PLAN OF STUDY TO QUANTIFY THE HYDROLOGIC RELATIONS BETWEEN THE RIO GRANDE AND THE SANTA FE GROUP AQUIFER SYSTEM NEAR ALBUQUERQUE, CENTRAL NEW MEXICO

By Douglas P. McAda

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
foot	0.3048	meter
mile	1.609	kilometer
square foot	0.09290	square meter
gallon	3.785	liter
acre-foot	0.001233	cubic hectometer
	43,560	cubic foot
acre-foot per acre	0.3048	cubic meter per square meter
acre-foot per year	0.001233	cubic hectometer per year
	0.0013803	cubic foot per second
	0.6184	gallon per minute
acre-foot per year per square mile	0.0004763	cubic hectometer per year per square kilometer
foot per day	0.3048	meter per day
gallon per minute	0.06309	liter per second
gallon per day	0.003785	cubic meter per day
per foot	3.281	per meter

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by the equation:

$$°F = 9/5\ (°C) + 32$$

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

EXECUTIVE SUMMARY

The Albuquerque Basin in central New Mexico covers an area of about 3,060 square miles. The Albuquerque area, about 410 square miles, is the major population center in the basin and included about 502,000 people in 1990, 89 percent of the basin population. Ground water is the principal source of water for municipal, domestic, commercial, and industrial uses in the basin. In 1994, 92 percent of the ground-water withdrawn in the basin was pumped from wells in the Albuquerque area, 72 percent of that pumped by the City of Albuquerque.

The aquifer system in the Albuquerque Basin is composed of valley and basin-fill deposits. The aquifer system is hydraulically connected to the Rio Grande and to a system of canals and drains through the alluvium in the Rio Grande inner valley.

Management of ground water in the Albuquerque Basin is related to the surface water in the Rio Grande. Because the aquifer system is hydraulically connected to the Rio Grande and water in the river is fully appropriated, any reduction in flow of the river caused by ground-water withdrawal must be offset by owning water rights on the river or by returning water to the river. The current method of estimating the reduction of flow in the Rio Grande from ground-water withdrawal is based on simplifying assumptions that typically result in an overestimation of this reduction. Because demands on the ground-water resources of the Albuquerque area are increasing and water levels are declining, this overestimation serves to dedicate water to the river that could otherwise be used to reduce stress on the aquifer system. Therefore, the ability to reliably estimate the effects of ground-water withdrawals on flow in the Rio Grande is important to the overall management of water resources in the Albuquerque area.

The purpose of this report is to (1) describe the components of the Rio Grande/Santa Fe Group aquifer system in the Albuquerque area and the data availability and data and interpretation needs relating to those components; and (2) present a plan of study to improve the understanding of and quantify hydrologic relations between the river and the aquifer system. Because about 92 percent of the ground water withdrawn in the Albuquerque Basin is pumped from wells in the Albuquerque area, the Albuquerque area is the focus of this report.

The City of Albuquerque has contributed substantially in developing the current base of geohydrologic information about the Albuquerque Basin, including much of what is known about the hydrologic interaction between the Rio Grande and the Santa Fe Group aquifer system. Much of this information has been gained through the City's test-well drilling program and through cooperative investigations programs with the New Mexico Bureau of Mines and Mineral Resources, U.S. Geological Survey, and Bureau of Reclamation.

Descriptions of the components of the river/aquifer system and data availability and needs related to these components are divided into two sections in the report. The "Physical and hydraulic characteristics of system components" section describes components that control the movement of water through the river/aquifer system. These include the physical and hydraulic characteristics of the Rio Grande, canals, drains, aquifer sediments, hydraulic heads, and aquifer storage. The "Flow characteristics of system components" section describes components that recharge water to or discharge water from the aquifer system, and the estimated magnitude of each component in the Albuquerque area. These components include ground-water withdrawal; Santa Fe Group aquifer system; Rio Grande, canal, and drain seepage; basin margin and tributary recharge; riparian and wetland evapotranspiration; irrigation seepage; and septic-field seepage.

To prioritize the study elements outlined in the "Plan of study" section, the information needs related to the components of the river/aquifer system are prioritized. Information that is necessary to improve the understanding or quantification of a component and the river/aquifer system is prioritized as essential. Information that could add additional understanding of the

system, but would not be necessary to improve the quantification of the system, is prioritized as useful. The essential and useful activities and information identified are summarized below.

Essential Activities and Information

Install additional observation wells

Measure the vertical distribution of hydraulic heads in the aquifer system and maintain a computerized data base of the measurements

Measure volume and three-dimensional location of ground-water withdrawals, and maintain a computerized data base of the measurements

Measure flow of the Rio Grande, canals, and drains at sections near river gages and maintain a computerized data base of the measurements

Document changes in the volume of water in aquifer storage

Monitor elastic and inelastic compaction

Estimate riverbed hydraulic conductivity

Define canal dimensions, bottom elevations, operating stage, percentage of time containing water, and location of lined or unlined segments

Define drain dimensions and bottom elevations (if water table is below bottom and if used for water conveyance)

Estimate vertical and horizontal hydraulic conductivity in the aquifer

Calculate seepage rates between the Rio Grande and the aquifer

Determine distribution of silts and clays in the inner valley alluvium

Document current (during life of project) changes to land uses (such as irrigated land), land covers (such as riparian vegetation), and inner valley surface-water features (such as the Rio Grande/canal/drain system)

Useful Activities and Information

Classify lithofacies units and fault locations in aquifer deposits beyond the Albuquerque area and estimate influence of faults on ground-water flow

Chemically analyze ground water, including environmental isotopes

Estimate basin margin and tributary recharge

Determine rate of evapotranspiration by cottonwoods and its relation to water-table depth

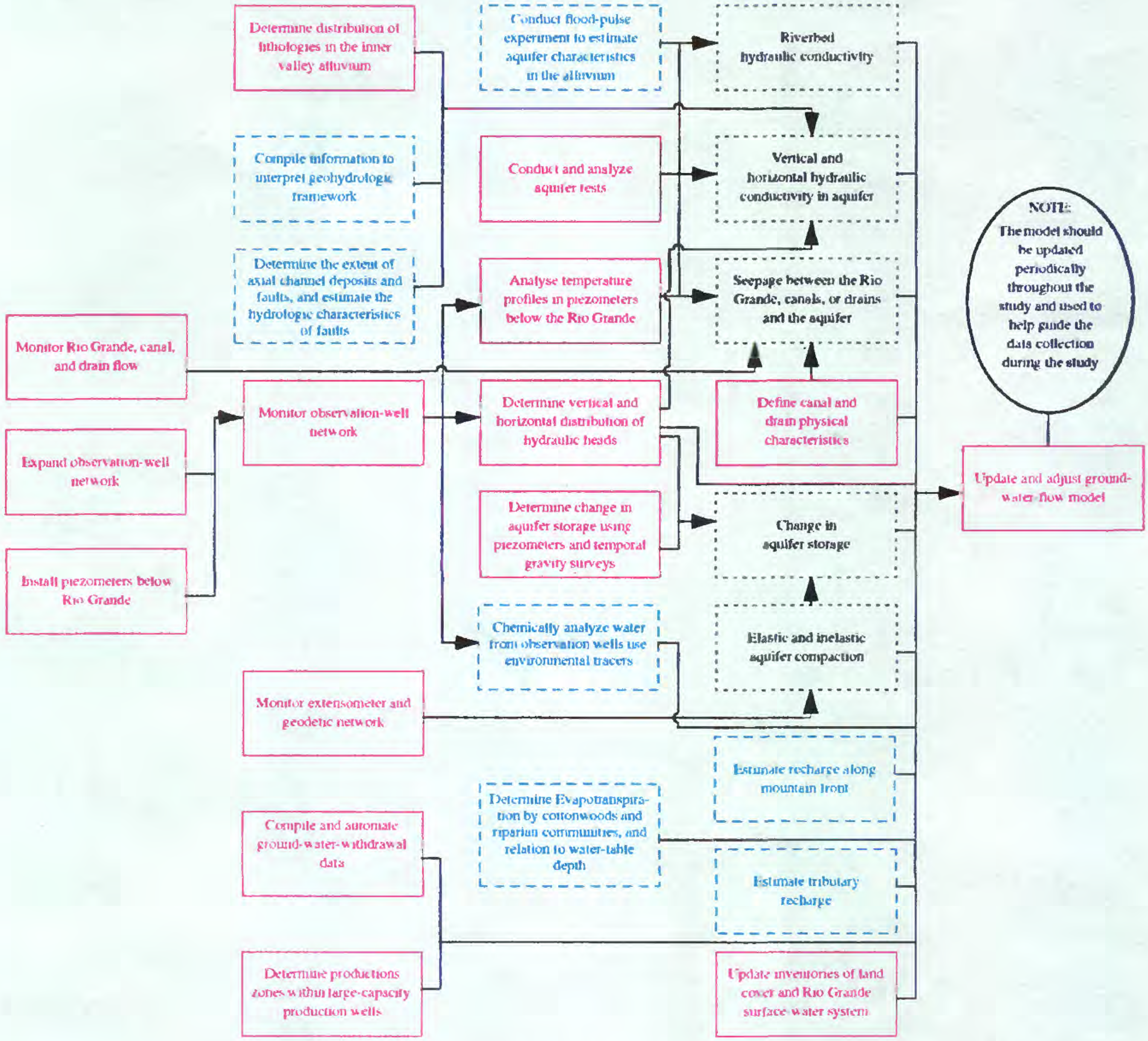
Hydrologic relations between the Rio Grande surface-water system and the aquifer system is complex in the interaction of hydrologic boundary conditions, aquifer materials, aquifer stresses, and system responses. A ground-water-flow model can help understand these complexities, and estimate the effects of particular stresses on the aquifer and river system. The recently developed ground-water-flow model of the Albuquerque Basin (Kernodle and others, 1995) can be a basis for developing this capability. The collection of additional information on the components of the river/aquifer system outlined in this report can be used to update and adjust the ground-water-flow model. The model can then be used to quantify ground-water and surface-water relations and to estimate the effects of ground-water withdrawal on flow in the Rio Grande.

The "Plan of study" section of the report presents a prioritized series of study elements designed to collect the additional essential and useful information. The study elements are prioritized in the same manner as the information needs; study elements designed to provide information considered necessary to improve the quantification of the system are prioritized as essential, and those designed to provide information that would add additional understanding of the system, but would not be necessary to improve the quantification of the system, are prioritized as useful. Several study elements are of an experimental nature--that is, the application of the techniques may not with certainty provide the information for which they are designed. The study elements, along with their priority and expected duration, are listed below.

Essential Study Element	Expected Duration
Update and adjust the Albuquerque Basin ground-water-flow model	Continuous
Expand observation-well network	Continuous
Install piezometers below Rio Grande	1-2 years
Monitor observation well network	Continuous
Compile and automate ground-water-withdrawal data	Continuous
Determine production zones within large-capacity production wells	Continuous
Monitor the Rio Grande, canal, and drain flows	Continuous
Define canal and drain physical characteristics	1-2 years
Conduct and analyze aquifer tests	3-5 years
Update inventories of land cover and Rio Grande surface-water system	10-year intervals
Determine distribution of lithologies in the inner valley alluvium	1-2 years
Monitor extensometer and geodetic network	Continuous
Analyze temperature profiles in piezometers below the Rio Grande (Experimental)	2-3 years
Determine change in aquifer storage through temporal gravity surveys (Experimental)	1 year to Continuous

Useful Study Element Expected Duration	
Chemically analyze water from observation wells and use environmental tracers	3-4 years
Compile information to interpret the geohydrologic framework north and south of Albuquerque	Continuous
Determine the extent of axial channel deposits and faults, and estimate the hydrologic characteristics of faults	2-3 years
Estimate recharge along the mountain front	2-3 years
Estimate tributary recharge (Experimental)	3-4 years
Determine evapotranspiration by cottonwoods and riparian communities and relation to water-table depth	2-3 years
Conduct flood-pulse experiment to estimate aquifer characteristics in the alluvium	1 year

Several of the study elements are dependent on implementation of other study elements. The plan of study flow diagram shown in figure 1 illustrates this dependency. The essential study elements would be implemented along the information flow paths as shown in figure 1.



EXPLANATION

ESSENTIAL STUDY ELEMENT

USEFUL STUDY ELEMENT

ESSENTIAL INFORMATION

DIRECTION OF INFORMATION FLOW

Figure 1.--Plan of study flow diagram.

PLAN OF STUDY TO QUANTIFY THE HYDROLOGIC RELATIONS BETWEEN THE RIO GRANDE AND THE SANTA FE GROUP AQUIFER SYSTEM NEAR ALBUQUERQUE, CENTRAL NEW MEXICO

By Douglas P. McAda

ABSTRACT

The Albuquerque Basin in central New Mexico covers an area of about 3,060 square miles. Ground water from the Santa Fe Group aquifer system of the Albuquerque Basin is the principal source of water for municipal, domestic, commercial, and industrial uses in the Albuquerque area, an area of about 410 square miles. Ground-water withdrawal in the basin has increased from about 97,000 acre-feet in 1970 to about 171,000 acre-feet in 1994. About 92 percent of the 1994 total was withdrawn in the Albuquerque area. Management of ground water in the Albuquerque Basin is related to the surface water in the Rio Grande. Because the aquifer system is hydraulically connected to the Rio Grande and water in the river is fully appropriated, the ability to reliably estimate the effects of ground-water withdrawals on flow in the river is important. This report describes the components of the Rio Grande/Santa Fe Group aquifer system in the Albuquerque area and the data availability and data and interpretation needs relating to those components, and presents a plan of study to quantify the hydrologic relations between the Rio Grande and the Santa Fe Group aquifer system.

The information needs related to the components of the river/aquifer system are prioritized. Information that is necessary to improve the understanding or quantification of a component in the river/aquifer system is prioritized as essential. Information that could add additional understanding of the system, but would not be necessary to improve the quantification of the system, is prioritized as useful.

The study elements are prioritized in the same manner as the information needs; study elements designed to provide information considered necessary to improve the quantification of the system are prioritized as essential, and those designed to provide information that would add additional understanding of the system, but would not be necessary to improve the quantification of the system, are prioritized as useful.

INTRODUCTION

The Albuquerque Basin in central New Mexico covers an area of about 3,060 square miles (fig. 2). The Albuquerque Basin is defined in this report as the extent of Cenozoic deposits from Cochiti Lake on the north to San Acacia on the south. In 1990, the population of the basin was about 564,000 people, or about 37 percent of the population of New Mexico (U.S. Department of Commerce, 1991). Ground water is the principal source of water for municipal, domestic, commercial, and industrial uses in the basin. The Rio Grande, which extends the length of the basin, is the principal source of water for irrigated agriculture. For a more detailed description of the basin, the reader is referred to Thorn and others (1993).

The Albuquerque area, as defined for this report (fig. 2), covers an area of about 410 square miles. It is the major population center in the basin and included about 502,000 people in 1990, 89 percent of the basin population. Ground-water withdrawal in the basin is concentrated in this area as well; therefore, the Albuquerque area is the focus of this report.

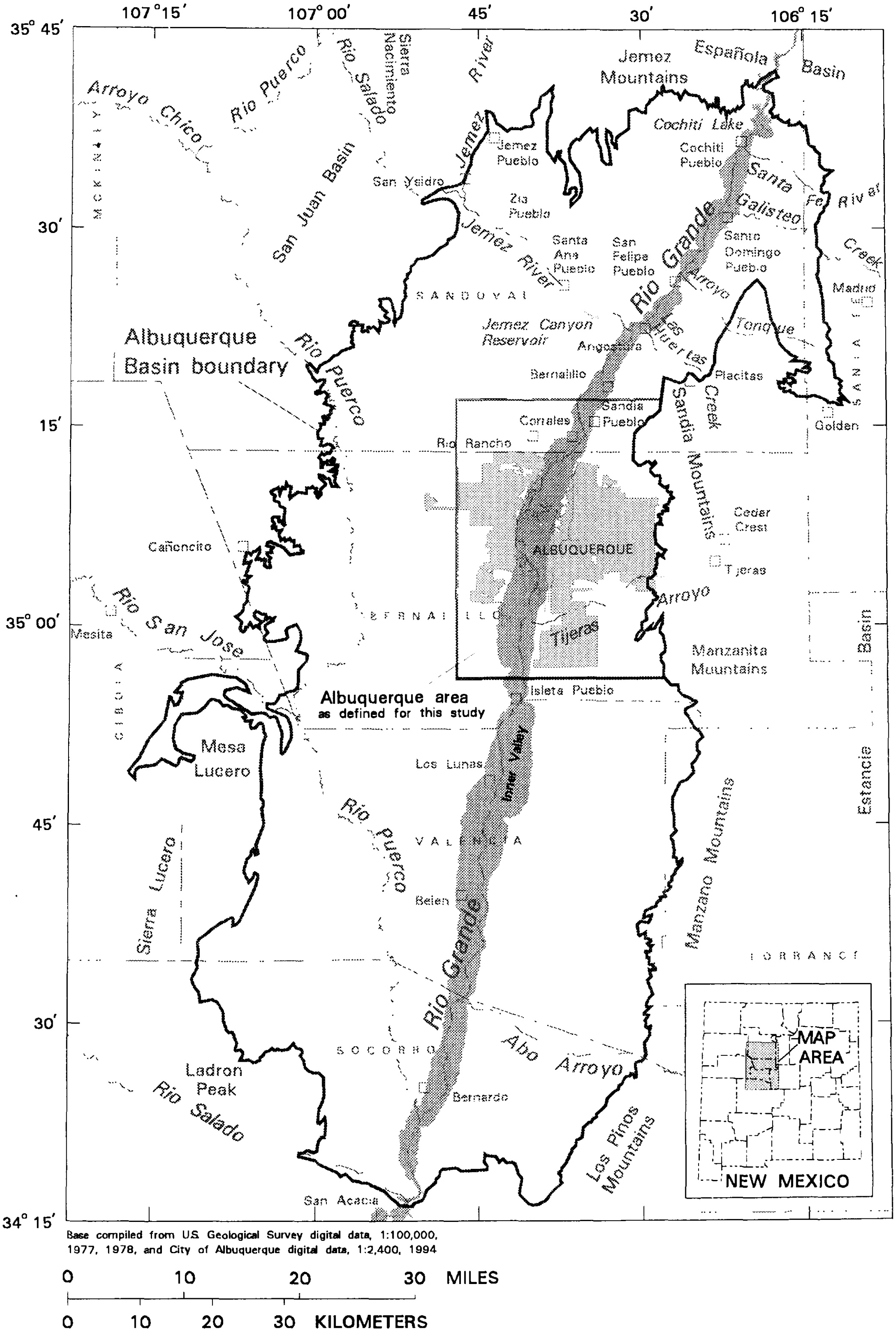


Figure 2.--Location of the Albuquerque Basin, central New Mexico.

The aquifer system in the Albuquerque Basin is composed of Santa Fe Group (middle Tertiary to Quaternary age) and post-Santa Fe Group (Quaternary age) valley and basin-fill deposits. The Santa Fe Group aquifer system is hydraulically connected to the Rio Grande and to a system of canals and drains through the alluvium in the Rio Grande inner valley (fig. 2).

Ground-water withdrawal in the Albuquerque Basin has increased dramatically since the early part of this century. The City of Albuquerque is the largest user of ground water in the basin. Annual ground-water withdrawal by the City increased from about 2,000 acre-feet in 1933 (Bjorklund and Maxwell, 1961, p. 30), to about 59,000 acre-feet in 1970, and to about 123,000 acre-feet in 1994 (files of the City of Albuquerque). More than half of the water the City of Albuquerque has withdrawn from the aquifer since 1932 (a 62-year period) has been removed in the last 15 years--1980-94 (Kernodle and others, 1995, figs. 39-41). Total ground-water withdrawal in the basin was estimated to be about 97,000 acre-feet in 1970 (Thorn and others, 1993, p. 54) and about 171,000 acre-feet for the year ending in March 1994 (Kernodle and others, 1995, table 6). Of that estimated 171,000 acre-feet withdrawn, an estimated 157,000 acre-feet (92 percent) was withdrawn in the Albuquerque area, 123,000 acre-feet (72 percent) of that withdrawn by the City of Albuquerque.

