Simulation-Optimization Approach to Management of Ground-Water Resources in the Albuquerque Area, New Mexico, 2006 through 2040

Prepared in cooperation with the
CITY OF ALBUQUERQUE PUBLIC WORKS DEPARTMENT

Scientific Investigations Report 2004-5140

U.S. Department of the Interior
U.S. Geological Survey

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U.S. Department of the Interior
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U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch	2.54	centimeter
foot	0.3048	meter
mile	1.609	kilometer
square mile	2.590	square kilometer
acre-foot	1,233	cubic meter
gallon	3.785	liter
cubic foot per second	0.02832	cubic meter per second

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

SIMULATION-OPTIMIZATION APPROACH TO MANAGEMENT OF GROUND-WATER RESOURCES IN THE ALBUQUERQUE AREA, NEW MEXICO, 2006 THROUGH 2040

By Laura M. Bexfield, Wesley R. Danskin, and Douglas P. McAda

ABSTRACT

In response to continually declining water levels in the Santa Fe Group aquifer system of the Middle Rio Grande Basin, the City of Albuquerque has adopted a water-supply strategy that calls for a transition from the current (2003) complete reliance on ground-water withdrawals to the use of surface-water diversions to meet most city water demand. An integrated system of water-supply lines will allow ground-water withdrawals to supplement surface-water supplies during times of high demand or drought. A simulation-optimization approach was used to investigate how the City of Albuquerque could distribute ground-water withdrawals among its municipal-supply wells for 2006 through 2040 to achieve certain management objectives for the river-aquifer system of the Middle Rio Grande Basin.

The most recent revision of the U.S. Geological Survey ground-water-flow model for the Middle Rio Grande Basin was used to simulate the response of the aquifer system to unit stresses (ground-water withdrawals) applied in each of the 25 well fields operated by the City of Albuquerque for municipal supply. The resultant "response functions" provided important information on the effects of ground-water withdrawals in different locations on the quantity of water depleted from aquifer storage, the quantity of leakage from the Rio Grande and associated ground-water drains, and the magnitude of water-level declines over time. The well fields that caused the smallest depletion of aquifer storage in the simulation model generally also had the largest effect on the river system. Most of these fields are located very close to the Rio Grande, but others located several miles from the river also had a large effect on the river system because the wells are completed in high-conductivity sediments with a good hydraulic connection to the river system. Well fields with the largest effect on aquifer storage and the smallest effect on the river system included fields located farthest from the Rio Grande and fields completed in low-conductivity sediments that allowed only a poor connection with the river system, despite their location within a couple miles of the Rio Grande.

The response functions from the simulation model were incorporated into five optimization models that were designed in a mathematical programming software package and solved with a linear approach. The five models were designed to optimize the annual withdrawal between 2006 and 2040 from each well field to achieve specified objectives. The objectives of all five optimization models were to minimize the effects of ground-water withdrawal on aquifer storage and (or) leakage from the river and drains. All five models also included constraints related to projected annual ground-water demand, annual well field capacity, and annual minimum withdrawal per well. Selected models also included constraints related to maximum allowable water-level decline, maximum blended arsenic concentration, and (or) maximum induced infiltration from the river system.

Results from the optimization models demonstrated that altering the relative distribution of ground-water withdrawal that was used by the City of Albuquerque in 2000 could achieve substantial changes to components of the river-aquifer system over the period of interest. The models that incorporated objectives to minimize use of water from aquifer storage indicated that optimization of ground-water withdrawals over a 34-year period could result in about 242,000 acre-feet greater recovery of water in aquifer storage than the non-optimal distribution—enough water to supply City of Albuquerque customers for about 2 years at year-2000 rates of water demand. Simulated water-level rises as a result of this greater recovery of aquifer storage were as much as 70 feet in parts of Albuquerque between 2000 and 2040. Alternatively, a model that incorporated an objective to minimize leakage of water from the river system indicated that river depletion could be reduced by about 214,000 acre-feet over a 34-year period. Another optimization model was designed to minimize leakage from the river system until the quantity of streamflow that the City of Albuquerque is legally required to contribute to the Rio Grande (to offset the effects of

ground-water withdrawals until that time) had been reduced to zero, and to subsequently minimize use of water from aquifer storage. The model indicated that this "debt" to the Rio Grande could be eliminated after about 9 years by using an optimal withdrawal distribution, which is about 9 years earlier than would be achieved using the year-2000 distribution of ground-water withdrawal. The objectives of this model also could be achieved while keeping water-level declines less than about 2.5 feet per year.

Results of the optimization models were evaluated for their ability to approximate the water budgets and water-level declines produced by the simulation model, as well as for their applicability to a range of river-aquifer conditions. Comparison between optimization calculations and simulation results indicated that all five optimization models provided a reasonable approximation of the river-aquifer system as represented in the ground-water-flow model, despite the nonlinearities inherent in that model. The response functions used in the optimization models, and therefore the results of the optimization models, also were found to be applicable to a reasonable range of river conditions and ground-water withdrawal scenarios. Although the exact solutions to the optimization models would vary with changes in future water demand, the locations of municipal-supply wells, or other factors, the broader implications of model results for the river-aquifer system would remain important to the management of regional water resources. In particular, information learned about the timing and magnitude of effects of ground-water withdrawals in different locations on aquifer storage and on the river system could be applied to multiple management issues in the Middle Rio Grande Basin, and perhaps in other alluvial basins of the Southwestern United States.

INTRODUCTION

In 2003, U.S. Department of the Interior Secretary Gale Norton declared the Middle Rio Grande Basin (MRGB) of central New Mexico (fig. 1) to be an area with a high likelihood of experiencing a water-supply crisis by 2025 (U.S. Department of the Interior, 2003). The surface waters of the Rio Grande, which is the main drainage for the basin, are considered fully appropriated (Bartolino and Cole, 2002). The river system is hydraulically connected to the sediments of the Santa Fe Group aquifer system, from which more than 100,000 acre-feet (acre-ft) of ground water is pumped each year. Because ground-water pumping can affect the river system and New Mexico's obligations to Texas under the Rio Grande Compact, the New Mexico State Engineer established guidelines in 2000 for review of applications for ground-water rights within the Middle Rio Grande Administrative Area (New Mexico Office of the State Engineer, 2003). The stated objectives of these guidelines reflect several of the major management issues within the MRGB, including "to ensure compliance with the Rio Grande Compact, to prevent impairment to existing rights, to limit the rate of decline of groundwater levels so that the life of the aquifer is extended, and to minimize land subsidence" (New Mexico Office of the State Engineer, 2003, p. 1).

The largest current (2003) user of ground water within the MRGB, the City of Albuquerque (COA), has adopted a water-supply strategy that calls for a transition from complete reliance on ground-water withdrawals from about 90 municipal-supply wells to the use of surface-water diversions to meet most city water demand. City managers decided to begin exercising Albuquerque's surface-water rights through direct diversions to attempt to delay or avoid the potential deleterious effects of continuous and large declines in ground-water levels in the major aquifer of the MRGB. This substantial shift in the primary source of water used for Albuquerque municipal supply will have a large effect on the river-aquifer system. Although surface-water diversions are anticipated to meet most city demand, ground-water withdrawals will be needed to supplement surface-water supplies during times of high demand or drought. A study conducted by the U.S. Geological Survey (USGS), in cooperation with the COA Public Works Department, used a ground-water-flow model to estimate the effects of various distributions of city ground-water withdrawals on the water budget and water levels of the aquifer. Simulation-optimization techniques were then used to determine the ground-water withdrawal distributions that could best achieve certain management objectives for the river-aquifer system of the MRGB. Many of the conclusions from this study also are likely to apply to other alluvial basins of the Southwestern United States with similar hydrologic regimes and water-management issues.

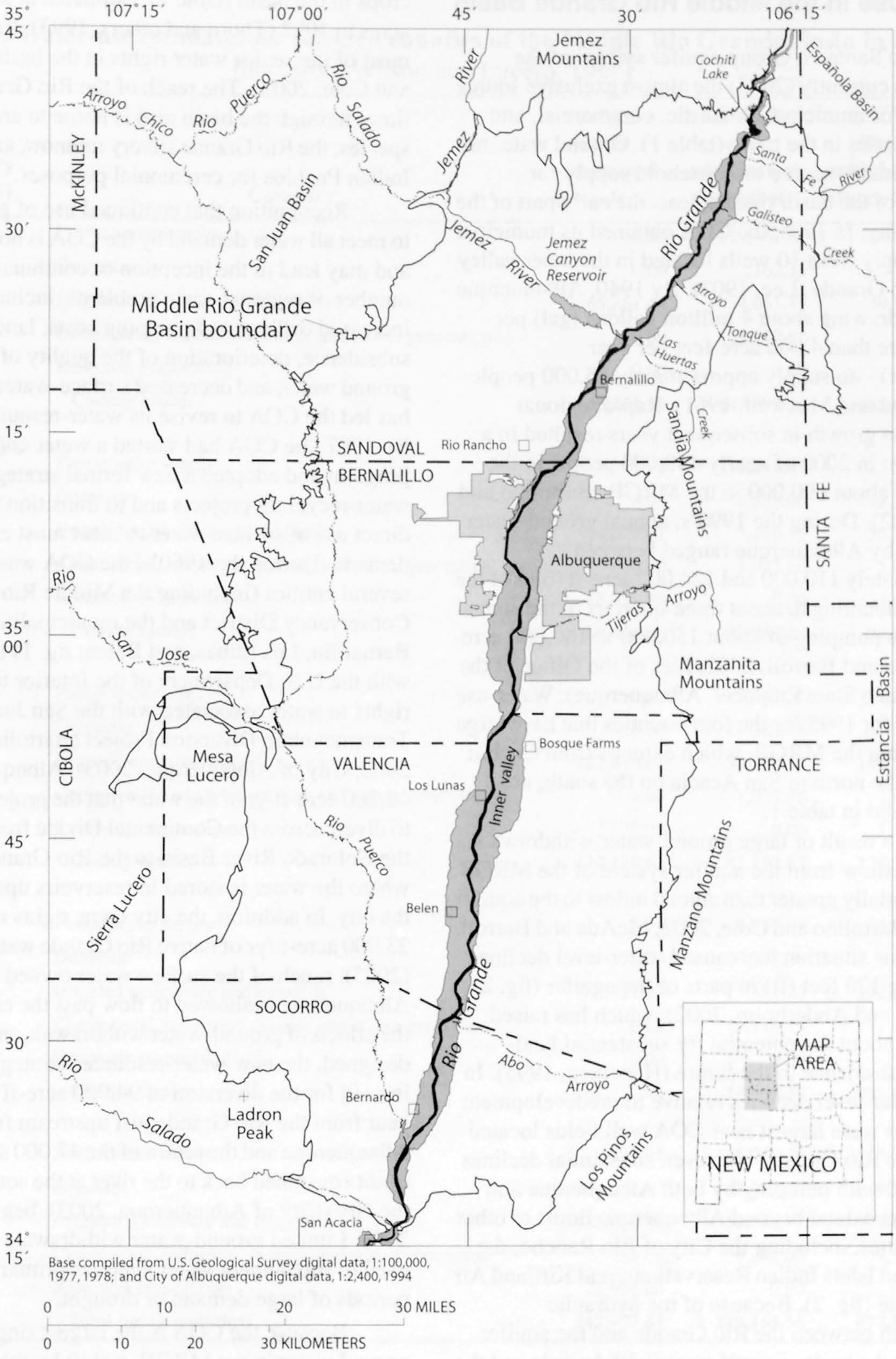


Figure 1. Selected features of the Middle Rio Grande Basin, central New Mexico.

Water Use in the Middle Rio Grande Basin

The Santa Fe Group aquifer system of the MRGB is currently (2003) the almost exclusive source of water for municipal, domestic, commercial, and industrial uses in the basin (table 1). Ground water has been a primary source of household supply for residents of the basin since at least the early part of the 20th century. In 1905, the COA obtained its municipal water supply from 10 wells located in the inner valley of the Rio Grande (Lee, 1907). By 1940, Albuquerque was withdrawing about 4 million gallons (gal) per day—more than 4,000 acre-feet per year (acre-ft/yr)—to supply approximately 35,000 people (Bjorklund and Maxwell, 1961). Rapid regional population growth in subsequent years resulted in a population in 2000 of nearly 449,000 people in the COA and about 690,000 in the MRGB (Bartolino and Cole, 2002). During the 1990's, annual ground-water pumping by Albuquerque ranged between approximately 110,000 and 124,000 acre-ft (files of the COA), amounting to about three-quarters of the annual basinwide pumping of about 150,000 to 160,000 acre-ft (McAda and Barroll, 2002; files of the Office of the New Mexico State Engineer, Albuquerque). Water-use estimates for 1995 for the four counties that have large areas within the MRGB, which extends from Cochiti Lake on the north to San Acacia on the south, are summarized in table 1.

As a result of large ground-water withdrawals, annual outflow from the aquifer system of the MRGB is substantially greater than annual inflow to the aquifer system (Bartolino and Cole, 2002; McAda and Barroll, 2002). This situation has caused water-level declines exceeding 120 feet (ft) in parts of the aquifer (fig. 2) (Bexfield and Anderholm, 2002), which has raised concerns about the potential for substantial land-surface subsidence in the future (Haneberg, 1995). In 2002, water-level declines relative to predevelopment conditions were largest near COA well fields located east of the Rio Grande. However, substantial declines associated with pumping by both Albuquerque and other users extend beyond Albuquerque limits to other communities, including the City of Rio Rancho, the Sandia and Isleta Indian Reservations, and Kirtland Air Force Base (fig. 2). Because of the hydraulic connection between the Rio Grande and the aquifer system in the basin, ground-water withdrawals and the associated water-level declines have decreased flow in the Rio Grande (McAda and Barroll, 2002). The Rio Grande provides most of the water used for irrigated crops in the basin (table 1), estimated at about 63,000 acres in 1992 (Thorn and others, 1993). Irrigators hold most of the senior water rights in the basin (Bartolino and Cole, 2002). The reach of the Rio Grande that flows through the basin also is home to an endangered species, the Rio Grande silvery minnow, and is used by Indian Pueblos for ceremonial purposes.

Recognition that continued use of ground water to meet all water demand by the COA is not sustainable and may lead to the inception or continuation of a number of regional-scale problems, including increased drilling and pumping costs, land-surface subsidence, deterioration of the quality of available ground water, and decreased surface-water availability, has led the COA to revise its water-resources strategy. By 1997, the COA had started a water conservation program and adopted a new formal strategy to begin water-recycling projects and to transition toward the direct use of surface water to meet most city water demand. During the 1960's, the COA was one of several entities (including the Middle Rio Grande Conservancy District and the municipalities of Bernalillo, Los Lunas, and Belen; fig. 1) to contract with the U.S. Department of the Interior to purchase rights to water associated with the San Juan-Chama Transmountain Diversion Project (Bartolino and Cole, 2002; City of Albuquerque, 2003). Albuquerque owns 48,200 acre-ft/yr of the water that the project is allowed to divert across the Continental Divide from streams in the Colorado River Basin to the Rio Grande Basin, where the water is stored in reservoirs upstream from the city. In addition, the city owns rights to about 23,000 acre-ft/yr of native Rio Grande water. Currently (2003), much of the surface water owned by Albuquerque is allowed to flow past the city to offset the effects of ground-water withdrawals on the river. As designed, the new water-resources strategy calls instead for the diversion of 94,000 acre-ft of water per year from the Rio Grande just upstream from Albuquerque and the return of the 47,000 acre-ft/yr that is not consumed back to the river at the southern end of the city (City of Albuquerque, 2003), beginning in 2006. Limited ground-water withdrawals would be used to supplement water supplies primarily during periods of large demand or drought.

Because the COA is the largest single user of ground water in the MRGB, a shift by the COA to a municipal water supply based primarily on surface-water diversions will have substantial effects on the river-aquifer system of the basin. Using the McAda and

Table 1. Water-use estimates for selected counties of the Middle Rio Grande Basin in 1995
[data from Wilson and Lucero, 1997]

County (fig. 1)	Category	Surface-water withdrawal (acre-feet)	Ground-water withdrawal (acre-feet)	Total withdrawal (acre-feet)
Bernalillo	Public water supply	0.00	135,467.80	135,467.80
	Domestic	0.00	2,162.33	2,162.33
	Irrigated agriculture and livestock	65,261.43	4,661.87	69,923.30
	Commercial, industrial, mining, and power generation	0.00	5,107.96	5,107.96
	Reservoir evaporation	0.00	0.00	0.00
	County totals:	**65,261.43**	**147,399.96**	**212,661.39**
Sandoval	Public water supply	125.95	15,201.07	15,327.02
	Domestic	0.00	2,529.00	2,529.00
	Irrigated agriculture and livestock	54,629.41	1,166.95	55,796.36
	Commercial, industrial, mining, and power generation	10.00	1,987.60	1,997.60
	Reservoir evaporation	15,033.00	0.00	15,033.00
	County totals:	**69,798.36**	**20,884.62**	**90,682.98**
Socorro	Public water supply	0.00	2,183.55	2,183.55
	Domestic	0.00	323.23	323.23
	Irrigated agriculture and livestock	122,610.61	38,596.13	161,206.74
	Commercial, industrial, mining, and power generation	0.00	1,079.76	1,079.76
	Reservoir evaporation	7,570.00	0.00	7,570.00
	County totals:	**130,180.61**	**42,182.67**	**172,363.28**
Valencia	Public water supply	0.00	4,917.37	4,917.37
	Domestic	0.00	3,302.98	3,302.98
	Irrigated agriculture and livestock	182,737.03	9,361.22	192,098.25
	Commercial, industrial, mining, and power generation	0.00	1,116.73	1,116.73
	Reservoir evaporation	0.00	0.00	0.00
	County totals:	**182,737.03**	**18,698.30**	**201,435.33**
Totals	Public water supply	125.95	157,769.79	157,895.74
	Domestic	0.00	8,317.54	8,317.54
	Irrigated agriculture and livestock	425,238.48	53,786.17	479,024.65
	Commercial, industrial, mining, and power generation	10.00	9,292.05	9,302.05
	Reservoir evaporation	22,603.00	0.00	22,603.00
	Total for all counties:	**447,977.43**	**229,165.55**	**677,142.98**

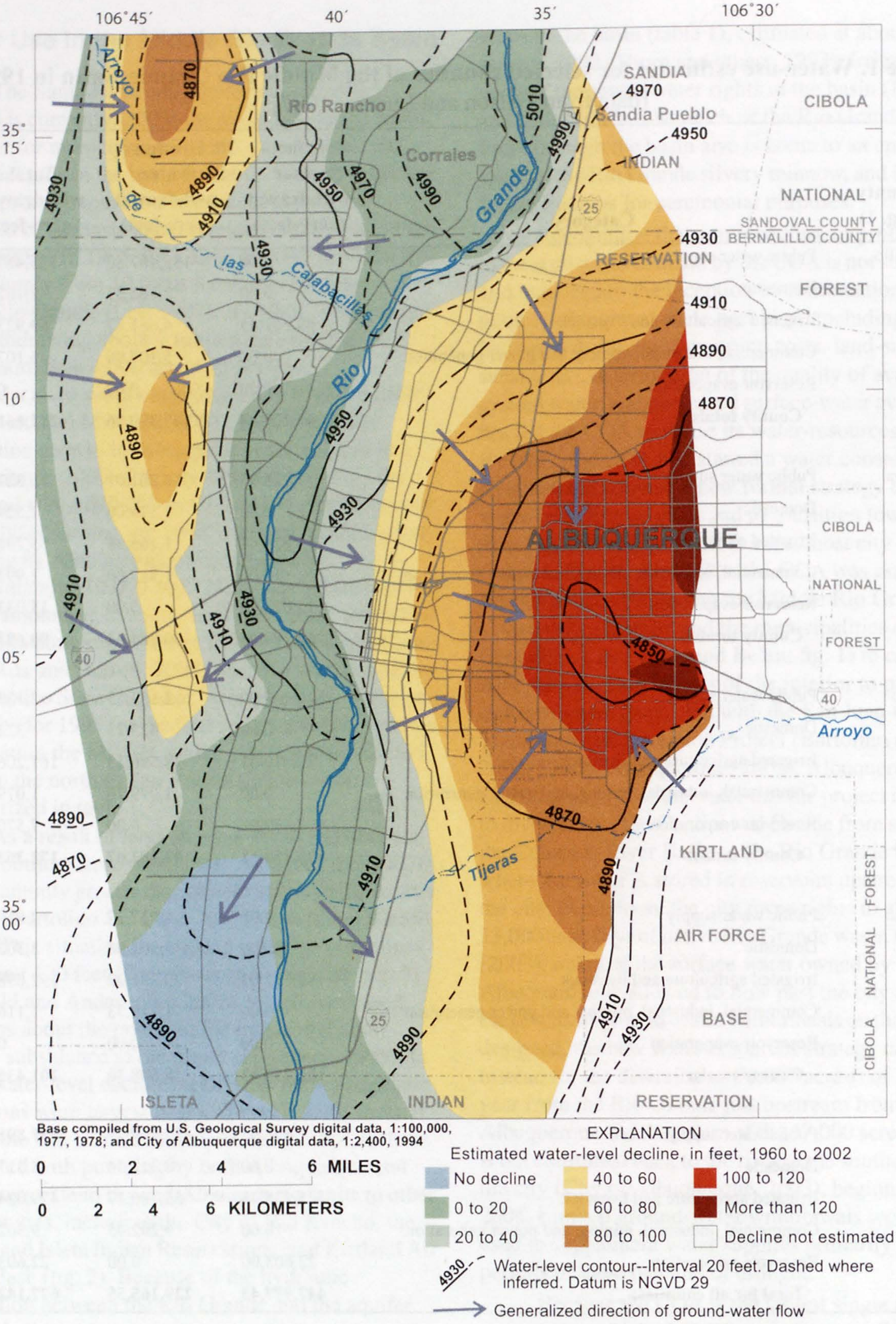


Figure 2. Water levels representing 1999-2002 conditions in the production zone and estimated water-level declines, 1960 to 2002 (modified from Bexfield and Anderholm, 2002).

Barroll (2002) ground-water-flow model of the MRGB, Bexfield and McAda (2003) simulated the water-budget and water-level effects of different rates of annual ground-water withdrawals by the COA through 2040. The McAda and Barroll (2002) model, which is the most recent of several computer models developed by the USGS for the basin, incorporates improvements in the knowledge of the geohydrology of the basin obtained through a 6-year effort started in 1995 by the USGS and other agencies (including the New Mexico Bureau of Geology and Mineral Resources, the New Mexico Office of the State Engineer (NMOSE), the COA, and the University of New Mexico) to gain additional scientific information needed for water-resources management in the basin (Bartolino, 1997). Although the solutions provided by ground-water-flow models to posed problems are approximate, models that provide a reasonable representation of the complex geohydrologic processes of the basin can be very useful in water-resources planning by estimating the effects of particular stresses on the river-aquifer system (McAda and Barroll, 2002).

Because the ground-water-flow model of the MRGB can provide estimates of the effects of individual stresses (particularly specified locations and magnitudes of ground-water withdrawals) on water levels and on the various components of the water budget, the model can be used in combination with optimization techniques to help determine pumping strategies that will best achieve particular management objectives. When the COA shifts to surface water as its primary source of municipal water supply, associated changes in infrastructure will allow much greater flexibility in pumping strategies than has previously been possible. Individual city well fields, which are limited at the current time (2003) to supplying water to only small sections of city customers, will be interconnected to allow a single well field to supply any of the city's customers. This change (along with reduced ground-water withdrawals relative to overall well capacity) will permit Albuquerque to select pumping strategies that not only meet immediate obligations to water customers, but that also benefit the multitude of regional water users and the hydrologic system as a whole. Examples of management objectives that might be beneficial to regional water users include minimizing water-level decline in the aquifer or minimizing induced leakage from the Rio Grande.

Purpose and Scope

This report presents results of a simulation-optimization approach to the assessment of strategies for ground-water withdrawal by the COA that can be used to best achieve particular management objectives for 2006 through 2040. The ground-water-flow model of McAda and Barroll (2002) for the MRGB was used to estimate the effects of specified quantities of ground-water withdrawal from individual COA well fields on water levels and water budgets for the aquifer. This report discusses the simulated effects and their implications for management of water resources in the basin. The simulated effects were used in the formulation of five constrained optimization models designed to achieve specified objectives by adjusting the distribution of ground-water withdrawal among COA well fields through 2040. The five models incorporate objectives of minimizing depletion of aquifer storage and (or) minimizing leakage from the river system into the aquifer. All five optimization models include constraints related to water demand, well-field capacity, and minimum withdrawal requirements. Three models also include constraints related to water-level declines, arsenic concentrations, and (or) water-rights issues. This report presents the formulation and results of all five optimization scenarios.

Previous Investigations

Comprehensive publications on the geohydrologic framework of the MRGB (also known as the Albuquerque Basin) were published in the early 1990's, perhaps most notably by Hawley and Haase (1992) and Thorn and others (1993). Hawley and Haase (1992) presented a detailed geologic framework for the basin that addressed structure, stratigraphy, and lithology. The reader is referred to their publication for information about major geologic studies in the basin up to that time. Thorn and others (1993) detailed the hydrologic knowledge of the MRGB, including the work of Bjorklund and Maxwell (1961) and subsequent investigators. The ground-water-flow model developed by Kernodle and others (1995) was based on the geohydrologic framework of Hawley and Haase (1992) and Thorn and others (1993) and represented a significant update to previous ground-water-flow models based on earlier knowledge. The Kernodle and others (1995) model formed the primary basis for subsequent modifications by Kernodle (1998), Tiedeman and others (1998), and Barroll (2001).

The McAda and Barroll (2002) ground-water-flow model (hereafter referred to as the McAda and Barroll model) is the most recent substantial update to modeling efforts for the MRGB and is the culmination of a focused 6-year effort by the USGS and other agencies (including the New Mexico Bureau of Geology and Mineral Resources, the NMOSE, the COA, and the University of New Mexico) to gain further insight into the geohydrology of the basin. Studies associated with this 6-year effort included geologic mapping to improve knowledge of the structural and stratigraphic framework of the Santa Fe Group sediments, airborne geophysical surveys to identify detailed fault patterns and better characterize hydrologic properties of geologic units, use of environmental tracers to better estimate mountain-front recharge and streamflow loss, and investigation of ground-water flow using chemical and isotopic data (Slate, 1998). Information on the design and results of these studies can be found in Bartolino and Cole (2002), as well as in collections of extended abstracts edited by Bartolino (1997), Slate (1998), Bartolino (1999), and Cole (2001). In addition, ongoing study of the stratigraphy of the MRGB is described in Connell (2001).

A simulation-optimization approach similar to the one used in the study described in this report has been used in several previous studies to address various aspects of water-resource management. Only a few examples of such studies are provided here. A fairly large body of literature is available on the use of linear, quadratic, and (or) mixed-integer programming techniques to determine the optimal placement and pumping rates of wells to achieve containment of ground-water contaminants at the lowest overall extraction rate. Constraints used to guarantee containment in these scenarios commonly involve bounds on head gradients (Tiedeman and Gorelick, 1993) or velocity directions (Ratzlaff and others, 1992). Simulation-optimization also has been applied to the identification of ground-water withdrawal strategies to control shallow water tables in areas of irrigated agriculture. For example, Barlow and others (1996) explicitly linked a MODFLOW (McDonald and Harbaugh, 1988) simulation model of ground-water flow in the western San Joaquin Valley, California, with an optimization program to minimize the areal extent of the shallow water table. Conversely, optimization techniques have been applied to the problem of minimizing water-level decline within specified demand constraints. Danskin (1998) used a semi-quantitative optimization approach to this problem in the Owens Valley of east-central California. Barlow and Dickerman (2001) used a simulation-optimization approach to evaluate alternatives for the conjunctive management of ground- and surface-water resources in eastern Rhode Island, wherein ground-water withdrawals were maximized within specified limitations on streamflow depletion. As a final example of the use of optimization techniques in water-resources management, Nishikawa (1998) used a MODFLOW simulation model of ground-water flow in the Santa Barbara, California, area in combination with optimization software to minimize the total cost of water supply from both ground- and surface-water sources while meeting demand and satisfying constraints related to water-supply capacity, pumping distribution, and heads in the aquifer along the seacoast.

Acknowledgments

The authors thank Greg Gates with CH2M Hill for providing the projections of future water demand for the COA that were used in this study. The authors also thank John Stomp with the COA Public Works Department for supporting this study and for helping to identify optimization scenarios that would be of the greatest benefit to regional water users.

BACKGROUND ON THE STUDY AREA AND THE GROUND-WATER-FLOW MODEL

A complete understanding of the water-resource management issues in the MRGB and the simulation-optimization approach used in this report to address them requires knowledge of the study area and the ground-water-flow model used to represent it. Therefore, this section describes the geohydrologic and water-use characteristics of the MRGB, followed by a discussion of the design of the McAda and Barroll model.

Description of the Study Area

The geohydrology of the MRGB has been described previously by Hawley and Haase (1992), Thorn and others (1993), Bartolino and Cole (2002), and McAda and Barroll (2002). Therefore, only a brief summary of the information available in those publications is provided here. As defined for this study, the MRGB covers about 3,060 square miles (mi^2) in central New Mexico, delineated by the extent of deposits of Cenozoic age between Cochiti Lake on the north and San Acacia on the south (fig. 1). The MRGB is one of a series of alluvial basins stretching along an area of Cenozoic crustal extension known as the Rio Grande Rift and is hydraulically connected to the Española Basin to the north and the Socorro Basin to the south. The basin is bounded along most of the east and southeast by the Sandia, Manzano, Los Pinos, and Joyita Uplifts (fig. 3), which exceed 10,000 ft in altitude in places. The Jemez and Nacimiento Uplifts and Jemez Mountains form boundaries of similar magnitude along the north and northwest. The generally more subdued boundaries along the west and southwest include the Lucero and Ladron Uplifts. The MRGB is composed of three subbasins, the Santo Domingo, Calabacillas, and Belen subbasins (fig. 3), which are separated by bedrock structural highs. The deep, inner portions of these subbasins, where the thickness of alluvial fill exceeds 14,000 ft in places, generally are bordered on the sides by relatively shallow benches. In addition to major faults that bound the MRGB, numerous faults occur within the Santa Fe Group sediments of the basin (fig. 3). Faults in the region align primarily north to south and offset sediments of substantially different lithology in some areas.

The generally unconsolidated to moderately consolidated basin-fill sediments of the MRGB include primarily the Santa Fe Group deposits of late Oligocene to middle Pleistocene age and the post-Santa Fe Group alluvium of Pleistocene to Holocene age. These sediments tend to be hydraulically connected, and together they form the Santa Fe Group aquifer system as defined by Thorn and others (1993). Hawley and Haase (1992) divided the Santa Fe Group deposits into broad lower, middle, and upper parts of distinct age and depositional environment. The lower Santa Fe Group sediments, which range in thickness from less than 1,000 to about 3,500 ft, contain a substantial fraction of basin-floor playa deposits, which compose poor aquifer materials (Hawley and Haase, 1992). The middle Santa Fe Group sediments, which range from about 250 to 9,000 ft thick, accumulated during a time of large sedimentation rates and include substantial fluvial deposits in the north in addition to piedmont-slope deposits along basin margins and playa deposits in the south (Hawley and Haase, 1992). Sediments of the Santa Fe Group are most permeable in the upper section, which tends to be less than 1,000 ft thick and consists largely of intertonguing piedmont-slope and fluvial basin-floor deposits (Hawley and Haase, 1992). Quaternary post-Santa Fe Group sediments include the valley fill (as much as about 130 ft in thickness) that accumulated during cutting and partial backfilling episodes of the Rio Grande and Rio Puerco (Hawley and Haase, 1992). Water-supply wells used by the COA are completed primarily in sediments of the upper or middle Santa Fe Group (fig. 4).

