aquifer, and less than 5 feet in the Dawson aquifer after 60 years. By using the hypothetical well field for part of the pumpage in those areas where suburban demand would likely be largest, drawdown and consequent dewatering of the aquifers in the populated areas may be alleviated substantially.

Alternatively, similarly superimposed simulated pumping of about 20 cubic feet per second from the three lower aquifers, where they underlie Colorado Springs, would result in incremental drawdowns that would be as much as 200 feet in the Laramie-Fox Hills and Arapahoe aquifers, and 100 feet in the Denver aquifer. Some dewatering of the Arapahoe and Denver aquifers in and near Colorado Springs also would result from such pumpage.

INTRODUCTION

Recent and projected population growth in Colorado Springs, Colo., and vicinity has led local public officials to express concern regarding the adequacy of public water supplies for the area in the next several decades. Growth of local industries, in particular the aerospace and related high-technology industries, has spurred speculation among land developers. Housing developments and military, commercial, and industrial installations, which would be at least partly dependent on ground water, have been proposed. Local officials have responded by helping to initiate studies designed to aid in making decisions related to the use of water resources. The U.S. Geological Survey, in cooperation with the City of Colorado Springs, began a study in 1985 to quantitatively appraise the geohydrology of the Denver basin bedrock-aquifer system--the bedrock aquifers and their associated confining units. Particular emphasis was on the southern part of the basin, including the areas of El Paso, Douglas, and Elbert Counties that might be affected by population growth and consequent ground-water development in Colorado Springs, its suburbs, and nearby communities.

A previous study of the Denver basin bedrock aquifers is documented in Robson and Romero (1981a; 1981b), Robson and others (1981a), Robson and others (1981b), and Robson (1983), culminating in a quantitative appraisal of the system (Robson, 1984; 1987). Robson (1984) described a digital ground-water flow model developed for the Denver basin bedrock-aquifer system; in many ways, his work forms the framework for this study. To avoid extensive duplication of work, the present study has been developed from the results published in these previous reports and provides a current (1986) analysis utilizing a refined model capable of more detail in the Colorado Springs area than was possible by using Robson's (1984) model.

Purpose and Scope

The purpose of this study was to evaluate the current geohydrologic conditions in the bedrock aquifers in El Paso and neighboring counties and to simulate, using this information and an updated version of Robson's (1984) model, the response of water levels in the aquifers to various rates and distributions of pumping. The scope of the work included measuring water levels in wells, compilation and analysis of aquifer-property data, measuring gain and loss in streamflow, and digital modeling of ground-water flow in the bedrock-aquifer system. This report discusses findings made from January 1985 through December 1986.

Location of the Study Area

The area of greatest interest is in El Paso and neighboring counties to the north, where the southernmost part of the Denver ground-water basin lies (fig. 1). However, for modeling purposes and to make the report useful to as large an audience as possible, the study area includes the entire Denver ground-water basin, which covers an area of approximately 6,700 mi^2. The basin extends from near Greeley in the north to Colorado Springs in the south and from the foothills of the Front Range in the west to near Limon in the

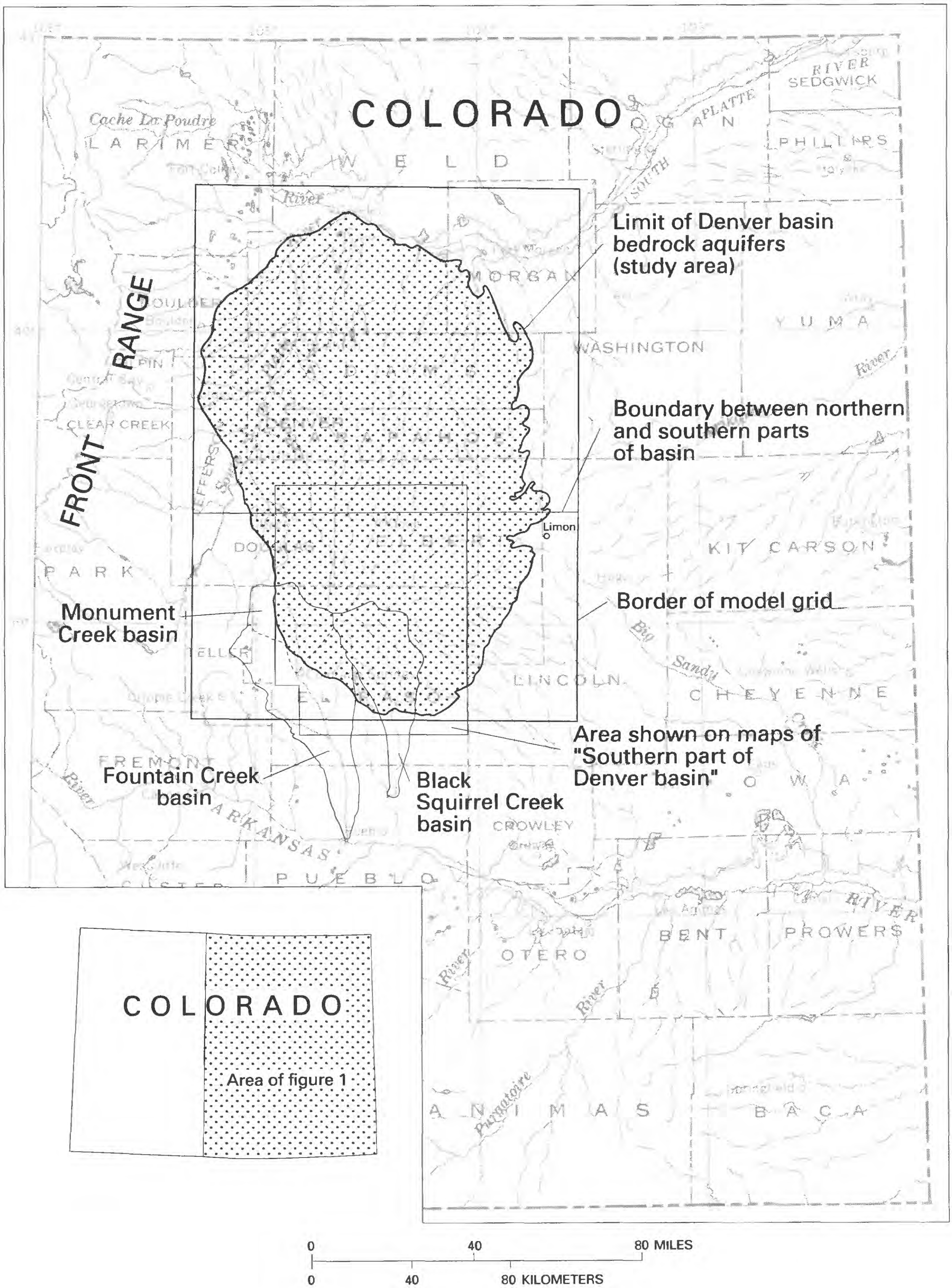

Figure 1.--Location of study area.

east (fig. 1). Some of the figures and tables in this report apply only to the southern part of the Denver basin, in accordance with the purposes of the project. For these purposes, the basin is divided into a northern and a southern part by an east-west line passing through the town of Castle Rock.

Acknowledgments

Appreciation is given to P.C. Saletta of the City of Colorado Springs for help in assembling names and addresses of water suppliers and for data used in this study, to S.G. Robson of the U.S. Geological Survey for guidance in many phases of the data analysis and modeling processes, and to the water suppliers who provided pumpage information.

GEOHYDROLOGY

The Denver basin bedrock-aquifer system consists of the sequence of consolidated, clastic Cretaceous and Tertiary sedimentary rocks overlying the Cretaceous Pierre Shale in the Denver ground-water basin. The less permeable layers in these rocks form natural divisions between the more permeable materials. Three thick sequences of the less permeable rocks have been designated as confining units and divide the bedrocks overlying the Pierre into the four aquifers discussed in this report: the Laramie-Fox Hills, the Arapahoe, the Denver, and the Dawson aquifers. Much of the material discussed in this section is described in more detail in Robson (1983; 1984).

Aquifers and Confining Units

The Laramie-Fox Hills aquifer is the lowermost of the four bedrock aquifers studied (table 1); it consists of the Cretaceous Fox Hills Sandstone and the lower part of the overlying Cretaceous Laramie Formation. In some places, the upper 100 to 200 ft of the Pierre Shale contain relatively coarse-grained layers. These layers represent a transition between marine shale, which dominates the Pierre, and terrestrial deposits, which form the Fox Hills Sandstone and overlying formations. Where these coarse-grained layers of the Pierre are likely to be permeable, they are included in the Laramie-Fox Hills aquifer. The Fox Hills Sandstone is predominantly sandstone with some siltstone and a few shale beds. The lower part of the Laramie Formation is sandstone, interbedded with some siltstone and shale. The overall thickness of the Laramie-Fox Hills aquifer generally ranges from 200 to 300 ft. The thickness of water-yielding materials (sandstone and siltstone) generally ranges from 100 to 250 ft. The upper part of the Laramie Formation forms the upper confining unit for the Laramie-Fox Hills aquifer, and it will be called the Laramie confining unit in this report. It is 400 to 500 ft thick, and it is mostly shale, interbedded with coal and some siltstone and sandstone. The massive shale beds of the Pierre exceed 5,000 ft in thickness and are considered to form an effective lower confining unit for the Denver basin bedrock-aquifer system.

Table 1.--*Generalized correlation of geologic units, geohydrologic units, and equivalent layers in the Denver basin digital model*

System	Geologic unit	Geohydrologic unit of Robson (1984; 1987)	Geohydrologic unit (this report)	Equivalent layer in digital flow model
TERTIARY	Dawson Arkose (Also designated Cretaceous by some authors)	Dawson aquifer	Dawson aquifer	4
TERTIARY	Denver Formation	Denver aquifer	Upper Denver confining unit	*
			Denver aquifer	3
CRETACEOUS			Lower Denver confining unit	*
	Arapahoe Formation	Arapahoe aquifer	Arapahoe aquifer	2
	Laramie Formation	Confining unit	Laramie confining unit	*
	Fox Hills Sandstone	Laramie-Fox Hills aquifer	Laramie-Fox Hills aquifer	1
	Pierre Shale	Where permeable	Where permeable	
		Basal confining unit	Basal confining unit	Not represented in model

*Simulated as a membrane which has vertical conductance, but neither thickness nor horizontal permeability.

The Cretaceous Arapahoe Formation ranges in thickness from 400 to 700 ft, overlies the Laramie Formation, and forms the Arapahoe aquifer. It consists of interbedded conglomerate, sandstone, siltstone, and shale. Shale is less prevalent in the southern part of the basin. Water-yielding conglomerate, sandstone, and siltstone generally make up 200 to 300 ft of the overall thickness of the aquifer.

The Denver aquifer is found in approximately the middle one-third of the Cretaceous and Tertiary Denver Formation. The Denver Formation generally ranges in thickness from 600 to 1,000 ft and overlies the Arapahoe Formation. The upper one-third and lower one-third of the Denver Formation are predominantly shale; whereas, the middle one-third consists of interbedded shale, claystone, siltstone, and sandstone. The predominantly shale intervals are the major confining units between the Denver aquifer and the adjacent aquifers. The basal shale interval in the Denver Formation is called the lower Denver confining unit in this report; it separates the Denver aquifer from the underlying Arapahoe aquifer. The shale interval at the top of the Denver Formation is called the upper Denver confining unit in this report; it separates the Denver aquifer from the overlying Dawson aquifer. The thickness of water-yielding siltstone and sandstone in the Denver aquifer generally ranges from 100 to 300 ft.

The Tertiary Dawson Arkose (also designated Cretaceous by some authors) generally ranges in thickness from 200 to 900 ft, overlies the Denver Formation, and forms the Dawson aquifer. The Dawson Arkose consists of interbedded conglomerate, sandstone, and shale. Water-yielding conglomerate and sandstone range in thickness from 100 to 400 ft.

Previously published maps showing altitude and configuration of top and base for the various aquifers (Robson and Romero, 1981a; 1981b; Robson and others, 1981a; and Robson and others, 1981b) were revised, based on onsite geological mapping done by S.G. Robson (U.S. Geological Survey, written commun., 1985) in the vicinity of the U.S. Air Force Academy. The revised maps are shown on plates 1 and 2. The differences between the previously published maps and the revised maps are greatest near the Air Force Academy; no changes were made to the maps at distances farther than 30 mi from the Academy.

Hydraulic Characteristics of Aquifers

Lateral hydraulic conductivity, transmissivity, storage coefficient or specific yield, and vertical hydraulic conductivity are the aquifer properties most relevant in analyzing the hydraulics of an aquifer system. Hydraulic conductivity is the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow (Lohman and others, 1972). Transmissivity is the product of hydraulic conductivity and aquifer thickness; therefore, it is characteristic of the entire thickness of an aquifer at a given geographic location. The terms storage coefficient and specific yield are related in that they are measures of how much water is released from, or goes into, storage in the aquifer material as the hydraulic head in the aquifer changes. In the remainder of this report, the shorter term "head" is used

Figure 2.--Transmissivity of the Laramie-Fox Hills aquifer in the southern part of the Denver basin.

EXPLANATION

— 70 — LINE OF EQUAL TRANSMISSIVITY--Values in feet squared per day. Interval is variable

_____ APPROXIMATE LIMIT OF THE LARAMIE-FOX HILLS AQUIFER

• DATA LOCATION--Data from Robson (1983)

o DATA LOCATION--Data from W.C. Wells and Company, written communication, 1985, or Bishop, Brogden, and Rumph, Inc., 1985

in place of "hydraulic head." Storage coefficient is the volume of water released by an aquifer per unit surface area per unit change in head. Specific yield is the ratio of volume of water yielded to the volume of aquifer material drained. Storage coefficient is used where an aquifer is confined; that is, where the water level in a well completed in the aquifer would rise above the bottom of a relatively impermeable layer immediately overlying the aquifer. Specific yield is used where an aquifer is unconfined; that is, where no relatively impermeable layer restricts the upward flow of water, as is the case in a confined aquifer. When the head in an unconfined aquifer is lowered, as by pumping a well, virtually all water released from storage comes from partial draining by gravity of the interstitial pores in the aquifer material. In contrast, when the head in a confined aquifer is lowered, water is released from storage by compression of the rock matrix and by expansion of the water. Much more water is yielded by gravity drainage of pores than by expansion of water and compression of the rock matrix. Areas where aquifers are unconfined, as of 1985, are shown on plate 2. In some areas, the unconfined part of the Denver aquifer overlies areas where drawdown has created unconfined conditions in the Arapahoe aquifer. In these areas, the Denver aquifer can be considered as locally perched.

Lateral hydraulic-conductivity values calculated from aquifer tests and laboratory measurements of the water-yielding materials in the Laramie-Fox Hills aquifer range from 0.01 to 7.2 ft/d; in the Arapahoe aquifer, from 0.002 to 10 ft/d; in the Denver aquifer, from 0.01 to 8.5 ft/d; and in the Dawson aquifer, from 0.01 to 6.2 ft/d (Robson, 1983). Hydraulic-conductivity data (W.C. Wells and Company, written commun., 1985; Bishop, Brogden, and Rumph, Inc., 1985) collected since Robson's (1983) report are in the ranges expected, based on areas delineated on Robson's (1983) maps. Values for vertical hydraulic conductivity of the confining units separating the aquifers are given in the section "Simulated Geohydrologic System of the Study Area" because they are derived from calibration of the steady-state model.

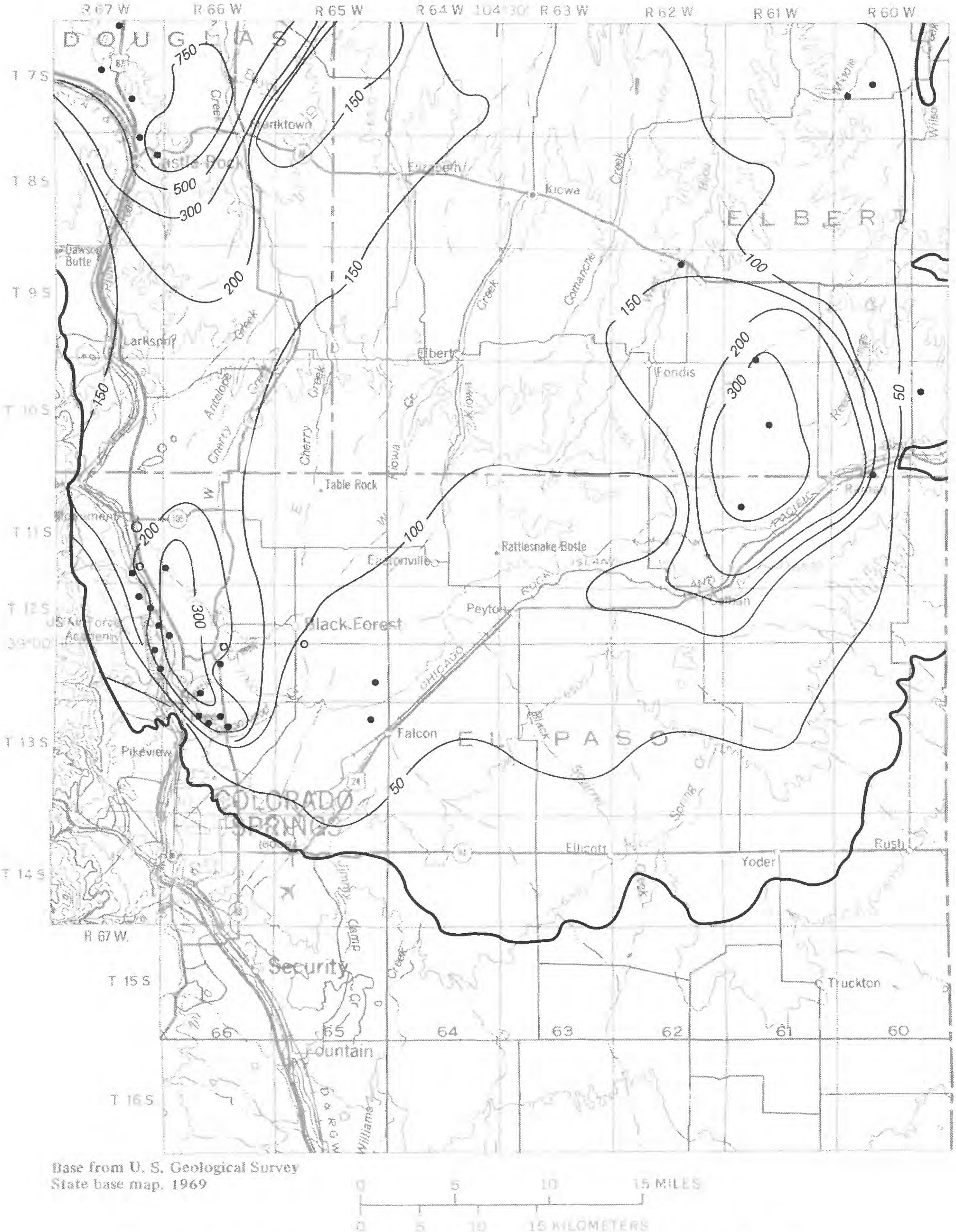

Figure 3.--Transmissivity of the Arapahoe aquifer in the southern part of the Denver basin.

EXPLANATION

— 50 — **LINE OF EQUAL TRANSMISSIVITY--Values in feet squared per day. Interval is variable**

——— **APPROXIMATE LIMIT OF THE ARAPAHOE AQUIFER**

• **DATA LOCATION--Data from Robson (1983)**

○ **DATA LOCATION--Data from W.C. Wells and Company, written communication, 1985, or Bishop, Brogden, and Rumph, Inc., 1985**

Transmissivity values, based on aquifer tests and laboratory analyses of the water-yielding materials, are as much as about 1,000 ft^2/d for the Laramie-Fox Hills aquifer, about 2,100 ft^2/d for the Arapahoe aquifer, about 400 ft^2/d for the Denver aquifer, and about 1,200 ft^2/d for the Dawson aquifer. Transmissivity for each aquifer diminishes to zero at the aquifer limit. No new transmissivity data for the Dawson aquifer have become available since Robson's (1983) report; however, new data for the other aquifers have become available. The computed transmissivity from one aquifer test in the Denver aquifer (W.C. Wells and Company, written commun., 1985) is in the range expected, based on Robson's (1983) map. Transmissivities from four aquifer tests in the Arapahoe aquifer and three in the Laramie-Fox Hills aquifer (W.C. Wells and Company, written commun., 1985; Bishop, Brogden, and Rumph, Inc., 1985) require that minor modifications be made to the previously published transmissivity maps (Robson, 1983). Maps showing the revised transmissivity values for the Laramie-Fox Hills and Arapahoe aquifers are shown in figures 2 and 3.

Storage-coefficient values used in the model were computed as the product of the thickness of the water-yielding material in each aquifer and average specific storage, which was derived from the porosity and compressibility of the rock (Robson, 1983). Estimated storage coefficients range from about 2×10^{-4} to about 4×10^{-4} for the Laramie-Fox Hills aquifer, from about 2×10^{-4} to about 8×10^{-4} for the Arapahoe aquifer, from about 4×10^{-4} to about 6×10^{-4} for the Denver aquifer, and from about 2×10^{-4} to about 8×10^{-4} for the Dawson aquifer. Specific-yield values for the water-yielding materials, derived from Robson (1987), average 20 percent and range from 4.8 to 38 percent for the Laramie-Fox Hills aquifer, average 18 percent and range from 3.3 to 33 percent for the Arapahoe aquifer, average 14 percent and range from 0.2 to 29 percent for the Denver aquifer, and average 18 percent and range from 3.6 to 34 percent for the Dawson aquifer.

Recharge and Discharge

Precipitation in the study area ranges from 11 to 18 in/yr and averages 14 in/yr (Robson, 1984). This precipitation supplies most of the recharge to the bedrock aquifers either by percolating directly into the aquifers in outcrop areas (pl. 2) or by seeping from streams draining the area. Only a small fraction of the estimated 5.0×10^6 acre-ft of precipitation that falls on the area in an average year (Robson, 1984) recharges the bedrock aquifers; the rest is lost through surface runoff and evapotranspiration. Using computer modeling, Livingston and others (1976) estimated that long-term average precipitation recharge to the outcrop areas of the Arapahoe, Denver, and Dawson aquifers in El Paso County varied with geographic location from less than 0.05 to 2.2 in/yr.

Exchange of water between bedrock aquifers and streams or alluvial aquifers in the Denver basin is important with regard to recharge and discharge. Streams that originate in the mountains west of the Denver basin and then cross the margin of the aquifer-outcrop areas generally recharge these aquifers. The South Platte River is either a source of recharge or a sink for discharge, depending on location, along the reach crossing the aquifers. The river recharges the aquifers where the river emerges from the mountains; whereas, water is discharged to the river in the vicinity of Greeley. Water is discharged from the bedrock aquifers through springs and seeps, and, where the water table is not far below land surface, through evapotranspiration.

The small permeability and large thickness of the Pierre Shale, which underlies the bedrock-aquifer system, make it an effective lower confining unit. Leakage through this layer is assumed to be negligible for the purposes of this study.

For this study, a streamflow gain-and-loss investigation was done on January 22, 1986, on Monument Creek, between the town of Palmer Lake and the mouth of Monument Creek at Colorado Springs. Analyses of data from this and previous gain-and-loss investigations dating back to April 1973 (U.S. Geological Survey, 1975; 1979) indicate that gains and losses in the reach vary greatly. Fifteen gain-and-loss investigations on Monument Creek were made between April 1973 and August 1979. Of these, only two included measurements along the reach from the town of Palmer Lake to Monument; these two did not include measurements downstream from Pikeview. Analysis of the data from the 13 previous investigations of the reach from Monument to the mouth of Monument Creek indicates that gain to the main stem of Monument Creek from ground water ranged from 0.3 to 21.2 ft^3/s. The median value of gain was 4.3 ft^3/s, and 50 percent of the values were between 2.0 and 8.6 ft^3/s; the mean of the 13 values was 6.8 ft^3/s. Gain to the main stem measured in January 1986 in the reach from Palmer Lake to the mouth of Monument Creek was 11.3 ft^3/s; however, melting of shore ice during the 1986 investigation may have caused the measured gain to be more than the gain due to discharge of ground water.

Livingston and others (1976), on the basis of seven gain-and-loss investigations made in 1973 and 1974, estimated that the Arapahoe, Denver, and Dawson aquifers in 1975 discharged water to Monument Creek at a rate of 7.5 ft^3/s. Their model analysis indicated that the steady-state discharge had been 8.4 ft^3/s. Their analysis of gain-and-loss investigations also indicated that Monument Creek was recharging the Laramie Formation (and, therefore, the Laramie-Fox Hills aquifer) at a rate of 2.0 ft^3/s. Using computer modeling, Robson (1984) estimated steady-state discharge from the bedrock aquifers to the various drainage basins in the Denver basin. The Fountain Creek basin and the Black Squirrel Creek basin are the two major drainage basins in the area of greatest interest in this study. The Monument Creek basin is a subbasin of the Fountain Creek basin (fig. 1). For the Fountain Creek basin, Robson (1984) estimated that discharge was 8.0 ft^3/s, and, for the Black Squirrel Creek basin, he estimated that the discharge was 1.8 ft^3/s. For the four bedrock aquifers, Robson (1984) estimated that steady-state recharge and discharge was 54.7 ft^3/s.

Withdrawal of water from wells completed in the bedrock aquifers comprise a substantial part of the discharge from the aquifers. Analysis of well data for the Denver basin south of T. 7 S., obtained in May 1986 from the Office of the State Engineer (Colorado Division of Water Resources, 1986; written commun., 1986), indicates that about 5,947 domestic, stock, or domestic and stock wells are completed in the bedrock aquifers. About 154 irrigation wells, about 56 commercial or industrial wells, about 91 municipal wells, and about 184 wells designated for household or other use also are completed in the bedrock aquifers. Pumpage from various types of wells in the Denver basin was estimated by Robson (1984). For stock and domestic wells, he estimated pumpage as 0.6 acre-ft/yr per well; for commercial and industrial wells as 9 acre-ft/yr; and for irrigation wells, as 41 acre-ft/yr. Because of uncertainty in numbers of wells and pumping rates, Robson (1984) estimated the uncertainty in the basin-wide pumpage estimates for each of these categories as ±30 percent or more.

Water-use data for all sources, which generally were bedrock wells, were obtained from each of 13 public water suppliers in the southern part of the basin. Average annual pumpage reported for individual public supply bedrock wells for the period of use between 1978 and 1985 ranged from 0.0003 acre-ft to more than 20 acre-ft. Data on population served by individual suppliers, which were obtained in July 1986 from the Office of the State Engineer (Colorado Division of Water Resources, written commun., 1986), and the water-use data were used to estimate bedrock-well pumpage by other public water suppliers according to per capita use. For 11 of the public water suppliers, per capita water use ranged from 21,900 to 128,740 gal/yr per person; weighted-average per capita water use was 42,139 gal/yr per person or about 115 gal/d per person. Because the pumping rates for the wells permitted for "household and other" use likely are small, total pumpage from these wells probably is negligible, compared to the uncertainty in the estimates of pumpage from other types of wells.

The pumpage data collected for the southern part of the basin were combined with estimates from Robson (1984; 1987) for the rest of the basin for the four aquifers to provide revised estimates of basin-wide pumping rates for 1985. Basin-wide pumping for 1985 is estimated to have been 8.0 ft^3/s for the Laramie-Fox Hills aquifer, 25.9 ft^3/s for the Arapahoe aquifer, 10.8 ft^3/s for the Denver aquifer, and 11.2 ft^3/s for the Dawson aquifer. The total for all four aquifers is estimated to have been 55.9 ft^3/s.

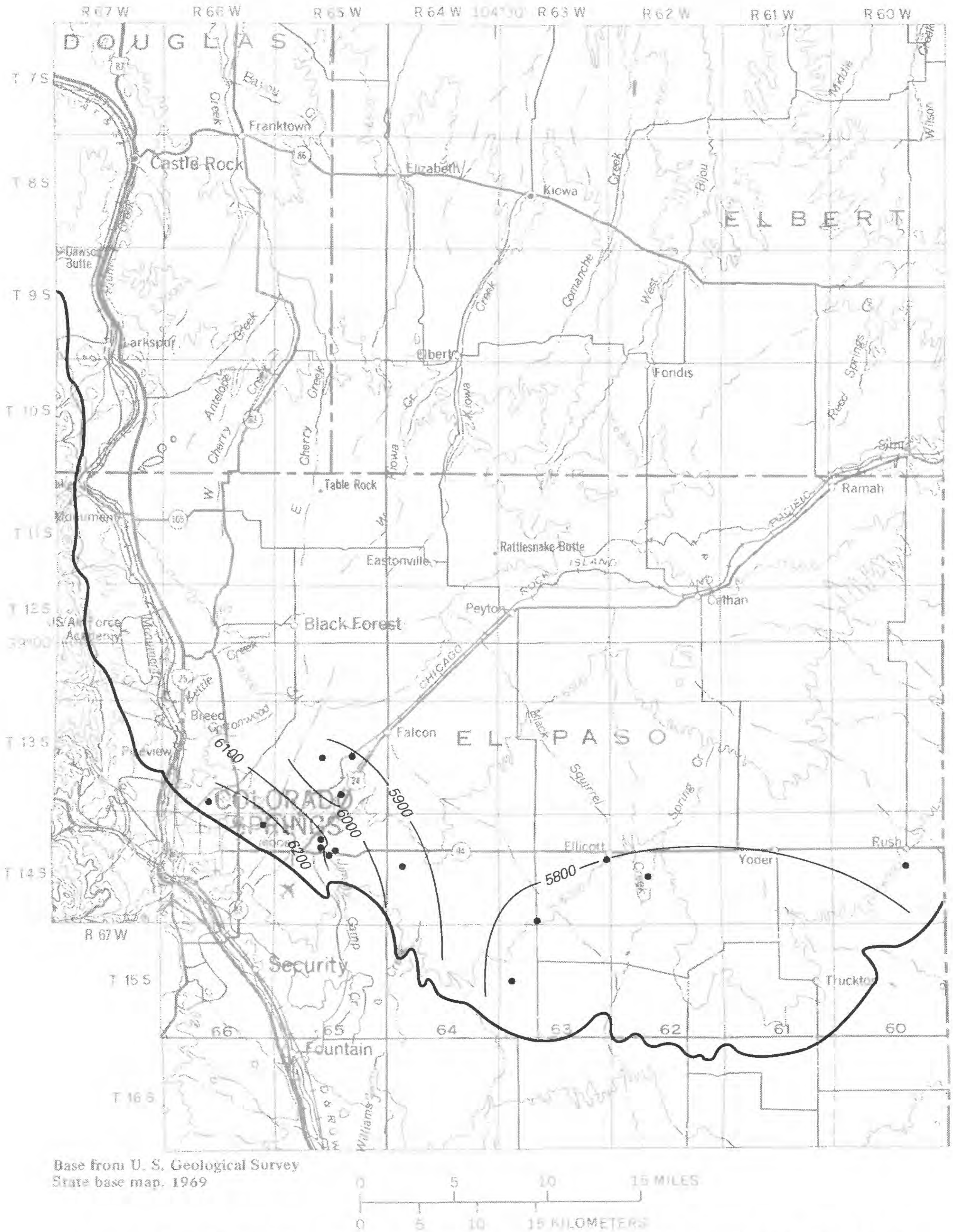

Figure 4.--Potentiometric surface for the Laramie-Fox Hills aquifer in the southern part of the Denver basin, 1985.

