HYDROGEOLOGY AND SIMULATED EFFECTS OF GROUND-WATER DEVELOPMENT ON AN UNCONFINED AQUIFER IN THE CLOSED BASIN DIVISION, SAN LUIS VALLEY, COLORADO

By Guy J. Leonard and Kenneth R. Watts

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CONVERSION FACTORS AND ABBREVIATIONS

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

Multiply inch-pound unit	*By*	*To obtain metric unit*
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
cubic foot per second (ft^3/s)	28.32	liter per second
cubic foot per day (ft^3/d)	0.00283	cubic meter per day
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per second (ft/s)	0.3048	meter per second
foot per year (ft/yr)	0.3048	meter per year
inch (in.)	2.54	centimeter
inch per year (in/yr)	2.54	centimeter per year
mile (mi)	1.609	kilometer
square foot (ft^2)	0.09290	square meter
square foot per day (ft^2/d)	0.09290	square meter per day
square mile (mi^2)	2.590	square kilometer

Temperature can be converted to degrees Fahrenheit (°F) or degrees Celsius (°C) by the following equations:

$$°F=(9/5\ °C)+32 \qquad °C=5/9\ (°F-32)$$

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 "Mean Sea Level of 1929."

GLOSSARY

Water-resource terms are defined in the GLOSSARY and are italicized where first used in this report.

aquifer.--Formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

confined aquifer.--An aquifer bounded above and below by beds of distinctly lower permeability than that of the aquifer itself, in which ground water is under pressure significantly greater than that of the atmosphere.

confining unit.--A body of "impermeable" material that is stratigraphically adjacent to one or more aquifers. Its hydraulic conductivity may range from nearly zero to some value distinctly smaller than that of the aquifer.

evaporation.--The process by which water is discharged as vapor from water or soil surfaces into the atmosphere.

evapotranspiration.--The combined discharge of water as vapor to the atmosphere and that results from evaporation from soil and water surfaces and from transpiration by plants.

graben.--An elongate, relatively depressed crustal unit or block that is bounded by faults on its long sides (Bates and Jackson, 1980).

horst.--An elongate, relatively uplifted crustal unit or block that is bounded by faults on its long sides (Bates and Jackson, 1980).

hydraulic conductivity.--Volume of water at the existing kinematic viscosity that will move through a porous medium in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

hydraulic gradient.--Rate of change in hydraulic head per unit of distance of flow in a given direction that generally is assumed to be the direction of maximum rate of decrease in hydraulic head.

hydraulic head.--Height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point; synonymous with static hydraulic head (Lohman and others, 1972).

hydrograph.--A graph showing stage, flow, velocity, or some other characteristic of water with respect to time.

hydrologic budget.--A quantitative statement of the balance between the total gains and losses of an aquifer for a given period of time.

phreatophyte.--Literally, a ground-water plant. Plants with roots that extend to the water table and that are capable of extracting their moisture requirements directly from the saturated zone.

potentiometric surface.--An imaginary surface that represents the static hydraulic head of ground water and is defined by the levels to which water will rise in tightly cased wells (Lohman and others, 1972).

specific yield.--Ratio of the volume of water that the saturated porous medium will yield by gravity to the volume of the porous medium.

steady state.--Equilibrium conditions when hydraulic heads and the volume of water in storage do not change substantially with time.

transmissivity.--Rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

transpiration.--The process by which water vapor is discharged to the atmosphere through plant respiration.

unconfined aquifer.--An aquifer in which ground water possesses a free surface that is open to the atmosphere.

vertical conductance.--The ratio of the hydraulic conductivity measured in the vertical direction across an aquifer or confining unit to the thickness of the aquifer or confining unit. Also known as the leakage coefficient.

HYDROGEOLOGY AND SIMULATED EFFECTS OF GROUND-WATER DEVELOPMENT ON AN UNCONFINED AQUIFER IN THE CLOSED BASIN DIVISION, SAN LUIS VALLEY, COLORADO

By Guy J. Leonard and Kenneth R. Watts

ABSTRACT

Wells completed in an unconfined aquifer of the Closed Basin Division of the San Luis Valley Project are expected to provide about 101,800 acre-feet of ground water annually to the Rio Grande when the project is completed. The Closed Basin Division is located in a closed basin, which is north of the Rio Grande in the San Luis Valley of south-central Colorado. Lowering the water table in the unconfined aquifer probably will result in retention of some of the ground water that otherwise would be lost by evapotranspiration. The San Luis Valley overlies a structural trough that is filled with several thousand feet of unconsolidated, fine- to coarse-grained alluvial and lacustrine deposits, volcanic flows, and volcaniclastic rocks. Structural and stratigraphic conditions are complex and only partly defined. The aquifer system consists of an unconfined aquifer that is 50 to 130 feet thick which overlies a thick, leaky confined aquifer. Ground water moves from the edges of the closed basin toward a topographic low in the center of the basin, where it is discharged from the unconfined aquifer as evapotranspiration. A ground-water flow model was used to simulate the effect of projected water withdrawals from the unconfined aquifer; the model incorporated the effects of upward leakage from an underlying confined aquifer and evapotranspiration. Simulated withdrawals of about 141 cubic feet per second from 168 wells for a period of 20 years resulted in projected drawdown of the water table of 0.1 foot or more in an area of about 370 square miles. Model simulation indicated that the maximum drawdown would be about 25 feet. At the end of 20 years, about 66 percent of the cumulative pumpage would be derived from decreases of evapotranspiration, 26 percent from induced upward leakage from the underlying confined aquifer, and 8 percent from storage of the confined aquifer. Model simulations were based only on withdrawals from wells completed in the unconfined aquifer. Pumpage from the confined aquifer was not simulated. Upward leakage from the confined aquifer predicted by the model resulted from the simulated declines of the potentiometric surface in the unconfined aquifer. Additional study of the rates of evapotranspiration from the aquifer and of upward leakage into the aquifer is needed for more reliable simulation of the ground-water system in the closed basin. Three-dimensional model simulation is needed to evaluate changes in water levels in the confined aquifer and leakage caused by pumping-induced hydraulic-head declines.

INTRODUCTION

Since the 1880's, water diverted from the Rio Grande has been used for irrigation in the San Luis Valley of south-central Colorado. Water from the Rio Grande also is used downstream for irrigation in the States of New Mexico and Texas and in the Republic of Mexico. The apportionment of water from the Rio Grande is governed by international treaty--Rio Grande Convention of 1906--and an interstate compact--Rio Grande Compact of 1929. Because of natural climatic variation, the flow of the Rio Grande in Colorado periodically is inadequate to fulfill demand of users in the San Luis Valley of Colorado and to meet commitments to downstream users in New Mexico, Texas, and Mexico. Public Law 92-514, which was enacted by Congress on October 20, 1972, authorized the development of a multipurpose water-resources project, called the Closed Basin Division, primarily to supplement the flow of the Rio Grande with ground water, but also to provide water for recreation and wildlife within the area. When the project is completed, wells completed in the project area are expected to provide about 101,800 acre-ft/yr of ground water for use in the Rio Grande basin. Public Law 92-514 stipulates that the project shall not adversely affect other water users in the San Luis Valley.

This study was done by the U.S. Geological Survey in cooperation with the U.S. Bureau of Reclamation to evaluate the potential effects of future ground-water development within the Closed Basin Division on the hydrologic system in the San Luis Valley. The study began during 1975 with an analysis of proposed production- and observation-well networks. A numerical model was used to evaluate well spacing and pumping rates during design and test drilling of the production wells. The numerical model then was used to evaluate the potential hydrologic effects of the proposed ground-water development on the hydrologic system.

Purpose and Scope

This report describes the hydrogeology of the San Luis Valley and emphasizes the closed basin in the northern part of the valley. This report also presents results from a numerical model of ground-water flow that was used to evaluate potential changes in water levels, rates of leakage, and *evapotranspiration* losses that may be caused by future ground-water development in the Closed Basin Division throughout a 20-year projection period. Water-level data for January 1983 was used in this analysis to define the depth to water and the saturated thickness of the *unconfined aquifer*. During the winter, water levels recover from the previous year's pumping but are not affected by recharge from snowmelt.

Location of the Study Area

The study area (fig. 1) includes most of the San Luis Valley of south-central Colorado where it is underlain by saturated valley-fill deposits. The San Luis Valley, part of the Rio Grande basin, is an arid intermontane valley that is about 3,200 mi^2 in area between the Sangre de Cristo Mountains on the east and the San Juan Mountains on the west. The northern part of the Rio Grande basin is a closed basin that is about 2,900 mi^2 in area, of which about

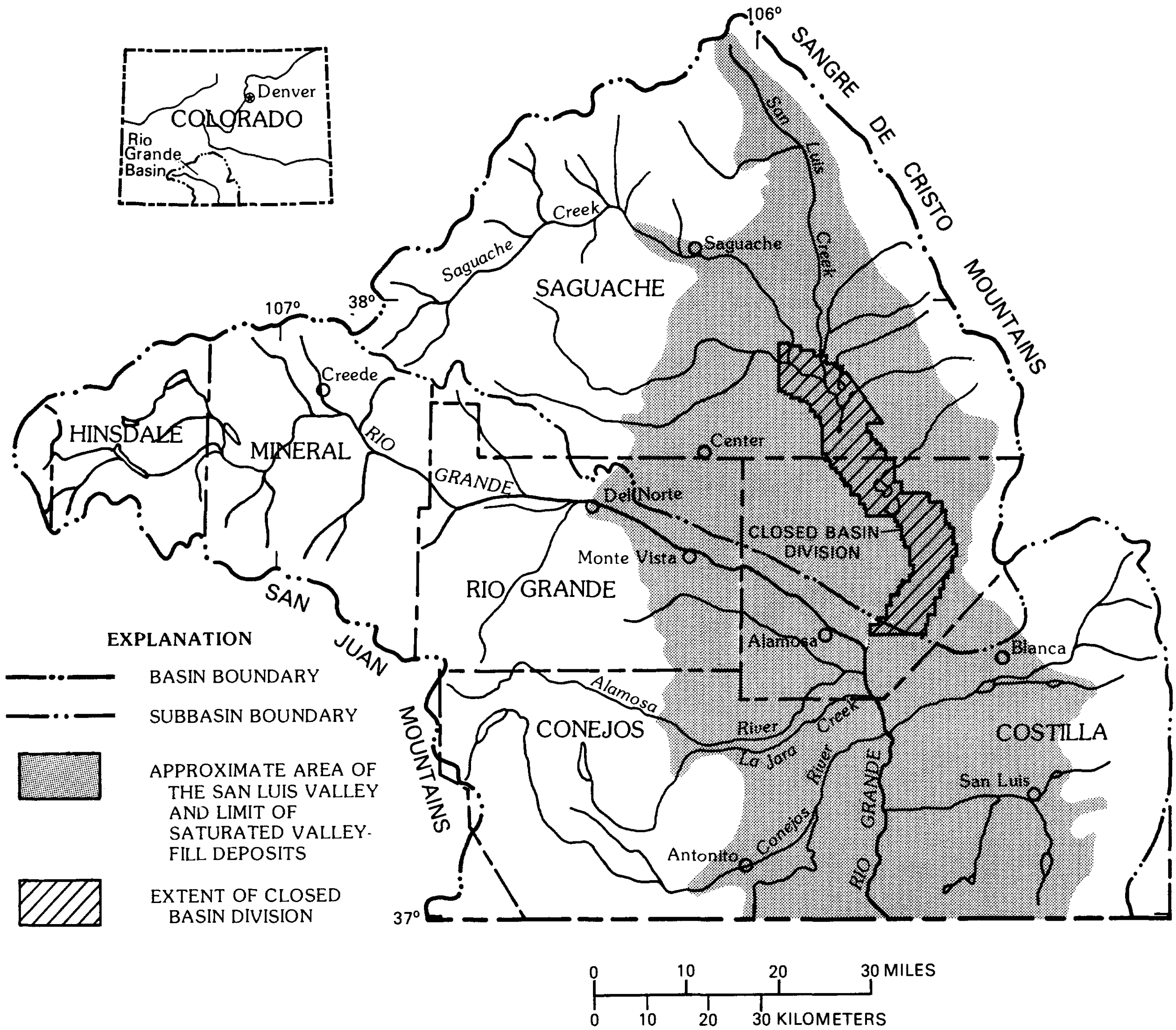


Figure 1.--Location of the Closed Basin Division in the San Luis Valley.

1,000 mi^2 is in the San Luis Valley and is underlain by saturated valley-fill deposits. The southern limit (fig. 1) of the closed basin is a low drainage divide. The Closed Basin Division is located along the topographic low of the closed basin and includes an area of about 200 mi^2.

Description of the Closed Basin Division

The Closed Basin Division (fig. 2) is a multipurpose water-resources project that is designed to provide additional water for use in the Rio Grande basin. The water is considered salvage because it normally is wasted (discharged to the atmosphere) by *evaporation* and *transpiration* in the lowest part (sump) of the closed basin. When needed, the water will be withdrawn by about 168 wells and delivered through about 100 mi of buried pipeline to the main conveyance channel. When the project is completed and fully operational, a maximum of about 101,800 acre-ft/yr of salvaged water is expected to be available for beneficial use in the Rio Grande basin. The primary use of the salvaged water will be to supplement the flow of the Rio Grande, so that the State of Colorado can meet its commitments to downstream water users.

The production wells, pipelines, and a conveyance channel of the Closed Basin Division are being constructed by the U.S. Bureau of Reclamation in cooperation with the Rio Grande Water Conservation District in Alamosa. The project is being developed in five stages (fig. 2). The main conveyance channel is completed. Production wells in stages 1-2 (fig. 2) at the southern end of the area, have been completed and were operational during 1986. However, no significant pumping from the project occurred during 1986 and 1987 because a sufficient quantity of surface water was available to meet demands of water users. Production wells in stage 3 have been completed and should be operational during 1988. Production wells in stages 4 and 5 may be operational sometime after 1988, contingent on funding.

The premise of the Closed Basin Division is that pumping of ground water will lower the water table; this will decrease the quantity of water evaporated and transpired. If all the water pumped by the Closed Basin Division represents decreases of evapotranspiration, then no long-term changes in the hydrologic system are likely to occur outside the well field's cone of depression. Because the rate of upward leakage from the underlying *confined aquifer* is *hydraulic-head* dependent, lowering the water table will increase the upward *hydraulic gradient*, and also will increase net upward leakage. Public Law 92-514 stipulates that water withdrawals in the Closed Basin Division shall not cause drawdowns in the water table in excess of 2 ft beyond the project's boundaries and shall not substantially affect water use from deeper *aquifers*.