In the semiarid MRGB, where potential evapotranspiration greatly exceeds precipitation, any contribution made to the aquifer system by direct recharge of precipitation is negligible. Most recharge occurs by infiltration of water through streams, subsurface inflow from adjacent basins, or mountain-front/tributary recharge along basin margins (Thorn and others, 1993; Kernodle and others, 1995; McAda and Barroll, 2002). Recharge also occurs through irrigation and septic-field seepage (McAda and Barroll, 2002). Maps of conditions in the MRGB prior to about 1960 (Meeks, 1949; Bjorklund and Maxwell, 1961; Titus, 1961; Bexfield and Anderholm, 2000) show that the primary direction of ground-water flow through the basin is north to south, and that components of east-west flow are largest near basin margins. However, ground-water withdrawals by the COA and others have since resulted in large-scale alteration of hydraulic heads near Albuquerque, so that ground-water movement is toward the major pumping centers (both east and west of the Rio Grande) from all directions (fig. 2). Head declines also have induced greater leakage from the river system into the aquifer than occurred under predevelopment conditions. Ground-water withdrawals are a major component of modern discharge from the aquifer system, as are evapotranspiration and loss of water to the drain system or to some reaches of the Rio Grande (McAda and Barroll, 2002). Some ground water also discharges to the Socorro Basin to the south.The Rio Grande, which is inset in a terraced valley more than 5 miles wide in places, extends the entire length of the MRGB from north to south and is the main surface-water feature of

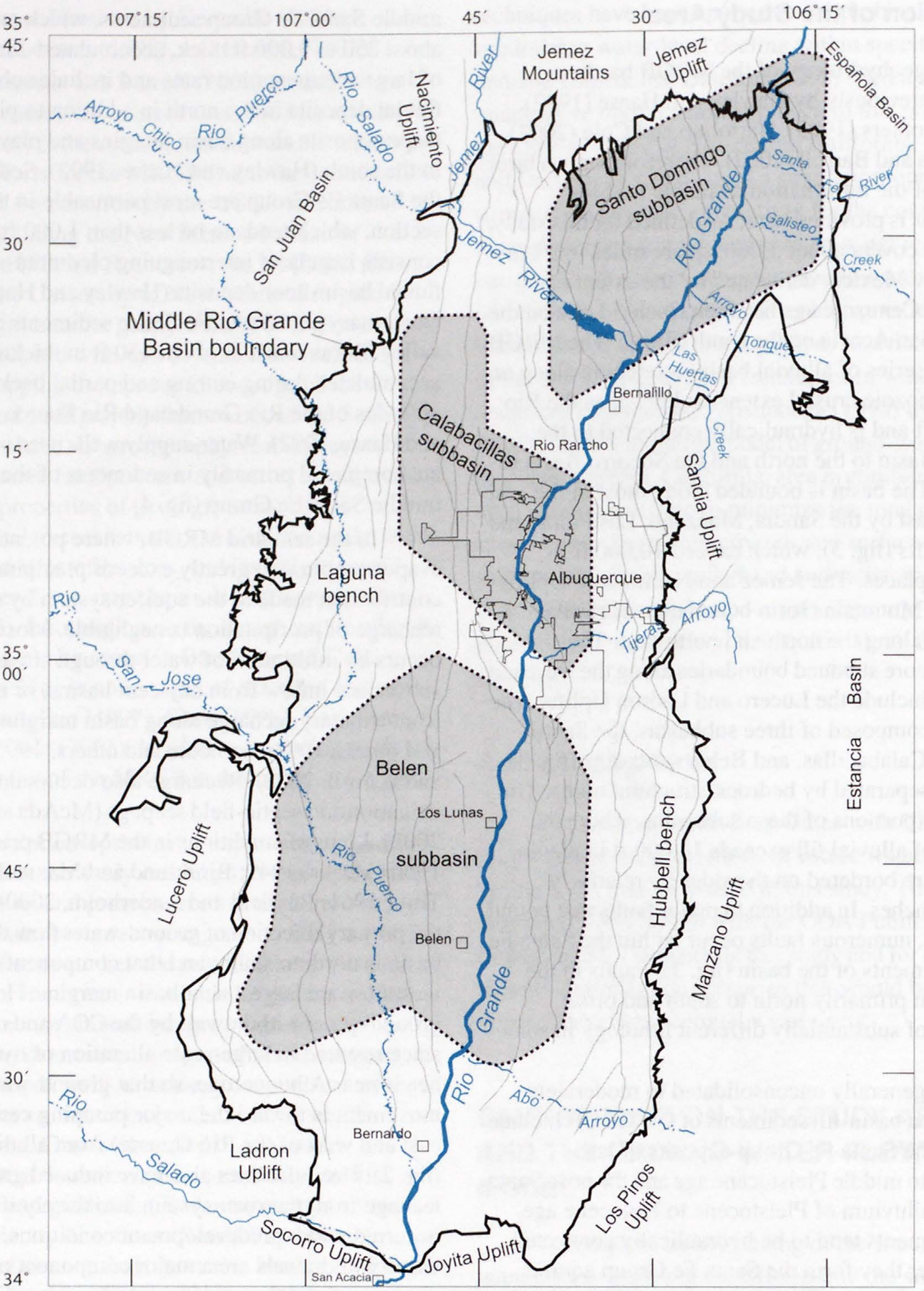
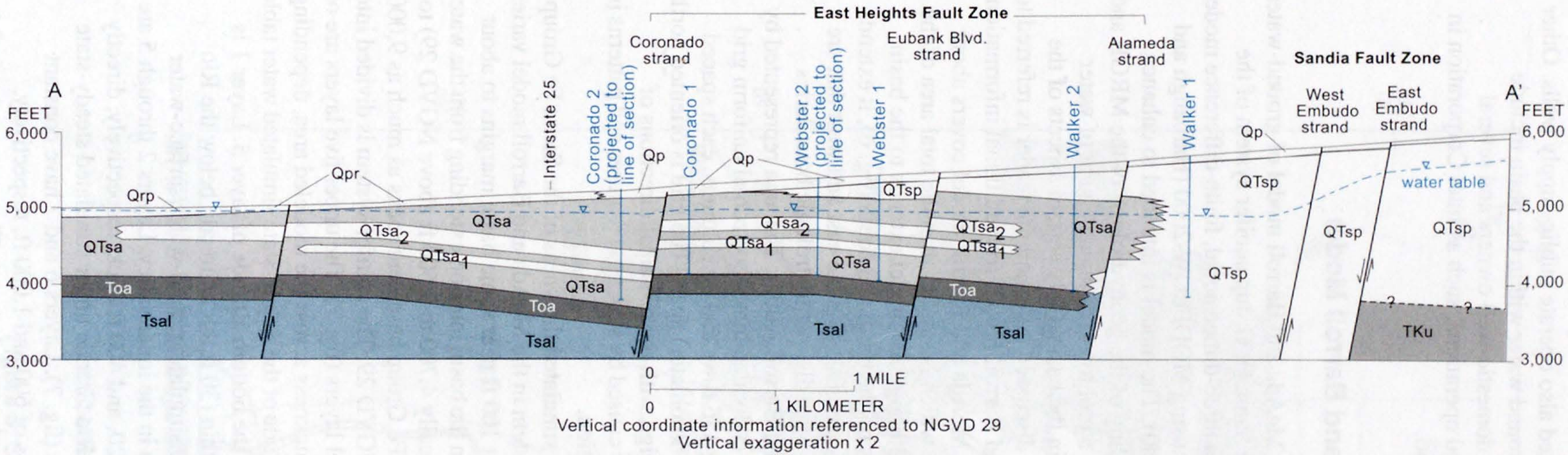


Figure 3. Major structural features of the Middle Rio Grande Basin (subbasin locations modified from Grauch and others, 1999).



EXPLANATION

Qrp: Los Padillas Formation (historical to uppermost Pleistocene)--Unconsolidated to poorly consolidated, fine- to coarse-grained sand and rounded gravel with interbeds of fine-grained sand, silt, and clay derived from the Rio Grande

Qp: Piedmont and stream alluvium, undivided (historical to middle Pleistocene)

Qpr: Fluvial deposits, piedmont alluvium, and stream alluvium, undivided (historical to middle Pleistocene)

QTsa: Axial-fluvial deposits of the ancestral Rio Grande, undivided (lower Pleistocene to Pliocene); part of the upper Santa Fe Group of Hawley and Haase (1992)

$QTsa_2$: Upper sandy mudstone marker bed (Pliocene)

$QTsa_1$: Lower sandy mudstone marker bed (Pliocene)

QTsp: Piedmont deposits (lower Pleistocene to Miocene); part of the upper Santa Fe Group of Hawley and Haase (1992)

Toa: Arroyo Ojito Formation, Atrisco Member (Pliocene)--Moderately to well consolidated, locally cemented succession of fine-grained silty sandstone and mudstone; part of the middle Santa Fe Group of Hawley and Haase (1992)

Tsal: Lower fluvial deposits (Pliocene to upper Miocene); part of the middle Santa Fe Group of Hawley and Haase (1992)

TKu: Lower Tertiary and Cretaceous sedimentary rocks, undivided (Paleogene-Cretaceous)

⇌ Fault showing relative movement

Walker 2 Municipal-supply well

Figure 4. Geologic section along Paseo del Norte in northern Albuquerque (modified from Connell, 1997). See figure 5 for section location. Formations and member names usage of New Mexico Bureau of Geology and Mineral Resources.

the basin (fig. 1). The mean annual discharge of the Rio Grande at Albuquerque was about 1,400 cubic feet per second for 1974 through 2000 (Ortiz and others, 2001), which equals an annual volume of riverflow of about 1.01 million acre-ft. Human influences on the flow of the modern-day Rio Grande include reservoirs, irrigation diversions and return flows, inflow from wastewater-treatment plants, and inflow from the San Juan-Chama Project. Within the MRGB, anthropogenic structures confine the Rio Grande to a single channel and divert water from the river into a network of irrigation canals that extend throughout the inner valley. Ground-water drains intercept seepage from the irrigation canals, applied irrigation water, and the Rio Grande and ultimately discharge this water back into the river. The system of drains prevents the water table from rising close enough to land surface to harm crops. Tributaries that contribute flow to the Rio Grande within the MRGB include the Santa Fe River, Jemez River, Rio Puerco, and Rio Salado; of these, only the Jemez River is perennial through most of its length within the basin. Within the MRGB, the Rio Grande and the Jemez River lose water to the aquifer throughout most reaches (McAda and Barroll, 2002).

As indicated in table 1, combined surface-water withdrawals for the major counties of the MRGB are larger than combined ground-water withdrawals. The main consumptive use of surface water is for irrigated agriculture, primarily along the Rio Grande and the Jemez River. Surface water also is consumed by reservoir evaporation, recharge to ground water, and evapotranspiration by riparian vegetation (Bartolino and Cole, 2002). Nonconsumptive uses of surface water in the basin include recreation and ceremonial use by Pueblos. Within the basin, the Rio Grande also provides habitat for the endangered Rio Grande silvery minnow. As indicated in the "Introduction," the COA plans to begin withdrawing most of its municipal supply directly from the Rio Grande in 2006. Albuquerque currently (2003) withdraws the largest amount of ground water from the basin, pumping about 114,000 acre-ft in 2000. The more than 90 municipal-supply wells owned by Albuquerque are scattered throughout the city (fig. 5). As discussed by Bartolino and Cole (2002), other municipalities that currently withdraw ground water for public supply include Bernalillo, Rio Rancho, Bosque Farms, Los Lunas, and Belen. Kirtland Air Force Base, the University of New Mexico, and private utilities such as Sandia Peak Utility Company and New Mexico Utilities Incorporated also operate public-supply wells. Other users of ground water within the basin include numerous domestic-well owners and several commercial operations, such as Intel Corporation in Rio Rancho.

McAda and Barroll Model

The McAda and Barroll model of ground-water flow in the Santa Fe Group aquifer system of the MRGB is a three-dimensional, finite-difference model developed using MODFLOW-2000 (Harbaugh and others, 2000). The model is intended to enhance understanding of the geohydrology of the MRGB and to provide a tool to aid in management of water resources in the basin. Only certain aspects of the model are discussed here, and the reader is referred to McAda and Barroll (2002) for additional information.

The McAda and Barroll model covers about 2,350 mi^2, which is smaller than the total area of the MRGB. Although the model extends to the basin boundaries on the north and south (fig. 6), it extends only to selected faults on the east and west that are thought to form distinct hydrologic boundaries (McAda and Barroll, 2002). The area represented by the model is divided into a horizontal uniform grid containing 156 rows and 80 columns, each spaced 3,281 ft (1 kilometer) apart. The grid is oriented north-south to align with the principal directions of anisotropy caused by structural features and patterns in sedimentation.

The simulated thickness of the Santa Fe Group aquifer system in the McAda and Barroll model varies from about 100 ft near some basin margins to about 14,000 ft in the basin interior, extending from the water table (typically 4,700 to 5,600 ft above NGVD 29) to pre-Santa Fe Group basement rocks as much as 9,000 ft below NGVD 29. The aquifer system is divided into nine model layers (fig. 7). The upper five layers are of variable thickness across the modeled area, depending on the altitude of the steady-state simulated water table relative to the bottom altitude of layer 5. Layer 1 is relatively thin (30 ft thick directly below the Rio Grande) to simulate ground-water/surface-water interaction in the inner valley. Layers 2 through 5 are 50, 100, 220, and 400 ft thick, respectively, directly below the Rio Grande under simulated steady-state conditions (fig. 7). Layers 6 and 7 have constant thicknesses of 600 and 1,000 ft, respectively, throughout the modeled area. The top one-third of the

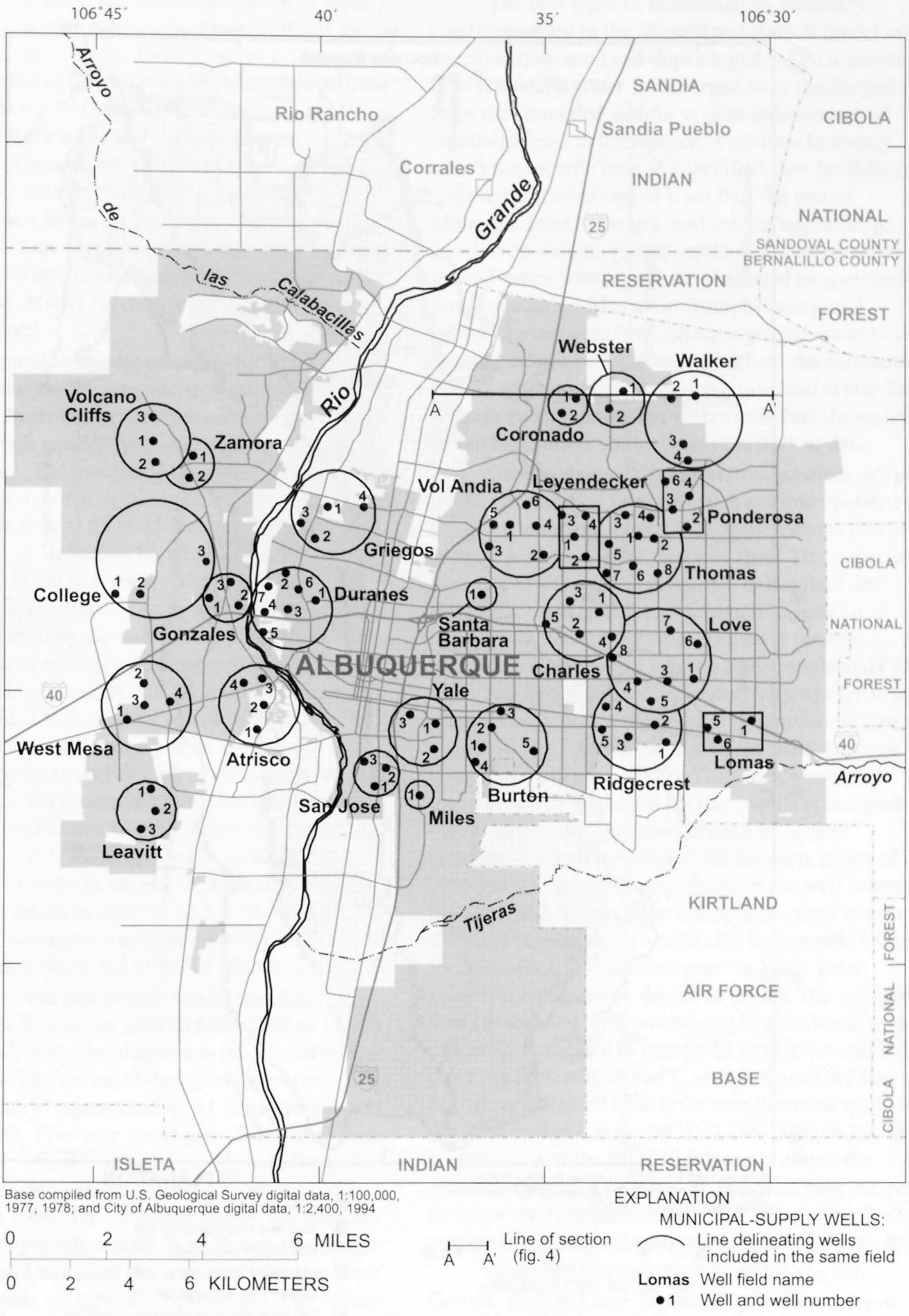


Figure 5. City of Albuquerque municipal-supply wells.

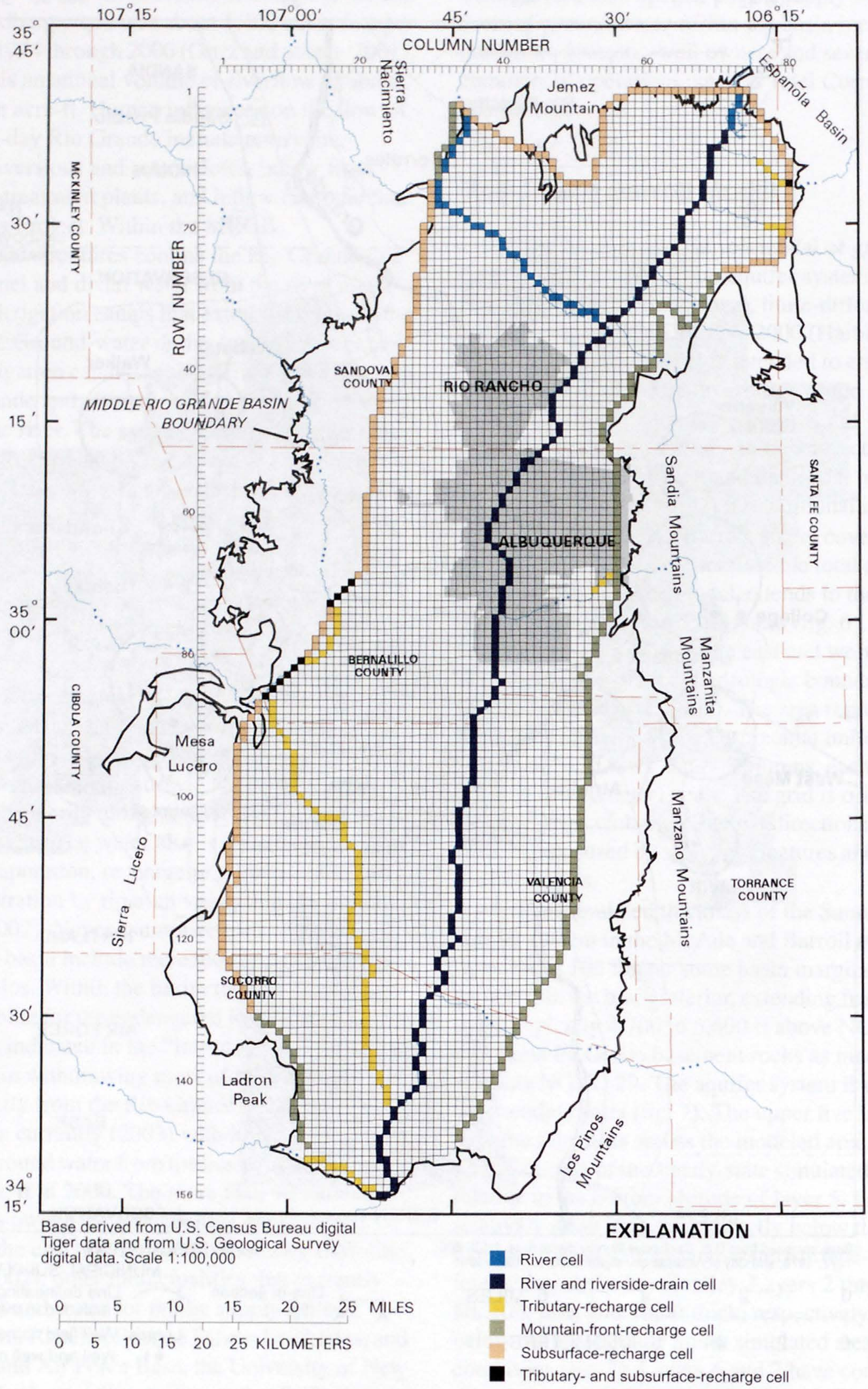


Figure 6. Model grid showing active cells in layer 1 of the McAda and Barroll (2002) model (modified from McAda and Barroll, 2002, fig. 7).

Santa Fe Group thickness below the bottom of layer 7 is assigned to layer 8, and the bottom two-thirds are assigned to layer 9 (fig. 7). Cells in layers 1-7 are active where the center of the cell is higher in altitude than the base of the Santa Fe Group, whereas cells in model layers 8 and 9 are active only where their combined thickness is at least 1,200 ft. To allow the simulated water table to transfer to the next lower cell as simulated water levels decline below the bottom of a cell, layers 1-4 are represented as convertible between confined and water-table conditions (Harbaugh and others, 2000). Model layers 5-9 are represented as always confined.

Horizontal hydraulic conductivity, vertical hydraulic conductivity, specific storage, and specific yield are the hydrologic properties used to represent the Santa Fe Group aquifer system in the McAda and Barroll model. The horizontal hydraulic conductivity in the east-west direction (along model rows; K_x) of the model ranges from 0.05 to 45 feet per day (ft/d). Distributions of simulated horizontal hydraulic conductivity in the east-west direction are shown in figure 8 for layers 4 and 5, from which most ground-water withdrawal by the COA is simulated to occur. The hydraulic conductivity in the north-south direction (along model columns; K_y) of the model ranges from 0.05 to 60 ft/d. The horizontal anisotropy ratio (K_y / K_x) varies over the model domain from 1:1 to 5:1. Hydraulic conductivity between model cells is reduced in some areas where selected faults are simulated as horizontal flow barriers (fig. 8). A vertical anisotropy ratio (K_x / K_z) of 150:1 is applied over the model domain. This results in simulated vertical hydraulic-conductivity values ranging from 3×10^{-4} to 3×10^{-1} ft/d. Specific storage is simulated to be 2×10^{-6} ft^{-1} and specific yield is simulated to be 0.2 (dimensionless).

The McAda and Barroll model simulates ground-water flow in the MRGB from 1900 to March 2000. A steady-state simulation was performed prior to each transient simulation of the historical period, 1900 to 2000, which is represented by 51 stress periods of varying length. Five-year stress periods are used from 1900 to 1974, 1-year stress periods are used from 1975 through 1989, and seasonal stress periods are used beginning in 1990. The irrigation-season (or summer-season) stress periods extend from March 16 through October 31 and represent the period of time that most irrigation canals are typically operational. The winter-season stress periods extend from November 1 to March 15.

The two types of mathematical boundary conditions used in the McAda and Barroll model are specified flow and head-dependent flow. At a specified-flow boundary, water is recharged to or discharged from the simulated aquifer system independent of simulated head in the aquifer. A no-flow boundary, which is a specific case of a specified-flow boundary, is imposed at the bottom of layer 9 of the model. Mountain-front, tributary, and subsurface recharge; canal, crop-irrigation, and septic-field seepage; and ground-water withdrawal are simulated as specified-flow boundaries. Mountain-front, tributary, and subsurface recharge from adjacent ground-water basins are specified to be constant throughout the simulation period, whereas canal, crop-irrigation, and septic-field seepage and ground-water withdrawal vary through the simulation period on the basis of historical data.

Ground-water withdrawal from production wells with large screened intervals, such as those operated by the COA, must be divided among the various model layers that the screened intervals span. The screened intervals of COA wells (available in Bexfield and others, 1999) extend across as much as 1,000 ft of aquifer and four model layers (layers 3 through 6). A previous well-bore flow logging study in selected COA wells indicated that higher conductivity aquifer layers often do not provide the greatest proportion of flow to a well because of encrustation of the well screen or other factors (Thorn, 2000). Therefore, simulated ground-water withdrawal for these wells is assigned to model layers without consideration of aquifer conductivity. In most cases, withdrawal is assigned in proportion to a known percentage of the well screen installed within each layer. Exceptions occur when the withdrawal assigned to a particular layer would be very small or when assumptions must be made about unknown construction details of a well. The specified flows associated with ground-water withdrawal in the model are simulated to pass to the next lower cell if the cell for which withdrawal is assigned goes dry (see McAda and Barroll (2002) for modifications made to the Well Package of the MODFLOW-2000 code). This modification to the MODFLOW code allows the recorded historical withdrawal quantities to occur even as water levels decline, rather than terminating the portion of withdrawal assigned to a cell that goes dry.

In the McAda and Barroll model, the Rio Grande, Cochiti Lake, Jemez River, Jemez Canyon Reservoir, riverside drains, interior drains, and riparian evapotranspiration are simulated as head-dependent

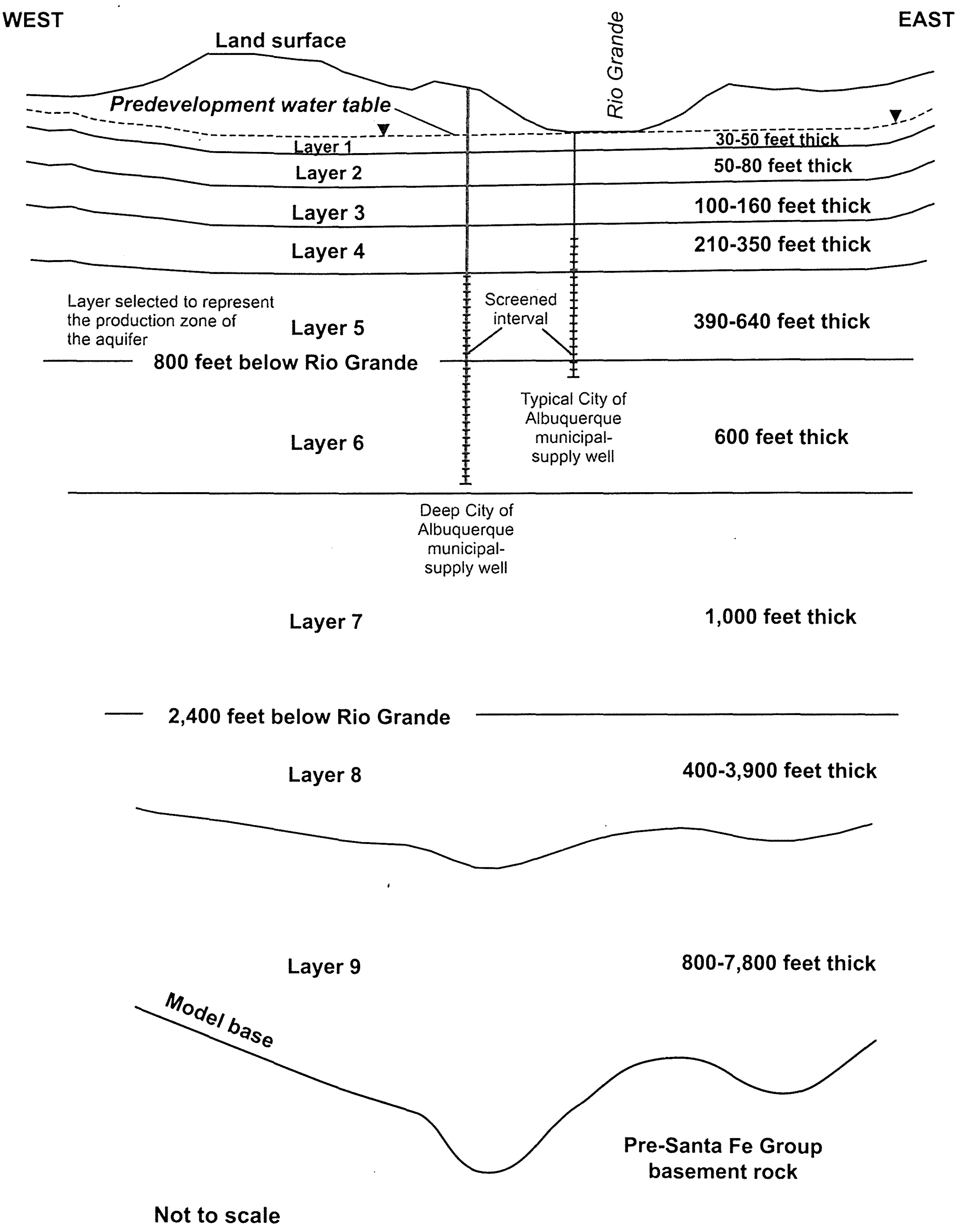


Figure 7. Configuration of layers in the McAda and Barroll (2002) model (modified from McAda and Barroll, 2002, fig. 8).

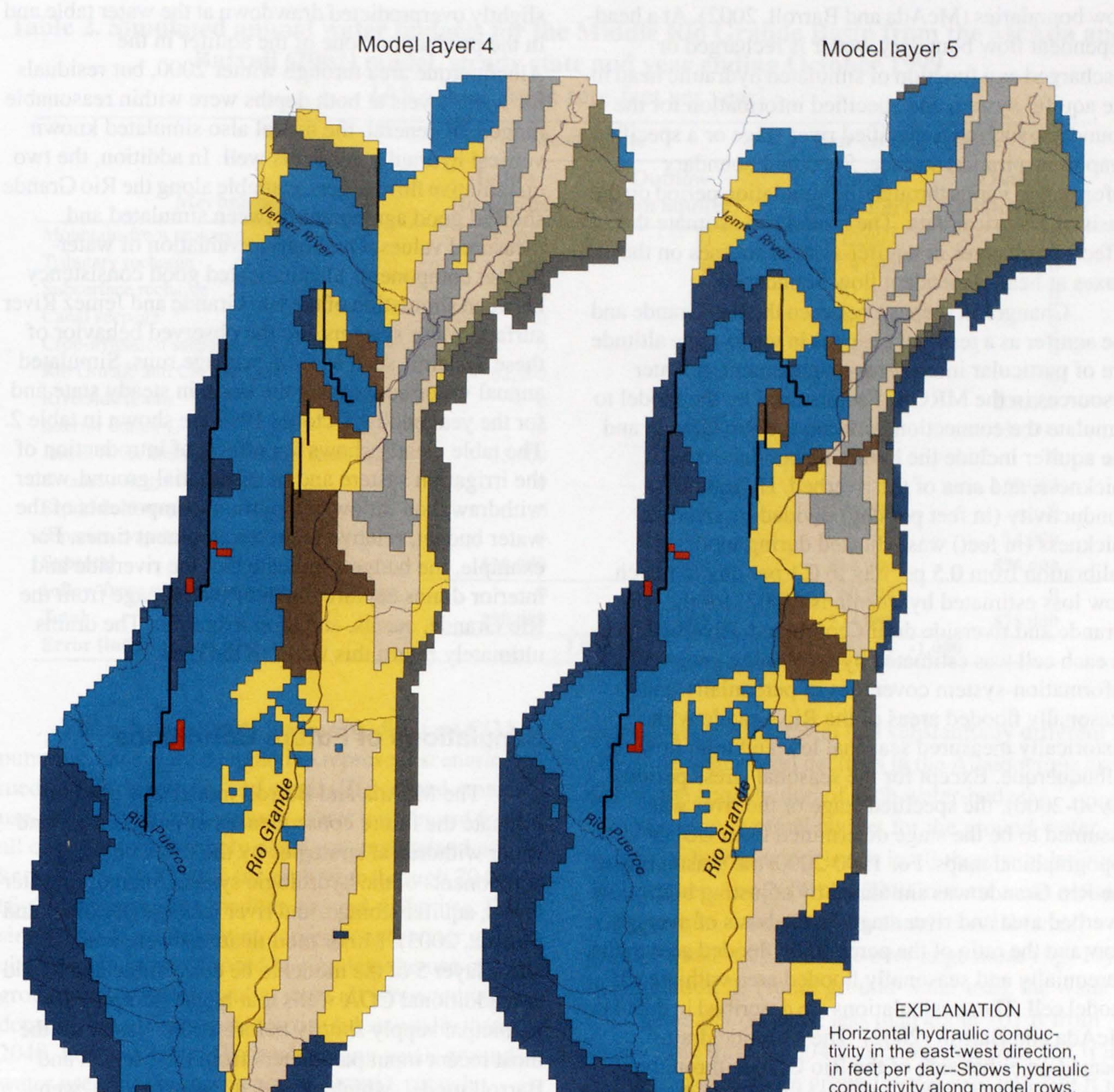


Figure 8. Distribution of simulated horizontal hydraulic conductivity in the east-west direction for selected layers of the McAda and Barroll (2002) model (modified from McAda and Barroll, 2002, fig. 12).

flow boundaries (McAda and Barroll, 2002). At a head-dependent flow boundary, water is recharged or discharged as a function of simulated hydraulic head in the aquifer system and specified information for the boundary, such as a specified river stage or a specified evapotranspiration surface. Specified boundary information varies through the simulation period on the basis of historical data. The model can estimate the effects of changes in aquifer-system stresses on the fluxes at head-dependent flow boundaries.

Changes in seepage between the Rio Grande and the aquifer as a result of changes in water-table altitude are of particular interest for management of water resources in the MRGB. Factors used by the model to simulate the connection between the Rio Grande and the aquifer include the hydraulic conductivity, thickness, and area of the riverbed. Hydraulic conductivity (in feet per day) divided by riverbed thickness (in feet) was adjusted during model calibration from 0.5 per day to 0.1 per day to match flow loss estimated by Veenhuis (2002) for the Rio Grande and riverside drains combined. Riverbed area in each cell was estimated by combining geographical-information-system coverages of perennially and seasonally flooded areas of the Rio Grande with historically measured seasonal low and high flows at Albuquerque. Except for the seasonal stress periods (1990-2000), the specified stage of the river was assumed to be the stage determined from USGS topographical maps. For 1990-2000, the seasonality of the Rio Grande was simulated by adjusting both riverbed area and river stage on the basis of average flow and the ratio of the perennially flooded area to the perennially and seasonally flooded area within each model cell. These calculations are described in detail in McAda and Barroll (2002). The riverside drains located on either side of the Rio Grande throughout most of the MRGB are closely associated with the river and are simulated as separate entities within the same model cells as the Rio Grande. Because of their varying functions, as described by McAda and Barroll (2002), the riverside drains are simulated to allow for either the loss or gain of water.