Management of ground water in the Albuquerque Basin is related to the surface water in the Rio Grande. Because the aquifer system is hydraulically connected to the Rio Grande and water in the river is fully appropriated, any reduction in flow of the river caused by ground-water withdrawal must be offset by owning water rights on the river or by returning water to the river. Under current (1995) regulations, the reduction in flow of the river is calculated using the analytical method described by Glover and Balmer (1954). To apply this method, the following assumptions are made: the river is in full hydraulic connection with the aquifer and extends to the same depth as the pumping well, the aquifer is homogeneous and isotropic, and the drawdown in the aquifer is insignificant compared to the thickness of the strata from which water is extracted. However, these simplifying assumptions are not representative of conditions in the river/aquifer system and typically result in an overestimation of the reduction of flow in the river (Sophocleous and others, 1995). Therefore, the flow of the river is augmented by compensating for the flow-volume reduction calculated using the Glover and Balmer (1954) method. This insures that the river flow is protected from the effects of ground-water withdrawal. However, with increasing demands on ground-water resources of the Albuquerque area and decreasing water-levels (Thorn and others, 1993, figs. 28, 30), it also serves to dedicate water to the river that could otherwise be used to reduce stress on the aquifer system. The ability to reliably estimate the effects of ground-water withdrawals on flow in the Rio Grande is therefore, important to the overall management of water resources in the Albuquerque area.

Purpose and Scope

The purpose of this report is to (1) describe the components of the Rio Grande/Santa Fe Group aquifer system, data availability, and data and interpretation needed relating to those components; and (2) present a plan of study to improve understanding of and quantify hydrologic relations between the Rio Grande and the Santa Fe Group aquifer system. Through this quantification, the effects of ground-water withdrawals in the Albuquerque area on flow in the Rio Grande can be estimated using the most up-to-date concept of the river/aquifer system. Because about 92 percent of the ground water withdrawn in the Albuquerque Basin is pumped from wells in the Albuquerque area, the Albuquerque area is the focus of this report. However, the procedures and studies outlined in this report have transfer value to other areas of the basin.

Although the hydraulic connection between the Rio Grande surface-water system and the Santa Fe Group aquifer system is in the inner Rio Grande valley, the interaction of water between the two systems is influenced by movement of water in the aquifer system beyond the inner valley. Therefore, any component of the aquifer system that influences movement of water within the aquifer is considered a component of the surface-water/ground-water system and is within the scope of this report.

Many components of the Rio Grande/Santa Fe Group aquifer system cannot be directly measured--they can only be estimated on the basis of observation and analysis of controlled tests or existing conditions. To apply all of the techniques available to quantify these components, some simplifying assumptions must be made. Therefore, the absolute reliability of estimated values of stream/aquifer components, and estimated effects of ground-water withdrawals on flow in the Rio Grande cannot be assured. However, acquiring additional information on key components of the river/aquifer system can improve these estimates.

No study can be proposed that would result in complete understanding of the river/aquifer system. Additional information and understanding of the system will be acquired into the future. Some of this additional information will invalidate assumptions previously made. Therefore, concepts of the system need to be continually adjusted. The study elements proposed in this report are obtainable objectives that would provide a better base of understanding of the system and therefore a better quantification of the system.

To prioritize the study elements outlined in the "Plan of study," the information needs related to the components of the river/aquifer system (discussed in the "Hydrologic relations between the Rio Grande and Santa Fe Group aquifer system" section of this report) are prioritized. Information that is necessary to improve the understanding or quantification of a system component and the river/aquifer system is prioritized as essential. Information that could provide additional understanding of the system, but would not be necessary to improve the quantification of the system, is prioritized as useful. Study elements are prioritized in the same way: study elements that would provide information considered necessary to improve the quantification of the system are prioritized as essential, and those that could provide information that would add additional understanding of the system, but would not be necessary to improve the quantification of the system, are prioritized as useful.

Previous Investigations

Current (1995) understanding of the geohydrologic framework of the Albuquerque Basin in the Albuquerque area is described by Hawley and Haase (1992), and Hawley and others (in press). Hawley and Haase (1992, chap. III, p. 1-2) and Hawley and others (in press) list previous geologic works on which the current understanding is based.

Hydrologic conditions in the Albuquerque area have been described by various authors. Bloodgood (1930), Theis (1938), and Theis and Taylor (1939) described early ground-water conditions in the middle Rio Grande Valley, and Bjorklund and Maxwell (1961) and more recently Thorn and others (1993) described hydrologic conditions in the Albuquerque area. Ground-water levels at various times in the Albuquerque area have been reported by Bjorklund and Maxwell (1961), Titus (1961), U.S. Army Corps of Engineers (1979), Hudson (1982), Kelly (1982), Kues (1986; 1987), Anderholm and Bullard (1987), Peter (1987), Summers (1992a), Thorn and others (1993), Rankin (1994), and Kues and Garcia (1995). Reeder and others (1967) projected water-level declines from 1960 to 2000 using an analytical model. Water budgets in the vicinity of Albuquerque were described by Hansen (in press) and P.F. Frenzel (Hydrologist, U.S. Geological Survey, written commun., June 23, 1995). A water budget for the Albuquerque Basin was presented by Thorn and others (1993). Gould (1995) calculated surface-water budgets for 1935, 1955, 1975, and 1993 by subunits in the Albuquerque Basin.

A few numerical ground-water-flow models of the Albuquerque Basin have been constructed. Kernodle and Scott (1986) and Kernodle and others (1987) constructed steady-state and transient models, respectively, based on the geohydrologic understanding of the basin presented by Bjorklund and Maxwell (1961). Kernodle and others (1995) constructed a ground-water-flow model of the basin and projected water-level declines from 1994 to 2020. This model was based on the geologic framework presented by Hawley and Haase (1992) and the hydrologic conditions presented by Thorn and others (1993).

Several ground-water-quality and geochemical studies have been done in the Albuquerque area. Hiss and others (1975) described the chemical quality of ground water in the northern part of the Albuquerque Basin and suggested that although water quality is relatively good in the upper part of the aquifer, it may deteriorate significantly with depth. Yapp (1985) used deuterium-hydrogen ratios to determine probable sources of ground-water recharge in particular parts of the aquifer in the Albuquerque area. Anderholm (1987) related ground-water chemistry in the Albuquerque Basin to local hydrologic conditions and land use. Anderholm (1988) described the distribution of ground-water quality in the Albuquerque Basin and discussed the chemical processes resulting in differing ground-water quality. Logan (1990) presented water-chemistry data for the Albuquerque area including deuterium, tritium, and oxygen-18 isotopes and suggested possible recharge pathways and geochemical processes resulting in the chemistry of water in different parts of the aquifer.

The Bureau of Reclamation has recently conducted several investigations regarding the interaction of surface water and ground water in the flood plain of the Rio Grande near Albuquerque. The Bureau of Reclamation (1994a) calculated the consumptive use and rate of applied irrigation water that recharges the water table in the middle Rio Grande Valley for various crops and soil series. Gould and Hansen (1994) calculated canal leakage rates for selected canals in the Albuquerque area using ponding tests. The Bureau of Reclamation (1994c) calculated Rio Grande gains and losses at five sites in the Albuquerque area using permeameters. Hansen (in press) used long-term average differences of surface-water inflows and outflows to estimate the net loss of water from the Rio Grande/canal/drain system through Albuquerque. The Bureau of Reclamation (1995) estimated aquifer characteristics adjacent to the Rio Grande near Albuquerque based on analysis of a change in stage in the Rio Grande and changes in water levels in observation wells.

Many studies contributing to the current (1995) knowledge of geologic and hydrologic conditions in the Albuquerque area have been made through the cooperative programs between the City of Albuquerque and the New Mexico Bureau of Mines and Mineral Resources, U.S. Geological Survey (USGS), and Bureau of Reclamation. Reports describing those investigations are footnoted in the "Selected references" section of this report.

Numerous investigations of hydrologic relations between aquifer and river systems have been conducted in areas outside the Albuquerque Basin. Winter (1995) presented a summary of recent investigations that used various methods to quantify ground-water/surface-water interaction in river valleys, as well as other types of terrain. Studies that demonstrate the use of methods outlined in the plan of study presented in this report are cited as the study elements are presented (see "Plan of study" section of this report).

Acknowledgments

This study was done in cooperation with the City of Albuquerque Public Works Department. The author acknowledges the contribution by the City of Albuquerque in developing the current base of geohydrologic information for the Albuquerque Basin, including much of what is known about the hydrologic interaction between the Rio Grande and the Santa Fe Group aquifer system. Much of this information has been gained through the City's test-well drilling program and cooperative investigations programs with the New Mexico Bureau of Mines and Mineral Resources, USGS, and Bureau of Reclamation.

A workshop on ground-water/surface-water relations in the Albuquerque Basin was held in Albuquerque, New Mexico, during October 12-14, 1994 (see "Supplemental information" section of this report). The purpose of the workshop was to identify and evaluate possible methods for improving the understanding of the hydrologic relations between the Rio Grande and the Santa Fe Group aquifer system in the Albuquerque area and quantifying those relations. The workshop was attended by many who work on geology, hydrology, and water management in the Albuquerque Basin, or who have done work on ground-water/surface-water interaction in other areas. Many of the elements of the plan of study outlined in this report were derived from that workshop. The author thanks the workshop participants and gratefully acknowledges their participation in the study plan development process. Those individuals are: Peter Balleau, Balleau Groundwater; Reid Bandeen, Camp Dresser and McKee; Mike Bitner, CH2M Hill; Gary Daves, Douglas Earp, Norman Gaume, and Tom Shoemaker, City of Albuquerque; Bob Grant, Grant Enterprises, Inc; Steve Hansen and Tom Pruitt, Bureau of Reclamation; John Hawley, New Mexico Bureau of Mines and Mineral Resources; Franz Lauffer, Sandia National Laboratories; Stephen Lee, Kirtland Air Force Base; Linda M. Logan, Tom Morrison, Bhasker Rao, and James T. Smith, New Mexico State Engineer Office; Alan O'Brien, Rio Rancho Utilities Corp.; John Shomaker, John Shomaker and Associates; John Sorrell, and Bill White, Bureau of Indian Affairs; W.K. Summers; and Alan Burns, Chuck Heywood, Mike Kernodle, Stan Leake, Frank Riley, Condé Thorn, Ed Weeks, and Dennis Woodward, USGS.

HYDROLOGIC RELATIONS BETWEEN THE RIO GRANDE AND THE SANTA FE GROUP AQUIFER SYSTEM

The Rio Grande surface-water system in the Albuquerque area consists of the Rio Grande and a series of canals and drains in the Rio Grande inner valley (fig. 3). Mean annual flow of the Rio Grande through Albuquerque is about 1,043,000 acre-feet per year (after the closure of Cochiti Dam, water years 1974-93; Cruz and others, 1994, p. 201). Water is diverted from the Rio Grande to canals for irrigation within the inner valley. The diversion of water for use within the Albuquerque area is at Angostura, and the next downstream diversion is at Isleta Pueblo (fig. 2). Riverside drains, installed in the late 1920's through early 1930's and revitalized in the 1950's, intercept seepage from the Rio Grande that previously contributed to waterlogging of irrigated land in the inner valley. These drains are open channels dug to a level below the water table. Interior drains, most of which are also open channels, were installed beginning at the same time as the riverside drains. The interior drains intercept seepage from canals and irrigation in the inner valley, then discharge to the riverside drains. The riverside drains then return the water to the river downstream. Although interior drains continue to be installed in some areas of the inner valley in the Albuquerque Basin, many interior drains in the middle part of the Albuquerque area are no longer functional as drains because ground-water withdrawal and the transfer of irrigated land to other uses have lowered the water table.

As described previously, the Santa Fe Group aquifer system in the Albuquerque area is composed of middle Tertiary to Quaternary Santa Fe Group and Quaternary post-Santa Fe Group deposits. The Santa Fe Group is as much as about 14,000 feet thick in the Albuquerque area and is divided into three parts--the upper, middle, and lower. According to Hawley and Haase (1992), the upper part of the Santa Fe Group in the Albuquerque area is as much as about 1,500 feet thick, the middle part as much as about 9,000 feet thick, and the lower part as much as about 3,500 feet thick (Hawley and Haase, 1992, figs. III3-III5).

The most permeable aquifer zones in the Albuquerque area are within the upper part of the Santa Fe Group and are composed of channel sediments deposited by an ancestral Rio Grande (Hawley and Haase, 1992; Hawley and others, 1995, fig. 2). These deposits consist of a large percentage of sand and gravel that result in relatively large hydraulic-conductivity values (in the range of 30 to greater than 100 feet per day; Thorn and others, 1993, table 2). The largest known extent of these deposits is beneath the eastern part of Albuquerque in a south-trending zone as much as 3 miles in width and greater than 1,000 feet in maximum thickness (Hawley and others, 1995, p. 47).

In general, sediments in the middle and lower parts of the Santa Fe Group in the Albuquerque area are less permeable than those in the upper part. In the Rio Rancho area however, ground water is primarily withdrawn from the middle and lower parts of the Santa Fe Group (J. W. Hawley, New Mexico Bureau of Mines and Mineral Resources, oral commun., November, 1995).

The alluvium in the Rio Grande inner valley (fig. 2) consists of post-Santa Fe Group deposits from the most resent erosion and deposition sequence of the Rio Grande (Hawley and Haase, 1992, p. II-7). This inner valley alluvium provides the hydraulic connection between the Rio Grande surface-water system and the underlying Santa Fe Group aquifer system. The channel and flood-plain sediments composing the inner valley alluvium form the shallow part of the aquifer system. These sediments are as much as 130 feet thick (Hawley and Haase, 1992, p. II-7) and average about 80 feet thick. Post-Santa Fe Group deposits adjacent to the inner valley are remnants of prior erosion and deposition sequences of the Rio Grande. These deposits are as much as 200 feet thick, and, where exposed, form terraces along the margins of the inner valley (Hawley and Haase, 1992, p. II-7). For more detailed descriptions of the geologic and hydrologic framework of the Santa Fe Group aquifer system in the Albuquerque area, the reader is referred to Hawley and Haase (1992), Thorn and others (1993), and Hawley and others (in press).

Hydrologic relations between the Rio Grande surface-water system and the Santa Fe Group aquifer system are complex in the interaction of hydrologic boundary conditions, aquifer materials, aquifer stresses, and system response. A ground-water-flow model can help understand these complexities and estimate the effects of particular stresses on the aquifer and river system. The recently developed ground-water-flow model of the Albuquerque Basin (Kernodle and others, 1995) can be a basis for developing this capability. The collection of additional information on the components of the river/aquifer system outlined in this report can be used to update and adjust the ground-water-flow model. The model can then be used to quantify ground-water/surface-water relations.

Simulations using the model of Kernodle and others (1995) are cited periodically in this report to illustrate the importance of particular components of the river/aquifer system and to help identify additional data needs that would improve understanding of river/aquifer hydrologic relations. Values of aquifer components used in the model are also cited throughout this report for comparison with values reported from other sources. These comparisons help to illustrate how well a component of the river/aquifer system is known.

Physical and Hydraulic Characteristics of System Components

Physical and hydraulic characteristics of the river/aquifer system control the movement of water through the system. These components include the Rio Grande, canals, drains, Santa Fe Group deposits, inner valley alluvium, hydraulic heads, and aquifer storage.

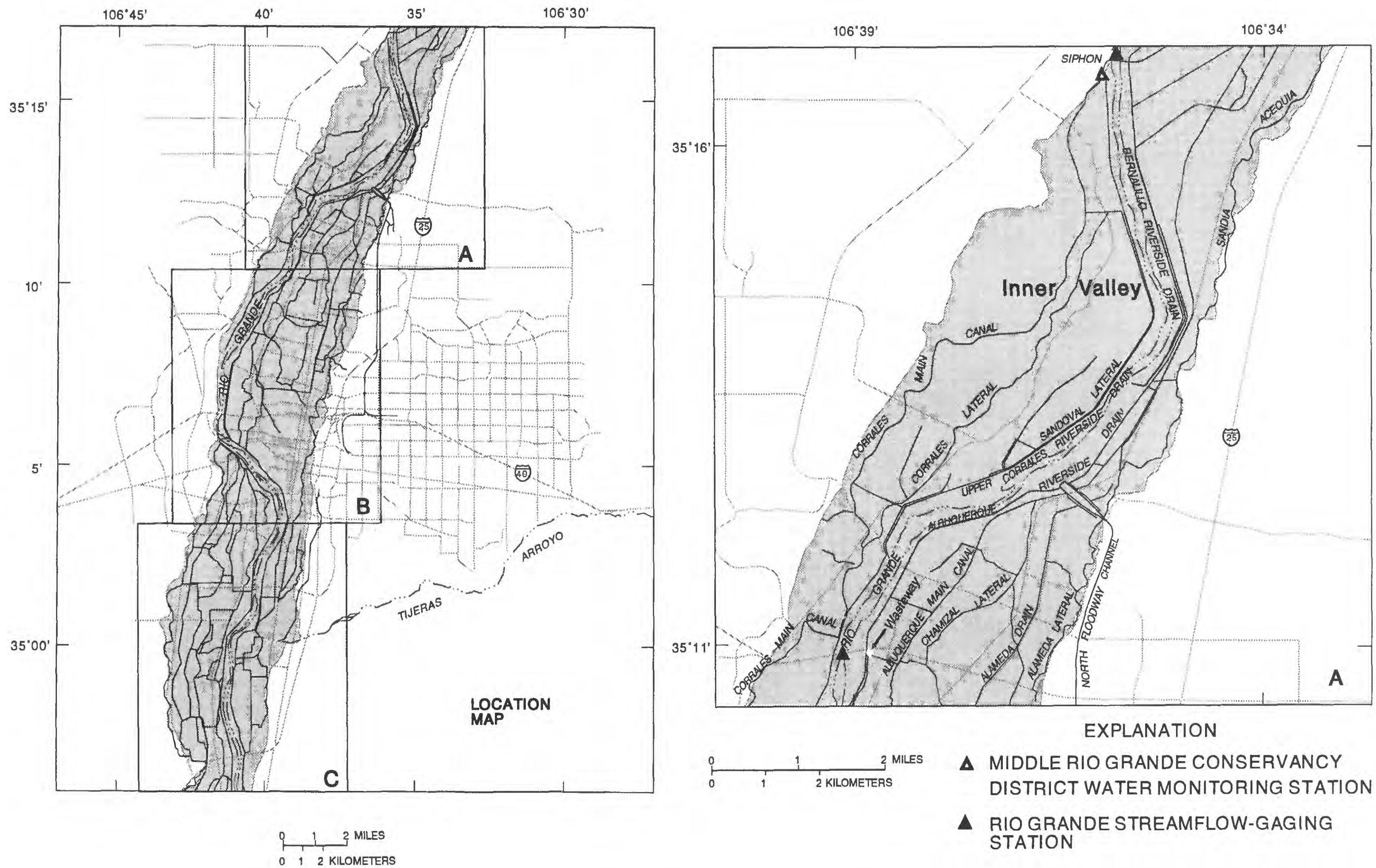


Figure 3.--Rio Grande surface-water system in the Albuquerque area (modified from Bureau of Reclamation 1992 digital data).