Previous Investigations

Previous investigations of the hydrology and geology of the San Luis Valley and evaluations of proposed water-salvage plans in the Closed Basin Division were used in the compilation of a data base and in the development of conceptual and numerical models of the unconfined aquifer. Siebenthal (1910) summarized the geology of the San Luis Valley and described "the

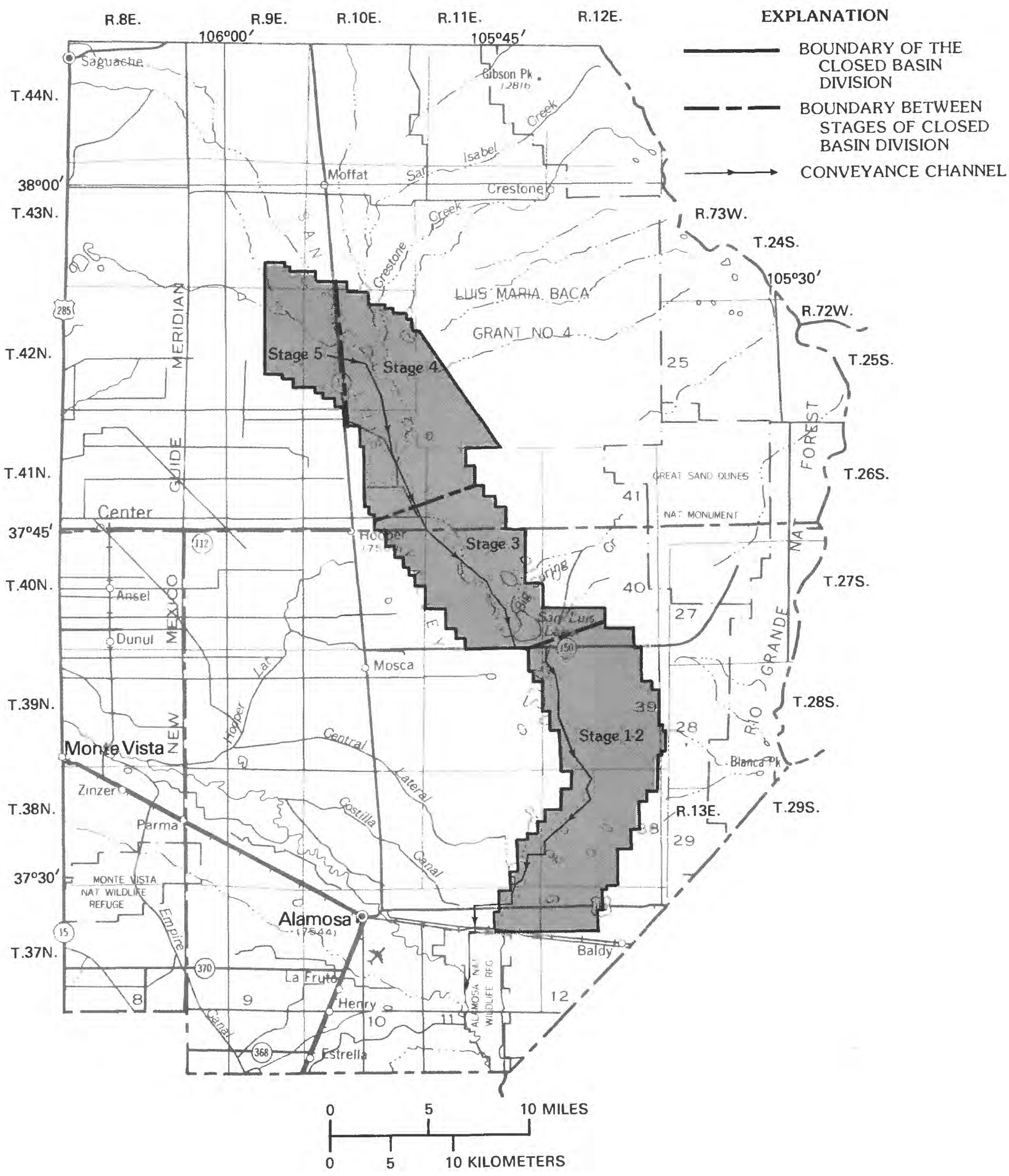


Figure 2.--Stages of development of the Closed Basin Division.

relation of the artesian basin to the geologic structure." Bryan (1938) outlined the geology of the Rio Grande depression in Colorado and New Mexico and summarized ground-water conditions in the Rio Grande drainage area. Robinson and Waite (1938) described ground-water conditions of the San Luis Valley of Colorado. Blaney and others (1938) described water use in the upper Rio Grande basin and reported the results of "tank experiments" that were used in estimating evapotranspiration. Upson (1939) described the physiographic subdivisions in the San Luis Valley. Powell (1958) studied the ground-water resources of the San Luis Valley with emphasis on estimating the probable quantity and quality of water that would be intercepted by a proposed drainage system for the closed basin [a previous proposal of the current (1987) Closed Basin Division]. Powell also investigated ground-water conditions in the area irrigated using diversions from the Rio Grande and by ground-water pumping. Emery (1970) used an electric-analog model to evaluate a proposed water-salvage plan. Emery and others (1975) used an electric-analog model to investigate the hydrology of the San Luis Valley. Emery and others (1971; 1972) presented hydrologic data for the San Luis Valley. Emery and others (1973) presented a water budget for the San Luis Valley. Huntley (1979) investigated recharge to the aquifers in the closed basin of the San Luis Valley using water budgets and a steady-state model of vertical ground-water flow. Burroughs (1981) provided an updated summary of the geology of the San Luis basin with emphasis on geothermal potential. Burroughs' report describes the most current (1981) description of the structural geology of the San Luis Valley based on recent (1981) surface and borehole geophysical data. Crouch (1985) reported potentiometric data for the unconfined aquifer and water-level changes that occurred during 1969-80. Additional references are cited throughout the text and are listed in the "Selected References" section.

Data Collection and Analyses

Data collected during this study include: (1) Lithologic logs, well-construction logs, and results from aquifer tests and production tests done by the U.S. Bureau of Reclamation; (2) water-level data collected by the Rio Grande Water Conservation District, the U.S. Bureau of Reclamation, and the U.S. Geological Survey; and (3) temperature profiles of the subsurface.

Evapotranspiration of ground water from the closed basin was estimated by using data collected during lysimeter-tank experiments that were done in northwestern Alamosa County, Colorado, during the 1920's and 1930's (Blaney and others, 1938), in the Escalante Valley, Utah, during the 1920's (White, 1932), and near Winnemucca, Nevada, during the 1960's and 1970's (Grosz, 1969, 1970, 1971, 1972, 1973; Robinson and Waananen, 1970; Dylla and others, 1972). Temperature profiles of the subsurface were measured at 12 sites in the Closed Basin Division project area. These temperature data were analyzed using the method described by Sorey (1971) to estimate specific discharge (leakage).

A numerical model for aquifer simulation in two dimensions (Trescott and others, 1976) was used to evaluate the potential changes to the hydrologic system that may be caused by ground-water withdrawals of the Closed Basin Division. This numerical model simulates an unconfined aquifer with depth-dependent evapotranspiration, upward leakage through a leaky confining layer, and ground-water withdrawals by the salvage wells. The principles of superposition, as described by Reilly and others (1984), were used to evaluate the potential changes caused by the proposed ground-water withdrawals of the Closed Basin Division.

Hydrologic Setting

The Rio Grande basin of south-central Colorado, an area of about 8,000 mi^2, is bordered on the east by the Sangre de Cristo Mountains and on the west by the San Juan Mountains (fig. 1). This basin can be divided into three hydrogeologic regions: (1) The San Luis Valley, a broad, relatively flat, intermontane valley, about 3,200 mi^2 in area that is underlain by several thousand feet of volcanic rocks and unconsolidated sedimentary deposits; (2) the San Juan Mountains, a highland of volcanic rock rising gradually west of the San Luis Valley; and (3) the Sangre de Cristo Mountains, an uplifted block of Paleozoic and Mesozoic sedimentary rocks overlying a core of Precambrian igneous and metamorphic rocks that rise steeply east of the San Luis Valley.

The San Luis Valley may be subdivided, based on surface drainage, into: (1) The closed basin (fig. 1), an area of internal drainage that is north of the Rio Grande; and (2) the contributing drainage of the Rio Grande. The closed basin is bounded on the south by a very low drainage divide that extends from the edge of the valley, north of the Rio Grande near Del Norte, east to a point about 8 mi east of Alamosa, then northeast toward the edge of the valley near Blanca. The contributing drainage area to the closed basin is mainly from the mountains to the west and is about 1,800 mi^2 in area.

The major streams entering the closed basin are Saguache and San Luis Creeks (fig. 1). Numerous smaller streams also enter the closed basin from the Sangre de Cristo Mountains. Most of the surface-water inflow to the closed basin infiltrates into the valley fill within the first few miles after entering the valley. Generally, streamflow does not reach the Closed Basin Division near the center of the closed basin.

The altitude of the valley floor is about 7,500 to 7,600 ft in the topographic lows along the Rio Grande and in the closed basin and is about 8,000 to 8,500 ft at the heads of the alluvial fans along the valley's edge. Total relief from the mountain peaks to the valley floor is as much as 6,800 ft.

Irrigation began in the San Luis Valley during the 1880's with water diverted from the Rio Grande and its tributaries and later with ground water withdrawn by flowing wells. During the first half of this century, surface water was the principal source of irrigation water and ground water was used only during years of low runoff. Since 1950, more and more ground water has been withdrawn for use in irrigation.

Climate

The San Luis Valley is a high mountain desert valley that is characterized by small quantities of precipitation, rapid rate of evaporation, moderate-to-frigid temperature, moderate winds, and abundant sunshine. Much of the precipitation in the valley occurs during the spring and summer (fig. 3) when the rate of evaporation is greatest.

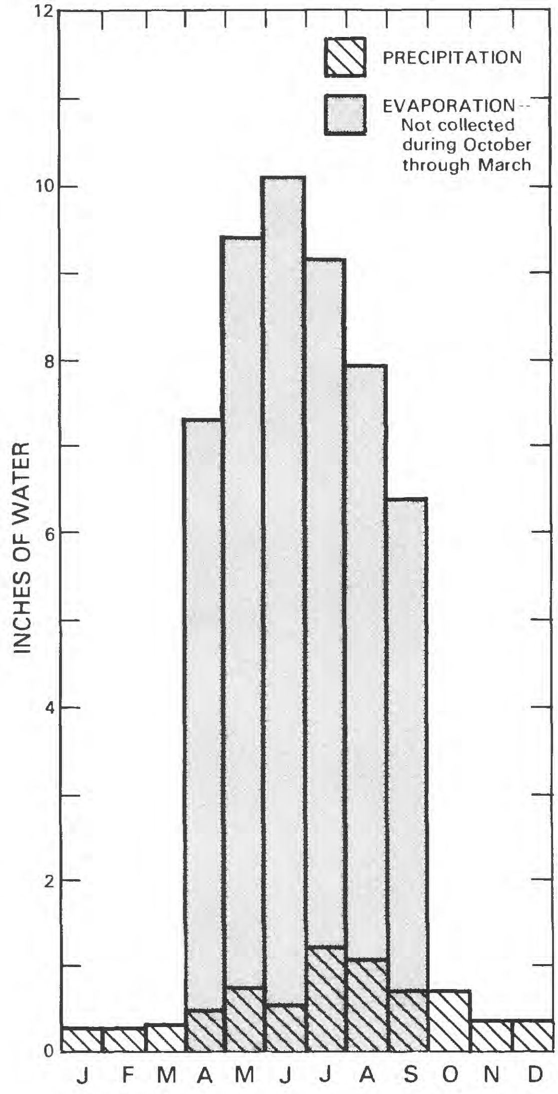


Figure 3.--Average monthly precipitation, 1951-80, and average monthly evaporation from a class-A pan, 1960-80, at Alamosa.

Climatological records (National Oceanic and Atmospheric Administration, 1951-80) for the weather station at the Alamosa airport indicate that the average annual precipitation at Alamosa during 1951-80 was 7.13 in. Daily precipitation equaled or exceeded 1.0 in. only 8 times in the 30-year period. During the growing season, evaporation from a class-A pan (fig. 3) exceeds precipitation by almost one order of magnitude. Total evaporation from a class-A pan for April through October at Alamosa averaged about 57 in. for 1960-80. Monthly totals for October were reported for only 2 years during 1960-80. Farnsworth and others (1982) estimated that annual evaporation from free-water surfaces in the San Luis Valley is about 50 in.

Average annual precipitation in the mountains that border the closed basin is directly proportional to altitude (orographically controlled). Average annual precipitation is as much as 30 to 40 in. on the mountain peaks. Huntley (1979) estimated average annual precipitation for a 359-mi^2 area of the Sangre de Cristo Mountains that drains to the closed basin to be about 26 in/yr and for a 1,185-mi^2 area of the San Juan Mountains that drains to the closed basin to be about 21 in/yr. Most of the runoff from these areas occurs as snowmelt during spring and summer.

Acknowledgments

The authors gratefully acknowledge the support and assistance given by personnel of the U.S. Bureau of Reclamation during this study. In particular, data about exploration and monitoring wells, and the proposed locations and discharges of salvage wells were provided by Robert K. Neal, Project Geologist, and Ben F. Morrison, Civil Engineer, Alamosa Project Office, San Luis Valley Project. Interpretation of aquifer characteristics was provided by Herbert H. Ham, Geologist, Division of Operation and Maintenance Technical Services, Drainage and Ground Water Branch.

HYDROGEOLOGY

The hydrogeology of the study area is complex and incompletely defined. The San Luis Valley, an extension of the Rio Grande Rift, is a large faulted trough that has been filled with interbedded fine- to coarse-grained alluvial and lacustrine deposits, volcanic flows, and volcaniclastic rocks. These valley-fill deposits are estimated to be as much as 19,000 ft thick (Burroughs, 1981). The distribution and thickness of these deposits in the San Luis Valley in part is structurally controlled. This report primarily is concerned with the unconfined aquifer; however, descriptions also are reported for the deeper valley-fill deposits. The topography, structural geology, and stratigraphy of the San Luis Valley affect the occurrence and movement of ground water in the valley.

The topography of the land surface of the San Luis Valley is that of an asymmetric north-south trending trough, with steep slopes of more than 50 ft/mi on the alluvial-fan deposits at the sides of the valley and gentle slopes of about 6 ft/mi on the valley floor. A conspicuous feature on the valley floor of the San Luis Valley is the closed basin that is north of the

Rio Grande in Alamosa and Saguache Counties. The topographic low in the closed basin has an altitude of about 7,500 ft, while the higher peaks of the Sangre de Cristo and San Juan Mountains are more than 14,000 ft. Maximum relief from mountain peak to the valley floor is about 6,800 ft. Local relief from the heads of the alluvial fans to the valley floor is about 500 ft.

The San Luis Valley can be divided into five physiographic subdivisions (fig. 4): the Alamosa Basin, the San Luis Hills, the Taos Plateau, the Costilla Plains, and the Culebra Reentrant (Upson, 1939). The Closed Basin Division lies largely within the Alamosa Basin. The San Luis Hills, a series of basalt hills and mesas across the southern part of the valley, form a physiographic, structural, and hydrologic divide that separates the Alamosa Basin from the southern part of the San Luis Valley.