EXPLANATION

—5800— **POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface for the Laramie-Fox Hills aquifer. Interval 100 feet. Datum is sea level.**

——— **APPROXIMATE LIMIT OF THE LARAMIE-FOX HILLS AQUIFER**

• **WELL--Site of 1985 water-level measurement**

Water Levels

During the summer of 1985, measurements of depth to water in 94 wells in El Paso County were collected to assess changes in the altitude of the potentiometric surfaces that occurred there between 1978 and 1985. Potentiometric-surface maps for the bedrock aquifers for 1978 are shown in Robson and Romero (1981a; 1981b), Robson and others (1981a), and Robson and others (1981b). Potentiometric-surface maps for 1985 are shown in figures 4 through 7. Changes in water levels between 1978 and 1985, documented by measurements made in the same wells in both years, were substantial in some locations. Water-level changes in the Laramie-Fox Hills aquifer near Colorado Springs ranged from 0 to a rise of more than 40 ft. In the area of Ellicott, Yoder, and Rush, water levels in the Laramie-Fox Hills aquifer generally declined; declines measured as much as 50 ft near Ellicott. Water-level changes in the Arapahoe aquifer ranged from a 10 ft rise at the U.S. Air Force Academy (the only rise measured) to a decline of more than 60 ft near Ellicott. Water-level rises of nearly 20 ft were measured in the Denver aquifer in the general area of Black Forest, Peyton, Falcon, and the Air Force Academy. Water-level declines occurred from Ramah to near Ellicott, where declines measured as much as 80 ft. All measured water-level changes in the Dawson aquifer were small rises of 11 ft or less.

SIMULATED GEOHYDROLOGIC SYSTEM OF THE STUDY AREA

The ground-water flow model developed during this study is a useful tool for understanding the ground-water flow system. Values for hydrologic properties of the rocks that make up the Denver basin bedrock-aquifer system are used to create the model. These properties include: (1) Altitude of the top and bottom of each aquifer, (2) transmissivity, (3) storage coefficient or specific yield, and (4) vertical conductance (a measure of the leakiness of the confining units between aquifers and defined as vertical hydraulic conductivity of the material in the confining layers divided by the thickness of the confining unit). The model simulates the distribution of hydraulic head in the aquifers in response to stresses imposed on the aquifers in the form of sources of, and sinks for, water. Such stresses include: (1) Recharge from percolation of precipitation, (2) recharge and discharge at streams and lakes and discharge at springs, and (3) pumpage of water from wells. Values are assigned to (1) and (3), and the model calculates (2). The model can simulate either steady-state or transient-state conditions.

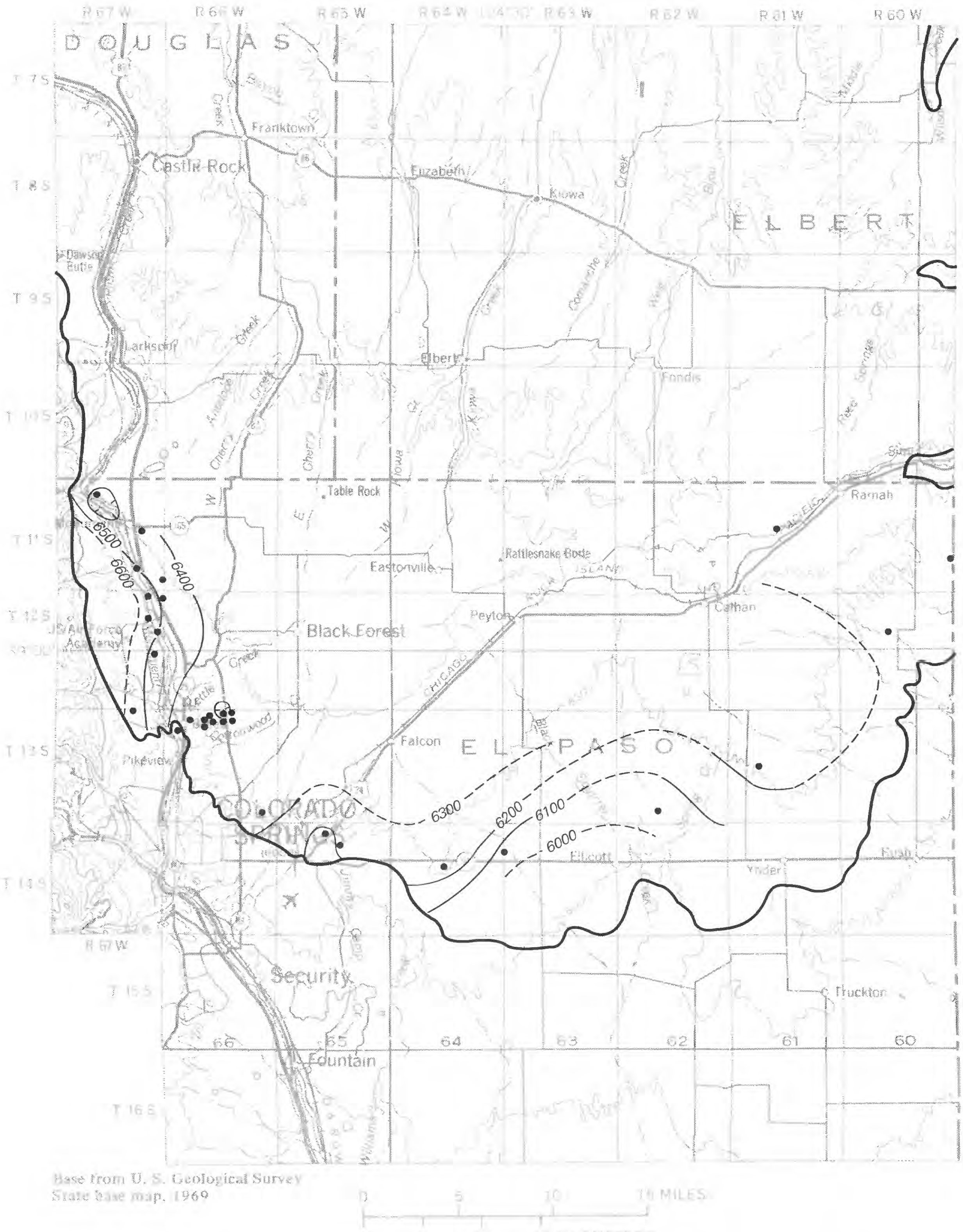

Figure 5.--Potentiometric surface for the Arapahoe aquifer in the southern part of the Denver basin, 1985.

EXPLANATION

—6300— **POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface for the Arapahoe aquifer. Interval 100 feet. Dashed where control is poor. Datum is sea level.**

——— **APPROXIMATE LIMIT OF ARAPAHOE AQUIFER**

• **WELL--Site of 1985 water-level measurement**

The steady-state ground-water flow model calculates the altitude of the potentiometric surface, or head distribution, in each simulated aquifer for the natural hydrologic conditions existing prior to withdrawal of water from wells. The set of potentiometric surfaces represents the equilibrium condition (condition assuming no change in aquifer storage) that would result from the set of aquifer-property values and steady-state stresses assigned. These potentiometric surfaces are compared with historical measurements of water levels that are assumed to represent predevelopment conditions in the aquifer system. Statistical techniques are then used to assess the differences between the measured and model-calculated heads. By use of the calculated heads and the aquifer properties assigned, the model calculates rates of flow into the model, out of the model, and within the model boundaries. The resulting water budget represents: (1) Recharge from streams and lakes; (2) discharge to streams, lakes, and springs; and (3) interaquifer flow. The surface-water features are simulated in the model by constant-head nodes. The heads at these nodes are specified as the average altitude of the water surface in the area represented by the node. During model calibration, the aquifer properties and stresses are adjusted within predetermined, reasonable limits in order to decrease the difference between measured and model-calculated heads to an acceptable level while maintaining flow rates at reasonable levels. Reasonable levels for flow out of the model are determined by analysis of discharges measured in streams in the area and by extrapolation to areas where discharge has not been measured.

In the transient-state model, an initial head distribution is assumed, and stresses derived for the steady-state model are imposed. In addition, man-caused stresses, such as pumpage from wells, and variations in natural stresses that deviate from the long-term average are simulated. In one area where measured water-level declines in an alluvial aquifer overlying the bedrock aquifers have been large, heads specified at constant-head nodes, which are in the model layers representing the bedrock aquifers, are modified to agree with the observed head changes. Ideally, an additional model layer would be the preferred method for simulating the alluvial aquifers. As with the steady-state model, a head distribution is simulated. In addition to the rates of flow calculated by the steady-state model, the transient-state model calculates how much water is coming from or going to storage in each simulated aquifer. In calibrating the transient-state model, reasonable adjustments are made to specified values, such as storage coefficient and specific yield, that affect the model's ability to simulate transient conditions. The object of calibration is to produce simulated head changes that approximate measured head changes, while maintaining aquifer properties and flow rates within reasonable limits.

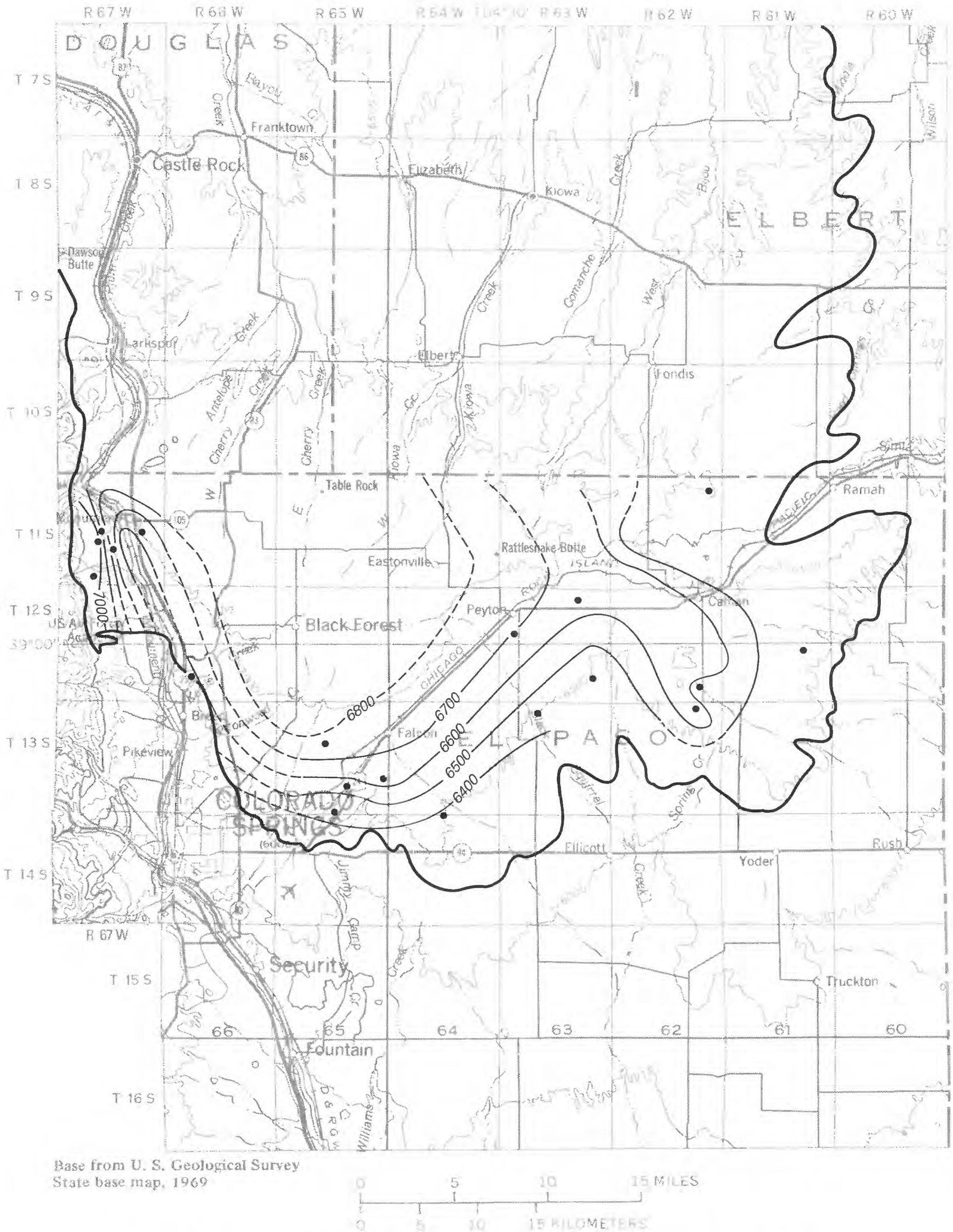

Figure 6.--Potentiometric surface for the Denver aquifer in the southern part of the Denver basin, 1985.

EXPLANATION

—6700— **POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface for the Denver aquifer. Interval 100 feet. Dashed where control is poor. Datum is sea level.**

——— **APPROXIMATE LIMIT OF DENVER AQUIFER**

• **WELL--Site of 1985 water-level measurement**

Model Description

The finite-difference model used in this study is described by Trescott (1975) and Trescott and Larson (1976). In using this model, the hydrologic characteristics of the aquifers and stresses that vary with geographic location are assigned to each aquifer, by considering the aquifer as being divided into three-dimensional blocks fitting into a rectangular grid. For mathematical reasons, the values of the aquifer properties for each of the blocks are associated with the center of the block, called a node. Values assigned to the nodes are chosen to be representative of the respective blocks. In the model described here, each aquifer is represented by one layer of nodes; the resulting four-layer system is the framework of the three-dimensional model. Initial values of the various aquifer characteristics were derived from Robson's (1984) model and from a series of reports (Robson and Romero, 1981a and 1981b; Robson and others, 1981a; Robson and others, 1981b; Robson, 1983). Minor changes from these initial values were made during model calibration.

The model grid used in this study is variably spaced and consists of 67 rows by 40 columns by 4 layers (pl. 2). Of the resulting 10,720 blocks, 5,430 contain active nodes; at other nodes, the aquifers are absent. The aquifers are numbered from the bottom up, so the Laramie-Fox Hills aquifer is model layer 1, the Arapahoe aquifer is model layer 2, the Denver aquifer is model layer 3, and the Dawson aquifer is model layer 4 (table 1). Many aspects of the model used in this study are derived from the previous model by Robson (1984). The model grid, for example, is identical to Robson's (1984) grid in the northwestern part of the model area: rows 1 through 31 and columns 1 through 16. A refinement of the rest of the model grid was necessary to simulate in greater detail the hydrologic conditions of the southern part of the Denver basin. Row and column spacing in the refined model grid each range from 1.5 to 7.0 mi.

Confining units between aquifers are simulated by assigning arrays of vertical-conductance values to be used in calculating flow between the four aquifer layers. Vertical conductance is the quotient of vertical hydraulic conductivity divided by confining-layer thickness.

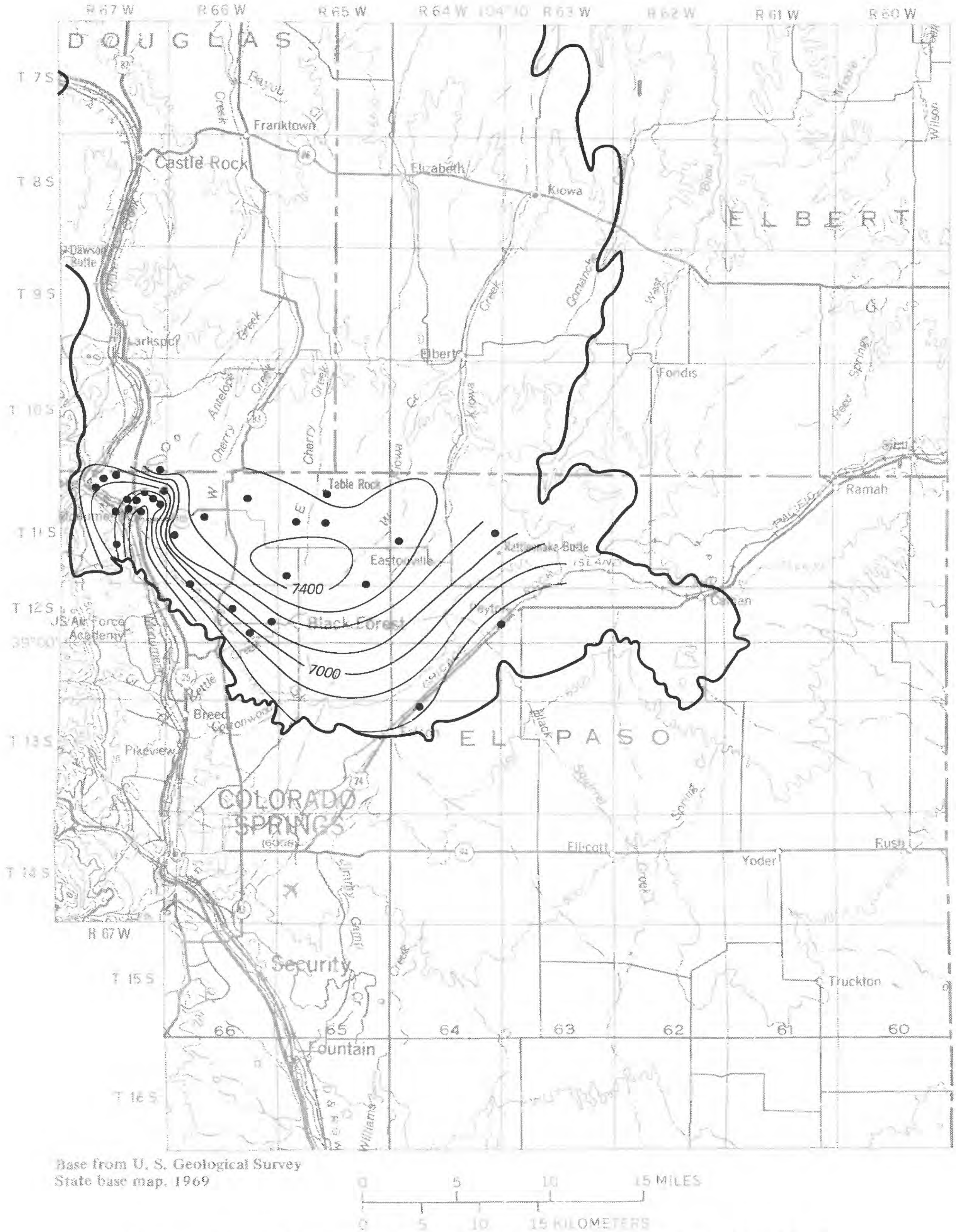

Figure 7.--Potentiometric surface for the Dawson aquifer in the southern part of the Denver basin, 1985.

EXPLANATION

—7400— **POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface for the Dawson aquifer. Interval 100 feet. Datum is sea level.**

——— **APPROXIMATE LIMIT OF DAWSON AQUIFER**

• **WELL--Site of 1985 water-level measurement**

Ground-water storage is represented by a storage coefficient for confined conditions or by a specific yield for unconfined conditions, depending on the altitude of the head in relation to the altitude of the top of the aquifer. If the head calculated for a node results in the aquifer going from confined to unconfined, or from unconfined to confined, the value of the storage property for that node is adjusted accordingly. Where an aquifer is unconfined, transmissivity varies according to the saturated thickness of the aquifer and is adjusted by the model to be proportional to the height of the water table above the base of the aquifer.

An option was written into the model code to allow designation of spring nodes. A spring node acts like a constant-head node, as long as discharge is greater than or equal to zero. If the model calculates that recharge would occur at a spring node, it is converted to an ordinary variable-head node. The changes made to the model code are listed in the "Supplemental Information" section at the back of the report.

Limitations of Model Results

Although a ground-water flow model is a valuable tool for aquifer analysis and for planning purposes, several factors that are inherent in developing a particular model limit the uses for which the results of the model can be applied with confidence.

The model, because it is a compartmentalized representation of a continuous aquifer system, requires much simplification. Aquifer properties are assumed to be constant in each grid cell. In the model discussed in this report, each of the smallest grid cells represents an area of 2.25 mi^2. The generalization of aquifer properties that is necessary to describe the aquifer system in terms of blocks this size is justified only when one is considering an area large enough to make these blocks seem small in comparison. To make inferences relative to a small area of one of the model-calculated head maps would be an inappropriate use of the model results. An analogous inappropriate use of a map would be to try to determine a reasonably accurate average altitude of a small parcel of land on the plains of eastern Colorado using a topographic map of Colorado for which the contour interval is 500 ft. Such a map would be good for estimating the extent of mountain ranges or the approximate area of a major drainage basin, but a map depicting a smaller area and having a smaller contour interval, such as 10 or 20 ft, would be better suited for determining the desired altitude.

As another example of a limitation of the model, consider a model-grid cell designated as being pumped during a simulation. The transient-state model calculates a head for the point in the center of the grid cell as if water were being withdrawn equally over the area represented by the grid cell. By contrast, in a real aquifer, a finite number of pumping wells would be located in the area represented by the grid cell. Each well would develop its own cone of depression, and heads would vary greatly with location in the area. The resulting drawdown in the aquifer locally might dewater the aquifer at one or more of the well sites. However, the model would simulate the same quantity of pumpage over the area of the grid cell and might calculate that the supply of water in the grid cell would be sufficient to supply the specified quantity without dewatering the grid cell.

Steady-State (Predevelopment) Model and Calibration

The steady-state model is used to simulate approximate equilibrium conditions, which existed prior to man's effects on the hydrologic system. The hydrologic conditions that existed before construction of wells and reservoirs approximate long-term, steady-state conditions, if seasonal changes and annual climatic variability are ignored. The steady-state model is calibrated against heads measured in the aquifers when the first wells in an area were drilled. The wells used for calibrating the steady-state model were drilled between the 1880's and the 1970's. The later wells are in remote areas, where the effects of earlier development are presumed to be negligible. Natural fluctuation due to climatic variability causes some uncertainty as to what the actual equilibrium head distribution would be. Water-level measurements, made at the time of well construction and assumed to represent predevelopment conditions at 45 well sites, were used in the calibration process. During the transient-state calibration and verification phases of the modeling process (discussed in the "Transient-State Model and Calibration" section), revision of the steady-state model was necessary to approximate heads in areas where the predevelopment head distribution had been impossible to define. As a result, the steady-state model effectively was calibrated against more than the original 45 measurements.

If the ground-water flow system is simulated realistically by the steady-state model, the calculated-head distribution approximates the condition that the system would tend to assume after a long period, during which stresses do not change. The period prior to man's development of the aquifers is assumed to have been subject to steady, long-term climatic conditions.

During the steady-state calibration procedure, head differences due to vertical position, particularly in the Dawson aquifer, caused a problem in the attempt to match model-calculated heads to observed heads. In the higher altitude areas underlain by the Dawson aquifer, where the Dawson aquifer tends to be thickest, a vertical head gradient, which induces downward flow, generally is present. The vertical gradient is likely the result of a combination of the following factors: (1) The aquifer generally thickens toward the Black Forest-Eastonville-Table Rock area (Robson and Romero, 1981a); (2) the highest land-surface altitudes and, consequently, the largest precipitation rates are found in the same area; and (3) most of the water flowing through the aquifer is recharged to the upper strata at high altitudes and discharged from the lower strata to streams or to the underlying Denver aquifer. The vertical gradient was shown to exist in the Monument area, where many wells were drilled in a short period of time in a relatively localized area. Initial water levels in 15 closely-spaced pairs of domestic wells that were completed at different stratigraphic levels in the aquifer were compared. The average vertical hydraulic gradient for these 15 pairs of wells was 30 ft of head difference per 100 ft of vertical separation between the midpoints of the perforated or screened intervals of the wells. The higher heads were associated with the higher positions in the aquifer.

Because of the model design, only one head value is computed for an aquifer for each grid cell; this computed value represents the head at the center of the aquifer. For comparison purposes, it was necessary to correct measured head values to the head that would have existed at the center of the aquifer. The need for correction of the measured values to heads at the center of the aquifer was dictated by the model design, the need for model calibration, and the availability of field head data. The corrected heads are based on the observed head, the depth to the midpoint of the interval in the well open to the aquifer, the depth to the center of the aquifer at the well site, and the vertical gradient of 30 ft/100 ft (0.30 ft/ft). For example, if a well is open to the aquifer from a depth of 100 to 300 ft at a point where thickness of the aquifer is 1,000 ft, a vertical distance of [(1,000/2) ft - (300 ft - 100 ft)] or 300 ft separates the midpoint of the open interval from the midpoint of the aquifer. The correction is 300 ft × 0.30 or 90 ft. If the measured water-level altitude is 7,400 ft above sea level, the head projected for the midpoint of the aquifer is (7,400 ft - 90 ft) or 7,310 ft. Water levels measured in wells completed in the lower part of the aquifer were projected upward in the same manner.

Steady-state calibration consisted of adjusting the rate of recharge from precipitation, vertical conductance between aquifers, and, in areas of sparse data, transmissivity, until a satisfactory agreement between measured and simulated heads was reached. Recharge, vertical conductance, and transmissivity were kept within ranges appropriate for those properties as described in previous sections. The level of agreement was judged by the mean square error, calculated as (Robson, 1984):

$$MSE = \overline{\Delta H}^2 + S^2;$$

where MSE = mean square error,

$\overline{\Delta H}^2 = (\Sigma_{i=1}^{n}(H_{ci} - H_{mi})/n)^2$,

S^2 ("variance") = $(\Sigma_{i=1}^{n}(\Delta H_i - \overline{\Delta H})^2)/(n - 1)$,

$\Delta H = H_c - H_m$,

H_c = the computed head at a grid block where a well is located,

H_m = the measured head at the corresponding well, and

n = number of wells.

Mean square error values for eight of the steady-state model runs are shown graphically in figure 8; run 8 on the graph represents the final calibration of the steady-state model. Values of the errors between computed heads and measured heads were plotted on maps throughout the calibration procedure; visual inspection of the errors produced by the final, calibrated model (pl. 2) indicated that the errors were randomly distributed. Values of estimated vertical hydraulic conductivity used in the final steady-state calibration run found by trial and error, are shown in table 2.

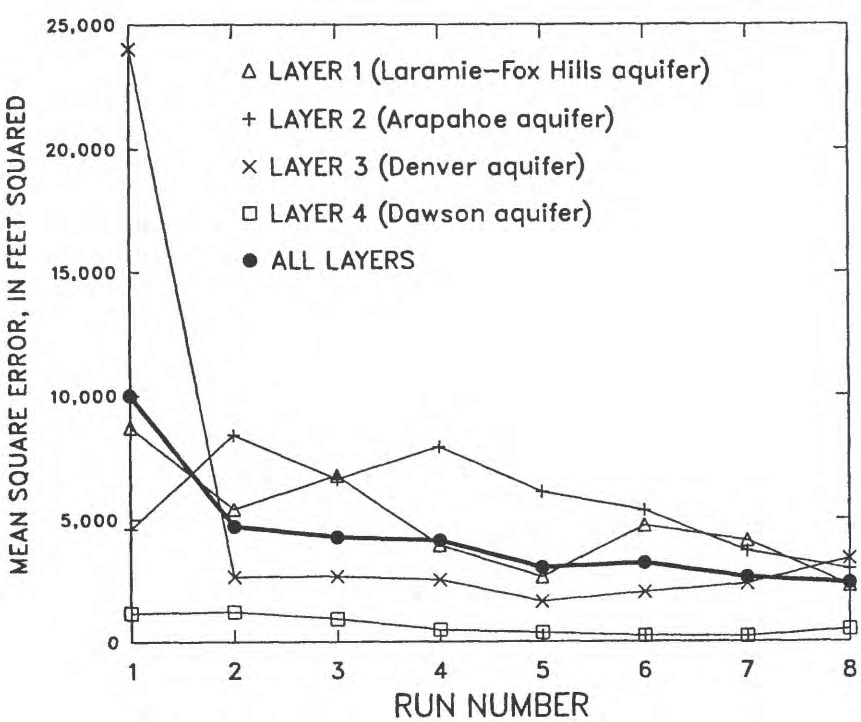

Figure 8.--Mean square error for eight sequential steady-state model runs.

Table 2.--*Estimated vertical hydraulic conductivity of confining units*

Confining unit	Vertical hydraulic conductivity (feet per day)
Upper Denver confining unit	4.1×10^{-5}
Lower Denver confining unit	1.3×10^{-5}
Laramie confining unit	6.2×10^{-7}

One of the most useful products of the steady-state model is the calculated rate of flow through the aquifer system. However, a model-calculated water budget is, to a degree, dependent on the size of the blocks that make up the model grid. For example, if a grid block is specified as a constant head, the model calculates the net flow into or out of that block that would be necessary to maintain the head at the specified value. If a second model of the same aquifer system is made with grid blocks half as large, both recharge and discharge may occur in the area, where, originally, only a single value of recharge or discharge was possible. The net flow into or out of the system for the area of the original grid block may be the same in both cases; however, larger values of recharge and discharge are generated in the second (finer grid) simulation. These larger values are reflected in a larger overall ground-water budget for the model having the finer grid. The physical analogy is that the model having the finer grid is able to simulate local, shorter flow paths; whereas, the coarser-grid model cannot.

The ground-water budget for the four-aquifer system, as calculated by the current steady-state model (table 3), indicates that total recharge and total discharge for the aquifers was about 59 ft^3/s. For comparison, the water budget for Robson's (1984) steady-state model indicated recharge and discharge was about 55 ft^3/s. The discrepancy is primarily the result of the effect of the finer grid of the current model. A summary of steady-state recharge and discharge at nodes representing interfaces between the bedrock aquifers and streams, alluvial aquifer systems, and springs in Monument Creek and Black Squirrel Creek basins (table 4) indicates that the upper three aquifers discharge to Monument Creek basin; whereas, the lowermost aquifer, the Laramie-Fox Hills, is recharged by Monument Creek. This conclusion is supported by a comparison between historical water levels in wells completed in the Laramie-Fox Hills near Monument Creek and the altitude of the creek; the water levels in the aquifer are far below the level of the creek. The model-calculated net steady-state discharge to Monument Creek basin, 6.06 ft^3/s, favorably compares with the measured gain-and-loss data discussed in the "Recharge and Discharge" section. The calculated value is larger than the median measured value (4.31 ft^3/s), but it is less than the mean value (6.79 ft^3/s). All four aquifers discharge to the Black Squirrel Creek basin.

Other products of the steady-state model are arrays of calibrated values for aquifer transmissivity, vertical hydraulic conductivity of confining units (table 2), and rates of recharge from precipitation. These results, required for the transient-state modeling phase, are, at best, estimates of areally averaged values of characteristics that vary spatially. The distribution of recharge from precipitation derived from model calibration is shown on plate 2.

Table 3.--*Steady-state (predevelopment) ground-water budget*

[Values in cubic feet per second; --, not applicable]

Sources and sinks	Aquifer				Total, four aquifers
	Laramie-Fox Hills	Arapahoe	Denver	Dawson	
Sources					
Recharge from precipitation---------	4.1	4.9	7.7	37.0	53.7
Recharge from streams, reservoirs, other surface-water bodies, and alluvial aquifers--	1.5	.9	.9	2.4	5.7
Net flow from overlying aquifer----------------	.4	4.5	7.0	--	--
Total flow from sources--	6.0	10.3	15.6	39.4	59.4
Sinks					
Discharge to streams, springs, other surface-water bodies, and alluvial aquifers--	6.0	9.9	11.1	32.4	59.4
Net flow to underlying aquifer----------------	--	.4	4.5	7.0	--
Total flow to sinks------	6.0	10.3	15.6	39.4	59.4

Table 4.--*Steady-state (predevelopment) flow rates to or from bedrock aquifers in Monument Creek and Black Squirrel Creek basins*

[Values in cubic feet per second; negative values indicate discharge from bedrock]

Aquifer	Net flow	
	Monument Creek basin	Black Squirrel Creek basin
Dawson-------------------	-4.71	-0.70
Denver-------------------	-1.36	-.47
Arapahoe-----------------	-.14	-.33
Laramie-Fox Hills--------	.15	-.21
Total, four aquifers-----	-6.06	-1.71

An analysis of the effects of constant-head boundaries was made. Water was initially assumed to flow laterally through the aquifers generally toward the perennial streams and rivers, most of which are located in the northern, western, and southwestern parts of the basin, with smaller amounts flowing downward across confining units. The computer model corresponding to this conceptual model had few sinks (constant-head or spring nodes) along the eastern and southern flanks of the aquifers, especially in the lower three aquifers. The resulting model-calculated heads were much higher than the heads measured in these areas. By adding spring nodes at points where seepage or evapotranspiration likely are larger, such as ephemeral-stream valleys, model-computed heads were lowered, and a better fit to the observed head distributions was achieved. Flux rates for these nodes generally are less than 2.0 in/yr, and are not more than 3.6 in/yr. For comparison, the free-water-surface evaporation, which is approximately equivalent to potential evapotranspiration, for the study area approximately ranges from 40 to 50 in/yr (Farnsworth and others, 1982). Thus the model-calculated flux rates realistically are much smaller than the prevailing potential evapotranspiration rate. However, the improvement in the head distribution indicates that discharge along ephemeral-stream valleys is an important part of the hydrologic system.