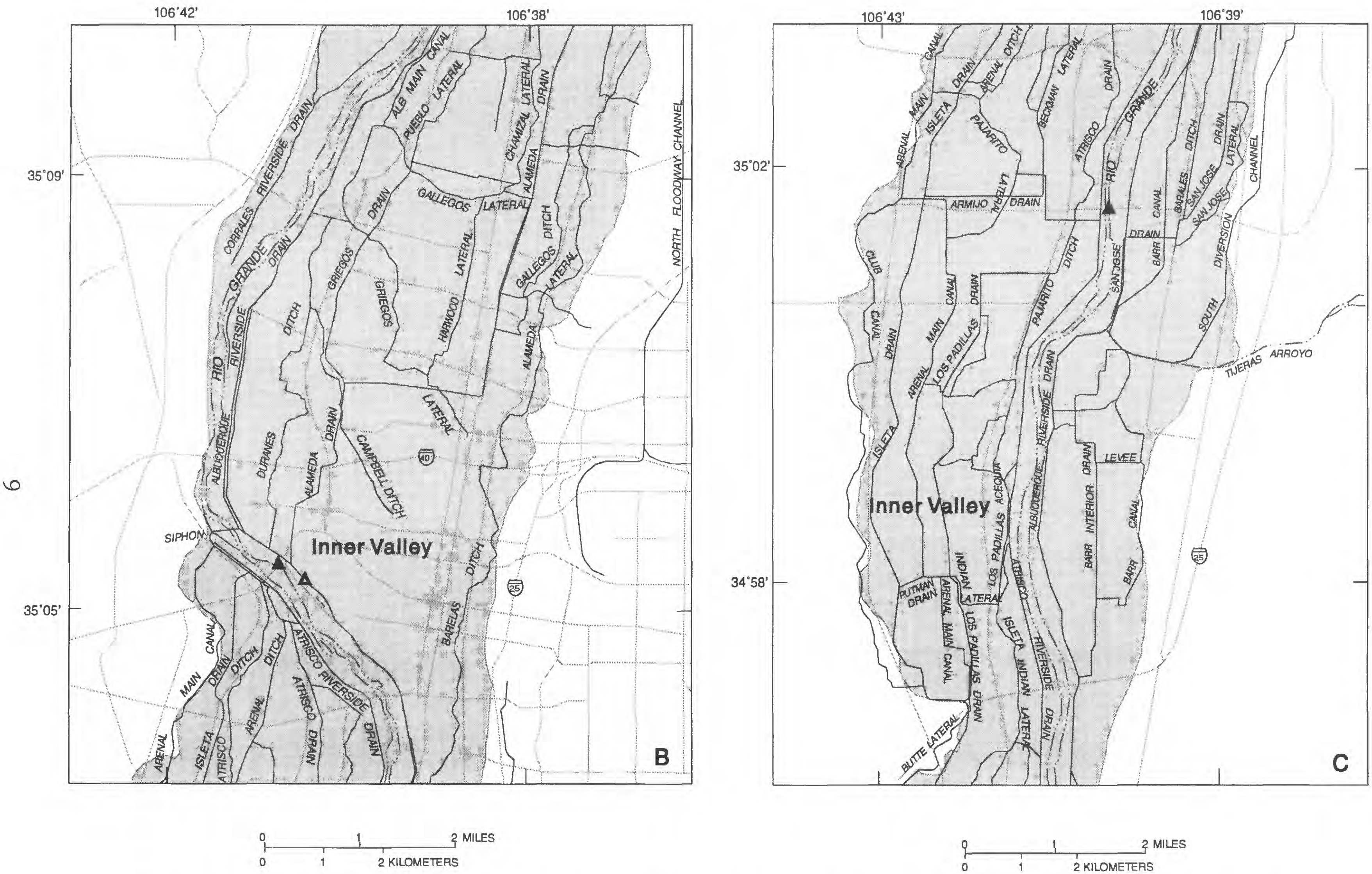


Figure 3.--Rio Grande surface-water system in the Albuquerque area (modified from Bureau of Reclamation 1992 digital data)--Concluded.

Rio Grande

The wetted perimeter of the Rio Grande, thickness and hydraulic conductivity of the riverbed, and difference between river stage and hydraulic head beneath the riverbed control the rate of water movement between the Rio Grande and the aquifer system. The physical extent of the Rio Grande channel is well known and is described with digital data at various time periods (Kernodle and others, 1995, p. 10). Digital data at a source scale of 1:24,000 are available from the National Biological Service for 1935 and 1989 and at a source scale of 1:12,000 are available from the Bureau of Reclamation for 1955, 1975, and 1992. Elevation of the riverbed, important for determining the difference between river stage and the hydraulic head beneath the riverbed, is available from USGS topographic maps. These data provide sufficient detail in describing channel extent and elevation; however the wetted perimeter of the river and river stage vary depending on the volume of its flow. Riverbed hydraulic conductivity may also be dependent on volume of riverflow if the texture of channel sediments or amount of silt sealing varies across the river.

To determine if changes in wetted perimeter and river stage make a significant difference in estimated seepage between the river system and the aquifer, the 1980-94 simulation of the ground-water-flow model described by Kernodle and others (1995) was modified. The wetted perimeter of the river and the thickness and hydraulic conductivity of the riverbed are reflected in the hydraulic conductance of the stream/aquifer interface (riverbed) (McDonald and Harbaugh, 1988, chap. 6). Kernodle and others (1995) assumed that the Rio Grande covered the entire channel and maintained a constant stage of 3 feet above the riverbed throughout the year. For the modified scenario, the simulated hydraulic conductance of the riverbed was reduced by half during the winter months to represent 50 percent less wetted perimeter, and the river stage was reduced by 0.75 foot to represent the generally lower flow conditions in the Rio Grande during that time period (Cruz and others, 1994, p. 201). The simulated hydraulic conductance of the riverbed was reduced by 10 percent during the summer months to represent an average condition of less than channel-capacity discharge. The resulting seepage from the river and canals was reduced about 5 percent from the original simulation in the Albuquerque area (river and canal seepage could not be separated in the model output). Because this is a combined reduction of river and canal seepage, seepage from the river alone was reduced by a larger percentage. Wetted perimeter and river stage are, therefore, important for quantifying seepage from the Rio Grande. This information can be interpolated using discharge and stage records from the existing Rio Grande streamflow-gaging stations in the Albuquerque area (fig. 4); therefore, additional information on these characteristics is not needed.

As noted in the previous paragraph, riverbed hydraulic conductance includes the thickness and hydraulic conductivity of the riverbed as well as the wetted perimeter. A reduction in the ratio of riverbed hydraulic conductivity divided by riverbed thickness also reduces the simulated seepage. Kernodle and others (1995, p. 20, 110) assumed riverbed hydraulic conductivity to be 0.5 foot per day and bed thickness to be 1 foot in their ground-water-flow model of the Albuquerque Basin. Sophocleous and others (1995, p. 587-588) reported that the riverbed hydraulic conductivity relative to aquifer hydraulic conductivity is the most significant factor contributing to overestimation of stream depletion based on the assumption that the river and aquifer are in full hydraulic connection. Therefore, it is essential to better define riverbed hydraulic conductivity. Because the hydraulic conductivity must be applied over the thickness of the riverbed to determine hydraulic conductance, the effective riverbed thickness must be determined in conjunction with hydraulic conductivity. The Bureau of Reclamation (1994c, p. 9) installed a drive point into the Rio Grande channel and encountered sand (they indicted it had a similarity to "quick sand") to a depth of 3 feet below the channel, clay from 3 to 8 feet, and a sand layer below the clay. In this example, the effective riverbed that would restrict the vertical movement of water between the river and the aquifer is the 5-feet thick clay. For calculating hydraulic conductivity across the riverbed, measuring the hydraulic head below the riverbed (about 8 feet below the river channel in the above example) and the stage of the river is essential.

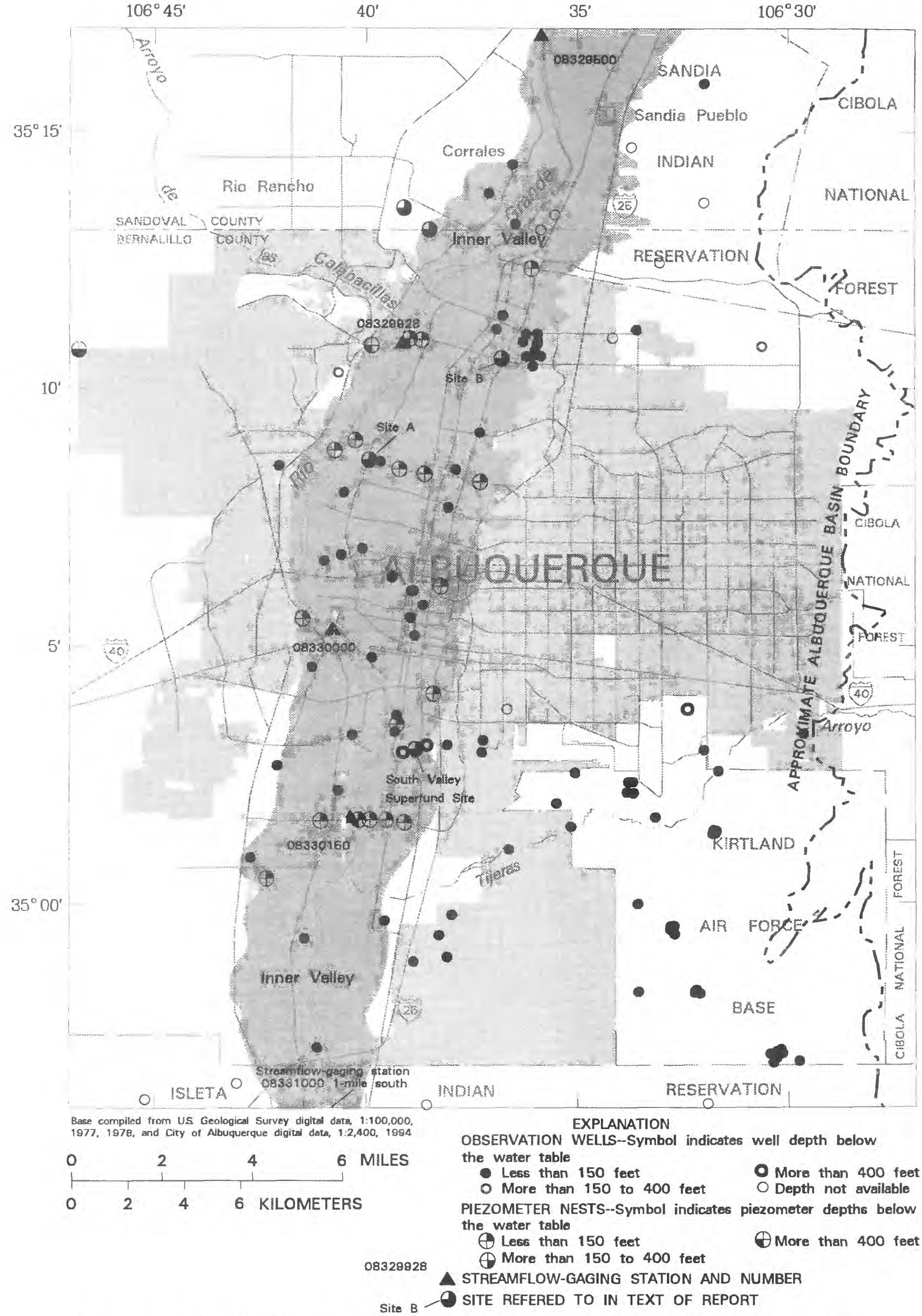


Figure 4.--Selected observation wells, piezometer nests, and streamflow-gaging stations in the Albuquerque area.

The Rio Grande channel has changed with time (National Biological Service digital data, 1935, 1989; Bureau of Reclamation, 1955, 1975, 1992). Documenting any changes that also may affect seepage is essential.

Canals

The system of canals in the Rio Grande inner valley is composed of main canals, laterals, and ditches. The main canals move water along the valley from the Angostura diversion for distribution to the irrigated areas upstream from the diversion at Isleta. In general, laterals distribute the water from the main canals to more localized irrigated areas, and ditches distribute the water from the main canals or laterals to irrigated fields. For the purpose of the following discussions, the term canals refers to all of these categories, unless they are specifically identified.

In the same manner as described for the Rio Grande, the rate of movement of water between canals and the alluvium in the inner valley is controlled by the wetted perimeter, thickness of the canal bed, hydraulic conductivity across the canal bed, and the difference in hydraulic head across the canal bed. Gould and Hanson (1994) describe the canals from Albuquerque to Isleta Pueblo to typically contain silt loam at the bottom (the lowest most surface-water sediment interface) that grades into sandy material at 1 to 3 feet below the canal bottom. The effective bed of the canal that would restrict the vertical movement of water would be about 1 to 3 feet thick. Because the silt in the canal bottoms grade into coarser material, 1 foot is probably a reasonable estimate for the average effective thickness of canal beds in the Albuquerque area. If the water table is at or above the bottom of the canal bed (about 1 foot below the canal bottom or higher), the hydraulic-head difference is the difference between the canal stage and the hydraulic head just beneath the canal bed (about 1 foot below the canal bottom). If the water table is below the canal bed, as it is in most of the Albuquerque area, the hydraulic-head difference is the difference between the canal stage and the elevation of the bottom of the canal bed. The canal system has the effect of spreading water over the inner valley. Because many interior drains no longer function as drains in the Albuquerque area, much of the canal seepage may now be retained in the aquifer system rather than be intercepted by the drains and returned to the river.

The digital data bases described earlier also include the distribution of canals in the Albuquerque area. The length of any particular canal reach can be estimated from these data, but not the canal dimensions. However, the 1972 and 1992 digital data from the Bureau of Reclamation include information on whether a canal is a main canal, lateral, or ditch, which may indicate some of the dimensions. The hydraulic conductivity of canal beds in the Albuquerque area can be estimated using canal seepage rates determined by Gould and Hansen (1994). These tests indicated that bed hydraulic conductivity below the normal operating level of canals is relatively consistent because of silt sealing. Based on the seepage rate (an average of 0.40 foot per day) determined for the Atrisco Ditch at the normal operation water surface, the water depth (1.8 feet), and an assumed thickness of 1 foot for the canal bed (the water table is below the bottom of the canal bed), the estimated hydraulic conductivity across the canal bed is 0.14 foot per day [0.40 / (1.8 + 1)]. On the basis of this information, Kernodle and others (1995, p. 20, 110) assumed canal-bed hydraulic conductivity to be 0.15 foot per day and assumed bed thickness to be 1 foot in their ground-water-flow model. The consistency of canal-bed hydraulic conductivity in the range of normal canal operation indicates that this component is sufficiently known. However, seepage from canals is dependent on the total hydraulic conductance of the bed (which includes the wetted perimeter) and on the head difference between the canal and the aquifer. To better quantify hydraulic relations between the canals and the aquifer system, the essential information needed is canal widths, elevations of canal bottoms, normal operating stage, proportion of time a canal contains water, and whether a canal is cement lined or unlined.

The main canals and laterals generally are operated continuously during the irrigating season; however, many ditches contain water only while fields along the ditches are being irrigated. It is essential to document changes to the canal system, such as new canals, abandonment, or change in operation.

Drains

Drains remove water from the aquifer system only if the water table is above the level of the drain bottom (the lowest most surface-water/sediment interface). The rate of water removal by drains is controlled by the wetted perimeter of the drain, the thickness and hydraulic conductivity of the drain bed, and the difference between the drain stage and the adjacent water-table elevation. As described previously, many interior drains in the Albuquerque area no longer function as drains because the water table remains below the drain bottom. However, some drains receive storm water and canal-return water (water in canals not diverted for irrigation flow into either another canal, wasteway, or drain), which, like canals, allows the movement of water from the drain to the aquifer. In addition, some drains are used to convey canal-return water to a point where the water can be diverted to another canal, such as from the Albuquerque Riverside Drain to the Arenal Main Canal (fig. 3B). The previously discussed digital data bases contain the distribution of drains, from which the length of drain reaches can be estimated, but not their dimensions.

Information on the horizontal hydraulic conductivity of soils with various textures was used in a drain design analysis for parts of the Albuquerque Basin (Willis, 1993). Hydraulic conductivities for 22 soil textures were estimated and ranged from 0.2 foot per day for a silty clay to 65 feet per day for a gravelly coarse sand. Kernodle and others (1995, p. 110) assumed drain-bed hydraulic conductivity to be 1 foot per day and assumed drain-bed thickness to be 1 foot in their ground-water-flow model. Hydraulic conductivities of beds of drains used to convey irrigation water probably are similar to those of canals.

The modified simulation using the Kernodle and others (1995) model described in the "Rio Grande" section illustrates the operation of the riverside drains. Although seepage from the river and canals was reduced about 5 percent from the original simulation, the total simulated effect on flow in the river, which includes drain and canal seepage, was changed less than one-half of 1 percent. The reduction in simulated seepage from the Rio Grande was almost completely compensated for by a reduction in seepage to the riverside drains, which return water to the river. This shows that the riverside drains have a buffering effect on seepage from the Rio Grande--that is, excess seepage from the river is captured by the drains and returned to the river.

The essential information needed related to drains includes depth, width, and bottom elevation, which along with the elevation of the water table would provide an estimate of wetted perimeter; the area in the inner valley where the drains are nonfunctional; and the reaches of drains that convey irrigation water. The buffering effect of the riverside drains on river seepage shows that changes in the drain system may have a significant effect on the amount of river seepage that recharges the aquifer system. Therefore, documenting changes to the drain system is essential.

Santa Fe Group

Movement of water in the Santa Fe Group aquifer system is controlled by the lithologic composition of the Santa Fe Group and adjacent deposits, and the location and characteristics of internal or bounding faults. Because the majority of ground-water withdrawal in the Albuquerque area is yielded from the Santa Fe Group, the stresses from those withdrawals must propagate through Santa Fe Group deposits to reach the inner valley alluvium and the Rio Grande. Because the inner valley alluvium is in direct hydraulic connection with the surface-water system, it is discussed in detail in the following section. The remainder of this section is devoted to the Santa Fe Group.

Hawley and Haase (1992, p. III-2) and Hawley and others (in press) divide the Santa Fe Group and post-Santa Fe Group deposits into six hydrostratigraphic units that are based on depositional environment, lithologic features, and time of deposition (table 1). They further divide the deposits into 10 primary lithofacies units based on texture, degree of induration, and geometry and distribution of contrasting textural zones within the units. The lithofacies units, their depositional setting, and composition are listed in table 2. Each of the lithofacies has distinctive properties that influence its hydraulic characteristics (table 3), thereby allowing estimation of the distribution of hydraulic characteristics of the Santa Fe Group in much of the Albuquerque area. Kernodle and others (1995) used the general distributions of the lithofacies units within the hydrostratigraphic units to estimate the distribution of horizontal hydraulic conductivity in the Albuquerque Basin. The horizontal hydraulic-conductivity values they estimated are summarized in table 1. Kernodle and others estimated vertical hydraulic conductivity by assuming a vertical to horizontal anisotropy ratio of 1:200.

Table 1.-Hydrostratigraphic units of Santa Fe Group and post-Santa Fe Group deposits, and estimated hydraulic-conductivity values in the Albuquerque Basin

[--, not applicable]

Hydrostratigraphic unit of Hawley and Haase (1992) and Hawley and others (in press)	Subdivisions used by Kernodle and others (1995)	Horizontal hydraulic conductivity estimated by Kernodle and others (1995), in feet per day
River alluvium (Holocene to late Pleistocene age)	Rio Grande inner valley	40
	Clay zone in the Albuquerque South Valley	0.5
	Rio Puerco inner valley	20
Valley-border alluvium (Holocene to middle Pleistocene age)	Not distinguished from upper Santa Fe unit for simulation purposes	--
Piedmont-slope alluvium (Holocene to middle Pleistocene age)	Not simulated--above saturated zone	--
Upper Santa Fe unit (early Pleistocene to late Miocene age)	Undifferentiated	10 or 15
	Piedmont-slope deposits	10
	Axial-channel deposits	30 to 70
Middle Santa Fe unit (late to middle Miocene age)	Undifferentiated	4
Lower Santa Fe unit (middle Miocene to late Oligocene age)	Undifferentiated	2
	Zia sand	4 or 10
	Cochiti Formation	4

Many areas near the margins of the Albuquerque area and beyond are not described in sufficient detail to estimate the distribution of hydraulic characteristics. The effects from ground-water withdrawal continue to propagate through the aquifer by spreading of the cone of depression, particularly as withdrawals increase and expand. As these effects propagate, the hydraulic characteristics of the deposits in these margin areas become more significant in the hydrologic interaction of the aquifer and surface-water system. For this reason, it is useful to continue expanding the classification of the deposits beyond the Albuquerque area.