Geology

The Alamosa Basin is divided by the Alamosa *horst*, a northward-trending uplifted fault block. The Alamosa horst separates the Monte Vista *graben* on the west from the Baca graben on the east (fig. 5). Burroughs (1981) reports that these structural features are hinged fault blocks, and that the terms horst and graben are not strictly valid; however, the terms were retained in this report for purposes of discussion. Maximum thickness of the valley-fill deposits is about 10,000 ft in the Monte Vista graben and about 5,400 ft over the Alamosa horst, and is estimated from geophysical data to be about 19,000 ft in the Baca graben about 10 mi north of the geologic section (Burroughs, 1981). The Closed Basin Division overlies the Baca graben.

The geologic section (fig. 5) in the Alamosa Basin consists of a basement complex of Precambrian plutonic and metamorphic rocks that are overlain by valley-fill deposits. The valley-fill deposits may be subdivided into three intervals based on gross lithologic characteristics. The basal interval consists of older volcanic and volcaniclastic rocks and the red-colored, fluvial clay, silt, sand, and gravel of the Eocene and Oligocene Vallejo Formation (Upson, 1941), undifferentiated Oligocene(?) volcaniclastic and volcanic rocks, and the Fish Canyon and Carpenter Ridge Tuffs of Oligocene age. Pre-Vallejo rocks probably are present only in the Baca graben. The Vallejo Formation, the undifferentiated Oligocene(?) volcaniclastic and volcanic rocks, and the Fish Canyon and Carpenter Ridge Tuffs generally are absent in the Baca graben.

The intermediate interval consists of interbedded volcanic, volcaniclastic, alluvial-fan, and alluvial deposits of the Los Pinos Formation and Santa Fe Formation. In general, the Los Pinos Formation consists of sandy gravel with interbedded volcaniclastic sandstone and tuffaceous material that was deposited as an eastward thickening wedge along the eastern border of the San Juan Mountains. The Los Pinos Formation is classified as Oligocene to Pliocene age. The Santa Fe Formation of Miocene and Pliocene age consists of buff to pinkish-orange clays with interbedded, poorly to moderately sorted silty sands. Locally, well-sorted sands predominate. Detrital fragments in the Santa Fe Formation indicate source areas from the Sangre de Cristo and San

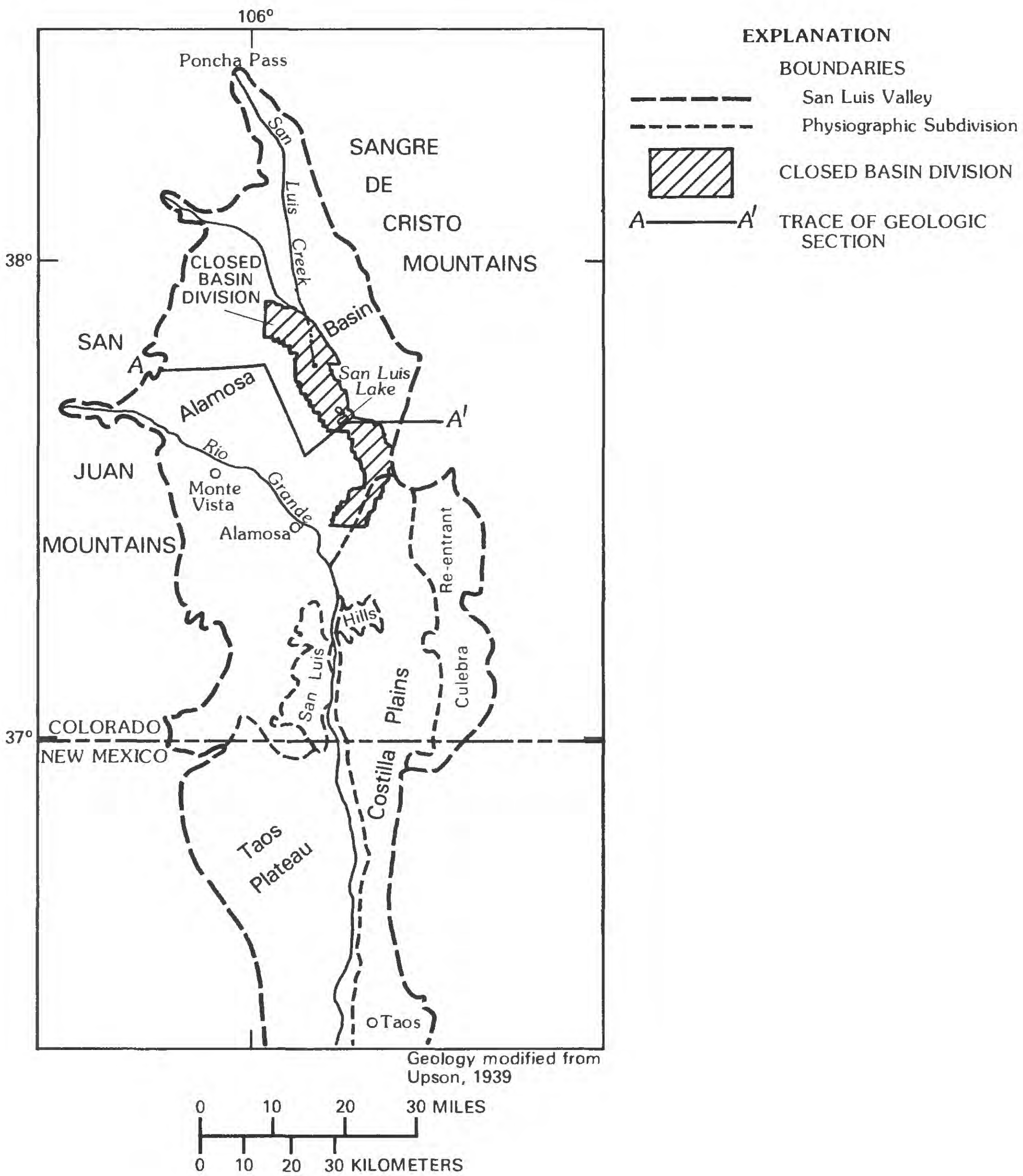
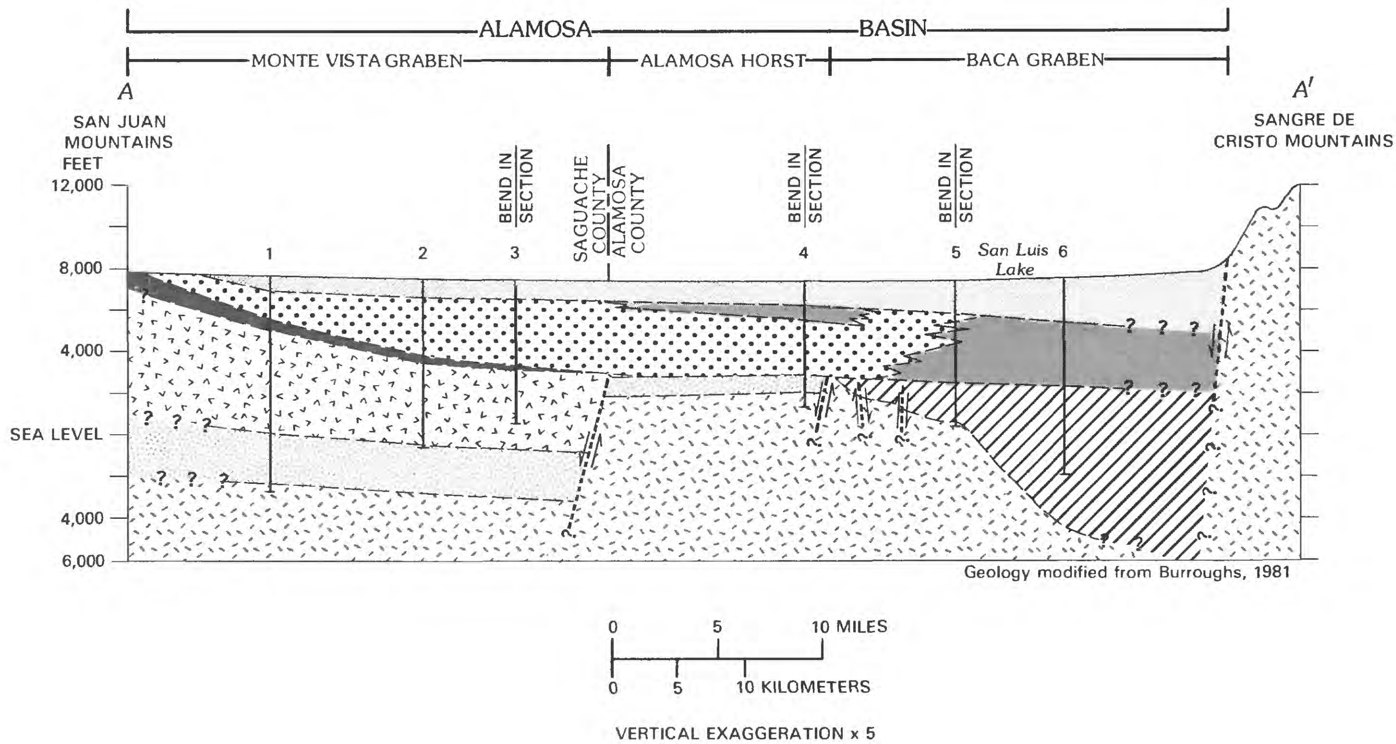


Figure 4.--Physiographic subdivisions of the San Luis Valley.



EXPLANATION

ALAMOSA FORMATION

LOS PINOS FORMATION

SANTE FE FORMATION

CARPENTER RIDGE AND FISH CANYON TUFFS

OLIGOCENE(?) VOLCANICLASTIC AND VOLCANIC ROCKS

VALLEJO FORMATION OF UPSON, 1941

PRE-VALLEJO (TERTIARY-CRETACEOUS (?)) ROCKS

PRECAMBRIAN ROCKS

INFERRED FAULT--Arrows indicate relative movement. Queried where poorly defined

CONTACT--Contact between geologic units. Queried where poorly defined

WELL AND NUMBER LISTED BELOW

1	NA04100714DC
2	NA04100813AAA
3	NA04100911C
4	NA03901016CD
5	NA04001133CD
6	NA04001232BD

Figure 5.--Generalized geologic section across the Alamosa Basin (trace of section shown in figure 4).

Juan Mountains. The Los Pinos Formation and Santa Fe Formation intertongue. The Los Pinos Formation is predominant in the Monte Vista graben and Alamosa horst, and the Santa Fe Formation is predominant in the Baca graben.

The upper lithologic interval, the one of primary interest to this study, consists of the Pliocene and Pleistocene Alamosa Formation and overlying undifferentiated Pleistocene and Holocene deposits. Because of the similarity between the Alamosa Formation and the overlying Pleistocene and Holocene deposits, Powell (1958) and Emery (1970) did not attempt to differentiate these deposits and their designation is retained in this report. They subdivided this interval based on its hydrology into unconfined and confined aquifers, according to the position of the uppermost blue clay or fine-grained sand in the Alamosa Formation or the uppermost layer of volcanic rock below the water table. The Alamosa Formation and overlying deposits consist of discontinuous beds of clay, silt, sand, and gravel. Eolian deposits occur at the surface in part of the area. In general, the valley-fill deposits become more fine grained and less permeable toward the topographic low of the closed basin (Emery and others, 1975).

Thicknesses of the stratigraphic units of the valley-fill deposits are variable; deposition was structurally controlled in part. The Alamosa Formation has a maximum thickness of about 2,050 ft in the topographic low (Burroughs, 1981). The thickness of the Alamosa Formation decreases towards the west, where it eventually pinches out against coarse-grained alluvial deposits or volcanic rocks. A decrease in the number of clay beds and their thicknesses corresponds to a decrease in thickness of the Alamosa Formation (Emery and others, 1975). Depth to the first clay (or *confining unit*) in the Alamosa Formation generally is between 60 and 120 ft in the closed basin as shown in figure 6. Test drilling by Powell (1958) indicated that individual clay layers in the Alamosa Formation are not laterally continuous; they are lenticular and interfinger with sand and gravel. Huntley (1979), citing the reduced nature of the clays, the generally fine-grained sands, and the presence of fresh-water invertebrates in the clays, postulated that the clays were deposited in a lacustrine (lake) or palustrine (marsh) environment, and that the sands were deposited in alluvial channels eroded into the clays.

Ground Water

The valley-fill deposits of the San Luis Valley form aquifers that contain ground water. Thousands of wells have been completed in the unconfined aquifer and in the upper part of the confined aquifer for irrigation of crops and pasture, domestic use, and municipal supply.

Inflow to the aquifers in the closed basin is from infiltration of surface water, underflow from volcanic rocks of the San Juan Mountains, and precipitation. Outflow from the unconfined aquifer mainly is by evaporation from bare soil and free-water surfaces and transpiration by crops and native vegetation, including *phreatophytes*. The water table is near (within 13 ft of) the land surface in most of the closed basin.

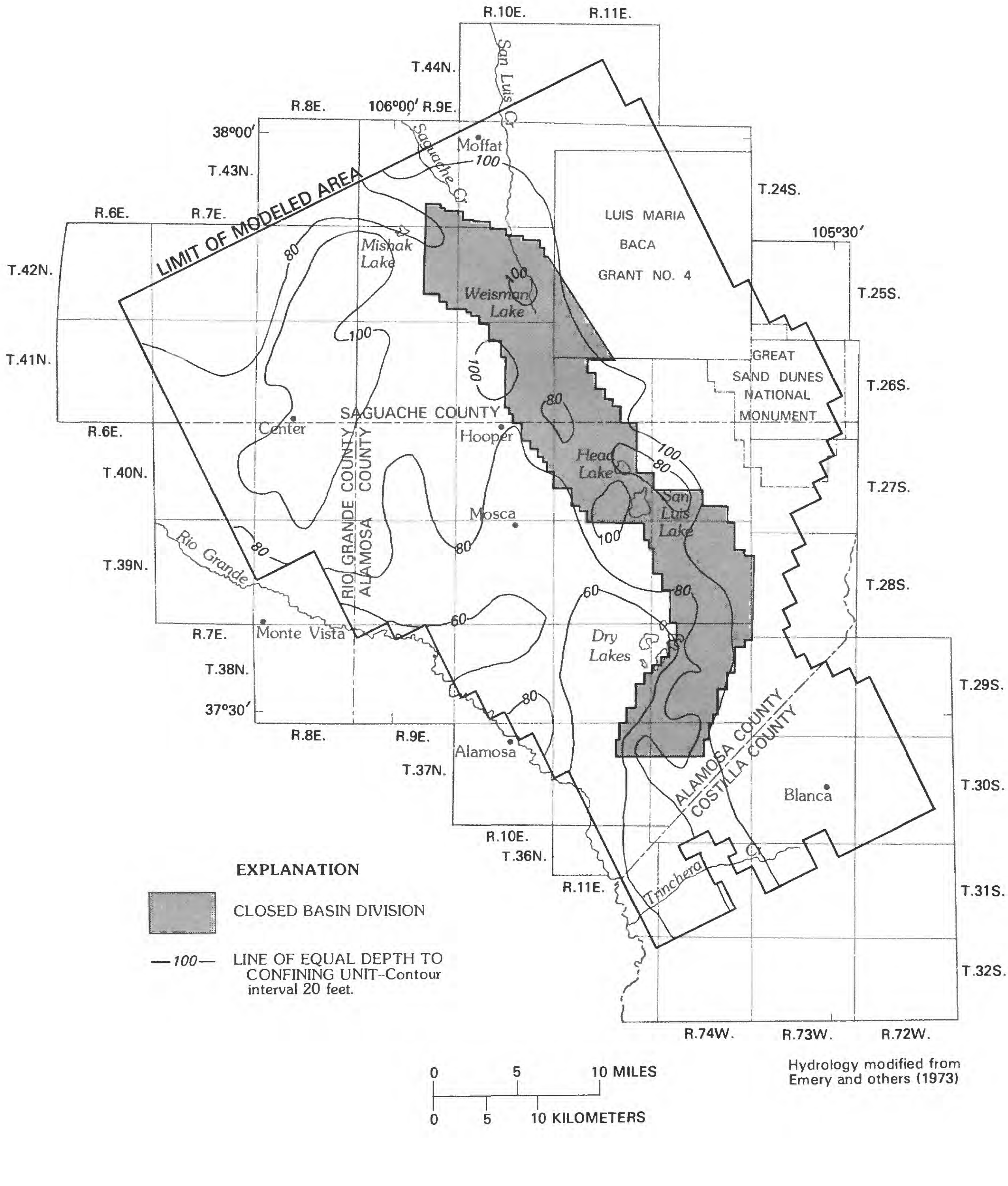


Figure 6.--Depth to the confining unit.

