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Survey of Hydrologic Models and Hydrologic Data Needs for Tracking Flow in the Rio Grande, North-Central New Mexico, 2010

Scientific Investigations Report 2011–5207

U.S. Department of the Interior
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KEN SALAZAR, Secretary

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Doug McAda and D. Michael Roark, hydrologists with the U.S. Geological Survey (USGS), were interviewed for their working knowledge of the hydrologic models. David Bjerklie of the USGS was very helpful in the survey of several surface-water models.

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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 1988 (NAD 88).

Altitude, as used in this report, refers to distance above the vertical datum.

Survey of Hydrologic Models and Hydrologic Data Needs for Tracking Flow in the Rio Grande, North-Central New Mexico, 2010

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Abstract

The six Middle Rio Grande Pueblos have prior and paramount rights to deliveries of water from the Rio Grande for their use. When the pueblos or the Bureau of Indian Affairs Designated Engineer identifies a need for additional flow on the Rio Grande, the Designated Engineer is tasked with deciding the timing and amount of releases of prior and paramount water from storage at El Vado Reservoir to meet the needs of the pueblos. Over the last three decades, numerous models have been developed by Federal, State, and local agencies in New Mexico to simulate, understand, and (or) manage flows in the Middle Rio Grande upstream from Elephant Butte Reservoir. In 2008, the Coalition of Six Middle Rio Grande Basin Pueblos entered into a cooperative agreement with the U.S. Geological Survey to conduct a comprehensive survey of these hydrologic models and their capacity to quantify and track various components of flow. The survey of hydrologic models provided in this report will help water-resource managers at the pueblos, as well as the Designated Engineer, make informed water-resource-management decisions that affect the prior and paramount water use. Analysis of 4 publicly available surface-water models and 13 publicly available groundwater models shows that, although elements from many models can be helpful in tracking flow in the Rio Grande, numerous data gaps and modeling needs indicate that accurate, consistent, and timely tracking of flow on the Rio Grande could be improved.

Deficient or poorly constrained hydrologic variables are sources of uncertainty in hydrologic models that can be reduced with the acquisition of more refined data. Data gaps need to be filled to allow hydrologic models to be run on a real-time basis and thus ensure predictable water deliveries to meet needs for irrigation, domestic, stock, and other water uses. Timeliness of flow-data reporting is necessary to facilitate real-time model simulation, but even daily data are sometimes difficult to obtain because the data come from multiple sources.

Each surface-water model produces results that could be helpful in quantifying the flow of the Rio Grande, specifically by helping to track water as it moves down the channel of the Rio Grande and by improving the understanding of river hydraulics for the specified reaches. The ability of each surface-water model to track flow on the Rio Grande varies according to the purpose for which each model was designed. The purpose of Upper Rio Grande Water Operations Model (URGWOM)—to simulate water storage and delivery operations in the Rio Grande—is more applicable to tracking flow on the Rio Grande than are any of the other surface-water models surveyed. Specifically, the strengths of URGWOM in relation to modeling flow are the details and attention given to the accounting of Rio Grande flow and San Juan–Chama flow at a daily time step. The most significant difficulty in using any of the surveyed surface-water models for the purpose of predicting the need for requested water releases is that none of the surface-water models surveyed consider water accounting on a real-time basis.

Groundwater models that provide detailed simulations of shallow groundwater flow in the vicinity of the Rio Grande can provide large-scale estimates of flow between the Rio Grande and shallow aquifers, which can be an important component of the Rio Grande water budget as a whole. The groundwater models surveyed for this report cannot, however, be expected to provide simulations of flow at time scales of less than the simulated time step (1 month to 1 year in most cases). Of those of the currently used groundwater models, the purpose of model 13—to simulate the shallow riparian groundwater environment—is the most appropriate for examining local-scale surface-water/groundwater interactions. The basin-scale models, however, are also important in understanding the large-scale water balances between the aquifers and the surface water. In the case of the Upper and Middle Rio Grande Valley, models 6, 10, and 12 are the most accurate and current groundwater models available.

Introduction

The Coalition of Six Middle Rio Grande Basin Pueblos in New Mexico would like to ensure predictable water deliveries to meet their needs for irrigation, domestic, stock, and other water uses at the six pueblos. The six Middle Rio Grande

Basin Pueblos are Native American tribes whose lands are located on the main stem of the Rio Grande downstream from the U.S. Geological Survey (USGS) Rio Grande at Otowi stream-gaging station (fig. 1) and are within the Middle Rio Grande Conservancy District (MRGCD) service area, which extends from below Cochiti Lake downstream to the northern boundary of the Bosque del Apache National Wildlife Refuge (Oad and others, 2009). From north to south, the six Middle Rio Grande Basin Pueblos include the Pueblos of Cochiti, Santo Domingo (Kewa), San Felipe, Santa Ana, Sandia, and Isleta (fig. 1).

The pueblos' rights to deliveries of water from the Rio Grande are based on laws spanning multiple centuries and multiple crowns (Mann, 2007). The pueblos' "prior and paramount" rights to water deliveries were recognized by the act of March 13, 1928 (45 Stat. 312) (hereafter, the act). The act authorized the Secretary of the Interior to execute an agreement with the MRGCD providing for, among other things, conservation, irrigation, drainage, and flood control for the Pueblo Indian lands in the Rio Grande Valley, New Mexico (Sanchez, 2007). A quantity of water based on historically irrigated pueblo acreage—called prior and paramount water—is stored at El Vado Reservoir (fig. 1) each year to be delivered when needed to the pueblos. Storage and release of water for the six Middle Rio Grande Pueblos have taken place at El Vado Reservoir since the reservoir was first used in 1935 (Sanchez, 2007). Procedures for the storage and release of prior and paramount water were outlined and agreed upon in a December 28, 1981, agreement titled "Procedures for the Storage and Release of Indian Water Entitlements of the Six Middle Rio Grande Pueblos, Between the Six Middle Rio Grande Pueblos and the Department of Interior" (Chemanji Shu-Nyamboli, written commun., Hydrologist, Pueblo of San Felipe, Sept. 2011). An analysis of the policies and procedures relating to calculations of storage and release of prior and paramount water is not addressed in this report.