The McAda and Barroll model was calibrated to measured hydraulic heads and water-budget components. In particular, the model-simulated predevelopment water table matched well with measured predevelopment water levels throughout most of the basin, including the general vicinity of Albuquerque. The model also was successful at reproducing the direction and magnitude of water-level changes in individual wells over time. The model slightly overpredicted drawdown at the water table and in the production zone of the aquifer in the Albuquerque area through winter 2000, but residuals for water levels at both depths were within reasonable ranges. In general, the model also simulated known vertical hydraulic gradients well. In addition, the two quantitative flow targets available along the Rio Grande showed good agreement between simulated and measured values. Qualitative evaluation of water-budget components also indicated good consistency between simulation of the Rio Grande and Jemez River surface-water systems and the observed behavior of these systems, such as from seepage runs. Simulated annual water budgets for the basin in steady state and for the year ending October 1999 are shown in table 2. The table clearly shows the effects of introduction of the irrigation system and of substantial ground-water withdrawal on inflow and outflow components of the water budget, relative to predevelopment times. For example, the budgets indicate that the riverside and interior drains capture much of the seepage from the Rio Grande, canals, and crop irrigation. The drains ultimately return this water to the river.

Simulations of Future Conditions

The McAda and Barroll model was used to evaluate the future consequences of potential ground-water withdrawal strategies by the COA on components of the hydrologic system, including water levels, aquifer storage, and river leakage (Bexfield and McAda, 2003). Minor modifications were made to allow layer 5 of the model to be convertible and to add two additional COA wells that began pumping for municipal supply shortly before 2000. Nearly all the most recent input parameters from the McAda and Barroll model, which extended through 2000, were duplicated without modification to lengthen the model through 2040. These parameters included the ones for mountain-front recharge, tributary recharge, underflow, recharge from irrigation and septic-tank seepage, drain conditions, and evapotranspiration conditions. Also, with the exception of COA data, the most recent data available in the McAda and Barroll model for ground-water withdrawal were duplicated for each year through 2040. Conditions in the Rio Grande were varied seasonally to match projections of future surface-water availability provided by Greg Gates (CH2M Hill, consultant to the City of Albuquerque, written commun., 2001), as described in more detail in Bexfield and McAda (2003).

Table 2. Simulated annual water budgets for the Middle Rio Grande Basin from the McAda and Barroll (2002) model, steady state and year ending October 1999

[All values are in acre-feet per year]

Mechanism	Steady state		Year ending October 1999	
	Inflow (to aquifer)	Outflow (from aquifer)	Inflow (to aquifer)	Outflow (from aquifer)
Mountain-front recharge	12,000	0	12,000	0
Tributary recharge	9,000	0	9,000	0
Subsurface recharge	31,000	0	31,000	0
Canal seepage	0	0	90,000	0
Crop-irrigation seepage	0	0	35,000	0
Rio Grande and Cochiti Lake	63,000	0	316,000	0
Riverside drains	0	0	0	208,000
Interior drains	0	0	0	133,000
Jemez River and Jemez Canyon Reservoir	15,000	0	17,000	0
Ground-water withdrawal	0	0	0	150,000
Septic-field seepage	0	0	4,000	0
Riparian evapotranspiration	0	129,000	0	84,000
Subtotal	**130,000**	**129,000**	**514,000**	**575,000**
Inflow from or outflow to aquifer storage	**0**	**0**	**60,000**	**0**
Total	**130,000**	**129,000**	**574,000**	**575,000**
Error (inflow minus outflow)	**1,000**		**-1,000**	

Three future simulations using different COA pumping rates were designed to represent scenarios of medium (I), large (II), and small (III) ground-water use. For simulation I, ground-water withdrawal from all city municipal-supply wells was maintained at known year-2000 rates for each year through 2040 (fig. 9), representing medium ground-water use. For simulation II (representing large ground-water use), city pumping was adjusted to simulate the use of ground-water withdrawal to meet all projected water demand, which is expected to rise substantially through 2040. For simulation III (representing small ground-water use), city pumping was adjusted to match projections of future ground-water use that assume surface water is available to meet much of the total water demand, resulting in decreased pumping. "Spikes" in the otherwise fairly smooth increase in projected ground-water withdrawals for simulation III (fig. 9) represent years of drought and correspondingly low surface-water availability. Greg Gates (written commun., 2001) provided all projections of future water demand and surface-water availability. Annual adjustments to COA pumping in the model were made by applying a multiplying factor to known year-2000 pumping rates (Bexfield and McAda, 2003).

Comparisons among the results for simulations I, II, and III indicate that the various scenarios of ground-water withdrawal had substantially different effects on water-level declines in the Albuquerque area and on the contribution of each water-budget component to the total budget for the ground-water system. Whereas water levels in all three simulations declined between 2000 and 2040 in some areas around Albuquerque, water levels in simulation III (small ground-water use) also rose over large areas (fig. 10). In simulation III (small ground-water use), the water table generally declined less than about 101 ft from steady state through 2040, as compared with 162 ft in simulation I (medium ground-water use) and 199 ft in simulation II (large ground-water use) (table 3). In addition to smaller water-level declines, the reduced pumping of simulation III resulted in substantially smaller inflow to the ground-water system from aquifer storage and river leakage than either simulation I or II. The cumulative retention of water in the river between 2000 and 2040 as a result of reduced pumping was about 732,000 acre-ft more than that for the medium ground-water use simulation and 872,000 acre-ft more than that for the large ground-water use simulation (table 3). The cumulative retention of ground water in storage in simulation III (small ground-water use) was 1,536,000 acre-ft more than that for the medium

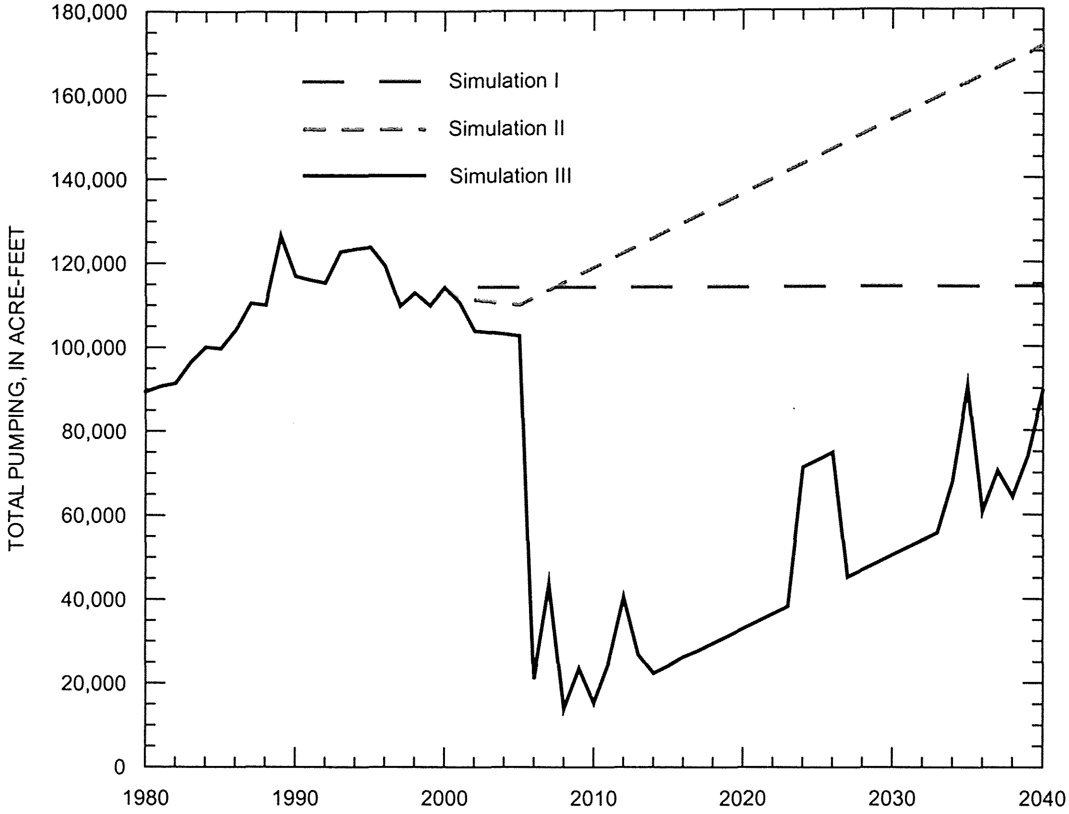


Figure 9. Annual City of Albuquerque pumping assigned for each simulation of future conditions using the McAda and Barroll (2002) model, 1980 to 2040 (from Bexfield and McAda, 2003, fig. 5).

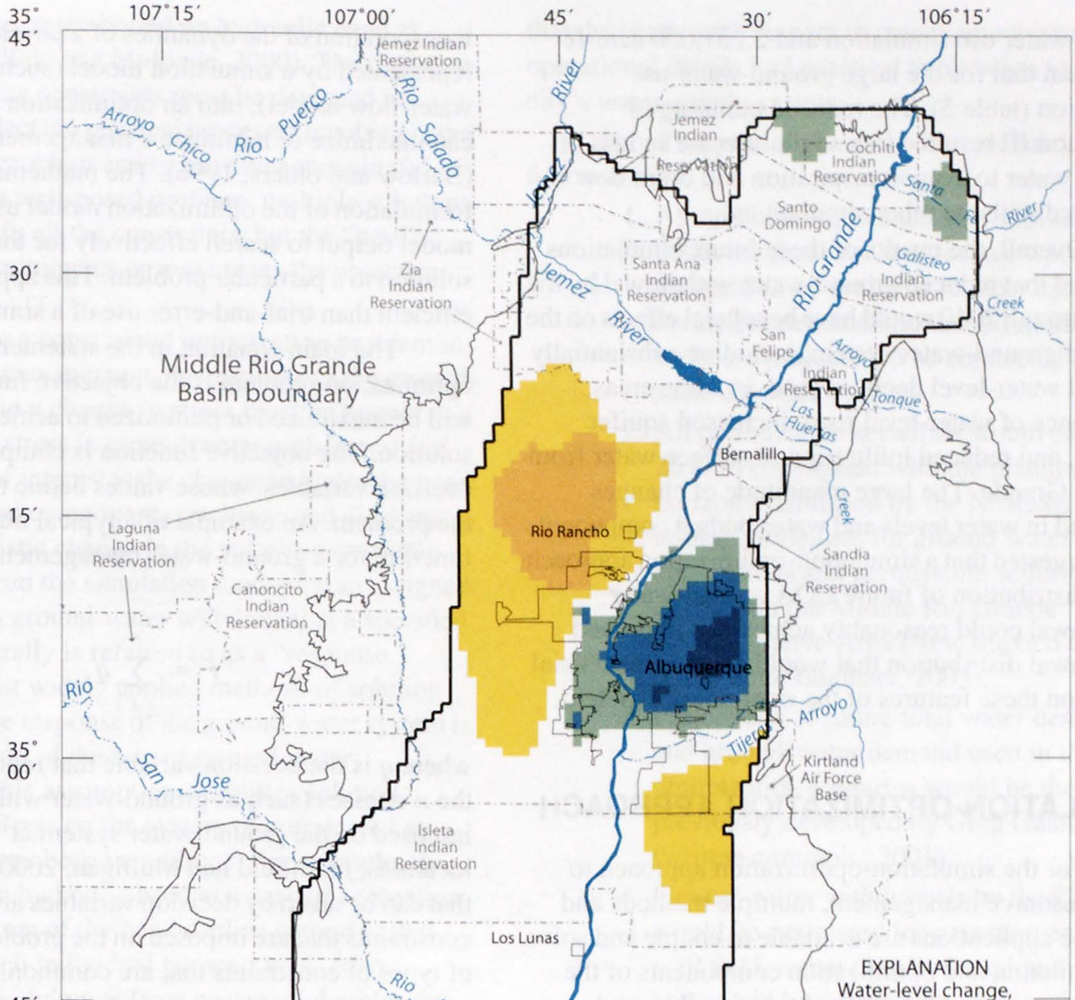


Figure 10. Simulated water-level change in the production zone (layer 5) between 2000 and 2040 for simulation III (small ground-water use) (from Bexfield and McAda, 2003, fig. 19).

ground-water use simulation and 2,257,000 acre-ft more than that for the large ground-water use simulation (table 3). The reduced pumping of simulation III resulted in a slight increase in loss of ground water to evapotranspiration and drain flow compared with the other simulations.

Overall, the results of these future simulations indicated that reduced ground-water withdrawal by the COA through 2040 would have beneficial effects on the regional ground-water system, including substantially reduced water-level declines (and, in some areas, occurrence of water-level rise), increased aquifer storage, and reduced infiltration of surface water from the Rio Grande. The large magnitude of changes observed in water levels and water-budget components also suggested that a simulation-optimization approach to the distribution of future COA ground-water withdrawal could reasonably achieve an improved withdrawal distribution that would enhance beneficial effects on these features of the river-aquifer system.

SIMULATION-OPTIMIZATION APPROACH

For the simulation-optimization approach to water-resource management, multiple methods and software applications are available to couple and solve the simulation and optimization components of the modeling system. The methods used in this study are described after an introduction to the general techniques of the simulation-optimization approach.

General Design of the Simulation-Optimization Approach

The simulation-optimization approach to water-resource management allows for the direct incorporation of the dynamics of a physical system, as represented by a simulation model (such as a ground-water-flow model), into an optimization program that can maximize or minimize a management objective (Barlow and others, 1996). The mathematical formulation of the optimization model uses simulation model output to search effectively for the "best" solution to a particular problem. This approach is more efficient than trial-and-error use of a simulation model.

The main equation in the statement of an optimization problem is the objective function, which will be maximized or minimized to achieve the desired solution. The objective function is composed of the decision variables, whose values define the solution of the problem. An example of a typical objective function for a ground-water management problem is:

$$f = \sum_{j=1}^{n} q_j \quad (1)$$

where q is the decision variable that represents one of the n stresses (such as ground-water withdrawal) imposed on the ground-water system at various locations, j (Ahlfeld and Mulligan, 2000). The values that can be taken by decision variables are restricted by constraints that are imposed on the problem. Examples of types of constraints that are commonly imposed on ground-water problems are individual stress bounds (such as allowable withdrawal rates from individual wells), bounds on total stress, head-bound constraints (such as allowable drawdown), head-difference constraints, and boundary-flux constraints. An example of a common constraint is:

$$h_i \le h_i^u \quad (2)$$

Table 3. Summary of major results for future simulations I, II, and III
[from Bexfield and McAda, 2003]

Simulation	95th percentile of water-table decline from steady state (in feet)	From 2000 to 2040, cumulative volume (in acre-feet) of:			
		Net inflow from river leakage	Net inflow from storage	Outflow to evapotrans-piration	Outflow to drain flow
I (medium pumping)	162	5,498,000	2,146,000	3,351,000	5,132,000
II (large pumping)	199	5,638,000	2,867,000	3,346,000	5,117,000
III (small pumping)	101	4,766,000	610,000	3,389,000	5,239,000

where h_i^u is the upper bound on hydraulic head at location i (Ahlfeld and Mulligan, 2000). The objective function and the constraints must be designed to accurately reflect the physical processes involved in the management problem and to provide a meaningful solution. For a well-posed problem, multiple solutions typically satisfy all the constraints, but the "best" solution also minimizes or maximizes the objective function.

To solve a constrained optimization problem in ground-water management, the response of the ground-water system to a change in stress must be known. Typically, the stress is ground-water withdrawal and the response of interest is the change in hydraulic head or water-budget components (recharge and discharge). The characteristic change in the system, commonly determined from the simulation model for an assigned unit change in ground-water withdrawal at a specified location, generally is referred to as a "response function." Most widely applied methods of solution assume that the response of the ground-water system is a linear function of the rate of ground-water withdrawal. This assumption simplifies solution because the effects on the system of withdrawal at various locations become additive. For example, the total decline in hydraulic head at a particular location becomes the sum of the head decline caused at that location by each individual pumped well. Also, doubling the withdrawal from each well doubles the total head decline. Whenever the assumption of linearity in response is used, its appropriateness for the system under study must be evaluated.

Simulation-Optimization Approach for the Middle Rio Grande Basin

As described in the "Introduction," the focus of the study described in this report is to determine the optimal distribution of projected ground-water withdrawals from COA municipal-supply wells that would help to achieve specific management objectives for the regional river-aquifer system of the MRGB. To construct a detailed simulation-optimization approach that was appropriate to the problem, certain parameters of the study had to first be defined. Specifically, decisions were required with respect to management horizons, projections of future water demand and availability, operational details for water delivery, and modeling techniques. Managers with the COA were included in discussions of study parameters to ensure that decisions with respect to management issues and operational details had practical application to the city's water-supply system.

Broad aspects of the study were defined as follows:

1. All optimization scenarios would start in 2006, the first year that surface water is assumed to be available to meet most municipal demand and that all municipal wells are projected to be connected into the same citywide system.
2. All optimization scenarios would end in 2040 to correspond with the planning horizon established by the NMOSE in issuing guidelines for ground-water permit applications and permissible water-level declines in the Middle Rio Grande Administrative Area (New Mexico Office of the State Engineer, 2003).
3. Projections of future total water demand and ground-water demand used in the optimization scenarios would be those previously developed by Greg Gates (written commun., 2001).
4. Ground-water withdrawals by the COA would be optimized for management by well field, rather than by individual well, and would be designed to assume that the number and geographical distribution of wells available in 2000 were available throughout the period of optimization.
5. Ground-water withdrawals would be optimized for management on an annual basis (rather than, for example, a monthly basis).
6. Management objectives would be related to components of the water budget, which would result in these budget components being involved in most response functions.
7. The McAda and Barroll model would be used without substantial modification (such as modifications to the number or length of stress periods or the sources and quantities of recharge) to generate all response functions.

With these guidelines, detailed design of methods for generating the response functions and for creating and solving the mathematical optimization models was possible.

Use of the Simulation Model to Generate Response Functions

Response functions for use in the optimization models of this study were generated with the McAda and Barroll model. Because management objectives for the optimization models were related to components of the water budget, response functions were needed to indicate how these components respond to a change in stress in the aquifer system. In addition, response functions were generated for hydraulic heads in the aquifer because constraints on water-level decline were included in some of the optimization models.

Generation of response functions for use in the optimization models required 26 simulations using the McAda and Barroll model—one simulation for each of the 25 COA well fields (to generate a separate characteristic response for a unit increase in ground-water withdrawal in each field) and one "base" simulation with constant ground-water withdrawal over time in each of the well fields. The base simulation provided the background conditions upon which a unit increase in withdrawal (unit stress) was added for each well field. Results of the base simulation were subtracted from results of each of the other 25 simulations to calculate the characteristic response for each well field.

The base simulation was designed to be fairly representative of typical hydrologic conditions projected to exist during the time period of interest for the optimization scenarios. By matching the typical hydrologic conditions as closely as possible, errors related to non-linearities in the ground-water-flow model were minimized. The simulation began with the hydraulic-head distribution from the McAda and Barroll model at the end of the winter 1999-2000 stress period. Most input parameters from the summer 1999 and winter 1999-2000 stress periods of the McAda and Barroll model were then duplicated without modification to lengthen the model to accommodate the period of interest. The exceptions were conditions in the Rio Grande and ground-water withdrawals by the COA. Average river conditions (stage and riverbed area) were calculated for the summer and winter stress periods from seasonal data in the McAda and Barroll model for 1990 to 2000; these average river conditions were used in all years of the base simulation. A constant annual rate of about 25,000 acre-ft for ground-water withdrawal by the COA was used in all years of the base simulation, with 76.2 percent of the withdrawal occurring during the summer stress period and 23.8 percent during the winter stress period (an average division of withdrawal determined from historical monthly data). This total annual withdrawal rate of 25,000 acre-ft is nearly equal to the average of the annual projected rates of withdrawal for the first 10 years after surface-water deliveries begin in 2006. The withdrawal for the base simulation was distributed among all COA wells in the same proportion that withdrawal was actually distributed during 2000.

In each of the other 25 simulations, the withdrawal rate for each well in a single well field was increased by 1,000 acre-ft for one year. Again, 76.2 percent of the increase was applied to the summer stress period (for 2006) and 23.8 percent was applied to the winter stress period (for 2006-07). All water-budget components were saved for each time step of the simulation, and hydraulic heads were saved for every cell of the model at the end of each winter stress period. Results from the base simulation were subtracted from the results of each of these 25 simulations to generate the response functions for each well field. For the water-budget components, the differences in water volume for each time step were summed to determine annual responses. Representative response functions for the Griegos and Leyendecker well fields, scaled by the number of wells in each field, are shown for water-budget components and water levels in figures 11 and 12, respectively. Because the Rio Grande and the riverside drains have a close hydraulic connection, the responses of these two components of the water budget were combined into a single response function (fig. 11). Also, any change in the river component of the water budget resulting from a change in recharge from the Jemez River was assumed to be negligible because of the large distance of all COA well fields from the Jemez River. Of the response functions generated for water levels, only those for the 25 simulation-model cells that were most affected by withdrawals in each of the 25 individual COA well fields were ultimately used in the optimization modeling, as discussed in more detail in the section describing optimization model 3.

As illustrated by the representative response functions of figures 11 and 12, the timing and magnitude of the greatest response of a particular aspect of the ground-water system can vary substantially depending on the location of the applied stress. Factors that can affect responses include horizontal distance from the site or feature of interest (such as the Rio Grande), aquifer properties between the location of applied stress and the site or feature of

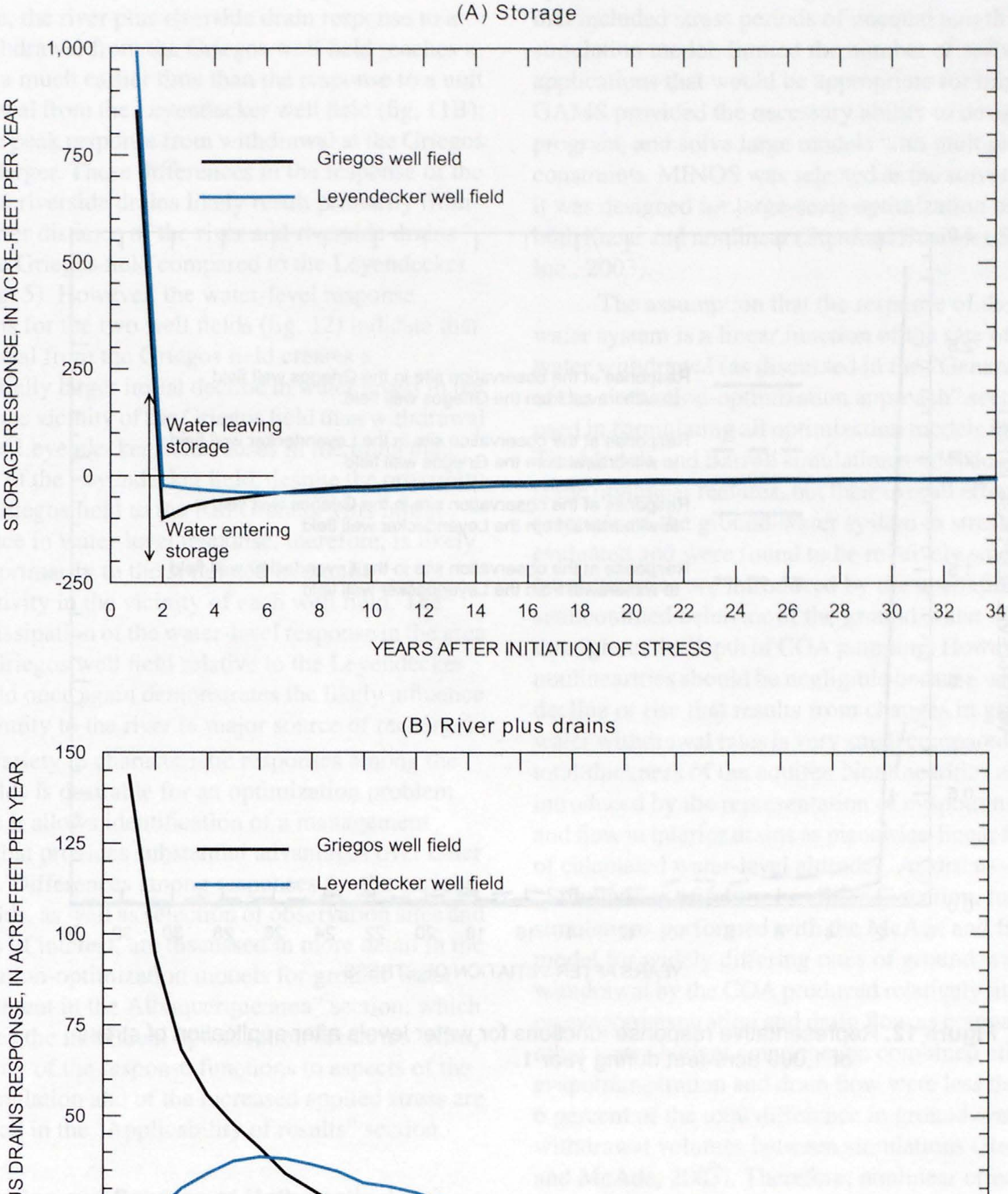


Figure 11. Representative response functions for the (A) storage and (B) river plus drains components of the water budget after application of stress of 1,000 acre-feet during year 1.

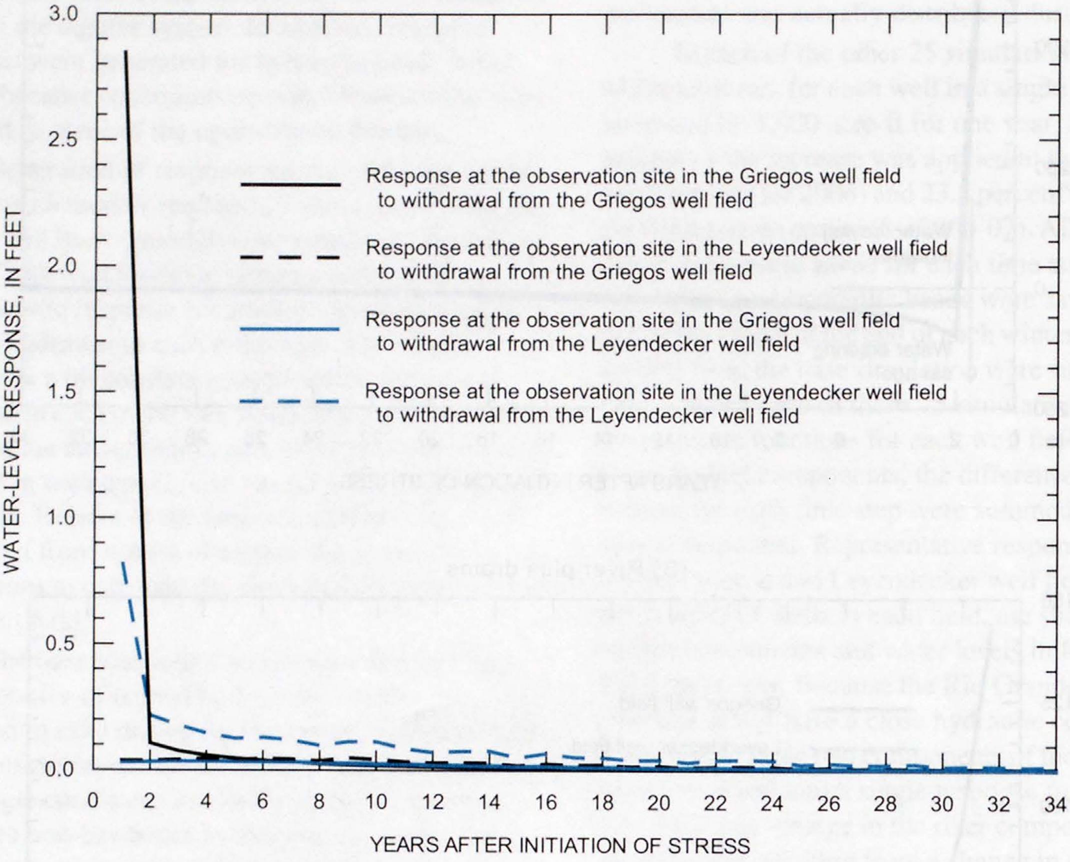


Figure 12. Representative response functions for water levels after application of stress of 1,000 acre-feet during year 1.

interest, and the depth interval of the applied stress. For example, the river plus riverside drain response to a unit withdrawal from the Griegos well field reaches a peak at a much earlier time than the response to a unit withdrawal from the Leyendecker well field (fig. 11B); also, the peak response from withdrawal at the Griegos field is larger. These differences in the response of the river and riverside drains likely result primarily from the shorter distance of the river and riverside drains from the Griegos field compared to the Leyendecker field (fig. 5). However, the water-level response functions for the two well fields (fig. 12) indicate that withdrawal from the Griegos field creates a substantially larger initial decline in water levels in the immediate vicinity of the Griegos field than withdrawal from the Leyendecker field causes in the immediate vicinity of the Leyendecker field, despite the proximity of the Griegos field to the Rio Grande. This initial difference in water-level response, therefore, is likely related primarily to the simulated hydraulic conductivity in the vicinity of each well field. The faster dissipation of the water-level response in the area of the Griegos well field relative to the Leyendecker well field once again demonstrates the likely influence of proximity to the river (a major source of recharge).

Variety in characteristic responses among the well fields is desirable for an optimization problem because it allows identification of a management option that provides substantial advantages over other options. Differences among responses for the various well fields, as well as selection of observation sites and features of interest, are discussed in more detail in the "Simulation-optimization models for ground-water management in the Albuquerque area" section, which describes the individual optimization scenarios. Also, sensitivity of the response functions to aspects of the base simulation and of the increased applied stress are addressed in the "Applicability of results" section.

Formulation and Solution of Mathematical Optimization Models

Formulation and solution of all optimization models for this study were performed using the General Algebraic Modeling System (GAMS), a mathematical programming software package (GAMS Development Corporation, 1998), coupled with the MINOS solver (Stanford Business Software, Inc., 2003). The relatively large number of decision variables (25 stress sites with different withdrawal rates for each of 34 years) and constraints involved in the optimization models, along with other complexities that included stress periods of unequal length in the simulation model, limited the number of software applications that would be appropriate for this study. GAMS provided the necessary ability to design, program, and solve large models with multiple constraints. MINOS was selected as the solver because it was designed for large-scale optimization problems, both linear and nonlinear (Stanford Business Software, Inc., 2003).

The assumption that the response of the ground-water system is a linear function of the rate of ground-water withdrawal (as discussed in the "General design of the simulation-optimization approach" section) was used in formulating all optimization models in GAMS. The McAda and Barroll simulation model does include some nonlinear features, but their overall effects on the response of the ground-water system to stresses were evaluated and were found to be relatively small. Nonlinearities are introduced by the unconfined or semiconfined behavior of the ground-water system throughout the depth of COA pumping. However, these nonlinearities should be negligible because water-level decline or rise that results from changes in ground-water withdrawal rates is very small compared with the total thickness of the aquifer. Nonlinearities also are introduced by the representation of evapotranspiration and flow in interior drains as piecewise-linear functions of calculated water-level altitudes. As discussed in the "Simulations of future conditions" section, future simulations performed with the McAda and Barroll model for widely differing rates of ground-water withdrawal by the COA produced relatively little effect on evapotranspiration and drain flow as compared with other water-budget components; combined effects on evapotranspiration and drain flow were less than about 6 percent of the total difference in ground-water withdrawal volumes between simulations (Bexfield and McAda, 2003). Therefore, nonlinear effects from the model representation of these two aspects of the ground-water system were expected to be small. One other potential source of nonlinear effects was predicted to be the model-simulated rise of water levels back to altitudes assigned to model cells that had previously gone dry. The re-wetting option in the layer-property flow package of MODFLOW-2000 (Harbaugh and others, 2000) was not used because experimental model simulations that included it indicated problems with solution instability. Therefore, water levels were merely allowed to rise above the top of the uppermost layer that had stayed wet throughout the simulation up to that time. The degree to which nonlinearities in the simulation model caused results of model simulations and their associated optimization models to diverge is addressed in the "Simulation-optimization models for ground-water management in the Albuquerque area" section.

For this study, the general design of the optimization models in GAMS involved an objective function that minimized the sum of particular effects of ground-water withdrawals on the ground-water system for all years. For each optimization model, constraints included the total annual demand to be met by ground-water withdrawal, the total annual capacity of each well field, and the minimum annual withdrawal required from each well field to maintain equipment in working order. Additional constraints related to water-level altitudes, water-quality issues, and water-rights issues were applied to selected models, as described below in the "Simulation-optimization models for ground-water management in the Albuquerque area" section.