The unconfined aquifer in the study area consists of the valley-fill deposits above the uppermost blue clay of the Alamosa Formation or above layers of volcanic rock. The lateral extent of the unconfined aquifer is the limit of saturated valley-fill deposits (fig. 1). The combined thickness of the saturated and unsaturated parts of the unconfined aquifer is equivalent to the depth below land surface of the uppermost confining unit (fig. 6). The unconfined aquifer consists of discontinuous, lenticular deposits, in which average grain size and permeability generally decrease towards the center of the basin. The lenticular nature and changes in lithology of these deposits result in an aquifer that locally is heterogeneous and anisotropic.

Hydraulic Properties

The *transmissivity* (fig. 7) of the unconfined aquifer was estimated from values reported by Emery (1970) and from aquifer tests done by the U.S. Bureau of Reclamation during construction of wells in the Closed Basin Division. The values of transmissivity of the unconfined aquifer generally range from 1,000 to 23,450 ft^2/d. The estimated transmissivity of the unconfined aquifer is largest in the western part of the Closed Basin Division and smallest in the southern part. The smaller values of transmissivity in the Closed Basin Division primarily result from decreases in the grain size of the aquifer's matrix toward the center of the basin. The small estimates of transmissivity in the coarse-grained alluvial-fan deposits east of the Closed Basin Division result from limited saturated thickness. Transmissivity is the product of the *hydraulic conductivity* of the aquifer and its saturated thickness.

The reported values of *specific yield* of the unconfined aquifer range from about 5 to 24 percent as determined from pumping tests of 24 to 48-hour duration (Powell, 1958). Powell reported that the apparent specific-yield value determined in these tests increased with time, indicating that drainage of the aquifer within the cone of depression was not complete during the tests. The specific-yield value of the aquifer probably is about 15 to 24 percent upon complete drainage. Emery (1970) and Emery and others (1975) used a specific-yield value of 20 percent for the unconfined aquifer in their electric-analog models of the San Luis Valley.

Emery and others (1975) used *hydrologic budgets* of the unconfined aquifer and an electric-analog model of three-dimensional ground-water flow in the unconfined-confined aquifer system to estimate values of vertical hydraulic conductivity. These estimates were: 0.059 and 0.062 ft/d for the upper 750 ft of the confined aquifer in the closed basin; 0.00059 ft/d where lava flows are the confining unit; and 59 ft/d along the fault or depositional contact of the valley fill with the San Juan Hills. Huntley (1979) estimated the value of vertical hydraulic conductivity of the clays of the Alamosa Formation by trial-and-error adjustment of a numerical model. These estimates were 0.04 ft/d for the eastern part of the closed basin, and 0.006 ft/d for the western part of the closed basin.

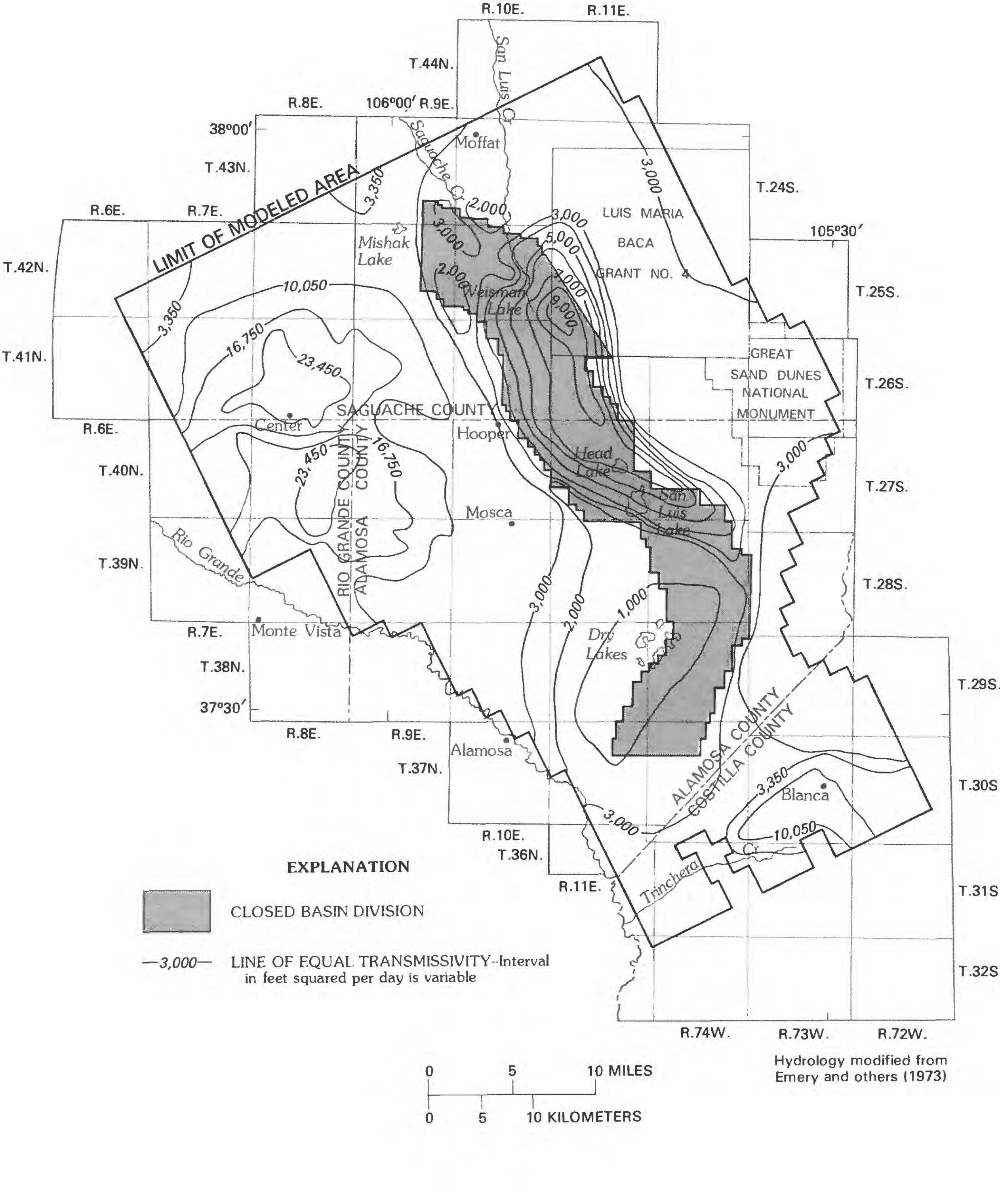


Figure 7.--Estimated transmissivity of the unconfined aquifer.

The *vertical conductance* of the confined aquifer in the closed basin, the vertical hydraulic-conductivity value of the confining unit (0.059 to 0.062 ft/d) divided by the estimated flow-path length (750 ft) used by Emery and others (1975) in their hydrologic budget, is about 8.3×10^{-5} d^{-1}. Because Huntley did not define the thickness of the confining units, the vertical-conductance value for his model could not be estimated.

Inflow

Inflow to the unconfined aquifer in the San Luis Valley consists of precipitation in excess of the soil's field capacity and evapotranspiration demand, return flow of irrigation water in excess of irrigation demand, seepage from irrigation canals and streams, ground-water underflow into the valley, and leakage from the confined aquifer. Reliable estimates of the rate of inflow cannot be made from the available data.

Annual precipitation in the San Luis Valley averages about 7 to 8 in. Most of the precipitation occurs during the growing season and is used in evapotranspiration at the surface or in temporarily increasing soil moisture until it is used by evapotranspiration. During the nongrowing season, some precipitation probably is returned to the atmosphere by evaporation and sublimation. Powell (1958) estimated recharge from precipitation to be as much as 20 percent of annual precipitation in areas with porous soils and gentle slopes. In areas with steep slopes and fine-grained soils, the percentage of precipitation recharging the unconfined aquifer would be much less. The average annual recharge to the unconfined aquifer from precipitation is estimated at about 0.05 ft, about 8 percent of precipitation. Because of the small quantity of precipitation, about 0.6 ft, the small percentage of precipitation that reaches the water table (0.05-0.12 ft), and the magnitude of evapotranspiration, errors in the estimate of recharge from precipitation do not greatly affect the estimates of total inflow.

Return flow of irrigation water is the major source of recharge to the unconfined aquifer. Because surface water and ground water from the unconfined and confined aquifers are and have been used for irrigation in the San Luis Valley and the spatial and temporal patterns of use are known only in general terms, their effects on the unconfined aquifer cannot be separated. During 1940-79, the average annual rate of surface-water diversions in the San Luis Valley was about 1,100,000 acre-ft. The annual surface-water diversions (fig. 8) ranged from about 500,000 acre-ft during 1977 to more than 1,600,000 acre-ft during each of the years 1941, 1952, 1957, and 1965. Ground-water withdrawals increased from about 3,000 acre-ft during 1941 to almost 1,000,000 acre-ft during 1977 (fig. 8). The increased use of ground water during the 1970's and smaller than average surface-water diversions resulted in water-level declines in the unconfined aquifer between 1969 and 1980 in much of the irrigated area on the west side of the closed basin (Crouch, 1985). Because water levels were declining, it can be assumed that return flow from irrigation was not substantial during 1969-80. Data are not available to estimate seepage losses from irrigation canals. Many of the smaller streams that flow into the valley are ungaged, and runoff must be estimated from empirical estimates of the relation between precipitation and runoff (Emery and others, 1973, pl. 1). Infiltration of surface water as it flows across the alluvial fans at the valley's edge generally occurs before surface flow reaches the Closed Basin Division.

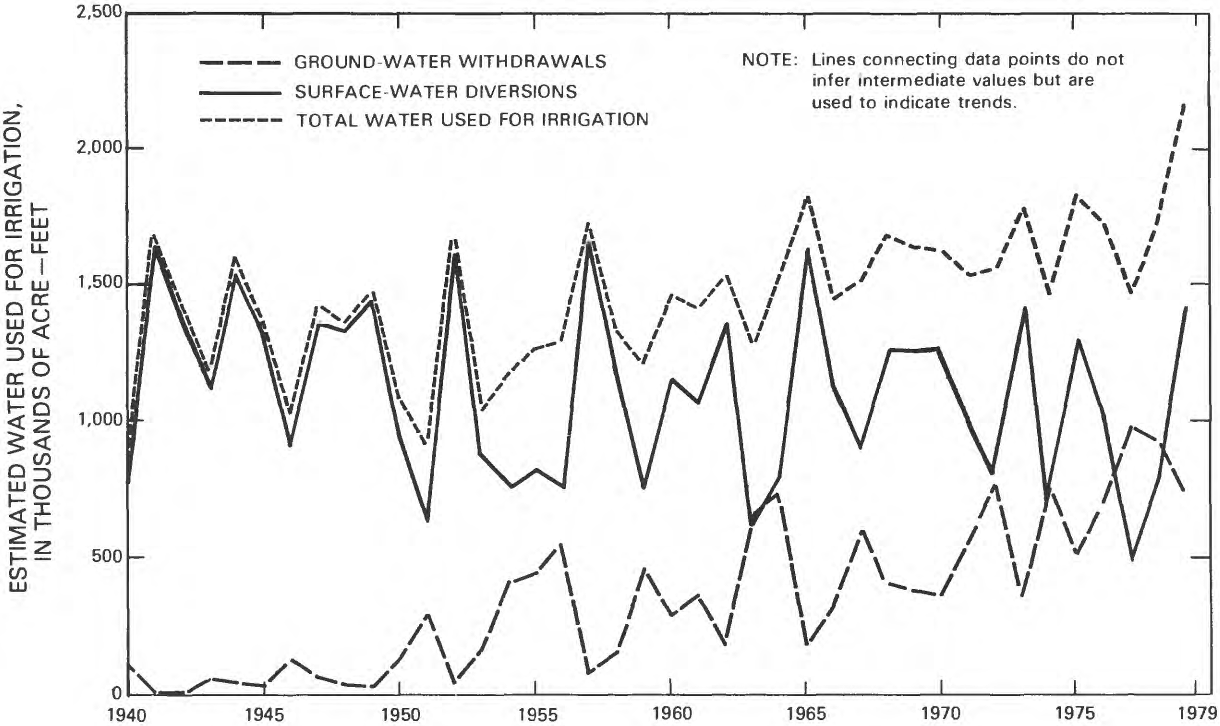


Figure 8.--Estimated annual water use for irrigation, ground-water withdrawals, and surface-water diversions in the San Luis Valley, 1940-79.

Leakage from the confined aquifer to the unconfined aquifer may be a substantial source of inflow. The rate of leakage was estimated by Emery and others (1975) using a hydrologic budget of the closed basin (with leakage as the unknown) at 4.53×10^7 ft^3/d in an area of 2.7×10^{10} ft^2 or a unit-area rate of 0.61 ft/yr. The estimated rate of leakage also includes all errors in the estimates of the other sources and sinks in the hydrologic budget. The actual rate of leakage may be greater than or less than this estimate.

Leakage also can be estimated as the velocity of ground-water flow through a vertical section, and it may be determined empirically from the temperature profiles of the subsurface. Stallman (1963) presented a mathematical model to describe the simultaneous flow of heat and water within the earth. Bredehoeft and Papadopulos (1965) solved the general equation given by Stallman for the *steady-state* case in one dimension, and these authors provided a set of type curves to match with the temperature profile in a well to compute the rate of vertical flow of ground water. Sorey (1971) determined the rate of upward movement of water through the semiconfining beds at the base of the unconfined aquifer at 1.2 ft/yr near Alamosa and 0.9 ft/yr at a site about 40 mi north of Alamosa.