Transient-State Model and Calibration

When the various factors that affect the steady-state model are adjusted to give a satisfactory equilibrium head distribution and water budget, the model is ready to be calibrated to simulate transient conditions. Realistic values for storage coefficient or specific yield are added to the model. The model approach used in this study could be described as a formation-type model because each model layer is assumed to represent a geologic formation or a sequence of beds, which may be made up of interbedded water-yielding and nonwater-yielding layers. In this approach, the thickness of the simulated aquifer is the overall thickness of the formation or sequence of beds. An alternative approach would be to assume that all the water-yielding layers are lumped together. The thickness of the simulated aquifer then would be the cumulative thickness of the water-yielding layers. Because the first approach is used in this study, specific yield is calculated as the weighted average of the specific yields for the water-yielding and nonwater-yielding layers. Storage coefficient is a function of the cumulative thickness of water-yielding layers; therefore, it is independent of the degree to which the water-yielding layers are interbedded with nonwater-yielding layers.

The objective of transient-state calibration is to make the model able to respond to changing stresses in a manner similar to the response observed in the physical system due to changes in stress. Pumping is simulated and may be changed for each pumping period during the model run. A 20-year period, 1958 to 1978, was used as an initial calibration period. The 1958 head distributions used for Robson's (1984) model were used as the initial head conditions for the calibration runs; model-calculated heads were compared to head measurements made in 1978 (Robson, 1987), which were substantially lower than those made in 1958 in the northern part of the basin. Three pumping periods, lasting 3, 13, and 4 years, were used to simulate this 20-year period.

Pumping rates from Robson's (1984) model were reassigned to the new grid; but, otherwise, they were unchanged. Simulated pumping always remains constant during a single pumping period. Pumping for these three periods, which is concentrated in the Denver metropolitan area, is summarized in table 5. Calibration consisted of adjusting storage-property values within reasonable limits, until model-calculated heads agreed satisfactorily with observed heads for all aquifers. Where the aquifers are confined, the storage-coefficient distributions in Robson (1983), with minor modifications, were determined to give good results and were used. Where the aquifers are unconfined, specific-yield values based on laboratory analysis of samples and mapping done by S.G. Robson (1984; S.G. Robson, U.S. Geological Survey, written commun., 1986) were used; they also were determined to give good results.

Table 5.--*Simulated pumping rates during the three pumping periods of the transient-state calibration, 1958 to 1978*

[Source: S.G. Robson (U.S. Geological Survey, written commun., 1985); values in cubic feet per second]

Aquifer	Pumping period and time interval		
	1958-61	1961-74	1974-78
Dawson	2.62	4.89	6.29
Denver	2.20	4.76	7.38
Arapahoe	12.55	14.00	18.27
Laramie-Fox Hills	2.98	4.00	5.36
Total, four aquifers	20.35	27.65	37.30

Because few water-level measurements representative of the beginning of the calibration run (1958) were available for the southern part of the Denver basin, model runs simulating an additional 7-year period from mid-1978 to mid-1985 were made. Heads calculated for mid-1978 were used as the initial heads. Heads calculated for mid-1985 were compared to measured 1985 heads. The simulated potentiometric surfaces for 1985 for all aquifers are shown on plate 3. The difference between the simulated potentiometric surface and the potentiometric surface determined from 1985 measurements (figs. 4-6) is generally less than 50 ft for the Laramie-Fox Hills, Arapahoe, and Denver aquifers, although the difference locally is about 100 ft. For the Dawson aquifer, the difference is as much as about 150 ft, and it exceeds 50 ft in a large area. Much of this discrepancy likely is due to vertical head differences in the Dawson aquifer, similar to those described in the "Steady-State Model and Calibration" section. Measured heads used to generate the 1985 potentiometric surface for the Dawson aquifer (fig. 7) were not adjusted to approximate the head at the center of the aquifer; whereas, the model calculates heads for the center of the aquifer. The discrepancy is greatest where the Dawson aquifer is thickest, which is where wells used for control for the measured potentiometric-surface map likely are completed in intervals far from the center of the aquifer.

Pumpage for the southern part of the Denver basin was simulated as constant during the 7-year period and was estimated using a combination of methods. Annual pumpage values reported by public water suppliers were averaged over the 7-year period and used directly. Pumpage was estimated on a per-capita consumption basis for the public water suppliers that did not report pumpage values. Pumpage from wells other than public-supply wells was estimated from well data obtained from the Colorado State Engineer's office (Colorado Division of Water Resources, 1986; written commun., 1986) using the method described in the "Recharge and Discharge" section. Preliminary simulations indicated that new, transient stresses to the aquifer system likely had resulted in two unanticipated effects on observed heads in the aquifer system. These effects are: (1) Rising water levels in western El Paso County during the period 1978 to 1985; and (2) substantial water-level declines in eastern El Paso County, where pumpage from the bedrock aquifers was small, between 1978 and 1985.

Generally rising water levels in western El Paso County indicated that recharge probably was larger than usual. Climatological records (U.S. Weather Bureau, 1920-1965; U.S. National Oceanic and Atmospheric Administration, 1966-1985) indicate that precipitation at each of seven weather stations in or near the southern part of the Denver basin for the years 1982 through 1984 was larger than normal for the period of record. Variation from normal annual precipitation, ranging from 15 to 46 percent greater than normal, was plotted on a map of the basin, and recharge in the model area was increased by this factor for the 3-year period. This change in recharge rate necessitated making two successive model runs to simulate the 7-year period because the Trescott (1975) model assumes recharge rates to be constant for the modeled period.

Measured water-level declines in eastern El Paso County seemed to be too large to be accounted for only by pumpage from bedrock aquifers, because the bedrock aquifers have undergone little development in this sparsely populated area. Studies by Livingston and others (1976) and by D.R. Buckles (U.S. Geological Survey, written commun., 1986) indicate that water-level declines in response to pumping in the Black Squirrel Creek alluvial aquifer have been as large as 60 ft during the period 1964 to 1984. Hydraulic connection between the alluvial aquifer and the bedrock aquifers probably is good; where the bedrock aquifers are overlain by the alluvial aquifer, head values in the bedrock and alluvial aquifers are likely to be nearly the same. Because of the large transmissivity of the alluvial aquifer relative to that of the bedrock aquifers [about 5,000 to 9,000 ft^2/d for the alluvial aquifer (D.R. Buckles, U.S. Geological Survey, written commun., 1986)] as compared to less than 50 to 100 ft^2/d for each of the bedrock aquifers in this area, the head in the alluvial aquifer strongly influences the head in the adjacent bedrock aquifers. This influence and the large extent of the area of bedrock aquifers that is overlain by the Black Squirrel Creek alluvial aquifer [about 105 mi^2 (D.R. Buckles, U.S. Geological Survey, written commun., 1986)] combine to make the head in the alluvial aquifer a dominating factor in the bedrock-aquifer head distributions in eastern El Paso County.

The decline in head in the Black Squirrel Creek alluvial aquifer was simulated by lowering the altitudes specified at the constant-head nodes representing bedrock aquifers overlain by, and hydraulically connected to, the alluvial aquifer. In the model, lowering of the altitudes of heads at these nodes has a controlling effect on the simulated heads in the bedrock aquifers in the vicinity of these nodes. The history of head measurements in the alluvial and bedrock aquifers indicates that the actual head changes in the bedrock aquifers are analogous to the simulated changes. The introduction into the model of increased recharge (described previously in this section) and lowered constant heads in the area of Black Squirrel Creek produced an acceptable agreement between simulated and measured heads. If no other stresses were changed in the model, a combined effect of the increased recharge and lowered constant-head altitudes would be an increase in discharge from the model through constant-head nodes in the Black Squirrel Creek basin, relative to the steady-state simulated rate of about 1.7 ft^3/s (table 4). However, simulated pumping from the bedrock aquifers and a decrease in discharge at spring nodes more than offset the effect of the increased recharge and lowered constant-head altitudes; simulated discharge from the bedrock through constant-head nodes in the Black Squirrel Creek basin at the end of the simulation (1985) was about 1.6 ft^3/s (table 6). A similar decrease in discharge in Monument Creek basin for 1985, compared with the steady-state water budget, is shown in table 6. For the Arapahoe aquifer in the Monument Creek basin (table 6), the simulated direction of net flow has reversed relative to steady-state conditions (table 4), although the magnitude of the change in flow probably is too small to be verified by streamflow gain-and-loss measurements. The magnitude of the simulated net recharge to the Arapahoe aquifer in the Monument Creek basin probably is less than the magnitude of the error inherent in the model; however, the trend toward decreased net discharge (or toward net recharge) is evident.

Table 6.--*Simulated 1985 flow rates to or from bedrock aquifers in Monument and Black Squirrel Creeks basins*

[Values in cubic feet per second, negative values indicate discharge from bedrock aquifers]

Aquifer	Net flow: Monument Creek basin	Net flow: Black Squirrel Creek basin
Dawson	-4.48	-0.67
Denver	-1.01	-.41
Arapahoe	.04	-.32
Laramie-Fox Hills	.19	-.19
Total, four aquifers	-5.26	-1.59

In some areas, such as the Denver metropolitan area and El Paso County north of Colorado Springs, the density of wells may exceed 50 wells per square mile. Apparently not all wells in the Denver and Arapahoe aquifers are completed so as to prevent interaquifer flow, because measured heads are substantially higher in the Arapahoe aquifer and lower in the Dawson aquifer than would be expected, based on preliminary calibration runs of the transient-state model. Measured heads for the Denver aquifer locally are higher or lower than would be expected, presumably as a result of vertical flow along some of these wells. By increasing the simulated vertical conductance of the upper and lower Denver confining units in small areas where well density is greatest, an acceptable agreement between measured and model-calculated 1985 heads was achieved. An increase in simulated interaquifer flow among the upper three aquifers is a result of this adjustment in vertical conductance.

Table 7.--*1985 ground-water budget*

[Values in cubic feet per second; --, not applicable]

Sources and sinks	Aquifer				Total, four aquifers
	Laramie-Fox Hills	Arapahoe	Denver	Dawson	
Sources					
Recharge from precipitation----------	4.6	5.5	8.9	45.9	64.9
Recharge from streams, reservoirs, other surface-water bodies, and alluvial aquifers--	3.9	4.2	3.4	2.4	13.9
Net flow from overlying aquifer----------------	.4	8.3	8.6	--	--
Net rate of decrease in ground-water storage---	4.2	13.1	5.4	1.6	24.3
Total flow from sources--	13.1	31.1	26.3	49.9	103.1
Sinks					
Discharge to streams, springs, other surface-water bodies, and alluvial aquifers------	5.1	4.8	7.2	30.1	47.2
Net flow to underlying aquifer----------------	--	.4	8.3	8.6	--
Pumping------------------	8.0	25.9	10.8	11.2	55.9
Total flow to sinks------	13.1	31.1	26.3	49.9	103.1

A basin-wide ground-water budget summarizing conditions, as of 1985, is presented in table 7. Note that compared to the predevelopment water budget (table 3), the total 1985 inflow and outflow nearly doubled, from 59 to 103 ft^3/s; pumping totaled about 56 ft^3/s. This rate of pumping exceeds the simulated, predevelopment rate of recharge from precipitation; it also is about 94 percent of the predevelopment total inflow and outflow rate of 59 ft^3/s. The 1985 water budget indicates larger recharge from precipitation, due to the series of years of greater-than-normal precipitation. As shown in table 7, additional recharge from alluvial aquifers and surface water was induced, from the predevelopment rate of about 6 to about 14 ft^3/s in 1985, an increase of about 8 ft^3/s. This increase supplied about 15 percent of the 1985 pumpage. Induced recharge is simulated to have been largest in the Arapahoe and Denver aquifers, where recharge from alluvial aquifers and surface water increased by a factor of about 4. About 22 percent of the 1985 pumpage was supplied by a decrease in discharge to alluvial aquifers and surface water. This captured discharge is simulated to have been most substantial in the Arapahoe aquifer, where discharge to alluvial aquifers and surface water approximately halved, from about 10 to about 5 ft^3/s. For the four aquifers, induced recharge and captured discharge accounted for about 37 percent of the 1985 pumpage. The volume of ground water in storage was declining at a simulated rate of about 24 ft^3/s in 1985; this decline in storage supplied about 43 percent of the 1985 pumpage. The remaining 20 percent came from the transient increase in recharge from precipitation.

SIMULATED EFFECTS OF FUTURE PUMPAGE

The simulations described in this section calculate the effects of a variety of possible scenarios of aquifer development for the 100-year period from 1985 to 2085 in the southern part of the Denver basin. The various scenarios differ in the ways the simulated system is stressed by pumpage. Although considerable effort was made to project future aquifer development in a way that would approximate actual future pumpage rates, the prediction of aquifer development, with respect to both magnitude and geographic distribution, is subject to a large degree of uncertainty. The aquifer-development projections used in this study do not reflect economic, technologic, demographic, legal, or political factors, which undoubtedly will have a substantial effect on actual future aquifer development. Also, the projections assume that the needs of additional population, where growth is projected in the Denver basin but outside the Colorado Springs city limits, are supplied entirely from Denver basin bedrock-aquifer sources. Colorado Springs is excluded because it is supplied from surface-water sources outside the Denver basin. If the population outside the city were supplied in part by surface-water sources, the pumpage from Denver basin bedrock aquifers would be decreased correspondingly. The intention of the modeling effort is to present the likely effects of certain scenarios of aquifer development and not to predict response to actual future pumpage.

Given a certain set of stresses, the accuracy of the model-calculated results depends on how well the calibrated model approximates the real aquifer system. Factors that affect the adequacy of calibration and the usefulness of the resulting model include: (1) The nonuniqueness of the model, (2) the duration of the calibration period relative to the duration of the simulation period, and (3) the magnitude of the pumping rates during calibration relative to the magnitude of the pumping rates during simulation. If an observed condition of the real aquifer system (such as an area of water-level decline in an aquifer) can be simulated by two or more models, differing in how the geohydrologic system is simulated, the model is not unique. The model described in this report is not unique in that additional model layers could have been used to represent, in greater deatail, the interbedded nature of the aquifers and confining units. The problem with a nonunique model is that, although it may simulate historical changes adequately during the calibration period, it may not simulate changes adequately during simulation runs because different sets of stresses are imposed. As the simulation duration exceeds the duration of the calibration period, inaccuracies in the calculated results can be expected to increase. Where the geographic distribution of pumping changes from that of the calibration period, errors can be immediate and large. Also, as pumping rates during the simulation run increase relative to pumping rates during calibration, inaccuracies in the results increase. A more detailed discussion of these and other types of modeling errors can be found in the "Supplemental Information" section of Robson (1984).

In all the simulations, precipitation recharge is assumed to occur at the rate calibrated for the steady-state model. This rate represents a decrease from the period 1982-85, for which the simulated recharge rate was larger than the calibrated steady-state rate.

In the modeling process, assessing effects of pumping in the southern part of the basin, independent of pumping in the northern part of the basin was desirable. For this reason, for each of the simulations, pumping from the aquifers in the northern part of the basin follows an unvarying pattern of increasing pumping rates. Pumping rates equal to those used for Robson's (1984) FULL-BASE simulation were used on the basis of opinions of officials of the Colorado Office of the State Engineer, that the FULL-BASE pumping rates most closely approximated actual pumping rates during the period 1979-85. The effect of this assumption on heads in El Paso County is discussed in the "Model Sensitivity" section. A summary of stresses assumed for each of the simulations, and of consequent deletion of nodes in the model because of simulated dewatering, is shown in table 8. Note that although an area may not be shown as being dewatered in a model simulation, if a well or group of wells were to be pumped at a large discharge rate for an extended period, the possibility exists that an aquifer may be dewatered in the immediate vicinity of the pumping site.

Table 8.--*Summary of predictive simulations*

[--, not applicable]

Simulation name	Description of simulation	Pumping rate from southern part of basin at end of simulation[1] (cubic feet per second)		Nodes that go dry in southern part of basin and are eliminated from model	
				Number	Node location (row, column, layer), followed by simulation year node goes dry
SIMBASE	Baseline simulation. Pumping in southern part of basin held constant at 1985 level. Pumping in northern part of basin increases, as in Robson's (1984) FULL-BASE simulation.	[2]Layer 1	0.9	0	--
		2	3.5		
		3	3.6		
		4	7.0		
		Total	15.0		
SIMGRO	Growth simulation. Pumping in southern part of basin increases in response to demand by growing population. Pumping in northern part of basin the same as for SIMBASE.	Layer 1	56.6	6	(55,19,4), 55; (54,14,3), 60; (59,17,2), 70; (53,14,3), 73; (55,20,4), 89; (54,15,3), 96
		2	50.0		
		3	38.8		
		4	25.4		
		Total	170.8		
SIMGWELL	Growth simulation plus well field. Pumping from hypothetical well field added to pumping simulated in SIMGRO. Well-field pumping from lower three aquifers begins in year 2025 at 10 million gallons per day (15.5 cubic feet per second).	Layer 1	59.6	7	(55,19,4), 55; (54,14,3), 60; (59,17,2), 70; (53,14,3), 73; (55,20,4), 89; (54,15,3), 96; (56,19,2), 100
		2	56.2		
		3	45.1		
		4	25.4		
		Total	186.3		
SIMGWSUB	Growth simulation; well-field pumping replaces some pumping near Colorado Springs. Pumping in primary growth area east of Colorado Springs is replaced step-wise, up to 10 million gallons per day (15.5 cubic feet per second), by pumping from well field.	Layer 1	51.5	3	(54,14,3), 60; (53,14,3), 73; (54,15,3), 96
		2	51.1		
		3	43.1		
		4	25.1		
		Total	170.8		
SIMGCITY	Growth simulation plus city pumpage. Pumping in Colorado Springs from lower three aquifers at discharge limit added to pumping simulated in SIMGRO. City pumping from lower three aquifers increases in year 2025 to 20.3 cubic feet per second.	Layer 1	66.8	11	(55,19,4), 55; (54,14,3), 60; (59,17,2), 70; (53,14,3), 72; (55,20,4), 89; (55,14,2), 93; (56,14,2), 94; (54,15,3), 94; (55,19,2), 99; (56,15,2), 99; (56,19,2), 99
		2	57.8		
		3	40.1		
		4	25.4		
		Total	190.1		

[1]Values shown are as coded in input files. Actual total pumping simulated is less for simulations during which pumped nodes go dry and, therefore, are eliminated from the model.

[2]Aquifers are numbered in ascending order. Accordingly, the Laramie-Fox Hills aquifer is designated as model layer 1; the Arapahoe, model layer 2; the Denver, model layer 3; and the Dawson, model layer 4.

Simulation SIMBASE

The simulation involving the least stress to the aquifer system is called SIMBASE. In this simulation, pumpage from the system in the southern part of the basin is held constant at 1985 levels. This simulation is unrealistic because it assumes ground-water development in the southern part of the basin stops increasing in 1985. However, it is useful as a prediction of the long-term effects of 1985 pumping rates and as a reference when assessing simulated effects of the other scenarios, in which increases in aquifer development in the southern part of the basin are simulated.

The most prominent features of the simulated 2085 potentiometric surfaces calculated for simulation SIMBASE for the Laramie-Fox Hills and Arapahoe aquifers (pl. 4) are the large, bowl-shaped depressions in the vicinity of the Arapahoe-Douglas County boundary. Depressions in the simulated 2085 potentiometric surfaces for the Denver and Dawson aquifers (pl. 4) are smaller and less well-defined for several reasons: (1) Pumpage from these aquifers is relatively small; (2) in the Denver aquifer, unconfined conditions predominate where pumpage is most concentrated; and (3) the transmissivity of the Dawson aquifer is large. Drawdowns during the SIMBASE simulation are largest in the Laramie-Fox Hills aquifer, as much as 1,800 ft in northern Douglas County, and they generally decrease in each overlying aquifer (pl. 4). Maximum drawdowns in the Arapahoe aquifer are about 800 ft, in the Denver aquifer, about 400 ft, and in the Dawson aquifer, about 300 ft.

To illustrate the way heads vary with time through the simulation, simulated hydrographs for 20 nodes are plotted in figures 9 through 28. The 1985 head is shown at 0 simulation time of the hydrographs, and the head calculated at the end of each 10-year pumping period is shown as a symbol on the curve. The variability in the shapes of the hydrographs demonstrates how different parts of the aquifers respond differently, mostly depending on distance from pumping centers and on whether the aquifer is confined or unconfined in the area. Most of the SIMBASE hydrographs shown exhibit a moderate decline. Some, such as in figure 25, show a rapid decline during the first pumping period. This decline is a result of the change from the larger recharge rate from precipitation of 1982-85 back to the calibrated steady-state rate.

In simulation SIMBASE, simulated pumpage from the southern part of the basin stays constant at 15.0 ft^3/s (table 8); whereas, simulated pumpage from the basin as a whole increases from the 1985 level of 55.9 ft^3/s to 127.5 ft^3/s in 2085 (tables 7 and 9). A large increase in the rate at which ground water in storage is depleted, from about 24 ft^3/s in 1985 to 87 ft^3/s in 2085, supplies 68 percent of the simulated 2085 pumping rate. All four aquifers undergo large increases in rate of depletion of ground water in storage to supply the simulated pumping. During the period 1985 to 2085, simulated induced recharge from streams, other surface-water bodies, and alluvial aquifers increases the recharge from these sources from about 14 to about 21 ft^3/s. In addition, some simulated discharge is captured during this period, so that discharge to surface-water bodies and alluvial aquifers is decreased from about 47 ft^3/s to about 34 ft^3/s. By 2085, the total inflow and outflow rate is simulated to be about 2.7 times the rate for predevelopment conditions. No nodes go dry in the southern part of the basin during simulation SIMBASE.

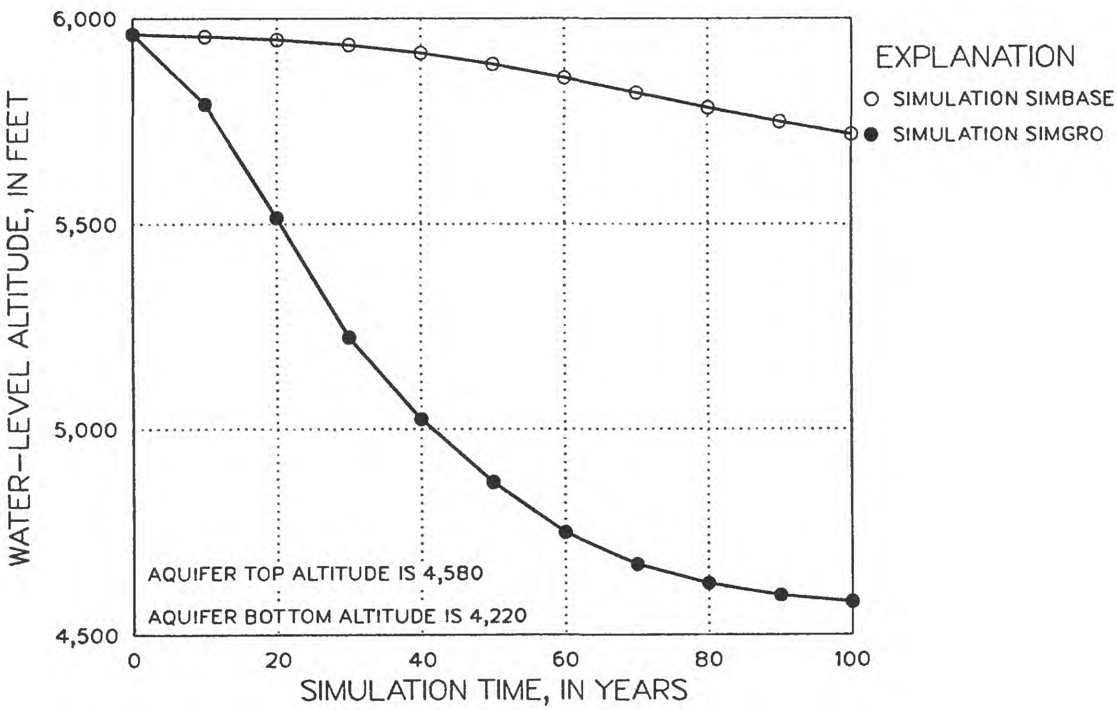

Figure 9.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (46,14,1).

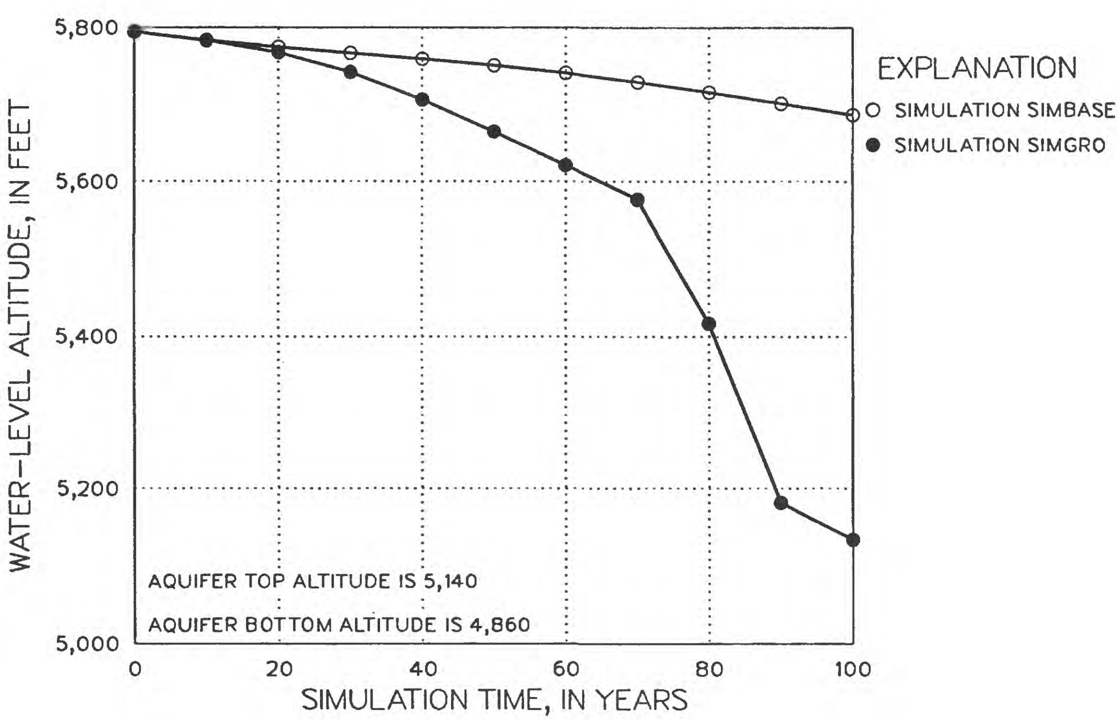

Figure 10.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (46,31,1).

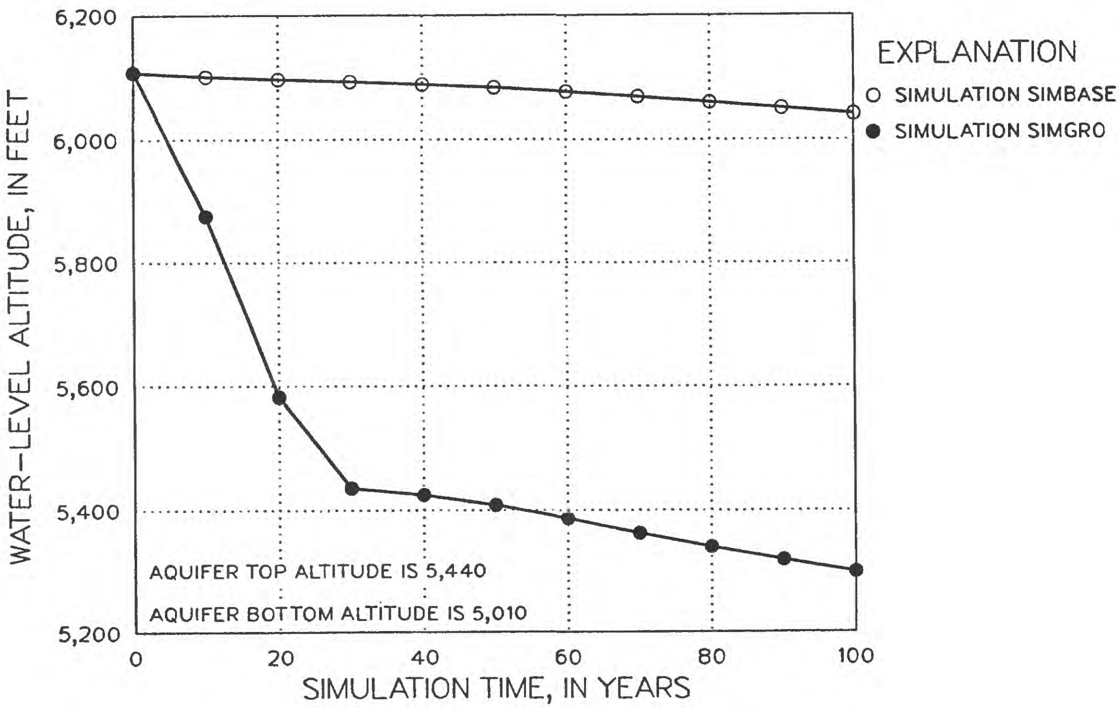

Figure 11.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (54,15,1).

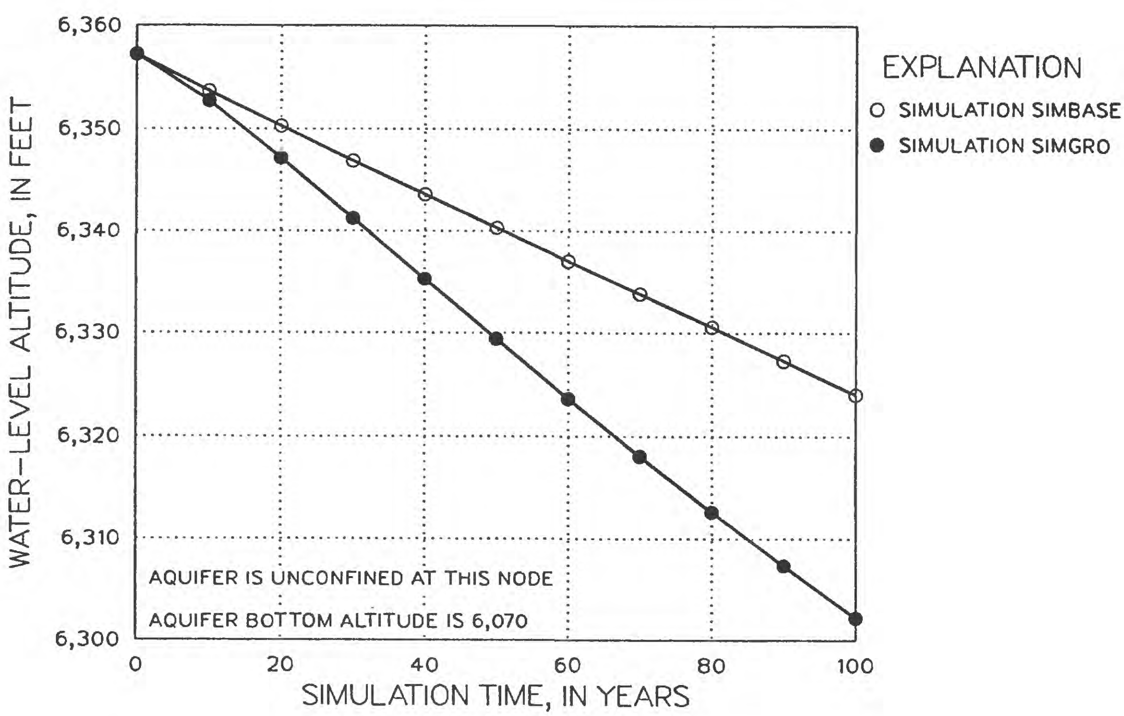

Figure 12.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (58,14,1).