The prior and paramount water is delivered as a parcel of water along the Rio Grande and then through the MRGCD's diversions and canal system. The Secretary of the Interior through the Bureau of Indian Affairs has designated a technical expert, called the Designated Engineer, to oversee the delivery of prior and paramount water to the pueblos, among other tasks.

When the pueblos identify a need for prior and paramount water releases, the Designated Engineer is responsible for deciding the timing and amount of releases of prior and paramount water to meet the needs of the pueblos. Deliveries of prior and paramount water that occur too late or that are of insufficient quantity may be unusable by the pueblos. The challenge to the pueblos and the Designated Engineer is to know, with sufficient warning time, when steamflows in the Rio Grande will become too low for the pueblos' needs and to correctly estimate timing and volume of prior and paramount water releases from El Vado Reservoir so that the release will fulfill the needs of the pueblos.

Over the last three decades, numerous hydrologic models have been developed by Federal, State, and local agencies in New Mexico to simulate, understand, and (or) manage flows of the Rio Grande upstream from Elephant Butte Reservoir. None of these models were developed specifically to manage prior and paramount water; however, certain elements within some or all of the models that can account for or quantify and track various hydrologic elements might be applicable to the management of prior and paramount waters and therefore helpful to the pueblo water-resource managers and the Designated Engineer. In 2008, the Coalition of Six Middle Rio Grande Basin Pueblos entered into a cooperative agreement with the USGS to conduct a comprehensive survey of these hydrologic models and their capacity to quantify and track various components of flow. The survey of hydrologic models provided in this report will help water-resource managers at the pueblos, as well as the Designated Engineer, make informed water-resource-management decisions that affect the prior and paramount water use.

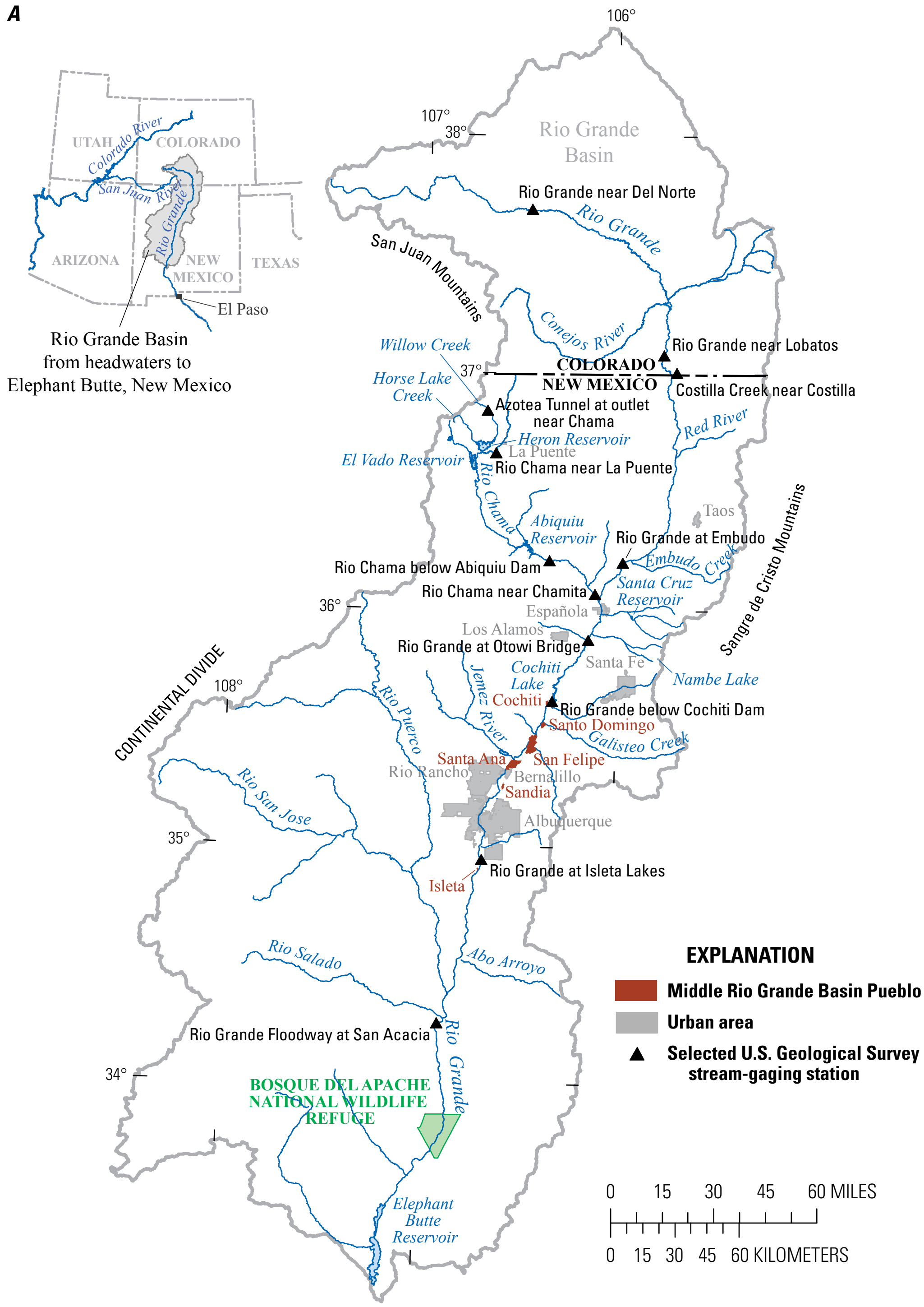
Purpose and Scope

This report provides a detailed survey of selected hydrologic models in the form of comparison tables to be used as tools to help readers evaluate the models for multiple uses, including tracking of flow on the Rio Grande. The report also includes discussion of hydrologic data that are not yet being collected but would be useful in facilitating a more accurate accounting of water in the Rio Grande. Hydrologic elements that can be accounted by the hydrologic models can include stored water, tributary inflow, intermountain transfer water, prior and paramount water, or any other specified flow to be accounted or tracked along the Rio Grande. The hydrologic models surveyed for this report are all publicly available surface-water or groundwater models covering some portion of the reach of the Rio Grande and its tributaries from the Rio Grande at Embudo, New Mexico, downstream to Isleta Pueblo, New Mexico.