Temperature profiles were measured in 12 wells in the Closed Basin Division. Analyses of the temperature profiles indicate that upward leakage into the unconfined aquifer ranges from about 0.3 to 2.0 ft/yr (fig. 9). The average rate of leakage, estimated from temperature profiles measured during this study, was about 1.5 ft/yr. However, horizontal flow in the aquifer, temperature differences between the well and the aquifer, small ground-water velocities, and the heterogeneity of the unconfined aquifer and confining unit may affect the accuracy of the estimation technique. Therefore, the estimates need to be considered preliminary.

Potentiometric Surface and Movement of Ground Water

A map of the January 1983 *potentiometric surface* (fig. 10) of the unconfined aquifer indicates that ground-water movement in the unconfined aquifer is toward the topographic low. The water table is a potentiometric surface in an unconfined water body at which pressure is atmospheric. Because water levels from existing wells of various depths were the only measurements available, water levels used in preparation of figure 10 represent potentiometric levels of the unconfined aquifer at depths at which the pressure may be greater than atmospheric. The hydraulic gradient of the potentiometric surface of the unconfined aquifer is toward the potentiometric low that is coincident with the topographic low. In this area, water is discharged to the atmosphere by evapotranspiration.

The potentiometric surface of the confined aquifer (Emery and others, 1975, pl. 5) is similar in configuration and generally is higher in altitude than the potentiometric surface of the unconfined aquifer. This difference in potentiometric surfaces indicates that flow is from the confined aquifer to the unconfined aquifer in most of the closed basin. Recharge to the confined aquifer is from the volcanic rocks of the San Juan Mountains on the west and from downward flow through the unconfined aquifer around the edge of the valley (Huntley, 1979).

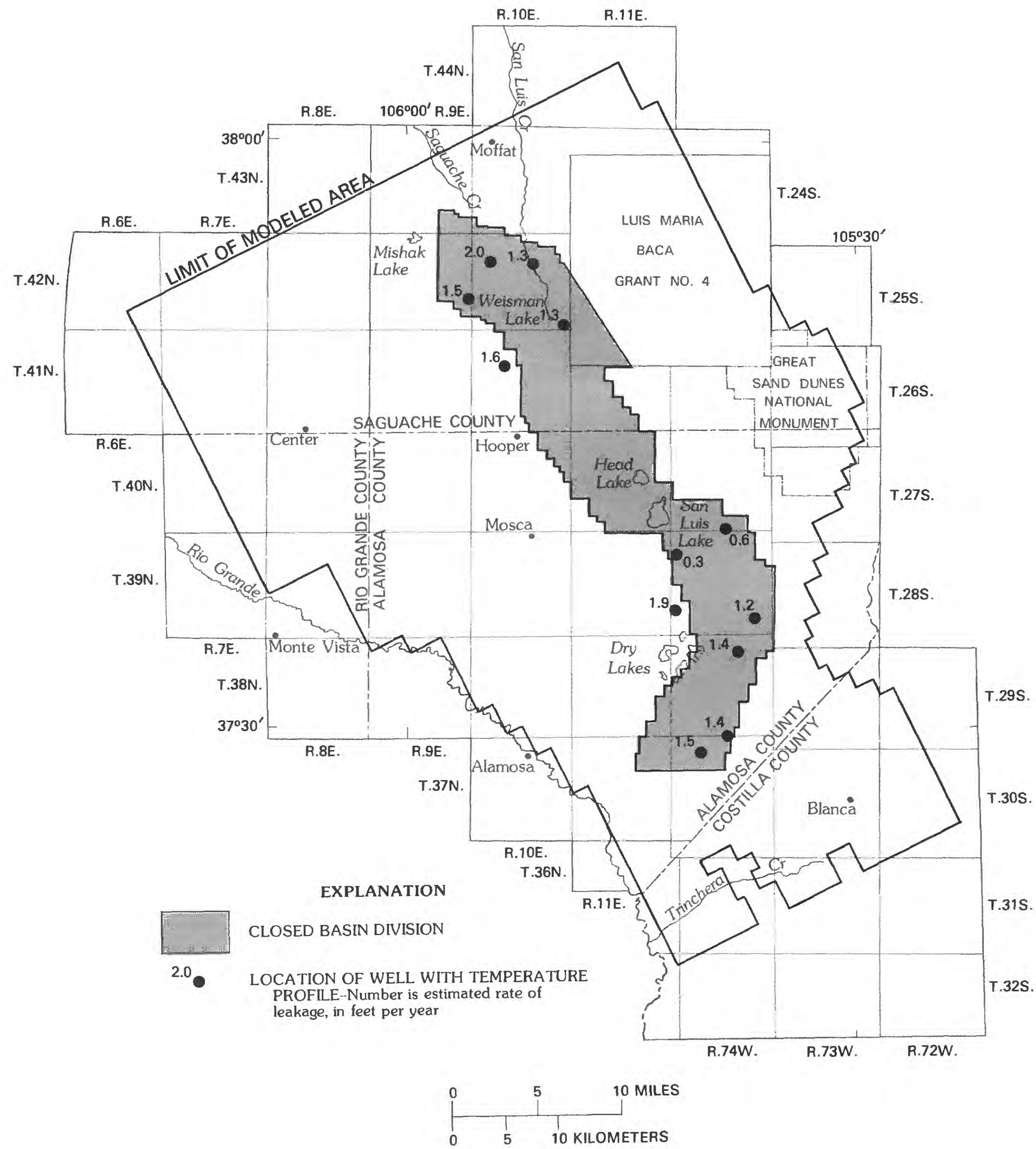


Figure 9.--Locations of temperature-profile sites and estimated rates of leakage.

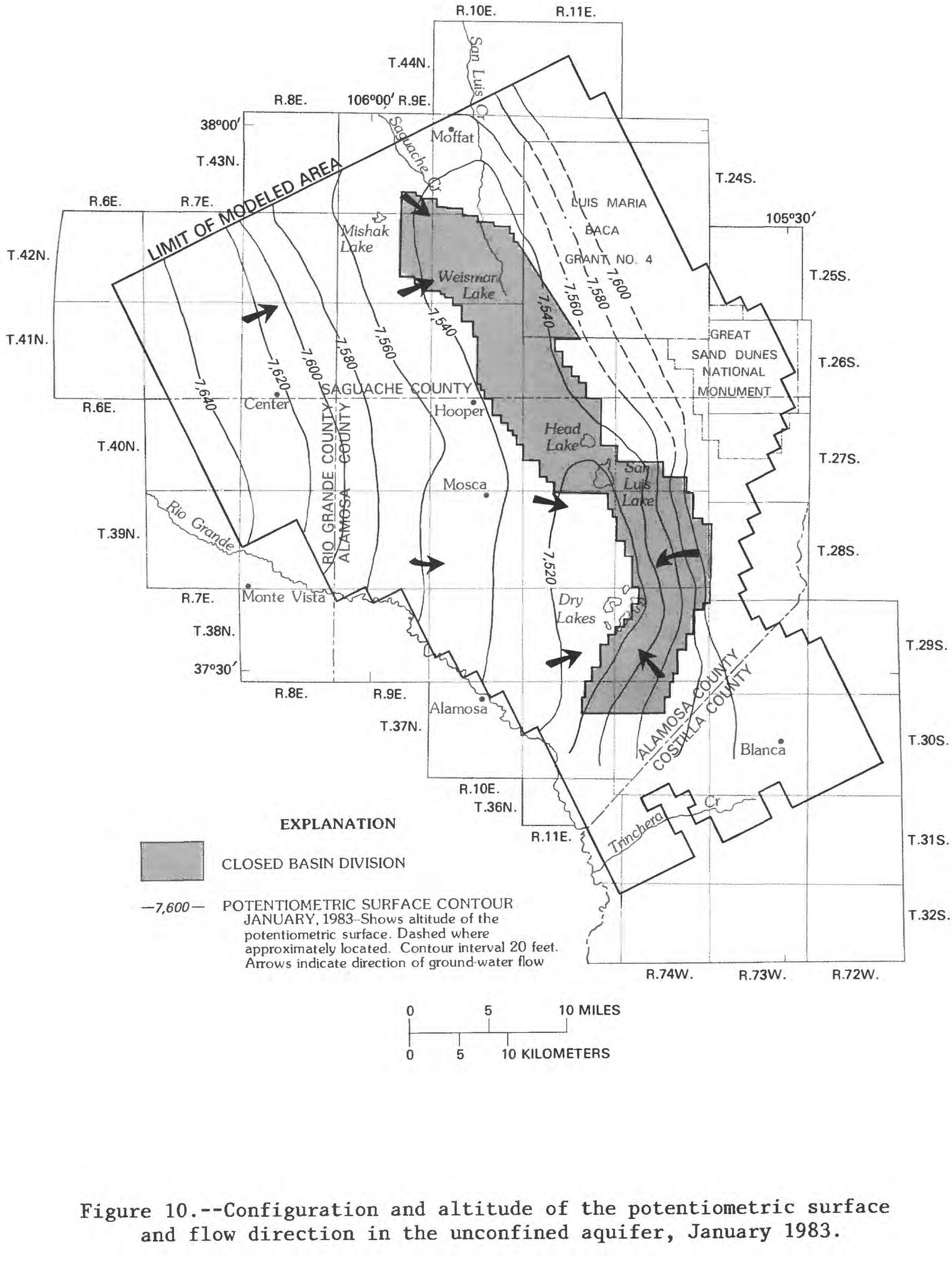


Figure 10.--Configuration and altitude of the potentiometric surface and flow direction in the unconfined aquifer, January 1983.

The map of the potentiometric surface of the unconfined aquifer (fig. 10) and maps of the potentiometric surface of the confined aquifer that were prepared by previous investigators (Powell, 1958, pl. 5, 8, 9, 10; Emery and others, 1973, pl. 1, 6; Crouch, 1985, sheet 1) indicate that ground water in the unconfined and confined aquifers moves from the edge of the closed basin toward the central topographic low of the basin. The low ground-water divide that closely parallels the southern limit of the closed basin (fig. 1) has migrated with time. Powell (1958) and Crouch (1985) reported the movement of segments of the ground-water divide south toward the Rio Grande. This divide does not represent a hydraulic barrier to flow, but it indicates local recharge and discharge conditions. Prior to irrigation in the San Luis Valley, a ground-water divide probably existed along the valley of the Rio Grande.

Changes in the potentiometric surface of the unconfined aquifer occur as a result of seasonal and long-term changes in climatically controlled inflow and outflow; changes in the potentiometric surface also occur as a result of irrigation practices. *Hydrographs* of shallow observation wells in the Closed Basin Division indicate the seasonal effects of evapotranspiration. Changes in the sources of irrigation water, in irrigation methods, and in the area irrigated affect inflow and outflow of the aquifer and cause water-level changes. Prior to large-scale diversions of surface water into the closed basin (before 1880), the water table on the west side of the valley was reportedly 50 to 100 ft below ground surface. Over a period of years, the infiltration of surface water and the discharge from flowing artesian wells raised the water table to near ground surface (Powell, 1958). During the drought of the 1950's, ground-water withdrawals from the unconfined aquifer increased because of limited surface-water supply. During the 1960's and 1970's, many fields that were formerly subirrigated or flood irrigated were converted to center-pivot irrigation. These changes in inflow and outflow of the unconfined aquifer have caused water levels to fluctuate. Crouch (1985) reported water-level declines of 5 to more than 20 ft from 1969 through 1980, in the main irrigated area in the southwestern part of the closed basin. These declines seem to have resulted from increased use of ground water from the unconfined aquifer and decreased surface-water diversions.

Outflow by Ground-Water Evapotranspiration

Ground water primarily is discharged from the unconfined aquifer in the closed basin by evapotranspiration. Although small quantities of ground water may flow across the southern boundary of the closed basin, the direction of ground-water movement in the unconfined aquifer is toward the topographic low (fig. 10). Evapotranspiration in the closed basin consists of transpiration by irrigated crops and native vegetation, including phreatophytes and evaporation from soil and free-water surfaces. Evapotranspiration includes water used by plants and water evaporated from soil, wetted surfaces of plants, and free-water surfaces. Sources of water for evapotranspiration by crops in the study area include irrigation (surface water and ground water from the unconfined and confined aquifers), ground water directly from the water table, soil moisture, and precipitation. Sources of water for evapotranspiration by native vegetation include ground water directly from the water table, soil moisture, and precipitation.

The rate of evapotranspiration is affected by climatic, soil, aquifer, and plant characteristics. Because of the complexity and interaction of these characteristics, the rate of evapotranspiration is site-dependent. In this study, ground-water evapotranspiration by native phreatophytes primarily was assumed to be a function of depth to water. Depth to water in the unconfined aquifer is near land surface (within 13 ft) in much of the closed basin (fig. 11).

Evapotranspiration of ground water by crops from the unconfined aquifer in the closed basin has not been quantitatively defined. Annual irrigation demand and acreage (table 1) of the irrigated crops grown in the closed basin (Davis Engineering Service, Inc., 1977; G.A. Hearne and J.D. Dewey, U.S. Geological Survey, written commun., 1984) were used to estimate evapotranspiration by crops. The estimated irrigation demand ranges from 1.0 ft/yr for small grains to 1.76 ft/yr for alfalfa and averages about 1.37 (Davis Engineering Service, Inc., 1977) to 1.51 ft/yr (G.A. Hearne and J.D. Dewey, U.S. Geological Survey, written commun., 1984) for the estimated 359,200 irrigated acres in the closed basin. The product of irrigated area and irrigation demand yields a total irrigation demand that ranges from about 492,000 to 542,000 acre-ft/yr. Total irrigation demand is assumed to equal evapotranspiration by crops and pasture. However, it is not an estimate of ground water withdrawn from the unconfined aquifer because of the multiple sources of irrigation water.