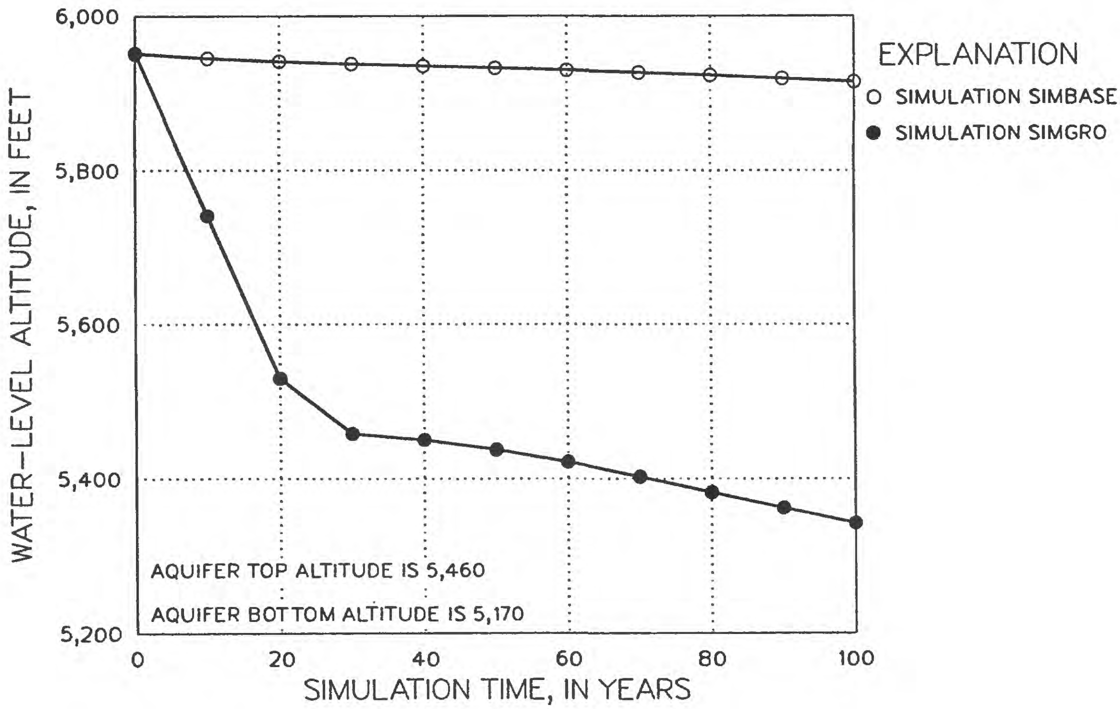

Figure 13.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (59,22,1).

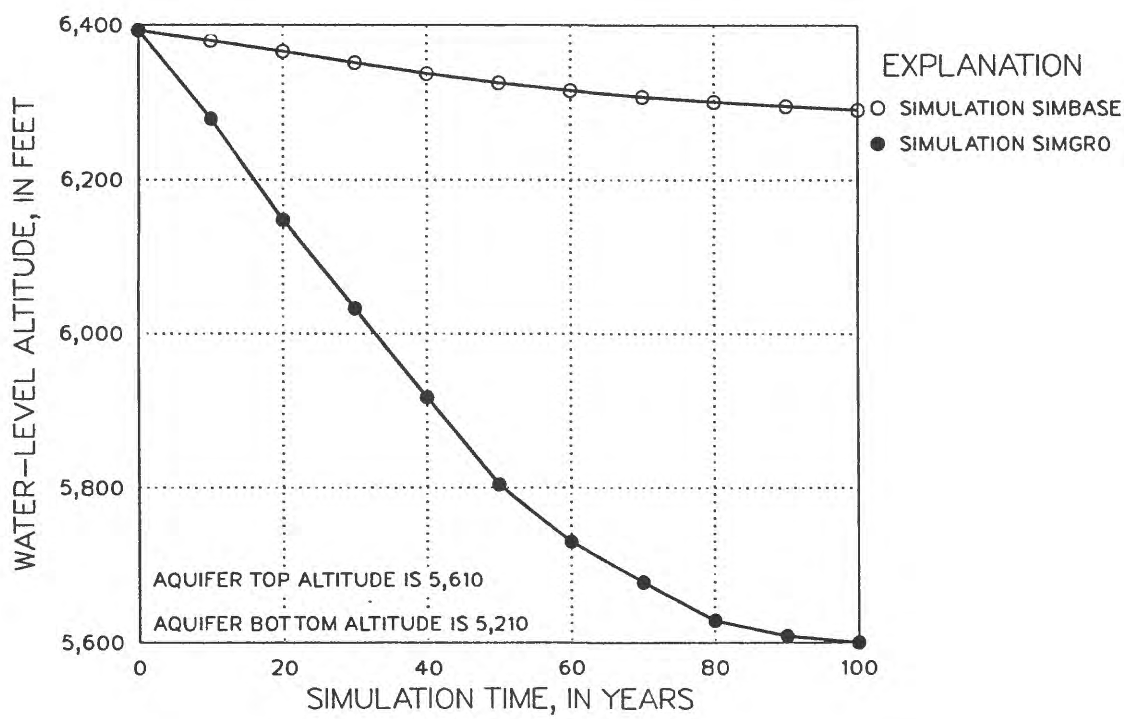

Figure 14.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (49,14,2).

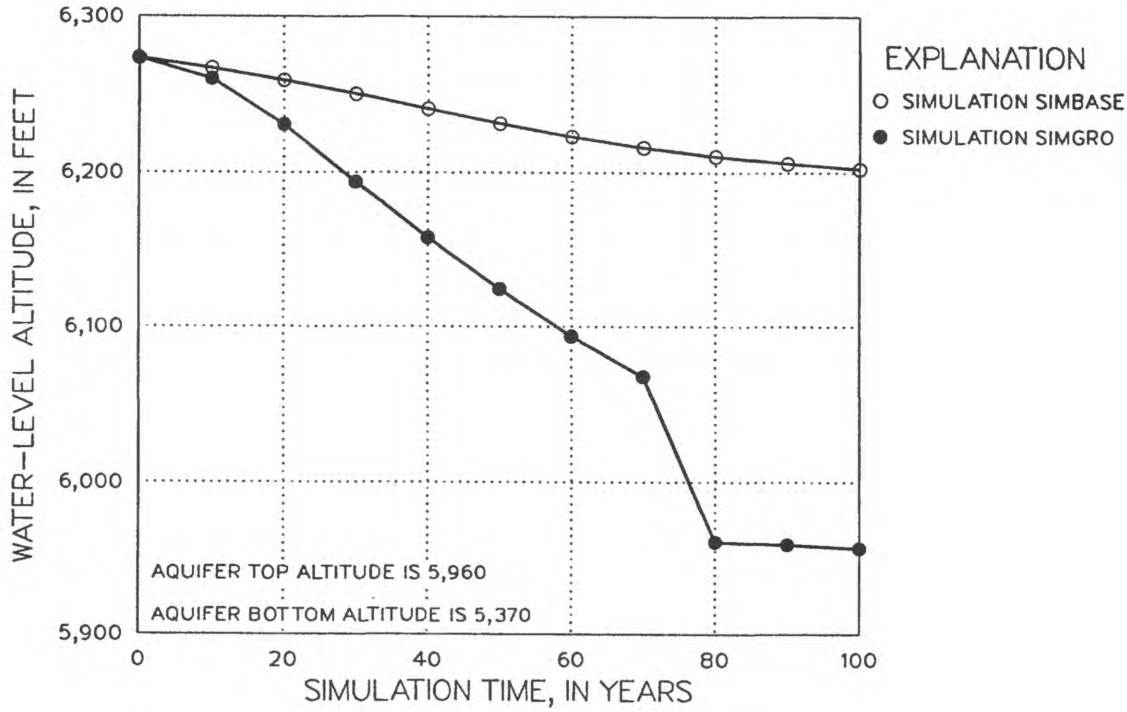

Figure 15.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (49,26,2).

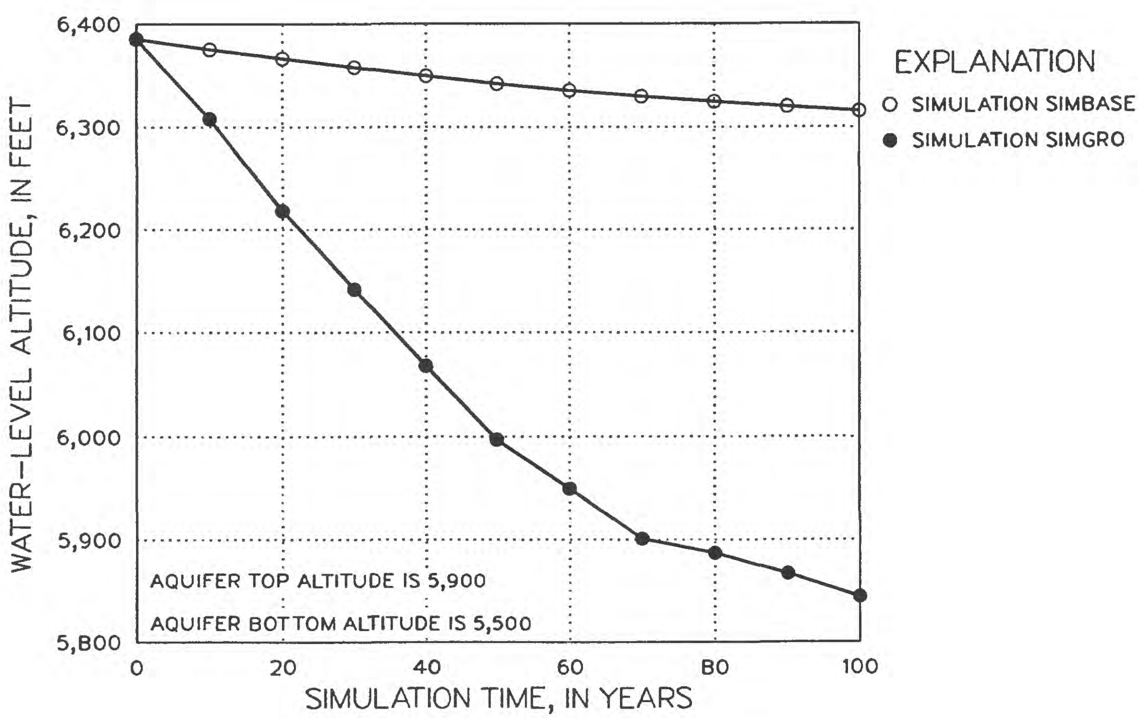

Figure 16.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (52,15,2).

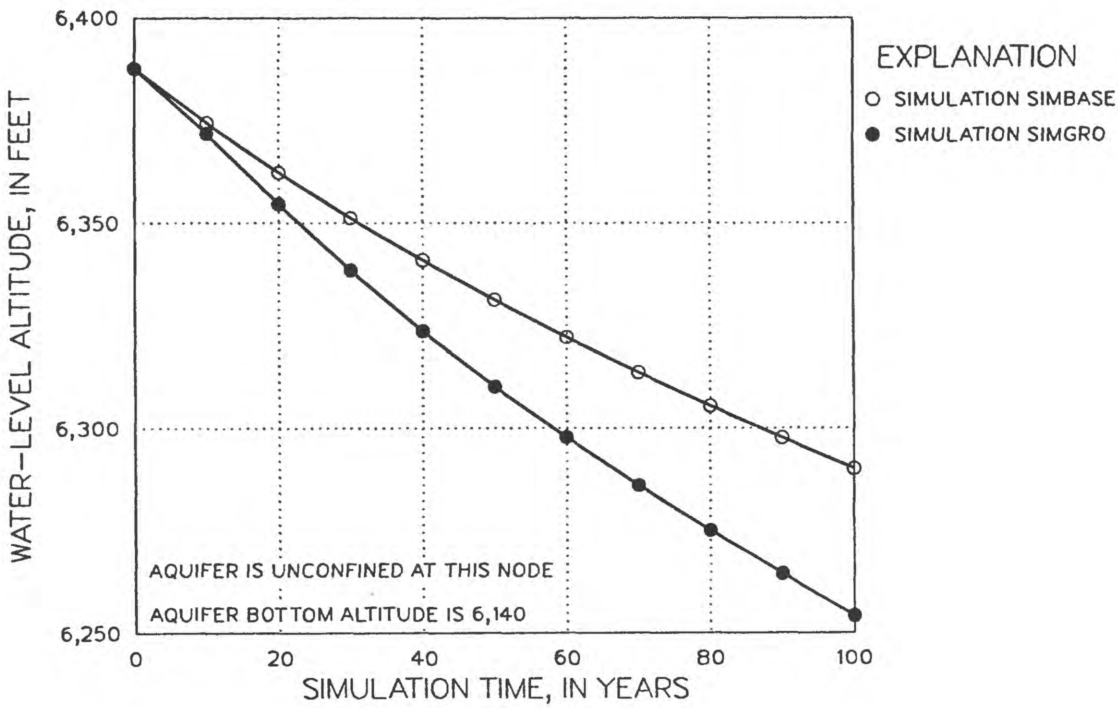

Figure 17.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (57,15,2).

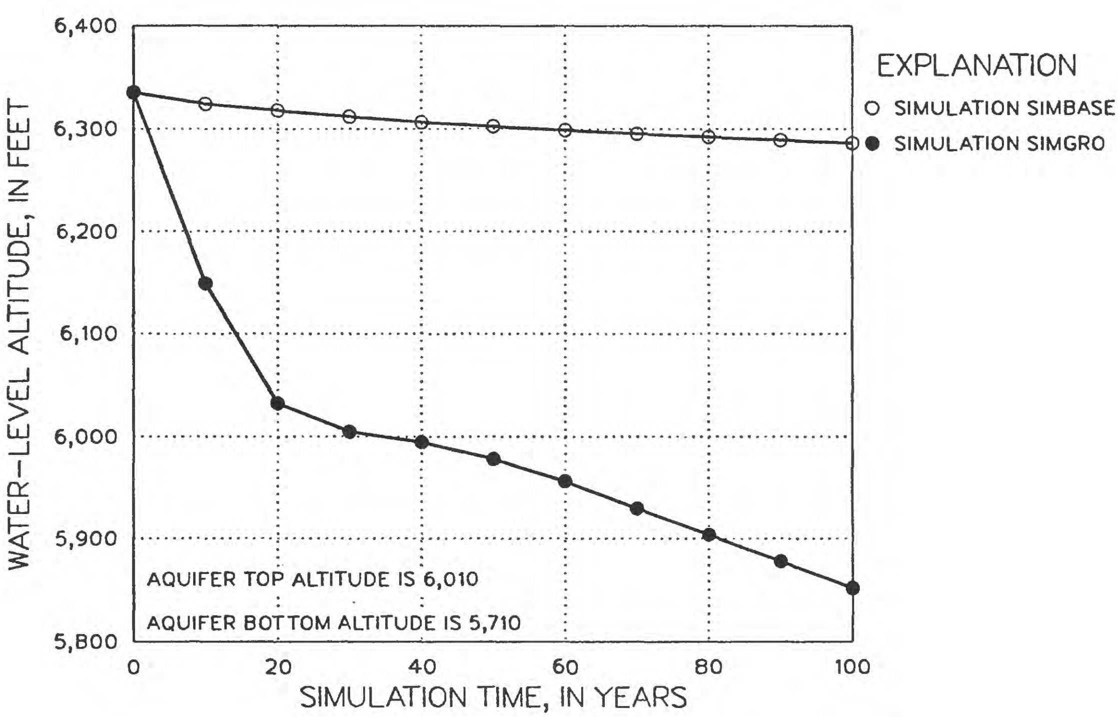

Figure 18.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (58,19,2).

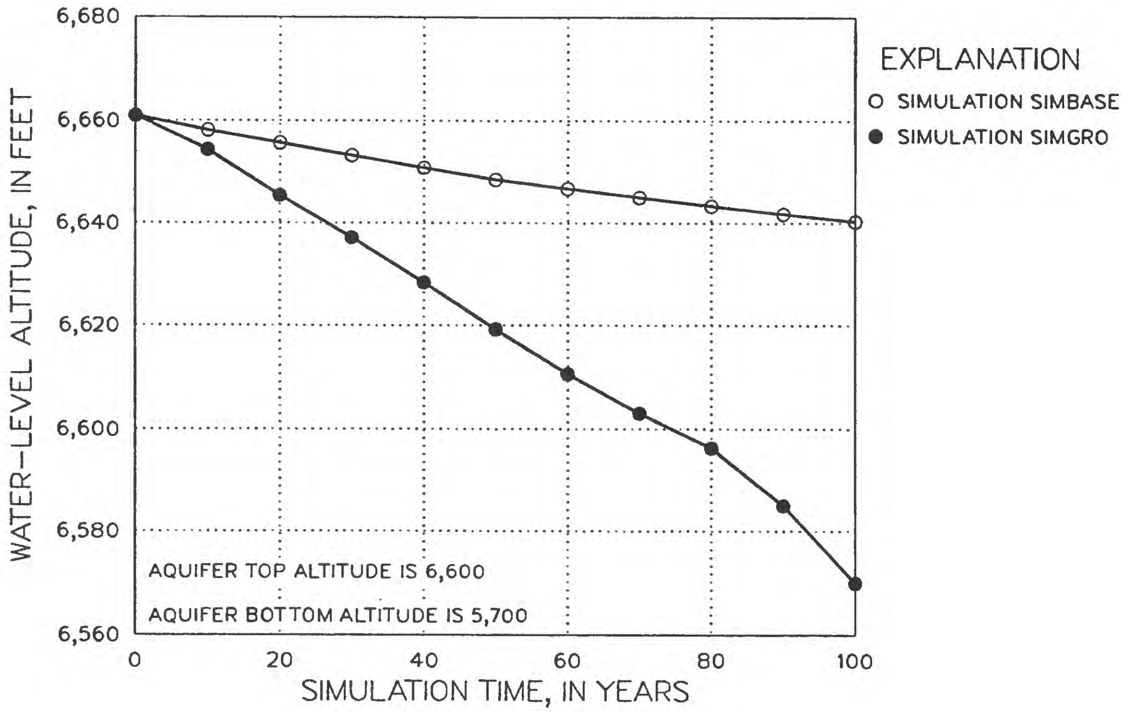

Figure 19.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (46,23,3).

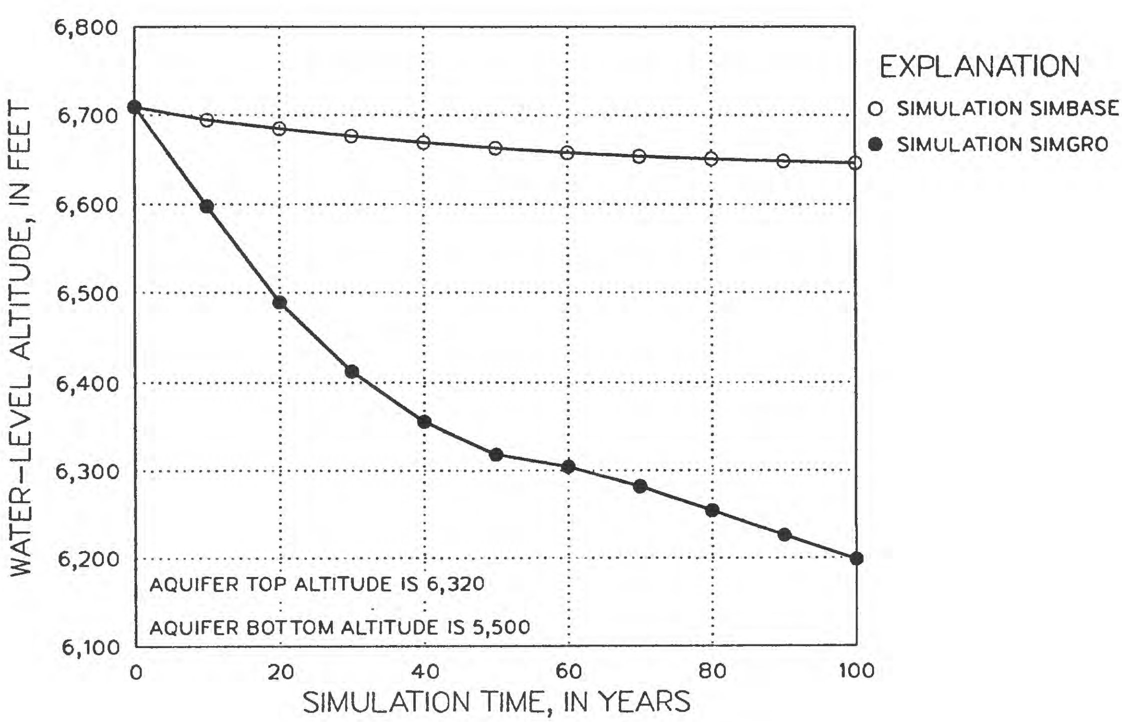

Figure 20.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (47,13,3).

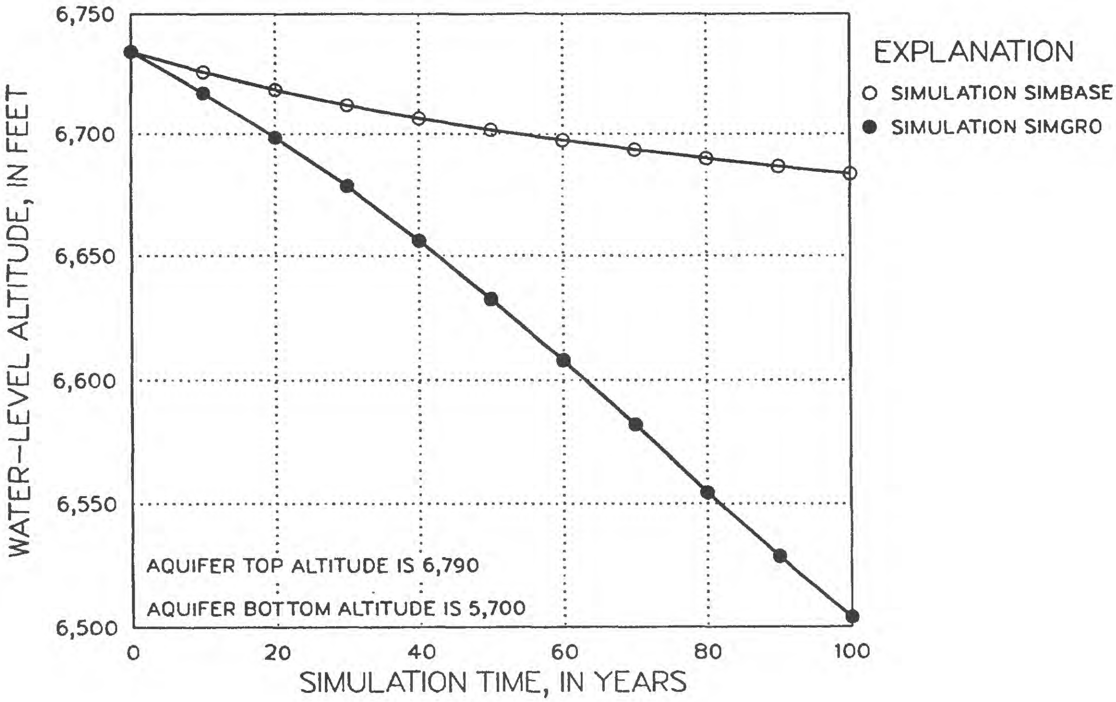

Figure 21.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (52,16,3).

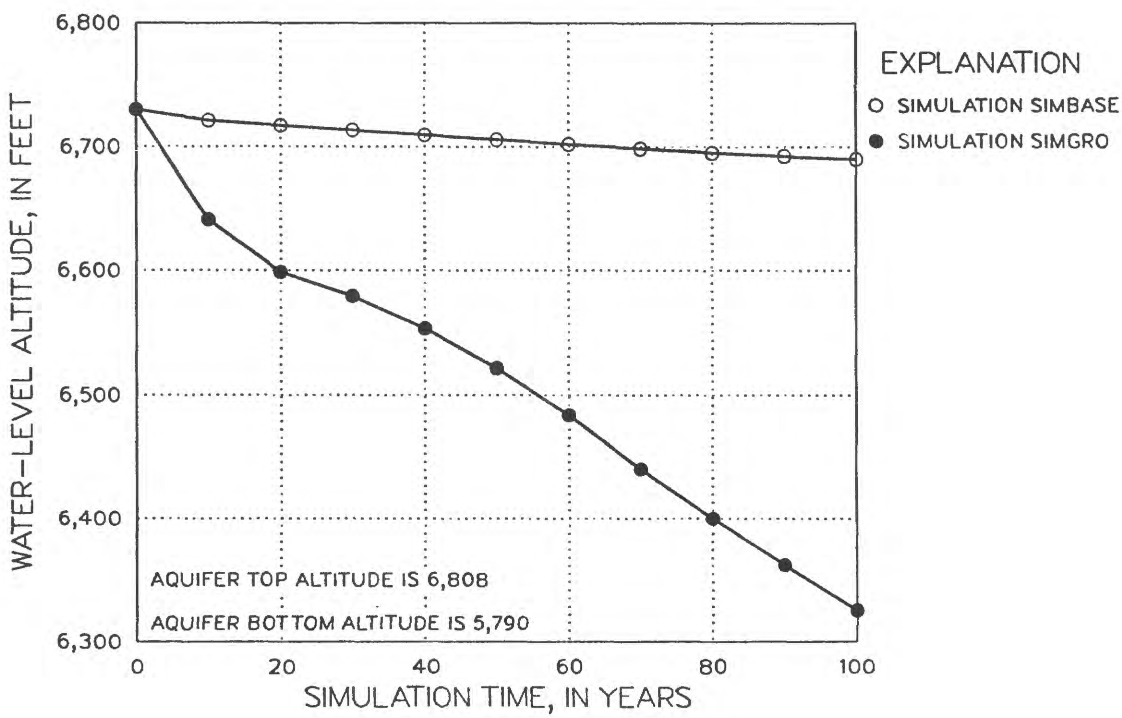

Figure 22.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (55,19,3).

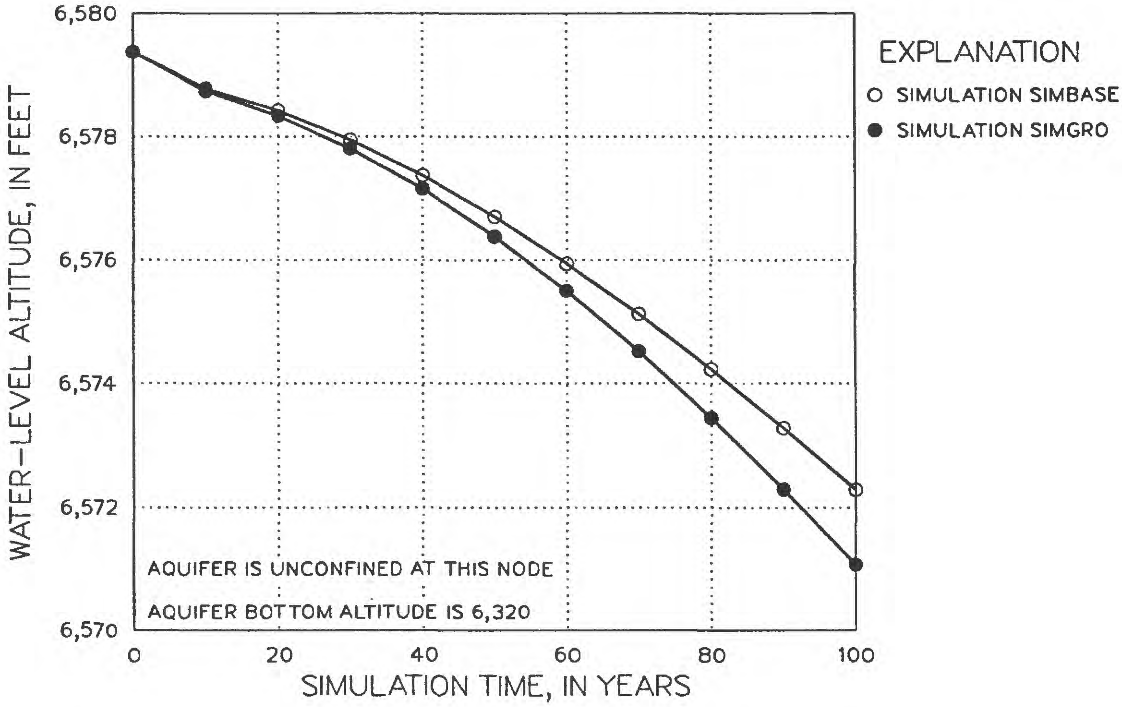

Figure 23.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (58,16,3).

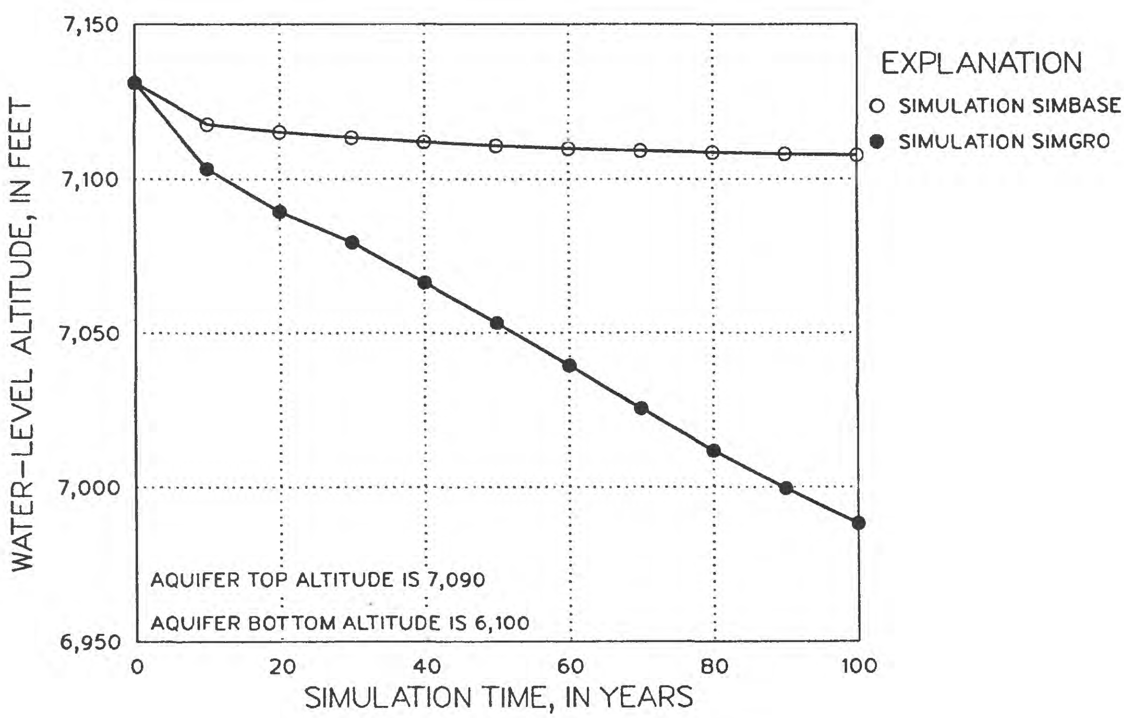

Figure 24.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (46,13,4).