Effects on the ground-water system were calculated using the individual response functions simulated by the McAda and Barroll model for a single-year increase in withdrawal of 1,000 acre-ft per well in each of the 25 COA well fields. The response functions were scaled by coefficients that GAMS adjusted for withdrawal at each well field during each year when solving the optimization. The total response of a particular water-budget component or hydraulic head in a given year is defined as the total effect of all withdrawals during that year and previous years on the budget component or head. For the first year of the model, this total response equals the sum of the products of the first year's response from withdrawal at each well field with the coefficient assigned by GAMS for the withdrawal at that field, giving:

$$Total\ response_1 = \sum_{j=1}^{25} (c_{j,1})(r_{j,1}) \quad (3)$$

where $c_{j,1}$ is the GAMS-adjusted coefficient for withdrawal at well field j in year 1 and $r_{j,1}$ is the response of the ground-water system in the first year after withdrawal at well field j. For the second year of the model, the total response equals the sum of the response from withdrawal in year 2 and the residual response from withdrawal in year 1, which gives:

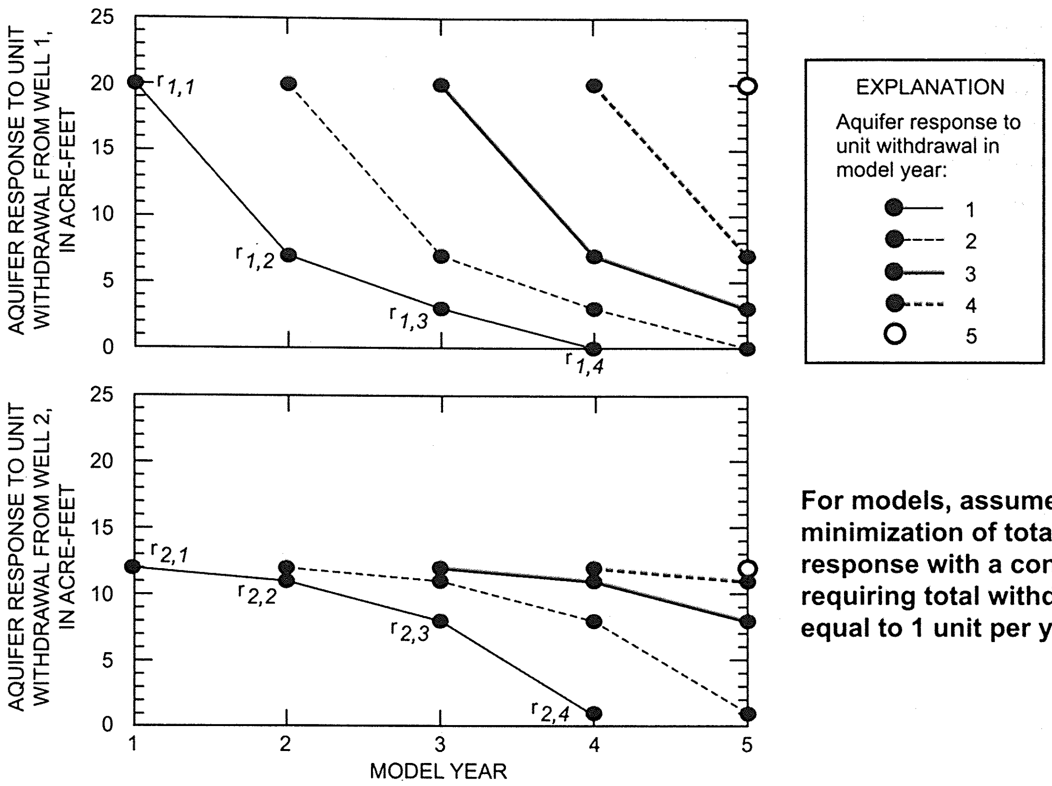
$$Total\ response_2 = \sum_{j=1}^{25} [(c_{j,2})(r_{j,1}) + (c_{j,1})(r_{j,2})] \quad (4)$$

where $c_{j,2}$ is the GAMS-adjusted coefficient for withdrawal at well field j in year 2 and $r_{j,2}$ is the response of the ground-water system in the second year after withdrawal at well field j. This same general approach works for every year of the model because all boundary conditions are assumed to be constant, meaning that the effect of a unit withdrawal in year 2 on the water budget and hydraulic heads in year 3 is assumed to be exactly the same as the effect of a unit withdrawal in year 1 on the water budget and hydraulic heads in year 2. Therefore, to calculate the total response of the ground-water system in a particular year, the GAMS-adjusted coefficient for that year is multiplied by the response for the first year after withdrawal, whereas the GAMS-adjusted coefficient for the previous year is multiplied by the response for the second year after withdrawal, the GAMS-adjusted coefficient for the year before that is multiplied by the response for the third year after withdrawal, and so on. Then, the overall response of the ground-water system to withdrawal in all years is the sum of the total response for each individual year. An example of the calculation of the total response of an imaginary system to withdrawal from two wells during a 5-year period is shown in figure 13.

For each optimization model of this study, GAMS, in combination with MINOS, determines the optimal coefficient for withdrawal at each well field during each year for an equation of the same general form as equation 3. The final coefficients are chosen to satisfy the objective function within the constraints of the individual optimization model.

Selection of Time Horizons

As discussed earlier in the "Simulation-optimization approach for the Middle Rio Grande Basin" section, the optimization models for this study were intended to provide the optimal distribution of ground-water withdrawals from COA wells between 2006 and 2040 (a total of 34 years) to achieve particular management objectives for the river-aquifer system of the basin. The end of the time period was selected to



For models, assume minimization of total aquifer response with a constraint requiring total withdrawal equal to 1 unit per year

Solution for a 2-year model:

Final adjusted coefficients, $c_{j,t}$

Well, j	Model year, t = 1	2
1	0.0	0.0
2	1.0	1.0

Solution for a 5-year model:

Final adjusted coefficients, $c_{j,t}$

Well, j	Model year, t = 1	2	3	4	5
1	1.0	1.0	1.0	0.0	0.0
2	0.0	0.0	0.0	1.0	1.0

Calculations for the 2-year model:

$$\text{Total response}_{2\ years} = [\text{Total response}_1] + [\text{Total response}_2]$$

$$\text{Total response}_{2\ years} = \sum_{j=1}^{2} \{[(c_{j,1})(r_{j,1})] + [(c_{j,2})(r_{j,1}) + (c_{j,1})(r_{j,2})]\}$$

$$= \{[(0.0)(20)] + [(0.0)(20) + (0.0)(7)]\} + \{[(1.0)(12)] + [(1.0)(12) + (1.0)(11)]\} = 0 + 35 = 35$$

Calculations for the 5-year model:

$$\text{Total response}_{5\ years} = [\text{Total response}_1] + [\text{Total response}_2] + [\text{Total response}_3] + [\text{Total response}_4] + [\text{Total response}_5]$$

$$\text{Total response}_{5\ years} = \sum_{j=1}^{2} \{[(c_{j,1})(r_{j,1})] + [(c_{j,2})(r_{j,1}) + (c_{j,1})(r_{j,2})] + [(c_{j,3})(r_{j,1}) + (c_{j,2})(r_{j,2}) + (c_{j,1})(r_{j,3})] + [(c_{j,4})(r_{j,1}) + (c_{j,3})(r_{j,2}) + (c_{j,2})(r_{j,3}) + (c_{j,1})(r_{j,4})] + [(c_{j,5})(r_{j,1}) + (c_{j,4})(r_{j,2}) + (c_{j,3})(r_{j,3}) + (c_{j,2})(r_{j,4})]\}$$

$$= \{[(1.0)(20)] + [(1.0)(20) + (1.0)(7)] + [(1.0)(20) + (1.0)(7) + (1.0)(3)] + [(0.0)(20) + (1.0)(7) + (1.0)(3) + (1.0)(0)] + [(0.0)(20) + (0.0)(7) + (1.0)(3) + (1.0)(0)]\} + \{[(0.0)(12)] + [(0.0)(12) + (0.0)(11)] + [(0.0)(12) + (0.0)(11) + (0.0)(8)] + [(1.0)(12) + (0.0)(11) + (0.0)(8) + (0.0)(1)] + [(1.0)(12) + (1.0)(11) + (0.0)(8) + (0.0)(1)]\} = 90 + 35 = 125$$

Figure 13. Example calculations of the total response of a hypothetical system to withdrawal from two wells.

correspond with the planning horizon established by the NMOSE in issuing guidelines for ground-water permit applications and permissible water-level declines in the Middle Rio Grande Administrative Area (New Mexico Office of the State Engineer, 2003). However, the selection of 2040 as the end of the management time horizon is not intended to imply that effects on the ground-water system beyond that year are of no consequence. On the contrary, the management objectives of this study, which relate to mitigation of the deleterious effects of ground-water withdrawal on river infiltration and (or) ground-water levels, would generally be perceived by regional water managers as long-term objectives with no specific ending date. Therefore, the ideal models for this study would take into account the full response of the ground-water system to an individual stress, even when the time necessary for that response to dissipate completely extended beyond the chosen management horizon through 2040. Only then could a ground-water withdrawal distribution be determined that would have the optimal effect on a system response being targeted for long-term management.

Once response functions had been generated with the McAda and Barroll model, they were evaluated to determine how much of the complete response of the ground-water system to the applied stress was captured during 34 years. Although the effects of increased withdrawal of 1,000 acre-ft for a single year (mid-March 2006 to mid-March 2007) had almost entirely dissipated for several well fields 34 years later, the effects of the increased withdrawal in many other well fields were still quite substantial. For example, in year 34, the response of the river plus drains component of the water budget to withdrawal from the Griegos well field was only about 2.6 percent of the maximum response; however, the response to withdrawal from the Leyendecker well field was still about 18.8 percent of the maximum response (fig. 11). The length of time required for river-aquifer system responses to dissipate completely is a reflection of the distances between the locations of applied stress and of system response (for example, the Rio Grande), in addition to the physical properties of the system between those two points. In the MRGB, the response functions indicate that the river-aquifer system commonly continues to adjust to moderate stresses even decades after these stresses are applied.

Because the long-term effects of ground-water withdrawals are relevant to this study, the response functions generated from the simulation model for use in the optimization models were extended to capture as much information as reasonably possible about the overall response of the ground-water system. Therefore, the model simulations and associated response functions were extended for 54 years beyond the application of the unit stress. Simulations were terminated at this time because of the likely limitations of the predictive ability of the simulation model so far beyond the last year when data observations were available for input and because of issues with solution stability after such a long period of sustained withdrawals, particularly at basin margins close to sites of withdrawal. For all but five well fields, at least 75 percent of the effects on aquifer storage from the single year of increased withdrawal had dissipated after 54 years. Therefore, the selected length of the response functions, which is a result of the time horizon for response of the river-aquifer system in the MRGB to an applied stress, should be sufficient to capture all but a relatively small part of system response.

Efforts to design study methods that would account for the long-term response of the river-aquifer system to stresses resulted in extension of the time horizons of the optimization models as well as of the response functions. To include all 54 years of information provided by the response functions in the calculations performed by the optimization models, the models also had to be extended in length to at least 54 years. However, the nature of the optimization formulations necessitated an even further extension of the time horizon of the models to take full advantage of information provided by the response functions and arrive at the optimal long-term solution for each model.

As described in the preceding section, in any particular year x, only the response of the ground-water system in the first year after withdrawal is relevant to the calculation of the effects of withdrawal during year x. In year $(x+1)$, only the response of the ground-water system in the second year after withdrawal is relevant to the calculation of the continuing effects of withdrawal during year x. If the model ended in year $(x+1)$, the optimal withdrawal distribution determined for year x would be determined on the basis of only the first 2 years of all response functions, rather than on the basis of the entire long-term response of the system (that is, all years of the response functions). This concept is illustrated in the example calculations for the 2-year model in figure 13. The approach of ending the model at the final year of interest is appropriate when effects on the ground-water system beyond the final year of the optimization model are irrelevant to the objectives of the model. However, when the long-term effects of withdrawal beyond the years being modeled are relevant to the objectives of an investigation, the optimal withdrawal distribution during each year of the model should be selected on the basis of the long-term response of the system, to the full extent of available knowledge (rather than on the basis of only a part of the known response). Inclusion of the full extent of available knowledge in the withdrawal distribution selected for each year of the model requires extending the model beyond the final year of interest. The model must be extended to a total length equaling the length of the period of interest plus the length of the response functions, minus 1 (because any individual year of interest overlaps with the first year of the response function). This approach is illustrated by the 5-year model in figure 13. Extension of the model from 2 to 5 years resulted in a change in the optimal withdrawal distribution for years 1 and 2, which are assumed to be the years of interest and which are the only years of the model that have the full effect of withdrawal on the system taken into account.

For this study, which has long-term objectives, consideration of the full extent of knowledge about the effects of withdrawal was important for each year of the 2006-40 management period. Therefore, the optimization model time horizon was extended to be 34 years (the length of the period of interest) plus 54 years (the length of the response functions), minus 1, which equals a total length of 87 years.

To summarize, the long-term management objectives of this study necessitated adjustment to the time horizons used in the optimization modeling. Long-term management objectives analogous to the ones of this study are common in simulation-optimization modeling for water-resource management, and the issues addressed here should be considered when approaches are designed to solve similar management problems elsewhere. For this study, even though the current planning horizon for the basin requires that results be provided for only 34 years, the goal to provide the optimization models with information about the complete response of the system to individual stresses for this study required an extension of the time horizon for the response functions to 54 years. Then, the goal to provide the optimization model with the same complete information on system response during year 54 as it had during year 1 required that the length of the optimization model be extended to 87 years. Within the optimization model, the response after 54 years of all components of the ground-water system to the single year of increased withdrawal was manually set to zero. This effectively told the optimization model that all system responses after 54 years were negligible, which appeared reasonable based on the simulated response functions. Therefore, the well field that had the most advantageous effect on the river-aquifer system through year 54 was assumed in the model to still have the most advantageous effect on the system for any years beyond 54. Although the optimization models designed for this study have a total length of 87 years, results for only the first 34 years are appropriate to the scenarios being investigated, and so only those results are reported here.

SIMULATION-OPTIMIZATION MODELS FOR GROUND-WATER MANAGEMENT IN THE ALBUQUERQUE AREA

As discussed in the "Introduction," the COA plans to begin using surface water from the Rio Grande as its main municipal supply in 2006. At that time, all city well fields are expected to be interconnected, and Albuquerque will have the ability to distribute supplemental ground-water withdrawals among the well fields in a manner that will achieve particular management objectives. In a broad sense, the management objectives addressed in this study are to satisfy the water demand of city customers while minimizing adverse effects on the river-aquifer system. One adverse effect is substantial decline of water levels in the aquifer (depletion of aquifer storage), which can potentially result in increased drilling and pumping costs for Albuquerque and neighboring municipalities, deterioration of the quality of available ground water, and land-surface subsidence. Induced infiltration of water from the Rio Grande can also be considered an adverse effect because, although it helps to maintain water levels in the aquifer, it reduces the availability of surface water for downstream users and habitat preservation.

Other than aquifer storage, the component of the overall hydrologic system of the MRGB that responds substantially to ground-water withdrawals is the river system—in particular, the Rio Grande and associated riverside and interior ground-water drains. With sustained ground-water withdrawals, aquifer storage is reduced and ground-water levels decline across an area that becomes more extensive through time. Water-level declines continue to propagate until the associated changes in hydraulic gradient result in sufficient reductions in the rates of natural discharge and (or) increases in the rates of induced recharge to balance the rate of ground-water withdrawal—a condition that may never be achieved. The rates of most sources of recharge to the Santa Fe Group aquifer system (such as mountain-front, tributary, and subsurface recharge and canal, crop-irrigation, and septic-field seepage) are relatively fixed in magnitude over time scales of decades or longer and are simulated in the McAda and Barroll model as specified inflows that cannot change as ground-water levels decline. The primary hydrologic features in the MRGB that can provide additional recharge to the aquifer system when ground-water levels decline are the Rio Grande and the riverside drains. (Some additional recharge could also be induced from the Jemez River, Jemez Canyon Reservoir, and Cochiti Reservoir (fig. 1), but these features are more distant from Albuquerque and less extensive.) Similarly, the discharge features that can be affected by ground-water-level declines are located in the inner valley of the Rio Grande. These features are the Rio Grande, the interior and riverside ground-water drains, and the areas of riparian evapotranspiration. Therefore, other than changes in aquifer storage, most of the effects of ground-water withdrawal in the basin can be observed in changes in the rates of recharge from the Rio Grande and riverside drains or changes in the rates of discharge through ground-water drains and evapotranspiration.

All ground-water withdrawal by the COA has an indirect effect on the features of the river system of the MRGB as described above. The magnitude and timing of that effect depend on the locations and rates of ground-water withdrawal and the aquifer properties between the locations of withdrawal and the features of the river system. When the city begins drawing water from the Rio Grande for direct delivery to customers, each acre-foot of decreased ground-water withdrawal will be substituted with an acre-foot of surface-water withdrawal. Therefore, city water use will have a more immediate, direct effect on the river system and on the availability of surface water for downstream use or for aquifer recharge. In contrast, the associated decrease in the use of ground water will allow water levels in the aquifer to rise over time, which will decrease the quantity of induced infiltration of water from the river system. Because COA water-supply wells are located at various distances from the river system in aquifer materials with varying properties, the distribution of ground-water withdrawal among these wells can influence how quickly water levels in the aquifer recover and how greatly the river system of the MRGB is affected by ground-water withdrawals. In general, when ground water is withdrawn from wells that have a good connection to the river system, induced infiltration occurs relatively quickly and is relatively large, which allows for the use of less water from aquifer storage and results in less water-level decline. However, this pumping strategy also results in less water being available in the river at any particular time for downstream uses. When ground water is instead withdrawn from wells that have a poor connection to the river, effects on the river system generally are delayed and drawn out in time, resulting in a smaller effect at any given point. However, more water is drawn from aquifer storage, causing greater water-level declines. Response functions generated by the McAda and Barroll model for COA well fields help to illustrate these concepts and are discussed below.

The five optimization models of this study are designed to explore distributions of ground-water withdrawal that can address the two primary management objectives for the water resources of the MRGB discussed above, given certain management constraints. In particular, withdrawal strategies are investigated that could (1) minimize water-level decline/maximize water-level recovery in the aquifer, (2) minimize the quantity of infiltration induced from the river system, or (3) be a combination of (1) and (2). Also, the magnitude of the effects that various withdrawal strategies can have on the water budget and water levels of the aquifer system is examined. As described below and shown in table 4, optimization models 1, 3, and 4 have objectives related to minimizing net depletion of aquifer storage and, by extension, overall water-level decline. Optimization model 2 has an objective related to minimizing effects on the river system. Optimization model 5 combines the two primary objectives. The simulation model included in the simulation-optimization techniques used here is not capable of simulating detailed river management throughout the basin or exact river conditions for a particular day and location, but it is capable of simulating the overall effects of ground-water management on the river system under typical conditions. Therefore, although the techniques used in this study do not provide guidance on day-to-day management of the water resources of the basin, they do provide insight into the timing and magnitude of the response of the various components of the hydrologic system to imposed stresses, which is essential to overall management to achieve primary objectives.

All five optimization models described in the following sections were determined to be feasible, and the model output for each was evaluated for the optimal distribution of ground-water withdrawal each year, the overall effect on water-budget components and water levels (when relevant), and the apparent validity of the results when compared with the response functions. The optimal distribution of ground-water withdrawal for each model was then input to a simulation using the McAda and Barroll model, and the effects on the ground-water system predicted by the optimization model and the simulation model were compared. This comparison indicated the general magnitude of nonlinearity in the representation of the aquifer system in the McAda and Barroll model, and, therefore, the appropriateness of using a linear approximation of the system. Results of the simulations using optimal withdrawal distributions also were compared with results using the withdrawal distribution of 2000 (that is, the proportion of total withdrawal drawn from each well field in 2000) for each year through 2040. This comparison was used to examine the degree to which management objectives could be better met by using the solutions to the optimization models.

Table 4. Characteristics of each optimization model

Model number and name	Objective	Constraints
1 Minimize net depletion of aquifer storage	Minimize use of water from aquifer storage for all years (2006 to 2040)	Meet projected annual ground-water demand Do not exceed maximum annual capacity for any well field Withdraw at least 40 acre-feet from each well annually
2 Minimize net infiltration from the Rio Grande	Minimize leakage from the river system for all years (2006 to 2040)	Same as model 1
3 Minimize net depletion of aquifer storage, with water-level constraints	Minimize use of water from aquifer storage for all years (2006 to 2040)	Same as model 1, plus: Do not produce more than the maximum annual water-level decline of 2.5 feet at any observation site
4 Minimize net depletion of aquifer storage, with constraints on water levels and arsenic concentrations	Minimize use of water from aquifer storage for all years (2006 to 2040)	Same as models 1 and 3, plus: Do not allow the arsenic concentration of blended ground water to exceed the maximum concentration of 10 micrograms per liter during any year
5 Minimize net depletion of aquifer storage after eliminating river "debt"	Minimize leakage from the river system until river "debt" owed by the City of Albuquerque is eliminated, then minimize use of water from aquifer storage for all remaining years	Same as models 1 and 3, plus: Once river "debt" is first eliminated, do not allow the accumulation of any additional river "debt"

Optimization Model 1: Minimize Net Depletion of Aquifer Storage

For the first optimization model, the management objective was to determine the distribution of withdrawal from COA well fields that would minimize overall depletion of aquifer storage through 2040 (table 4). In effect, minimizing overall depletion of aquifer storage would minimize water-level decline (or maximize water-level rise) across the entire region as a whole, without regard to spatial considerations. This approach allowed the problem of water-level decline to be addressed without requiring individual response functions for the change in water level in each model cell. The decision variables for the model were, therefore, the annual declines in the overall volume of aquifer storage caused by increased withdrawal in each city well field for each year, giving an objective function to be minimized of:

$$f = \sum_{t=1}^{87} \sum_{j=1}^{25} (c_{j,t})(s_{j,t}) \qquad (5)$$

where $c_{j,t}$ is the GAMS-assigned coefficient of ground-water withdrawal for each of the 25 well fields (j) during each of the 87 years of the model (t), and $s_{j,t}$ is the change in aquifer storage (storage response) for each well field during each year as a result of the unit increase in withdrawal (1,000 acre-ft for 1 year). The values of the storage-response variable, $s_{j,t}$, were determined as described in the "Use of the simulation model to generate response functions" section. The coefficient of withdrawal, $c_{j,t}$, was restricted to values of zero or greater, signifying in GAMS that ground water was being withdrawn from the aquifer; negative values, which would have signified the injection of water, were not permitted.

All three constraints in model 1 were directly related to the required ground-water withdrawals (table 4). The first constraint was that the predicted ground-water demand for each year be met. This constraint was achieved by placing a lower bound on the total withdrawal for each year that equaled the ground-water demand for the corresponding year. The ground-water demand as projected for 54 years (through 2060) by Greg Gates (written commun., 2001) was used. However, his annual projections by calendar year were adjusted to apply to years running from mid-March to mid-March to match the design of stress periods in the McAda and Barroll model. Because no projections were available beyond 54 years, the slope of the demand curve for the last several years of available projections was used to extend the demand curve out to the end of the model; no attempt was made to duplicate periods of drought that were built into the first 54 years of projections (fig. 14). An upper bound on ground-water withdrawal was not required in the optimization model because, in this case, the objective function dictates that withdrawal not be any greater than necessary. The second constraint was that the maximum annual capacity for a well field (determined from files of the COA, including historical withdrawal data and measured capacities) not be exceeded in any year. This constraint was achieved by placing an upper bound on the annual withdrawal from each well field that equaled the annual well field capacity (table 5). The well field capacity was assumed to be constant for each well field throughout the time period of the model. The third constraint was that a certain minimum quantity of water be withdrawn from each well field during each year to maintain equipment in working order. The lower bound on withdrawal from each well field was assigned to ensure that the minimum withdrawal from each well was 40 acre-ft/yr. This initial optimization model was intended to demonstrate which well fields cause the least depletion of aquifer storage for a unit increase in ground-water withdrawal over the period of simulation (as simulated by the McAda and Barroll model) and how much depletion would result when an optimal distribution of withdrawal was used, as opposed to a distribution similar to the one used in 2000. By keeping the constraints on this optimization model relatively simple, a fairly general blueprint for minimizing water-level declines could be achieved. Also, the results of a relatively simple model could be compared with the response functions generated from the simulation model to determine whether the results were reasonable and whether the formulation of the model was correct. To keep the first model sufficiently simple, only three relatively minor constraints were applied.

The first optimization model required only one set of response functions. These response functions were for the effect of withdrawal from an individual well field on the storage component of the water budget for the aquifer system. The cumulative response over time of aquifer storage obtained from the McAda and Barroll model (as described in the "Use of the simulation model to generate response functions"

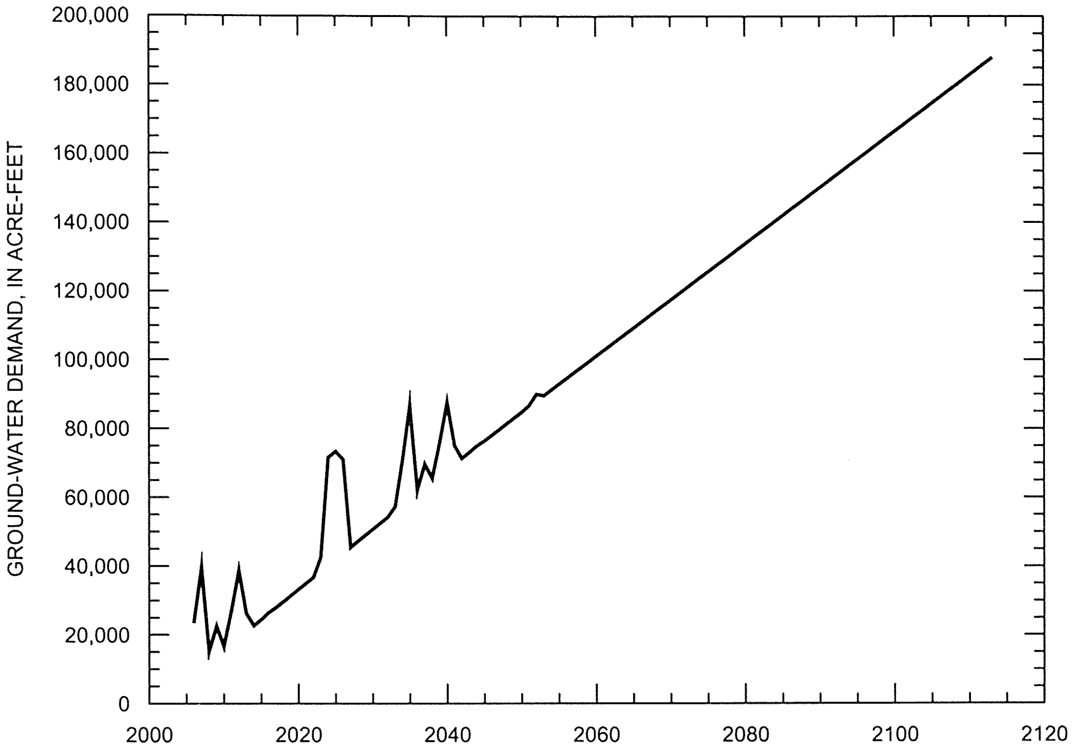


Figure 14. Projected ground-water demand curve for all optimization models.

Table 5. Annual well-field capacities used for all optimization models

[All values are in thousands of acre-feet]

Well field (fig. 5)	Capacity	Well field (fig. 5)	Capacity
Atrisco	11.27	Ponderosa	23.58
Burton	23.11	Ridgecrest	23.56
Charles	28.89	San Jose	7.06
College	6.32	Santa Barbara	5.52
Coronado	8.15	Thomas	24.45
Duranes	24.54	Vol Andia	30.24
Gonzales	11.24	Volcano Cliffs	11.60
Griegos	10.56	Walker	14.44
Leavitt	8.96	Webster	9.93
Leyendecker	16.32	West Mesa	9.24
Lomas	11.64	Yale	13.35
Love	20.33	Zamora	7.93
Miles	4.15		

section) for each COA well field is shown in figure 15; the functions have been scaled by the number of wells in each field to indicate the response per well. The functions in figure 15 display the same storage response information as presented for two example well fields in figure 11A, except that the functions in figure 15 are cumulative. (The cumulative storage responses shown in figure 15 decrease over time because using water from storage to satisfy the ground-water withdrawal during the first year makes a positive contribution to the cumulative response, whereas the subsequent replenishment of aquifer storage through leakage of river water to the aquifer system is a negative term in the summation.) This graphical method of presenting the storage response emphasizes the overall, long-term effect of withdrawal from any individual well field on aquifer storage. Table 6 lists the cumulative effect per well on aquifer storage through the last year of the response function (year 54) for each well field, ranked from the smallest to the largest effect. Because response functions for the river plus drains component of the water budget were needed for optimization model 2 and had already been generated for that purpose, they were used to calculate the effects of the solution to optimization model 1 on the river system. However, the response functions for the river plus drains are not discussed in detail until the section on optimization model 2 below.

As discussed briefly above in the "Use of the simulation model to generate response functions" section, the response of aquifer storage to withdrawal from different COA well fields can vary substantially, depending on the location of the applied stress both within the hydraulic-conductivity field of the simulation model and in relation to major hydrologic features. The information in figure 15 and table 6 clearly indicates the differences among the responses of aquifer storage to withdrawal from the various well fields and provides insight into operation of the hydrologic system as represented by the McAda and Barroll model.

Each cumulative storage response in figure 15 shows a similar overall pattern, wherein the volume of water in aquifer storage is immediately depleted by a quantity approaching the 1,000-acre-ft increase in withdrawal in year 1, and then gradually is replenished subsequent to the year in which the 1,000-acre-ft increase was applied. However, the magnitude of initial storage depletion and the speed of storage recovery differ substantially. As might be expected, these differences appear to be closely related to the general distance of the well field from the Rio Grande (the major surface drainage of the area) and the ease of communication between the location of the well field and the river, as specified in the McAda and Barroll model through hydraulic conductivity and horizontal-flow barriers. For example, withdrawals from the San

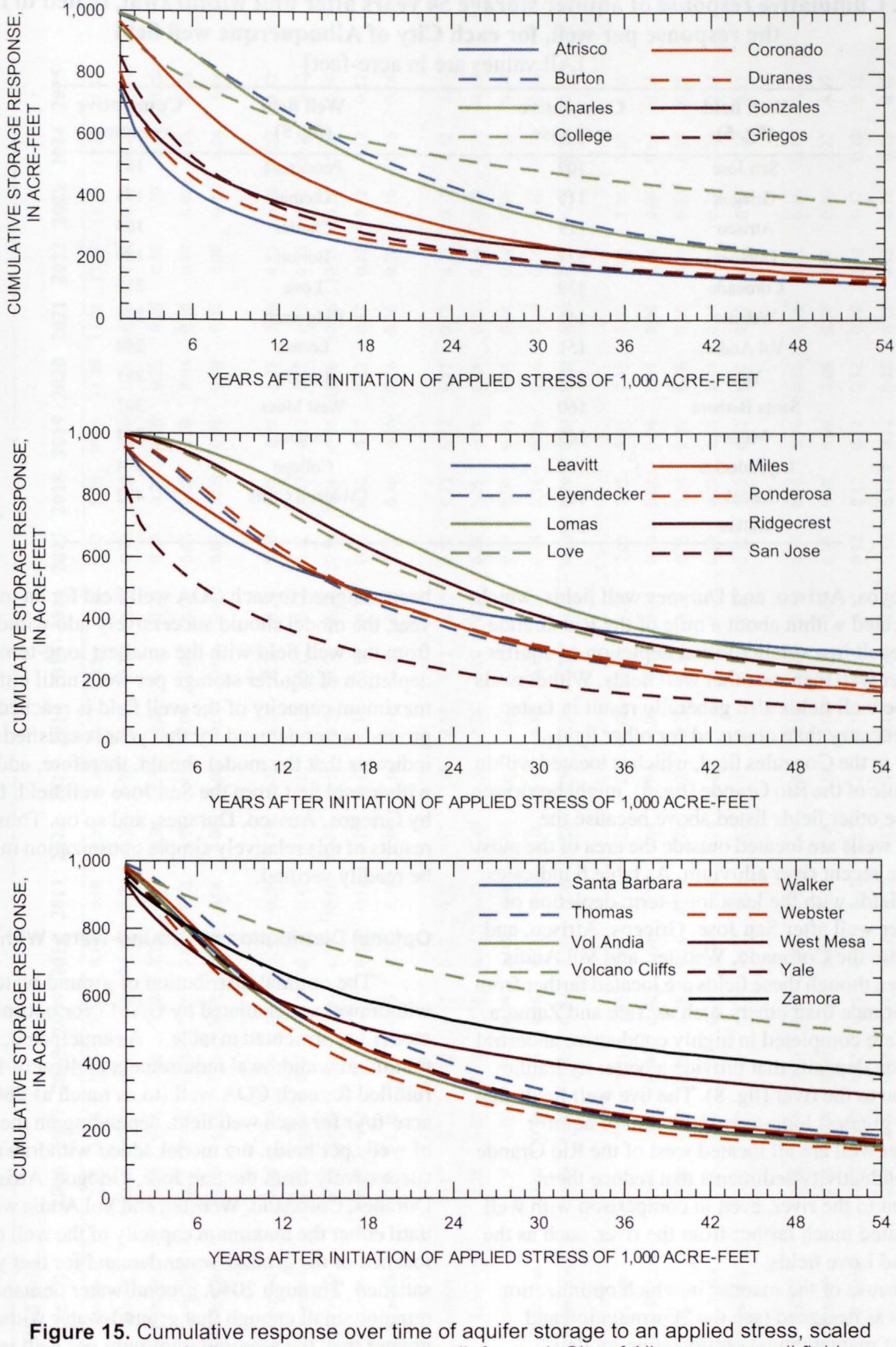


Figure 15. Cumulative response over time of aquifer storage to an applied stress, scaled to indicate the response per well, for each City of Albuquerque well field.