Water is discharged from the unconfined aquifer in the closed basin by the transpiration of plants and by evaporation from bare soil. Because few data are available to evaluate the rates of transpiration and evaporation separately, they are considered as one process, evapotranspiration. The native plants that are capable of obtaining water from the water table are saltgrass (Distichlis); greasewood (Sarcobatus); and rabbitbrush (Chrysothamnus). P.A. Emery (U.S. Geological Survey, written commun., 1983) observed that greasewood did not flourish where depth to water exceeded 12 ft. Emery (1970, fig. 3) developed a curve (line AB, fig. 12) to estimate ground-water evapotranspiration in the San Luis Valley from depth to water in the unconfined aquifer. Evaporation from saturated soil and transpiration by saltgrass was determined from lysimeter-tank experiments that were done during 1927-28 and 1930-31 near the Garnett Post Office in northwestern Alamosa County (Blaney and others, 1938) (fig. 12). Because depth to water was less than 3 ft in all the experiments, and because transpiration by greasewood and rabbitbrush were not evaluated, data from similar experiments that were done outside the San Luis Valley were used to define the relation between depth to water and ground-water evapotranspiration. Results from experiments with saltgrass and greasewood that were done during 1927 in the Escalante Valley, Utah (White, 1932) and with saltgrass, greasewood, and rabbitbrush that were done during the 1960's and early 1970's near Winnemucca, Nevada (Grosz, 1969, 1970, 1971, 1972, 1973; Robinson and Waananen, 1970; Dylla and others, 1972) were used to supplement data available for the San Luis Valley. The data plotted in figure 12 are the reported consumptive use minus the precipitation that occurred during the experiments. The data from outside the San Luis Valley may not be representative of values obtained in the valley because of differences in climate, soils, water chemistry, experimental procedures, and other factors. However, they do help define the general inverse relation between evapotranspiration and depth to water. The lysimeter-tank-experiment data

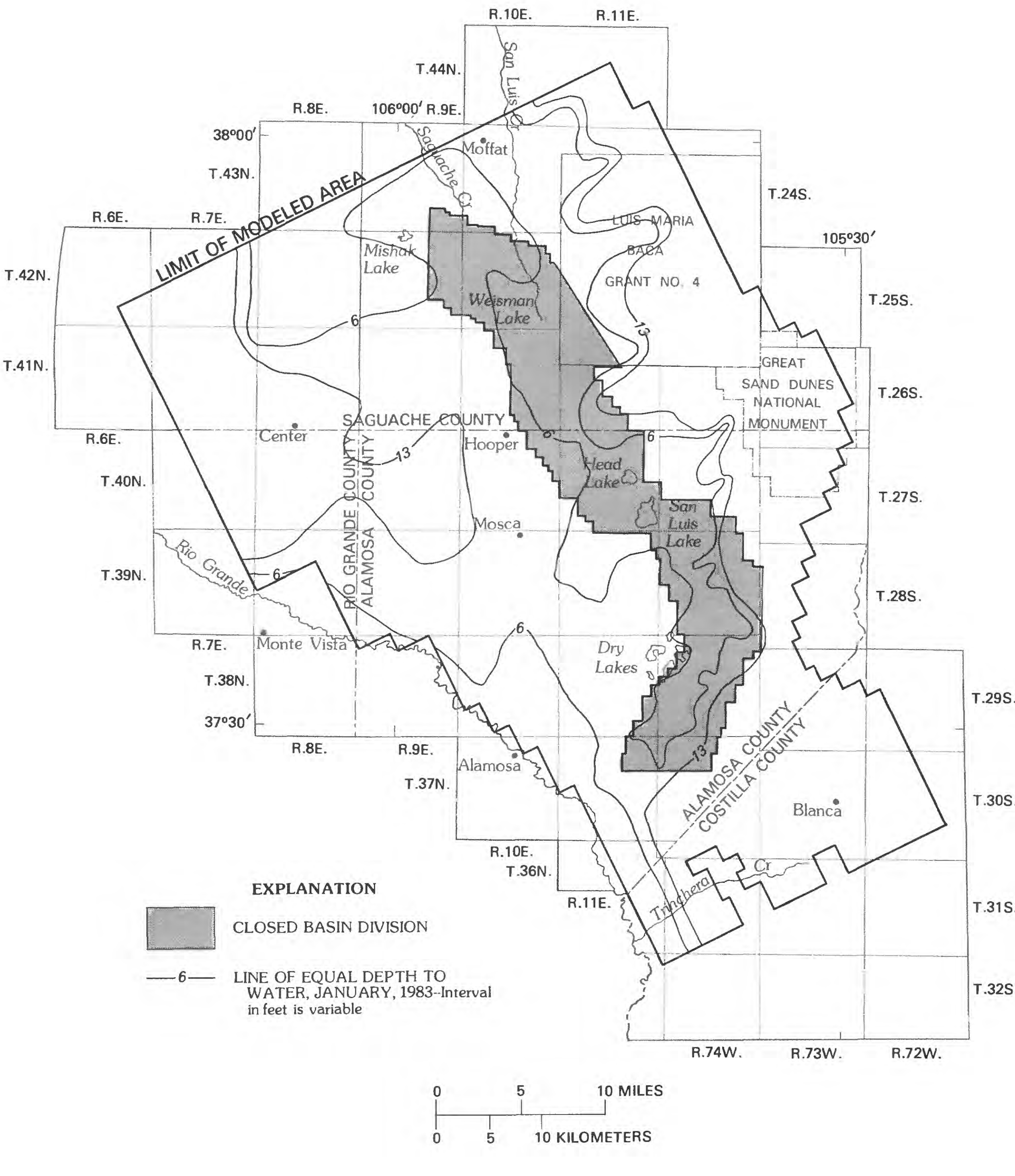


Figure 11.--Depth to water in the unconfined aquifer, January 1983.

indicate that Emery's curve is realistic at depths to water of 4 to 8 ft. However, the data for depths to water less than 4 ft indicate that Emery's curve may be the upper limit of the function. The spread in the lysimeter-tank-experiment data (fig. 12) for depths to water of 0 to 2 ft indicate that other factors have affected the results, or that considerable error is present in the data. The maximum rate of ground-water evapotranspiration probably is 1 to 2 ft/yr in the closed basin. An effective depth for evapotranspiration is assumed to be that estimated by P.A. Emery (U.S. Geological Survey, written commun., 1983).

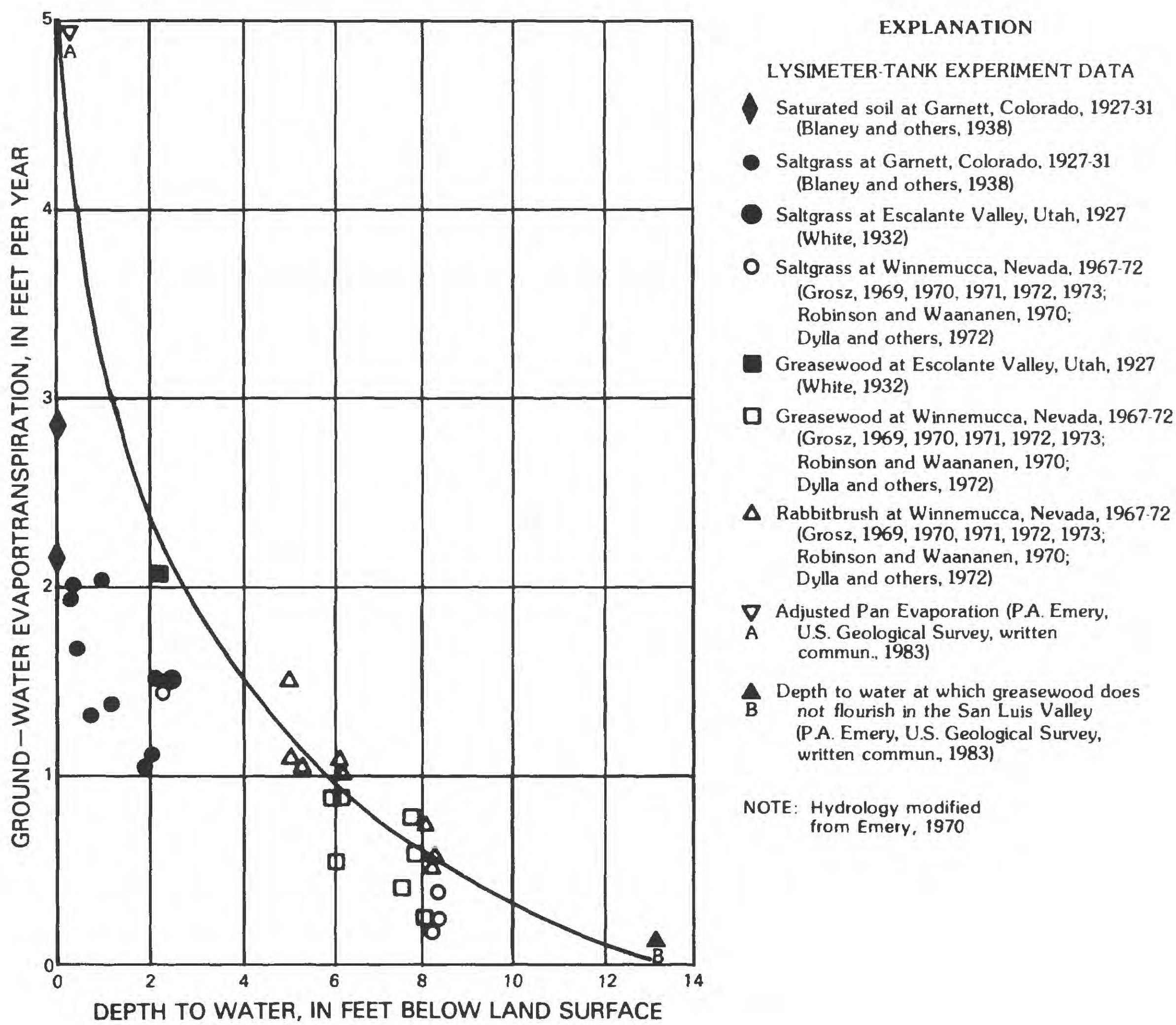


Figure 12.--Relation between evapotranspiration from lysimeters and depth to water.

Table 1.--*Estimated irrigation demand for crops and pasture and area-weighted irrigation demand in the closed basin*

Crop type	Annual or[1] seasonal total irrigation demand (feet)	Annual[2] irrigation demand (feet)	Irrigated area (acres)	Percentage of total irrigated area	Area-weighted[1] annual or seasonal total irrigation demand (feet)	Area-weighted[2] annual irrigation demand (feet)
Alfalfa	1.76	1.69	[3]67,100	18.7	0.33	0.32
Other hay	[4]1.39	[4]1.47	[3]64,400	17.9	.25	.26
Small grains	1.00	1.44	[3]64,400	17.9	.18	.26
Potatoes	1.12	1.61	[3]30,000	8.4	.09	.13
Pasture	1.39	1.47	[5]133,300	37.1	.52	.54
Totals			359,200	100	1.37	1.51

[1]Estimated irrigation demand near Center, Colorado (Davis Engineering Service, Inc., 1977).

[2]Estimated irrigation demand in the San Luis Valley, Colorado (G.A. Hearne and J.D. Dewey, U.S. Geological Survey, written commun., 1984).

[3]Average irrigated acreage harvested in Alamosa, Rio Grande, and Saguache Counties during 1950-80 (Colorado Department of Agriculture, 1950-80).

[4]Irrigation demand for "other hay" was assumed to be equal to irrigation demand for "pasture."

[5]Estimated acreage of irrigated pasture in Alamosa, Rio Grande and Saguache Counties (G.A. Hearne and J.D. Dewey, U.S. Geological Survey, written commun., 1984).

Hydrologic Budgets

A hydrologic budget is a quantitative description of the rates of inflow and outflow for a hydrologic unit. Emery and others (1973) developed a hydrologic budget for the San Luis Valley of Colorado for the period 1924 through 1969 (table 2). In this budget, fluxes of the confined and unconfined aquifers are not separated. Ground-water underflow to the valley is not considered to be substantial. Huntley (1979) developed hydrologic budgets (table 3) for the closed basin of the San Luis Valley and contributing drainage areas of the Sangre de Cristo and San Juan Mountains. Huntley also did not develop separate budgets for the confined and unconfined aquifers, but he did estimate ground-water underflow from the mountains to the valley-fill deposits.

Table 2.--*Hydrologic budget for the San Luis Valley, 1924-69*

[Modified from Emery and others (1973, fig. 1); surface area 3,200 square miles]

	Inflow (thousand acre-feet per year)		Outflow (thousand acre-feet per year)
Precipitation	1,220	Evapotranspiration	2,420
Surface water	1,580	Surface water	330
		Ground water	50
Total	2,800		2,800

Table 3.--*Hydrologic budgets for the closed basin of the San Luis Valley and contributing drainage areas in the Sangre de Cristo and San Juan Mountains, 1940-76*

[Modified from Huntley (1979, tables 1 and 2); contributing areas: Sangre de Cristo Mountains, 330 square miles; San Juan Mountains, 1,185 square miles; closed basin, 1,749 square miles]

	Inflow (thousand acre-feet per year)		Outflow (thousand acre-feet per year)
Closed basin of the San Luis Valley			
Precipitation	765	Evapotranspiration	1,847
Streamflow	258	Streamflow	0
Surface water diversions	266	Ground water	0
Ground water	558		
Total	1,847		1,847
Sangre de Cristo Mountains			
Precipitation	459	Evapotranspiration	189
		Streamflow	205
		Ground water	65
Total	459		459
San Juan Mountains			
Precipitation	1,292	Evapotranspiration	738
		Streamflow	69
		Ground water	485
Total	1,292		1,292

A hydrologic budget (table 4) was developed for the unconfined aquifer in the Closed Basin Division. This budget represents a conceptual model of inflow and outflow of the aquifer. This hydrologic budget is based on the following assumptions: (1) Inflow to the unconfined aquifer in the closed basin from infiltration of precipitation occurs at a rate of about 0.05 ft/yr, (2) infiltration of surface water and from flowing artesian wells is not substantial, (3) ground-water underflow into the area is steady, (4) ground-water evapotranspiration is not substantial during the months of November through March, (5) no change of storage occurs, and (6) leakage is steady and uniform in the study area. Ground-water evapotranspiration was estimated from an assumed maximum rate of evapotranspiration of 1.6 ft/yr, a maximum depth to water of 13 ft, and a map of depth to water in January 1983 (fig. 11).

Table 4.--*Hydrologic budget for the unconfined aquifer in the Closed Basin Division, 1983*

	Quantity (acre-feet per year)	Remarks
Inflow[1]		
Precipitation	6,900	Recharge of 0.05 foot per year on 138,500 acres.
Underflow	19,500	Based on water levels measured January 1983.
Leakage	98,000	Rate of 0.71 foot per year on 138,500 acres; includes leakage, other sources, and errors of estimates.
Total	124,400	
Outflow		
Evapotranspiration		
Depth to water 0 to 6 feet[2]	113,000	Average evapotranspiration of 1.44 feet per year on 78,500 acres.
Depth to water 6 to 13 feet[2]	11,400	Average evapotranspiration of 0.21 foot per year on 54,400 acres.
Depth to water greater than 13 feet	0	No evapotranspiration on 5,600 acres.
Total	124,400	

[1]Does not include discharge of flowing wells or surface-water infiltration.

[2]Based on depth to water during January 1983.

The rate of leakage, 0.71 ft/yr, estimated by using the hydrologic budget, is in the range of previous estimates of 0.61 ft/yr by Emery and others (1975) but is substantially less than the 1.5 ft/yr estimated from temperature-profile data. Errors in the estimates of other inflows (precipitation, underflow, surface-water infiltration, and recharge from flowing wells) and outflow (evapotranspiration) directly affect the accuracy of the estimated rate of leakage. If leakage is 1.5 ft/yr, as estimated from temperature-profile data, then outflow from the unconfined aquifer is underestimated in the budget by about 50 percent. Errors in the estimated rate of ground-water evapotranspiration and in the depths at which evapotranspiration is not substantial affect the accuracy in estimates of the rate of leakage.