The areal extents of surface-water models surveyed in this report were from the Rio Grande at Embudo, New Mexico, stream-gaging station to a diversion structure at Isleta Pueblo (figs. 1*A* and 1*B*). The areal extents of groundwater models surveyed were from the Rio Grande at Otowi stream-gaging station to Elephant Butte Reservoir (fig. 1*A*). Some of the models surveyed have areal extents that are beyond the study area; however, only the portions of those models that are within the study area were surveyed. The models' documentations were acquired, and the assumptions and dependencies upon which these models are based are presented in this report. Because documentation for each model is available to the public, indepth descriptions of model processes are not included in this report.

Description of the Study Area

The study area encompasses the Rio Grande, its valley, and major tributaries in north-central New Mexico from the USGS stream-gaging station on the Rio Grande at Embudo



Base from U.S. Geological Survey digital data, 2000, 1:24,000
Universal Transverse Mercator, zone 13
North American Datum of 1988

Figure 1. *A*, Rio Grande Basin from headwaters in southern Colorado to Elephant Butte Reservoir, New Mexico. *B*, Detail from 1*A* showing stream network.

B

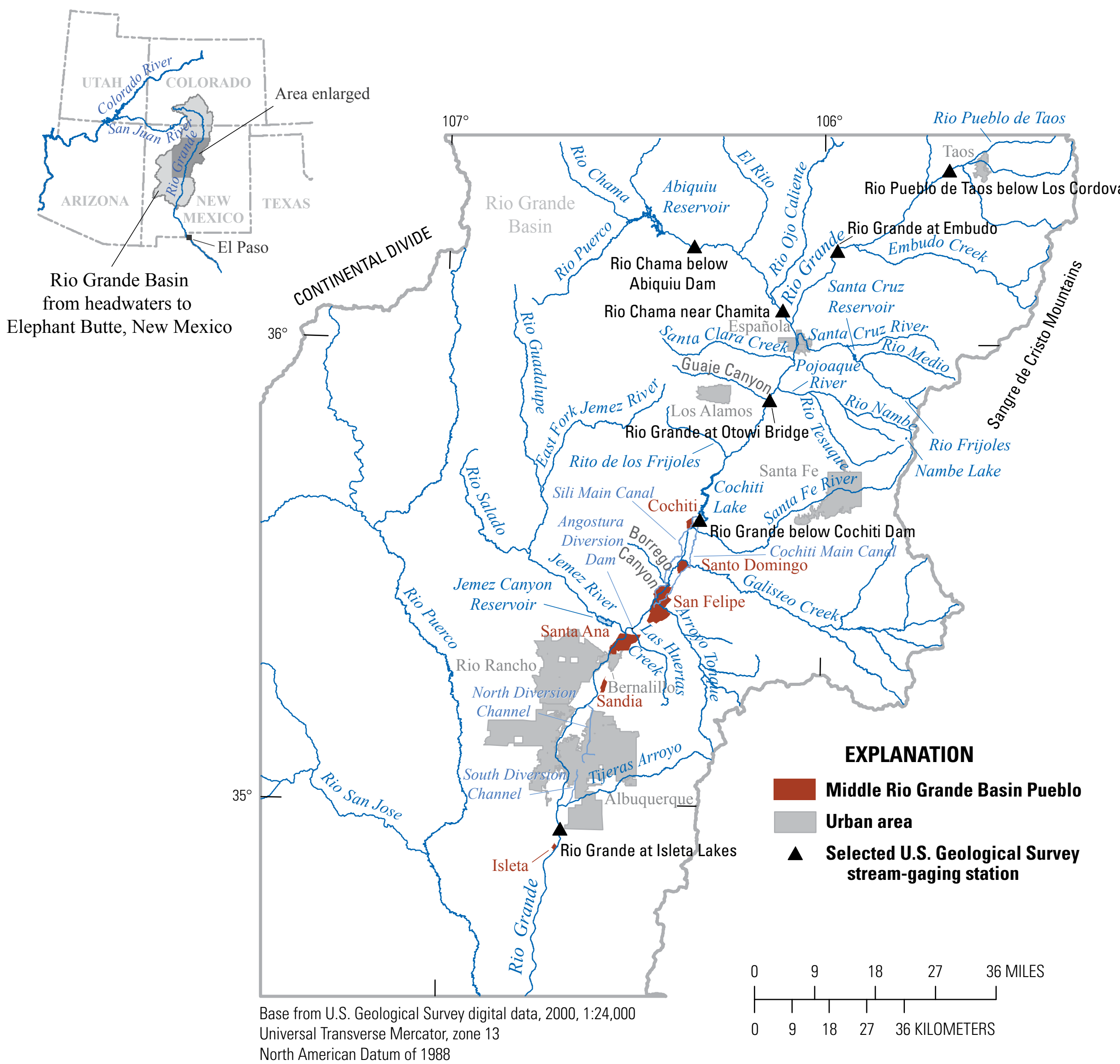


Figure 1. *A*, Rio Grande Basin from headwaters in southern Colorado to Elephant Butte Reservoir, New Mexico. *B*, Detail from 1*A* showing stream network.—Continued

downstream to the diversion at Isleta Pueblo south of Albuquerque (figs. 1*A* and 1*B*). For the purposes of this report the terms “Upper Rio Grande Valley” and “Middle Rio Grande Valley” refer to the geographic location of the Rio Grande within the State of New Mexico. “Upper Rio Grande” generally refers to the Rio Grande north of Cochiti Lake (fig. 1*B*) (although two of the models surveyed include the word “upper” in their titles and have geographic domains that extend some distance south of Cochiti Lake). “Middle” refers to the section of the Rio Grande roughly between Cochiti Lake and Elephant Butte Reservoir.