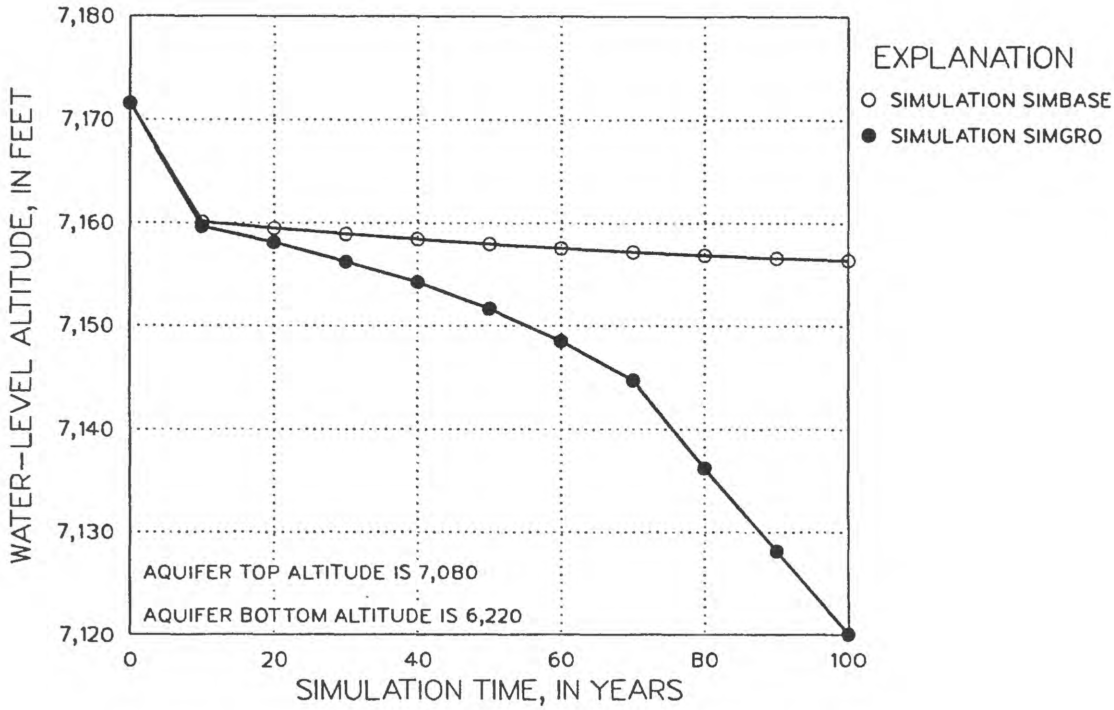

Figure 25.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (46,19,4).

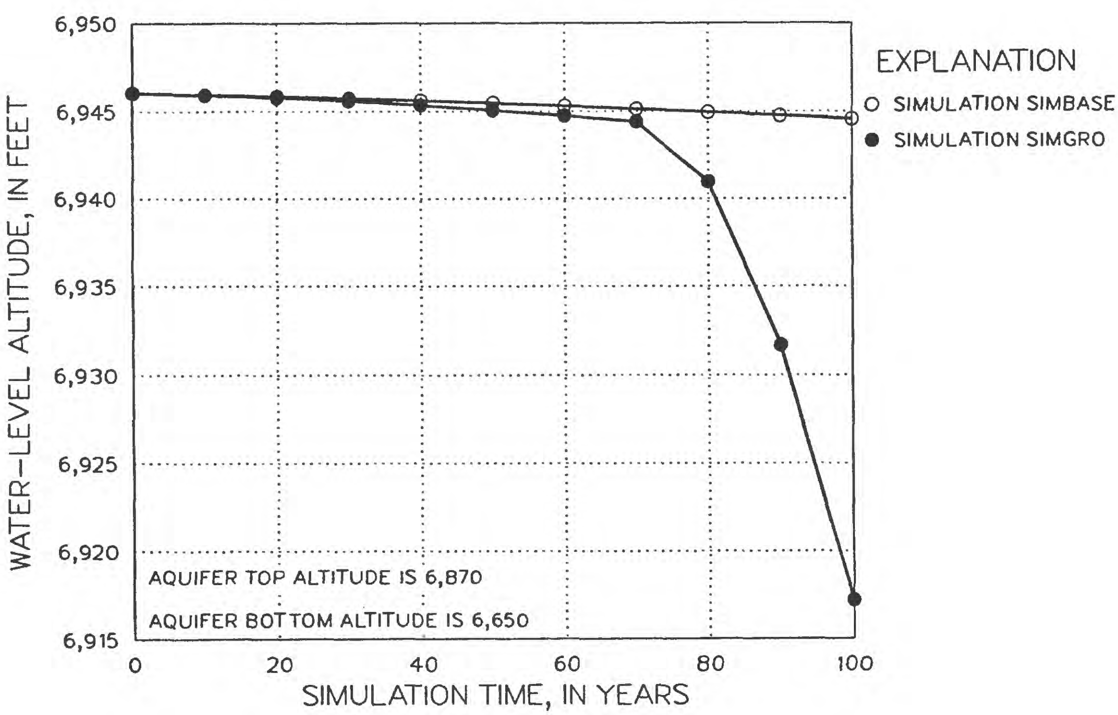

Figure 26.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (50,24,4).

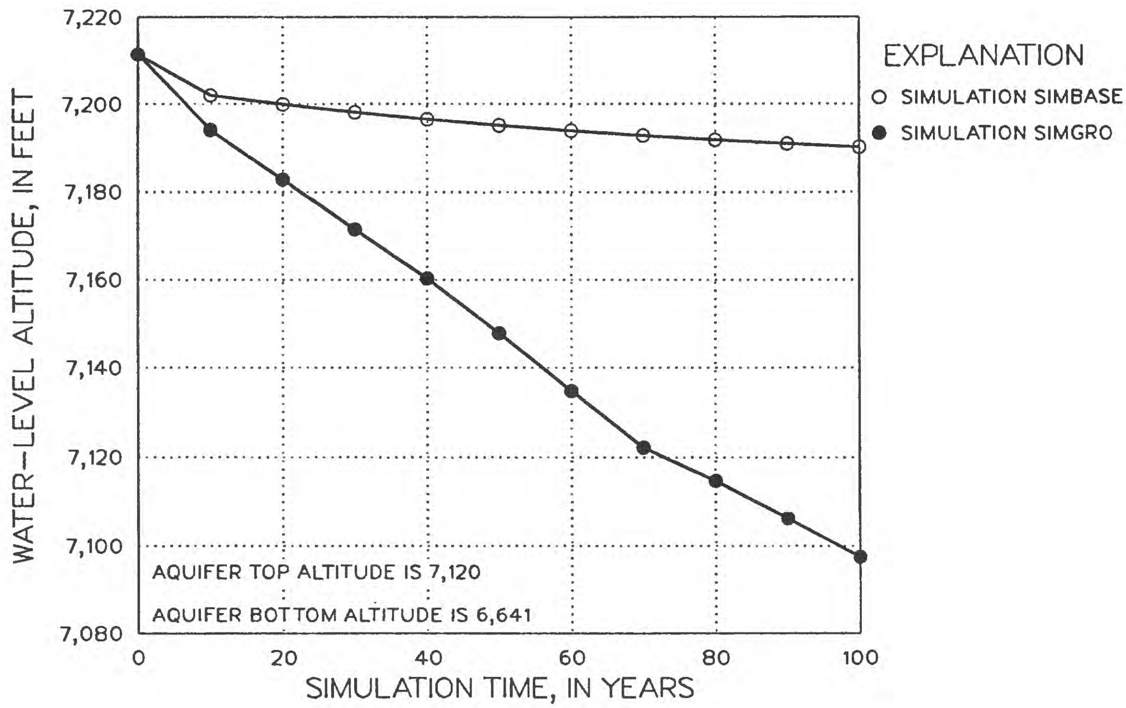

Figure 27.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (51,17,4).

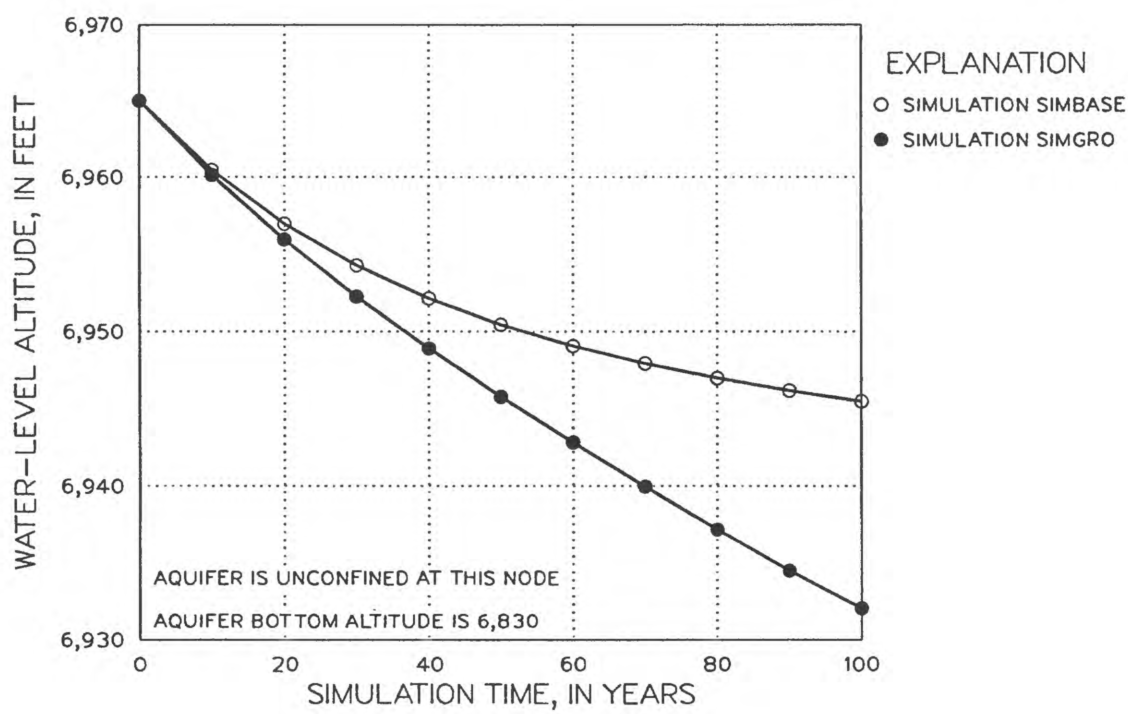

Figure 28.--Model-calculated heads for simulations SIMBASE and SIMGRO at model node (53,16,4).

Table 9.--*2085 ground-water budget for simulation SIMBASE*

[Values in cubic feet per second; --, not applicable]

Sources and sinks	Aquifer				Total, four aquifers
	Laramie-Fox Hills	Arapahoe	Denver	Dawson	
Sources					
Recharge from precipitation----------	4.1	4.9	7.7	37.0	53.7
Recharge from streams, reservoirs, other surface-water bodies, and alluvial aquifers--	6.7	4.9	4.5	5.1	21.2
Net flow from overlying aquifer-----------------	1.0	12.8	11.4	--	--
Net rate of decrease in ground-water storage---	17.4	43.4	12.4	13.8	87.0
Total flow from sources--	29.2	66.0	36.0	55.9	161.9
Sinks					
Discharge to streams, springs, other surface-water bodies, and alluvial aquifers------	3.8	3.8	5.4	21.4	34.4
Net flow to underlying aquifer-----------------	--	1.0	12.8	11.4	--
Pumping------------------	25.4	61.2	17.8	23.1	127.5
Total flow to sinks------	29.2	66.0	36.0	55.9	161.9

Simulation SIMGRO

This simulation takes into account projected population growth and associated ground-water development in the southern part of the Denver basin. It also is the basis from which the other three "growth" simulations (SIMGWELL, SIMGWSUB, and SIMGCITY) are derived. A population-growth projection was supplied by officials of the City of Colorado Springs; it is based on the following assumptions: (1) Total El Paso County population grows approximately linearly from about 100,000 in 1960 to about 1,380,000 in 2085 (actual 1986 population is about 370,000); (2) population within Colorado Springs current (1986) city limits reaches 561,000 in the year 2023, then ceases to increase; (3) from 1985 to 2023, Colorado Springs contains about 75 percent of the El Paso County population (the actual Colorado Springs 1986 population is about 262,700); and (4) 70 percent of the population growth in El Paso County outside the City of Colorado Springs occurs in the area underlain by the Denver basin bedrock-aquifer system, and this growing part of the population in El

Paso County outside Colorado Springs is dependent on the water in those aquifers. Per capita water use is assumed to be 150 gal/d, including commercial and light-industrial use. Heavy industrial and irrigation use of water from the bedrock aquifers is assumed not to change substantially from 1985 rates.

The projected distribution of the growing population and its associated water needs is based, to a large extent, on a map showing planned land use in part of El Paso County (El Paso County-Colorado Springs-Fountain Cooperative Planning Program, 1986). In areas where growth is projected, model-grid nodes are assigned to primary-, secondary-, or tertiary-growth areas (pl. 2), where the primary-growth area is assumed to be the fastest growing. In the primary growth area, simulated ground-water development proceeds to the limit on well pumpage imposed by Colorado State rules and regulations (Colorado Department of Natural Resources, 1986) with respect to nontributary ground water. No attempt was made to differentiate areas underlain by tributary or nontributary ground water, as defined in Colorado Revised Statutes (1985). The discharge limit is defined by the following equation:

$$\text{Annual discharge limit} = \text{Area} \times M \times SY \times 0.01;$$

where Area = area of parcel of land; in this case, area of a grid block;
M = saturated thickness of water-yielding materials; and
SY = average specific yield of water-yielding materials.

For the purposes of assigning a withdrawal limit for each grid cell, the average specific yield of the water-yielding materials in each aquifer is assumed to be that given in the State rules and regulations (Colorado Department of Natural Resources, 1985): Dawson aquifer, 20 percent; Denver and Arapahoe aquifers, 17 percent; and Laramie-Fox Hills aquifer, 15 percent. In the primary-growth area, the discharge limit is projected to be reached in 2045. The resulting population density for the primary-growth area after 2045 averages 3.7 persons per acre. For comparison, current (1986) population density in Colorado Springs is about 7 persons per acre.

Population in the secondary-growth area is assumed to begin growing at the beginning of the simulation, and it is allowed to reach an average density of 2.0 persons per acre in 2055. Population in the tertiary-growth area begins growing in 2055, and it is allowed to reach an average density of 1.0 person per acre in 2075. Pumpage is simulated from each aquifer present in a given growth area, and it is distributed among the aquifers based on the relative quantities of available water, calculated in accordance with the State rules and regulations (Colorado Department of Natural Resources, 1985).

The 2085 potentiometric-surface maps for simulation SIMGRO (pl. 5) for the lower three aquifers show distinct troughs in northwestern El Paso and southeastern Douglas Counties. The potentiometric surface in the Dawson aquifer is lower than that in the SIMBASE simulation, but no trough is evident. Drawdowns in the southern part of the basin for the period 1985 to 2085 (pl. 5) exceed 1,300 ft in the Laramie-Fox Hills aquifer north of the town of Black Forest. In the Arapahoe aquifer, drawdowns exceed 900 ft in about the same location. In the Denver aquifer, drawdowns are more than 600 ft along the Interstate Highway 25 corridor between Monument and Larkspur, and they exceed 700 ft locally. In the Dawson aquifer, drawdowns exceed 200 ft in a small area north of Monument.

Hydrographs showing heads during simulation SIMGRO are plotted with those for simulation SIMBASE, for ease of comparison, in figures 9 through 28. Because of the larger pumpage during simulation SIMGRO, most of the SIMGRO hydrographs indicate a marked divergence from corresponding SIMBASE hydrographs. This divergence in results between the first two simulations indicates the large extent to which pumpage rates affect model results. The various simulations predict effects of particular pumping rates; if actual pumping rates differ substantially from those simulated, the effects on the aquifer system can be expected to differ substantially from the model results. Many of the SIMGRO hydrographs exhibit a flattening (fig. 9) or inflection (fig. 13) when the aquifer goes from a confined state to an unconfined state. Some of the hydrographs have a pronounced change in slope at the 70-year mark (fig. 20). This abrupt downward trend is found in areas that are strongly affected by the start of development in the tertiary-growth area after 70 years of simulation.

Pumping from the southern part of the basin reaches about 171 ft^3/s during the final pumping period of the simulation (table 8). The basin-wide ground-water budget for the final pumping period of simulation SIMGRO is shown in table 10. For this time period, 2075 to 2085, about 229 ft^3/s of the 280 ft^3/s being pumped from the system is coming from a decrease in ground-water storage. By 2085, pumping constitutes more than 90 percent of simulated discharge from the bedrock aquifers. The simulated 2085 pumping rate is more than five times the predevelopment recharge rate; about 80 percent of this pumpage is supplied by withdrawal of ground water from storage. Simulated discharge to alluvial aquifers and surface water, as of 2085, is about 43 percent of the predevelopment rate. The total inflow and outflow in 2085 are about twice those for simulation SIMBASE. As a result of the increased pumpage relative to simulation SIMBASE, 6 nodes go dry in the southern part of the basin, are eliminated from the model, and become completely inactive; locations of these 6 nodes are listed in table 8.

Discharge to the two major drainage basins in El Paso County is decreased by the pumpage. In the Monument Creek (fig. 29) and Black Squirrel Creek (fig. 30) basins, the exchange of water between the bedrock aquifers and the streams or alluvial aquifer changes from a net discharge from the bedrock aquifers to a net recharge to the bedrock aquifers. For the Monument Creek basin, discharge from the bedrock aquifers decreases from about 5.2 ft^3/s in 1985 to about -0.6 ft^3/s in 2085. For comparison, discharge at the end of the SIMBASE simulation was about 3.7 ft^3/s. For the Black Squirrel Creek basin, discharge from the bedrock aquifers decreases from about 1.6 ft^3/s in 1985 to about -0.9 ft^3/s in 2085; at the end of the SIMBASE simulation, discharge was about 1.2 ft^3/s. Although these changes in discharge during simulation SIMGRO are small in comparison with the pumping rates in the southern part of the basin, the effects of the pumpage on discharge to streams and alluvial aquifers are large relative to that discharge.

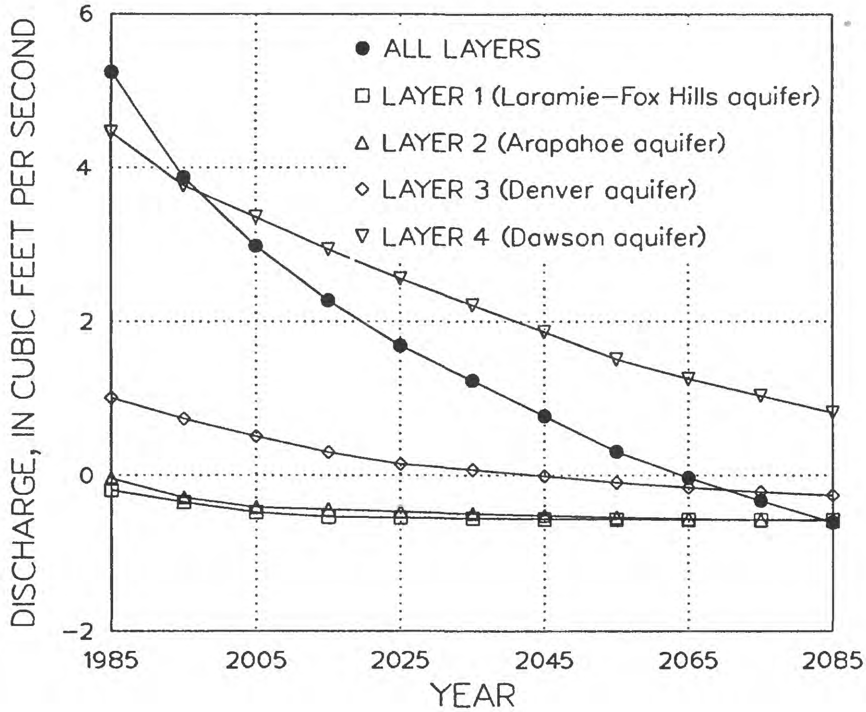

Figure 29.--Simulated discharge to alluvial aquifer and surface water in Monument Creek basin for simulation SIMGRO.

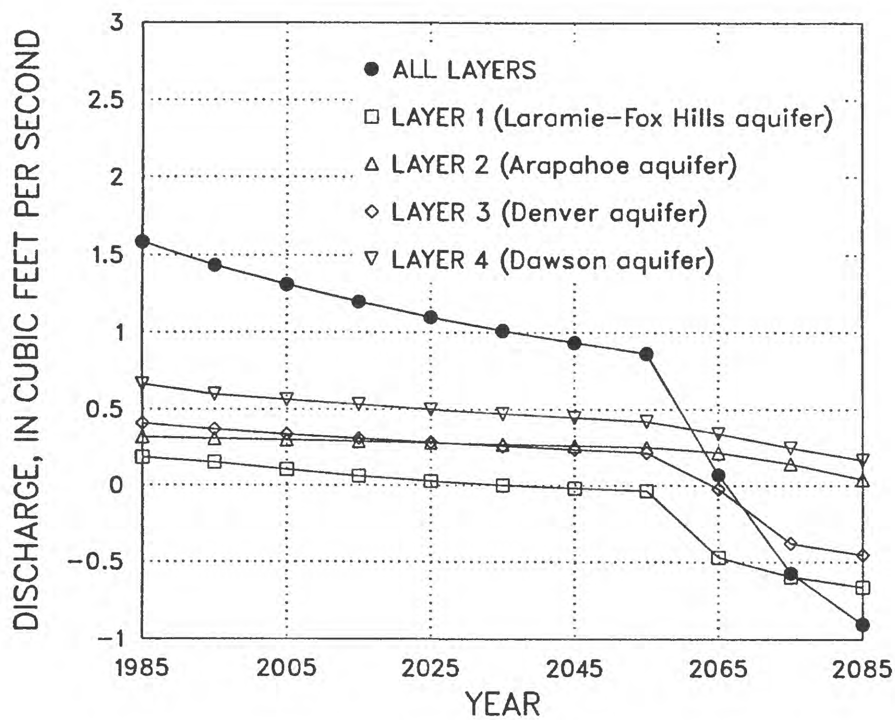

Figure 30.--Simulated discharge to alluvial aquifer and surface water in Black Squirrel Creek basin for simulation SIMGRO.

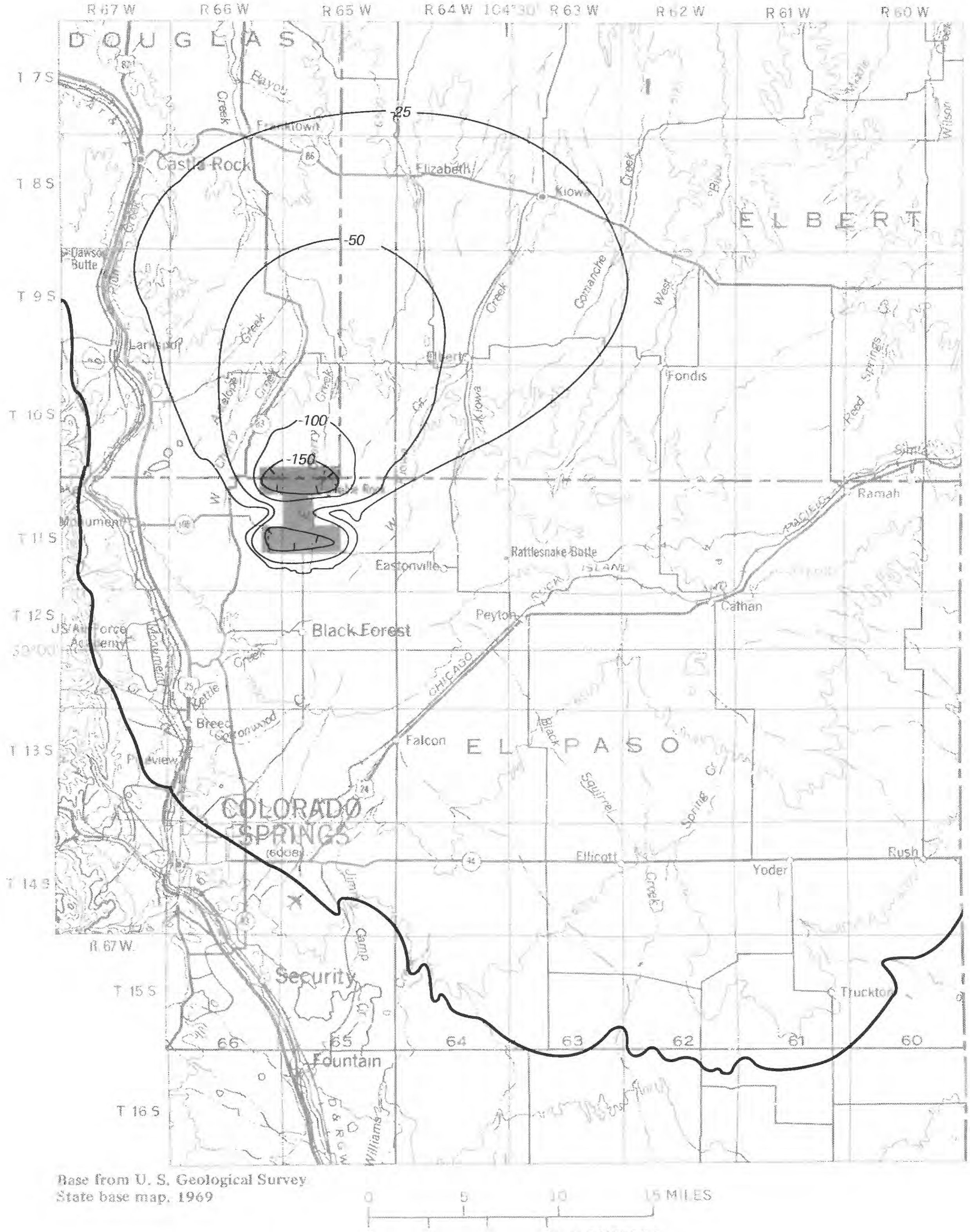

Figure 31.--Simulated head difference for 2085 between simulations SIMGWELL and SIMGRO for the Laramie-Fox Hills aquifer.

EXPLANATION

HYPOTHETICAL WELL FIELD

—-100— LINE OF EQUAL HEAD DIFFERENCE--Shows difference between 2085 heads calculated for simulations SIMGWELL and SIMGRO. Negative values indicate SIMGWELL head is lower than SIMGRO head. Interval, in feet, is variable

——— APPROXIMATE LIMIT OF LARAMIE-FOX HILLS AQUIFER

Table 10.--*2085 ground-water budget for simulation SIMGRO*

[Values in cubic feet per second; --, not applicable]

Sources and sinks	Aquifer				Total, four aquifers
	Laramie-Fox Hills	Arapahoe	Denver	Dawson	
Sources					
Recharge from precipitation---------	4.1	4.9	7.7	37.0	53.7
Recharge from streams, reservoirs, other surface-water bodies, and alluvial aquifers--	7.1	5.1	5.6	5.7	23.5
Net flow from overlying aquifer----------------	1.2	14.1	15.8	--	--
Net rate of decrease in ground-water storage---	71.8	87.7	39.6	29.7	228.8
Total flow from sources--	84.2	111.8	68.7	72.4	306.0
Sinks					
Discharge to streams, springs, other surface-water bodies, and alluvial aquifers------	3.6	3.6	3.9	14.6	25.7
Net flow to underlying aquifer----------------	--	1.2	14.1	15.8	--
Pumping-----------------	80.6	107.0	50.7	42.0	280.3
Total flow to sinks------	84.2	111.8	68.7	72.4	306.0

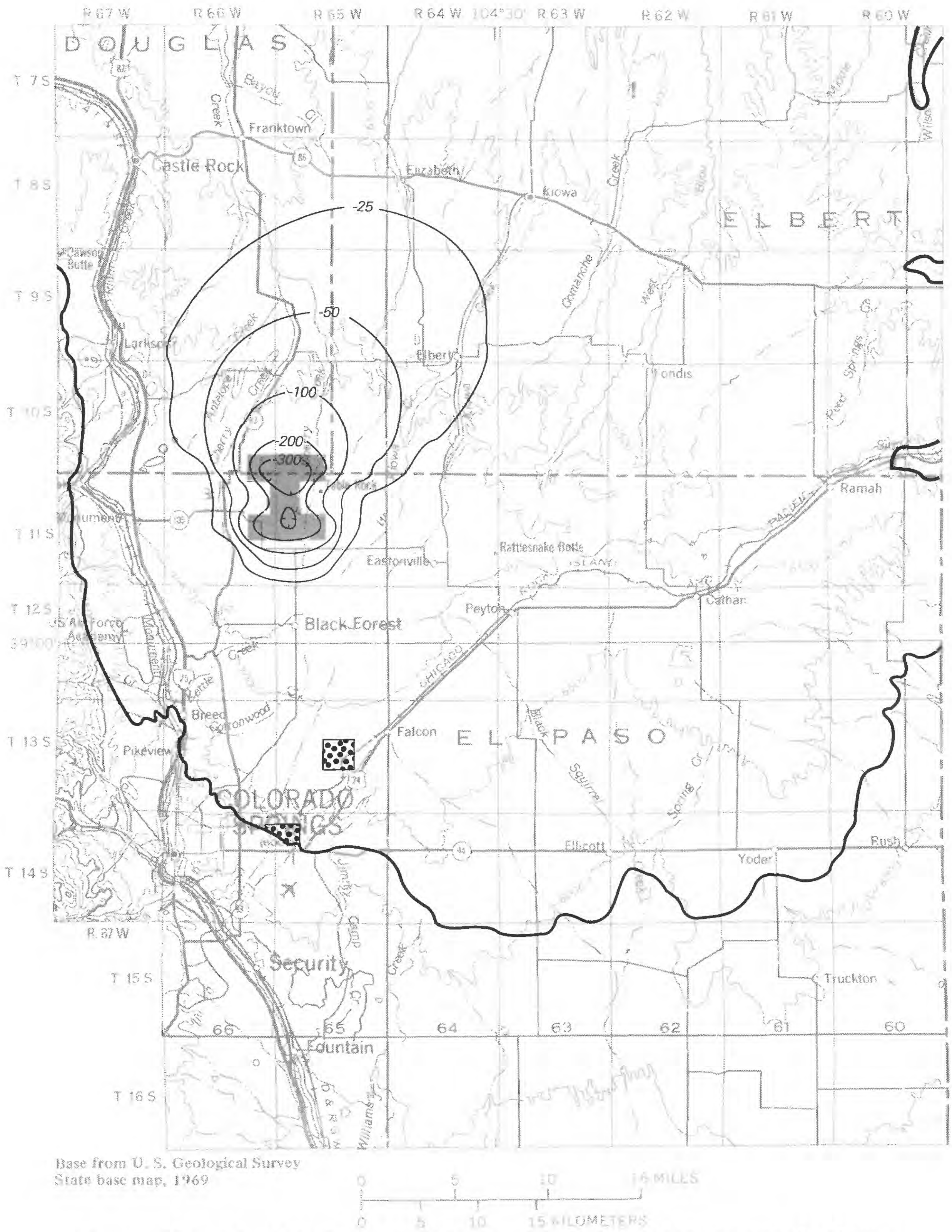

Figure 32.--Simulated head difference for 2085 between simulations SIMGWELL and SIMGRO for the Arapahoe aquifer.

EXPLANATION

HYPOTHETICAL WELL FIELD

DEWATERED AREA-- Water level in aquifer falls below base of aquifer during model simulation

— -200— LINE OF EQUAL HEAD DIFFERENCE--Shows difference between 2085 heads calculated for simulations SIMGWELL and SIMGRO. Negative values indicate SIMGWELL head is lower than SIMGRO head. Interval, in feet, is variable

——— APPROXIMATE LIMIT OF ARAPAHOE AQUIFER

Simulation SIMGWELL

In this simulation, pumpage from a hypothetical well field is added to the pumpage in simulation SIMGRO, beginning in 2025. The simulated well field pumps from the lower three aquifers at the locations shown on plate 2 at 10 million gal/d (15.5 ft^3/s). The arrangement of pumped nodes simulating the well field was chosen to avoid the potential problem of excessive drawdown near the center of the well field. Pumpage is distributed among these three aquifers as follows: Laramie-Fox Hills, 3.0 ft^3/s; Arapahoe, 6.2 ft^3/s; and Denver, 6.3 ft^3/s. The location and pumping rate of the hypothetical well field were selected by the City of Colorado Springs. The distribution of pumpage was chosen to be similar to the relative proportion of water contained in each aquifer at the selected site, except that the Dawson aquifer was excluded at the request of the City.