Table 2.--Summary of Santa Fe Group and post-Santa Fe Group lithofacies depositional settings and composition in the Albuquerque Basin [modified from Hawley and Haase, 1992, table III-2]

Lithofacies	Lithofacies subdivision	Depositional setting	Composition
I		Undifferentiated fluvial	Cobble to pebble gravel, sand, silt, and silty clay
	Iv	River valley and basin-floor fluvial	Sand and pebble to cobble gravel
	Ib	River valley and basin-floor fluvial; braided streams	Sand and pebble gravel; lenses of silt and silty clay
II		Basin-floor fluvial; locally eolian	Sand; lenses of pebbly sand, silt, and silty clay
III		Basin-floor alluvial and playa lake; locally eolian	Interbedded sand, silt, and silty clay; lenses of pebbly sand
IV		Basin-floor eolian and distal piedmont alluvial fan	Sand and silt; lenses of silty clay and clay
V		Undifferentiated distal to medial piedmont-slope alluvial fan	Gravel, sand, silt, silty clay, and clay
	Vf	Distal to medial piedmont-slope alluvial fan associated with small watersheds; alluvial-fan distributary channel and debris flow	Gravelly sand, silt and clay; lenses of sand, gravel, and silty clay
	Vd	Distal to medial piedmont-slope alluvial fan associated with large watersheds; alluvial-fan distributary channel	Sand and gravel; lenses of gravelly to nongravelly sand, silt, and clay
	Vv	Arroyo and river-valley border alluvial	Sand, silt, silty clay, and gravel
VI		Proximal to medial piedmont-slope alluvial fan; debris flow; distributary channel	Coarse gravelly sand, silt, and clay; lenses of sand and gravel; cobbles and boulders
VII		Distal to medial piedmont-slope alluvial fan; alluvial-fan distributory channel and debris flow	Gravel, sand, silt, and clay; indurated V, Vf, Vd, Vv
VIII		Proximal to medial piedmont-slope alluvial fan	Coarse gravelly sand, silt,and clay; lenses of sand and gravel; cobbles; indurated VI
IX		Basin-floor playa lake and alluvial flat; distal-piedmont alluvial	Silty clay interbedded with silty sand, silty clay, and clay
X		Basin-floor playa lake and alluvial flat; distal-piedmont alluvial	Silty clay interbedded with silty sand, silty clay, and clay; indurated IX

Table 3.--Summary of properties that influence ground-water production potential of Santa Fe Group lithofacies (modified from Hawley and Haase, 1992)

[>, greater than; <, less than]

Lithofacies	Ratio of sand plus gravel to silt plus clay[1]	Bedding thickness (feet)	Bedding configuration[2]	Bedding continuity (feet)[3]	Bedding connectivity[4]	Hydraulic conductivity	Ground-water production potential
I	High to moderate	>5	Elongate	>500	High	High to moderate	High to moderate
Iv	High to moderate	>5	Elongate	>500	High	High to moderate	High
Ib	High	>5	Elongate	>500	High	High	High
II	High to moderate	>5	Elongate	>500	Moderate to high	High to moderate	High to moderate
III	Low	1 to 5	Planar	>500	Low	Low	Low
IV	Low to moderate	1 to 5	Planar to elongate	100 to 500	Low to moderate	Moderate to low	Moderate to low
V	Moderate	1 to 5	Elongate to lobate	100 to 500	Moderate to high	Moderate	Moderate
Vf	Moderate	1 to 5	Elongate to lobate	100 to 500	Moderate	Moderate to low	Moderate to low
Vd	Moderate to high	>5	Elongate to lobate	100 to 500	High	Moderate to high	Moderate to high
VI	High	>5	Lobate	<100	Moderate	Moderate to high	Moderate
VII	Moderate	1 to 5	Elongate to lobate	100 to 500	Moderate to high	Moderate to low	Moderate to low
VIII	High	>5	Lobate	<100	Moderate	Moderate to low	Moderate to low
IX	Low	<1	Planar	>500	Low	Low	Low
X	Low	<1	Planar	>500	Low	Low	Low

[1]High >2; moderate 0.5-2; low <0.5.
[2]Elongate (length to width ratios >5); planar (length to width ratios 1-5); lobate (asymmetrical or incomplete planar beds).
[3]Measure of the lateral extent of an individual bed of given thickness and configuration.
[4]Estimation of the ease with which ground water can flow between individual beds within a particular lithofacies. Generally, high sand + gravel/silt + clay ratios, thick beds, and high bedding continuity favor high bedding connectivity. All other parameters being equal, the greater the bedding connectivity, the greater the ground-water production potential of a sedimentary unit (Hawley and Haase, 1992, p. VI).

As described previously, the most permeable part of the aquifer system is composed of fluvial sediments containing a high percentage of sand and gravel deposited by an ancestral Rio Grande (lithofacies Ib of Hawley and Haase, 1992). The extent of these deposits is of particular significance in the hydrologic interaction of the aquifer system and the surface-water system because the deposits provide a preferential path for movement of water in the Santa Fe Group. The extent of these deposits within Albuquerque is reasonably well known and is shown by Haneberg and Hawley (in press). However, the extent of these deposits north and south of Albuquerque is not well known. Kernodle and others (1995, p. 37, 104) assumed that the axial-channel deposits were unsaturated just north of the Bernalillo-Sandoval County line, but extended southward in the saturated zone to the southern end of the basin.

Faults within or bounding the Santa Fe Group are partial barriers to ground-water flow. Juxtaposed lithologic units of different hydraulic conductivities reduce the hydraulic conductivity across faults. In addition, many faults in the Albuquerque Basin are probably cemented to some degree, further decreasing hydraulic conductivity across the faults. Kernodle and others (1995, fig. 4 and p. 37) reduced the area-weighted mean horizontal hydraulic conductivity to one-fifth for model cells that contained an interpreted location of a major fault. Haneberg and Hawley (in press) have revised the interpreted locations of major faults in the Albuquerque area. Because many of these faults are buried and do not have surface exposures over most of their lengths, actual locations can only be inferred. Additional evidence of the location of these faults and the extent of these and other faults beyond the Albuquerque area would be useful for additional understanding of the Santa Fe Group.

Being able to estimate the effects of faults on ground-water flow involves more than determining the position of a fault. Without additional information, the hydraulic characteristics of a particular fault can only be inferred on the basis of observation or estimation of the degree of cementation or estimated on the basis of degree of offset of differing lithologic units across the fault. Where steady-state hydraulic gradients on either side of a fault are available, the relative transmissivities of the fault zone and the aquifer on either side of the fault can be calculated (Haneberg, 1995a). Knowledge of fault-zone thickness and one of the transmissivities is needed to calculate the other transmissivities. This technique is not applicable for areas where ground-water development has significantly altered hydraulic gradients and predevelopment gradients are not available. Where ground-water development is significant, hydrologic characteristics of a fault may be estimated on the basis of observation of aquifer stresses (particularly ground-water withdrawals) and the resulting changes in hydraulic head in different parts of the aquifer system. This can be done only if observation wells are available and the aquifer stress is of a great enough magnitude for the partial barrier to ground-water flow, in this case a fault, to be significant. For this reason, faults and other partial barriers to ground-water flow such as changes in lithology, and others yet unknown, will become more significant in the study of hydraulic relations between the aquifer system and the surface-water system as the effects of ground-water withdrawals in the Albuquerque Basin continue to increase and expand.

As discussed above, hydraulic conductivity may be estimated based on the lithology of the basin-fill material. Sophocleous and others (1995, p. 585-588) found that aquifer heterogeneity was one of the most significant factors contributing to overestimation of stream depletion based on the assumption that the aquifer is homogeneous (hydraulic conductivity does not vary spacially) and isotropic (hydraulic conductivity is equal in all directions). Therefore, determining values of horizontal and vertical hydraulic conductivity is essential and needs to be calculated by other methods to provide a basis for extrapolating or estimating values based on lithology.

Inner Valley Alluvium

As described previously, the channel and flood-plain deposits in the inner valley constitute the hydraulic connection between the Rio Grande surface-water system and the remainder of the Santa Fe Group aquifer system. Therefore, the lithologic composition of this alluvium and adjacent deposits is a major factor controlling the volume of water that can move between the surface-water system and the primary production intervals of wells in the Albuquerque area, which are completed in the Santa Fe Group. The hydraulic characteristics of these alluvial deposits can, in part, be estimated on the basis of their lithologic composition.

Basin- and valley-fill aquifers are heterogeneous (hydraulic conductivity varies spacially within the aquifer) and anisotropic (hydraulic conductivity varies depending on direction). As a result, hydraulic conductivity is dependent on the size of a part of the aquifer under consideration. For example, channel deposits in the inner valley alluvium generally contain sand and gravel. A localized part of the aquifer containing only sand and gravel would have relatively large values of hydraulic conductivity. Values of horizontal hydraulic conductivity for these coarse deposits in the inner valley alluvium have been estimated to be about 90 to 350 feet per day by the Bureau of Reclamation (1994b; based on an auger-hole method described by Maasland and Haskew, 1957), and Willis (1993) reported the hydraulic conductivity of gravelly coarse sand to be 65 feet per day. The wide range in possible values (65 to 350 feet per day) for these coarse deposits can be explained by the degree of sorting--larger values of hydraulic conductivity are associated with more uniform grain sizes in the coarser deposits. Flood-plain deposits containing silt and clay have relatively small values of hydraulic conductivity: Willis (1993) listed the conductivity of silty clay to be 0.2 foot per day. A larger part of the aquifer is likely to contain layers or lenses of deposits with different grain sizes and varying degrees of sorting. In such a system, hydraulic conductivity parallel to the layers or lenses (typically horizontal) is in general equal to the weighted arithmetic average of the hydraulic conductivities of each of the deposits. Therefore, when considering a part of an aquifer large enough to be representative of the aquifer's heterogeneity, a middle range of values, rather than the extreme values of horizontal hydraulic conductivity is more representative. Hydraulic conductivity perpendicular to the layers (typically vertical), however, is controlled primarily by the layers having small values of hydraulic conductivity. Individual grains tend to be deposited in an alluvial system flat side down, which also contributes to reduced hydraulic conductivity in the vertical direction compared to the horizontal direction. Average vertical hydraulic conductivity in vertically anisotropic aquifer material, such as the inner valley alluvium, can often be about two or more orders of magnitude less than the average horizontal hydraulic conductivity (Freeze and Cherry, 1979, p. 34).

As discussed above, layers of low-conductivity deposits control the vertical hydraulic conductivity and, therefore, the vertical movement of water in the inner valley alluvium. Flood-plain deposits consist primarily of silt and clay deposited by water moving at lower velocity than water in the active channel. Layers of silty clay exist within much of the inner valley. Many of these silty-clay layers are discontinuous and may be as much as about 15 feet thick locally (Anderholm and Bullard, 1987). An extensive silty-clay layer at a depth of about 20 feet below land surface has been mapped based on about 470 borehole logs at a Super Fund site in the Albuquerque South Valley (Jacobs Engineering Group, 1995). However, the extent of these clay layers throughout the inner valley is not well known. The continuity of silty-clay layers can significantly effect the vertical hydraulic conductivity. A part of the aquifer with a continuous silty-clay layer will have a lower effective vertical hydraulic conductivity than a part with a discontinuous silty-clay layer of the same thickness and texture. Therefore, knowledge of the nature and distribution of the silts and clays in the inner valley alluvium is essential information to help provide a better understanding of the ability of the alluvium to transmit water vertically between the Santa Fe Group and the Rio Grande.

Horizontal hydraulic conductivity of most of the inner valley alluvium was assumed to be 40 feet per day by Kernodle and others (1995, p. 25, 110; table 1). They assumed a value of 0.5 foot per day for the silty-clay layer in the vicinity of the Albuquerque South Valley (table 1). The ratio of vertical to horizontal hydraulic conductivity was assumed to be 1:200 throughout the inner valley alluvium.

As noted in the previous section on the Santa Fe Group, calculated values of horizontal and vertical hydraulic conductivity are essential for providing a basis for extrapolating or estimating hydraulic conductivity on the basis of lithology. This is particularly important for the inner valley alluvium because it is the hydraulic connection between the Rio Grande surface-water system and the remainder of the Santa Fe Group aquifer system.

Areas where coarse sediments of the inner valley alluvium are adjacent to coarse terrace Santa Fe Group deposits provide preferential pathways for water to move laterally through the alluvium to the main part of the Santa Fe Group aquifer system. Whitworth and Hawley (in press) have identified some of these areas.

Hydraulic Heads

The distribution of hydraulic head in an aquifer system represents the effects of all stresses on the aquifer. Hydraulic head varies vertically as well as horizontally throughout an aquifer system, most significantly in areas of recharge or discharge. The difference between the hydraulic head in the aquifer at the interface between the ground-water and surface-water systems and the head or stage of the surface-water body is the driving force of the hydraulic interaction or movement of water between the two systems. Aquifer stresses must be propagated through the aquifer to a ground-water/surface-water interface to influence the movement of water between the two systems. This results in changes in hydraulic head. Although other characteristics must be estimated using analysis of changes or variations in hydraulic head, hydraulic head is one of the few characteristics of an aquifer system that can be directly measured. Therefore, measuring hydraulic heads in the aquifer system is essential.

Hydraulic heads are measured in some wells in the Albuquerque area (fig. 4), but few of these are dedicated observation wells where measurements represent the vertical head distribution in the aquifer. The majority of these dedicated observation wells that do represent the vertical head distribution are in the Rio Grande inner valley. Many observation wells are converted production wells, which are generally open to a large vertical interval of the aquifer. Heads measured in these wells cannot easily be related to a specific vertical location within the aquifer because they are vertically averaged over a large interval.

The largest volume of ground-water withdrawal in the Albuquerque area is east of the inner valley. Few observation wells are in this area and none are screened in the production intervals. As a result, water levels measured in high-capacity City production wells are the only source of information on hydraulic head. Not only are these wells open to a large vertical section of the aquifer, but also the water levels in them are largely influenced by recent pumping of the wells. Vertically averaged measurements of head over large screened intervals can indicate long-term trends, but are of little use for observing and analyzing the propagation of the effects of ground-water withdrawals through the aquifer system. Because these wells are in the major production zone of the aquifer, the vertically averaged hydraulic heads measured in them will be lower than the elevation of the water table.

Additional observation wells are essential in the Albuquerque area to fill in gaps where meaningful hydraulic-head measurements are not available. Knowledge of the vertical distribution of hydraulic heads is essential for measuring aquifer response to stresses, such as ground-water withdrawal, and for estimating vertical hydraulic conductivity. In turn, information on the aquifer response to stresses and the vertical hydraulic conductivity is essential for quantifying the river/aquifer hydraulic interaction. Suggested general locations for additional observation wells are shown in figure 5. These locations were selected because the observation wells would be in areas between major production wells, and the hydraulic-head measurements would represent aquifer responses to stresses in the system rather than be overwhelmed by the withdrawal from nearby wells. As the area of influence from ground-water withdrawal in the Albuquerque area expands, so will the need for additional observation wells. Areas north and south of Albuquerque on the east side of the Rio Grande have experienced declines in hydraulic heads from the cone of depression in east Albuquerque propagating north and south (Thorn and others, 1993, figs. 30, 33; Kernodle and others, 1995, figs. 26, 27).

Aquifer Storage

Knowing the storage characteristics of the aquifer is important to better understand surface-water and ground-water interactions. All water withdrawn by wells must initially come from aquifer storage. For the withdrawal to influence the surface-water system, the resulting cone of depression must propagate to the ground-water/surface-water interface, causing a reduction in hydraulic head. Only then can part of the depletion of aquifer storage be replenished by induced recharge from, or decreased discharge to, the surface-water system. Specific yield and specific storage characterize the storage properties of an aquifer.

Specific yield (dimensionless) characterizes the proportion of the volume of water added to or taken from storage relative to the total volume of aquifer filled or dewatered by gravity at the water table. Specific yield generally averages between about 0.1 and 0.25 for the types of materials composing the Santa Fe Group aquifer system, although values vary depending on type of material (clay, silt, sand, or gravel) and the degree of particle-size sorting (Johnson, 1967). Average values of specific yield in the aquifer system can be estimated on the basis of distribution of these material types. Kernodle and others (1995, p. 110) assumed specific yield to be 0.15 in their ground-water-flow model. No aquifer tests have been done in the basin from which values of specific yield can be calculated.

Below the water table, the volume of water added to or taken from storage relative to a change in hydraulic head is dependent on expansion or contraction of the water and the compressibility of the aquifer material. This is characterized by the specific storage (dimensions are per unit of length), which is the volume of water added to or taken from storage in a volume of aquifer material relative to a unit change in hydraulic head. In an unconfined aquifer, the specific storage component of aquifer storage is negligible in comparison to the specific yield component (about 10^{-6} per foot of aquifer thickness compared to about 0.15). However, it is necessary to consider specific storage in evaluating a transient three-dimensional flow system (Lohman and others, 1972), such as the Santa Fe Group aquifer system.

As described above, specific storage is dependent on expansion or contraction of the water and the compressibility of the aquifer material. The expansion or contraction of water is elastic--that is, the portion of water taken from storage due to expansion of water as hydraulic head declines, may be restored with a subsequent equivalent increase in hydraulic head. There are two components to the compressibility of the aquifer material, an elastic component and an inelastic component. As water is withdrawn from storage, the aquifer will react elastically if hydraulic head is not lowered beyond the point that the aquifer has been previously stressed--that is, the water taken from storage can be restored with a subsequent increase in hydraulic head. If hydraulic head is decreased beyond the point that the aquifer has been previously stressed, the aquifer will react inelastically and permanent compaction will occur (Leake and Prudic, 1988). The portion of water released by inelastic compaction cannot be restored to the aquifer with an equivalent increase in hydraulic head; it is a one-time withdrawal of water from storage, and the storage characteristics of the aquifer are permanently changed. Although all types of basin-fill sediments (clay, silt, sand, and gravel) can respond inelastically, inelastic response is most significant in clays.