At the Rio Grande at Embudo stream-gaging station, the drainage area of the Rio Grande is 10,400 square miles (mi^2) with 7,460 mi^2 contributing to the flow of the Rio Grande. Internally drained basins such as playas and the closed basin in Colorado make up the difference between noncontributing and contributing areas in the watershed. The elevation of the gage at Embudo is 5,789 feet (ft) above the National Geodetic Vertical Datum of 1929 (NGVD 29). At Isleta, the drainage area is 17,666 mi^2 with 14,626 mi^2 contributing to the flow of the Rio Grande. The elevation of the gage at Isleta is 4,870 ft (NGVD 29). Precipitation for the study area ranges from 45 inches annually at the higher elevations of the Sangre de Cristo Mountains at the headwaters of Embudo Creek to 9 inches annually in the lower elevations of the study area around Albuquerque (PRISM Climate Group, 2009). The river reaches specified in this study include five reservoirs:

- Heron Reservoir on Willow Creek, a tributary to the Rio Chama,
- El Vado Reservoir on the Rio Chama,
- Abiquiu Reservoir on the Rio Chama,
- Jemez Canyon Reservoir on the Jemez River, and
- Cochiti Lake on the Rio Grande (figs. 1*A* and 1*B*).

Two small reservoirs, Nambe Lake and Santa Cruz Reservoir, are on tributaries of the Rio Grande near the City of Española (fig. 1*B*). Many of the tributaries to the Rio Chama and Rio Grande are ephemeral, flowing only in response to precipitation events or snowmelt in the higher elevations.

The alluvial basins in the study area formed as a result of extension associated with the Rio Grande Rift. The basins are bounded by faults and are filled with sediment derived locally from adjacent uplifted areas and from upstream basins to the north. The total thickness of the basin fill may be in excess of 15,000 ft in some locations (Kernodle, 1992). Most basins in New Mexico are shallower, with 2,000–3,000 ft of basin fill being the most common range (Kernodle, 1992). The fill material is identified as the Santa Fe Group of the Cenozoic Era, which is generally unconsolidated and consists of fine-grained playa and lacustrine deposits, alluvial fan conglomerates, eolian fine sands, fluvial gravels, and occasional lava flows and ash deposits (Kernodle, 1992).

The northwestern and eastern boundaries of the upper Rio Grande system are defined by the San Juan and Sangre de Cristo Mountains, respectively. These mountains also provide snowmelt, a primary source of runoff, to the river system. In north-central and northwestern New Mexico, the upper Rio Grande and Rio Chama valleys are entrenched in deep, narrow canyons. Agricultural development along these reaches is limited by the narrow width of the flood plains on the canyon floors. In this reach, the Rio Grande tends to gain water from mountain-front recharge and tributary inflows faster than the water is lost to the atmosphere or to human or agricultural consumption, resulting in a net gain in flow (Roach, 2007). Between the Rio Grande at Otowi stream-gaging station and Cochiti Lake, the river is entirely entrenched in deep canyons and there is no flood plain to speak of.

Downstream from Cochiti Lake, the Middle Rio Grande Valley becomes shallower and begins to widen. The flood plain reaches widths of up to 5 miles (mi) downstream from Isleta Pueblo. The increased width of the flood plain is accompanied by an increase in agricultural development downstream from Cochiti Lake. Agricultural development continues southward until it is replaced by the urban development of the Albuquerque metropolitan area; south of Albuquerque, agricultural development continues. In 2010, the combined population of the cities of Albuquerque (545,852 people) and nearby Rio Rancho (87,521 people) made up nearly 31 percent of the population of the entire State of New Mexico (U.S. Census Bureau, 2010). Flow in the Rio Grande decreases between Cochiti Lake and Albuquerque. Irrigation diversions, evapotranspiration, and seepage losses to groundwater are the primary factors that reduce flow in this reach of the Rio Grande (Kernodle, 1992). The potential annual evapotranspiration rate alone can be as much as 6 ft of water per year (Kernodle, 1992), particularly in the riparian areas in proximity to the Rio Grande. Historical accounts indicate that the Rio Grande would frequently cease to flow by the time it got to the Mesilla Basin upstream from El Paso, Texas, until reservoirs began to be constructed in the early 1900s (Kernodle, 1992).

Riverside drains and levees run along both banks of the Rio Grande starting a few miles south of the diversions at Cochiti Lake and continuing intermittently as far south as Elephant Butte Reservoir (Oad and others, 2009). The locations of the riverside drains range from several hundred to several thousand feet from the river. The drains are designed to intercept shallow groundwater resulting from irrigation return flow and river seepage. By intercepting this shallow groundwater, the drains function to keep the ground surface surrounding the river from becoming saturated. Intercepted groundwater is funneled back to the river downstream through the drains.

Colorado River water is delivered to users along the Rio Grande by the San Juan–Chama Project (Oad and others, 2009). The San Juan–Chama project takes water from the San Juan River Basin, a tributary of the Colorado River, and diverts it under the Continental Divide into the Rio Grande Basin by use of 27 mi of tunnels. The diverted water from the Azotea Tunnel discharges into a tributary of the Rio Chama upstream from Heron Reservoir. Water that is transported from the San Juan River Basin to the Rio Grande Basin by way of intermountain tunnels is locally referred to as the “San Juan–Chama water” or “SJC” water.

Previous Work

Published documentation for most models includes a synopsis of previous models and reasons for the development of the new model (Roach and Tidwell, 2009; McAda and Barroll, 2002; Sanford and others, 2003). Reports have been written that compare the output of two or more models that model the same hydrogeologic setting (Reddi and others, 1990). Documents designed to compare and contrast large numbers of existing models, however, have not been developed for the Middle Rio Grande area. The only comprehensive report summarizing multiple hydrologic models including models of the Middle Rio Grande area was published by Kernodle (1992) in a study that evaluated USGS groundwater-flow models for multiple States in the Southwest. The report by Kernodle (1992) was designed to summarize the available models developed by the USGS, identify commonly simulated hydrogeologic characteristics, and isolate preferred approaches to simulating groundwater flow in the various basin-fill aquifer systems in Colorado, New Mexico, and Texas. The models discussed in that report that include the Middle Rio Grande Valley were Hearne (1985a, 1985b), Reeder and others (1967), and Kernodle and Scott (1986).

Methods Used To Survey Hydrologic Models and Assess Data Needs

All publicly available surface-water and groundwater models, including those that model surface-water/groundwater interactions that have been developed for the Rio Grande within the study area, were identified and surveyed for this study. The models were surveyed by using comprehensive lists of hydrologic elements identified by generalized conceptual models developed for this study. Data needs identified during the model-survey process were documented to facilitate improvements in future data-collection activities.