Table 6. Cumulative response of aquifer storage 54 years after unit withdrawal, scaled to indicate the response per well, for each City of Albuquerque well field

[All values are in acre-feet]

Well field (fig. 5)	Cumulative response	Well field (fig. 5)	Cumulative response
San Jose	109	Ponderosa	180
Griegos	116	Thomas	184
Atrisco	119	Charles	184
Duranes	127	Burton	189
Coronado	139	Love	215
Webster	141	Ridgecrest	221
Vol Andia	151	Lomas	248
Yale	159	Leavitt	285
Santa Barbara	160	West Mesa	301
Miles	165	Zamora	364
Leyendecker	166	College	374
Gonzales	167	Volcano Cliffs	482
Walker	170		

Jose, Griegos, Atrisco, and Duranes well fields, which are all located within about a mile of the Rio Grande (fig. 5), result in a smaller initial depletion of aquifer storage per well than the other well fields. Withdrawals from these well fields also generally result in faster storage recovery than observed for other fields. Recovery in the Gonzales field, which is located within about a mile of the Rio Grande (fig. 5), might be slower than in the other fields listed above because the Gonzales wells are located outside the area of the most permeable recent river alluvium. As table 6 indicates, the well fields with the least long-term depletion of storage per well after San Jose, Griegos, Atrisco, and Duranes are the Coronado, Webster, and Vol Andia fields. Even though these fields are located farther from the Rio Grande than others such as Yale and Zamora, the wells are completed in highly conductive ancestral Rio Grande deposits that provide a better hydraulic connection to the river (fig. 8). The five well fields that cause the greatest long-term depletion of aquifer storage per well are all located west of the Rio Grande in low-conductivity sediments that reduce their connection to the river, even in comparison with well fields located much farther from the river, such as the Lomas and Love fields.

Because of the manner in which optimization model 1 was designed (see the "Formulation and solution of mathematical optimization models" section), once the minimum required withdrawal has been assigned to each COA well field for an individual year, the model should successively add withdrawal from the well field with the smallest long-term depletion of aquifer storage per well, until either the maximum capacity of the well field is reached or the ground-water demand for that year is satisfied. Table 6 indicates that the model should, therefore, add withdrawal first from the San Jose well field, followed by Griegos, Atrisco, Duranes, and so on. Thus, the results of this relatively simple optimization model can be readily verified.

Optimal Distribution of Ground-Water Withdrawal

The optimal distribution of ground-water withdrawal as calculated by GAMS for optimization model 1 is presented in table 7. As anticipated, once the minimum withdrawal requirement of 40 acre-ft/yr was fulfilled for each COA well (to as much as 280 acre-ft/yr for each well field, depending on the number of wells per field), the model added withdrawal successively from the San Jose, Griegos, Atrisco, Duranes, Coronado, Webster, and Vol Andia well fields until either the maximum capacity of the well field was reached or the ground-water demand for that year was satisfied. Through 2040, ground-water demand remains small enough that ground-water withdrawal greater than the required minimum per well is needed from only these seven well fields.

Table 7. Optimal distribution of ground-water withdrawal for optimization model 1

[All values are in thousands of acre-feet]

Well field (fig. 5)	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Atrisco	3.03	11.26	0.16	1.57	0.16	6.10	11.26	5.30	1.73	3.53	5.52	7.02	8.79	10.55	11.26	11.26	11.26	11.26	11.26	11.26
Burton	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Charles	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
College	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Coronado	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	8.14	8.14
Duranes	0.28	7.80	0.28	0.28	0.28	0.28	6.85	0.28	0.28	0.28	0.28	0.28	0.28	0.28	1.33	3.08	4.83	10.69	24.52	24.52
Gonzales	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Griegos	10.56	10.56	4.68	10.56	6.12	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56
Leavitt	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Leyendecker	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Lomas	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Love	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Miles	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Ponderosa	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Ridgecrest	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
San Jose	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05
Santa Barbara	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Thomas	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Vol Andia	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
Volcano Cliffs	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Walker	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Webster	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	7.22	8.97
West Mesa	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Yale	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Zamora	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Table 7. Optimal distribution of ground-water withdrawal for optimization model 1--Concluded

Well field (fig. 5)	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
Atrisco	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26
Burton	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Charles	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
College	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Coronado	8.14	0.08	0.08	0.08	0.08	0.08	0.08	0.98	8.14	8.14	5.81	8.14	8.14	8.14
Duranes	24.52	13.59	15.34	17.09	18.84	20.57	22.30	24.52	24.52	24.52	24.52	24.52	24.52	24.52
Gonzales	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Griegos	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56
Leavitt	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Leyendecker	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Lomas	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Love	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Miles	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Ponderosa	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Ridgecrest	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
San Jose	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05
Santa Barbara	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Thomas	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Vol Andia	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	12.60	0.24	0.24	0.24	1.89
Volcano Cliffs	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Walker	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Webster	6.62	0.08	0.08	0.08	0.08	0.08	0.08	0.08	6.58	9.93	0.08	5.28	1.23	9.93
West Mesa	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Yale	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Zamora	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Comparison of GAMS and MODFLOW Results

The optimal distribution of ground-water withdrawal determined by GAMS for COA well fields for 2006 through 2040 (table 7) was provided as input to the McAda and Barroll simulation model. The water budget of this simulation with optimal ground-water withdrawal was compared with the water-budget calculations of the optimization model. To make the comparison between budgets as accurate as possible, the model simulation was performed using the same input parameters that were used when response functions for the optimization model were generated (see the "Use of the simulation model to generate response functions" section); only the quantity and distribution of ground-water withdrawal by the COA differed. The GAMS calculations of the effects of 2006 to 2040 withdrawal on the net storage and river plus drains components of the water budget for the aquifer system, which were computed using the response functions generated from the simulation model, were summed with the simulated effects of pre-2006 ground-water withdrawal on these components of the water budget after 2006, which had been determined using two simulations of the McAda and Barroll model. The first model simulation through 2040 included known COA withdrawals through the end of 2000 and projected city withdrawals through 2006, followed by no city withdrawals. The second model simulation through 2040 included no city withdrawals during any year. The water-budget results of the second simulation were subtracted from those of the first simulation to determine the lingering effects of COA withdrawals prior to 2006 on components of the water budget beyond 2006. The sum of the effects of 2006 to 2040 withdrawal calculated by GAMS with the simulated effects of pre-2006 withdrawal provides the overall effect of COA ground-water withdrawal on each budget component. This value was compared with the MODFLOW budget output from the simulation with the optimal withdrawal minus the budget output from a simulation with no COA withdrawal at any time, again giving the overall effect of only COA withdrawal on each budget component.

The overall results from GAMS and MODFLOW for both the storage and river plus drains components of the water budget are very similar during the first 10 years of the modeled period (fig. 16), differing by less than 10 percent each year. During or soon after 2015, the results of the two models begin to differ more appreciably for both budget components; the GAMS model overpredicts the use of water from aquifer storage and underpredicts the contribution of river plus drain leakage to the aquifer system as compared to the MODFLOW model. If the GAMS and MODFLOW results for 2006 to 2040 withdrawal only are compared, by subtracting the MODFLOW-simulated effects of pre-2006 ground-water withdrawal (see the dashed lines in fig. 16), the differences between the two models become more apparent. These differences are largest for the storage components of the water budget, particularly during times when ground-water withdrawals are fluctuating over a broad range, resulting in correspondingly large fluctuations in simulated hydraulic heads. However, the differences are generally less than 6,000 acre-ft and no more than 7,215 acre-ft for any particular year, and both models capture the same major features of the trends in budget components over time (fig. 16). Given that the differences represent only a small percentage (less than 2 percent) of the total volume of water moving through the aquifer system in an individual year (simulated aquifer inflow/outflow for the year ending in October 1999 was about 575,000 acre-ft; McAda and Barroll, 2002), these results indicate that the GAMS model is providing a reasonable approximation to the McAda and Barroll simulation model despite the presence of nonlinearities in the simulation model.

Comparison of Simulation Results for Optimal and Non-Optimal Distributions of Ground-Water Withdrawal

The water budget and water levels of the simulation with optimal ground-water withdrawal also were compared with the results of a simulation with the same quantity of total withdrawal, but with the continued use of the non-optimal year-2000 withdrawal distribution, to evaluate the magnitude of changes that could be achieved. The simulation using the non-optimal withdrawal distribution was very similar to simulation III performed by Bexfield and McAda (2003) using the McAda and Barroll model, as described in the "Simulations of future conditions" section, except that a constant river condition was used to allow direct comparison with the simulation using the optimal withdrawal distribution. Comparison of the net volume of change in budget components from 2006 to 2040 for both simulations indicates that the optimal distribution of ground-water withdrawal results in

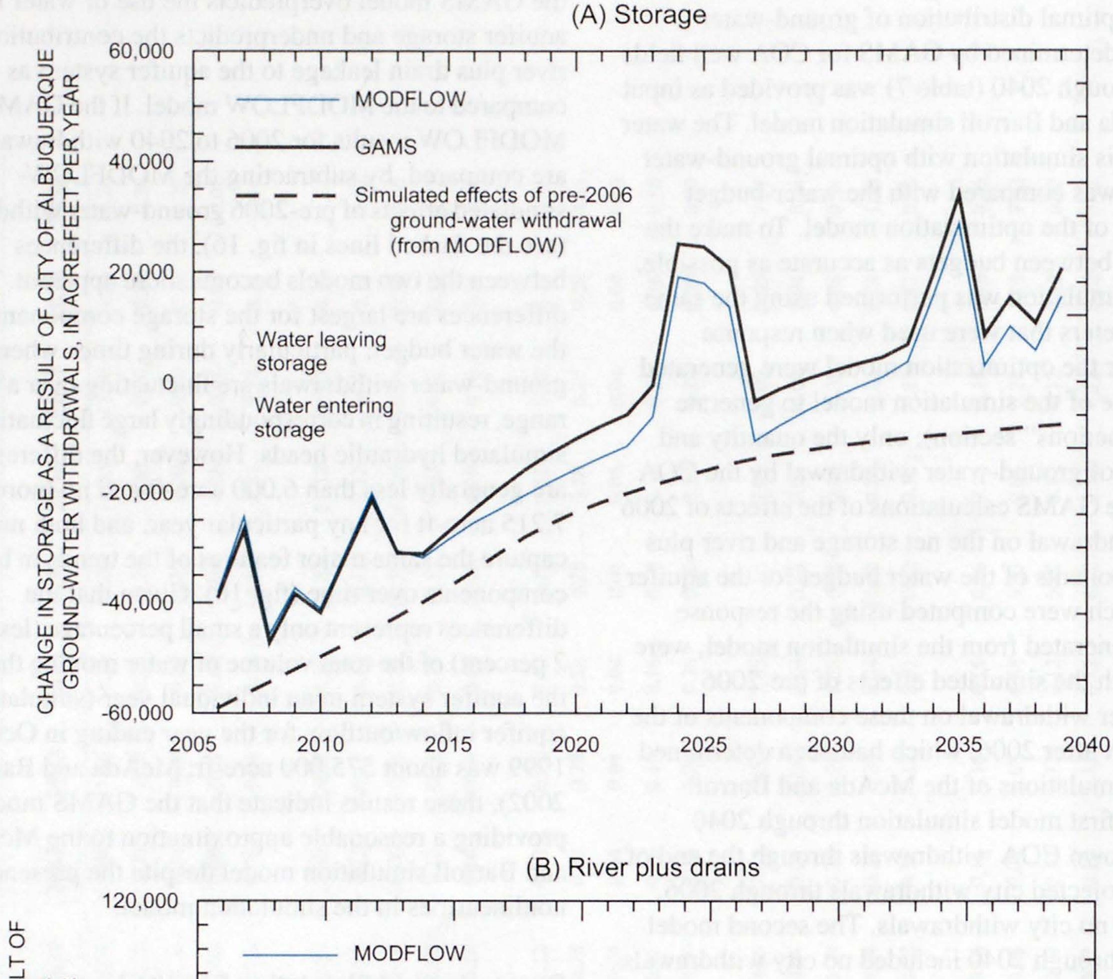


Figure 16. Comparison of (A) storage and (B) river plus drains components of the water budgets from GAMS and MODFLOW for optimization model 1.

about 242,000 acre-ft greater recovery of water in aquifer storage than the non-optimal distribution (table 8 and fig. 17). Nearly all this storage recovery is derived from increased leakage from the Rio Grande and the system of ground-water drains. The increased storage recovery in the optimal case compared with the non-optimal case results in a greater magnitude of water-level rise in the production zone of the aquifer across much of the eastern part of Albuquerque and in isolated areas west of the Rio Grande (figs. 18 and 19). However, water-level decline in the optimal case is increased along the Rio Grande, particularly near the San Jose, Griegos, Atrisco, and Duranes well fields, because this is the area where ground-water withdrawal is concentrated for the optimal case. This comparison demonstrates that optimization of the distribution of ground-water withdrawal can result in a significant reallocation of water among the various components of the water budget for the aquifer system. The comparison also indicates that nearly all this reallocation occurs between the storage and river plus drains components of the budget.

Optimization Model 2: Minimize Net Infiltration from the Rio Grande

Design of the second optimization model was nearly identical to that of the first optimization model, except that the decision variables were changed to achieve the management objective of minimizing net infiltration from the Rio Grande (table 4). Because the ground-water drains in the Rio Grande Valley are closely interrelated with the river itself, the decision variables for the model were the annual volume of leakage from the river plus the drains, as caused by increased withdrawal in each city well field for each year. The objective function was of the same form as presented in equation 5:

$$f = \sum_{t=1}^{87} \sum_{j=1}^{25} (c_{j,t})(l_{j,t}) \qquad (6)$$

where $c_{j,t}$ is again the GAMS-assigned coefficient of ground-water withdrawal for each of the 25 well fields (j) during each of the 87 years of the model (t), and $l_{j,t}$ is the change in river plus drains leakage for each well field during each year as a result of the unit increase in withdrawal (1,000 acre-ft for 1 year). Also, the constraints applied in optimization model 2 were the same as those detailed above for optimization model 1. Similar to model 1, this second optimization model was intended to provide a general blueprint for how ground-water withdrawals could be distributed among the COA well fields to minimize effects on the surface-water system, as well as to demonstrate the magnitude of the decrease in river infiltration that could be achieved by optimizing the distribution of withdrawals.

The second optimization model required a set of response functions for the effect of withdrawal from an individual well field on the river plus drains component of the water budget for the aquifer system. Figure 20 shows the cumulative response over time of the river plus drains obtained from the McAda and Barroll model (as described in the "Use of the simulation model to generate response functions" section) for each COA well field; the functions have been scaled by the number of wells in each field to indicate the response per well. The functions in figure 20 display the same information on river plus drains response as presented for two example well fields in figure 11B, except that the functions in figure 20 are cumulative. These graphs show that, even after ground-water withdrawal ceases at the end of year 1, water continues to enter the aquifer system from the river and drains to replenish the water drawn out of storage during year 1. For each well field, table 9 lists the cumulative effect per well on the river plus drains in the final year of the response function, ranked from the smallest to the largest effect.

Optimal Distribution of Ground-Water Withdrawal

As with the response functions for aquifer storage discussed for optimization model 1, the response functions for the river plus drains vary quite substantially, depending on the location of the applied stress. Two broad patterns of response are evident in the cumulative functions shown in figure 20. For well fields located within about 1 or 2 miles of the Rio Grande, such as the Atrisco and Duranes fields, the river plus drains response is largest in the first year after the applied stress, and begins to level off relatively quickly. For well fields located a longer distance from the Rio Grande, the response of the river plus drains typically is delayed and drawn out over a longer period of time (fig. 20). Well fields far from the Rio Grande also generally demonstrate a substantially smaller cumulative response than fields near the river.

Table 8. Comparison of water-budget components from the MODFLOW simulation using the non-optimal distribution of ground-water withdrawal for 2000 and simulations using the optimal distribution of ground-water withdrawal from each model

[Values represent volumes resulting from operation of City of Albuquerque municipal-supply wells only; na, not applicable]

Model	Cumulative volume from 2006 to 2040 (in acre-feet) of:		Difference relative to the non-optimal case (in acre-feet) of:[1]	
	Net inflow to aquifer from river plus drains leakage	Net change in storage[2]	Net inflow to aquifer from river plus drains leakage	Net change in storage
Non-optimal withdrawal	1,559,000	116,000	na	na
Optimization model 1	1,800,000	358,000	241,000	242,000
Optimization model 2	1,345,000	-118,000	-214,000	-234,000
Optimization model 3	1,800,000	358,000	241,000	242,000
Optimization model 4	1,790,000	347,000	231,000	231,000
Optimization model 5	1,747,000	303,000	188,000	187,000

[1]A positive value signifies that the value is larger for the optimal case than for the non-optimal case; a negative value signifies that the value is smaller for the optimal case than for the non-optimal case

[2]Inflow to the aquifer system from storage (storage depletion) is negative; outflow from the aquifer system to storage is positive (storage recovery)

Table 9. Cumulative response of the river plus drains 54 years after unit withdrawal, scaled to indicate the response per well, for each City of Albuquerque well field

[All values are in acre-feet]

Well field (fig. 5)	Cumulative response	Well field (fig. 5)	Cumulative response
Volcano Cliffs	492	Miles	782
Zamora	599	Leyendecker	782
College	600	Santa Barbara	784
West Mesa	662	Yale	791
Leavitt	672	Gonzales	794
Lomas	706	Webster	798
Ridgecrest	733	Vol Andia	800
Love	742	Coronado	806
Burton	765	Duranes	823
Ponderosa	769	Griegos	828
Charles	771	Atrisco	840
Thomas	772	San Jose	842
Walker	779		

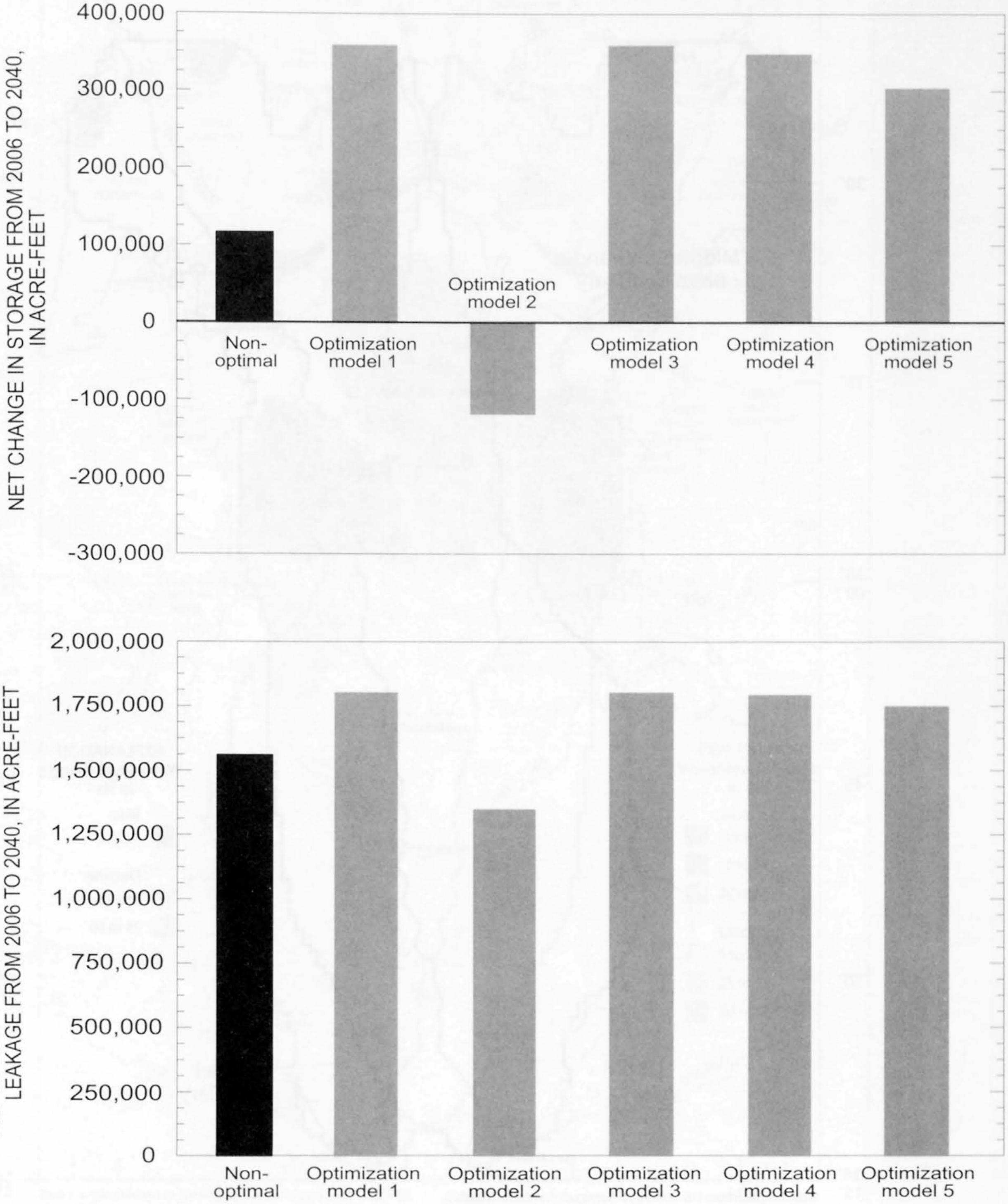


Figure 17. Comparison of selected water-budget components from MODFLOW for simulations using various ground-water withdrawal distributions. Values represent volumes resulting from operation of City of Albuquerque municipal-supply wells only.

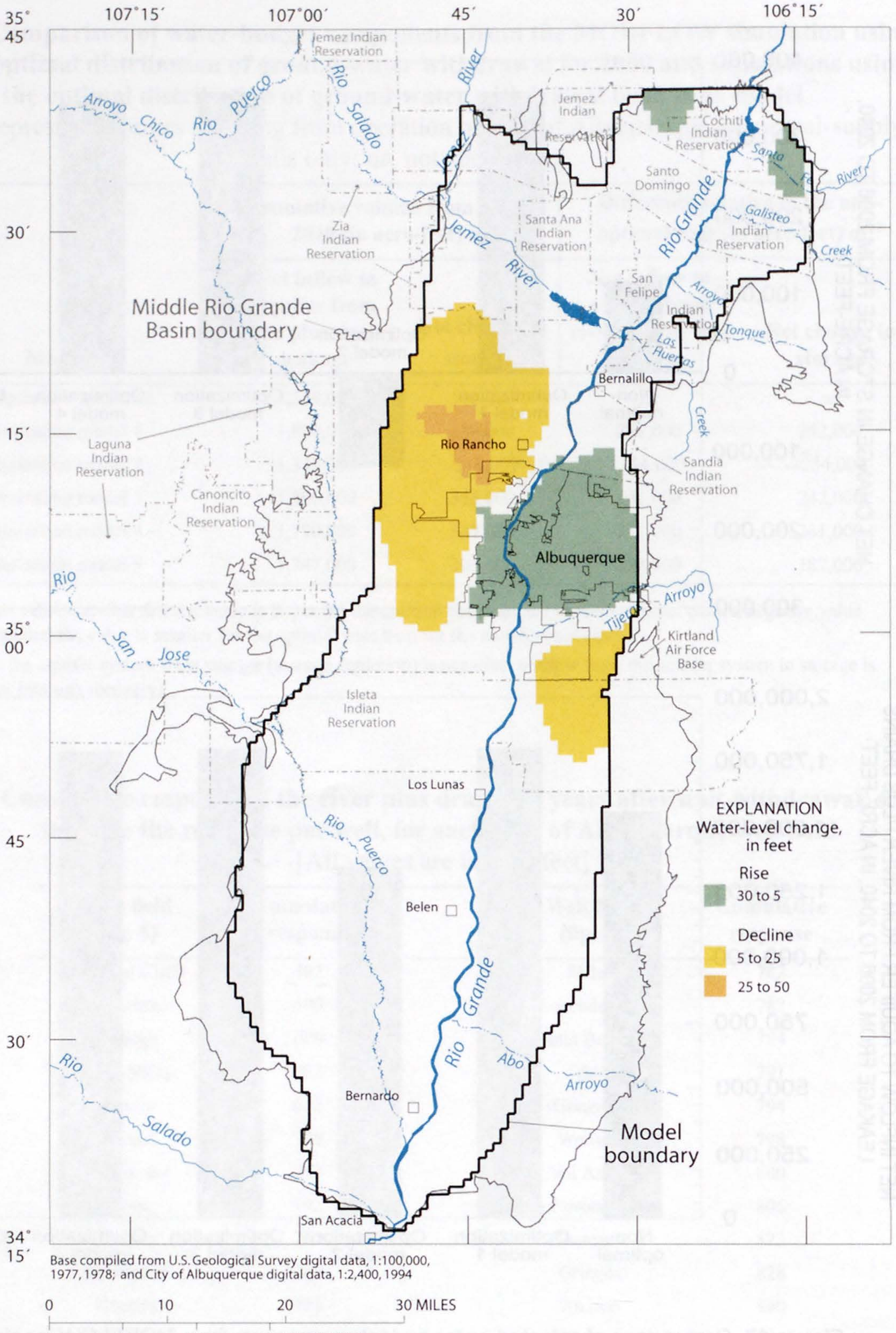


Figure 18. Simulated water-level change in the production zone (layer 5) between 2000 and 2040 for non-optimal ground-water withdrawal.

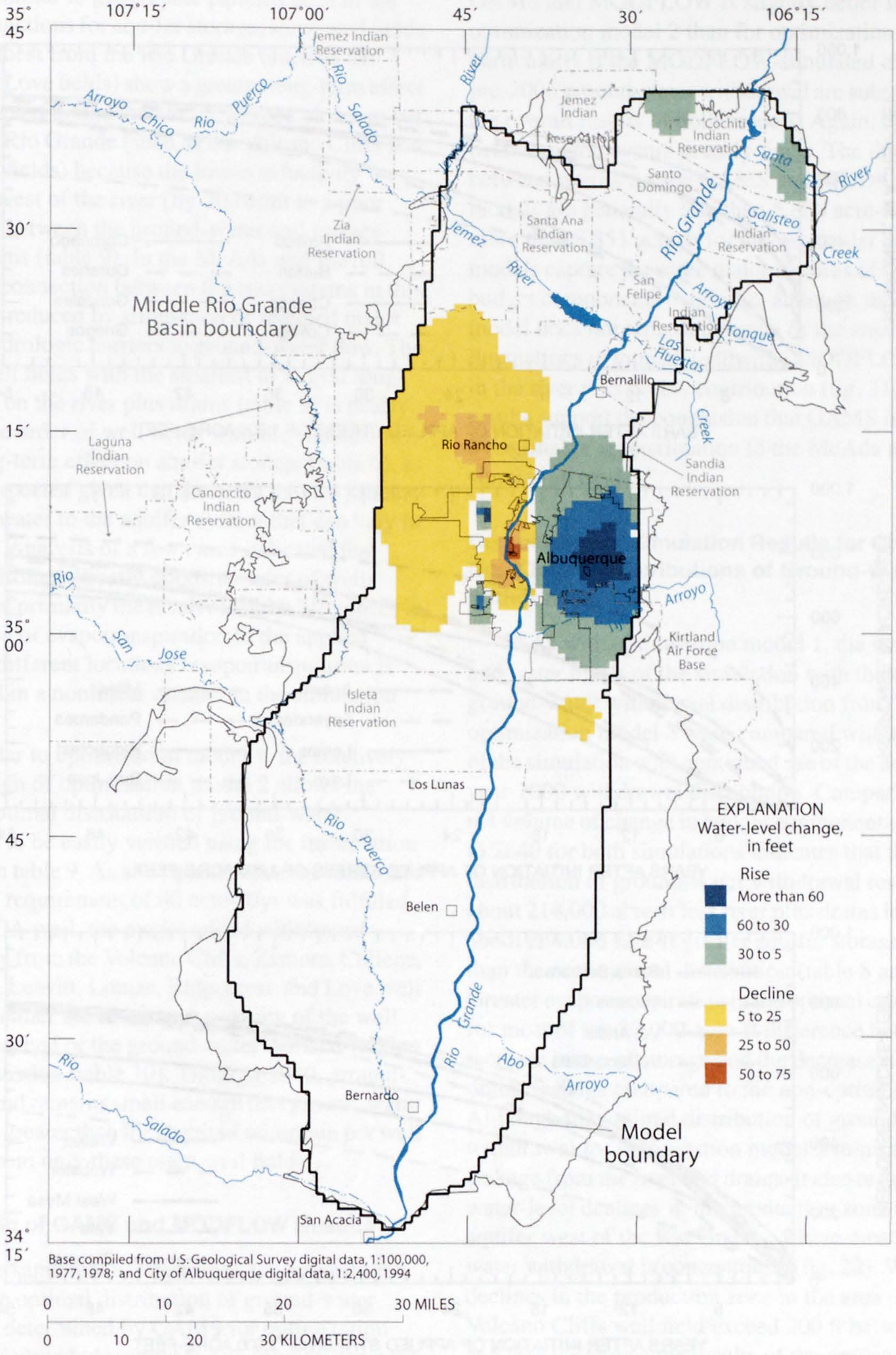


Figure 19. Simulated water-level change in the production zone (layer 5) between 2000 and 2040 for optimal ground-water withdrawal from optimization model 1.

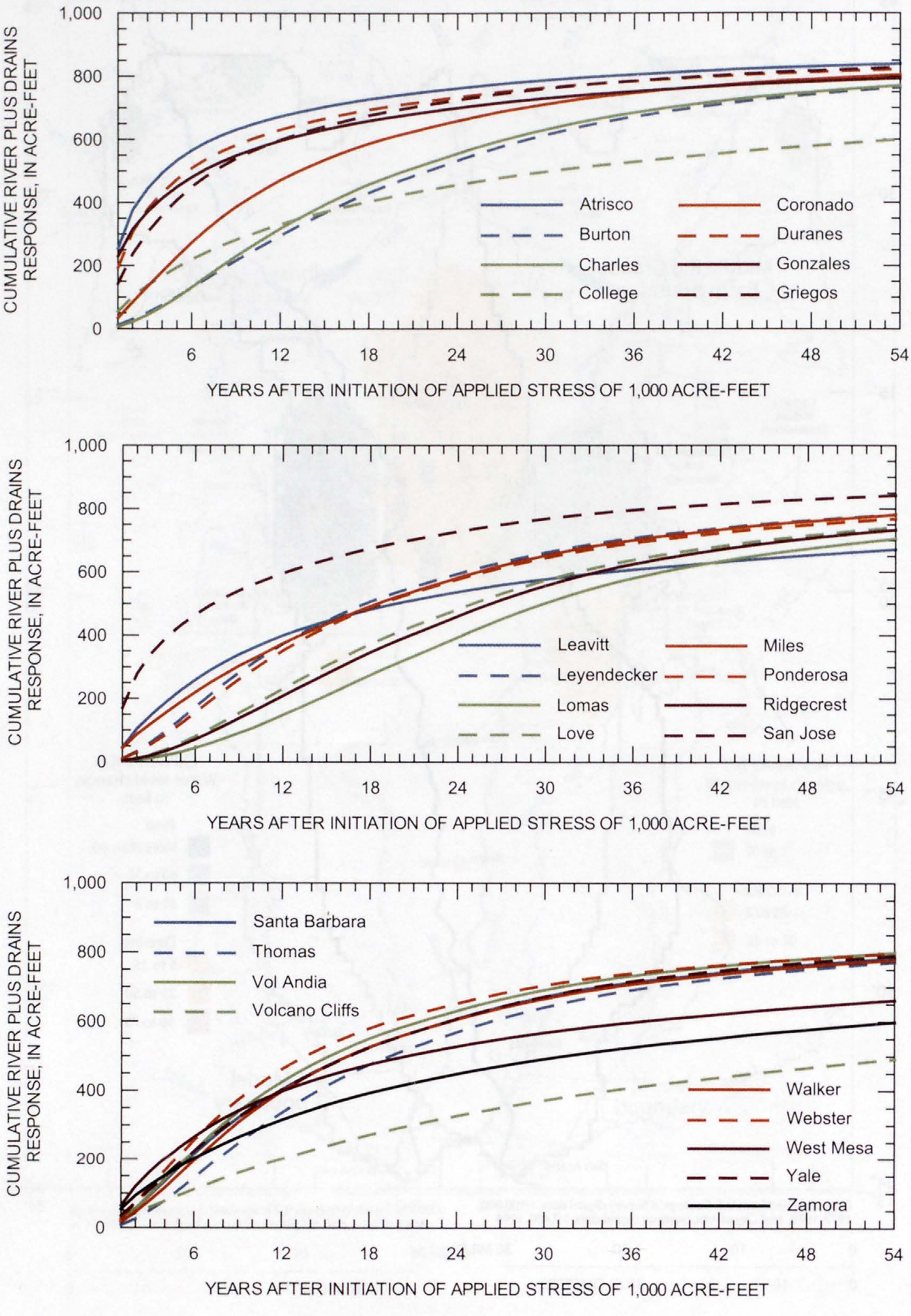


Figure 20. Cumulative response over time of the river plus drains to an applied stress, scaled to indicate the response per well, for each City of Albuquerque well field.

However, similar to geographic patterns seen in the response functions for aquifer storage, some well fields located farthest from the Rio Grande (such as the Lomas and Love fields) show a greater long-term effect on the river and drains than fields located closer to but west of the Rio Grande (such as the Volcano Cliffs and West Mesa fields) because the low-conductivity sediments west of the river (fig. 8) result in a poor connection between the ground-water and surface-water systems (table 9). In the McAda and Barroll model, the connection between the two systems in this area also is reduced by simulation of selected major faults as hydrologic barriers to ground-water flow. The order of well fields with the smallest to largest long-term effect on the river plus drains (table 9) is nearly opposite the order of well fields with the smallest to largest long-term effect on aquifer storage (table 6), as would be expected given that these are the two primary sources of water to the aquifer system that can vary in magnitude. Analysis of a few cases indicated that deviations from a directly opposite order of wells probably are primarily the result of slight differences in the response of evapotranspiration to the applied stresses at different locations (evapotranspiration is represented in a nonlinear manner in the simulation model).