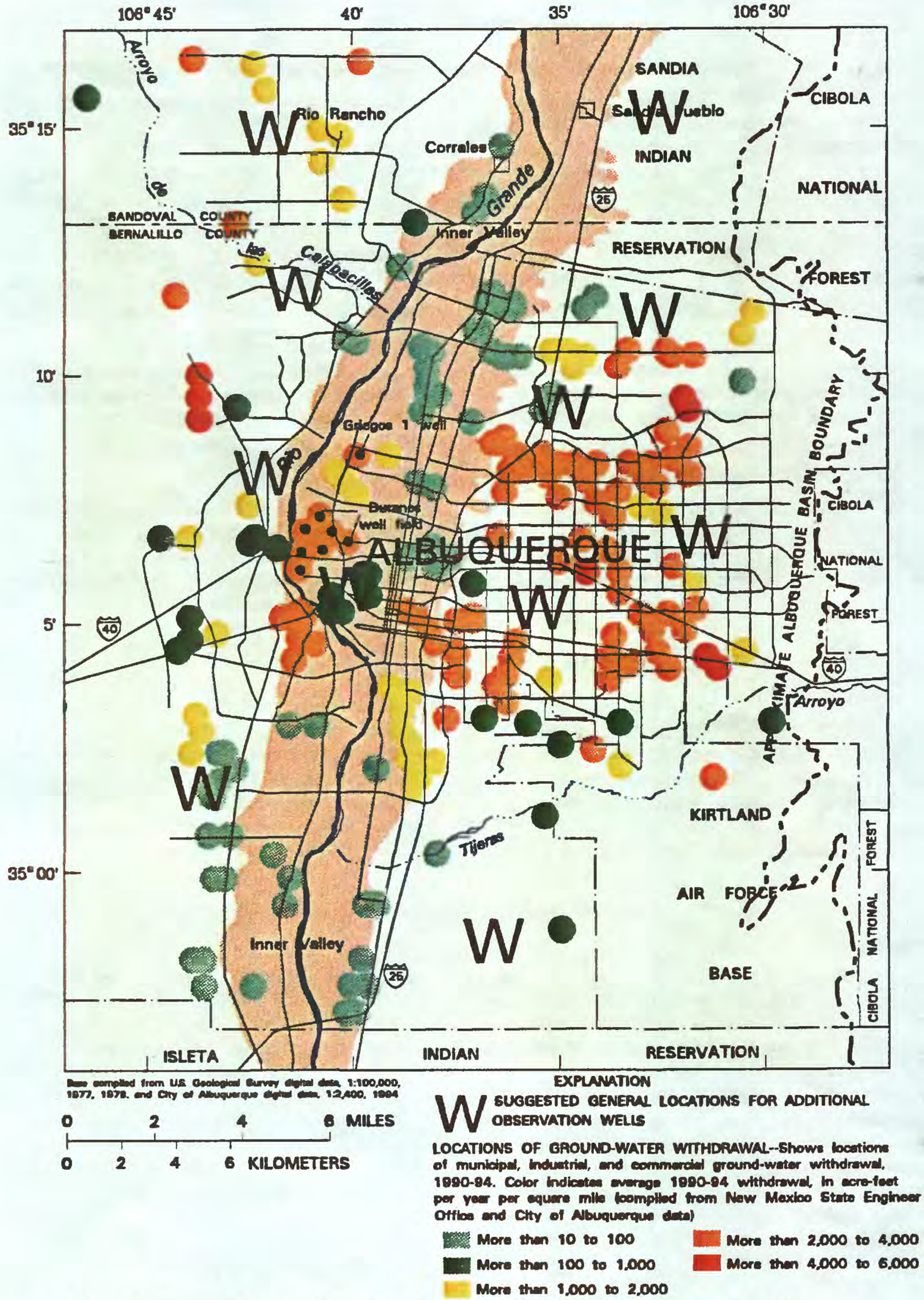


Figure 5.--Suggested general locations for additional observation wells in the Albuquerque area and average ground-water withdrawal, 1990-94.

Elastic specific storage (sum of the elastic specific storage components) is generally about 10^{-6} per foot of aquifer thickness (Lohman, 1979, p. 8). By measuring changes in aquifer thickness in an extensometer and hydraulic heads in piezometers during an aquifer test in the Albuquerque area, C. E. Heywood (Hydrologist, U.S. Geological Survey, written commun., May 1995) calculated the average elastic specific storage over the 1,000-foot depth of the extensometer to be 2×10^{-6} per foot. Although, other calculated values of elastic specific storage are not available for the Albuquerque Basin, this is consistent with values calculated for other basin-fill aquifers summarized by Haneberg (1995b, p. 63-64). Kernodle and others (1995) used an elastic specific-storage value of 1×10^{-6} per foot in the initial simulations using their ground-water-flow model. However, it was adjusted to 2×10^{-6} per foot to obtain better matches between simulated and measured hydraulic heads.

The inelastic specific storage component of aquifer compressibility (which would result in a one-time release of water from storage) is commonly one to two orders of magnitude larger than the elastic specific storage (Haneberg, 1995b, p. 63). Haneberg (1995b) calculated the inelastic specific storage component to be about 6×10^{-5} to 2×10^{-4} per foot based on porosity logs from 5 wells in the Albuquerque area.

Monitoring the aquifer in the Albuquerque area for elastic and inelastic compaction is essential to more fully understand aquifer storage characteristics, and thus, to understand aquifer/surface-water system interaction. The USGS, in cooperation with the City of Albuquerque, has established a geodetic network and installed an extensometer to detect aquifer compaction.

Flow Characteristics of System Components

Components of the flow system considered in this section are those that recharge water to or discharge water from the aquifer system, and flow within the aquifer system itself. The recharge and discharge components include ground-water withdrawal; Rio Grande, canal, and drain seepage; basin margin and tributary recharge; riparian and wetland evapotranspiration; irrigation seepage; and septic-field seepage. These system components are discussed in decreasing order of relative volumes of water in the ground-water budget for the Albuquerque area as calculated from the Kernodle and others (1995) ground-water-flow model.

Ground-Water Withdrawal

Ground-water withdrawal in the Albuquerque area was estimated by Kernodle and others (1995) to be about 157,000 acre-feet for the year ending in March 1994. Ground-water withdrawal by wells is a human-induced stress on the ground-water/surface-water system. The water withdrawn by wells initially comes from storage within the aquifer. The withdrawal of water creates a cone of depression in the potentiometric surface near the well, creating a hydraulic gradient toward the well. The cone of depression spreads, as shown by changes in hydraulic head as it propagates through the aquifer. When the cone of depression comes in contact with a ground-water/surface-water interface, the withdrawal will have an effect on the movement of water between the aquifer and the surface-water system. The effect can be either an increase in the volume of water moving from the surface-water system to the aquifer or a decrease in the volume of water moving from the aquifer to the surface-water system. In either case, the result is a reduction of the volume of water in the surface-water system. Each additional withdrawal creates an additional effect.

Changes in hydraulic head in the aquifer system and any resulting effects on the surface-water system are a function of all stresses in the system. The magnitude and timing of these changes at any point in the aquifer system are dependent on the hydraulic characteristics of the aquifer, magnitude of the stresses, and the distance and direction (vertical as well as horizontal) of the stresses from the point in the aquifer system. In order to interpret relations between withdrawals by wells and resulting changes in hydraulic head, it is essential to have accurate measurements of the magnitude and the three-dimensional location of all ground-water withdrawals that could significantly affect hydraulic heads in the vicinity.

Major production wells are screened over large intervals of the aquifer. For example, the distance between the top and bottom of the screened intervals in City of Albuquerque production wells ranges from about 350 to 1,000 feet and averages about 700 feet (City of Albuquerque files). The effect of withdrawals from these and similar wells on the aquifer and on the surface-water system is therefore dependent on the distribution of withdrawal along the length of each well's screen. Wells having large screened intervals generally do not draw equal volumes of water along the entire well screen, and the primary contributing zones along the screened interval may change with time. As an example, during a recent (1995) flow metering of the Griegos 1 City production well, water was yielded only from the screened interval above the depth of 640 feet (C.R. Thorn, written commun., April 4, 1995), although the screened interval of the well extends from a depth of 232 to 802 feet below land surface. The most permeable zone in the well's screened interval was originally (the well was drilled in 1955) the lower part, but cementation over the years has clogged this zone.

Information on the volume of ground-water withdrawal from production wells (other than private domestic wells) in the Albuquerque Basin is collected and recorded by the New Mexico State Engineer Office. Maintaining the accuracy and completeness of these records is essential for interpreting any observed changes in hydraulic heads in the aquifer system and any resulting effects on the surface-water system. Withdrawal by large production wells (producing more than about 100 acre-feet per year), such as those for the City of Albuquerque and other major water users, potentially have the largest effects on the aquifer and surface-water system. Accurate metering of withdrawals by these wells, and at a minimum, records of monthly withdrawals is essential. It will also be useful to maintain daily records for these wells in areas where continuous measurements of the vertical distribution of hydraulic heads are available so that aquifer stress and response relations can be analyzed and aquifer characteristics in the vicinity of particular wells can be estimated. Records of withdrawal for other production wells are needed on at least an annual basis; however, if withdrawals from those wells fluctuate significantly during the year, records maintained on a more frequent basis are needed to include those fluctuations. Because of the large amount of withdrawal data that would be generated, maintaining the data in a computerized data base is essential for practical application.

Although withdrawal information is readily obtainable, information on the vertical distribution of withdrawal is not. This information is essential for wells screened over large intervals, such as City of Albuquerque wells and other large production wells in the area. The vertical distribution of withdrawal from the majority of wells having smaller screened intervals can be estimated within reason using existing well-completion information.

Because of the large number of private domestic wells in the basin and the relatively small volume of withdrawal from each well (3 acre-feet per year maximum), maintaining records for each well is impractical. Withdrawals from these wells can be estimated using the population in areas not served by water systems and average per capita water use, or by the number of domestic wells in an area and average household water use. Rural per capita water use in New Mexico where outdoor watering is insignificant has been estimated to be about 64 gallons per capita per day; however, where outdoor watering is common, 150 gallons per capita per day may be more realistic (Wilson, 1992, p. 18, 96). Digital population data are available from the

U.S. Bureau of Census (1970, 1980, 1990), and average number of persons per household by area as well as other census information is available from the U.S. Department of Commerce (1991). Average depth of withdrawal can be estimated in particular areas using well-completion records (New Mexico State Engineer Office files, Albuquerque).

Santa Fe Group Aquifer System

Water removed from storage in the Santa Fe Group aquifer system in the Albuquerque area is a source of water to the flow system. Withdrawal of ground water from storage in the Albuquerque area was estimated using the Kernodle and others (1995) model to be about 72,000 acre-feet for the year ending in March 1994. This volume is about 46 percent of the 157,000 acre-feet per year withdrawn by wells in the Albuquerque area. Because withdrawal from storage is a large component of the water budget, documenting changes in the volume of water in storage in relation to the volume withdrawn is essential. Essential information needed to document changes in storage are the hydraulic-head and aquifer-compaction measurements described previously (see "Aquifer storage" section of this report) and measurements that would indicate changes in aquifer storage, such as measurement of hydraulic heads in piezometers and temporal gravity surveys (discussed in the "Plan of study" section of this report).

Ground water moving into the Albuquerque area from other parts of the aquifer system is also a source of water to the flow system. Based on the Kernodle and others (1995) model this was estimated to be about 20,000 acre-feet for the year ending in March 1994. Yapp (1985) and Logan (1990) have used ground-water-chemistry information, including environmental isotopes, to identify possible pathways for ground-water flow within and into the Albuquerque area. Continuing the collection of information on the chemical composition (including environmental isotope concentrations) of ground water in various parts of the aquifer would be useful, particularly if this information is collected from the proposed additional observation wells described previously. These observation wells would enable water-sample collection from particular depths in the aquifer, which would provide information on changes in chemical composition vertically within the aquifer. Many ground-water samples collected previously have been from production wells and are, therefore, composite samples over a vertical section of the aquifer. Existing and additional ground-water chemical analyses would then be useful in conceptualizing the ground-water flow system and in refining a ground-water-flow model of the Albuquerque Basin.

Rio Grande, Canal, and Drain Seepage

Rio Grande and canal seepage to the aquifer system in the Albuquerque area was estimated by Kernodle and others (1995) to be about 79,000 acre-feet for the year ending in March 1994, and seepage from the aquifer to the drains was estimated to be about 43,000 acre-feet for the year ending in March 1994. The estimated net seepage from the Rio Grande surface-water system to the aquifer system was 36,000 acre-feet per year (79,000 minus 43,000), or about 23 percent of the withdrawal by wells.

Seepage between the Rio Grande, canals and drains, and the aquifer system has been estimated by the Bureau of Reclamation in various investigations. Hansen (in press) estimated that 33,000 acre-feet of water per year seeps from the Rio Grande channel and riverside drain system to the aquifer system and about 34,000 acre-feet per year seeps from the canals and applied irrigation water to the aquifer system between Bernalillo and Isleta Pueblo. Gould and Hansen (1994, p. 17-18) calculated seepage rates for five selected canals in the Albuquerque area to average from 0.38 to 0.42 foot per day at normal water-surface elevations and from 0.21 to 0.22 foot per day below normal water-surface elevations. The water table was below the bottom of the canals at the five canal sites; therefore the difference in hydraulic head between the canal and the water table was not a factor in determining the seepage rates. Gould and Hansen (1994, p. 19) considered about 0.2 foot per day to be an appropriate estimate for canal operating conditions over an irrigation season. The Bureau of Reclamation (1994c) used channel permeameters in an effort to estimate seepage rates from the Rio Grande in the Albuquerque area. Although the results were inconclusive, they recommended that the procedures be modified and additional work of this type be done (Bureau of Reclamation, 1994c, p. 11-12). Seepage rates between the aquifer and drains is variable throughout the Albuquerque area because of the dependency on the water-table elevation and the use of some drains for the conveyance of irrigation and storm water. Bjorklund and Maxwell (1961, p. 55) noted that flow in some drains varies significantly seasonally and annually.

As noted in the previous "Canals" sections, the essential information needed to better quantify canal seepage is canal dimensions, bottom elevations, operating stage, proportion of time they contain water, and location of lined and unlined segments. The essential information needed to better quantify drain seepage is drain dimensions, bottom elevations, location of nonfunctional interior drains, and the reaches of drains that convey irrigation water (see previous "Drains" section). Estimates of seepage rates between the river channel and the aquifer are essential for model adjustments.

Seepage of water between a river system and an aquifer can be estimated by determining the difference in flow along particular reaches, if the river gain or loss is significantly greater than the measurement error of the flow in the river system. Flow records of the Rio Grande through Albuquerque are generally considered good, which means that 95 percent of the daily flow values are considered to be accurate within plus or minus 10 percent (Borland and Ong, 1995, p. 10, 189). Total loss of flow from the Rio Grande surface-water system between Bernalillo and Isleta Pueblo was estimated by Hansen (in press) to be about 113,500 acre-feet per year, which is almost 11 percent of the Rio Grande average annual flow of 1,053,000 acre-feet (Borland and Ong, 1995, p. 189). Because this estimate is very close to the measurement error of flow in the river, detecting loss of water in the surface-water system between two points of measurement would be difficult using single sets of measurements. However, by calculating the difference between long-term averages of flow measurements upstream and downstream from a reach during periods of low flow and accounting for inflows and outflows within the reach, statistically significant estimates can be made. This calculation becomes more complicated for the growing season because of riparian evapotranspiration and the diversion of water for crop irrigation. For the winter, however, when crop irrigation is not a factor and evapotranspiration is minimal, these calculations may produce realistic results.

The USGS monitors five streamflow-gaging stations on the Rio Grande in the Albuquerque area (fig. 4). Two of the gages, Rio Grande near Bernalillo (08329500) and Rio Grande near Isleta (08331000; continuous recording gage installed upstream of site where periodic water-discharge measurements were previously made), were installed in 1995 to provide measurements of Rio Grande flow into and out of the Albuquerque area. The five gages provide measurements of flow through four reaches of the river in the Albuquerque area.

River, canal, and drain flow at sections across the inner valley at the Rio Grande near Alameda (08329928) and Rio Grande at Rio Bravo Bridge (08330150) gages has been measured (Thorn, 1995) to calculate total surface-water inflow and outflow of the reach between the gages. To calculate total flow of the Rio Grande surface-water system into and out of the Albuquerque area it is essential to measure river, canal, and drain flow at sections across the inner valley at the two new gages (08329500 and 08331000; fig. 4).

The Middle Rio Grande Conservancy District (MRGCD, the agency that operates and maintains the irrigation system, including diversions, canals, and drains) measures canal and drain flow with continuous recording gages at four locations between Angostura and Isleta Pueblo and is proposing several more (Ray Gomez, Middle Rio Grande Conservancy District, written commun., September 22, 1995). The riverside drain and the diversion into the Albuquerque Main Canal are monitored just downstream from the diversion at Angostura. The Corrales Main Canal is monitored downstream from the siphon (fig. 3A), and the Albuquerque Riverside Drain is monitored downstream from its confluence with the Alameda Drain (fig. 3B). Additional continuous recording stations are proposed for the canal and drain system returns to the Rio Grande. This would allow separation of gains or losses in the drain and canal systems from those in the river channel.

Basin-Margin and Tributary Recharge

The aquifer system at the margins of the Albuquerque Basin is recharged by inflow of ground water from adjacent basins and by mountain-front recharge. Ground-water inflow from adjacent basins, such as the Española or San Juan Basins (fig. 2), occurs at depth in the aquifer system. Mountain-front recharge enters the aquifer system at the contact of basin-fill deposits and adjacent mountain blocks, such as the Sandia Mountains east of Albuquerque. Mountain-front recharge occurs as infiltration of water from streams draining the mountains and as seepage of shallow ground water from mountain valleys or near-surface fractured rock of the mountain block.

Tributary recharge originates as infiltration of water from streams and arroyos that flow toward the Rio Grande from the basin margins. Most tributary recharge is from unlined channels that contain flow for significant time periods. Ephemeral arroyos probably contribute little recharge in comparison because they flow for only short periods as a result of large thunderstorms. Much of the water infiltrated into the arroyo channels during these periods is subsequently evapotranspired to the atmosphere, leaving little water to percolate to the water table (Thomas, 1995, p. 21).

In the Albuquerque area, basin-margin recharge is from the Sandia and Manzanita Mountains, and tributary recharge is along Tijeras Arroyo. Ground-water inflow into the Albuquerque area comes from other parts of the Albuquerque Basin, as discussed previously (see "Santa Fe Group aquifer system" section), rather than from basins adjacent to the Albuquerque Basin. Basin-margin and tributary recharge cannot be directly measured and therefore must be estimated. Basin margin and tributary recharge in the Albuquerque area was estimated using the Kernodle and others (1995) model to be about 25,000 acre-feet for the year ending in March 1994. The ground-water-flow model (Kernodle and others, 1995, figs. 36C and 37A) shows that simulated change in aquifer storage in the basin was sensitive to simulated change in mountain-front and tributary recharge, as well as simulated change in ground-water withdrawal. Because changes in stresses to the aquifer system primarily result in either a change in aquifer storage or a change in the rate of water movement between the surface-water system and the aquifer system, the ability to reasonably estimate recharge would be useful in order to better understand hydrologic relations between the surface-water and ground-water systems.

Riparian and Wetland Evapotranspiration

Evapotranspiration from riparian and wetland areas is a discharge of water from the aquifer system. Types of riparian vegetation, such as cottonwood, tamarisk (saltcedar), and Russian olive, are phreatophytes and draw water from the capillary fringe above the water table. Water in wetland areas, where the water table is at or very near land surface, evaporates directly from the water table or through the capillary fringe of the water table. Evapotranspiration from irrigated areas--such as cropland, yards, or parks--comes from applied irrigation water, and therefore is not a direct discharge from the aquifer system.

Riparian and wetland evapotranspiration in the Albuquerque area was estimated using the Kernodle and others (1995) model to be about 12,000 acre-feet for the year ending in March 1994. Evapotranspiration in riparian areas was assumed in the model to attain a maximum rate of 2.6 feet per year when the water table was at land surface and to decrease linearly to zero when the water table was 20 feet below land surface. The maximum evapotranspiration rate from swampy land was assumed to be 5 feet per day.