Gains and Losses Identified

Generalized conceptual models that include the substantial gains and losses of water that affect the amount of water in those systems were constructed for both the surface-water and groundwater systems (fig. 2). In the surface-water conceptual model, hydrologic gains are characterized as inflows to the surface-water channel, and losses are characterized as outflows (fig. 2*A*). In the groundwater conceptual model, hydrologic gains are characterized as recharge to the aquifer, and losses are characterized as discharge from the aquifer (fig. 2*B*).

In general, hydrologic gains to a surface-water body such as a river can be divided into the naturally occurring gains such as rainfall runoff, snowmelt runoff, seepage gains, tributary contributions, and springs and the human-induced gains such as effluent/irrigation return and intermountain transfer of water (for example, the water transferred from the San Juan River Basin to the Rio Grande Basin). Hydrologic losses to a surface-water body also occur naturally or by human induction. Examples of naturally occurring hydrologic losses from a surface-water body are evapotranspiration and seepage loses. Human-induced losses from a surface-water body include diversions of water for municipal or irrigation use. Diversions on the Rio Grande downstream from the Rio Chama can involve Rio Grande water or San Juan–Chama water. Water that is stored in reservoirs and later released creates a human-induced hydrologic gain to the river downstream at the time of the release. When the volume of water in storage in a reservoir is increased, a human-induced hydrologic loss occurs in the river downstream. The distinction between naturally occurring and human induced, as applied to hydrologic gains or losses, is required for tracking or "accounting" natural flow in a river. "Natural flow" is a term that is commonly used among hydrologists, ecologists, and persons with an interest in water rights. Although there is no single accepted definition, natural flow is generally accepted as the flow that would have passed a certain point in a stream without upstream human intervention.

Hydrologic gains and losses affecting aquifers also can be characterized as naturally occurring or human induced. An example of naturally occurring hydrologic gains to an aquifer would be precipitation recharge, and an example of human-induced gains would be seepage from drains and canals and artificial recharge (intentionally injecting surface water into an aquifer for storage [Reese, 2009]). An example of a naturally occurring hydrologic loss from an aquifer would be groundwater discharge to rivers, and a human-induced loss would be groundwater pumping for municipal or agricultural purposes.

Physical processes occurring at reservoirs involve a variety of gains and losses occurring simultaneously, such as precipitation, infiltration, evaporation, and transpiration, in addition to the storage of inflow or release of previously stored water. The net difference between the gains and losses occurring at a reservoir at any given time may vary in relation to temperature, recent precipitation patterns, or other factors. Hydrologic processes acting on the water stored in a reservoir can cause either net gains or net losses to the stored water depending on conditions. The river reaches specified in this study include

- five major reservoirs
    - Heron Reservoir
    - El Vado Reservoir
    - Abiquiu Reservoir on the Rio Chama
    - Jemez Canyon Reservoir on the Jemez River
    - Cochiti Lake on the Rio Grande
- and two minor reservoirs
    - the Santa Cruz Reservoir and
    - Nambe Lake.

Interactions between surface water and shallow groundwater also can vacillate between net flow into or out of the surface-water body in relation to the season, temperature, or water-use patterns and are ultimately dependent on hydraulic head or stage in the surface-water body in relation to the hydraulic head in the aquifer (Winter and others, 1998). For the purpose of this survey, surface-water/groundwater interactions are characterized as seepage gains to or seepage losses from the surface-water system.

Model Surveys

The generalized conceptual models (fig. 2) were used to design a framework for comparison of model treatments of