For this simulation and the following two simulations, effects of the imposed stresses on the potentiometric surfaces are illustrated by maps showing differences in water levels between simulations, where the standard for comparison is the potentiometric surface calculated for the end of simulation SIMGRO. Negative values indicate that the calculated potentiometric surface derived from simulation SIMGWELL is below that for simulation SIMGRO. For example, results of simulation SIMGRO for the Laramie-Fox Hills aquifer indicate that drawdown at the town of Elbert over the 100-year simulation period would be about 800 ft (pl. 5). For simulation SIMGWELL, the water-level difference for the Laramie-Fox Hills aquifer at Elbert would be about -45 ft (fig. 31), or an incremental drawdown of 45 ft. The total simulated drawdown at Elbert therefore would be about 845 ft.

The 2085 water-level difference map for the Laramie-Fox Hills aquifer for simulation SIMGWELL (fig. 31) shows an incremental drawdown of 50 to 150 ft in the vicinity of the well field. The area showing more than 25 ft of incremental drawdown extends north from the well field as far as Franktown and Kiowa. The incremental water-level change maps for the Arapahoe and Denver aquifers (figs. 32 and 33) show smaller areas affected by 25 ft or more of incremental drawdown. However, incremental drawdowns in the area surrounding

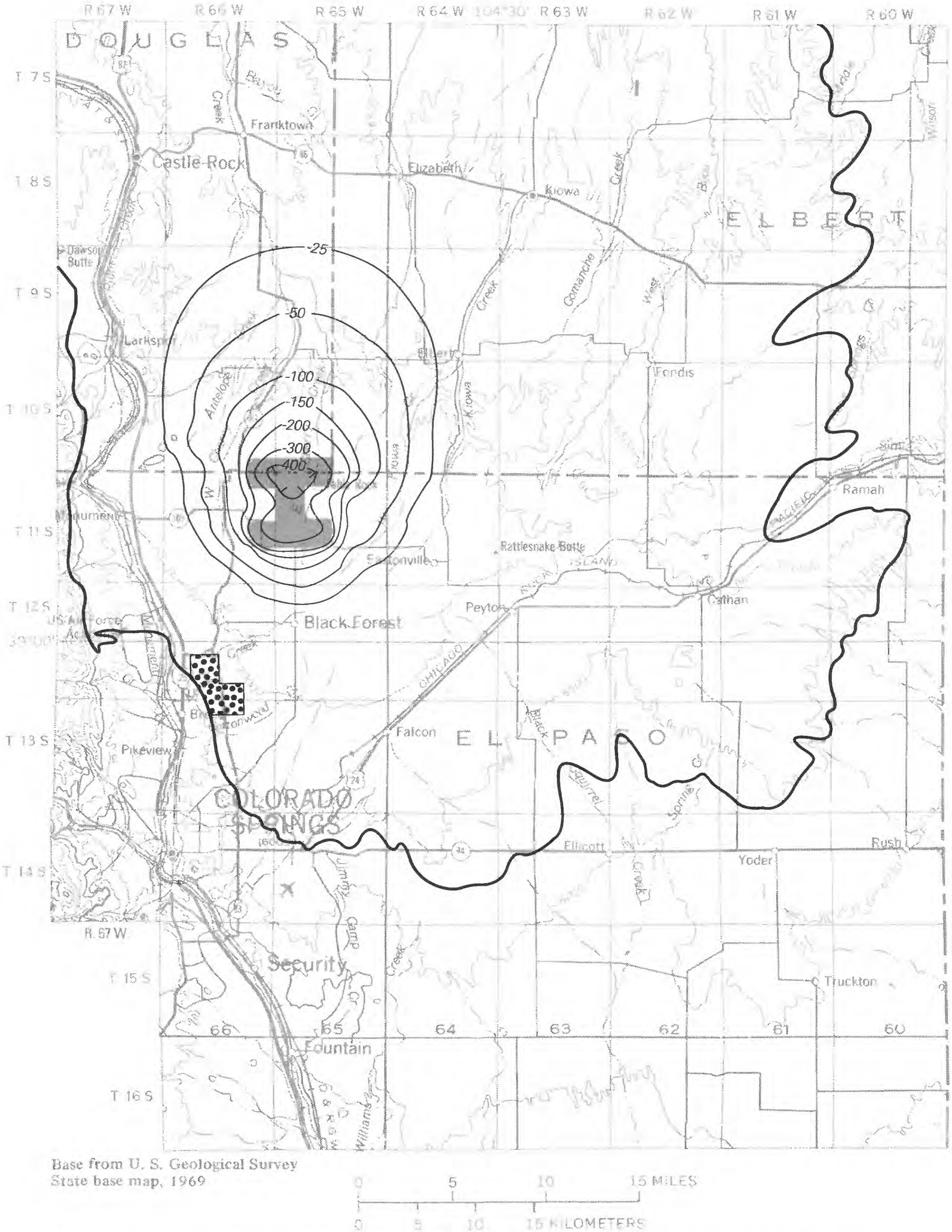

Figure 33.--Simulated head difference for 2085 between simulations SIMGWELL and SIMGRO for the Denver aquifer.

EXPLANATION

HYPOTHETICAL WELL FIELD

DEWATERED AREA--Water level in aquifer falls below base of aquifer during model simulation

—-200— **LINE OF EQUAL HEAD DIFFERENCE--Shows difference between 2085 heads calculated for simulations SIMGWELL and SIMGRO. Negative values indicate SIMGWELL head is lower than SIMGRO head. Interval, in feet, is variable**

APPROXIMATE LIMIT OF DENVER AQUIFER

the well field exceed 150 ft in the Arapahoe aquifer, and they exceed 200 ft in the Denver aquifer. The asymmetry evident in the lines of equal incremental water-level change on these maps is due to the location of the hypothetical well field relative to areas of the aquifers that are simulated as unconfined. In general, nodes in the three growth areas previously described either are simulated as unconfined at the start of the simulations or are converted from confined to unconfined during the simulations. Because the hypothetical well field is located at the northern edge of the growth areas, simulated drawdown is more widespread in the area of confined conditions north of the growth areas, and it is less widespread in the area of generally unconfined conditions in the growth areas.

The simulated water-level difference for the Dawson aquifer due to the hypothetical well field is small, not exceeding 5 ft, because of four factors: (1) The hypothetical well field does not withdraw from the Dawson aquifer, (2) the confining unit separating the Denver and Dawson aquifers has small vertical conductance, (3) the simulated transmissivity of the Dawson aquifer is large relative to the simulated transmissivity of the underlying Denver aquifer, and (4) nearly all the nodes representing the Dawson aquifer are simulated as unconfined by the end of the simulations. No water-level difference map is shown for the Dawson aquifer because of the small difference.

The basin-wide water budget for this simulation (table 11) indicates the effects of pumpage from the well field. Most of the water withdrawn by the well field comes from a decrease in ground-water storage. Other effects on the ground-water budget are similar to, but slightly more pronounced than, those for simulation SIMGRO. As a result of the additional pumpage, one more node goes dry, compared to simulation SIMGRO; locations of the 7 nodes that go dry in the southern part of the basin are listed in table 8.

Figure 34.--Simulated head difference for 2085 between simulations SIMGWSUB and SIMGRO for the Laramie-Fox Hills aquifer.

EXPLANATION

HYPOTHETICAL WELL FIELD

— -100— **LINE OF EQUAL HEAD DIFFERENCE--Shows difference between 2085 heads calculated for simulations SIMGWSUB and SIMGRO. Negative values indicate SIMGWSUB head is lower than SIMGRO head. Interval, in feet, is variable**

APPROXIMATE LIMIT OF LARAMIE-FOX HILLS AQUIFER

Table 11.--*2085 ground-water budget for simulation SIMGWELL*

[Values in cubic feet per second; --, not applicable]

Sources and sinks	Aquifer				Total, four aquifers
	Laramie-Fox Hills	Arapahoe	Denver	Dawson	
Sources					
Recharge from precipitation----------	4.1	4.9	7.7	37.0	53.7
Recharge from streams, reservoirs, other surface-water bodies, and alluvial aquifers--	7.1	5.1	5.6	5.8	23.6
Net flow from overlying aquifer-----------------	1.2	14.1	16.5	--	--
Net rate of decrease in ground-water storage---	74.8	93.9	45.2	30.0	243.9
Total flow from sources--	87.2	118.0	75.0	72.8	321.2
Sinks					
Discharge to streams, springs, other surface-water bodies, and alluvial aquifers------	3.6	3.6	3.9	14.3	25.4
Net flow to underlying aquifer----------------	--	1.2	14.1	16.5	--
Pumping------------------	83.6	113.2	57.0	42.0	295.8
Total flow to sinks------	87.2	118.0	75.0	72.8	321.2

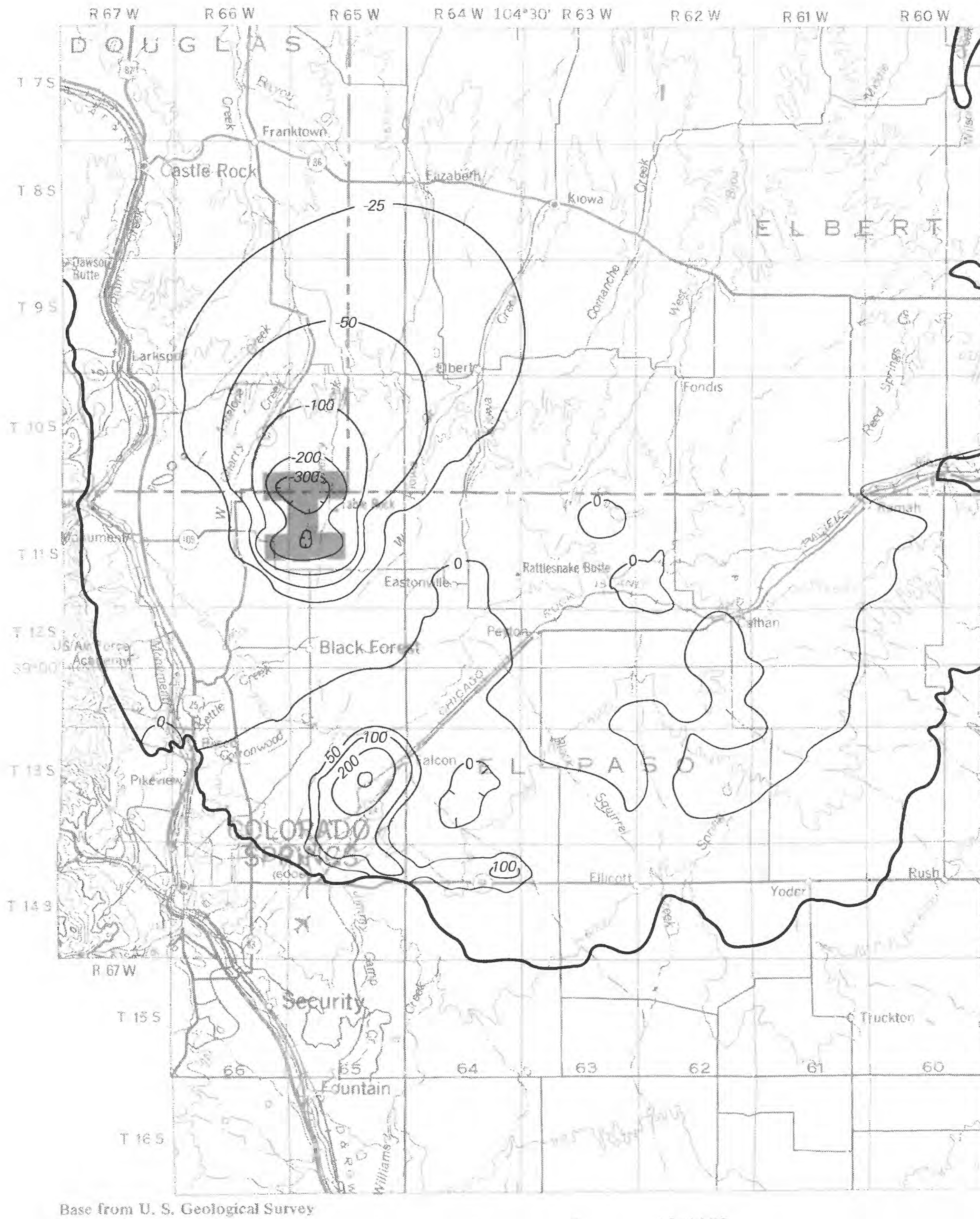

Figure 35.--Simulated head difference for 2085 between simulations SIMGWSUB and SIMGRO for the Arapahoe aquifer.

EXPLANATION

HYPOTHETICAL WELL FIELD

— -100— LINE OF EQUAL HEAD DIFFERENCE--Shows difference between 2085 heads calculated for simulations SIMGWSUB and SIMGRO. Negative values indicate SIMGWSUB head is lower than SIMGRO head. Interval, in feet, is variable

—— APPROXIMATE LIMIT OF ARAPAHOE AQUIFER

Simulation SIMGWSUB

In this simulation, the water needs of the growing population, in the part of the primary-growth area east of Colorado Springs (generally along U.S. Highway 24 and Colorado Highway 94) are assumed to be supplied from the hypothetical well field described for simulation SIMGWELL, beginning in 1985. Pumpage from the well field increases, until it reaches 10 million gal/d; then, pumpage begins in that part of the growth area to fulfill the remainder of that population's needs. The net effect is a relocation of some of the pumping simulated in SIMGRO, while the total pumpage for each pumping period is kept the same as in SIMGRO.

The water-level difference in the vicinity of the well field for each aquifer is similar to that for simulation SIMGWELL. However, in the primary-growth area east of Colorado Springs, water levels are substantially higher than at the end of simulation SIMGRO, because of decreased pumpage there. The maximum difference in this area is more than 200 ft in the Laramie-Fox Hills and Arapahoe aquifers (figs. 34 and 35), and more than 150 ft in the Denver aquifer (fig. 36). In the Dawson aquifer, the difference in head does not exceed 40 ft, and the difference exceeds 10 ft at only 2 nodes (columns 19 and 20 in row 55). For this reason, a water-level difference map is not shown for the Dawson aquifer.

In comparison with simulation SIMGRO, simulation SIMGWSUB results in fewer nodes going dry: three rather than six (see table 8 for a list of the nodes that go dry). This represents a substantial decrease in area of aquifer dewatered. Because fewer nodes go dry, the pumping rate shown in the ground-water budget (table 12) is slightly larger than the rate shown for simulation SIMGRO (table 10). The main difference between the two water budgets is the distribution of the source and sink rates among the various aquifers.

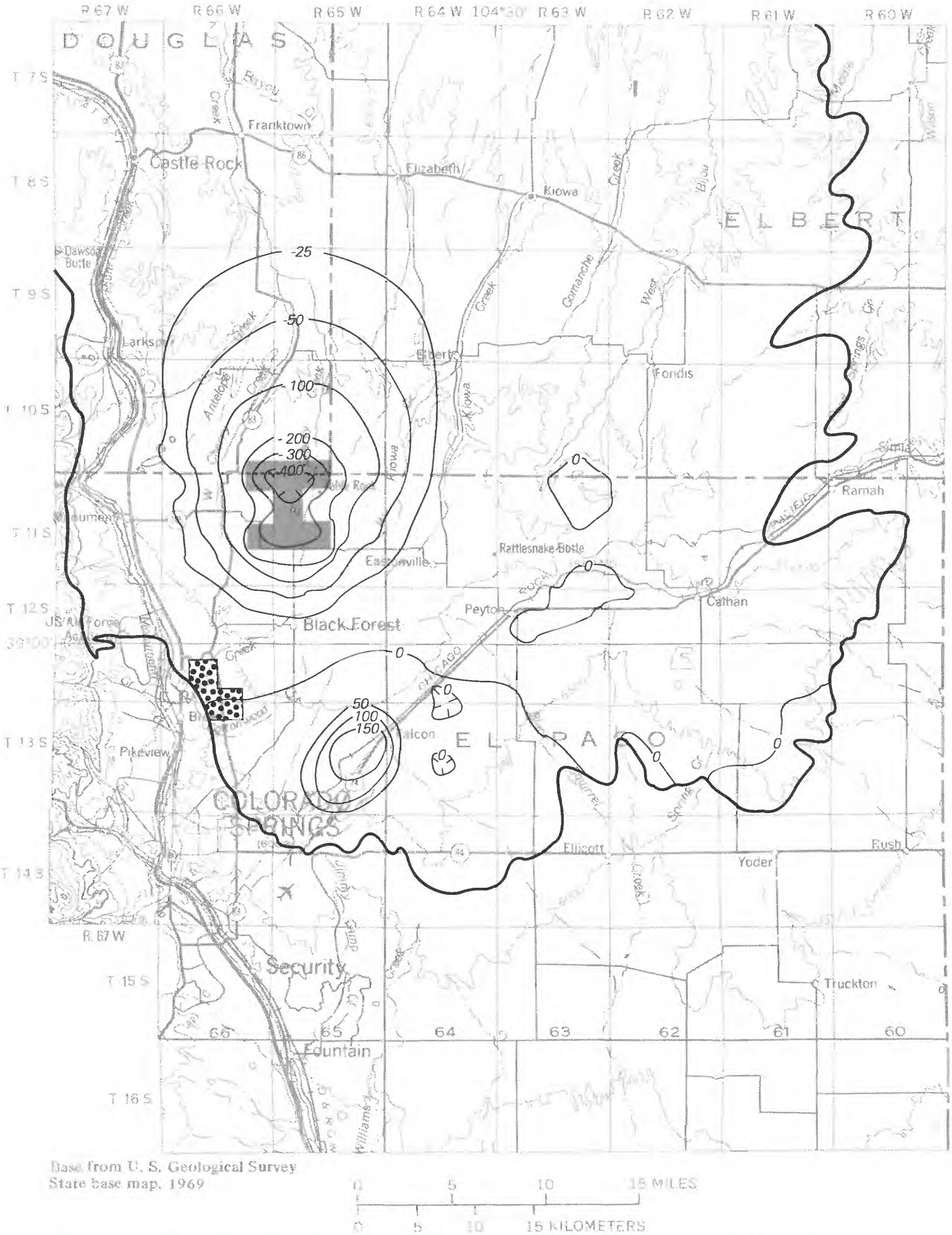

Figure 36.--Simulated head difference for 2085 between simulations SIMGWSUB and SIMGRO for the Denver aquifer.

EXPLANATION

HYPOTHETICAL WELL FIELD

DEWATERED AREA--Water level in aquifer falls below base of aquifer during model simulation

—-200— LINE OF EQUAL HEAD DIFFERENCE--Shows difference between 2085 heads calculated for simulations SIMGWSUB and SIMGRO. Negative values indicate SIMGWSUB head is lower than SIMGRO head. Interval, in feet, is variable

APPROXIMATE LIMIT OF DENVER AQUIFER

Table 12.--*2085 ground-water budget for simulation SIMGWSUB*

[Values in cubic feet per second; --, not applicable]

Sources and sinks	Aquifer				Total, four aquifers
	Laramie-Fox Hills	Arapahoe	Denver	Dawson	
Sources					
Recharge from precipitation----------	4.1	4.9	7.7	37.0	53.7
Recharge from streams, reservoirs, other surface-water bodies, and alluvial aquifers--	7.1	5.1	5.7	5.7	23.6
Net flow from overlying aquifer----------------	1.2	14.1	16.6	--	--
Net rate of decrease in ground-water storage---	66.6	88.9	43.3	30.0	228.8
Total flow from sources--	79.0	113.0	73.3	72.7	306.1
Sinks					
Discharge to streams, springs, other surface-water bodies, and alluvial aquifers------	3.6	3.6	4.0	14.2	25.4
Net flow to underlying aquifer----------------	--	1.2	14.1	16.6	--
Pumping------------------	75.4	108.2	55.2	41.9	280.7
Total flow to sinks------	79.0	113.0	73.3	72.7	306.1

Figure 37.--Simulated head difference for 2085 between simulations SIMGCITY and SIMGRO for the Laramie-Fox Hills aquifer.

EXPLANATION

APPROXIMATE AREA OF COLORADO SPRINGS UNDERLAIN BY LARAMIE-FOX HILLS AQUIFER

— -100— LINE OF EQUAL HEAD DIFFERENCE--Shows difference between 2085 heads calculated for simulations SIMGCITY and SIMGRO. Negative values indicate SIMGCITY head is lower than SIMGRO head. Interval 50 feet.

APPROXIMATE LIMIT OF LARAMIE-FOX HILLS AQUIFER

Simulation SIMGCITY

Of the five simulations described, the pumpage from the bedrock aquifers is largest for simulation SIMGCITY. In this simulation, pumpage in Colorado Springs from the lower three aquifers, as allowed according to regulations of the City of Colorado Springs (1985) and at the withdrawal limit calculated according to the State rules and regulations (Colorado Department of Natural Resources, 1985), is simulated in addition to the pumpage of simulation SIMGRO. Officials of Colorado Springs provided estimates of these withdrawal limits within the city water-service area. These estimates are: Laramie-Fox Hills aquifer, 10.3 ft^3/s; Arapahoe aquifer, 8.3 ft^3/s; Denver aquifer, 1.7 ft^3/s; total for lower 3 aquifers, 20.3 ft^3/s.

The water-level difference map for the Laramie-Fox Hills aquifer (fig. 37) indicates incremental water-level declines of as much as about 200 ft, relative to the potentiometric surface calculated for the end of simulation SIMGRO; however, the effects are localized to the immediate vicinity of the city. In the Arapahoe aquifer, incremental drawdowns locally are more than 200 ft (fig. 38). In the Denver aquifer, incremental drawdowns locally are more than 100 ft (fig. 39). Incremental water-level declines in the Dawson aquifer do not exceed 3 ft; therefore, they are not mapped.

The basin-wide ground-water budget (table 13) reflects only part of the additional water assigned to be pumped from the aquifers underlying the city, because of the large number of nodes going dry in simulation SIMGCITY. All of the additional simulated pumpage (relative to simulation SIMGRO) comes from ground water in storage. Eleven nodes go dry in the southern part of the basin in this simulation; whereas, six went dry in simulation SIMGRO; the nodes that go dry are listed in table 8. Although the city, according to the State rules and regulations, may withdraw more than 20 ft^3/s from the lower three aquifers, the model results indicate that a long-term effect of this pumping rate is extensive dewatering of the aquifers.

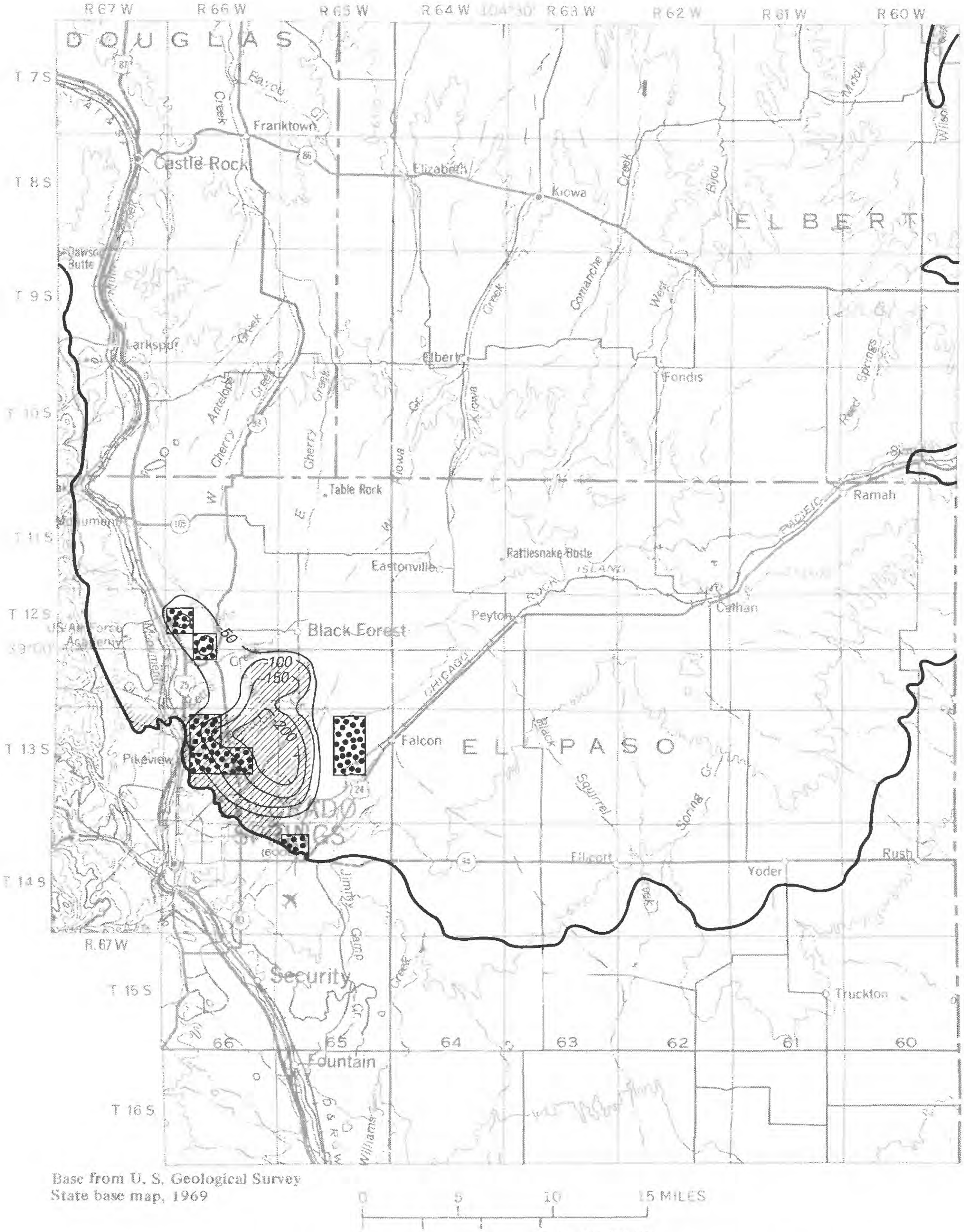

Figure 38.--Simulated head difference for 2085 between simulations SIMGCITY and SIMGRO for the Arapahoe aquifer.

EXPLANATION

APPROXIMATE AREA OF COLORADO SPRINGS UNDERLAIN BY ARAPAHOE AQUIFER

DEWATERED AREA--Water level in aquifer falls below base of aquifer during model simulation

— -100— **LINE OF EQUAL HEAD DIFFERENCE--Shows difference between 2085 heads calculated for simulations SIMGCITY and SIMGRO. Negative values indicate SIMGCITY head is lower than SIMGRO head. Interval 50 feet.**

APPROXIMATE LIMIT OF ARAPAHOE AQUIFER

Table 13.--*2085 ground-water budget for simulation SIMGCITY*

[Values in cubic feet per second; --, not applicable]

Sources and sinks	Aquifer				Total, four aquifers
	Laramie-Fox Hills	Arapahoe	Denver	Dawson	
Sources					
Recharge from precipitation----------	4.1	4.9	7.7	37.0	53.7
Recharge from streams, reservoirs, other surface-water bodies, and alluvial aquifers--	6.5	5.1	5.7	5.8	23.1
Net flow from overlying aquifer----------------	1.2	14.2	15.9	--	--
Net rate of decrease in ground-water storage---	82.0	93.1	40.8	29.7	245.6
Total flow from sources--	93.8	117.3	70.1	72.5	322.4
Sinks					
Discharge to streams, springs, other surface-water bodies, and alluvial aquifers------	3.6	3.6	3.9	14.6	25.7
Net flow to underlying aquifer----------------	--	1.2	14.2	15.9	--
Pumping-----------------	90.2	112.5	52.0	42.0	296.7
Total flow to sinks------	93.8	117.3	70.1	72.5	322.4

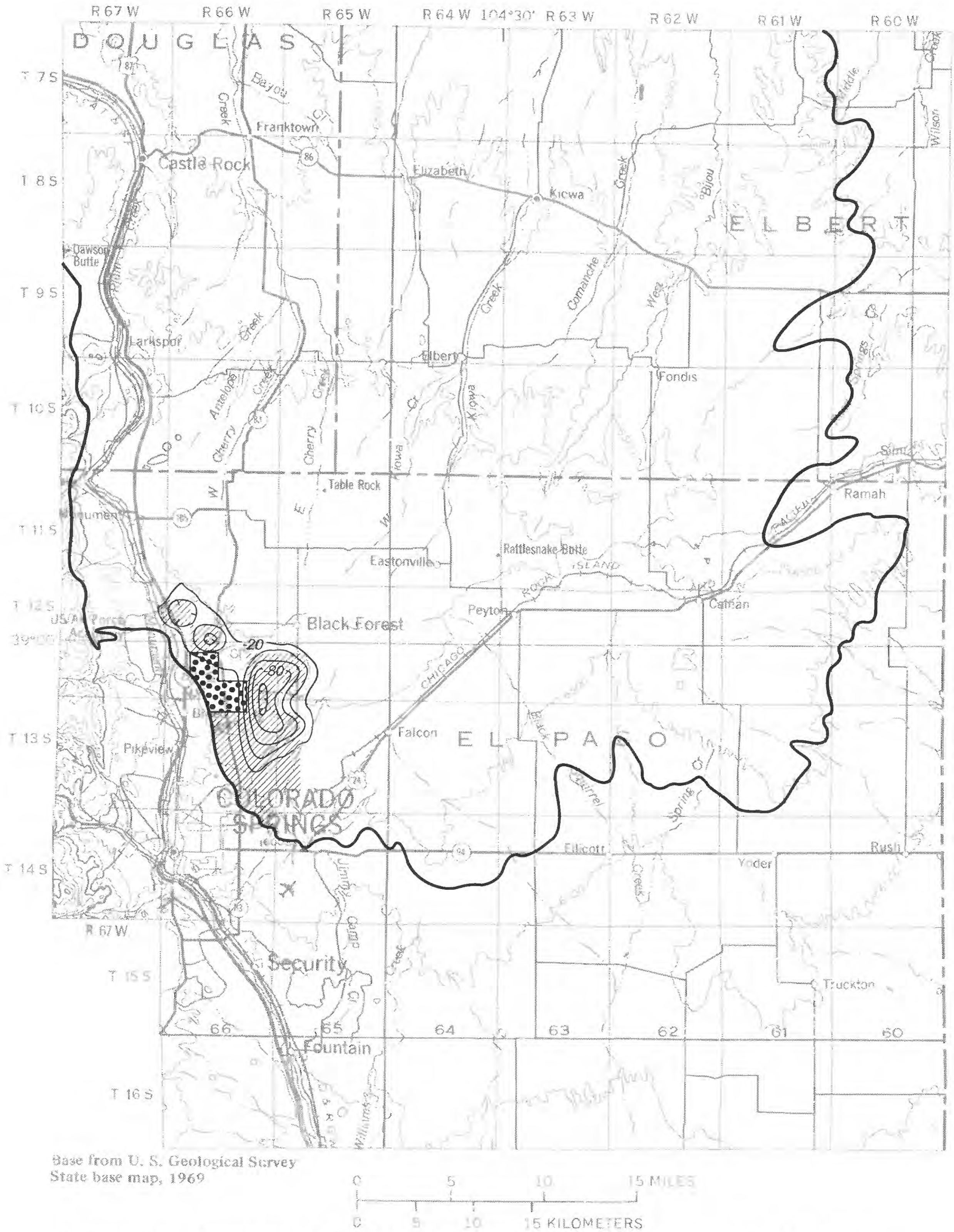

Figure 39.--Simulated head difference for 2085 between simulations SIMGCITY and SIMGRO for the Denver aquifer.

EXPLANATION

APPROXIMATE AREA OF COLORADO SPRINGS UNDERLAIN BY DENVER AQUIFER

DEWATERED AREA--Water level in aquifer falls below base of aquifer during model simulation

— -80 — LINE OF EQUAL HEAD DIFFERENCE--Shows difference between 2085 heads calculated for simulations SIMGCITY and SIMGRO. Negative values indicate SIMGCITY head is lower than SIMGRO head. Interval 20 feet.