Digital data containing the distribution of riparian and wetland areas in the Albuquerque Basin are available for 1935 and 1989 from the National Biological Service. Cottonwood, the dominant vegetation species, is 64 percent, tamarisk is 28 percent, and Russian olive is 6 percent of the riparian area in the Albuquerque Basin (National Biological Service, 1989 digital data). Estimates of evapotranspiration rates by various classifications of land cover, including free-water surfaces and bosque (riparian vegetation), are summarized by Blaney and others (1938, p. 336-341). Water use by phreatophytes in the Safford Valley of Arizona, a hotter climate than in the Albuquerque area, was reported by Gatewood and others (1950). More recently, the Bureau of Reclamation (1973a; b) conducted investigations in the Albuquerque Basin on evapotranspiration by tamarisk, Russian olive, and saltgrass and the relation between evapotranspiration rates and depth to the water table. During these investigations, evapotranspiration by tamarisk ranged from 1.8 to 4.5 feet per year and averaged 3.4 feet per year for depths to the water table ranging from 0 to 9 feet below land surface (Bureau of Reclamation, 1973b, p. 9-10). However, evapotranspiration by tamarisk did not always decrease with an increase in depth to water as was assumed in the ground-water-flow model. Evapotranspiration by Russian olive ranged from 1.5 to 4.3 feet per year and averaged 2.4 feet per year for a depth to water of 3 feet below land surface (Bureau of Reclamation, 1973b, p. 8). Data for tamarisk and Russian olive showed that young plants consume more water than mature plants. Tamarisk and Russian olive are two common species of riparian vegetation in the basin. Evapotranspiration by cottonwood, the most dominant species, and the relation between the cottonwood evapotranspiration rate and depth to the water table were not investigated. Since estimated rates of evapotranspiration by riparian communities are available from Blaney and others (1938, p. 336-341) as described above, additional information relating to cottonwood evapotranspiration in not considered essential. However, rates of cottonwood evapotranspiration, the relation to water-table depth, and additional information relating evapotranspiration by individual species to evapotranspiration by a riparian community would be useful for improving estimates of evapotranspiration in the inner Rio Grande Valley. Because the ground-water-flow model now assumes that evapotranspiration decreases linearly with depth and the Bureau of Reclamation (1973a; b) studies indicate that this may not be true for at least some species, the relation between cottonwood evapotranspiration and depth to water would be particularly useful.

The largest changes in riparian and wetland evapotranspiration estimated by Kernodle and others (1995, p. 59, 68) were a result of changes in the distribution of riparian and wetland areas and drains (drains may capture water that otherwise could be evapotranspired by riparian vegetation or from wetlands). Therefore, documenting changes to the distributions of riparian and wetland areas and drains is essential.

Irrigation Seepage

Irrigation water is applied to crops in the Rio Grande inner valley through a distribution system of canals, laterals, and ditches. Water that is applied to fields in the Rio Grande inner valley, but is not evapotranspired, becomes recharge to the aquifer system. Irrigation seepage in the Albuquerque area was estimated using the Kernodle and others (1995) model to be about 9,600 acre-feet for the year ending in March 1994. Kernodle and others (1995, p. 17-18, 110) assumed the irrigation seepage rate to be 1 acre-foot per acre per year, based on 3 acre-feet per acre per year being applied. Bjorklund and Maxwell (1961, p. 53) estimated that about one-third of the irrigation water applied reaches the water table and that 3 acre-feet per acre per year is usually applied to most crops (excluding alfalfa, which requires more than 4 acre-feet per acre per year). The Bureau of Reclamation (1994a, table 8) has estimated the rate of this recharge to range from 0.10 to 1.22 acre-feet per acre per year in the Rio Grande inner valley, depending on crop type and soil series. Total applied irrigation water ranged from 1.1 to 4.2 acre-feet per acre per year, depending on crop type and soil series. The average for all crops and soil series was 2.5 acre-feet per acre per year.

By assuming that irrigation practices are consistent with those estimated by the Bureau of Reclamation (1994a), reasonable estimates of the rate and distribution of irrigation seepage that recharges the aquifer from cropland can be made based on the estimates described above and the distribution of crops. Digital data that include the distribution of irrigated areas in the inner valley of the Albuquerque Basin at a source scale of 1:24,000 are available from the National Biological Service for 1935, and digital data at a source scale of 1:12,000 are available from the Bureau of Reclamation for 1955, 1975, and 1992. The 1992 data distinguish crop type. Distribution of crops by county is available from the New Mexico Crop and Livestock Reporting Service (1962-94). Distribution of soil series in the Albuquerque area is reported by the U.S. Department of Agriculture (1977).

About 14,000 acres of cropland were irrigated in the Albuquerque area in 1975 and about 9,600 were irrigated in 1992 (Bureau of Reclamation digital data). Hansen (in press) estimated that about half of the recharge from the Rio Grande surface-water system between Bernalillo and Isleta Pueblo comes from canal and irrigation seepage. Reduction of irrigated cropland in the Albuquerque area may, therefore, have a significant effect on recharge from the inner valley (Steve Hansen, written commun., 1995), which would influence ground-water/surface-water interaction. It is, therefore, essential to document changes in the amount and distribution of irrigated cropland in the Rio Grande inner valley.

The measurement of water diverted into the canal system at Angostura by the MRGCD and their proposed measurements of return flow to the river would enable the separation of river- channel seepage from canal, drain, and irrigation seepage. Comparing return-flow measurements with diversion measurements during the irrigation season would show net seepage in canals, drains, and irrigated areas, and return-flow measurements during the winter would show drain seepage. This information is essential for adjusting the ground-water-flow model, thus improving the estimates of irrigation seepage as well as canal and drain seepage.

Septic-Field Seepage

Water from septic leach fields that reaches the water table is recharge to the aquifer system. Septic-field seepage in the Albuquerque area was estimated using the Kernodle and others (1995) model to be about 6,000 acre-feet for the year ending in March 1994. This number was based on an assumed seepage rate of 75 gallons per person per day in areas not served by sewer systems (Kernodle and others, 1995, p. 18-19, 110). Siegrist and others (1976, p. 536-537) calculated wastewater production from 11 rural Wisconsin households to average 43 gallons per capita per day and noted that this is consistent with other studies from other parts of the country. The smaller number is probably more reasonable for the volume of water reaching leach fields. However, if vegetation is growing over a leach field, some of the water will be evapotranspired by the vegetation.

Information is available to estimate evapotranspiration from leach fields. Consumptive use by various types of vegetation was reported by Blaney and others (1938) and the Bureau of Reclamation (1994a, 1973a, b). Information needed to determine the distribution of septic-field seepage includes digital population data, available from the U.S. Bureau of Census (1970, 1980, 1990), and average number of persons per household by area, reported by the U.S. Department of Commerce (1991). Information on leach-field sizes can be obtained from information required by the State and counties for permits. Bernalillo County, which includes most of the Albuquerque area, maintains a digital data base containing this information. Although the data base is estimated to contain data for only about one-third of the estimated 20,000 septic tanks in the county (City of Albuquerque and Bernalillo County, 1992, p. 25), it can provide an estimate of average septic-field size in the area.

Because of the relatively small volume of water septic-field seepage contributes to the estimated water budget of the area, estimates can be improved using only information that is currently available. Additional data collection or field experiments would not be cost efficient based on the additional understanding of ground-water/surface-water interaction that would be provided.

Summary of Information Needs

The previous two sections describing components of the Rio Grande and the Santa Fe Group aquifer system discussed essential additional information and useful additional information needed to improve quantification of hydrologic relations between the surface- and ground-water systems. Essential information is considered necessary to improve the quantification of the system. Useful information, although not necessary to improve the quantification of the system, would add additional understanding of the system. The essential and useful activities and information identified in the previous sections are summarized below.

Essential Activities and Information

Install additional observation wells

Measure the vertical distribution of hydraulic heads in the aquifer system and maintain a computerized data base of the measurements

Measure volume and three-dimensional location of ground-water withdrawals, and maintain a computerized data base of the measurements

Measure flow of the Rio Grande, canals, and drains at sections near river gages and maintain a computerized data base of the measurements

Document changes in the volume of water in aquifer storage

Monitor elastic and inelastic compaction

Estimate riverbed hydraulic conductivity

Define canal dimensions, bottom elevations, operating stage, percentage of time containing water, and location of lined or unlined segments

Define drain dimensions and bottom elevations (if water table is below bottom and if used for water conveyance)

Estimate vertical and horizontal hydraulic conductivity in the aquifer

Calculate seepage rates between the Rio Grande and the aquifer

Determine distribution of silts and clays in the inner valley alluvium

Document current (during life of project) changes to land uses (such as irrigated land), land covers (such as riparian vegetation), and inner valley surface-water features (such as the Rio Grande/canal/drain system)

Useful Activities and Information

Classify lithofacies units and fault locations in aquifer deposits beyond the Albuquerque area and estimate influence of faults on ground-water flow

Chemically analyze ground water, including environmental isotopes

Estimate basin margin and tributary recharge

Determine rate of evapotranspiration by cottonwoods and its relation to water-table depth

Hydraulic heads at points in the aquifer system, volume and location of ground-water withdrawals, and surface flows at specific sections across the valley are key components of the river/aquifer system and among the few that can be directly measured. These measurements provide a basis for calculating much other essential information, such as changes in the volume of water in aquifer storage, calculation of riverbed and aquifer hydraulic conductivity, and calculation of seepage between the river and aquifer systems.

As discussed previously (see "Hydrologic relation between the Rio Grande and the Santa Fe Group aquifer system" section) hydrologic relations between the Rio Grande surface-water system and the Santa Fe Group aquifer system are complex. The recently developed ground-water-flow model of the Albuquerque Basin (Kernodle and others, 1995) can be used as a basis for a better understanding and quantification of the river/aquifer system. The additional information described above would be collected and used for improving the ground-water-flow model.

Participants of the 1994 workshop (see "Acknowledgments" section) produced a list of possible methods to improve the understanding of hydrologic relations between the Rio Grande and the Santa Fe Group aquifer system in the Albuquerque area. The list is shown in the "Supplemental Information" section of this report. Most methods on the list are directed toward the activities and information needs listed above and are incorporated into the plan of study described in this report. Calculating deep percolation of irrigation seepage by improving estimates of consumptive use of water by crops, and installing piezometer nests in leach fields are not included in the plan of study. The reasoning for not including these is discussed below.

Deep percolation of applied irrigation water (irrigation seepage) to various crops has been estimated by the Bureau of Reclamation (1994a). Improving these estimates using improved estimates of crop consumptive use is not included in the plan of study. The rate of irrigation seepage that recharges the aquifer can be reasonably estimated by assuming that irrigation practices are consistent with those estimated by the Bureau of Reclamation (1994a). Documenting changes in the amount and distribution of irrigated cropland in the inner valley is essential information related to irrigation seepage and is included in the plan of study.

Estimates of septic-tank return (septic-field seepage) represent a relatively small part of the aquifer water budget in the Albuquerque area in comparison to other components of the river/aquifer system. Because of this, field experiments, which would need to be extrapolated over the area, would not substantially add to the understanding of the ground-water/surface-water interaction in the Albuquerque area. Reasonable estimates can be made using existing information.

PLAN OF STUDY

The following plan of study is proposed to collect the additional needed information identified previously in this report, use that information to develop a better understanding of hydrologic relations between the Rio Grande surface-water system and the Santa Fe Group aquifer system, and quantify those relations. Through this quantification, the effects of particular stresses, such as ground-water withdrawal by individual wells or groups of wells, on the aquifer and surface-water system can be determined. Because of the complexity of the aquifer and surface-water system in the Albuquerque area, an updated ground-water-flow model of the Albuquerque Basin (Kernodle and others, 1995) could be used to quantify the aquifer/surface-water system.

The proposed study elements and prioritized program for completing these elements are shown in table 4. The prioritization method used for the study elements is the same method used for prioritizing the information needs. Study elements that would provide information considered necessary to improve the quantification of the system are prioritized as essential, and those that would provide information that would add additional understanding of the system, but would not be necessary to improve the quantification of the system, are prioritized as useful.

Several study elements are of an experimental nature-- that is, the application of the techniques may not with certainty yield the information for which they are designed. These experimental study elements are noted in table 4 and in the following discussions of the study elements. The necessity of the information (essential or useful) obtained if the technique is successful is also noted.

The plan of study flow diagram (fig. 1 in the "Executive summary") illustrates the dependency of essential information on the study elements, as well as the dependency among study elements. The essential study elements would be implemented along the information flow paths as shown in figure 1.

Data storage is common to all of the study elements, and it is essential that the data developed be publicly accessible and readily retrievable for data analysis and incorporation into applications such as ground-water-flow models. Therefore, data storage in computerized data bases is essential. Because of the variety of information that would be obtained, a single data base is not practical for all data. However, all data in the data bases would be referenced by geographic location through a recognized map projection (such as longitude and latitude). This would allow pertinent data for a particular application to be retrieved and incorporated into a Geographic Information System (GIS) for analysis. The use of a GIS was essential for managing the large amount of information needed for the ground-water-flow model of the Albuquerque Basin developed by Kernodle and others (1995, p. 6). Some types of data, such as land uses at a particular time period, are amenable for storing directly in a GIS. However, data such as multiple (often thousands) hydraulic-head measurements from observation wells are more amenable to storage in a separate data base where particular measurements may be retrieved and incorporated into a GIS for analysis.

Table 4.--Prioritized plan of study to quantify hydrologic relations between the Rio Grande and the Santa Fe Group aquifer system

EXPLANATION

River/aquifer system components addressed: indicates the Rio Grande/Santa Fe Group aquifer system components for which information will be gained from the study element. AFS, aquifer flow system; AS, aquifer storage; C, canals; D, drains; E, riparian evapotranspiration; GWW, ground-water withdrawal; HH, hydraulic head, IS, irrigation seepage; IVA, inner valley alluvium; R, mountain-front recharge; RG, Rio Grande; SFG, Santa Fe Group.

Priority: priority of the study element in terms of the usefulness of the information obtained by the study. E, will yield essential information; X/E, experimental but if successful will yield essential information; U, will yield useful information; X/U, experimental but if successful will yield useful information.

Estimated time: estimated range of time to complete the study element. Continuous indicates data should be collected on a continuing basis.

Study element	River/aquifer system components addressed	Priority	Estimated time, in years
Update and adjust the Albuquerque Basin ground-water-flow model	AFS,R,RG,C,D,IVA, SFG,AS,E,IS	E	Continuous
Expand observation-well network	HH	E	Continuous
Install piezometers below Rio Grande	HH,RG	E	1-2
Monitor observation-well network,	HH	E	Continuous
Compile and automate ground-water withdrawal data	GWW	E	Continuous
Determine production zones within large-capacity production wells	GWW	E	Continuous
Monitor the Rio Grande, canal, and drain flows	RG,C,D	E	Continuous

Table 4.--Prioritized plan of study to quantify hydrologic relations between the Rio Grande and the Santa Fe Group aquifer system--Concluded

Study element	River/aquifer system components addressed	Priority	Estimated time, in years
Define canal and drain physical characteristics	RG,C,D	E	1-2
Conduct and analyze aquifer tests	RG,IVA,SFG	E	3-5
Update inventories of land cover and Rio Grande surface-water system	IS,E,RG,C,D	E	10-year intervals
Determine distribution of lithologies in the inner valley alluvium	IVA	E	1-2
Monitor extensometer and geodetic network	AS	E	Continuous
Analyze temperature profiles in piezometers below the Rio Grande	RG,IVA	X/E	2-3
Determine change in aquifer storage using piezometers and temporal gravity surveys	AS	X/E	1-Continuous
Chemically analyze water from observation wells and use environmental tracers	AFS	U	3-4
Compile information to interpret geohydrologic framework north and south of Albuquerque	SFG	U	Continuous
Determine the extent of axial channel deposits and faults, and estimate the hydrologic characteristics of faults	SFG	U	2-3
Estimate recharge along the mountain front	R	U	2-3
Estimate tributary recharge	R	X/U	3-4
Determine evapotranspiration by cottonwoods and riparian communities and relation to water-table depth	E	U	2-3
Conduct flood-pulse experiment to estimate aquifer characteristics in the alluvium	IVA	U	1

Update and Adjust the Albuquerque Basin Ground-Water-Flow Model

The information developed on all of the components of the hydrologic system during the suggested series of studies, as well the information already available, would be used to update the ground-water-flow model of the Albuquerque Basin (Kernodle and others, 1995) and to adjust it to reasonably simulate responses observed in the system. Thus, a better understanding of hydrologic relations between the Rio Grande and the Santa Fe Group aquifer system and a tool for estimating the effects of ground-water withdrawal on the surface-water system would be developed. The model is listed at the beginning of the plan of study because it would be updated periodically throughout the study so that it can help guide data collection during the study, as well as provide the tool to quantify the river/aquifer system.

As noted in table 4, updating the model would be a continuous effort. No study can be proposed that would result in the complete understanding of the river/aquifer system, thus, no ground-water-flow model can be developed that can completely simulate the system. Additional information and understanding of the system will continue into the future, thus the need to periodically update the model.

Expand Observation-Well Network

The observation-well network in the Albuquerque area needs to be expanded. Existing wells would be inventoried and added to the network if they are found to be suitable for measuring hydraulic heads at specific depths in the aquifer. Nested piezometers would be installed in areas where measurements of hydraulic head at different depths in the aquifer are needed (fig. 5) and suitable existing wells are not available. A minimum of three piezometers would be installed at each location--one near the bottom of the production interval of wells in the vicinity, one in the upper half of the production interval, and one near the water table. If it is feasible based on the type of sediment below the production interval, an additional piezometer below the production interval would be installed at selected locations. The lithology of drill cuttings would be described and borehole-geophysical logging would be conducted for the deepest piezometer in each nest to provide information on the characteristics of the aquifer at each piezometer nest. Water samples would be collected from each installed piezometer, and at a minimum, analyzed for specific conductance, temperature, pH, dissolved oxygen, alkalinity, dissolved major and minor chemical constituents, trace elements, and radiochemicals as described in the "Chemically Analyze Water from Observation Wells and Use Environmental Tracers" study element. In addition, it would be useful to analyze for environmental tracers, also described in that section.

The observation-well network would be reviewed every 2 to 3 years. Additional observation wells would be added to monitor hydraulic heads in areas to which the influence of ground-water withdrawals is extending.

Install Piezometers below the Rio Grande

Three nests of four piezometers would be installed directly below the Rio Grande to monitor vertical hydraulic gradients below the river and river stage would be monitored at the piezometer-nest sites. In addition, ground-water temperature with depth in the deepest piezometer in each nest would be measured to apply the temperature profile method for estimating vertical flow velocity of water moving between the river and the aquifer (see "Analyze temperature profiles in piezometers below the Rio Grande" study element). Because the temperature-profile method is experimental, three nests are suggested so that some of the variation in ground-water flow below the river can be measured and comparisons can be made between sites to determine the consistency of the calculated rates, given the vertical hydraulic gradients at each site.

One piezometer in each nest would be located directly below the riverbed (within the upper 10 feet of alluvium), one near the mid-depth of the alluvium, one in the alluvium near its base (approximately 80 feet below the riverbed), and one in the Santa Fe Group below the alluvium. The actual depths of piezometers would be based on the type (clay, silt, sand, and gravel) and depth distributions of the sediment penetrated. Because river-stage measurements are necessary, locations near the Rio Grande streamflow gages would be considered for placement of the piezometer nests. However, installation of piezometers below the river is a complicated process, requiring access onto the river, and other locations may be more suitable. In that case, a mechanism for monitoring river stage would also be installed.

Two piezometer nests exist adjacent to the Rio Grande near streamflow gages (fig. 4). If these sites are not suitable for a nest of four piezometers, a single piezometer would be added just below the riverbed near each of these locations. This would add the needed information for determining vertical gradients between the river, just below the river bed, and in the alluvium and Santa Fe Group. However, because the existing piezometers are to the side of the river, the measured temperature profile would be affected by a significant horizontal component of flow. This would violate the assumption of vertical flow needed to apply the temperature-profile method.

Monitor Observation-Well Network

Monitoring of observation wells would be continuous, and the frequency of measurements would depend on the particular situation of each well. For example, wells that are not dedicated piezometers, particularly production wells screened over a relatively large interval of the aquifer, are useful for documenting long-term trends in water-level changes. They would be monitored on a frequency ranging from monthly to semiannually (summer, when pumping is greatest, and winter, when pumping is smallest). Selected piezometers, including those to be drilled for measuring hydraulic heads at specific depths in the aquifer, would be monitored continuously (and recorded in intervals ranging from less than 1 minute to daily, depending on the situation) through the use of pressure transducers and data recorders. Water-level measurements in all wells and piezometers in the network, along with completion information, would be stored in the National Water Information System (NWIS) digital data base (Dempster, 1990; Mathey, 1990).