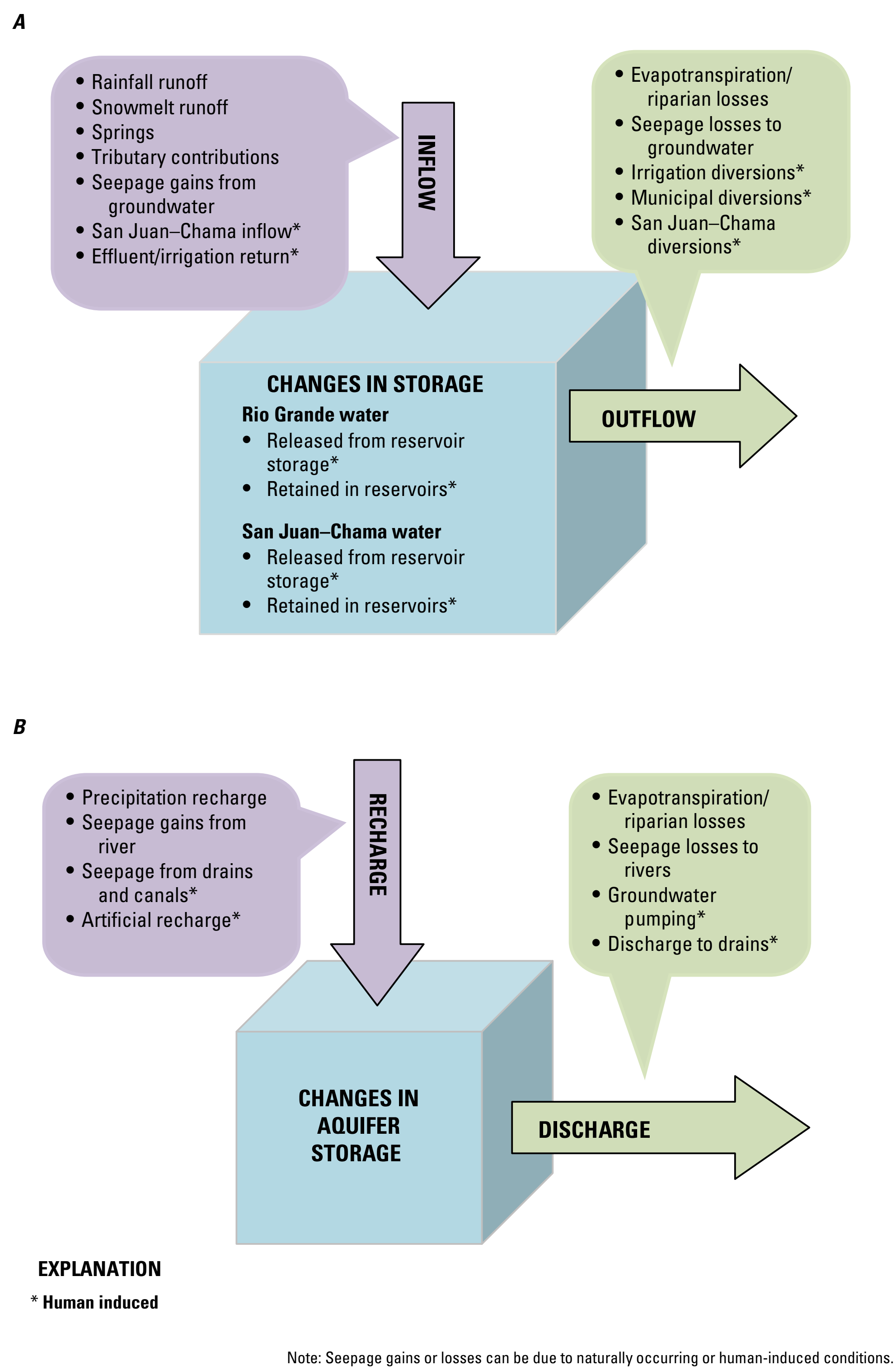


Figure 2. Conceptual model diagrams. *A*, Generalized surface-water conceptual model. *B*, Generalized groundwater conceptual model.

the known gains and losses specific to the study area. Physical occurrences of the types of elements identified in the conceptual model (such as tributary inflow) were identified for the study reach on the basis of maps and interviews with pueblo personnel. In the survey, known significant tributaries in the study area are identified by name whenever possible.

Each publicly available model was surveyed for the inclusion and treatment of the various hydrologic elements identified through the use of the conceptual model. Surface-water models and groundwater models were surveyed separately. Model characteristics such as time steps and calibration methods were included in the surveys to give readers additional information about how the individual models operate. Tabular documentation of model characteristics and model treatment of identified hydrologic elements identified provide a summary comparison of the models for each element of interest (tables 1–6 at end of report).

The tables of detailed information on the hydrologic models (tables 1–6) can be used as tools to help readers evaluate the models for multiple uses, including accounting types of flow in the Rio Grande. The hydrologic elements presented in the surface-water hydrologic element table (table 2) are divided into three river reaches and generally presented in an upstream to downstream order, starting with inflow elements and followed by outflow elements. The three reaches are (1) the Rio Grande from Embudo to Otowi Bridge, (2) the Rio Chama, and (3) the Rio Grande from Otowi Bridge to Isleta Pueblo. A list of hydrologic elements also was designed for the groundwater resources in the study area.

Each gain and loss identified contributes to a category of water in the Rio Grande such as natural flow, stored water released, or intermountain transfer water. For example, inflow from the Azotea Tunnel would be a component of intermountain transfer water but not of natural flow. Although the tables herein do not have the hydrologic gains and losses identified as naturally occurring or human induced, each gain and loss is identified such that the user can follow those hydrologic elements of interest for their purposes.

The surveys were completed by using model documentations and interviews. Interviews were conducted with people who previously used or currently use the hydrologic models or were involved in their development. The purpose of the interviews was to get information from people most familiar with the models on the model utility and applicability in accounting or tracking types of flow in the Rio Grande.

Hydrologic Data Needs

During the course of conducting the model surveys, hydrologic data were identified that are needed to accurately account water in the Rio Grande but do not exist. Data needs were identified from a combination of (1) observations of data that were approximated in all models and (2) suggestions from authors for ways to improve upon their models or model calibrations.

Hydrologic Models Surveyed

For each model surveyed, a brief overview is provided that describes model development and purpose. The individual elements surveyed for each model are generally presented in tabular form (tables 1–6). Elements that cannot be presented in tabular form are discussed in the Model Surveys section.

Surface-Water Models

Four publicly available surface-water models were identified for this study: (1) the Upper Rio Grande Water Operations Model (URGWOM) (U.S. Army Corps of Engineers [USACE] and others 2005a, 2005b); (2) the Upper Rio Grande Simulation Model (URGSiM) (Roach, 2007); (3) the Middle Rio Grande Conservancy District Decision Support System (DSS) (Oad and others, 2009); and (4) the Middle Rio Grande FLO-2D Flood Routing Model (FLO-2D) (Tetra Tech, Inc., 2004, and Riada Engineering, Inc., 2008). Each of the models was created for different purposes by using different software packages. The two large-scale surface-water models (URGWOM and URGSiM) cover the entire reach of the Rio Grande between Embudo and Isleta Pueblo. The third model (DSS) was designed to account flow in the Rio Grande irrigation canals from Cochiti Dam downstream to the Bosque del Apache National Wildlife Refuge, south of Isleta Pueblo. The fourth model (FLO-2D) was designed to simulate the hydraulics of the Rio Grande reach from Cochiti Dam to Elephant Butte Reservoir. Although additional surface-water models have been developed for discrete sections of the Rio Grande, their limited spatial extent and design excluded them from the current survey.

The four surface-water models surveyed produce results that could be useful in quantifying the flow of the Rio Grande, specifically by tracking water as it moves down the channel of the Rio Grande and by improving the understanding of river hydraulics for the specified reaches. The applicability of each model with respect to accounting different components of flow varies according to the purpose for which each model was designed. Table 1 lists some general characteristics of the four surface-water models.

Upper Rio Grande Water Operations Model

URGWOM is one of two publicly available surface-water models that cover the entire reach of this study. The geographic extents of URGWOM actually extend beyond the study reach. According to the URGWOM documentation, the upper Rio Grande is the reach of the Rio Grande between the Colorado–New Mexico State line and Cochiti Dam in New Mexico (USACE and others, 2005a). URGWOM was initially developed starting in 1996 through an interagency effort of six Federal agencies, including the U.S. Army Corps of Engineers (USACE), U.S. Bureau of Reclamation (USBOR), U.S. Fish and Wildlife Service, USGS, Bureau of Indian Affairs, and International Boundary and Water Commission. In 2007, other State and local agencies joined the effort for continuous development and improvement of the model.

URGWOM was envisioned as simulating water storage and delivery operations in the Rio Grande from its headwaters in Colorado to below Caballo Dam in southern New Mexico. The current model extents are from the Colorado–New Mexico State line to Caballo Reservoir. The model incorporates all water management rules (such as dam releases and other diversions) for managing reservoirs along the Rio Grande from the Colorado–New Mexico State line to Elephant Butte Reservoir. It simulates the physical system and tracks San Juan–Chama and Rio Grande waters separately.