Similar to optimization model 1, the relatively simple design of optimization model 2 allows the resulting optimal distribution of ground-water withdrawal to be easily verified using the information presented in table 9. As anticipated, once the minimum withdrawal requirement of 40 acre-ft/yr was fulfilled for each COA well, the model added withdrawal successively from the Volcano Cliffs, Zamora, College, West Mesa, Leavitt, Lomas, Ridgecrest, and Love well fields until either the maximum capacity of the well field was reached or the ground-water demand for that year was satisfied (table 10). Through 2040, ground-water demand remains small enough that ground-water withdrawal greater than the required minimum per well is needed from only these eight well fields.

Comparison of GAMS and MODFLOW Results

In the same manner described for optimization model 1, the optimal distribution of ground-water withdrawal determined by GAMS for optimization model 2 was provided as input to a simulation using the McAda and Barroll model, and the water budgets from GAMS and MODFLOW were compared. As figure 21 indicates, the match between the water budgets from GAMS and MODFLOW is slightly better for optimization model 2 than for optimization model 1, particularly if the MODFLOW-simulated effects of pre-2006 ground-water withdrawal are subtracted from the overall results of both models. Again, the best overall match occurs at early times. The differences between results for the GAMS and MODFLOW models are generally less than 5,000 acre-ft and no more than 5,851 acre-ft for any particular year. Both models capture the same major features of the trends in budget components over time, although the GAMS model does not reproduce some of the smaller scale fluctuations demonstrated by the MODFLOW results in the river plus drains contribution (fig. 21). These results support the conclusion that GAMS is providing a reasonable approximation to the McAda and Barroll simulation model.

Comparison of Simulation Results for Optimal and Non-Optimal Distributions of Ground-Water Withdrawal

As with optimization model 1, the water budget and water levels of the simulation with the optimal ground-water withdrawal distribution from optimization model 2 were compared with the results of the simulation with continued use of the non-optimal year-2000 withdrawal distribution. Comparison of the net volume of change in budget components from 2006 to 2040 for both simulations indicates that the optimal distribution of ground-water withdrawal results in about 214,000 acre-ft less river plus drains leakage and about 234,000 acre-ft greater aquifer storage depletion than the non-optimal distribution (table 8 and fig. 17). Greater evapotranspiration in the optimal case accounts for most of the 20,000-acre-ft difference between the increase in use of storage and the decrease in river plus drains leakage compared to the non-optimal case. Although the optimal distribution of ground-water withdrawal for optimization model 2 minimizes leakage from the river and drains, it also results in large water-level declines in the production zone of the aquifer west of the Rio Grande, where most ground-water withdrawal is concentrated (fig. 22). Water-level declines in the production zone in the area of the Volcano Cliffs well field exceed 200 ft between 2000 and 2040. Because the results of the optimization model include little withdrawal east of the Rio Grande, water levels in this area show substantial rise between 2000 and 2040 (fig. 22).

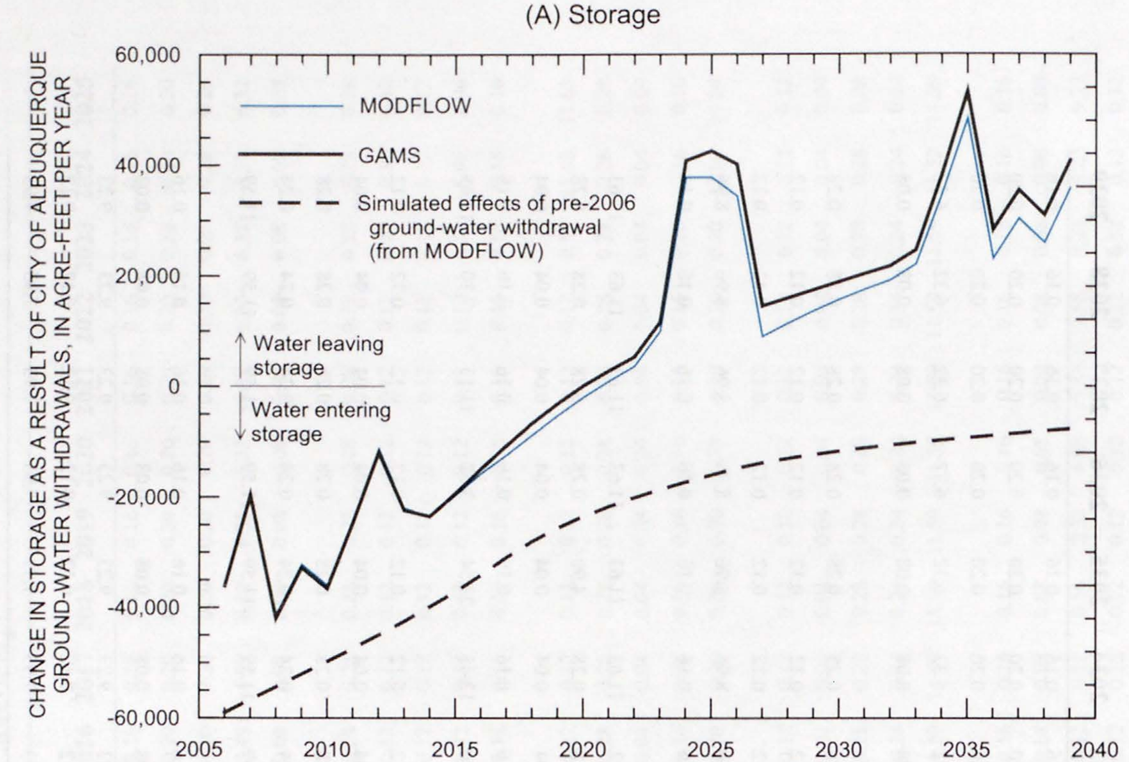
Table 10. Optimal distribution of ground-water withdrawal for optimization model 2

[All values are in thousands of acre-feet]

Well field (fig. 5)	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Atrisco	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Burton	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Charles	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
College	1.00	6.32	0.08	0.08	0.08	4.07	6.32	3.27	0.08	1.50	3.49	4.99	6.32	6.32	6.32	6.32	6.32	6.32	6.32	6.32
Coronado	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Duranes	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Gonzales	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Griegos	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Leavitt	0.12	1.44	0.12	0.12	0.12	0.12	0.49	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	4.33	8.96	8.96
Leyendecker	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Lomas	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	11.63	11.63
Love	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Miles	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Ponderosa	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Ridgecrest	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	13.09	14.84
San Jose	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Santa Barbara	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Thomas	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Vol Andia	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
Volcano Cliffs	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59
Walker	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Webster	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
West Mesa	0.12	9.23	0.12	0.12	0.12	0.12	9.23	0.12	0.12	0.12	0.12	0.12	0.56	2.32	4.08	5.83	7.58	9.23	9.23	9.23
Yale	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Zamora	7.93	7.93	0.10	7.39	1.54	7.93	7.93	7.93	7.55	7.93	7.93	7.93	7.93	7.93	7.93	7.93	7.93	7.93	7.93	7.93

Table 10. Optimal distribution of ground-water withdrawal for optimization model 2--Concluded

Well field (fig. 5)	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
Atrisco	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Burton	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Charles	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
College	6.32	6.32	6.32	6.32	6.32	6.32	6.32	6.32	6.32	6.32	6.32	6.32	6.32	6.32
Coronado	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Duranes	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Gonzales	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Griegos	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Leavitt	8.96	7.23	8.96	8.96	8.96	8.96	8.96	8.96	8.96	8.96	8.96	8.96	8.96	8.96
Leyendecker	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Lomas	11.63	0.12	0.14	1.89	3.64	5.37	7.10	10.22	11.63	11.63	11.63	11.63	11.63	11.63
Love	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	4.90	0.28	0.28	0.28	0.28
Miles	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Ponderosa	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Ridgecrest	12.49	0.20	0.20	0.20	0.20	0.20	0.20	0.20	12.45	23.54	3.62	11.15	7.10	17.45
San Jose	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Santa Barbara	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Thomas	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Vol Andia	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
Volcano Cliffs	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59	11.59
Walker	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Webster	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
West Mesa	9.23	9.23	9.23	9.23	9.23	9.23	9.23	9.23	9.23	9.23	9.23	9.23	9.23	9.23
Yale	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Zamora	7.93	7.93	7.93	7.93	7.93	7.93	7.93	7.93	7.93	7.93	7.93	7.93	7.93	7.93



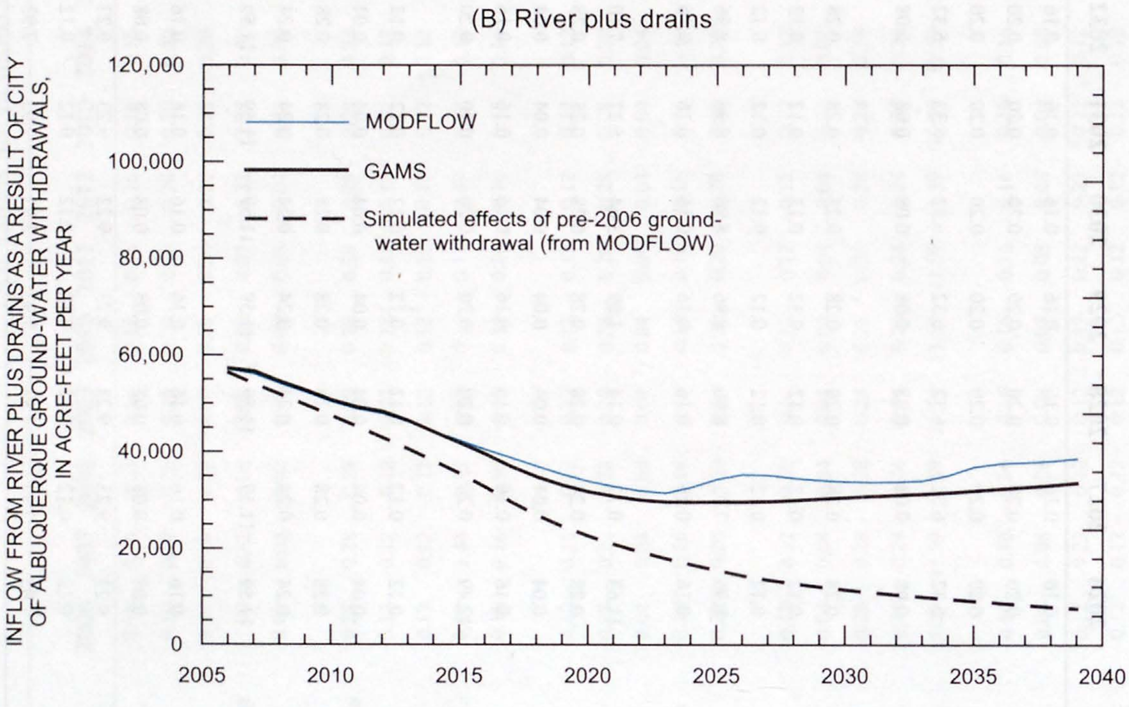


Figure 21. Comparison of (A) storage and (B) river plus drains components of the water budgets from GAMS and MODFLOW for optimization model 2.

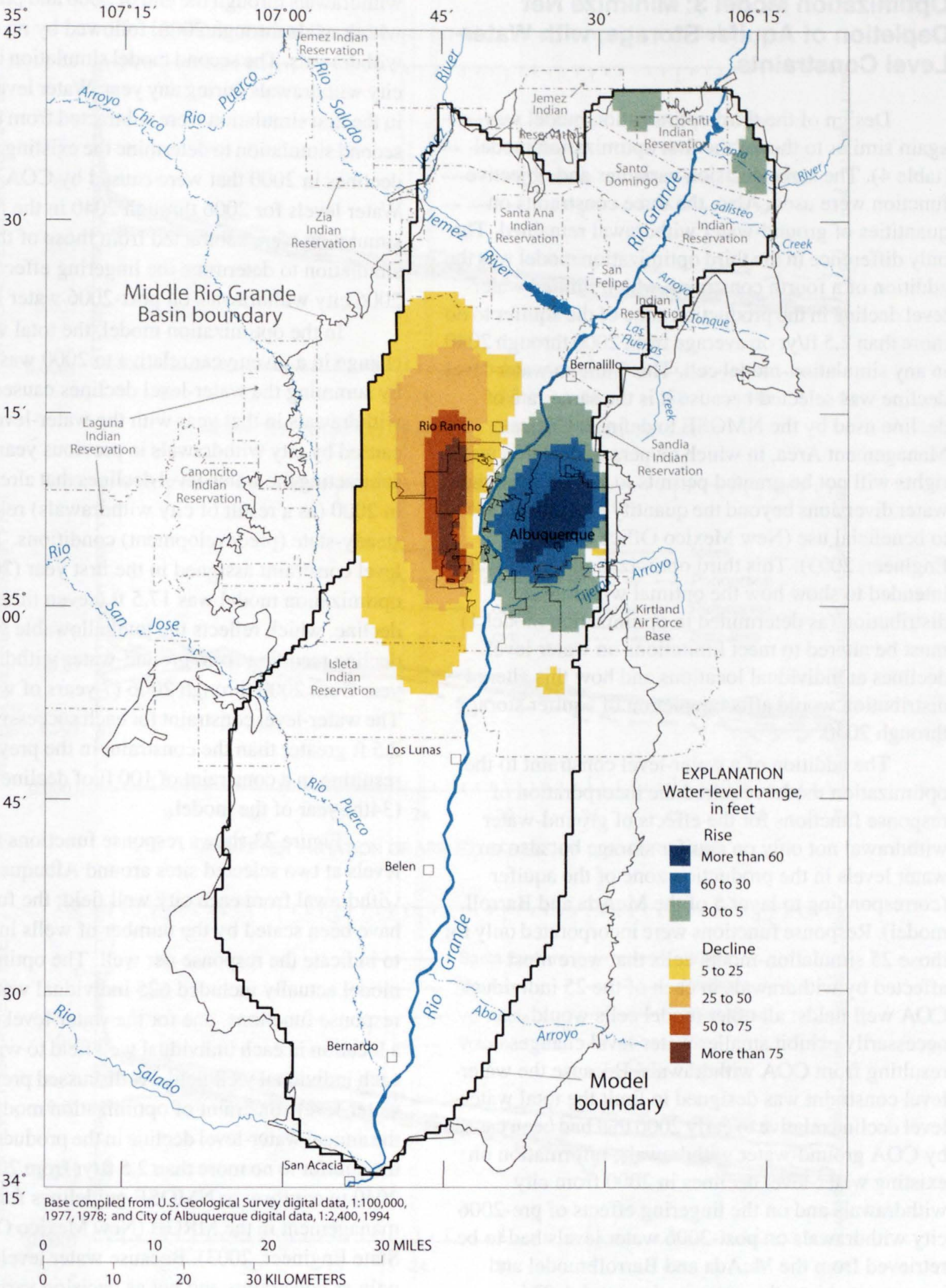


Figure 22. Simulated water-level change in the production zone (layer 5) between 2000 and 2040 for optimal ground-water withdrawal from optimization model 2.

Optimization Model 3: Minimize Net Depletion of Aquifer Storage, with Water-Level Constraints

Design of the third optimization model was again similar to that of the first optimization model (table 4). The same decision variables and objective function were used. Also, the three constraints on quantities of ground-water withdrawal remained. The only difference in the third optimization model was the addition of a fourth constraint, which limited water-level decline in the production zone of the aquifer to no more than 2.5 ft/yr on average from 2000 through 2040 in any simulation-model cell. This limit on water-level decline was selected because it is the same rate of decline used by the NMOSE to define a Critical Management Area, in which owners of declared water rights will not be granted permits to increase ground-water diversions beyond the quantity previously placed to beneficial use (New Mexico Office of the State Engineer, 2003). This third optimization model was intended to show how the optimal withdrawal distribution (as determined in optimization model 1) must be altered to meet limitations on water-level declines at individual locations and how this altered distribution would affect depletion of aquifer storage through 2040.

The addition of a water-level constraint to the optimization model required the incorporation of response functions for the effects of ground-water withdrawal not only on aquifer storage but also on water levels in the production zone of the aquifer (corresponding to layer 5 of the McAda and Barroll model). Response functions were incorporated only for those 25 simulation-model cells that were most affected by withdrawals in each of the 25 individual COA well fields; all other model cells would necessarily exhibit smaller water-level changes resulting from COA withdrawals. Because the water-level constraint was designed to limit the total water-level decline relative to early 2000 that had been caused by COA ground-water withdrawals, information on existing water-level declines in 2000 from city withdrawals and on the lingering effects of pre-2006 city withdrawals on post-2006 water levels had to be retrieved from the McAda and Barroll model and incorporated into the optimization model. This information was retrieved from the McAda and Barroll model using two separate simulations through 2040. The first model simulation included known COA withdrawals through the end of 2000 and projected city withdrawals through 2006, followed by no city withdrawals. The second model simulation included no city withdrawals during any year. Water levels for 2000 in the first simulation were subtracted from those of the second simulation to determine the existing water-level declines in 2000 that were caused by COA pumping. Water levels for 2006 through 2040 in the first simulation were subtracted from those of the second simulation to determine the lingering effects of pre-2006 city withdrawals on post-2006 water levels.

In the optimization model, the total water-level change in a given year relative to 2000 was calculated by summing the water-level declines caused by city withdrawals in that year with the water-level declines caused by city withdrawals in previous years, and then subtracting the water-level declines that already existed in 2000 (as a result of city withdrawals) relative to steady-state (predevelopment) conditions. The water-level constraint assigned in the first year (2006) of the optimization model was 17.5 ft (seven times 2.5 ft) of decline, which reflects the total allowable water-level decline resulting from ground-water withdrawal each year from 2000 through 2006 (7 years of withdrawal). The water-level constraint for each successive year was 2.5 ft greater than the constraint in the previous year, resulting in a constraint of 100 ft of decline in the final (34th) year of the model.

Figure 23 shows response functions for water levels at two selected sites around Albuquerque to withdrawal from each city well field; the functions have been scaled by the number of wells in each field to indicate the response per well. The optimization model actually included 625 individual water-level response functions, one for the water-level response at a location in each individual well field to withdrawal at each individual well field. As discussed previously, the water-level constraint of optimization model 3 limits the annual water-level decline in the production zone of the aquifer to no more than 2.5 ft/yr from 2000 through 2040 to conform to NMOSE guidelines for resource management in the MRGB (New Mexico Office of the State Engineer, 2003). Because water levels are used only as constraints and not as decision variables, the overall order of the cumulative effect of individual well fields on particular water-level response locations is not important to the solution of the optimization problem.

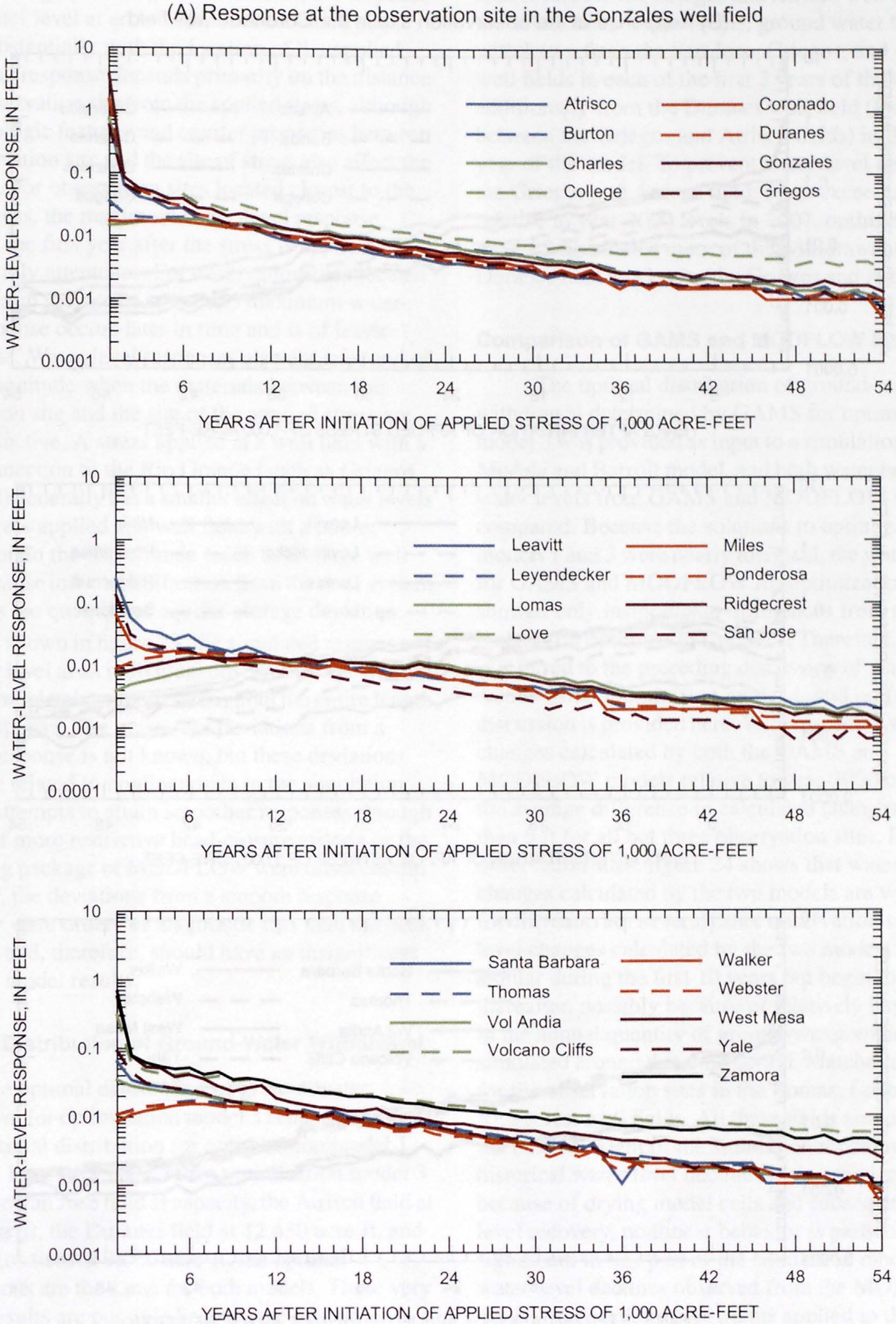


Figure 23. Response per well of water levels in the production zone at observation sites in the (A) Gonzales and (B) Coronado well fields to withdrawal from each City of Albuquerque well field.

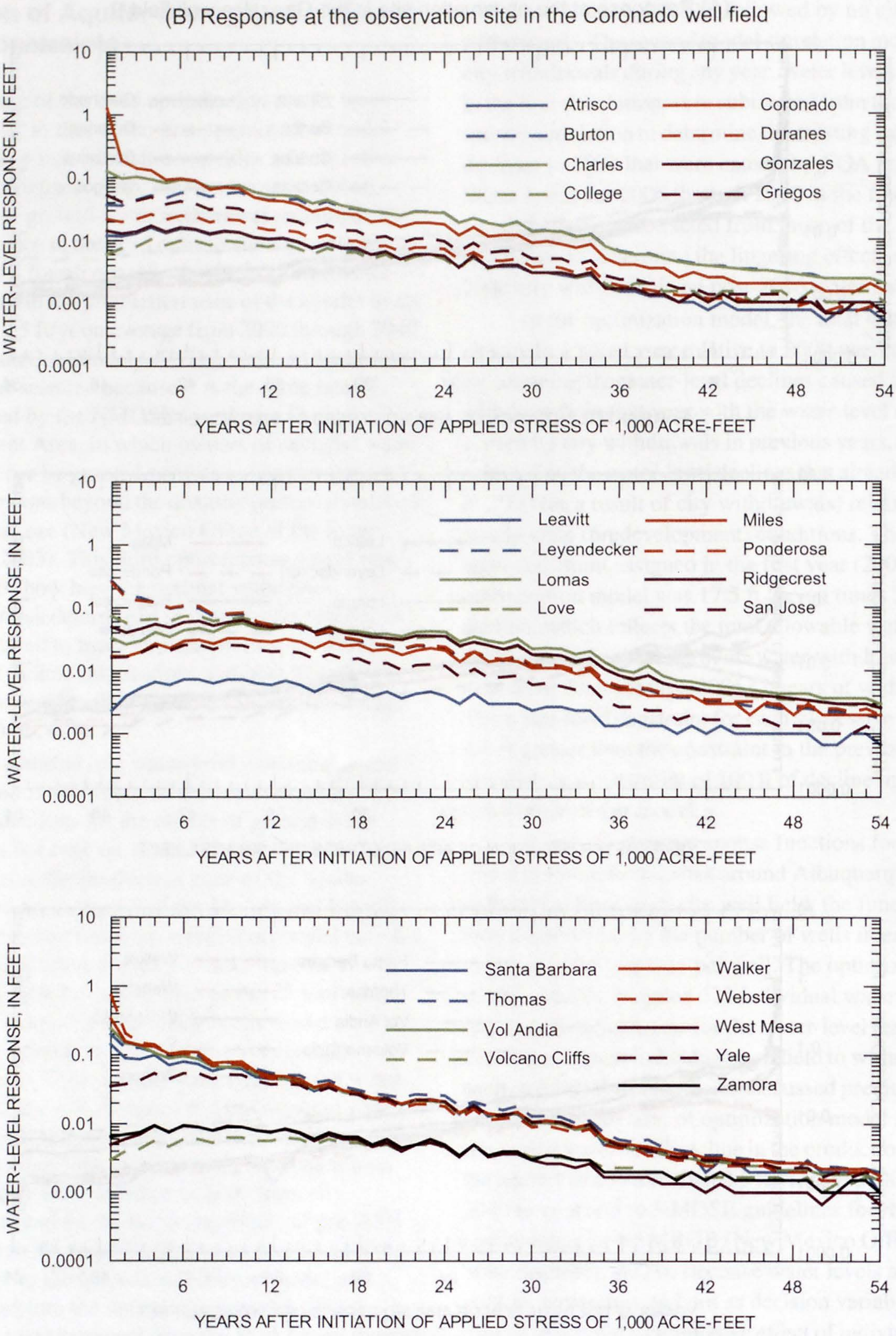


Figure 23. Response per well of water levels in the production zone at observation sites in the (A) Gonzales and (B) Coronado well fields to withdrawal from each City of Albuquerque well field--Concluded.

As the graphs in figure 23 indicate, the response of the water level at an individual observation site varies substantially with the location of the applied stress. The response depends primarily on the distance of the observation site from the applied stress, although the hydrologic features and aquifer properties between the observation site and the site of stress also affect the response. For observation sites located closest to the site of stress, the maximum water-level response occurs in the first year after the stress is applied and subsequently attenuates. For observation sites located farthest from the site of stress, the maximum water-level response occurs later in time and is of lesser magnitude. Water-level responses also are later and of lesser magnitude when the materials between the observation site and the site of the applied stress are less conductive. A stress applied at a well field with a good connection to the Rio Grande (such as Griegos well field) generally has a smaller effect on water levels than a stress applied at a well field with a poorer connection to the Rio Grande (such as College well field) because induced infiltration from the river system decreases the quantity of aquifer-storage depletion.

As shown in figure 23, the simulated response of the water level at an individual observation site was not always completely smooth throughout the entire length of the response. The reason for deviations from a smooth response is not known, but these deviations likely are related to nonlinearities in the simulation model. Attempts to attain smoother responses through the use of more restrictive head-closure criteria or the re-wetting package of MODFLOW were unsuccessful. However, the deviations from a smooth response generally were orders of magnitude less than the peak response and, therefore, should have an insignificant effect on model results.

Optimal Distribution of Ground-Water Withdrawal

The optimal distribution of ground-water withdrawal for optimization model 3 is nearly identical to the optimal distribution for optimization model 1 (table 7). Except in 2007, when optimization model 3 pumps the San Jose field at capacity, the Atrisco field at 8,110 acre-ft, the Duranes field at 12,430 acre-ft, and the Griegos field at 9,080 acre-ft, the optimal distributions are the same for both models. These very similar results are possible because the constraint allowing no more than 2.5 ft of water-level decline per year is binding on the solution in only the second year of the model and for only two observation sites (the sites located in the Griegos and Atrisco well fields). For the solutions to both models, ground water is withdrawn from the San Jose, Griegos, and Atrisco well fields in each of the first 2 years of the model and additionally from the Duranes well field (located between the Griegos and Atrisco fields) in the second year of the model. To prevent water-level declines in the Griegos and Atrisco fields from exceeding 20 ft relative to year-2000 levels in 2007, optimization model 3 distributes more of the withdrawal to the Duranes field and less to the Griegos and Atrisco fields.

Comparison of GAMS and MODFLOW Results

The optimal distribution of ground-water withdrawal determined by GAMS for optimization model 3 was provided as input to a simulation using the McAda and Barroll model, and both water budgets and water levels from GAMS and MODFLOW were compared. Because the solutions to optimization models 1 and 3 were nearly identical, the water budgets for GAMS and MODFLOW for optimization model 3 showed only insignificant differences from the water budgets for optimization model 1. Therefore, the reader is referred to the preceding discussion of water-budget results from optimization model 1, and no further discussion is provided here. With respect to water-level changes calculated by both the GAMS and MODFLOW models relative to year-2000 conditions, the average difference in calculated changes was less than 8 ft for all but three observation sites. For several observation sites, figure 24 shows that water-level changes calculated by the two models are very similar for all years. For several other observation sites, water-level changes calculated by the two models are very similar during the first 10 years but begin to deviate thereafter, possibly because of relatively large swings in the annual quantity of ground-water withdrawal simulated around this time period. Matches are poorest for the observation sites in the Lomas, Love, and Ridgecrest well fields. All these fields are located near the eastern extent of the simulation model, where historical water-level declines have been largest; because of drying model cells and subsequent water-level recovery, nonlinear behavior is particularly significant in this part of the simulation model. No water-level declines observed from the MODFLOW model exceeded the constraints applied in the GAMS model. Overall, the GAMS model appears to have provided a reasonable approximation to water-level changes simulated by the McAda and Barroll model.

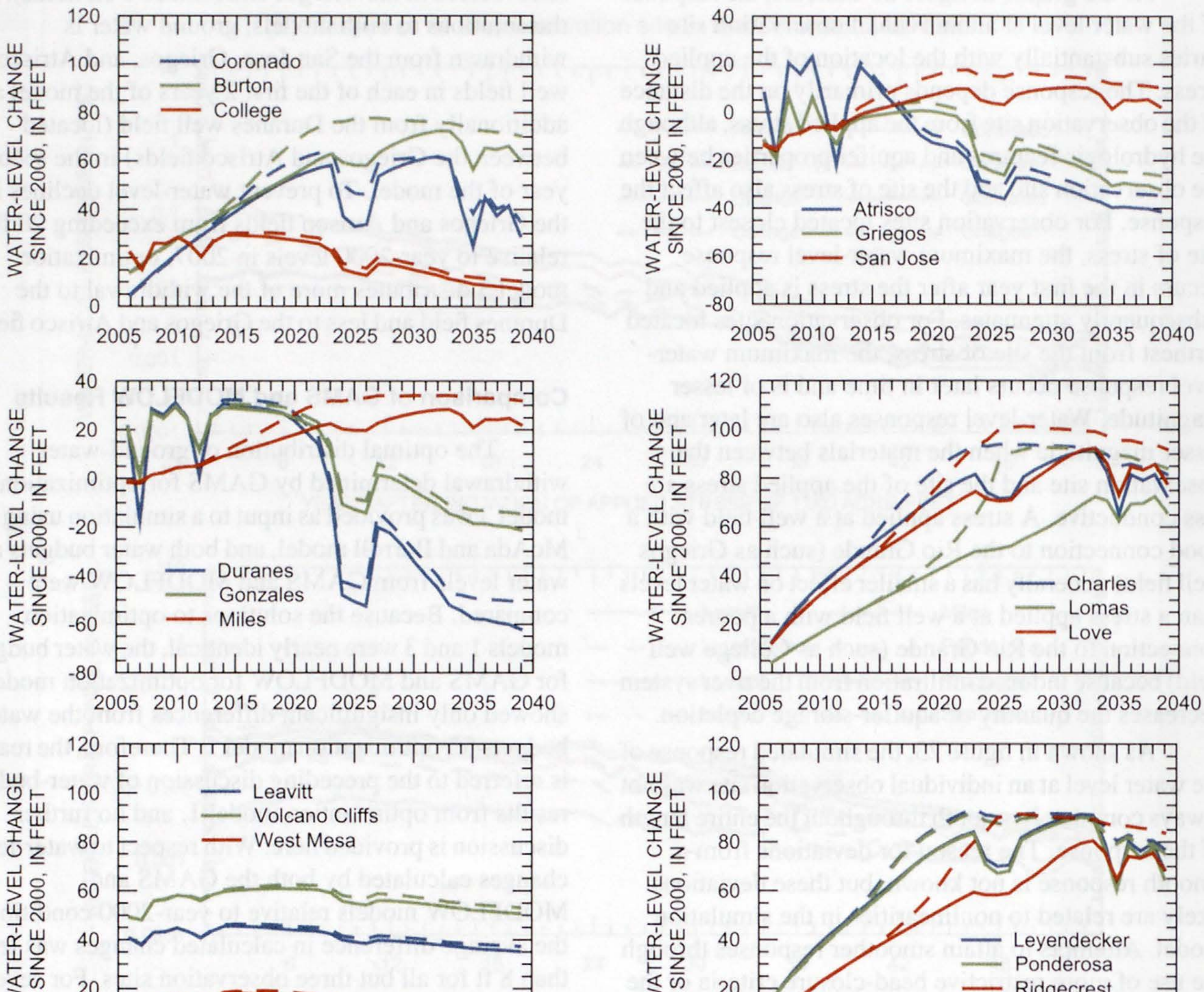


Figure 24. Comparison of water-level changes from GAMS and MODFLOW for optimization model 3.