Compile and Automate Ground-Water Withdrawal Data

All measurements of ground-water withdrawal from all production wells other than private domestic wells in the Albuquerque area would be compiled and entered into a computerized data base along with well identification and well location. The accuracy and completeness of the data base would be maintained. Withdrawals for large production wells (wells producing more than about 100 acre-feet per year) would be accurately measured and the records maintained on at least a monthly basis. Records of withdrawal for other production wells would be maintained on at least an annual basis; if withdrawals have significant seasonal fluctuations, records would be maintained on a more frequent basis.

Although not essential, it would be useful for users of large volumes of ground water, such as Albuquerque, Rio Rancho, and Kirtland Air Force Base, to archive digital data records containing daily pumpage by well. If detailed analysis is needed for a particular area of the aquifer and hydraulic heads measured in nearby piezometers are available, these digital records would then be available for use in a ground-water-flow model for detailed analysis of part of the aquifer system.

Determine Production Zones within Large-Capacity Production Wells

Large-capacity production wells that have long screened intervals would be logged with a flow meter to determine the distribution of water production along the length of the screens. This requires pulling the well pumps and inserting flow-metering equipment, down-hole cameras, and special pumping equipment, and would be done on existing wells when pumps are removed for reconditioning and on new wells prior to being put into production. This information would be used in conjunction with ground-water-withdrawal records to vertically distribute the withdrawal for use in the ground-water-flow model.

Monitor the Rio Grande, Canal, and Drain Flows

The five existing streamflow gages would operate continuously. River stage and discharge would be stored in the NWIS (Dempster, 1990) digital data base at 15-minute intervals.

Canal and drain flow at sections near the gages near Alameda (08329928; fig. 4) and at Rio Bravo Bridge near Albuquerque (08330150; fig. 4) was measured monthly from August 1989 to February 1995 (Thorn, 1995). Flow in canals and drains at the Rio Grande at Albuquerque gage (08330000) was not measured because the difference in flow between that gage and the two other gages (08329928 and 08330150) was not large enough to calculate gains or losses. The calculated summer and winter losses in flow between the two gages in the entire surface-water system highly correlates with the calculated losses in flow in the Rio Grande channel (Jack Veenhuis, Hydrologist, U.S. Geological Survey, oral commun., 1995). Therefore, canal and drain flow measurements have been discontinued, and river flow at the two gages is used to estimate average loss or gain from the surface-water system in that reach of the inner valley.

Canal and drain flow at sections across the inner valley at the two new gages (08329500 and 08331000) would be measured to calculate total flow of the Rio Grande surface-water system into and out of the Albuquerque area. These measurements would be made monthly for at least 3 years. If, after 3 years, a high correlation is obtained between calculated summer and winter losses in flow in the entire surface-water system and calculated losses in flow in the Rio Grande channel, the monthly measurements of canals and drains can be discontinued.

Because flow loss in the canal system is closely tied to irrigation in the inner valley, significant changes in the distribution of irrigated cropland or the canal system may invalidate the relations between gain or loss in the surface-water system and gain or loss in the Rio Grande channel. If significant changes are identified (see "Update inventories of land cover and Rio Grande surface-water system" study element), measurements of canal and drain flow at sections near the gages (08329500, 08329928, 08330150, and 08331000) would be resumed.

Average seasonal (summer and winter) gains or losses of the surface-water system would be calculated for the inner reach of the system (between gaging stations 08330000 and 08330150) and for the overall Albuquerque area (between gaging stations 08329500 and 08331000). These seasonal gains or losses would be calculated on the basis of average seasonal flows at the sections near the gaging stations, excluding measurements that include storm-water runoff. Measurements of diversions to and returns from the canal and drain system by the MRGCD would then be used to separate seepage in the river from seepage in the canal and drain system. This calculated seepage would then be compared with seepage calculated using the ground-water-flow model of the Albuquerque Basin and used as a basis for adjusting the model.

Define Canal and Drain Physical Characteristics

Information would be collected on the physical characteristics of canals and drains, including bottom elevations, cross-sectional dimensions, operating stage, location of lined and unlined canal segments, and average time noncontinuously operated ditches contain water. Cross sections of canals and drains, including design dimensions, design-flow capacities, and design slope, are available from files of the MRGCD and would be compiled. MRGCD personnel familiar with canal-system operation would be interviewed to identify ditches that are abandoned or not operated continuously during the irrigation season and the average frequency and pattern of operation. A reconnaissance survey of the canal and drain system would be done to spot-check dimensions, operating stage, and bottom elevations and to identify lined canal segments. Effective canal- and drain-bed thicknesses and sediment textures would be checked by hand augering and describing the material encountered in selected canal and drain beds. Land-surface and drain-bottom elevations and water-level altitudes measured in shallow observation wells in the inner valley would be compared to identify areas where the water table is below the interior drain bottoms. All of this information would be combined with the GIS coverages of the canal and drain system compiled by the Bureau of Reclamation (1992 digital data) and used to update the ground-water-flow model of the Albuquerque area.

Conduct and Analyze Aquifer Tests

Aquifer tests would be conducted and analyzed to estimate vertical and horizontal hydraulic conductivity in the aquifer system. In addition, tests done in the vicinity of the Rio Grande would be analyzed to estimate riverbed hydraulic conductance and seepage from the river as a result of well pumping. Few large-scale aquifer tests have been conducted in the Albuquerque area from which these values can be estimated.

A large-scale aquifer test was recently (1995) conducted using the City of Albuquerque Griegos 1 production well as the pumping well (fig. 5). Water levels were monitored in 19 piezometers during the 2-month pumping (at 2,300 gallons per minute) and 1-month recovery period of the test. The aquifer test is currently (1995) being analyzed with conventional curve-matching techniques and ground-water-flow modeling analysis using trial-and-error calibration. The curve-matching techniques can provide estimates of average aquifer transmissivity and vertical and horizontal hydraulic conductivity but cannot provide estimates of riverbed hydraulic conductance or the amount of seepage from the river resulting from pumping during the aquifer test. Model analysis of the test can provide estimates of aquifer transmissivity, vertical and horizontal hydraulic conductivity, riverbed hydraulic conductance, and amount of seepage from the river. However, trial-and-error calibration is limited in that (1) whether another set of estimated hydraulic characteristics would better satisfy the calibration criteria is unknown; (2) determining if some of the characteristics are highly correlated, which would not allow those characteristics to be uniquely estimated is difficult; and (3) the reliability of an estimate of a characteristic can only be qualitatively evaluated by manually changing hydraulic-characteristic values in the model and determining the sensitivity of the simulated results to those changes.

A nonlinear regression technique would be used to estimate values of aquifer transmissivity, vertical and horizontal hydraulic conductivity, riverbed hydraulic conductance, and amount of seepage from the river in the vicinity of the aquifer test. The nonlinear regression technique (Cooley and Naff, 1990; Hill, 1992) is used to (1) estimate values of hydraulic characteristics that produce the minimum value of an objective function, which is defined on the basis of the ground-water-flow model calibration criteria; and (2) quantitatively determine model reliability through statistics. This technique has been incorporated into the USGS modular finite-difference ground-water-flow model, MODFLOW (McDonald and Harbaugh,

1988) to create MODFLOWP (Hill, 1992). The MODFLOWP model would be used for this analysis. An example application of this model is given by Yager (1993). The results of this analysis would then be used to update the ground-water-flow model of the Albuquerque Basin.

Piezometers installed below the Rio Grande (see "Install piezometers below the Rio Grande" study element) may be used in additional aquifer tests to further evaluate the vertical hydraulic conductivity below the river, riverbed hydraulic conductance and seepage from the river. One of the piezometer nests below the river would be located near a large-capacity production well. One location that would be considered is near the Duranes well field (fig. 5) because three of the Duranes wells are directly adjacent to the Rio Grande. Once the piezometers are installed, hydraulic head in the piezometers, stage in the river, and production from nearby wells would be monitored, evaluated and used in designing an aquifer test. The production information would include determination of the production zones within the production wells (see "Determine production zones within large-capacity production wells" study element). The aquifer test would be designed after evaluation of the preliminary data, but could be an analysis of the normal operation of nearby production wells or an analysis of prescribe pumping of one or more nearby wells. The test would be analyzed using a ground-water-flow model. The type of model analysis (trial-and-error calibration or nonlinear regression) would be determined based on the experience gained in the model analyses of the Griegos well test.

The addition of piezometers described in the "Expand observation-well network" study element would provide the opportunity to monitor hydraulic head at the water table, two intervals in the aquifer-production zone, and possibly an interval below the production zone. The purpose of these piezometers is to monitor hydraulic heads in the aquifer system that represent aquifer responses to regional stresses in the aquifer system, rather than responses from a single pumping well. Therefore, an aquifer test using these piezometers along with a single pumping well may not be practical in most cases. However, the hydraulic heads measured in the piezometers, records of daily well pumpage in large production wells (see "Compile and automate ground-water withdrawal data" study element), and information on the production zones within the wells (see "Determine production zones within large-capacity production wells" study element) may be used in a ground-water-flow model analysis of a multiple-pumping-well aquifer test. The practicality of such an analysis would be evaluated after the piezometers are installed and sufficient data for evaluation have been collected.

Aquifer tests would be conducted and analyzed to estimate vertical and horizontal hydraulic conductivity of the inner valley alluvium. There are several shallow observation wells and piezometer nests in the inner valley (fig. 4). Records of these wells along with records of nearby shallow production wells would be reviewed and evaluated for use in aquifer tests. Some of the piezometer nests contain more than one piezometer in the alluvium (completed at various depths), which can be used in aquifer tests designed to estimate vertical as well as horizontal hydraulic conductivity within the alluvium. Aquifer tests would be conducted at about 3 to 5 locations. The necessity for more tests would be evaluated based on the results of these tests. Lithologic logs of the material encountered in the wells would be used in conjunction with the calculated hydraulic characteristics to help estimate hydraulic characteristics in other parts of the alluvium based on the distribution of lithologies (see "Determine distribution of lithologies in the inner valley alluvium" study element).

Update Inventories of Land Cover and Rio Grande Surface-Water System

Digital data containing relatively current distributions of riparian vegetation and wetlands (National Biological Service 1989 digital data), irrigated cropland, canals, and drains (Bureau of Reclamation 1992 digital data) are available. Because several components of the surface- and ground-water system are dependent on the distribution of these features, these digital data bases would be updated on approximately a 10-year interval. This update would include information on canal and drain physical characteristics.

Determine Distribution of Lithologies in the Inner Valley Alluvium

Available logs for wells in the inner valley would be compiled and analyzed to determine the distribution of sediment of different lithologic types in the inner valley alluvium. Because low-conductivity deposits tend to control vertical hydraulic conductivity, the distribution of clay or silty-clay lenses in the alluvium is of particular interest. As noted previously, an extensive silty-clay layer has been mapped based on about 470 borehole logs at a Super Fund site in the Albuquerque South Valley (Jacobs Engineering Group, 1995). Although this map does not extend to other areas of the inner valley, drillers' logs are available from files of the New Mexico State Engineer Office (Albuquerque), and lithologic and geophysical logs are available from files of the USGS (Albuquerque). Files from other agencies, such as the New Mexico Environment Department, would also be checked for availability of logs.

Surface electromagnetic surveys would be done in areas where well logs are not available. In an electromagnetic sounding, current is induced into the ground by generating a magnetic field; the current in the ground produces a secondary magnetic field. The intensity of the secondary magnetic field, which is measured in a receiver, provides information on the resistivity in the ground (Fitterman and Stewart, 1986). The depth of penetration can be controlled by the particular electromagnetic system selected and the way a sounding is set up. The system used for this study element would penetrate to approximately the depth of the alluvium, an average of about 80 feet. This assumes that with consistent aquifer material, differences in resistivity may be attributed to differences in water quality. Conversely, with consistent water quality, differences in resistivity may be attributed to differences in aquifer material. Therefore, the consistency of water quality would be evaluated to indicate whether resistivity differences can be attributed to water quality rather than lithology. In addition, borehole electromagnetic soundings would be done in boreholes where the lithology is known for comparison with the surface electromagnetic soundings. Examples of electromagnetic techniques applied to ground-water problems are described by Fitterman (1986) and Fitterman and Stewart (1986).

Monitor Extensometer and Geodetic Network

C. E. Heywood (written commun., 1994) has installed an extensometer to measure aquifer compressibility and established a geodetic network to detect aquifer compaction. The extensometer, which extends to a depth of 1,036 feet below land surface, is installed next to four piezometers ranging from 177 to 983 feet below land surface (fig. 4, site A). Calculations of aquifer compressibility are made based on continuous measurements of change in aquifer thickness in relation to changes in hydraulic head (pore pressure) in the piezometers. Aquifer compressibility is then used to calculate storage characteristics of the aquifer. Extensometer and piezometer monitoring would be continued to provide information on changes in the elastic and inelastic storage characteristics of the aquifer. The geodetic network, first measured in March 1993, was established to detect changes in land-surface elevation in the Albuquerque area that may result from inelastic aquifer compaction. Because detectable changes in land-surface elevation (about 2 centimeters) will probably not occur over a short time period, measurements would be repeated at approximately a 5-year interval. As hydraulic heads in the aquifer system continue to decline, inelastic compaction may become more pronounced, emphasizing the need to continue monitoring the extensometer and geodetic network.

Analyze Temperature Profiles in Piezometers below the Rio Grande

Profiles of ground-water temperature with depth below a river can be used to calculate the rate of vertical movement of ground water between the river and the aquifer (Stallman, 1963, 1965; Sorey, 1971; Lapham, 1989). This is based on the principles that river temperature varies seasonally (or diurnally), ground-water temperature is constant at some depth, and movement of water between the river and the aquifer affects the vertical distribution of ground-water temperature. It must be assumed that ground-water flow is vertical and is constant with time and depth below the river. By making measurements of hydraulic heads at various depths below the river, the rate of vertical flow can be used to estimate the vertical hydraulic conductivity. An example of the application of the temperature-profile method is given by Lapham (1989).

River stage, river temperature, hydraulic heads in piezometers, and the profile of ground-water temperature with depth (in the deepest piezometer of each nest) would be measured monthly at each of the piezometer nests installed below the Rio Grande (see "Install piezometers below Rio Grande" study element). At least 1 year of monthly measurements must be collected to analyze the data using seasonal temperature fluctuations. Diurnal temperature fluctuations would be checked to determine if they are large enough for analysis. If so, a series of daily measurements would be collected at each nest for analysis.

As noted by Lapham (1989, p. 31), values of vertical flow velocity and vertical hydraulic conductivity calculated by the temperature-profile method are specific to a point in the river reach. More than one piezometer nest would be used because vertical flow likely varies along the Rio Grande in the Albuquerque area. Because this method is experimental, three nests are suggested. Analyses for three nests would provide comparisons to determine if calculated flow rates at each site are consistent with those at other sites, considering the vertical hydraulic gradients at each site. If the method proves to be successful, it could then be applied to other locations.

Channel permeameters, such as those used by the Bureau of Reclamation (1994c) would be used at the piezometer sites in conjunction with the temperature-profile method to compare results. The Bureau of Reclamation suggested that the procedures used in their 1994 study be modified because of inconclusive results. One such modification may be to drive the permeameters into the first clay or silt layer in the riverbed to minimize the possibility of water moving through permeable channel sediments between the permeameter and the river.

Determine Change in Aquifer Storage using Piezometers and Temporal Gravity Surveys

Temporal gravity surveys would be conducted in the Albuquerque area to determine changes in storage of water within the aquifer. With no mass changes at the land surface, such as the erection of a large building, changes in the gravitational pull of the earth at a point on the surface can be interpreted to represent the change in mass due to the removal of water from the aquifer. By repeating gravity measurements at specified points, the change in aquifer storage below those points can be calculated. Gravity methods were described by Hinze (1990).

This method is considered experimental because of the potential for interference in the gravity measurements from activities in the mostly urban Albuquerque environment. In addition to changes that can occur over time (such as construction of buildings), automobile traffic and particularly heavy truck traffic can interfere with the measurements. Care would be taken to minimize this interference. Taking measurements during times of minimal traffic, such as late at night or very early in the morning, would be considered for areas where traffic may interfere.

Gravity measurements would be made on approximately a 2-mile spacing throughout the Albuquerque area so that change in aquifer storage in the entire area can be calculated. The water table was projected by Kernodle and others (1995, p. 90-93) to decline throughout the Albuquerque area from 1994 to 2020 with even the smallest amount of projected ground-water withdrawal. Gravity measurements would be done specifically at locations where piezometers monitor the water table to help determine the reliability of the gravity measurements and to calculate specific yield. Gravity measurements would be made near the end of winter when ground-water withdrawal is at a minimum and near the end of summer when ground-water withdrawal is at a maximum. The winter measurements would provide the most stable ground-water levels for comparison of long-term changes in aquifer storage. The differences between the winter and summer measurements may provide a more immediate check on the reliability of the gravity measurements. Seasonal changes and long-term changes in aquifer storage would provide a basis for comparison and adjustment of the ground-water-flow model.

The gravity surveys would be done seasonally for at least the first year and, if successful, would be continued. Winter measurements would be repeated the second year, even if the seasonal measurements are not considered successful. Continuation of the gravity surveys and the repeat interval would be determined on the basis of information obtained during this first series of surveys.

Chemically Analyze Water from Observation Wells and Use Environmental Tracers

Water chemistry of ground water provides information on possible recharge sources and possible pathways of water through the aquifer. Certain chemical constituents in ground water can be used as environmental tracers. Some environmental tracers may be used to age-date ground water; others may be used to help identify possible aquifer recharge sources. As discussed in the "Previous investigations" section, several ground-water-quality and geochemical studies have been done in the Albuquerque area (Hiss and others, 1975; Yapp, 1985; Anderholm, 1987, 1988; Logan, 1990). Many of the analyzed ground-water samples were collected from production wells that are screened over large intervals of the aquifer; therefore, they represent a composite of water from a large vertical section of the aquifer. The addition of the proposed piezometer nests provides the opportunity to sample ground water from specific depths of the aquifer in areas where only composite samples previously have been analyzed. These samples from the additional piezometer nests, along with those from existing piezometers, may provide a better understanding of the aquifer flow system.

The general chemistry of water would be determined from each piezometer installed as part of the observation-well network expansion. Records of existing piezometers in the Albuquerque area would be reviewed and samples collected from those that have not previously been sampled for chemical analysis. Specific conductance, temperature, pH, dissolved oxygen, and alkalinity would be measured on site for water samples from each piezometer. Each water sample would be analyzed for the dissolved major and minor chemical constituents, trace elements, and radiochemicals listed on the following page.