There are four separate modules within URGWOM that are utilized for decision support: Planning, Forecast, Accounting, and Water Operations. The Planning module is used to simulate different operation scenarios to evaluate long-term impacts of proposed actions. The Forecast module uses hydrologic data from past records for similar years along with current forecasted runoff information provided by the Natural Resources Conservation Service (NRCS) and the National Weather Service (NWS) to compute inflows for the Water Operations and Planning modules. The Accounting and Water Operations modules are the most useful URGWOM modules for estimating and tracking prior and paramount water releases. The Accounting module can be run on a daily time step and is used to simulate year-to-date conditions and provide updated status of account storage in reservoirs and deliveries made to water users (USACE and others, 2005b). The Water Operations module is run on a daily time step to simulate forecast operations, deliveries, and resulting flows through the end of a calendar year. Output from the Water Operations module is used for determining forecasted flows and reservoir storage for annual operating plans in order to reduce waste, eliminate unnecessary reservoir spills, prevent downstream flooding, and allow effective distribution of available water supplies.

The Accounting module tracks reservoir storage and release of 20 different water user accounts starting at Heron Reservoir. The accounts modeled at Heron Reservoir include one Rio Grande water account and 19 San Juan–Chama water accounts including accounts for various counties, municipalities, tribes, recreation areas, MRGCD, and uncontracted water. Downstream from Heron Reservoir at El Vado Reservoir, the Rio Grande accounts of (1) Supplemental ESA (Endangered Species Act), (2) Rio Grande, (3) MRGCD Drought, and (4) Indian Storage (prior and paramount storage) are simulated in the model. All accounts are tracked downstream as far as Elephant Butte Reservoir or to appropriate storage or diversion locations. Diversions include the MRGCD diversions at Cochiti Dam, near San Felipe, and at Isleta and the Drinking Water Project at Albuquerque. Accounting module simulations are completed by using inputs for actual operations, whereas the Water Operations module simulations are completed by using rules for reservoir operations.

The basic inputs to URGWOM are gaged streamflows at Rio Grande near Lobatos, Colorado, and at northern tributaries of the Rio Grande including Red River, Rio Pueblo de Taos below Los Cordovas, and Embudo Creek (figs. 1*A* and 1*B*). Other inputs include San Juan diversions through the Azotea Tunnel, Willow Creek, Rio Chama above El Vado Reservoir, Galisteo Creek, Jemez River, Albuquerque's North and South Diversion Channels, Tijeras Arroyo, and the Rio Puerco. The model does not incorporate or predict monsoonal precipitation variables. The model is divided into 23 total reaches: five main reaches on the Rio Chama; eight reaches on the upper Rio Grande from the Rio Grande near Lobatos, Colorado, streamgaging station to Cochiti Lake, New Mexico; six reaches on the Middle Rio Grande from Cochiti Lake to Elephant Butte Reservoir, New Mexico; and four reaches from Elephant Butte Reservoir, New Mexico, to El Paso, Texas (USACE and others 2005a).

Upstream from Cochiti Lake, URGWOM uses a variable time lag for river routing, which is based on comparisons with historical data. The variable time lag is a simplified routing method based on a relation between velocity (hence lag time) and flow. Downstream from Cochiti Lake a straight time lag is used. Tables are developed (USACE and others, 2002) that relate discharge to time lag for each river reach modeled.

Although URGWOM is primarily aimed at quantifying flow on the Rio Grande, it also incorporates surface-water/groundwater interaction in two ways. The Middle Rio Grande portion of the model contains a shallow groundwater component that is three cells wide for each of the 21 subreaches of the 6 river reaches modeled. The three cells represent the right and left flood-plain areas, with widths ranging from 0.1 mi to nearly 3 mi, and the area directly below the river channel, extending to the riverside drains and with a width of about 0.5 mi. Each cell is 5–7 mi long. The purpose of including this shallow groundwater component is to capture the head-dependent flux between the river and the shallow aquifer, which is based on difference in head and a conductance term. The deep aquifer groundwater head values calculated by the McAda and Barroll (2002) regional groundwater model are inputs to the groundwater simulation in URGWOM.

The Upper Rio Grande Simulation Model

URGSiM is the second of two models that cover the entire reach of the study area and continue south of Elephant Butte Reservoir. URGSiM is an integrated climate, hydrologic, groundwater, and socioeconomic model of the upper Rio Grande that serves as a future water-planning decision support tool. URGSiM was funded by Sandia National Laboratory and created through a cooperative effort with the URGWOM technical committee. Additional funding provided by the USACE and the USBOR allow for continual updates to the model.

URGSiM is a monthly time step Powersim (http://www.powersim.com) model that employs a system dynamics computational technique. It is a water-balance model that dynamically integrates surface-water, reservoir operations, water demand, and groundwater models for the entire New Mexico reach of the Rio Grande. The model uses data recorded from 1975 through 1999 for calibration, uses data recorded from 2000 through 2004 for validation, and then runs forward from 2005 in a scenario-evaluation mode (Roach, 2007).

URGSiM simulates groundwater with coarsely gridded variants of the regional groundwater model by McAda and Barroll (2002), the Española Basin model by Frenzel (1995), and a Socorro Basin model by Shafike (2005). Reservoir operations and water demand are also integrated into the URGSiM model. Groundwater contributions are determined by the coarsely gridded groundwater model as adapted and integrated in URGSiM. Surface-water contribution is determined by streamflow gages, and mass balance is closed by ungaged surface-water inflows and crop consumption.

URGSiM runs well on a personal computer and is designed to be a rapid screening tool for use in stakeholder outreach for water-resource planning and management decisions. It was designed so that it could be operated in support of URGWOM. URGSiM is designed to be consistent with URGWOM regarding model structure, physical processes, operations rules, equations, and inputs. Basic inputs to URGSiM include total gaged surface-water flows at the upstream model boundary, monthly climate data, human groundwater extraction and wastewater returns, and agricultural and riparian areas by plant type. It does not incorporate rainfall runoff or snowmelt relations. URGSiM is divided into 17 surface water reaches and 79 groundwater cells based on the locations of available stream-gaging stations. The reaches between Embudo and Isleta are covered by 10 of these surface-water reaches and 50 of the groundwater cells.