APPROXIMATE LIMIT OF DENVER AQUIFER

MODEL SENSITIVITY

The values chosen for the aquifer properties that are assigned in the digital model are subject to varying amounts of uncertainty for any or all of the following reasons: (1) A single value must represent either a large area or a large volume of aquifer, within which the property likely will be variable; (2) the property has not been measured at enough points to know in detail the spatial variability from block to block or within individual blocks; (3) the property (such as recharge from precipitation) may vary with time; and (4) point measurements are subject to errors, such as those resulting from poor measurement technique and lack of well-completion details.

Aquifer properties required for the model, such as transmissivity, vertical conductance, storage coefficient or specific yield, recharge from precipitation, and maximum rate of leakage from streams or alluvial aquifers to bedrock aquifers, affect the model calibration to varying, but measurable, degrees. Other aspects of the model, such as nature of the boundary conditions, also affect the calibration and usefulness of the model, but these may be difficult to quantify.

Knowledge of how sensitive the model is to changes in the value of a particular property can be gained by varying the value of that property, while all other aspects of the model are kept the same. If the model-calculated results, either in terms of head distribution or of recharge and discharge rates, vary greatly in response to relatively small changes in the property, the model can be considered sensitive to that property. That property must be well defined to give satisfactory results. If the model is insensitive to a property, satisfactory results may be obtained even if that property is not well defined.

Transmissivity, vertical conductance, and precipitation recharge were varied, one property at a time, in the steady-state model to determine the sensitivity of the model to each property. Mean square error of the model-calculated heads and discharge to Monument and Black Squirrel Creek basins were plotted to allow comparison between the three sensitivity tests (figs. 40, 41, and 42). One way to compare sensitivity among the various properties is to look at the extent a property must be changed to produce a given change in mean square error. A mean-square-error value of 4,000 ft^2 was arbitrarily chosen as a criterion for comparison purposes, because the curves shown in figures 40, 41, and 42 are relatively well defined in the vicinity of this value. By graphical interpretation of figures 40, 41, and 42, the model results can be seen to be as good or better than those represented by this arbitrary value of mean square error, when: (1) Transmissivity is varied within a range of -18 to +40 percent of the calibrated value, (2) vertical conductance is varied within a range of 0.64 to 2.1 times the calibrated value, or (3) recharge from precipitation is varied within a range of -40 to +27 percent of the calibrated value. If the accuracy with which one of these characteristics is known can be improved by direct measurement to a range smaller than that listed, the model likely could be improved substantially. For example, if future study could improve the accuracy with which vertical conductance is known to less than the range indicated more easily than it could improve accuracy of estimates of the other characteristics, then uncertainty in the vertical conductance logically would be the first problem to address. Although recharge from precipitation also is not known accurately, improvement in the accuracy would be difficult to achieve because areal variation likely would be large, and because knowledge of evapotranspiration rates (which may be an important control on net recharge) is limited. In comparison, transmissivity of the aquifers already is relatively well known. Discharges to the two major basins in El Paso County virtually are unaffected by changes in aquifer transmissivity (fig. 40). Discharge to Monument Creek basin is affected substantially by changes in vertical conductance, but discharge to Black Squirrel Creek basin is affected only slightly. As would be expected, discharge to both basins is affected to a large degree by changes in recharge rates.

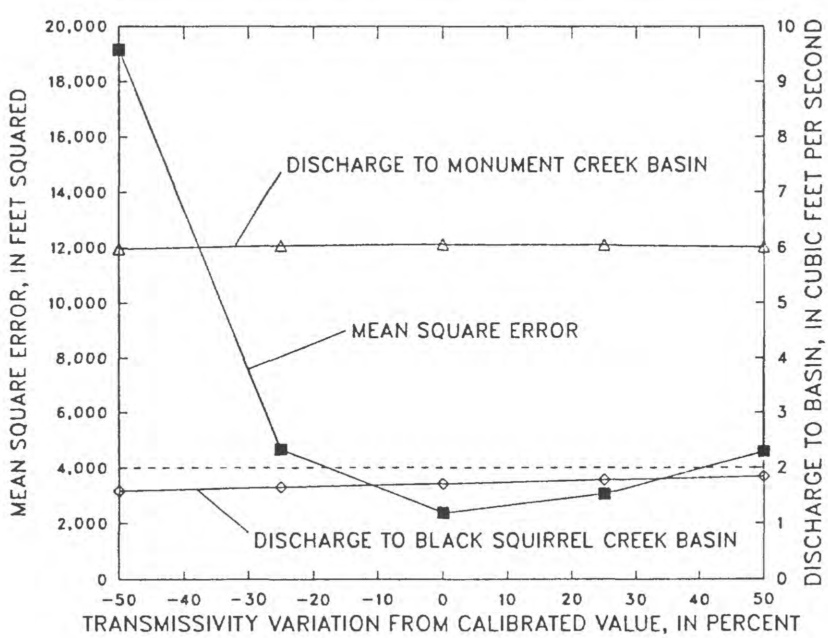

Figure 40.--Effects of transmissivity variations on mean square error and discharge to Monument Creek and Black Squirrel Creek basins.

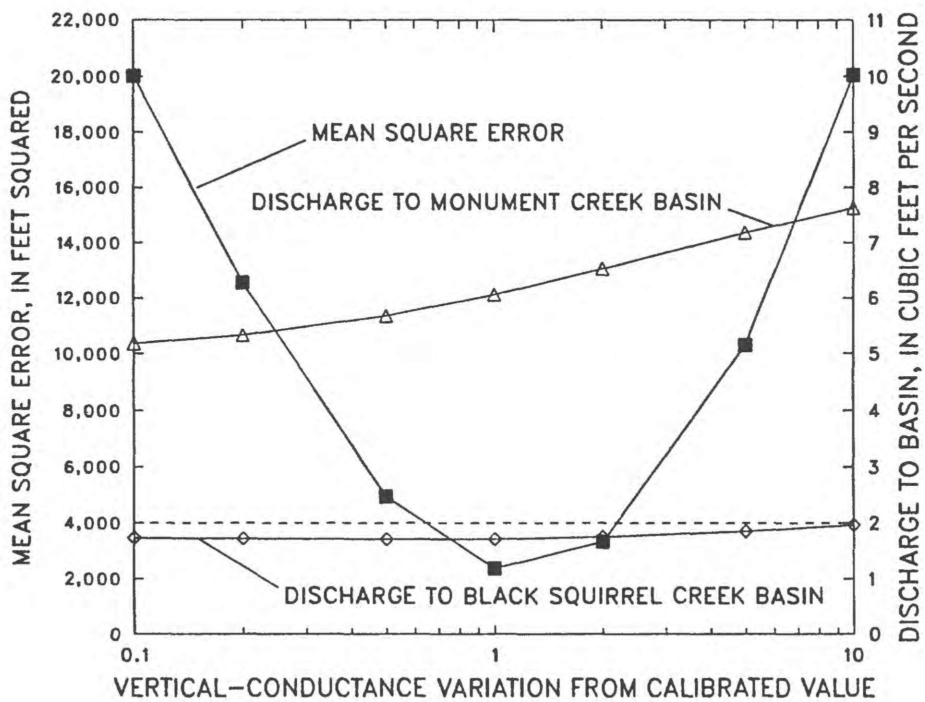

Figure 41.--Effects of vertical-conductance variations on mean square error and discharge to Monument Creek and Black Squirrel Creek basins.

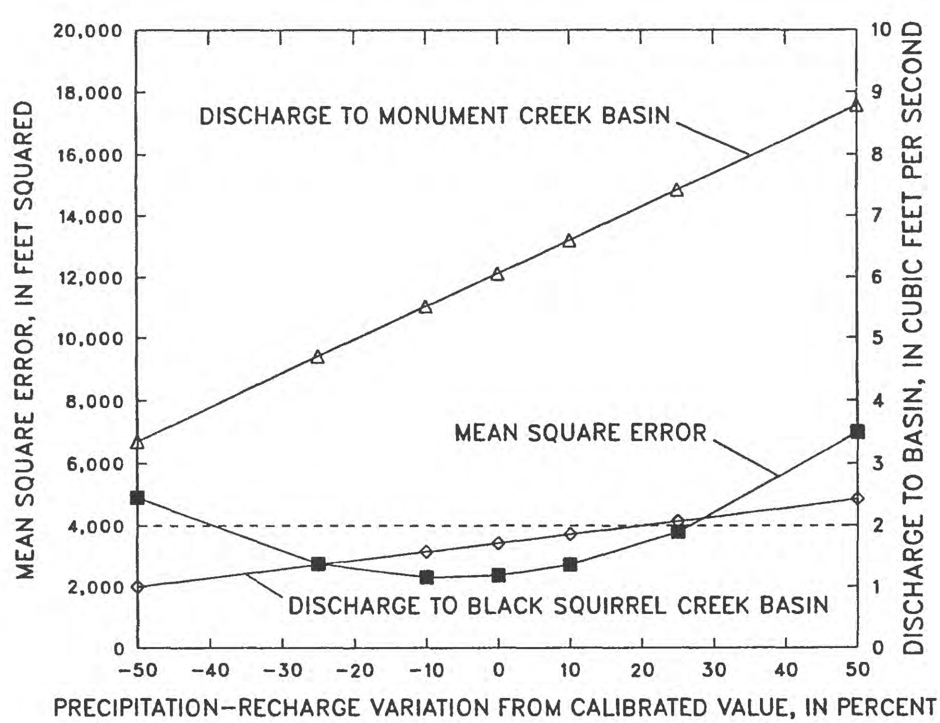

Figure 42.--Effects of variations in recharge from precipitation on mean square error and discharge to Monument Creek and Black Squirrel Creek basins.

Sensitivity of the model to changes in storage coefficient and specific yield was tested by using the transient-state model. Because mean square error was not calculated for the transient-state model, an alternative method of presenting the results is used. The time-dependent differences in model-calculated results at selected nodes due to changes of ±20 percent in storage property (storage coefficient or specific yield) for simulation SIMGRO are shown in figures 43 through 48. Generally, these hydrographs show that uncertainty in storage property causes uncertainty in head that generally is small compared to total drawdown for the simulation. The variation in head due to a 20-percent change in storage property ranges from 0 to about 75 ft. The largest difference occurs in model layer 1, simulating the Laramie-Fox Hills aquifer near Monument (fig. 43), where the head decreases rapidly during the simulation. Divergence of the hydrographs for simulations for which storage property was varied, particularly apparent in figures 46 and 48, indicates the degree to which uncertainty in this property affects the model results.

In the model, recharge at constant-head nodes, which represent surface-water bodies such as streams and reservoirs or alluvial aquifers, is limited to a value considered reasonable by the hydrologist. If the recharge rate exceeds this limit at a particular constant-head node at the end of a time step, the node is converted to an ordinary variable-head node. A maximum constant-head recharge rate or limit of $(0.133\ ft^3/s)/mi^2$ was used in this model, following Robson (1984). An analysis was made during the current study of the sensitivity of model results to changes of ±50 percent in the value of this limit. The effects of these changes are largest near constant-head nodes that are converted to variable-head nodes during the simulation. Differences in head of less than 20 ft are shown in figures 49 and 50, which are typical of hydrographs showing the largest differences due to changes in the limit; each of the corresponding two nodes is within three nodes of a constant-head node that converts to a variable-head node during simulation SIMGRO.

To assess the effect of a change in projected pumping rate for the northern part of the basin on water levels in the southern part of the basin, a model run was made for which simulated pumpage in the northern part was decreased by 25 percent. Hydrographs for nodes located in the lower three aquifers near the northern boundary of El Paso County illustrate the differences due to the decreased pumpage (figs. 51 through 53). The differences at these nodes do not exceed 20 ft, and the effects decrease with distance south of the northern boundary of El Paso County. The effects of the decreased pumpage on calculated heads in the Dawson aquifer in El Paso County are less than 1 ft.

The effects of changes in recharge from precipitation also were evaluated in the context of the transient-state model. Such an evaluation serves two purposes: (1) To evaluate the transient effects of changes in recharge from precipitation and (2) to compare the results of the transient-state sensitivity analyses with the results of the steady-state sensitivity analyses. The degree to which recharge from precipitation was varied was determined by the steady-state sensitivity analysis; the values chosen are those that would have resulted in the arbitrarily chosen mean square error of 4,000 ft^2 discussed previously. The effects of these changes in recharge from precipitation on head are illustrated for two nodes in figures 54 and 55. As one would expect, the largest differences in calculated head are found in aquifer outcrop areas (fig. 55, pl. 2), where they may exceed 50 ft. Where an aquifer is deeply buried, effects are minimal (fig. 54).

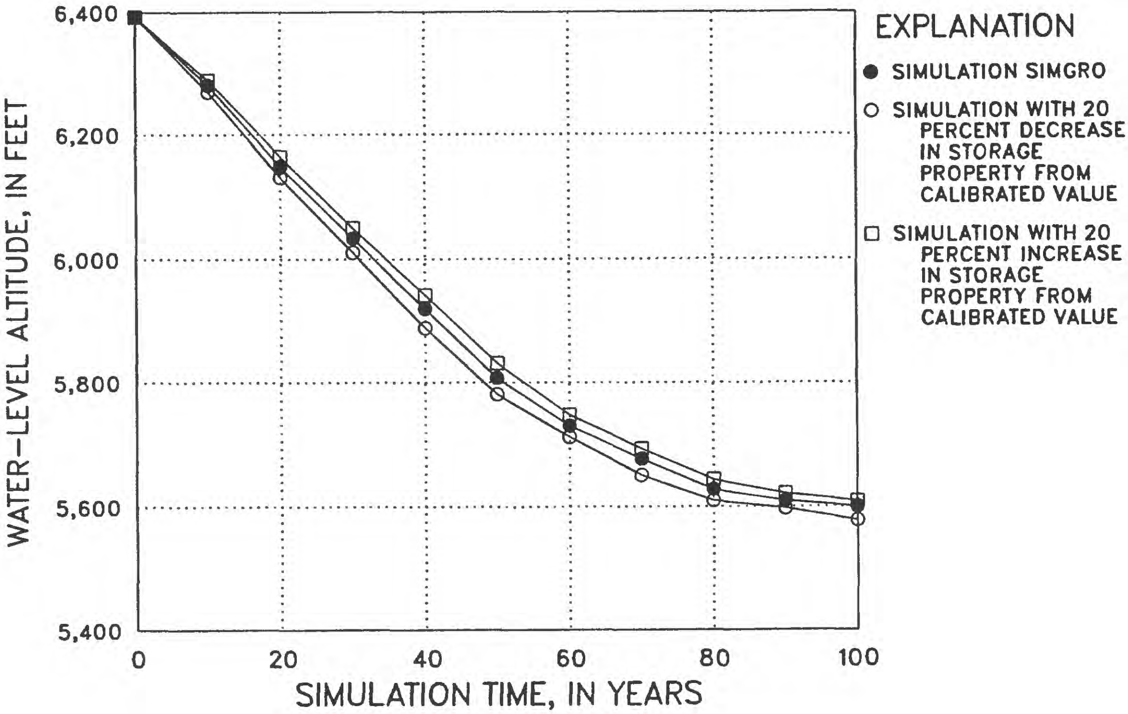

Figure 43.--Effect of changes in storage property on simulated head at model mode (46,14,1).

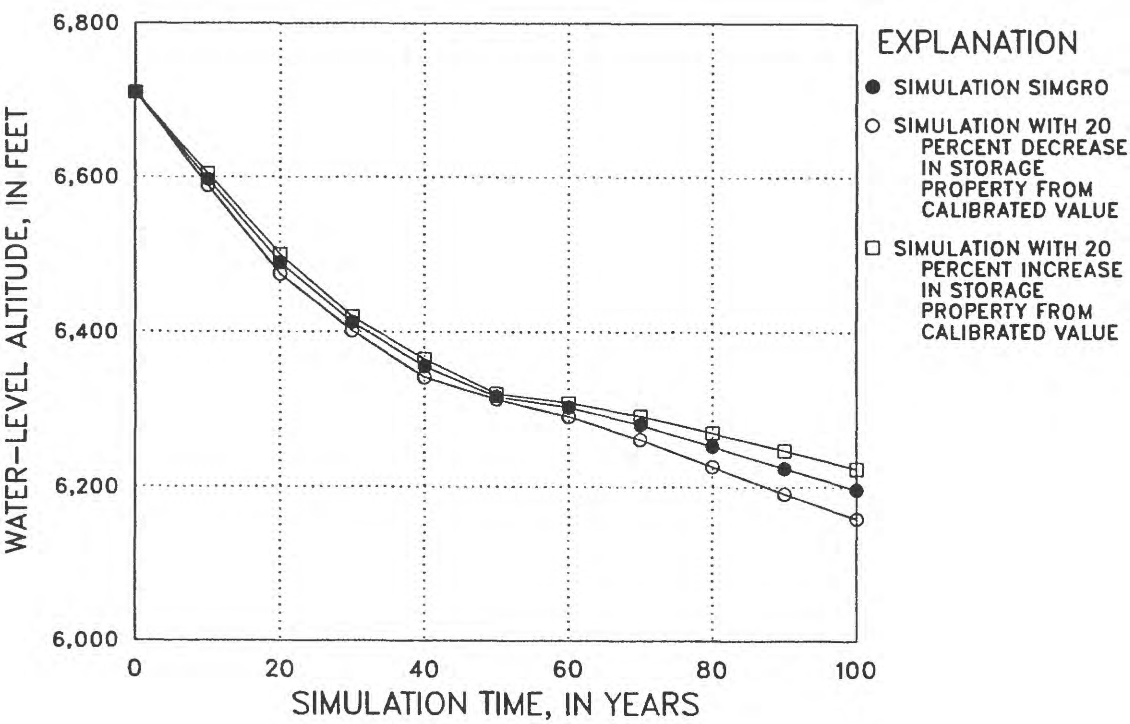

Figure 44.--Effect of changes in storage property on simulated head at model node (49,14,2).

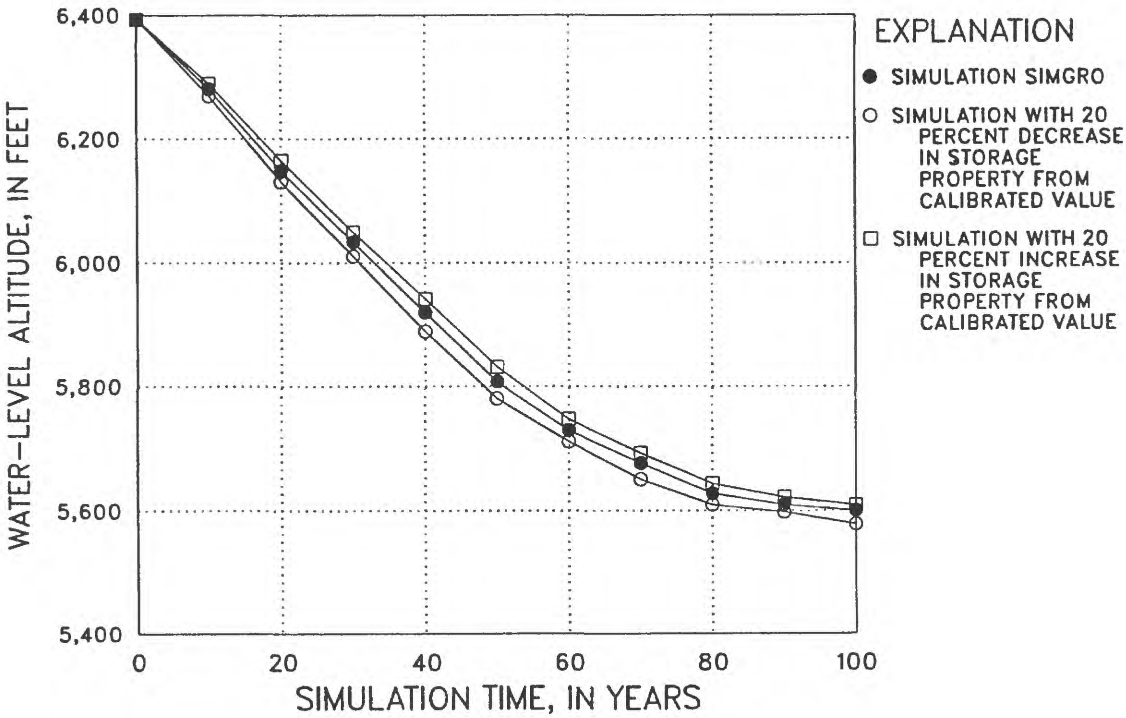

Figure 45.--Effect of changes in storage property on simulated head at model node (47,13,3).

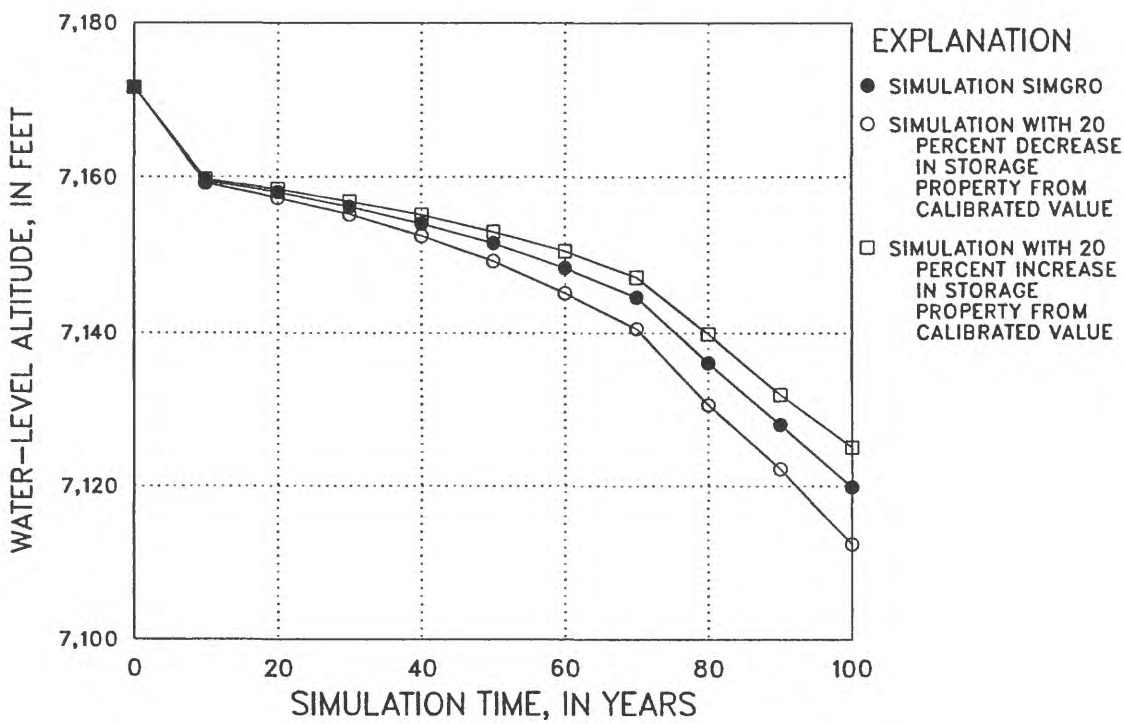

Figure 46.--Effect of changes in storage property on simulated head at model node (46,19,4).

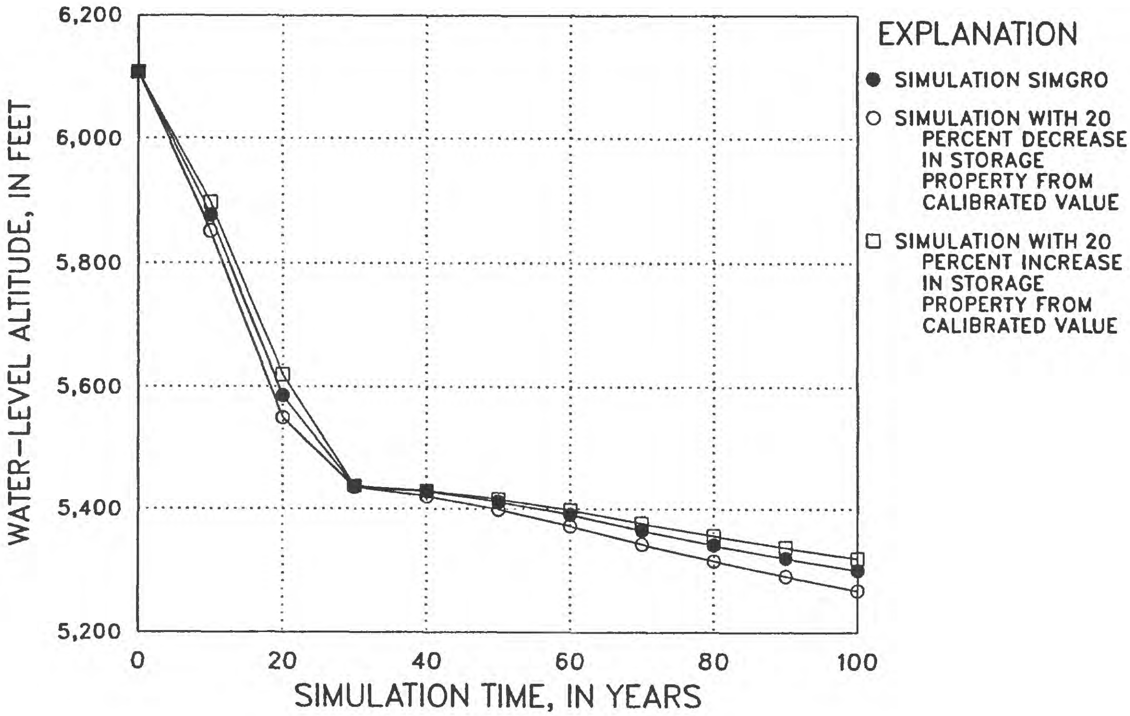

Figure 47.--Effect of changes in storage property on simulated head at model node (54,15,1).

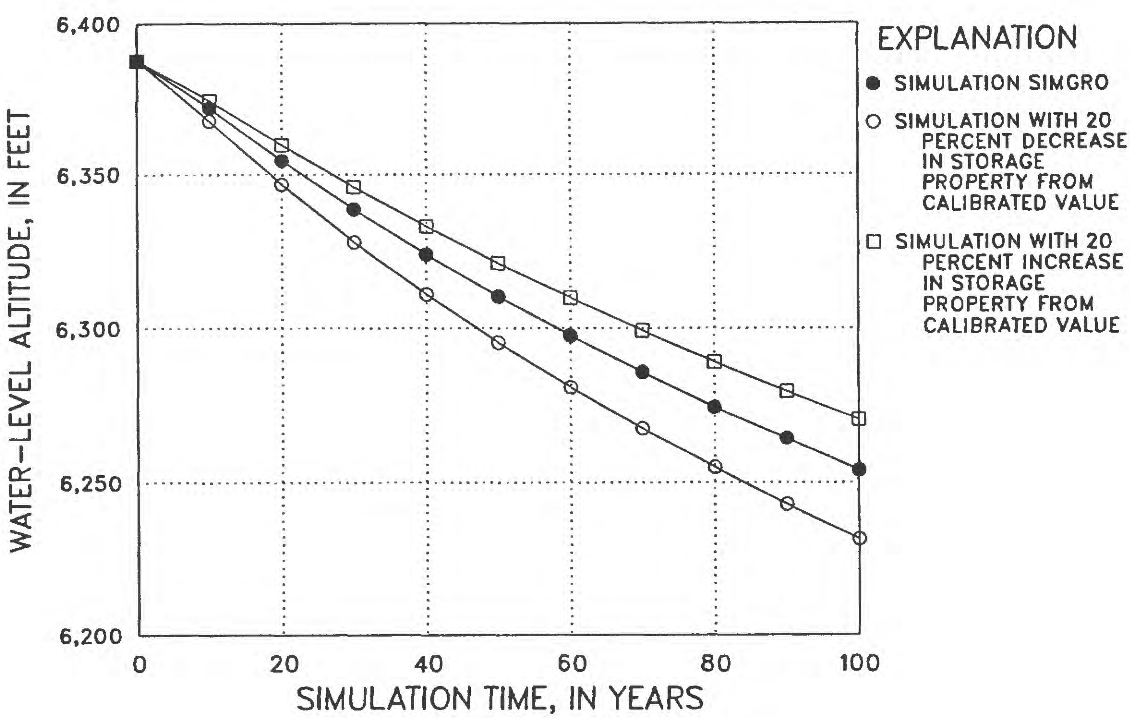

Figure 48.--Effect of changes in storage property on simulated head at model node (57,15,2).

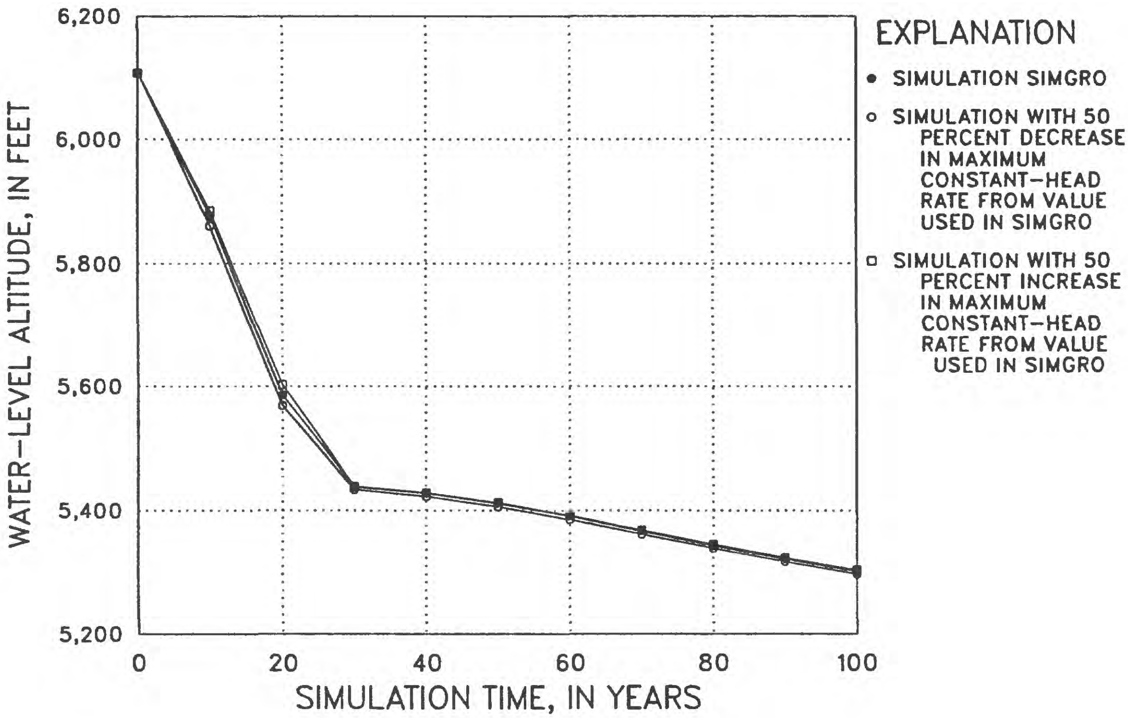

Figure 49.--Effect of changes in maximum constant-head leakage rate on simulated head at model node (54,15,1).