Comparison of Simulation Results for Optimal and Non-Optimal Distributions of Ground-Water Withdrawal

The results of the simulation model using the optimal distribution of ground-water withdrawal from optimization model 3 differed only slightly from the results using the optimal distribution from optimization model 1. Therefore, the reader is referred to the previous discussion that compares results for the optimal and non-optimal distributions with respect to optimization model 1; no further discussion is provided here.

Optimization Model 4: Minimize Net Depletion of Aquifer Storage, with Constraints on Water Levels and Arsenic Concentrations

The design of the fourth optimization model was nearly identical to that of the third optimization model (table 4). The same decision variables and objective function were used. Also, the three constraints on quantities of ground-water withdrawal and the constraint on water-level declines remained. The only difference in the fourth optimization model was the addition of a constraint on the total blended arsenic concentration of the ground water withdrawn for municipal supply, which was not allowed to exceed the U.S. Environmental Protection Agency (USEPA) drinking-water standard of 10 micrograms per liter that will go into effect in 2006 (U.S. Environmental Protection Agency, 2003). As table 11 indicates, most well fields west of the Rio Grande and in the far northeast part of Albuquerque have average arsenic concentrations greater than 10 micrograms per liter. Only nine well fields, located mostly in the central and southeastern parts of Albuquerque, have average concentrations less than 10 micrograms per liter.

For each year of the model, the blended arsenic concentration was calculated by multiplying the fraction of the total withdrawal drawn from each well field by the average of the median arsenic concentrations from all wells in that well field. The upper bound of the blended arsenic concentration was set at 10 micrograms per liter. The median arsenic concentrations for all but two wells came from 1988-97 data generally collected biannually by the COA from all its municipal-supply wells (Bexfield and others, 1999). Median arsenic concentrations for Gonzales 3 and Zamora 2, which were drilled in 1997, were provided by William Lindberg (City of Albuquerque, written commun., 2003) and were determined from samples collected from the time of drilling through April 2003. This model design assumes that no surface water is being blended with the ground-water supply and that each well in a field will always contribute an equal proportion of water compared to the total volume withdrawn from that field and blended for delivery to customers. The design also assumes little variation around the median for the arsenic concentration of ground water withdrawn from each well. Although these conditions undoubtedly will not always be met, this optimization model should provide a reasonable

Table 11. Representative arsenic concentrations used for each well field in optimization model 4

[All values are in micrograms per liter]

Well field (fig. 5)	Arsenic concentration	Well field (fig. 5)	Arsenic concentration
Atrisco	12.0	Ponderosa	19.3
Burton	10.2	Ridgecrest	3.0
Charles	2.4	San Jose	19.7
College	41.0	Santa Barbara	11.0
Coronado	22.0	Thomas	5.7
Duranes	9.1	Vol Andia	7.2
Gonzales	15.0	Volcano Cliffs	13.3
Griegos	8.3	Walker	25.0
Leavitt	35.7	Webster	31.0
Leyendecker	4.8	West Mesa	34.3
Lomas	2.7	Yale	10.3
Love	2.3	Zamora	15.5
Miles	16.0		

approximation of how substantially the optimal withdrawal distribution to minimize the depletion of aquifer storage must be altered to meet the USEPA arsenic standard and how substantially this altered distribution will affect depletion of aquifer storage through 2040. Because historical data indicate that the surface-water supply should generally have a smaller arsenic concentration than the ground-water supply, this model, which assumes no blending between the two water sources, should provide a "worst-case scenario" answer that indicates the greatest alteration that will have to be made to the optimal withdrawal distribution to satisfy the arsenic standard.

Optimal Distribution of Ground-Water Withdrawal

The constraint on arsenic concentration results in a substantially different optimal distribution of ground-water withdrawal for optimization model 4 (table 12) as compared to optimization models 1 (table 7) and 3. Of the seven well fields used in the optimal distributions of models 1 and 3 to minimize depletion of storage, four (San Jose, Atrisco, Coronado, and Webster) have average arsenic concentrations that exceed 10 micrograms per liter. Although ground water can still be withdrawn from these four fields for optimization model 4, the quantity of withdrawal from well fields with arsenic concentrations less than 10 micrograms per liter must be sufficient to reduce the concentration of the overall blend of water to 10 micrograms per liter. Because the model uses as much withdrawal as possible from the well fields with the least effect on storage (despite their average arsenic concentrations) to achieve the model objective, the arsenic constraint is binding in all years of the model. During the 34 years of the model, most ground-water withdrawal is preferentially from the Griegos, Atrisco, and Duranes well fields. Withdrawal from these well fields is supplemented by withdrawal from the San Jose, Vol Andia, and Coronado well fields during years of greater demand. Similar to that of optimization model 3, the water-level constraint of optimization model 4 is binding only in 2007. However, for model 4, the constraint is binding on three observation sites (in the Griegos, Atrisco, and Duranes well fields) rather than two. Therefore, the water-level constraint again has a small effect on the optimal distribution of ground-water withdrawal in the second year of the model.

Comparison of GAMS and MODFLOW Results

Water budgets and water levels from GAMS and from a MODFLOW simulation using the optimal distribution of withdrawal for optimization model 4 showed similar correlation as for optimization models 1 and 3 (figs. 25 and 26). Once again, the results from GAMS and MODFLOW for both the storage and river plus drains components of the water budget were very similar during about the first 10 years of the modeled period but began to differ more appreciably after about 2015; the GAMS model continually overpredicts the use of water from aquifer storage and underpredicts the contribution of river plus drains leakage to the aquifer system by as much as about 7,000 acre-ft compared to the MODFLOW model. Also, the average difference in water-level changes calculated by GAMS and MODFLOW was about 8 ft or less for all observation sites except the ones in the Lomas, Love, and Ridgecrest well fields.

Comparison of Simulation Results for Optimal and Non-Optimal Distributions of Ground-Water Withdrawal

Comparison of the water budget from the simulation using the optimal ground-water withdrawal distribution from optimization model 4 and the water budget of the simulation using the non-optimal year-2000 withdrawal distribution indicates that the optimal distribution of ground-water withdrawal results in about 231,000 acre-ft greater recovery of water in storage between 2006 and 2040 (table 8 and fig. 17). This quantity is about 10,000 acre-ft less storage recovery than resulted from the optimal distribution of ground-water withdrawal from optimization model 1, which included minimal constraints. Therefore, only about 4 percent of the cumulative "savings" in aquifer storage from optimization model 1 is lost when constraints on water-level decline and arsenic concentration are added. The storage recovery from the optimal distribution of ground-water withdrawal in optimization model 4 results in a pattern of water-level change (fig. 27) that is very similar to the one resulting from the optimal distribution from model 1 (fig. 19). For optimization model 4, there is slightly more water-level decline along the Rio Grande and slightly more water-level rise in the northern part of Albuquerque.

Table 12. Optimal distribution of ground-water withdrawal for optimization model 4

[All values are in thousands of acre-feet]

Well field (fig. 5)	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Atrisco	6.16	8.51	0.37	5.71	2.18	7.11	10.75	6.86	5.76	6.32	6.93	7.40	7.95	8.49	9.04	9.58	10.13	11.26	11.26	11.26
Burton	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Charles	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
College	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Coronado	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Duranes	4.08	13.10	0.28	3.07	0.28	6.20	14.28	5.65	3.19	4.43	5.80	6.83	8.05	9.26	10.48	11.68	12.89	17.43	24.52	24.52
Gonzales	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Griegos	10.56	8.82	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56
Leavitt	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Leyendecker	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Lomas	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Love	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Miles	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Ponderosa	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Ridgecrest	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
San Jose	0.12	1.53	0.96	0.12	0.59	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.31	5.73	6.13
Santa Barbara	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Thomas	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Vol Andia	0.24	4.95	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	16.76	18.12
Volcano Cliffs	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Walker	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Webster	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
West Mesa	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Yale	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Zamora	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Table 12. Optimal distribution of ground-water withdrawal for optimization model 4--Concluded

Well field (fig. 5)	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
Atrisco	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26
Burton	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Charles	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
College	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Coronado	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	1.82	0.08	0.08	0.08	0.08
Duranes	24.52	20.09	21.69	23.29	24.52	24.52	24.52	24.52	24.52	24.52	24.52	24.52	24.52	24.52
Gonzales	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Griegos	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56
Leavitt	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Leyendecker	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Lomas	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Love	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Miles	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Ponderosa	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Ridgecrest	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
San Jose	5.60	0.55	0.70	0.85	1.06	1.44	1.83	2.53	5.59	7.05	3.61	5.30	4.39	6.71
Santa Barbara	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Thomas	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Vol Andia	16.29	0.24	0.24	0.24	0.55	1.90	3.24	5.66	16.26	28.77	9.41	15.25	12.11	20.14
Volcano Cliffs	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Walker	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Webster	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
West Mesa	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Yale	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Zamora	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

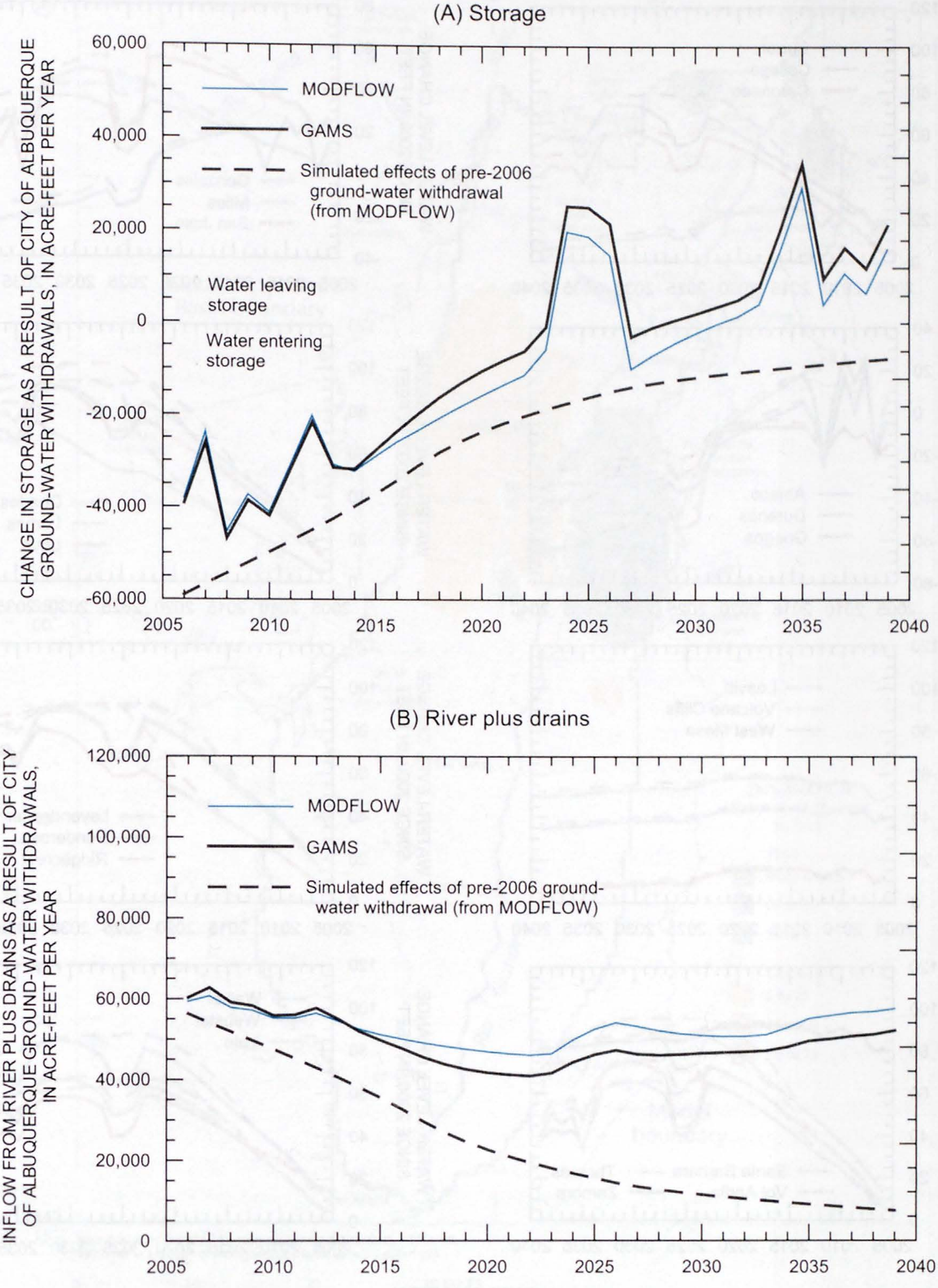


Figure 25. Comparison of (A) storage and (B) river plus drains components of the water budgets from GAMS and MODFLOW for optimization model 4.

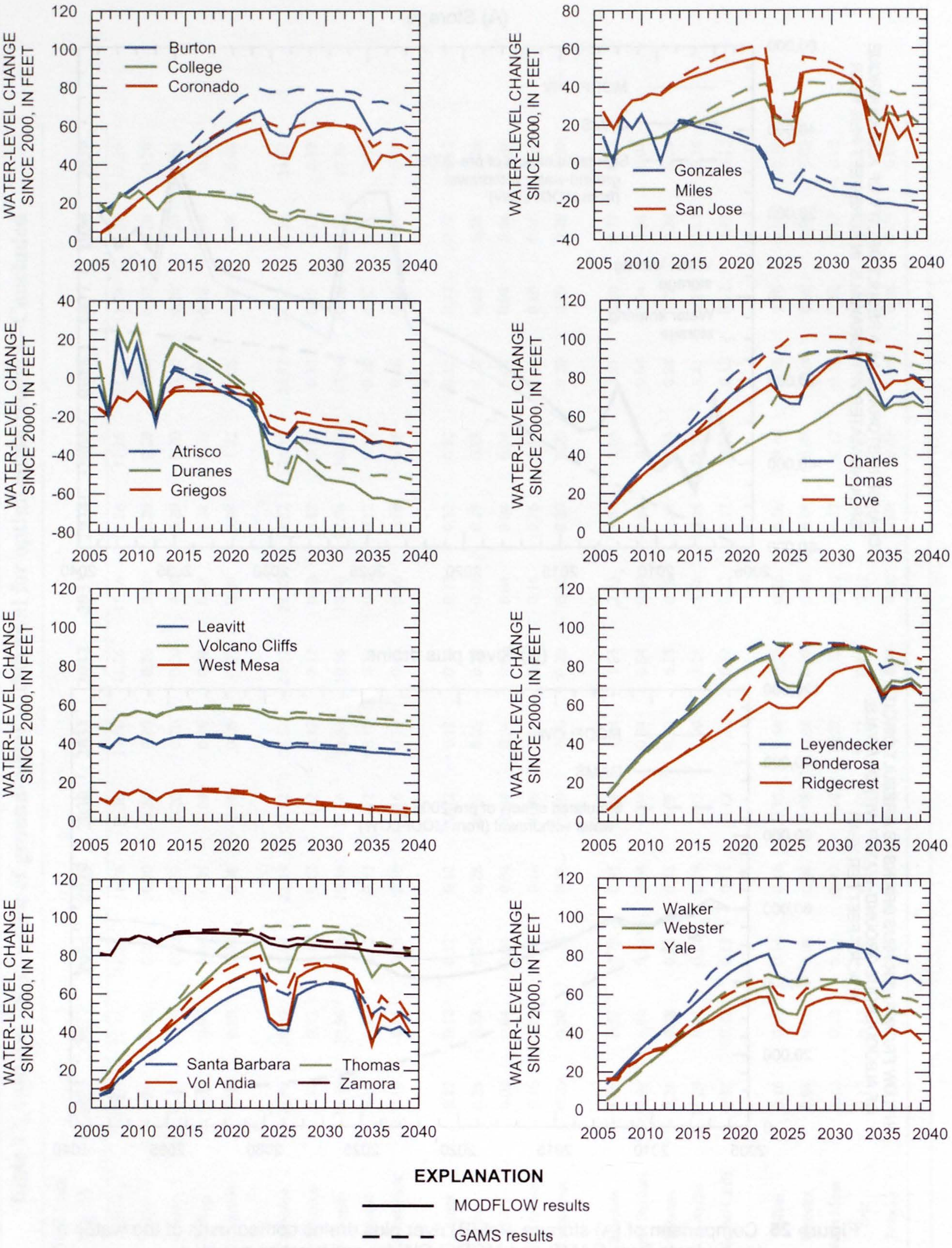


Figure 26. Comparison of water-level changes from GAMS and MODFLOW for optimization model 4.

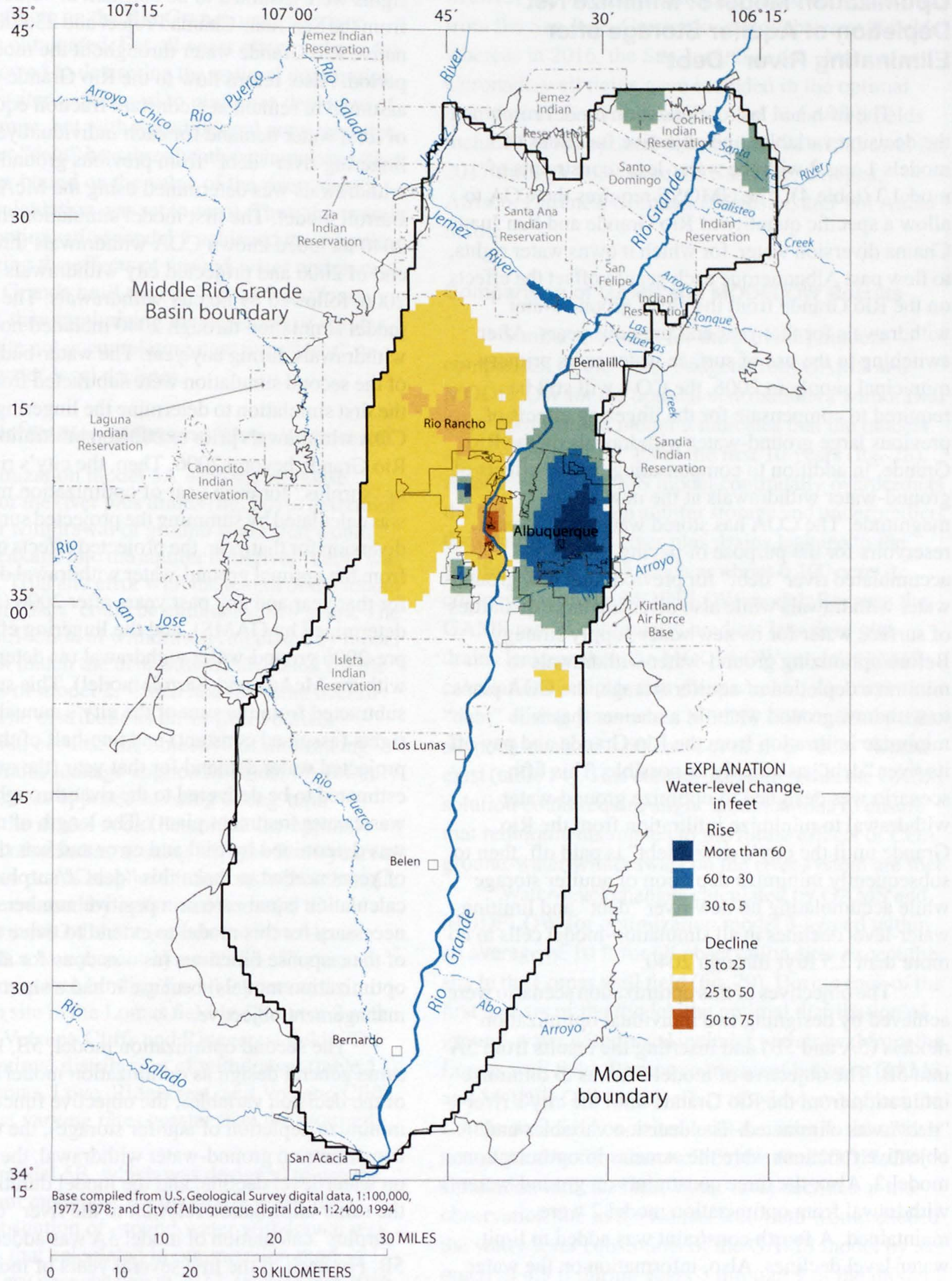


Figure 27. Simulated water-level change in the production zone (layer 5) between 2000 and 2040 for optimal ground-water withdrawal from optimization model 4.

Optimization Model 5: Minimize Net Depletion of Aquifer Storage after Eliminating River "Debt"

The fifth and last optimization model combines the decision variables and objective functions of models 1 and 2 with the water-level constraints of model 3 (table 4). The NMOSE requires the COA to allow a specific quantity of Rio Grande and San Juan-Chama diversion water, for which it owns water rights, to flow past Albuquerque each year to offset the effects on the Rio Grande from the city's ground-water withdrawals for that year and previous years. After switching to the use of surface water as its primary municipal supply in 2006, the COA will still be required to compensate for the lingering effects of previous large ground-water withdrawals on the Rio Grande, in addition to compensating for the effects of ground-water withdrawals at the new, lower magnitude. The COA has stored water in upstream reservoirs for the purpose of paying off this accumulated river "debt" for previous and new ground-water withdrawals while also diverting large quantities of surface water for its new water-supply strategy. Before optimizing ground-water withdrawals to minimize depletion of aquifer storage, the COA plans to withdraw ground water in a manner that will minimize infiltration from the Rio Grande and pay off its river "debt" as quickly as possible. This fifth scenario was designed to optimize ground-water withdrawal to minimize infiltration from the Rio Grande until the city's river "debt" is paid off, then to subsequently minimize depletion of aquifer storage while accumulating no new river "debt" and limiting water-level declines in all simulation-model cells to no more than 2.5 ft/yr through 2040.

The objectives of this optimization scenario were achieved by designing two individual optimization models (5A and 5B) and inserting the results from 5A into 5B. The objective of model 5A was to minimize infiltration from the Rio Grande until the city's river "debt" was eliminated. The decision variables and objective functions were the same as in optimization model 2. Also, the three constraints on ground-water withdrawal from optimization model 2 were maintained. A fourth constraint was added to limit water-level declines. Also, information on the water rights owned by the COA, projected surface-water diversions, and the lingering river "debt" accumulated from ground-water withdrawal by the city prior to 2006 was programmed into model 5A. Albuquerque's water rights were assumed to be constant at 48,200 acre-ft from the San Juan-Chama Project and 23,000 acre-ft of native Rio Grande water throughout the modeled period. Also, return flow to the Rio Grande was assumed to remain at a constant fraction equaling half of total water demand for each individual year. The lingering river "debt" from previous ground-water withdrawals was determined using the McAda and Barroll model. The first model simulation through 2040 included known COA withdrawals through the end of 2000 and projected city withdrawals through 2006, followed by no city withdrawals. The second model simulation through 2040 included no city withdrawals during any year. The water-budget results of the second simulation were subtracted from those of the first simulation to determine the lingering effects of COA withdrawals prior to 2006 on infiltration from the Rio Grande beyond 2006. Then, the city's river "debt" or "surplus" for each year of optimization model 5A was calculated by summing the projected surface-water diversion for that year, the projected effects on the river from the optimal ground-water withdrawal distribution for that year and any past years after 2006 (as determined by GAMS), and the lingering effects from pre-2006 ground-water withdrawal (as determined with the McAda and Barroll model). This sum was subtracted from the sum of the city's annual water rights (assumed constant) and one-half of the total projected water demand for that year (the quantity estimated to be delivered to the river through the city's wastewater treatment plant). The length of model 5A was determined by trial and error and was the number of years needed to make this "debt"/"surplus" calculation equal zero or a positive number. It was not necessary for this model to extend to twice the length of the response functions (as was done for all the other optimization models) because it had a short-term management objective.

The second optimization model, 5B, had the same general design as optimization model 3 in terms of the decision variables, the objective function (to minimize depletion of aquifer storage), the three constraints on ground-water withdrawal, the constraint on water-level decline, and the model duration. Also, the same information relevant to the river "debt"/"surplus" calculation of model 5A was added to model 5B. For each of the first several years of model 5B, equal to the length of model 5A, the upper bound on river "debt" was set equal to the minimum possible value determined from model 5A. This constraint forced model 5B to use the same optimal distribution of ground-water withdrawal as determined from 5A to minimize effects on the Rio Grande until the river "debt" was eliminated. For all years afterward, model 5B was allowed to determine the optimal distribution of ground-water withdrawal to minimize depletion of aquifer storage, but with the additional constraint that no new river "debt" be subsequently accumulated (that is, the lower bound on the value of the river "debt"/ "surplus" calculation was set to zero). Thus, the overall design of optimization model 5 achieved the intention of minimizing the effects of ground-water withdrawal on the Rio Grande until the city's river "debt" was eliminated, then minimizing the depletion of aquifer storage while not accumulating new river "debt" or excessive water-level declines.

Optimal Distribution of Ground-Water Withdrawal

Optimization model 5A used the response functions for the river plus drains (fig. 20) to determine the optimal withdrawal of ground water that would minimize leakage into the aquifer until river "debt" was eliminated. Trial and error with the length of the model showed that "debt" could be eliminated in 9 years. The optimal distribution of withdrawal calculated by model 5A does not match the distribution calculated for the first 9 years of model 2, which had the same overall objective. The distributions differ for two main reasons. First, because the objective of minimizing river plus drains leakage applied in model 5A for only these 9 years (as opposed to being a long-term objective), the model could determine the optimal distribution of withdrawal using only the first 9 years of the river plus drains response functions rather than the entire 54 years used by optimization model 2. Secondly, model 2 did not include the water-level constraint that was present in model 5A. The water-level constraint was binding for all 9 years at the observation site in the Lomas field and for year 2 at the sites in the Volcano Cliffs and Ridgecrest fields. The resulting optimal distribution of withdrawal (table 13) uses the Lomas, Love, Ridgecrest, and Volcano Cliffs well fields at varying rates greater than the required minimum.

For model 5B, which was designed to use the solution from model 5A for the first 9 years, the optimal distribution of ground-water withdrawal was the same as that calculated in optimization models 1 and 3 for every year starting in 2017. In 2015 and 2016, the constraint precluding accumulation of river "debt" was binding and resulted in a different optimal distribution than the one calculated for models 1 and 3. In 2015, the optimal distribution called for withdrawal from the San Jose, Coronado, and Webster well fields, whereas in 2016, the San Jose, Griegos, Atrisco, and Coronado well fields were included in the optimal distribution. As with models 1 and 3, the well fields included in the optimal distributions of withdrawal for 2017 through 2039 were the San Jose, Griegos, Atrisco, Duranes, Coronado, Webster, and Vol Andia fields.

Comparison of GAMS and MODFLOW Results

Similar to results for the previous models, comparison of the water budgets from GAMS and MODFLOW for the optimal distribution of withdrawal from optimization model 5 indicates that the models agree quite well for about the first 10 years (fig. 28). Afterward, the GAMS model continually overpredicts the use of water from aquifer storage and underpredicts the contribution of river plus drains leakage to the aquifer system by as much as about 6,100 acre-ft compared with the MODFLOW model. Because the GAMS model continually predicts less river plus drains leakage than the MODFLOW model, GAMS calculations indicate that there would be no river "debt" during years when MODFLOW indicates that as much as about 3,600 acre-ft of river "debt" would exist (table 14). This comparison shows that the GAMS solution could require slight modifications to ensure that requirements related to the future effects of COA ground-water withdrawals on the river system are met.

Water-level changes calculated by GAMS and MODFLOW for optimization model 5 agreed within an average of 10 ft for all observation sites except the site in the Lomas well field (fig. 29). During each of the first 9 years of the model, the optimal distribution of ground-water withdrawal includes withdrawal from the Lomas well field. Because agreement between GAMS and MODFLOW for the effect of withdrawal from the Lomas well field on water-level declines in the area is not as good as for other well fields, the MODFLOW simulation indicates that water-level declines at the observation site in the Lomas well field would exceed the water-level constraints of the GAMS model by as much as 4.9 ft during years 3 through 9 of the model. All other water-level declines from the MODFLOW simulation remain within the constraints applied in GAMS.

Table 13. Optimal distribution of ground-water withdrawal for optimization model 5

[All values are in thousands of acre-feet]

Well field (fig. 5)	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Atrisco	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	2.80	7.02	8.79	10.55	11.26	11.26	11.26	11.26	11.26	11.26
Burton	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Charles	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
College	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Coronado	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	7.14	2.80	0.08	0.08	0.08	0.08	0.08	0.08	0.08	8.14	8.14
Duranes	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	1.33	3.08	4.83	10.69	24.52	24.52
Gonzales	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Griegos	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56
Leavitt	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Leyendecker	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Lomas	4.91	4.27	6.63	6.76	8.07	7.85	7.15	8.80	9.90	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Love	0.28	9.84	0.28	0.28	0.28	0.28	4.95	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Miles	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Ponderosa	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Ridgecrest	15.66	16.74	5.18	12.34	5.18	15.77	23.54	14.03	9.36	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
San Jose	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	3.95	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05
Santa Barbara	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Thomas	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Vol Andia	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
Volcano Cliffs	0.12	5.85	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Walker	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Webster	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	9.93	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	7.22	8.97
West Mesa	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Yale	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Zamora	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Table 13. Optimal distribution of ground-water withdrawal for optimization model 5--Concluded

Well field (fig. 5)	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
Atrisco	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26	11.26
Burton	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Charles	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
College	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Coronado	8.14	0.08	0.08	0.08	0.08	0.08	0.08	0.98	8.14	8.14	5.81	8.14	8.14	8.14
Duranes	24.52	13.59	15.34	17.09	18.84	20.57	22.30	24.52	24.52	24.52	24.52	24.52	24.52	24.52
Gonzales	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Griegos	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56
Leavitt	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Leyendecker	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Lomas	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Love	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Miles	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Ponderosa	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Ridgecrest	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
San Jose	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05
Santa Barbara	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Thomas	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Vol Andia	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	12.60	0.24	0.24	0.24	1.89
Volcano Cliffs	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Walker	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Webster	6.62	0.08	0.08	0.08	0.08	0.08	0.08	0.08	6.58	9.93	0.08	5.28	1.23	9.93
West Mesa	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Yale	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Zamora	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Table 14. Comparison of calculated effects on the river system from GAMS and MODFLOW for optimization model 5

[All values are in acre-feet]

Year	Annualized net river plus drains leakage from MODFLOW	River debt/ surplus from MODFLOW[1]	Annualized net river plus drains leakage from GAMS	River debt/ surplus from GAMS[1]	Percent difference between GAMS and MODFLOW river plus drains leakage[2]
2006	56,526	-10,130	56,592	-10,196	0.1
2007	54,603	6,652	54,774	6,480	0.3
2008	52,773	-16,898	52,969	-17,093	0.4
2009	50,886	-8,333	51,101	-8,547	0.4
2010	49,071	-11,432	49,317	-11,678	0.5
2011	47,302	-158	47,488	-344	0.4
2012	45,602	12,389	45,711	12,280	0.2
2013	43,998	588	43,913	674	-0.2
2014	42,436	-2,299	41,975	-1,837	-1.1
2015	42,271	-1,213	41,058	0	-2.9
2016	44,565	-2,402	42,163	0	-5.4
2017	46,157	-3,377	42,497	284	-7.9
2018	46,780	-3,118	42,319	1,343	-9.5
2019	47,092	-2,549	42,189	2,354	-10.4
2020	47,239	-1,816	42,131	3,292	-10.8
2021	47,352	-1,053	42,156	4,143	-11.0
2022	47,455	-280	42,234	4,941	-11.0
2023	48,247	3,905	43,168	8,984	-10.5
2024	51,701	28,614	46,599	33,715	-9.9
2025	54,265	26,925	48,900	32,291	-9.9
2026	56,070	21,896	50,378	27,588	-10.2
2027	55,111	-3,556	49,044	2,510	-11.0
2028	54,241	-1,810	48,616	3,815	-10.4
2029	53,705	-398	48,699	4,608	-9.3
2030	53,418	764	48,991	5,190	-8.3
2031	53,286	1,762	49,348	5,699	-7.4
2032	53,301	2,613	49,795	6,118	-6.6
2033	53,602	4,562	50,451	7,712	-5.9
2034	55,082	15,873	51,267	19,688	-6.9
2035	57,234	28,563	52,542	33,256	-8.2
2036	58,152	2,251	53,345	7,058	-8.3
2037	58,644	8,421	53,905	13,159	-8.1
2038	58,891	3,244	54,347	7,788	-7.7
2039	59,570	12,054	54,957	16,668	-7.7

[1] A positive number represents river "surplus"; a negative number represents river "debt"

[2] ((GAMS-MODFLOW)/MODFLOW) x 100

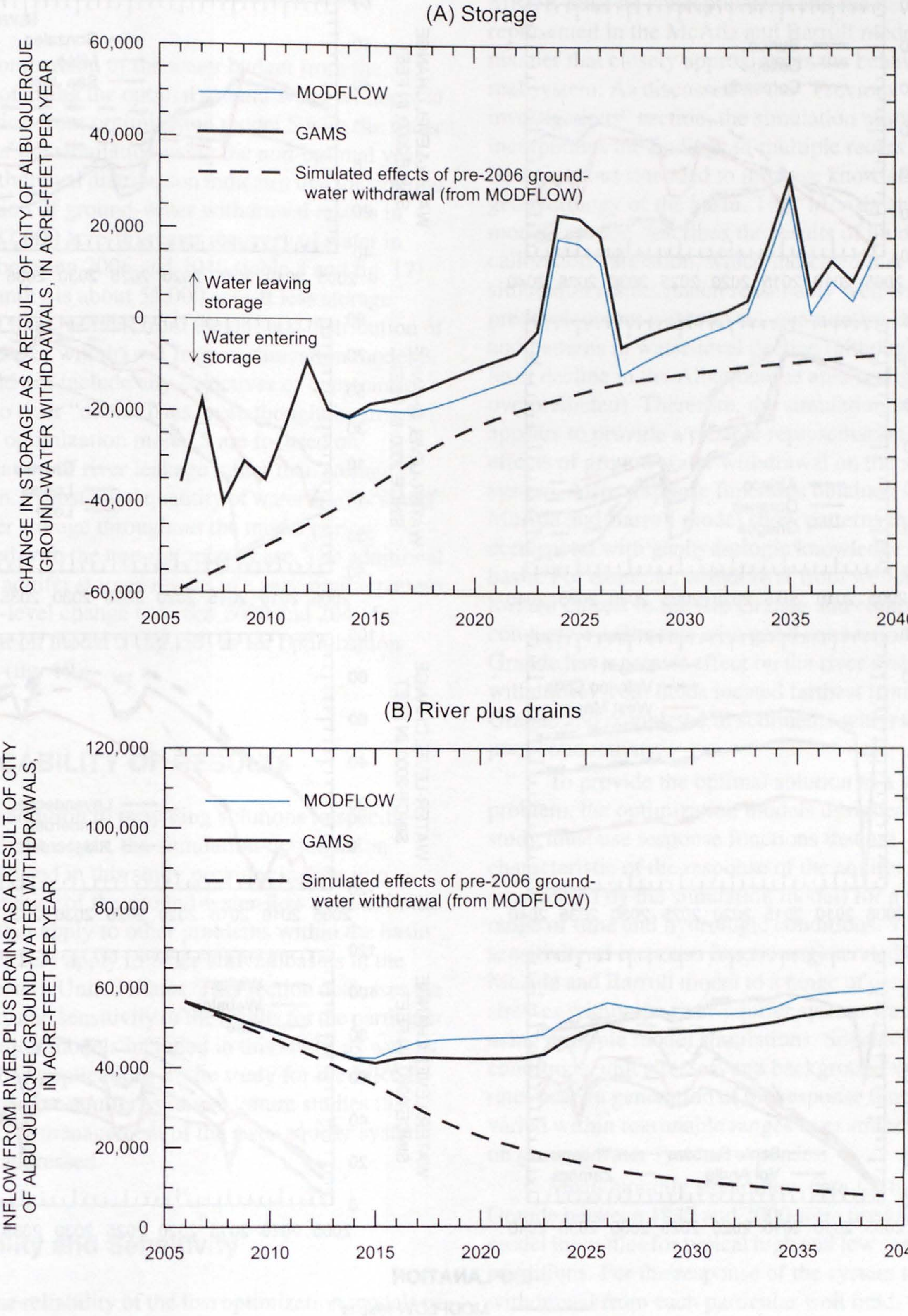


Figure 28. Comparison of (A) storage and (B) river plus drains components of the water budgets from GAMS and MODFLOW for optimization model 5.