MODEL DESCRIPTION

The model selected to simulate the potential effects of ground-water development on the ground-water system in the Closed Basin Division was a finite-difference model for aquifer simulation in two dimensions (Trescott, and others, 1976). This model uses the iterative alternating-direction implicit approximation of the ground-water flow equation described by Pinder and Bredehoeft (1968). The area to be modeled is divided into rectangular areas termed blocks; these blocks comprise the model grid. Average values for physical and hydraulic characteristics of the aquifer and rates of areal recharge and discharge by wells are specified at each block. Conditions need to be specified along the boundaries of the model to represent aquifer boundaries across which there is no flow or constant ground-water flow or boundaries along which the hydraulic-head remains constant.

Two methods commonly are used to simulate the reponse of an aquifer system to stress. One method is to model the actual flow regime in the aquifer. This method requires that hydraulic heads and all sources of recharge and discharge be defined in the model. Because pumpage in the southwestern and western part of the closed basin is not accurately defined, this method is not possible. The second alternative method involves modeling only the differences in aquifer response that are caused by changes in aquifer stress (a superposition model). By use of this method, the model calculates only the response (changes in hydraulic head and flow rates) to the proposed additional stress (pumpage) on the aquifer.

The principle of superposition, as described by Reilly and others (1984) permits evaluation of the potential response of a ground-water system to a stress (pumpage of the Closed Basin Division) without the necessity of defining all other stresses. Because the principle of superposition applies only to linear systems, and the equations defining ground-water flow in an unconfined system are nonlinear, the use of superposition for this study can only be justified if changes in the saturated thickness of the aquifer are not substantial.

This model simulates the unconfined aquifer in the closed basin with recharge from precipitation, leakage from the confined aquifer, discharge through wells, and discharge through evapotranspiration. The model requires information at each block about the relative positions of the water table, base of the aquifer, and land surface. Hydraulic-conductivity and specific-yield values are defined at each block. Recharge from precipitation is specified as a rate for each block. Simulation of leakage requires specification of the thickness and vertical hydraulic-conductivity values of confining layers and of the hydraulic head in the confined aquifer. Value of the hydraulic head in the confined aquifer is assumed to remain constant throughout the period simulated. Well pumpage is specified as a rate in selected blocks. Evapotranspiration is simulated as a rate that varies linearly with depth to water within specified limits.

Errors in the value and distribution that are assumed for the aquifer's hydraulic properties, geometry, and boundary conditions, and in the definition of the potentiometric surface of the aquifer will cause differences between the simulated and actual responses of the system. Sensitivity tests were done to evaluate the response of the system to changes in the relative value of selected modeled aquifer properties and conditions. The use of a two-dimensional model to represent a three-dimensional system also may cause some error in model results when they are compared to actual aquifer responses. Realistically, flow in the extensive but thin unconfined aquifer can be considered to be two dimensional and linear, unless its saturated thickness changes substantially.

Model Grid and Boundary Conditions

The model grid (fig. 13) consists of 1,939 active nodes that represent areas (blocks) ranging in size from 1/2 × 1 mi to 4 × 2 mi. Maximum size of the blocks representing the Closed Basin Division is 1/2 × 1 mi. The grid was oriented toward the northwest so that the longer sides of the rectangular blocks are roughly parallel to the equipotential lines of the water table along the eastern and western sides of the Closed Basin Division.

Lateral boundaries of the aquifer were treated as specified-flux (no flow) or constant hydraulic-head nodes. The nodes in the first and last position of all rows and columns are designated by the model as no-flow nodes. The internal no-flow boundaries specified in this model are designated by the wide line in figure 13. This model boundary approximates the limit of the saturated valley-fill deposits along the eastern side and part of the southern sides of the modeled area. The no-flow boundary on the northern side of the model represents a stream line, where ground-water flow in the unconfined aquifer is essentially parallel to the boundary. Drawdown at this boundary after 20 years of simulated pumpage from the Closed Basin Division was less than 0.1 ft. Therefore, it can be assumed that this model boundary did not substantially affect the model's results. The no-flow boundary on the western side of the model area, north of the Rio Grande, is sufficiently distant (minimum of 17 mi) from the Closed Basin Division that no drawdown was simulated at the boundary.

The Rio Grande was simulated as a constant hydraulic-head boundary (fig. 13). Because a constant hydraulic head is an infinite source or sink, simulated flow to or from a constant hydraulic-head node under some conditions could exceed the available supply of water. The absolute value of all inflows

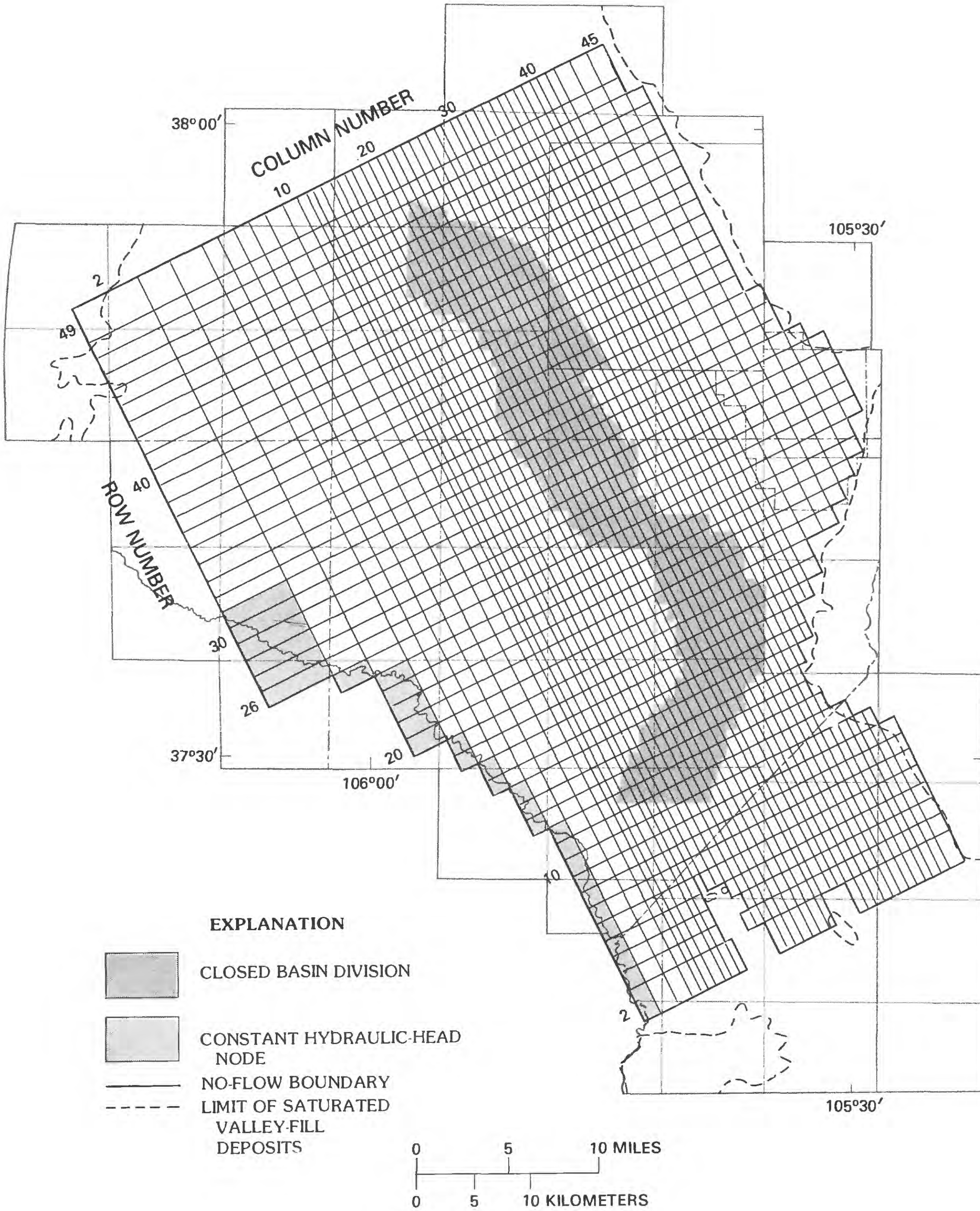


Figure 13.--Model grid and boundary conditions.

and outflows simulated across constant hydraulic-head boundaries was less than 0.1 ft^3/s, about 56 acre-ft/yr. This value does not exceed the normal flow of the Rio Grande in the study area. This boundary also could have been treated as a no-flow boundary without substantially affecting the results of the model.

Where the water table is below the extinction depth (zero discharge) for ground-water evapotranspiration, it is a free-surface boundary that may rise or fall in response to changes of inflow and outflow. Where the water table is above the extinction depth but within the zone of ground-water evapotranspiration, it is a hydraulic-head-dependent flux boundary.

Where the base of the unconfined aquifer is underlain by a leaky confined aquifer, it also is a hydraulic-head-dependent flux boundary. In the model, the hydraulic head in the confined aquifer was held constant throughout the simulation period. In reality, hydraulic heads in the confined aquifer will respond to withdrawals from confined and unconfined aquifers.

Model Data Base

Water-level data collected during January 1983 by the U.S. Geological Survey, U.S. Bureau of Reclamation, and Rio Grande Water Conservation District were used to map depth to water in the unconfined aquifer in the closed basin (fig. 11). Water levels in the unconfined aquifer reach minimum levels at the end of the growing-irrigation season, about October, and recover to their maximum level by the beginning of the next growing-irrigation season, about March. Water levels measured during January were therefore assumed to approximate the average depth to water in the unconfined aquifer. The value of hydraulic conductivity of the unconfined aquifer was calculated for each node as the quotient of transmissivity (fig. 10) and the saturated thickness (depth to water minus depth to confining unit).

Because the principle of superposition was used in this model, it was not necessary to define the potentiometric surface. A uniform value of 500 ft was arbitrarily assigned for the initial altitude of the water table and for the confined potentiometric surface at each node. By defining uniform values for the initial hydraulic head in the unconfined aquifer and for the hydraulic head on the opposite side of the confining unit, no leakage or horizontal flow was specified at the beginning of the simulation. A constant value of 0.175 was assigned for the specific yield for transient simulations. A constant value of 9×10^{-5} d^{-1} was assigned for vertical conductance of the confining unit in the closed basin, which is equivalent to the vertical hydraulic-conductivity value of 0.066 ft/d and the confining bed thickness of 750 ft; this value was used by Emery and others (1975).

Evapotranspiration was simulated as a linear function of depth to water. Data needed by the model to calculate the evapotranspiration flux are: (1) Maximum rate of evapotranspiration, (2) extinction depth of evapotranspiration, and (3) relative altitudes of water table and land surface. The maximum rate of evapotranspiration was assumed to be 1.6 ft/yr (a conservative estimate based on the data plotted in fig. 12). The extinction depth was assumed to be 13 ft (P.A. Emery, U.S. Geological Survey, written commun., 1983). The relative altitude of the land surface was calculated as 500 ft plus the depth to water from figure 7. Recharge needed to balance discharge by evapotranspiration in the modeled area was determined with a steady-state model to be about 562 ft^3/s (407,000 acre-ft/yr).

SIMULATED EFFECTS OF GROUND-WATER DEVELOPMENT IN THE CLOSED BASIN DIVISION

The model was used to evaluate the projected responses of the unconfined aquifer to hypothetical continuous pumpage from 168 wells in the Closed Basin Division at a combined rate of about 141 ft^3/s for 20 years. Location of the wells and the combined simulated rates of pumpage for the stages of the Closed Basin Division are shown in figure 14. Pumpage was simulated at 150 nodes in the model with some nodes representing the discharge of more than one well. All stages were assumed to begin pumping simultaneously. The simulation period of 20 years was divided into 24 time steps of unequal duration. Time step 1 was about 1 day. Step 24 was about 2,055 days (fig. 15).

Simulated changes in the rates of evapotranspiration, leakage, and water removed from storage in the unconfined aquifer (fig. 15) represent the sources of most of the water pumped by the salvage wells. Initially, most of the water pumped will be derived from storage (fig. 15). However, at the end of the 20-year period, only about 8 percent of the cumulative pumpage was derived from changes in storage, about 66 percent was derived from decreases of evapotranspiration, and about 26 percent was derived from induced leakage from the confined aquifer. No pumpage was simulated from the confined aquifer. Upward leakage from the confined aquifer predicted by the model reflects the simulated declines of the potentiometric surface in the unconfined aquifer. Simulated pumpage from the unconfined aquifer in the Closed Basin Division produced water-table drawdown greater than 0.1 ft in an area of about 370 mi^2 (fig. 16). Drawdowns greater than 2 ft occurred in a 165-mi^2 area that generally was limited to the Closed Basin Division, except for two small areas, one near Mishak Lake, southwest of Moffat, and one east of stage 1-2, northwest of Blanca. Maximum simulated drawdown was 25 ft in the southwestern corners of the stage-4 well field, about 4 mi northeast of Hooper.

SENSITIVITY OF THE MODEL

Additional model simulations were done to determine the sensitivity of the model to changes in the simulated values of the hydraulic properties of the unconfined aquifer, the vertical conductance of the confining bed, and the maximum rate of evapotranspiration (table 5). Five criteria were selected to evaluate the sensitivity of the model: (1) The maximum drawdown, (2) the area in which drawdown equaled or exceeded 2 ft, (3) the volume of water removed from storage, (4) the volume of induced leakage into the unconfined aquifer, and (5) the volume of water salvaged from evapotranspiration by the production wells in the Closed Basin Division.