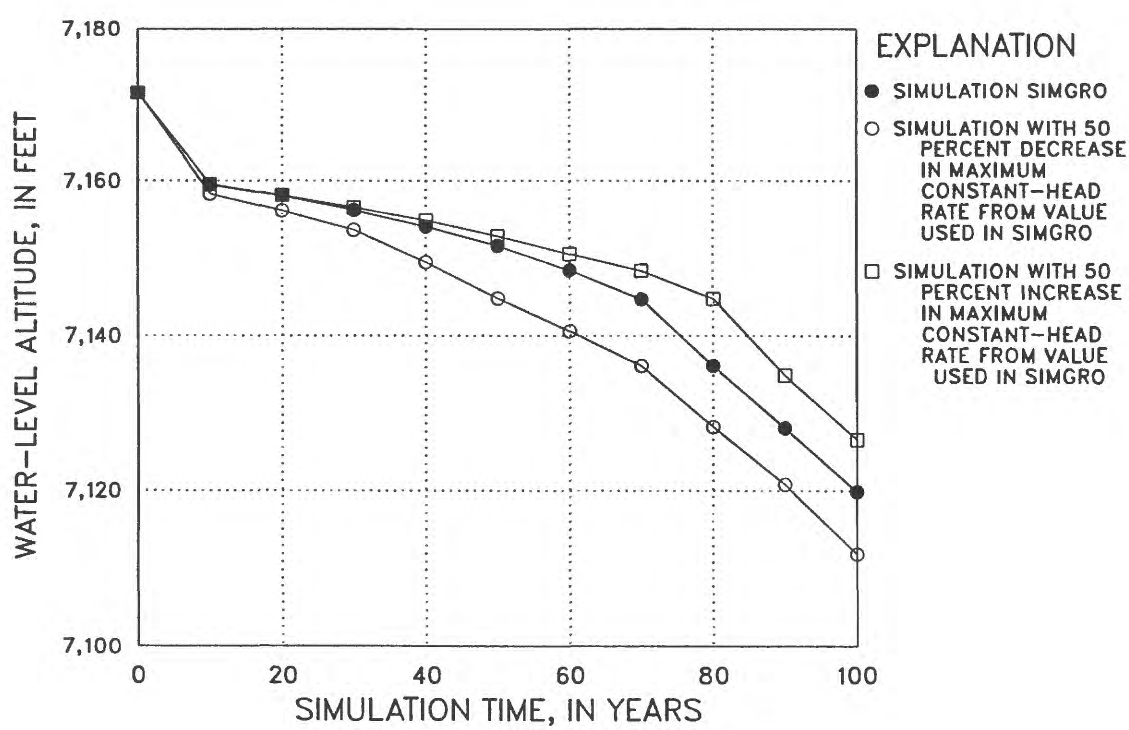

Figure 50.--Effect of changes in maximum constant-head leakage rate on simulated head at model node (46,19,4).

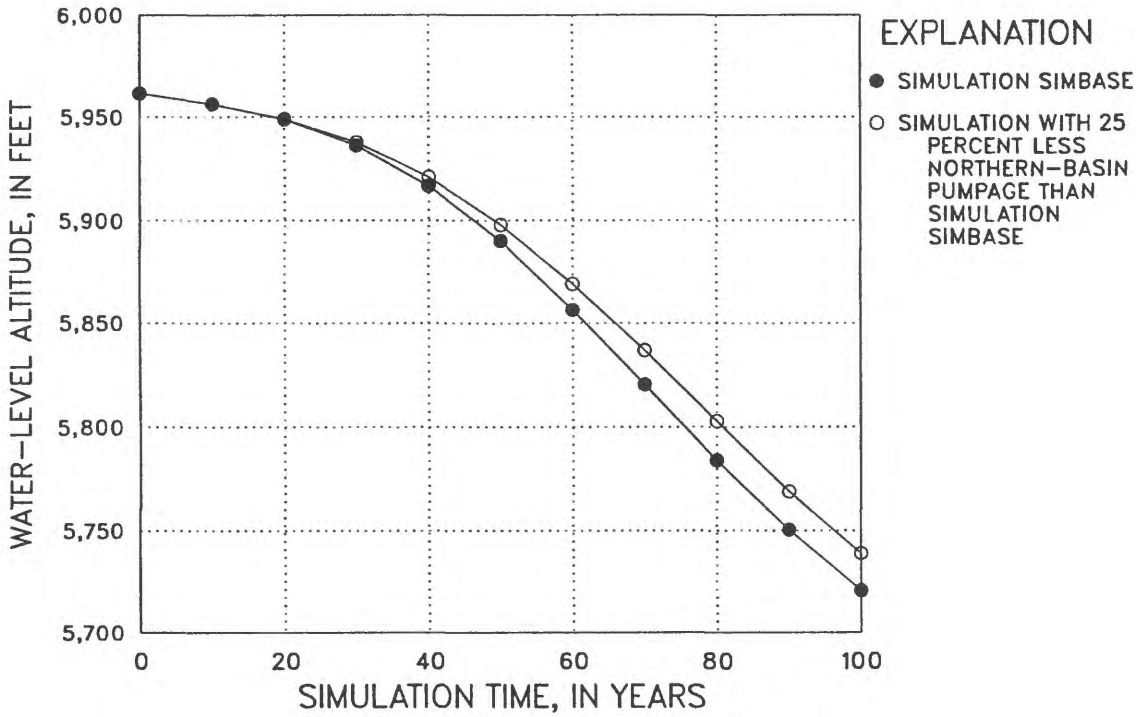

Figure 51.--Effect of changes in simulated pumpage from the northern part of the Denver basin on simulated head at model node (46,14,1).

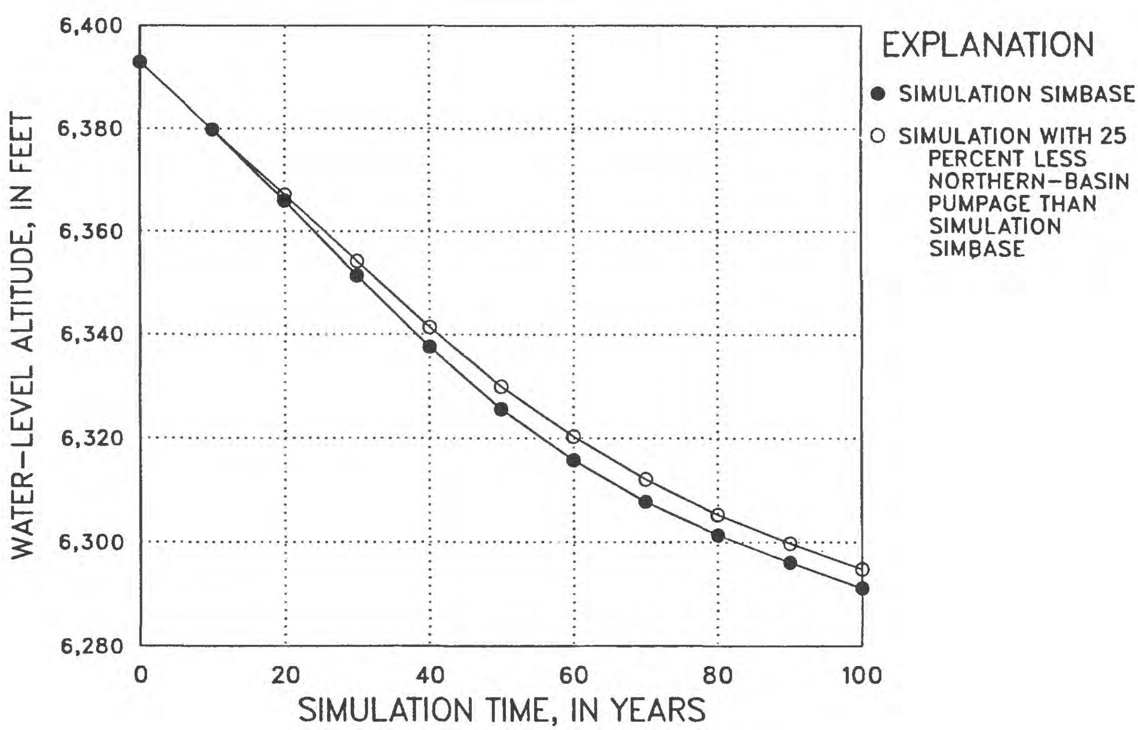

Figure 52.--Effect of changes in simulated pumpage from the northern part of the Denver basin on simulated head at model node (49,14,2).

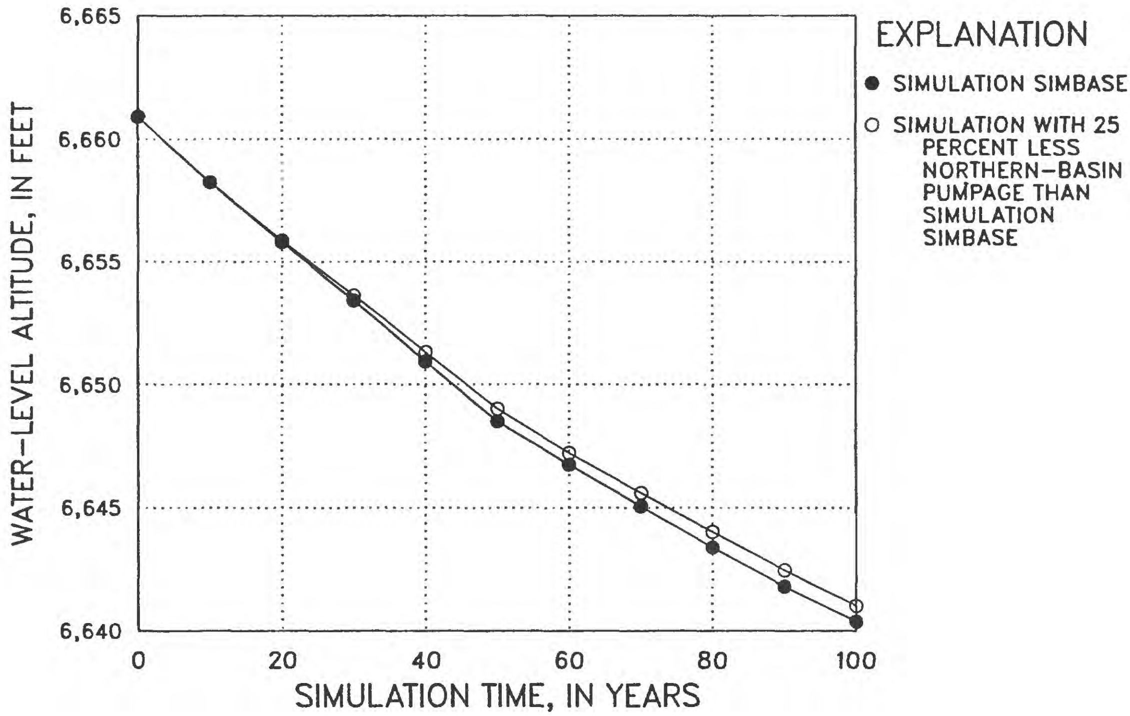

Figure 53.--Effect of changes in simulated pumpage from the northern part of the Denver basin on simulated head at model node (46,23,3).

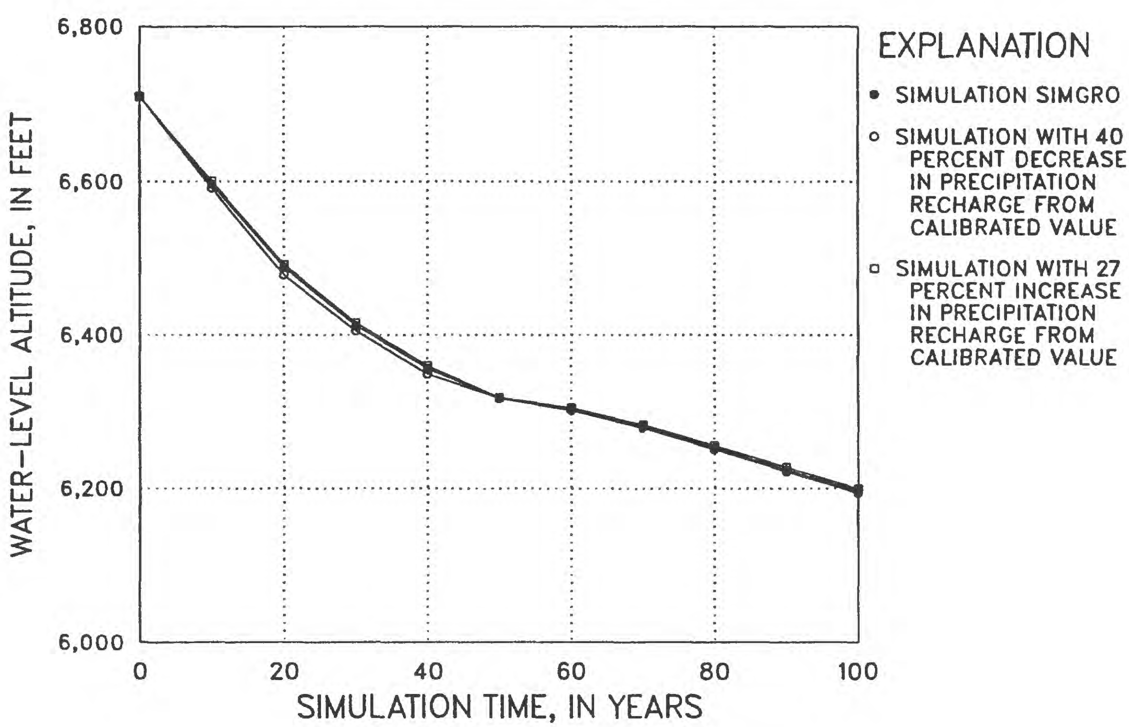

Figure 54.--Effect of changes in rate of recharge from precipitation on simulated head at model node (47,13,3), where aquifer is deeply buried.

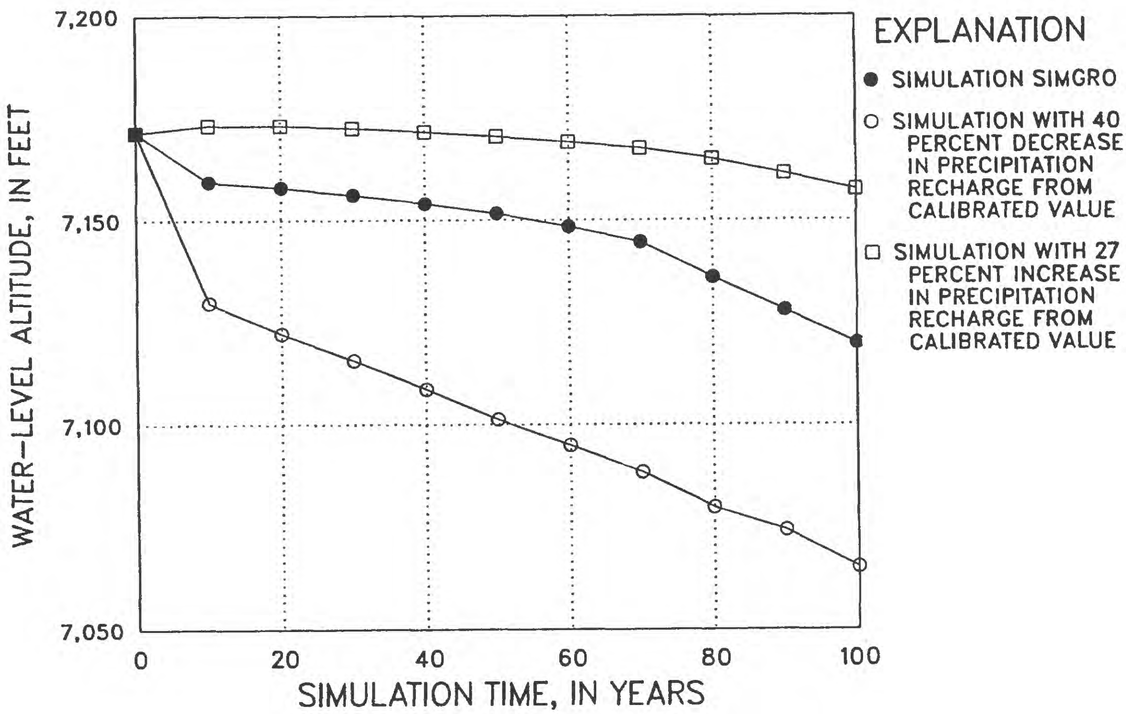

Figure 55.--Effect of changes in rate of recharge from precipitation on simulated head at model node (46,19,4), where aquifer outcrops.

SUMMARY AND CONCLUSIONS

The Denver ground-water basin underlies a 6,700 mi^2 area extending from the Front Range to Limon and from Greeley to Colorado Springs in eastern Colorado. The Laramie-Fox Hills, Arapahoe, Denver, and Dawson aquifers are, in ascending order, the four major bedrock aquifers that yield water to wells in the Denver basin. These aquifers are part of a bedrock-aquifer system that overlies the Cretaceous Pierre Shale, which is considered to be a basal confining unit for the aquifer system. Water-yielding materials are composed of permeable conglomerate, sandstone, and siltstone of Cretaceous and Tertiary age. The water-yielding materials are commonly interbedded with low permeability shale. Thicker intervals of shale form regional confining units between the aquifers.

This study was undertaken to evaluate current geohydrologic conditions in the bedrock aquifers in El Paso and neighboring counties and to predict likely hydrologic effects of a variety of possible future pumping scenarios. Data activities included measuring and collecting data on water levels in wells, streamflow gain and loss, aquifer properties such as transmissivity and storage coefficient, and geologic structure. The data collected were used to define current hydrologic conditions in the aquifers and to modify a previously formulated digital ground-water flow model. The revised digital model simulated ground-water flow using a 67-row by 40-column by 4-layer finite-differenct model. In addition to a steady-state model that simulated predevelopment conditions, three time periods were simulated in a transient-state model: (1) A 1958 to 1978 period; (2) a 1978 to 1985 period; and (3) a 1985 to 2085 period, for which the various hypothetical development scenarios were simulated.

Analysis of the data collected and simulation of the geohydrology of the aquifer system indicate that about 59 ft^3/s of water flowed into and out of the aquifers under predevelopment conditions. About 90 percent of this flow is estimated to have been supplied by recharge from precipitation; the rest was recharged from streams and alluvial aquifers. Discharge was mainly to the major streams and springs in the northern, western, and southwestern parts of the basin. However, discharge, in the form of springs, evapotranspiration, and interaquifer flow to ephemeral-stream alluvial-aquifer systems, apparently is substantial along the southern and eastern margins of the basin.

The two major surface-water drainage basins in the part of El Paso County underlain by the Denver ground-water basin are those of Monument Creek and Black Squirrel Creek. Predevelopment net discharge from the bedrock in the Monument Creek basin, where the upper three aquifers had a net discharge and Laramie-Fox Hills aquifer had a net recharge, was calculated to be about 6.1 ft^3/s, according to the steady-state-model results. All four aquifers discharged to the Black Squirrel Creek basin in the simulated predevelopment condition, resulting in a simulated net discharge of about 1.7 ft^3/s.

Water-level data collected in 1958, 1978, and 1985 and the digital model were used to analyze transient conditions in the aquifer system. By 1978, pumping from the four aquifers was about 37 ft^3/s, and water levels had declined substantially from predevelopment conditions in the northern part of the Denver basin.

Between 1978 and 1985, natural and man-caused stresses affected water levels in the bedrock aquifers. Three years (1982 through 1984) of increased recharge due to greater-than-normal precipitation generally caused water levels to rise in northwest El Paso County. In some areas, water levels rose more than 40 ft. Pumpage from the Black Squirrel Creek alluvial aquifer and consequent lowering of the water table in the alluvial aquifer contributed to water-level declines in the underlying bedrock aquifers. Water levels in the bedrock aquifers near Ellicott declined as much as 80 ft.

In 1985, pumping from the bedrock aquifers was about 56 ft^3/s, or about 94 percent of the simulated total predevelopment inflow and outflow. About 43 percent of the water simulated as pumped came from a decline in volume of ground water in storage; about 37 percent came from induced recharge and captured discharge. The remaining 20 percent came from the transient high rate of recharge from precipitation. Total simulated inflow and outflow were each about 103 ft^3/s, nearly twice the rate for predevelopment conditions. Net discharge to the Monument Creek basin, as calculated by the transient-state model, had decreased to about 5.3 ft^3/s, and net discharge to the Black Squirrel Creek basin had decreased to about 1.6 ft^3/s.

Five simulations of possible future aquifer conditions over a 100-year period, beginning in 1985, were made. For each of the simulations, pumping in the northern part of the Denver basin was made to follow the same pattern of increasing pumping.

If pumping rates in the southern part of the basin are assumed not to increase beyond the relatively small 1985 pumping rates, the total pumping rate for the basin is assumed to increase to about 127 ft^3/s by 2085. For this scenario, model calculations indicated large drawdowns in the northern part of the basin, especially in the lower aquifers, and smaller drawdowns in the southern part of the basin. The model also projected that no large-scale dewatering of the aquifers in the southern part of the basin would result from such a pumping program. Note that if a well or group of wells were to be pumped at large discharge rates for extended periods of time, the possibility exists that the aquifer may be dewatered in the immediate vicinity of the pumping site.

Increasing total pumping rates, up to about 280 ft^3/s in 2085, were simulated for the same 100-year period to supply the projected increasing population in the southern part of the Denver basin. For this scenario, simulated drawdowns, which tended to increase with depth of burial of the aquifers and intensity of pumping, were as much as 1,300 ft in the Laramie-Fox Hills aquifer, 900 ft in the Arapahoe aquifer, 700 ft in the Denver aquifer, and 200 ft in the Dawson aquifer. Some aquifer dewatering was indicated by the model in the most intensively pumped areas. Simulated net discharge to Monument Creek and Black Squirrel Creek basins from the bedrock aquifers decreased and reversed to become net recharge in response to the large rates of pumping.

The pumping rate of 280 ft^3/s was incremented by simulating additional pumping of about 16 ft^3/s from a hypothetical well field, starting in 2025. For this simulation, maximum difference in drawdown, or incremental drawdown, relative to the simulation for which pumping reached 280 ft^3/s, in 2085 was about 100 ft in the Laramie-Fox Hills aquifer, about 150 ft in the Arapahoe aquifer, and about 200 ft in the Denver aquifer. This rate of pumping from the well field resulted in slightly more aquifer dewatering than that calculated for the model run without the well field.

In another simulation, the pumping, at a rate of 280 ft^3/s, was redistributed so that pumping from the hypothetical well field replaced some of the pumping from an area projected to undergo rapid population growth. In this simulation, about the same drawdown was calculated in the vicinity of the well field as for the previous simulation, but much less drawdown was calculated for the area of rapid population growth. As a result, a substantial decrease in aquifer dewatering, relative to the previous simulation, is projected.

When pumping of about 20 ft^3/s from the lower three aquifers under Colorado Springs was simulated in addition to the 280-ft^3/s rate of pumping that would be required by the growing population adjacent to Colorado Springs, the effects were incremental drawdowns of about 200 ft in the Laramie-Fox Hills and Arapahoe aquifers, and of about 100 ft in the Denver aquifer, relative to the simulation without this additional pumpage. Considerable dewatering of the aquifers in and near Colorado Springs also was indicated by this simulation.

REFERENCES CITED

Bishop, Brogden, and Rumph, Inc., 1985, Drilling and completion of Laramie-Fox Hills aquifer well nos. KLF-11, 15, and 26 and monitor wells, Banning-Lewis Ranch, El Paso County, Colorado: Denver, 16.p.

City of Colorado Springs, 1985, Incorporation of Denver basin groundwater into water supply system of City, Part II, *in* The code of the City of Colorado Springs, Chapter 12, Department of Utilities, Article 4 water code: 2 p.

Colorado Department of Natural Resources, 1986, Rules and regulations applying exclusively to the withdrawal of ground water from the Dawson, Denver, Arapahoe, and Laramie-Fox Hills aquifers in the Denver basin: Denver 2 CCR 402-6, 37 p.

Colorado Division of Water Resources, 1986, Magnetic tape, Well-permit application data: Denver.

Colorado Revised Statutes, 1985, Legislative enactment concerning ground water, and making an appropriation in connection therewith, 37-90-103(10.5), Definitions (new subsection): Denver, 1 p.

El Paso County-Colorado Springs-Fountain Cooperative Planning Program, 1986, Master planned land use map: Colorado Springs, scale 1:48,000.

Farnsworth, R.K., Thompson, E.S., and Peck, E.L., 1982, Evaporation atlas for the contiguous 48 United States: National Oceanic and Atmospheric Administration Technical Report NWS 33, 26 p.

Livingston, R.K., Klein, J.M., and Bingham, D.L., 1976, Water resources of El Paso County, Colorado: Colorado Water Conservation Board, Colorado Water Resources Circular 32, 85 p.

Lohman, S.W., and others, 1972, Definitions of selected ground-water terms--revisions and conceptual refinements: U.S. Geological Survey Water-Supply Paper 1988, 21 p.

Robson, S.G., 1983, Hydraulic characteristics of the principal bedrock aquifers in the Denver basin, Colorado: U.S. Geological Survey Hydrologic Investigations Atlas HA-659, scale 1:500,000, 3 sheets.

_____1984, Bedrock aquifers in the Denver basin, Colorado--a quantitative water-resources appraisal: U.S. Geological Survey Open-File Report 84-431, 111 p.

_____1987, Bedrock aquifers in the Denver basin, Colorado--A quantitative water-resources appraisal: U.S. Geological Survey Professional Paper 1257, 73 p.

Robson, S.G., and Romero, J.C., 1981a, Geologic structure, hydrology, and water quality of the Dawson aquifer in the Denver basin, Colorado: U.S. Geological Survey Hydrologic Investigations Atlas HA-643, scales 1:250,000 and 1:500,000, 3 sheets.

_____1981b, Geologic structure, hydrology, and water quality of the Denver aquifer in the Denver basin, Colorado: U.S. Geological Survey Hydrologic Investigations Atlas HA-646, scale 1:500,000, 3 sheets.

Robson, S.G., Romero, J.C., and Zawistowski, Stanley, 1981a, Geologic structure, hydrology, and water-quality of the Arapahoe aquifer in the Denver basin, Colorado: U.S. Geological Survey Hydrologic Investigations Atlas HA-647, scale 1:500,000, 3 sheets.

Robson, S.G., Wacinski, Andrew, Zawistowski, Stanley, and Romero, J.C., 1981b, Geologic structure, hydrology, and water quality of the Laramie-Fox Hills aquifer in the Denver basin, Colorado: U.S. Geological Survey Hydrologic Investigations Atlas HA-650, scale 1:500,000, 3 sheets.

Trescott, P.C., 1975, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 75-438, 32 p.

Trescott, P.C., and Larson, S.P., 1976, Documentation of finite-difference model for simulation of three-dimensional ground-water flow, supplement to Open-File Report 75-438: U.S. Geological Survey Open-File Report 76-591, 21 p.

U.S. Geological Survey, 1975, Water-resources data for Colorado, water year 1974, part 1: Surface-water records: U.S. Geological Survey, 396 p.

_____1979, Water-resources data for Colorado, water year 1978: U.S. Geological Survey Water-Data Report CO-78-1, v. 1, 415 p.

U.S. National Oceanic and Atmospheric Administration, 1966-1985, Annual summaries, climatological data, Colorado: Asheville, N.C., National Climatic Data Center, v. 71-90.

U.S. Weather Bureau, 1920-1965, Annual summaries, climatological data, Colorado: Washington, D.C., v. 25-70.

SUPPLEMENTAL INFORMATION

Some of the capabilities of the model used for this study are not available in the original model documented in Trescott (1975) or in Trescott and Larson (1976). Changes and additions to the model source code used for transient simulations are given here. These changes allow the model user to specify spring nodes, where discharge, but not recharge, is allowed. The changes also require the user to specify a rate to be used as a limit for recharge at constant-head nodes. Where a line of code includes a line number in columns 73-79, the new line replaces the corresponding old line in the original documentation. The other lines of code are inserted into the original code where indicated. Changes to model input are given following the source-code changes.

```
     19,4), DUM(3), INSPG(4,67,40)                                      MAN0110
```

Insert following line MAN0190:

```
      COMMON /SPG/NSPG,INSPG,RIVH
```

Insert following line MAN0290:

```
      DATA INSPG/10720*0/
```

```
      READ (5,160) IO,JO,KO,ITMAX,NCH,NSPG                              MAN0370
      WRITE (6,180) IO,JO,KO,ITMAX,NCH,NSPG                             MAN0380
```

```
     20)),Y(L(22)))                                                     MAN1200
```

```
     2RATIONS =',I5//48X,'NUMBER OF CONSTANT HEAD NODES =',I5//         MAN2060
```

Insert following line MAN2060:

```
     355X,'NUMBER OF SPRING NODES =',I5)
```

Insert following line DAT0140:

```
      DIMENSION INSPG(4,67,40)
```

Insert following line DAT0240:

```
      COMMON /SPG/NSPG,INSPG,RIVH
```

```
      READ (5,330) NPER,KTH,ERR,LENGTH,RIVH                             DAT0320
      WRITE (6,340) NPER,KTH,ERR,RIVH                                   DAT0330
```

Insert following line DAT1390:

```
C
C     READ SPRING NODE LOCATIONS
C
      IF (NSPG .GT. 0) THEN
        DO 215 KIJ=1,NSPG
          READ (5,336) K,I,J
          INSPG(K,I,J)=1
  215   CONTINUE
      ENDIF
```

Insert following line DAT1920:
```
  336 FORMAT (3I10)
```

```
     1ETWEEN PRINTOUTS =',I5//51X,'ERROR CRITERIA FOR CLOSURE =',G15.DAT1940
```

Insert following line DAT1940:
```
     27//56X,'MAX RIVER LEAKAGE =',G15.7)
```

```
     1,DDN,TEST3,FLOW)                                             STP  20
```

```
     3(ITMX1), ITTO(50), FLOW(NCH), INSPG(4,67,40)                 STP 140
```

Insert following line STP 240:
```
      COMMON /SPG/NSPG,INSPG,RIVH
```

Insert following line STP1180:
```
C
C      ADJUST CONSTANT HEAD OR CONSTANT FLUX BOUNDARIES ALONG ALLUVIAL
C      AQUIFERS AND SPRINGS ON BASIS OF HEAD AND FLUX RATE
C
      II=0
      DO 165 K=1,KO
      DO 165 I=2,I1
      DO 165 J=2,J1
      IF(T(I,J,K).EQ.0.0) GO TO 165

      IF(S(I,J,K).GE.0.) GO TO 165
      AREA=DELX(J)*DELY(I)
      RMAX=RIVH*AREA/27878400.
      II=II+1
      IF(INSPG(K,I,J) .EQ. 1 .AND. FLOW(II) .GT. 0.0)THEN
        S(I,J,K)=-S(I,J,K)
        WRITE(6,350)' SPRING NODE CONVERTED TO VARIABLE-HEAD NODE AT
     1LOCATION ',I,J,' IN LAYER ',K,' AFTER TIME STEP ',KT
        INSPG(K,I,J)=0
        GO TO 165
      ENDIF
      IF(RMAX.GT.FLOW(II)) GO TO 165
      S(I,J,K)=-S(I,J,K)
      WELL(I,J,K)=WELL(I,J,K)+RMAX/AREA
      WRITE(6,355) I,J,K,KT,RMAX
  165 CONTINUE
```

Insert following line STP1390:
```
  350 FORMAT(A57,2I3,A10,I2,A17,I4)
  355 FORMAT(' ','CONSTANT HEAD NODE REMOVED FROM LOCATION', 3I3,' AFTER
     1 TIME STEP',I3,'  NEW WELL RATE =',G18.7)
```

To use the capabilities documented above, additional data need to be included in the model-input file. These instructions refer to Trescott (1975), Appendix III.

Group I, card (card image) 3 includes an input field in columns 51-60, format I10, variable NSPG, number of spring nodes.

Group II, card (card image) 1 includes an input field in columns 41-50, format G10.0, variable RIVH, maximum recharge rate for constant-head nodes, in $(ft^3/s)/mi^2$. If linear unit is other than foot, the code would need to be changed accordingly. If the recharge rate calculated at a constant-head node exceeds RIVH, the node is converted to an ordinary active node, and the head is allowed to vary.

Group III, data set 13, columns 1-30, format 3I10, variables K, I, and J, defines spring-node location: layer, row, and column. Each card (card image) defines one spring node, which acts as a constant head as long as net flow at the node represents discharge from the model; number of cards (card images) must equal NSPG. If recharge is calculated to occur, the node is converted to an ordinary active node, and the head is allowed to vary.

*U.S. GOVERNMENT PRINTING OFFICE: 1989-0-773-204/00034