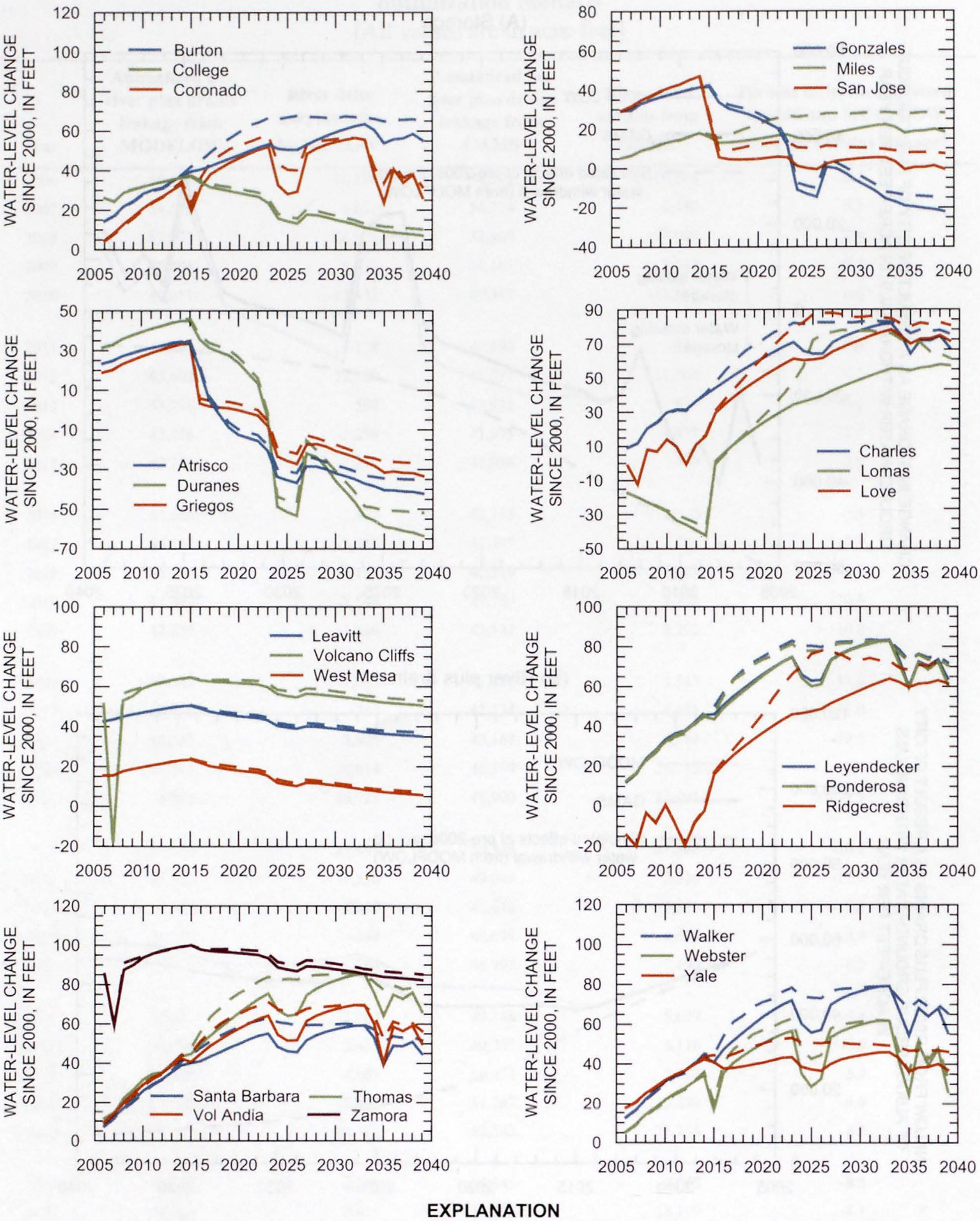


Figure 29. Comparison of water-level changes from GAMS and MODFLOW for optimization model 5.

Comparison of Simulation Results for Optimal and Non-Optimal Distributions of Ground-Water Withdrawal

Comparison of the water budget from the simulation using the optimal ground-water withdrawal distribution from optimization model 5 with the water budget of the simulation using the non-optimal year-2000 withdrawal distribution indicates that the optimal distribution of ground-water withdrawal results in about 187,000 acre-ft greater recovery of water in storage between 2006 and 2040 (table 8 and fig. 17). This quantity is about 55,000 acre-ft less storage recovery than resulted from the optimal distribution of ground-water withdrawal from optimization model 3, which did not include any objectives or constraints related to river "debt." Thus, even though the first 9 years of optimization model 5 are focused on minimization of river leakage rather than storage depletion, a substantial quantity of water is still "saved" in aquifer storage throughout the model period compared with the non-optimized case. The additional water in aquifer storage results in a very similar pattern of water-level change between 2000 and 2040 for optimization model 5 (fig. 30) as for optimization model 1 (fig. 19).

APPLICABILITY OF RESULTS

In addition to providing solutions to specific management issues, the simulation-optimization approach used in this study provides insight into characteristics of the ground-water-flow system in the MRGB that apply to other problems within the basin and that likely apply to other alluvial basins in the Southwestern United States. This section discusses the reliability and sensitivity of the results for the particular optimization models included in this study, as well as the broader implications of the study for the MRGB and other river-aquifer systems. Future studies that could aid in management of the river-aquifer system also are addressed.

Reliability and Sensitivity

The reliability of the five optimization models of this study in providing the optimal solutions to achieve their objectives depends on several factors related to the design of both the simulation and optimization models. First of all, the river-aquifer system of the MRGB must be conceptualized and mathematically represented in the McAda and Barroll model in a manner that closely approximates the behavior of the real system. As discussed in the "Previous investigations" section, the simulation model incorporates the findings of multiple recent investigations intended to improve knowledge of the geohydrology of the basin. The "McAda and Barroll model" section describes the results of model calibration/validation, which indicated that the simulation results match reasonably well with the predevelopment water levels, quantitative flow targets, and patterns in water-level decline (although water-level decline in the Albuquerque area is slightly overpredicted). Therefore, the simulation model appears to provide a reliable representation of the effects of ground-water withdrawal on the aquifer system. Also, response functions obtained from the McAda and Barroll model show patterns that correspond with geohydrologic knowledge of the basin. For example, withdrawal from well fields located closest to the Rio Grande and completed in conductive sediments with good connection to the Rio Grande has a greater effect on the river system than withdrawal from fields located farthest from the Rio Grande and completed in sediments with relatively poor conductivity.

To provide the optimal solution to a stated problem, the optimization models designed for this study must use response functions that are characteristic of the response of the aquifer system (as represented by the simulation model) for a reasonable range of time and hydrologic conditions. The sensitivity of response functions generated from the McAda and Barroll model to a range of conditions and stresses within the river-aquifer system was tested using multiple model simulations. Specifically, river conditions, unit stresses, and background withdrawal rates used in generation of the response functions were varied within reasonable ranges to examine the effects on ground-water system responses.

Mean monthly streamflow data for the Rio Grande between 1942 and 2000 were used to construct model input files for typical high and low seasonal river conditions. For the response of the system to withdrawal from each particular well field, two simulations were run with either a high or low river condition for all years of the simulation. For each of four well fields (Duranes, Leavitt, Ridgecrest, and

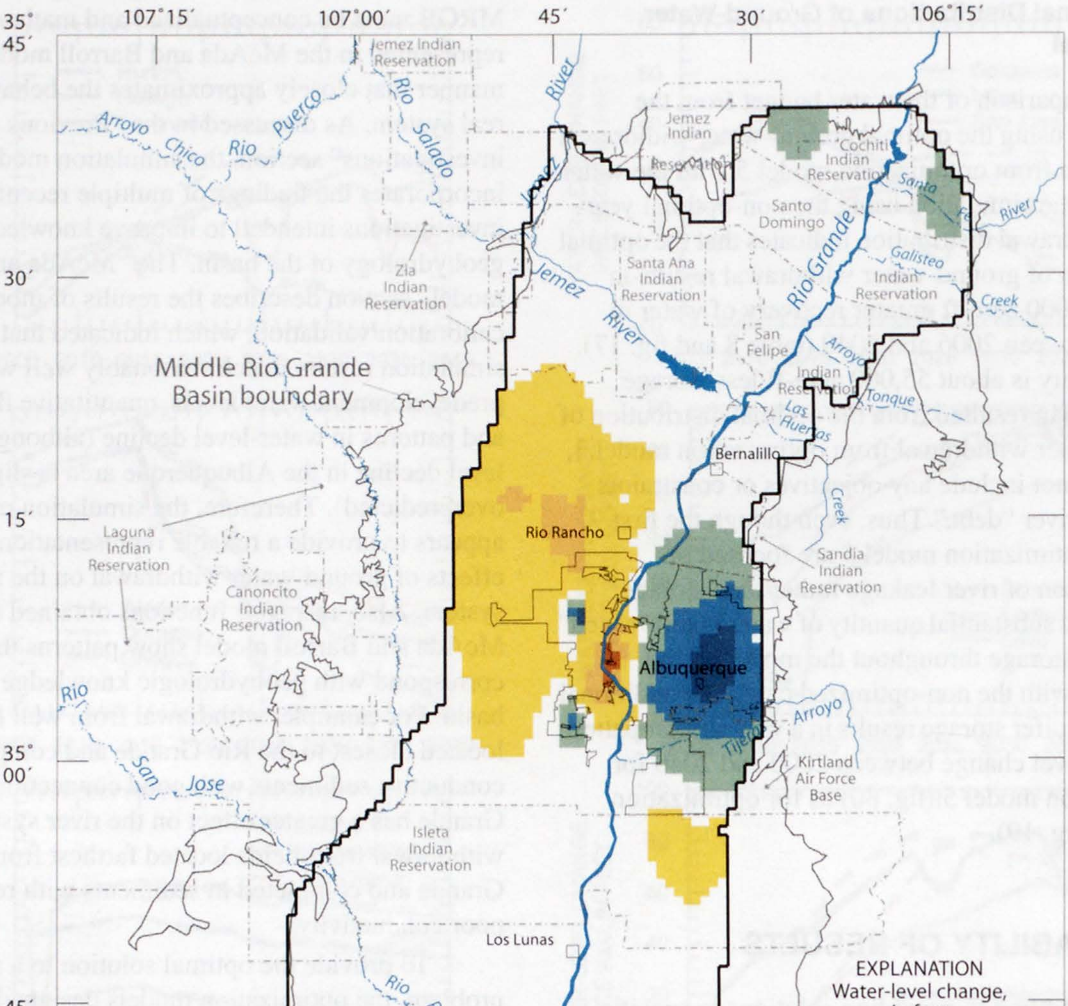


Figure 30. Simulated water-level change in the production zone (layer 5) between 2000 and 2040 for optimal ground-water withdrawal from optimization model 5.

Thomas) chosen to be representative of a variety of locations and aquifer characteristics, the response functions generated under these consistently high and low river conditions were compared with the response functions used in the optimization models, which had the same background withdrawal rate and unit stress but used an average river condition calculated from data for 1990 to 2000 (which was very similar to the average river condition calculated from the 1942 to 2000 data). For each well field, the mean difference in the annual response of the water-budget components for the high and low river conditions from the average condition was less than 3 percent with the exception of the Duranes well field, which showed a mean difference of about 13.5 percent between the average and low river conditions for the storage response. For the response of water levels in the production zone of the aquifer at 12 selected observation sites, the mean difference was about 2 percent or less for all fields except Duranes, where the difference was almost 12 percent for water-level responses between the average and low river conditions. The greatest difference in response functions for the well field located closest to the river system and the area of riparian evapotranspiration was anticipated. Overall, the differences observed were small enough to indicate that the response functions used in the optimization models were appropriate for a reasonable range of river conditions.

The response functions also were evaluated for sensitivity to the background rate of COA withdrawal used in generating them. In addition to the 25,000-acre-ft/yr background rate (approximating the average projected withdrawal between 2006 and 2015) of the simulations from which the final response functions used in the optimization models were obtained, background rates of about 45,000 acre-ft/yr and about 114,000 acre-ft/yr were tested. The 45,000-acre-ft/yr rate approximated the average projected withdrawal rate for 2006 through 2040, whereas the 114,000-acre-ft/yr rate approximated the rate of withdrawal in 2000. Comparing results for the 45,000- and 25,000-acre-ft rates, the average differences in the annual budget responses for the four well fields tested (Duranes, Leavitt, Ridgecrest, and Thomas) ranged from 2.9 to 14.6 percent; the average differences in the water-level responses ranged from less than 1 to 17.5 percent. Therefore, both the budget and water-level responses were quite similar for the 45,000- and 25,000-acre-ft background rates. Comparing results for the 114,000- and 25,000-acre-ft rates, the average differences for the four well fields ranged from 5.9 percent (for the storage response to withdrawal from the Leavitt field) to 39.3 percent (for the storage response to withdrawal from the Ridgecrest field) in annual budget responses, with most average differences less than 25 percent. The average differences in the water-level responses ranged from 18.7 to 49.9 percent. These results indicate that nonlinearities in the simulation model can have a substantial effect on budget and water-level responses when the background withdrawal rate varies within a wide range. Similar to the simulations performed using different river conditions, model simulations also were performed to investigate the effects of using different unit stresses. When the unit stress was increased from 1,000 to 3,000 acre-ft per well for a year, both the average annual budget and water-level responses to withdrawal in the Duranes, Leavitt, Ridgecrest, and Thomas well fields deviated by only as much as 3.5 percent from the response multiplier of 3.0 that would represent the increased response for a perfectly linear model of the system. Both positive and negative unit stresses (the negative stress equating to a decrease in pumping) of 333 acre-ft per well for a year were simulated for the Coronado, Yale, and Zamora well fields. These fields were selected because they were among the few fields with sufficient withdrawal from each well at the selected background pumping rates to allow the full decrease in withdrawal to be applied without resulting in the injection of water. The average annual budget responses for the positive unit stress of 333 acre-ft per well deviated by only as much as about 2.4 percent from the multiplier of 0.33 that would represent the decreased response for a perfectly linear model when the stress was reduced from 1,000 acre-ft to 333 acre-ft per well; for average annual water-level responses in the production zone, the deviation was as much as about 9.2 percent. Comparison of results between the positive and negative unit stresses of 333 acre-ft/yr showed that the budget responses were equal but opposite in sign to within about 3.6 percent and that water-level responses were equal but opposite in sign to within about 9.3 percent. Therefore, the response functions used in the optimization models appear to be appropriate for a reasonable range of unit stresses, either positive or negative.

Overall, the response functions used in this study are more sensitive to the background withdrawal rate than to river conditions or to the unit stress applied to each well field. Although the differences in response functions generated for the various background withdrawal rates do not invalidate the results of the optimization models, the sensitivity test indicates that the appropriateness of the background withdrawal rate selected for a particular optimization problem should be evaluated. For this study, the match between GAMS and MODFLOW results using response functions generated with the background withdrawal rate of 45,000 acre-ft was compared with the match using response functions generated with the background withdrawal rate of 25,000 acre-ft. This evaluation indicated that the lower withdrawal rate was more appropriate given the objectives and constraints of the optimization models being studied. If some aspects of the optimization problems were to change substantially, use of the same background withdrawal rate might or might not be appropriate.

When a linear approach to the design and solution of optimization models is used (as in this study), the model results are reliable only if they can provide a reasonable approximation of the behavior of the ground-water system despite its nonlinearities. As discussed in the "Formulation and solution of mathematical optimization models" section, nonlinear aspects of the ground-water system as represented in the McAda and Barroll model are the semiconfined character of the aquifer, the process of evapotranspiration, and interaction of the interior drain system with the shallow aquifer. Simulations performed with the McAda and Barroll model prior to the beginning of the optimization study indicated that these nonlinearities generally played only a minor role in simulation results. As a part of this study, effects of the optimal distributions of withdrawal from the five optimization models on water levels and components of the water budget were calculated using both GAMS and MODFLOW. Comparison of the effects as calculated by the two types of models indicated that the linear optimization models were providing a reasonable approximation of the system as represented by the simulation model. Although budget results from the two models generally began to diverge after about the first 10 years, the degree of divergence was small compared with the overall quantity of water simulated as moving through the ground-water system.

Of course, reliability of the results of an optimization model also depends on having a problem that is well posed and that is correctly represented mathematically. For this study, the first optimization models studied were designed to be simple enough to allow direct comparison between the model results and the response functions used in model construction. Evaluation of these results indicated that the models provided the solutions that were anticipated from the relations among the response functions. Even as more complex objectives and constraints were added to the optimization scenarios, comparison of the response functions, the optimal distributions of ground-water withdrawal, calculations of effects on the ground-water system in GAMS, and results of MODFLOW models using both optimal and non-optimal withdrawal distributions demonstrated that the optimization models were providing appropriate solutions.

Although results of the optimization models presented in this study are appropriate for the problems that have been posed, the applicability of the exact solutions of these models is necessarily limited by the accuracy of predictions of future conditions. Predictions of total water demand and of the availability of surface water for municipal supply (and, consequently, of the demand for ground water) are by their nature quite uncertain. Also, the likelihood is great that by 2040 municipal-supply wells currently in production will become unusable and new municipal-supply wells or well fields will come into production. Other aspects of the natural system and the water-supply system also may change in ways that have substantial effects on the applicability of the exact solutions to the optimization models. Nevertheless, the results of this study provide insight into the operation of the river-aquifer system of the MRGB that is applicable regardless of the exact conditions under which future water deliveries must be made, as discussed in the following section.

Implications for the Ground-Water System of the Middle Rio Grande Basin and Other Alluvial Basins of the Southwestern United States

The response functions and model solutions generated for this study provide important information about the response of the ground-water system of the MRGB to applied stresses. In particular, the results indicate the general timing and magnitude of water-budget and water-level responses. Much of this information is applicable to a variety of posed problems for management of the river-aquifer system of the basin and even has transfer value to other alluvial basins in the Southwestern United States. For example, response functions indicate that the time horizon required for the effects on the water budget and water levels of a 1,000-acre-ft stress (applied to the aquifer system over the period of 1 year) to dissipate completely can reasonably exceed 50 years. Therefore, the effects of even moderate annual ground-water withdrawals on river infiltration, aquifer storage, and water levels in river-aquifer systems of the same general size and hydrogeology as the MRGB can be substantial for ground-water management on the time scale of decades. Because of the length and magnitude of the effects of stresses, consideration of the full response of the river-aquifer system over time when management issues are addressed with simulation-optimization techniques is important.

The response functions generated for this study also illustrate the importance of various physical factors in determining the effects of a stress in an individual location on the components of the river-aquifer system. In particular, the response functions demonstrated that distance between the location of an applied stress and the river system is often not as important as the aquifer properties between the two features in determining the magnitude and timing of induced infiltration. Water levels are similarly affected by the degree of hydraulic connection between the location of the applied stress and the river. Knowledge of the COA well fields where withdrawal has the largest effect on aquifer storage or on the river system is applicable to a variety of management issues, under a broad set of conditions with respect to water demand and surface-water availability. The same physical factors shown to be important to the response functions generated for COA well fields also would be important in other areas of the MRGB, as well as in alluvial-aquifer systems elsewhere.

The optimization models included in this study also indicate the general magnitude of changes in aquifer-system response that can be expected from altering distributions of major ground-water withdrawal in the MRGB over a planning horizon of a few decades. The models that incorporated objectives related to minimizing use of water from aquifer storage demonstrated that optimization of ground-water withdrawals over a 34-year period can result in a "savings" in aquifer storage of enough water to supply COA customers for about 2 years at year-2000 rates of water demand. Models indicate that this "savings" in aquifer storage can result in water-level rises of as much as 70 ft in parts of Albuquerque between 2000 and 2040. Models further indicate that the NMOSE guidelines for average annual water-level declines through 2040 (New Mexico Office of the State Engineer, 2003) are not likely to be exceeded by COA ground-water withdrawals for most locations and years under current (2003) management objectives and projections of water demand. Results from model 5 show that alterations to the distribution of ground-water withdrawals by the COA could result in elimination of river "debt" about 9 years earlier than would be achieved using the year-2000 distribution of withdrawals. These results indicate that a simulation-optimization approach to ground-water management in the MRGB (and, therefore, likely in other Southwestern alluvial basins) can achieve substantial changes to components of the river-aquifer system.

Limitations and Future Needs

This study is able to indicate the general magnitude and timing of effects of changes in water management by a significant ground-water user in the MRGB on components of the river-aquifer system. However, the models and techniques used are not adequate to simulate detailed aspects of the surface-water system of the basin. For example, the models cannot include sufficient information to determine whether the full surface-water diversions planned by the COA would result in drying of the Rio Grande within the basin during any particular year. Therefore, the interests of all water users in the MRGB could not be addressed by this study. More detailed surface-water projections and models would be required to deal appropriately with surface-water issues. In the future, the models used here—as well as any detailed models of the surface-water system in the MRGB—would benefit from continued and perhaps enhanced monitoring of ground-water levels and of streamflow in the Rio Grande and associated irrigation canals and drains. Improved knowledge of ground-water/surface-water interactions within the MRGB also would be beneficial to future modeling efforts.

SUMMARY

Concerns about considerable water-level declines in the Santa Fe Group aquifer system have led the COA, which is the largest single user of ground water in the MRGB of central New Mexico, to adopt a

new strategy that calls for the direct use of surface water from the Rio Grande to meet most municipal water demand. This strategy will still require the use of ground-water withdrawals for municipal supply during times of high demand or drought. When the new strategy is implemented, all municipal-supply wells are anticipated to be tied into a single supply system for the entire city, as opposed to the current (2003) system, in which individual supply wells can supply only limited areas of the city. This configuration will allow management of the ground-water supply system as a whole to achieve particular objectives with respect to the river-aquifer system.

The USGS, in cooperation with the COA Public Works Department, used a simulation-optimization approach to determine the optimal distribution of ground-water withdrawal by the COA between 2006 and 2040 to achieve particular management objectives. The simulation model used in the approach was the McAda and Barroll ground-water-flow model, which incorporates knowledge of the geohydrology of the basin gained through a recent multiyear, multiagency investigation effort. The McAda and Barroll model was used to generate response functions that indicated the response of the ground-water system to a unit quantity of withdrawal from individual COA well fields. These response functions were incorporated into a linear approach for the design and solution of the optimization models. The mathematical programming software package GAMS was used in combination with the MINOS solver to achieve the solution to each linear optimization model.

All five optimization models included in the study described in this report had objectives related to minimization of the effects of ground-water withdrawal on aquifer storage and (or) leakage from the river and drains. The five models were designed to optimize the annual withdrawal from each well field, rather than each individual well, using projections of future total demand and ground-water demand. Because the objectives of the models were intended to take into account long-term effects on the river-aquifer system, both the response functions used in the optimization models and the duration of the mathematical models themselves were extended beyond 2040. This design allowed the full effect on the system for 54 years to be considered for every year of modeled ground-water withdrawal through 2040.

The first optimization model was designed to minimize total use of water from aquifer storage between 2006 and 2040, within constraints on annual ground-water demand, annual well-field capacity, and annual minimum withdrawal per well. Response functions showing the effect of ground-water withdrawal from an individual well field on aquifer storage for the following 54 years indicated that the well fields that would deplete aquifer storage the least over that time period were the San Jose, Griegos, Atrisco, Duranes, Coronado, Webster, and Vol Andia well fields. These fields include four (San Jose, Griegos, Atrisco, and Duranes) that are located close to the Rio Grande and three others that are located farther from the Rio Grande but that have wells completed in high-conductivity sediments, allowing a good hydraulic connection to the river system. Only these seven well fields were included in the optimal solution to optimization model 1 at withdrawal rates exceeding the assigned minimum. The design of optimization model 1 allowed easy comparison between the response functions and the model solution, which indicated that the model provided the solution that was expected. Effects of the optimal distribution of withdrawal on the water budget of the aquifer system as calculated in GAMS were compared with the effects indicated by a MODFLOW simulation using the optimal distribution. The comparison indicated that the GAMS model reasonably approximated the aquifer system as represented in the McAda and Barroll model (within only about 2 percent of the overall quantity of water simulated to move through the system), despite nonlinearities known to exist in the simulation model. Comparison of results from the MODFLOW simulation using the optimal distribution of ground-water withdrawal with a simulation using a non-optimal distribution approximating the distribution used in 2000 indicated that the optimal distribution results in about 242,000 acre-ft greater recovery of water in aquifer storage. Nearly all this storage recovery is derived from increased leakage from the river system. The increased storage recovery of the optimal case compared with the non-optimal case results in a greater magnitude of water-level rise in the production zone of the aquifer beneath much of Albuquerque.

The second optimization model was designed to minimize total leakage of water from the river system between 2006 and 2040, within the same constraints used in optimization model 1. Response functions showing the effect of ground-water withdrawal from an individual well field on leakage from the river plus drains for the following 54 years indicated that the well fields that would induce the least leakage over that time period were the Volcano Cliffs, Zamora, College, West Mesa, Leavitt, Lomas, Ridgecrest, and Love well fields. Five of these fields (Volcano Cliffs, Zamora, College, West Mesa, and Leavitt) are located west of the Rio Grande, in low-conductivity sediments that provide a poor connection to the river system; the McAda and Barroll model also simulates selected major faults in the area as hydrologic barriers to ground-water flow. The other three fields are located at large distances from the Rio Grande. Only these eight well fields were included in the optimal solution to optimization model 2 at withdrawal rates exceeding the assigned minimum. Analysis of model results indicated that the model provided the expected solution based on the response functions and that the GAMS model provided a reasonable approximation of the aquifer system as represented in MODFLOW. A MODFLOW simulation using the optimal distribution of ground-water withdrawal indicated that the optimal distribution results in about 214,000 acre-ft less river plus drains leakage and about 234,000 acre-ft greater storage depletion than the non-optimal distribution. The optimal distribution of model 2 also results in large water-level declines in the production zone of the aquifer west of the Rio Grande, where most of the ground-water withdrawal is concentrated.

The third optimization model was designed with the same objective and constraints as optimization model 1, with an added constraint on the allowable water-level decline for each year of the model relative to the decline present in 2000. This model required the use of response functions quantifying the effect of ground-water withdrawal from each well field on the water-level decline at each of 25 observation sites (one site located within each well field). The solution for optimization model 3 was nearly identical to the solution for optimization model 1 because the constraint allowing no more than 2.5 ft of water-level decline per year was binding on the solution in only the second year of the model and for only two observation sites (the sites located in the Griegos and Atrisco well fields). The optimal withdrawal differed only in 2007, resulting in nearly the same enhanced recovery of aquifer storage relative to the non-optimal case as was observed for optimization model 1. Comparison of water-level declines calculated by GAMS and declines simulated by MODFLOW using the optimal withdrawal distribution showed that the average difference was less than 8 ft for most observation sites.

The fourth optimization model was designed with the same objective and constraints as optimization model 3, with the added constraint that the arsenic concentration of the blended ground water could not exceed the USEPA drinking-water standard of 10 micrograms per liter. For this model, the arsenic concentration of water drawn from each well field was assumed to be equal to the average of the median concentrations from all wells in the field, as determined from available chemical data (typically, samples collected at least biannually over a period of 10 years). The constraint on arsenic concentration was binding in every year of the model, producing a solution that still used many of the same well fields as the solutions to optimization models 1 and 3 (the Griegos, Atrisco, Duranes, San Jose, Vol Andia, and Coronado fields), but with different ratios of withdrawal among the fields. Optimization model 4 again provides a reasonable approximation between the GAMS and MODFLOW results for both the water budget and water-level declines. The addition of the constraints on water-level declines and arsenic concentration in optimization model 4 results in a solution with only about 10,000 acre-ft less storage recovery than the solution for optimization model 1.

Optimization model 5 incorporated multiple objectives and constraints. The overall objective of the model was to minimize leakage from the river system until the "debt" owed by the COA to the Rio Grande as a result of ground-water withdrawals until that time had been eliminated, and to subsequently minimize use of water from aquifer storage. Constraints were the same as those used in optimization model 3 (related to ground-water demand, well-field capacity, minimum well-field withdrawal, and water-level decline), with the addition of a constraint that precluded accumulation of river "debt" after it was first eliminated. Calculations by the optimization model, which incorporated information on COA water rights and projected surface-water use and return flows, indicated that river "debt" could be eliminated after 9 years by withdrawing ground water from the Lomas, Love, Ridgecrest, and Volcano Cliffs well fields at rates greater than the required minimum. The constraint requiring the accumulation of no subsequent river "debt" was binding in years 2015 and 2016. Thereafter, the solution to optimization model 5 was identical to the solution of optimization models 1 and 3. Overall, the solution to optimization model 5 resulted in about 187,000 acre-ft greater recovery of water in storage between 2006 and 2040 than the non-optimal withdrawal distribution. This quantity is about 55,000 acre-ft less storage recovery than resulted from the optimal distribution of ground-water withdrawal from optimization models 1 and 3.

The five optimization models presented in this study provide a reasonable approximation of the river-aquifer system as represented in the McAda and Barroll ground-water-flow model, despite the nonlinearities inherent in that model. The McAda and Barroll model was designed to aid in management of the water resources of the MRGB, and has been previously shown to closely reproduce the observed effects of stresses on the aquifer system. Analysis of the response functions generated by the McAda and Barroll model and used in the optimization models indicates that they should be applicable to a reasonable range of river conditions and ground-water withdrawal scenarios for the basin. Although the exact solutions to the optimization models presented in this report would vary with changes in future water demand, the locations of municipal-supply wells, or other factors, the broader implications of the model results would remain important to the management of regional water resources. In particular, information learned about the timing and magnitude of the effects of ground-water withdrawals in different locations on aquifer storage and on the river system could be applied to multiple management issues in the MRGB, and perhaps in other alluvial basins of the Southwestern United States. Also, the models and techniques described in this report indicate that optimizing the distribution of ground-water withdrawal within the MRGB can achieve substantial changes in the quantity of aquifer-storage "savings," ground-water-level rise, and surface-water infiltration that occurs over the period of a few decades.

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