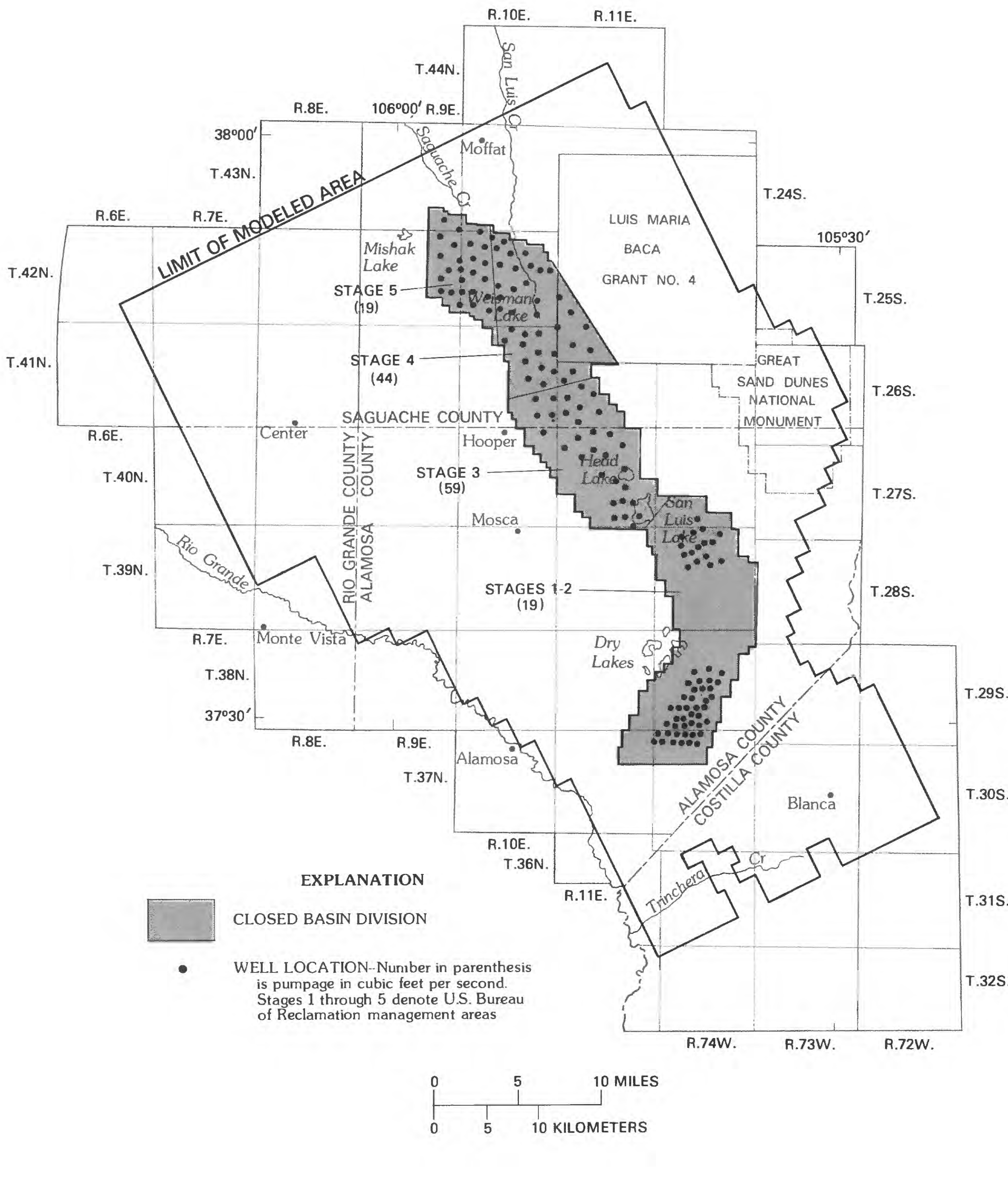


Figure 14.--Location of wells and simulated rates of pumpage in the Closed Basin Division.

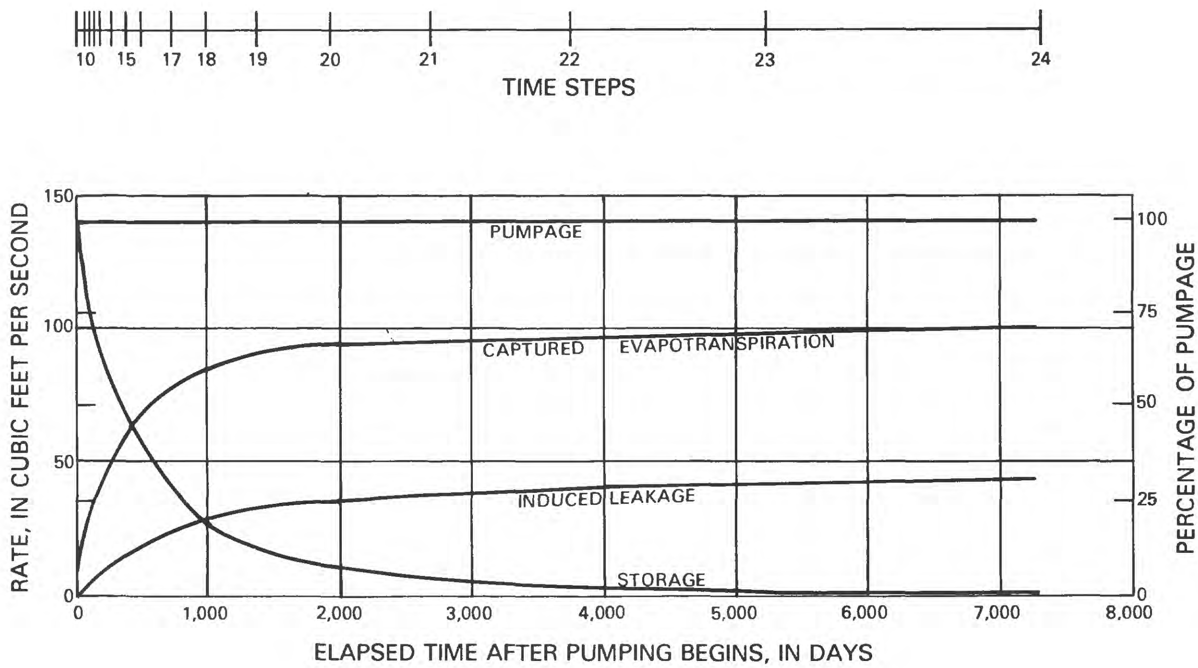


Figure 15.--Time-step length and changes in rates of evapotranspiration, leakage, and storage simulated in response to pumpage from the Closed Basin Division.

The model, as judged by the sensitivity criteria, is least sensitive to changes in the specific-yield value of the unconfined aquifer and most sensitive to the vertical hydraulic-conductance value of the confining bed and to the maximum rate of evapotranspiration. A 50 percent decrease in the hydraulic-conductivity value for the unconfined aquifer produced a 50 percent increase in maximum drawdown and an 11 percent decrease in the area in which drawdown equaled or exceeded 2 ft. A 50 percent decrease in the vertical hydraulic-conductance value of the confining layer produced a 32 percent increase in maximum drawdown, a 11 percent increase in the area in which drawdown was 2 ft or more, a 40 percent increase in the volume of water removed from storage, a 35 percent decrease in the volume of induced leakage, and a 9 percent increase in the volume of salvaged evapotranspiration. Changing the value of the maximum rate of evapotranspiration by 25 percent, substantially affected the volume of salvaged evapotranspiration, as well as the maximum drawdown, the area in which drawdown equals or exceeds 2 ft, and the volumes of induced leakage and water removed from storage.

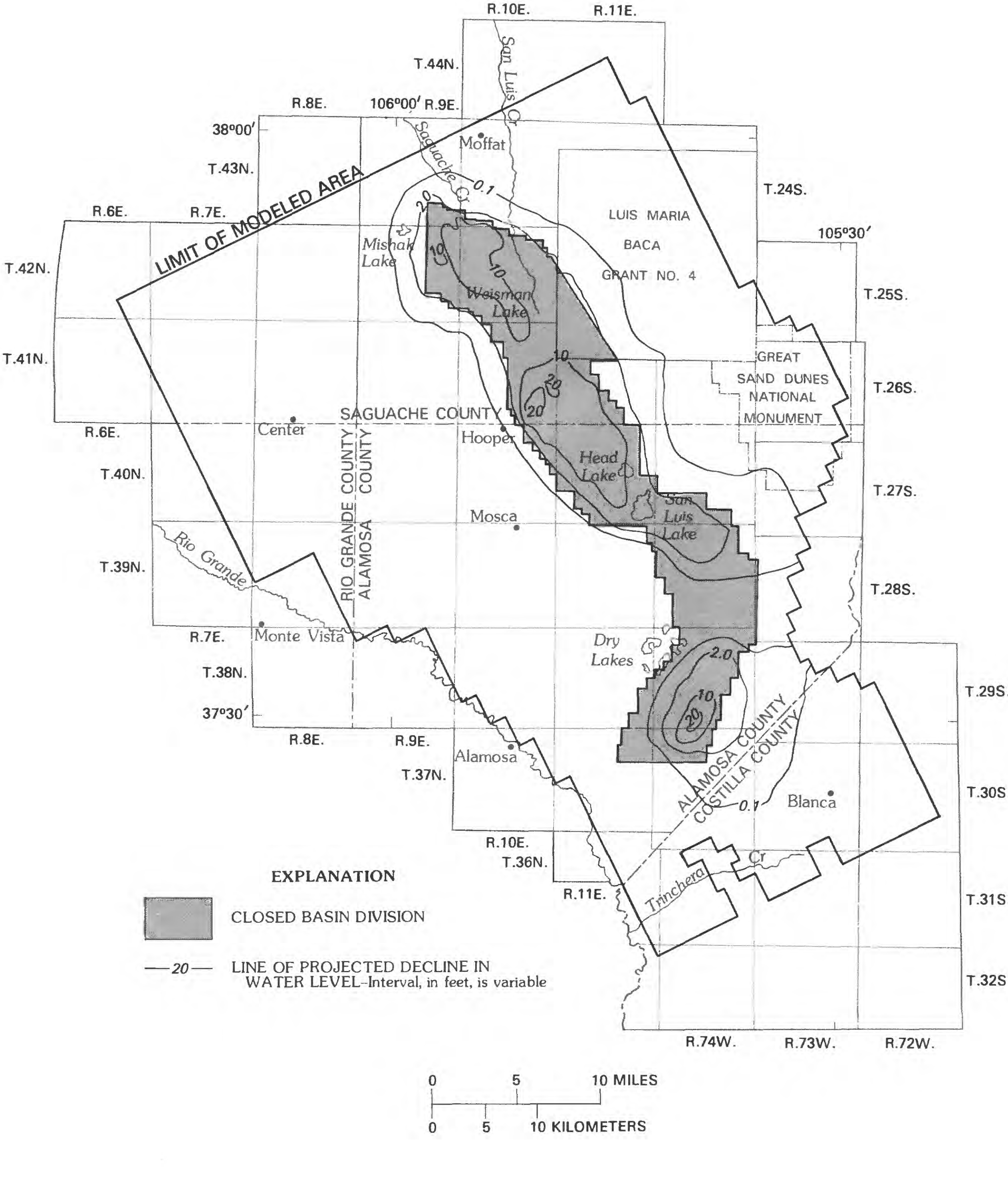


Figure 16.--Projected drawdown in the water table after 20 years of simulated ground-water development in the Closed Basin Division.

Table 5.--*Sensitivity of model to changes in selected hydraulic properties and maximum evapotranspiration rate*

Simulated changes from unadjusted model	Change in sensitivity criteria				
	Maximum drawdown (percent)[1]	Area with 2 feet or more of drawdown (percent)[2]	Volume of water removed from storage (percent)[3]	Volume of induced leakage (percent)[4]	Volume of salvaged evapotranspiration (percent)[5]
Specific yield increased by 14 percent	-2	-1	14	-2	-1
Specific yield decreased by 14 percent	0	6	-13	2	1
Hydraulic conductivity increased by 50 percent	-20	5	-4	-5	2
Hydraulic conductivity decreased by 50 percent	50	-11	10	10	-5
Vertical conductance increased by 50 percent	-17	-8	-19	25	-7
Vertical conductance decreased by 50 percent	32	11	40	-35	9
Maximum rate of evapo-transpiration increased by 25 percent	-20	-8	-21	-20	10
Maximum rate of evapo-transpiration decreased by 25 percent	26	10	33	30	16

[1]Maximum drawdown with the unadjusted model was 25 feet.

[2]Area was 106,000 acres with 2 feet or more drawdown with the unadjusted model.

[3]Volume of water removed from storage in the unconfined aquifer was 165,000 acre-feet with the unadjusted model.

[4]Volume of induced leakage from the confined aquifer was 530,000 acre-feet with the unadjusted model.

[5]Volume of salvaged evapotranspiration was 1,338,000 acre-feet with the unadjusted model.

The results from the sensitivity tests of the model emphasize the importance of better estimates of evapotranspiration in the closed basin and in determining the vertical hydraulic conductance of the confined aquifer. The flow regime of the aquifer system is dominated by vertical flow and leakage into and evapotranspiration loss from the unconfined aquifer. Although the model is sensitive to the value of hydraulic conductivity of the unconfined aquifer, the errors from this parameter are small, because adequate data were available to define horizontal hydraulic conductivity. The errors due to uncertainty in the rate of evapotranspiration and the vertical conductance are large, because the values are poorly defined by data and the model is sensitive to these parameters. The assumption that hydraulic head in the confined aquifer is invariant also contributes to error in the model results.

The model is not calibrated because of the lack of historical pumpage and water-use data. However, sensitivity tests were done to evaluate the effects of errors in the estimates of selected parameters. This model was designed to simulate aquifer response to pumpage in the Closed Basin Division. The model utilizes the principle of superposition and, therefore, cannot be used to predict absolute hydraulic heads in the aquifer. Natural fluctuations in recharge and discharge and pumping outside the Closed Basin Division affect depth to water in the aquifer. Because the model used rates based on average annual fluxes, it cannot be used to evaluate seasonal response to discharge and recharge processes. Errors in the estimates of the aquifer's hydraulic properties, particularly the vertical conductance of the confining unit and evapotranspiration, affect the results of the model.

SUMMARY

Wells completed in the unconfined aquifer of the Closed Basin Division of the San Luis Valley Project are expected to supply about 101,800 acre-ft/yr of ground water to the Rio Grande when the project is completed. Lowering of ground-water levels in the unconfined aquifer in response to these withdrawals is expected to decrease the quantity of ground water that is lost by evapotranspiration. The Closed Basin Division is located in a closed basin north of the Rio Grande in the San Luis Valley. The San Luis Valley is in a complexly faulted structural basin that is part of the Rio Grande Rift. The structural basin is filled with thousands of feet of saturated deposits consisting of interbedded fine- to coarse-grained alluvial and lacustrine deposits, volcanic flows, and volcaniclastic rocks. The aquifer system consists of an unconfined aquifer that is 50 to 130 ft thick, underlain by a confined aquifer. Ground water moves from the edges of the closed basin toward the topographic low, where it is discharged from the unconfined aquifer by evapotranspiration. A ground-water flow model for aquifer simulation in two dimensions was used to simulate the effect of projected ground-water development on the ground-water system; the model incorporated the effects of upward leakage from an underlying confined aquifer and evapotranspiration. During a 20-year period, simulated withdrawals of 141 ft^3/s from 168 wells in the Closed Basin Division resulted in projected drawdown greater than 0.1 ft in an area of about 370 mi^2 and drawdown equal to or greater than 2.0 ft in an area of about 165 mi^2. Model simulation indicated that the maximum drawdown would be about 25 ft. Simulations also indicated that about 66 percent of the cumulative pumpage at the end of the 20-year period would be derived from decreases of evapotranspiration, 26 percent from induced upward leakage from the confined aquifer and 8 percent from storage of the unconfined aquifer. Model simulations were based only on withdrawal from wells completed in the unconfined aquifer. No pumpage was simulated from the confined aquifer. Upward leakage from the confined aquifer predicted by the model resulted from simulated declines of the potentiometric surface in the unconfined aquifer.

Additional study of the rate of evapotranspiration from the aquifer and of upward leakage from the confined aquifer is needed to more realistically simulate the ground-water system in the closed basin. A three-dimensional model could more realistically simulate changes in water levels in unconfined and confined aquifers and leakage from the confined aquifer if additional data could be collected to define aquifer properties and flow rates.

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