Major and minor constituents	Trace elements	Radiochemicals
Hardness	Arsenic (As)	Radium (Ra)
Total dissolved solids	Barium (Ba)	Radon (Rn)
Calcium (Ca)	Cadmium (Cd)	Uranium (U)
Magnesium (Mg)	Chromium (Cr)	
Sodium (Na)	Copper (Cu)	
Potassium (K)	Lead (Pb)	
Bicarbonate (HCO_3)	Mercury (Hg)	
Carbonate (CO_3)	Selenium (Se)	
Sulfate (SO_4)	Silver (Ag)	
Chloride (Cl)	Zinc (Zn)	
Fluoride (F)		
Silica (SiO_2)		
Boron (B)		
Bromide (Br)		
Iron (Fe)		
Manganese (Mn)		
Organic carbon		

Deuterium (^2H) and oxygen-18 (^{18}O) are naturally occurring stable isotopes that are present in some water molecules. Because water molecules containing one or more of these isotopes are heavier than the standard water molecule, they tend to be less concentrated in water vapor than in source water and more concentrated in condensed water than in source water vapor. Therefore, the isotopic composition of water will vary depending on the climatic conditions in which water in the atmosphere has evolved and subsequently fallen as precipitation. The ratios of deuterium to hydrogen and of oxygen-18 to oxygen-16 measured in ground water can, therefore, be used to indicate the possible recharge source of ground water if more than one recharge source exists and the source waters have distinguishable isotopic compositions. Yapp (1985) used deuterium and Logan (1990) used deuterium and oxygen-18 in studying possible recharge pathways in the Albuquerque area. Most of the water samples collected for analysis in those studies were from City of Albuquerque production wells that are screened over large intervals. A few piezometers in the Albuquerque area have been sampled and analyzed for deuterium or oxygen-18 (Logan, 1990, p. 270; Norman Gaume, City of Albuquerque, written commun., August 1995). As suggested for the analysis of general water chemistry, water samples from available piezometers in the Albuquerque area would be analyzed for ratios of deuterium/hydrogen and oxygen-18/oxygen-16. These analyses of water from piezometers could provide information to help determine if water at different levels in the aquifer may have come from different recharge sources and if so, what those probable sources are.

Chlorofluorocarbons (CFC's) can be used as environmental tracers in ground water (Busenberg and Plummer, 1992). CFC's are stable, synthetic compounds used as aerosol propellants, refrigerants, and solvents. Detectable concentrations of CFC's in ground water indicate that at least a portion of the water recharged the aquifer after 1940. In addition, specific CFC compounds were manufactured during different time periods; their presence in ground water, therefore, can further distinguish recharge time frames. The presence of dichlorodifluoromethane (CFC-12) indicates that a portion of the water recharged the aquifer after about 1940, trichlorodifluoromethane (CFC-11) after about 1947, and trichlorotrifluoroethane (CFC-113) after about 1965 (L.N. Plummer and others, USGS, written commun., September 1995).

Tritium (^3H), a radioactive isotope of hydrogen with a half life of about 12.3 years (Hem, 1985, p. 150), is also useful as an environmental tracer in ground water. Although naturally occurring in the atmosphere, the concentration of tritium greatly increased with atmospheric nuclear-weapons testing. Busenberg and Plummer (1992, p. 2281) emphasized the usefulness of tritium concentrations in confirming or identifying inconsistencies in the dating of ground water using CFC's.

The shallow piezometers (depths less than about 150 feet below the water table) in the Albuquerque area (shown in fig. 4) and additional shallow piezometers that are installed (see "Hydraulic heads" section and fig. 5) would be sampled for determining concentrations of CFC-12, CFC-11, CFC-113, and tritium. If CFC's or tritium are not detected in water from the piezometers at approximately 150 feet below the water table, they would not be expected at greater depths. However, if they are detected in the 150 foot piezometers, deeper piezometers would be sampled. The CFC and tritium analyses would provide information on the time that the water entered the aquifer. If CFC and tritium analyses are used in conjunction with hydraulic-head and other water-chemistry information, probable flow paths and recharge sources of the water may be identified. Average flow velocities and hydraulic conductivity along flow paths may then be calculated.

Carbon-14 (^{14}C) is a naturally occurring radioactive isotope with a half life of 5,730 years (Hem, 1985, p. 151). Because of its relatively long half life, ^{14}C can be used to date water that recharged the aquifer from one or two thousand to a few tens of thousands of years ago. However, the exchange of carbon between ground water and the aquifer material and the mixing of water of different ages can significantly alter the indicated age. Therefore, the possible geochemical reactions that may have occurred along the flow path and possible mixing of water would be considered in evaluating the indicated ages. Seven piezometers in the inner Rio Grande Valley ranging in depth from about 68 to 980 feet below land surface have been sampled for analysis of ^{14}C (S.K. Anderholm, Hydrologist, U.S. Geological Survey, oral commun., August 1995; see sites A and B in fig. 4). All piezometers in the piezometer nests outside of the inner Rio Grande Valley (including the suggested additional nests that may be installed) and the piezometers (other than those already sampled) within the inner valley (fig. 4) deeper than about 150 feet below the water table would be sampled and analyzed for ^{14}C. Because ^{14}C can be used only to detect water older than one or two thousand years and mixing of water can alter the indicated age, it is not suggested that shallow piezometers in the inner valley be initially sampled for ^{14}C. If CFC and tritium analyses indicate that no recent water is present in an area of the shallow system, water may be upwelling from the deeper system and shallow wells would be sampled for ^{14}C in that area. The ^{14}C analyses would provide information on the time since the older water in the aquifer recharged. If analyses of ^{14}C are used in conjunction with hydraulic-head and other water-chemistry information, probable flow paths and recharge sources of the water may be identified. If flow paths can be identified, average flow velocities and hydraulic conductivity along the flow paths may then be calculated. Examples of the use of ^{14}C in studies of ground water are given by Winograd and Pearson (1976), Plummer (1977), and Back and others (1983).

Studying the ground-water chemistry of the Albuquerque area would help conceptualize the ground-water-flow system. Sampling the additional piezometers installed, as well as the existing piezometers, would add a third dimension to the knowledge of water chemistry of the aquifer, where in some areas, only vertically averaged samples were previously available. This information can be used to update and adjust the ground-water-flow model of the Albuquerque Basin, and the flow model can be used to help identify possible flow paths to compare to ground-water-chemistry data.

Compile Information to Interpret the Geohydrologic Framework North and South of Albuquerque

The division of Santa Fe Group sediments in the Albuquerque area into hydrostratigraphic (table 1) and lithofacies units (table 2) by Hawley and Haase (1992) and Hawley and others (in press) was based to a large extent on borehole cuttings, cores, lithologic logs, and geophysical logs. It is useful to continue collecting and compiling this type of information for wells as they are drilled throughout the Albuquerque Basin. As the effects from ground-water withdrawal continue to propagate beyond the Albuquerque area, the hydraulic characteristics of deposits in other parts of the basin will become more significant in the hydrologic interaction of the aquifer and surface-water system in the Albuquerque area. This information can provide a basis for interpreting the hydrostratigraphic and lithofacies units, which can then be used to estimate hydrologic characteristics.

Determine the Extent of Axial Channel Deposits and Faults, and Estimate the Hydrologic Characteristics of Faults

As described previously, the extent of permeable channel sediments deposited by the ancestral Rio Grande and the extent of faults north and south of Albuquerque are not well known. Ancestral Rio Grande channel deposits may provide a preferential path for movement of water in the Santa Fe Group and therefore, have an effect on ground- and surface-water interaction in the Albuquerque area. Faults can be barriers to ground-water flow, which also have an effect on ground- and surface-water interaction. Determining the extent of these features north and south of Albuquerque is useful. In addition to locating faults, the hydrologic characteristics of the faults would be estimated.

Patterson and Bosschart (1987) described the advantages of using airborne electromagnetic and magnetic measurements for evaluation of ground-water resources. Airborne measurements allow many measurements over a larger area in less time compared with ground-based measurements. The basis for electromagnetic soundings is the same as that described for another study element ("Determine distribution of lithologies in the inner valley alluvium"), although the targeted depth would be deeper. Electromagnetic soundings are useful for detecting lithologic differences in the aquifer, such as between the permeable ancestral Rio Grande channel deposits and less permeable adjacent deposits. Electromagnetic soundings are also useful for detecting faults based on lithologic differences, which are common across faults. The basis for the magnetic measurements is to detect variations in the earth's magnetic field caused by anomalies in the subsurface. Patterson and Bosschart (1987) suggest that airborne magnetic measurements be made along with electromagnetic measurements to help in the interpretation. Magnetic measurements are useful for detecting zones of weakness or stress, such as faults, and zones of deposits from different source rocks having different magnetic characteristics (Patterson and Bosschart, 1987; Hinze, 1990).

Airborne surveys, to make electromagnetic and magnetic measurements, would be done north and south of Albuquerque and east of the Rio Grande to help identify the extent of the ancestral Rio Grande channel deposits and faults in these areas. Cultural noise, such as electromagnetic fields induced by power lines, can interfere with the measurements. Therefore, the surveys would be done in areas where their influence is minimized. Suggested locations for these surveys are near the Bernalillo-Sandoval County line north of Albuquerque and the Isleta Indian Reservation boundary south of Albuquerque. If these surveys provide the information expected, they would be used to provide similar information in other areas of the basin.

The hydrologic characteristics of faults would be estimated. Haneberg (1995a) describes a method by which the relative vertically-averaged transmissivities of a fault zone and the aquifer on either side of the fault zone can be calculated based on the steady-state hydraulic gradients on either side of the fault. The method is a one-dimensional analysis of horizontal flow across a vertical fault zone based on continuity of hydraulic head and flux. Where estimates of the fault zone thickness and one of the transmissivities are available, the other two values of transmissivity may be calculated. This methods is applicable in areas where hydraulic gradients that have not been significantly influenced by ground-water development can be calculated. In areas where ground-water development is significant and predevelopment steady-state hydraulic gradients cannot be calculated, the hydrologic characteristics of faults may be estimated based on analysis of ground-water withdrawals and the resulting changes in hydraulic head in different parts of the aquifer system. Where ground-water withdrawal occurs at various locations in an aquifer system, as in the Albuquerque area, a ground-water-flow model could be used for this analysis. To analyze the withdrawal and response of hydraulic heads in the aquifer system, accurate data on the location and amount of ground-water withdrawal, and accurate measurements of hydraulic head at several points in the aquifer system are necessary. The "Expand observation-well network," "Monitor observation-well network," "Compile and automate ground-water withdrawal data," and "Determine production zones within large-capacity production wells" study elements described previously would provide much of this needed information. Both of the methods described above would be used to estimate the hydrologic characteristics of faults, which would provide information for updating and adjusting the ground-water-flow model of the Albuquerque Basin.

Estimate Recharge along the Mountain Front

Estimated mountain-front recharge in the Albuquerque area, which occurs along the Sandia Mountains (fig. 2), is useful. Methods of estimating mountain-front recharge, such as chloride mass balance (Anderholm, 1994, p. 29-32) and water balance (Wasiolek, 1995, p. 21-22), must be used with acceptance of a considerable potential for error. Therefore, application of one method alone may not provide enough information to estimate a range of possible values. Six estimates of mountain-front recharge in the Española Basin (fig. 2) were compared by Anderholm (1994, p. 37, 67). The chloride mass balance method used by Anderholm (1994) resulted in recharge values in the lower range of the six estimates; the water-balance method used by Wasiolek (1995) resulted in recharge values in the upper range of the six estimates. These two methods would be used in the Albuquerque area to provide a plausible range of mountain-front recharge.

The chloride mass-balance method is based on the conservation of the mass of chloride in water moving through a watershed. The mass of chloride brought into the watershed by precipitation equals the mass of chloride transported into the aquifer by recharge water, minus the mass of chloride transported beyond the mountain front by surface runoff:

$$\begin{array}{c}\text{(average chloride}\\ \text{concentration in}\\ \text{precipitation)}\\ \times\\ \text{(precipitation volume)}\end{array} = \begin{array}{c}\text{(average chloride}\\ \text{concentration in ground water}\\ \text{near the mountain front)}\\ \times\\ \text{(recharge volume)}\end{array} - \begin{array}{c}\text{(average chloride}\\ \text{concentration in surface runoff}\\ \times\\ \text{(runoff volume)}\end{array}$$

All values except recharge volume are estimated; recharge volume is then solved from the equation. Historical data would be reviewed for information on chloride concentrations and on precipitation and runoff in the mountain watersheds. Some additional data collection may be necessary.

As described by Anderholm (1994, p. 31), this technique requires that several assumptions be made: "(1) the only source of chloride in ground water is from precipitation, (2) the chloride concentration in precipitation and rate of precipitation have not changed with respect to time, (3) direct recharge and arroyo-channel recharge have not affected chloride concentrations in ground water, and (4) chloride is conservative (chemically nonreactive) and there is no change in the storage of chloride in the system." Anderholm (1994) pointed out that potential sources of chloride other than precipitation are septic-tank effluent and salting of roads, and the assumption of chloride concentration and rate of precipitation not changing with time is difficult to evaluate. The reader is referred to Anderholm (1994) for more detailed discussions of these assumptions.

The water budget method is based on the conservation of the volume of water moving through a watershed (no change in storage of water in the watershed):

(precipitation volume) = (runoff volume) + (evapotranspiration volume) + (recharge volume)

All values except recharge volume are estimated; recharge volume is then solved from the equation. Historical data would be reviewed for information to estimate precipitation, runoff, and evapotranspiration. The only estimate that would need to be made beyond what is needed for the chloride balance method is evapotranspiration in the mountain watershed. Wasiolek (1995, p. 21-22) stated that the evapotranspiration estimates may have the largest potential for error.

Both methods described above provide estimates of mountain-front recharge based on a residual. The possible error would therefore be evaluated. Because each input value to the equations is estimated and contains possible errors, the errors can compound in the estimate of recharge. Therefore, the estimated values of recharge need to be used with caution and an understanding of the range of possible error.

Estimated values of mountain-front recharge, with consideration of the range of possible errors, would then be used to update and adjust the ground-water-flow model. Recharge (within the plausible range of error) and other model components would be adjusted so that the model reproduces the measured response in the aquifer system and the flow paths and ground-water ages interpreted from water-chemistry data; the recharge estimates of the model can then be refined.

Estimate Tributary Recharge

Estimating tributary recharge in the Albuquerque area is useful. Thomas (1995, p. 21) showed that soil temperature below ephemeral arroyos in the Albuquerque area changed in response to infiltration of warmer or cooler water compared to the ambient ground temperature. C.L Thomas and Jim Constantz (USGS, written commun., June 21, 1995) described a temperature-profile method that would be used to estimate recharge rates below ephemeral arroyos in the Albuquerque area. Unlike the temperature-profile method described for use below the Rio Grande (see "Analyze temperature profiles in piezometers below the Rio Grande"), which is applicable to saturated sediments below a perennial river, the method described by Thomas and Constantz is applicable to unsaturated sediments below ephemeral arroyos. This temperature-profile method uses a series of temperature probes (five or more) installed below an arroyo ranging in depth from near surface to about 26 feet below the arroyo bed (C.L Thomas and Jim Constantz, written commun., June 21, 1995). Percolation of water through this section of sediments is estimated on the basis of measured temperature profiles. Any water percolating below 26 feet is assumed to be below the depth where it could be evapotranspired, and is therefore recharge to the aquifer system.

This study element is considered to be experimental and would be conducted in phases. C.L Thomas and Jim Constantz (written commun., June 21, 1995) suggested that feasibility, method verification, and data collection and interpretation phases be done. During the feasibility phase, arroyos and reaches within the arroyos would be surveyed and evaluated for their suitability for application of the method and for installation of temperature and arroyo-discharge monitoring equipment. During the method verification phase, three sites in one selected reach would be monitored for about 6 months and interpreted. If the first two phases are successful, 3 to 10 arroyo reaches would be instrumented and monitored, and the data interpreted. Estimates of recharge from these arroyo reaches would then be used to update and adjust the ground-water-flow model of the Albuquerque Basin.

Determine Evapotranspiration by Cottonwoods and Riparian Communities and Relation to Water-Table Depth

Determining evapotranspiration rates by cottonwoods in the riparian areas of the Rio Grande inner valley and the relation between evapotranspiration rate and depth to ground water is useful. Similar work using lysimeters has been done for tamarisk and Russian olive in the Albuquerque Basin (Bureau of Reclamation, 1973a). More recent technology is available that allows detection of fluid movement through a tree using heat pulses (J.P. King and T.L. Jones, New Mexico State University, written commun., June 1995), a technique that would be used for this study element.

The heat-pulse method uses a probe inserted into a tree's xylem to apply heat; a second probe, inserted above the first probe, senses the temperature change in the sap. The velocity of sap flow in the xylem can be calculated from the temperature change. Multiple pairs of probes can be inserted around the tree. The total sap flow can be calculated by summing the velocities from each pair times the area of xylem each pair represents (J.P. King and T.L. Jones, written commun., June 1995).

Evapotranspiration by groups of the common trees in a riparian community (cottonwood, tamarisk, and Russian olive) would be calculated in addition to evapotranspiration by individual cottonwood trees. The relation between evapotranspiration rates and depth to ground water and canopy density would be evaluated to make the information transferable to riparian communities throughout the inner valley.

Conduct Flood-Pulse Experiment to Estimate Aquifer Characteristics in the Alluvium

A flood-pulse (a rapid rise and fall of river stage) experiment was conducted on the Rio Grande in the Albuquerque area in spring 1994 (Bureau of Reclamation, 1995). The response of water levels in the aquifer was monitored in piezometers along the east side of the river. The flood pulse and water-level changes were analyzed using localized three-dimensional ground-water-flow models near two river cross sections to estimate the hydrologic characteristics of the alluvium near the river. The results of the test showed that the flood pulse (approximately a 1-

foot increase in river stage) propagated from the river to the riverside drains but was not distinguishable in piezometers beyond the drain (Bureau of Reclamation, 1995, p. 24). Therefore, the alluvium was tested only between the river and the riverside drains (fig. 3).

It would be useful to conduct a similar experiment, using a flood pulse in the riverside drain rather than the river. This would allow propagation of the flood pulse to the alluvium beyond the drain. An opportunity for this experiment may be near gaging station 08329928 (fig. 4). This location has existing piezometers (fig. 4) and a wasteway from the Albuquerque Main Canal to the riverside drain (fig. 3A). Water from the wasteway at times may provide enough increase in stage of the drain to detect the pulse in the piezometers. The possible change in stage could be evaluated to determine if the stage change would be large enough to provide a pulse sufficient for detection in the piezometers. If so, equipment would be installed for conducting the experiment to monitor drain stage and water levels in the piezometers.

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SUPPLEMENTAL INFORMATION

Methods to Improve Understanding of Rio Grande/aquifer Relations in the Albuquerque Basin and to Quantify the Effects of Ground-Water Withdrawals on the River

[Modified from minutes of the workshop on ground-water/surface-water relations in the Albuquerque Basin held in Albuquerque, New Mexico, October 12-14, 1994 (Douglas McAda, written commun., October 22, 1994)]

- Improve three-dimensional ground-water-flow model
- Improve understanding of river/alluvium/ Santa Fe Group connection
  - Aquifer test
  - Drillers' logs
  - Flood pulse
  - Piezometers in the river
  - Drain pulse
- Improve information on vertical hydraulic conductivity in aquifer system
  - Observation well network--fill in gaps and emphasize vertical definition
  - Aquifer test
    - Chemistry changes
    - Spinner tests to identify production zones within pumping well
    - Water chemistry in alluvium
    - Gravity measurements during test
    - Particular attention to vertical hydraulic conductivity between the production zone and the river
  - Temperature profiles in wells
- Identify boundaries from faults and facies changes within the aquifer system
  - Geophysical surveys
  - Aquifer tests
  - Continued interpretation of the geologic framework by Dr. Hawley and others
  - Environmental tracers
- Identify production zones within aquifer system
  - Spinner tests in wells
  - Chemical analyses
- Acquire hydraulic-head data in aquifer system
  - Good water-level monitoring
  - Observation-well network--fill in gaps and emphasize vertical definition
- Define change in storage
  - Observation well network--fill in gaps and emphasize vertical definition
  - Temporal gravity surveys
- Define inflows and outflows
  - Winter inflow/outflow water budgets
    - Streamflow measurements, including drains and canals at cross sections
    - Long-term statistical water balance
  - Drought pulse
  - Ground-water withdrawals
    - Major users are well defined
    - Need better definition of small and intermediate users
  - Evapotranspiration
    - Better definitions of cottonwoods
  - Irrigation seepage
    - Calculation of deep percolation by improving estimates of consumptive use of water by crops
  - Septic-tank seepage
    - Piezometer nests in leach fields