The Middle Rio Grande Conservancy District Decision Support System

The Middle Rio Grande Conservancy District DSS was developed during 2004 and 2005 through cooperative work between the New Mexico Interstate Stream Commission, Colorado State University, and the MRGCD. The purpose of the DSS is to help water managers and farmers determine when, how often, and for how long to irrigate in an effort to better serve farmers and their crops for more efficient use of water. The DSS can be updated and linked directly to water releases. The DSS does not allow for simulation of flow in the Rio Grande but does allow for water in the MRGCD canal system to be simulated. Because the DSS does not simulate flow in the Rio Grande, many of the elements identified in the hydrologic element table are not applicable.

The DSS uses a detailed simulation of the MRGCD canal system along with carefully measured and known crop data, weather data, and canal seepage losses to estimate water demand and develop water delivery schedules for the main canals and feeder channels. The DSS uses flow data for diversions and return flows that are collected by the MRGCD's real-time telemetry network. The DSS assumes that the estimated evaporation demand is representative of the study area as a whole, that seepage gain (return flow to the channel) is a fixed percentage of the water delivered, and that measurements of seepage loss to the groundwater for the canals and feeder channels are accurate and representative. Extensive collection of field data, including soil characteristics, water delivery rates, and on-farm water use, was conducted in 2008 (Oad and others, 2009) to validate the assumptions of the DSS. The model does not incorporate groundwater data.

The Middle Rio Grande FLO-2D Flood Routing Model

The Middle Rio Grande FLO-2D Flood Routing Model was developed by Tetra Tech, Inc. (2004), with the support of the U.S. Fish and Wildlife Service's Bosque Initiative Group, USACE, USBOR, and the New Mexico Interstate Stream Commission. The model is a two-dimensional, volume-conservation, flood routing model that distributes a flood hydrograph over a system of square grid elements. The model was designed to simulate river and overbank flow on the Rio Grande from Cochiti Dam to Elephant Butte Reservoir. It was initially completed with 500-ft grid spacing, but updates in 2007 reduced the grid spacing to 250 ft (Riada Engineering, Inc., 2008). The purposes of the model are to simulate flooding, to map inundated areas and depths, to assess riverine habitat conditions, to support habitat restoration efforts, and to simulate water transport traveltime. The model operates under the assumptions that flow is one dimensional in the channel but closer to two dimensional in the flood-plain areas. Inputs and land cover characteristics can be updated. There are no groundwater inputs to the program.

Table 2 summarizes how select hydrologic gains and losses (or elements) identified are treated by each of the surface-water models evaluated. Note that the DSS and FLO-2D models do not cover the entire reach surveyed.

Groundwater Models

Rivers in the Middle Rio Grande Basin interact with groundwater. Human activity also affects exchanges between groundwater and surface water: pumping from wells brings groundwater to the surface, while irrigation and wastewater discharges can infiltrate back to groundwater. The timing, location, and rate of these exchanges between groundwater and surface water are constantly changing. Models that simulate groundwater flows and, in most cases, simulate surface-water/groundwater interactions were surveyed in this study. Although many of the groundwater models surveyed do simulate exchange of groundwater with the surface, none of the groundwater models can simulate overall surface-water flows. In the discussion of the models below, if a river is listed as being simulated by a model, it means that a boundary condition has been included in the model to represent the river. In these cases, flows between the river and underlying aquifer and the effects of pumping on the river are, or can be, calculated by the model. If, however, the model was not designed for the purpose of determining the effects of pumping on the rivers listed, then the model should not be used for that purpose.

Thirteen groundwater models were identified for inclusion in this study and, for the purpose of discussion in this report, are identified as models 1 through 13. The geographic extents (domains) for the models are shown in figure 3. All but one of the groundwater models evaluated, model 12, were based on the software package MODFLOW (Harbaugh and others, 2000) or a precursor to MODFLOW. The URGSiM groundwater model was not evaluated in this section because it is based on two other models that were evaluated, model 6 and model 10. Seven of the thirteen models were extended or substantially modified versions of earlier models. For example, the model developed by McAda and Barroll (2002), model 10, was built on the foundation of three earlier models (Kernodle and others, 1995; Tiedeman and others, 1998; Barroll, 2001). In general, this is a common occurrence with groundwater models and results both from the desire to have models reflect the most recent data available and from the need to adapt old models to new uses. Table 3 indicates the relations between the models.

Table 4 lists the well fields that are included in each groundwater model. The Los Alamos, Santa Fe, and Albuquerque well fields are located in or near the communities bearing those names. The Guaje well field is located in Guaje Canyon (fig. 1*B*). The Pajarito well field is located south of the community of Los Alamos. The Buckman well field is located several miles south of the Rio Grande at Otowi Bridge gage and on the east side of the Rio Grande.

Model 1: Hearne (1985a) Mathematical Model of the Tesuque Aquifer System Near Pojoaque, New Mexico

Hearne (1985a) developed a transient groundwater model of the Tesuque aquifer. The model was capable of simulating groundwater interactions with the Rio Grande, Santa Fe, Pojoaque, and Santa Cruz Rivers. As described by Hearne (1985a), “The model was used to simulate the response of the aquifer system to an irrigation-development plan in the Pojoaque River Basin.” Modifications of this model exist but are not published or publicly available (Doug McAda, written commun., 2011).

Model 2: Kernodle and Scott (1986) Three-Dimensional Model Simulation of Steady-State Ground Water Flows in the Albuquerque–Belen Basin, New Mexico

Kernodle and Scott (1986) developed a steady-state model of the Albuquerque–Belen Basin aquifer. The model simulated flood-plain alluvium for the Rio Grande, Rio Puerco, Rio Salado, and Jemez River. The model was developed as part of the Regional Aquifer System Analysis (RASA) Program, a national research effort that studied 25 major aquifer systems across the Nation. The purpose of the model was to simulate steady-state groundwater flow conditions prior to 1960 in the Albuquerque–Belen Basin aquifer. This model was superseded by models 7 through 11.

Model 3: Kernodle and others (1987) Three-Dimensional Model Simulation of Transient Ground-Water Flow in the Albuquerque–Belen Basin, New Mexico

Kernodle and others (1987) extended the model by Kernodle and Scott (1986) (model 2) to perform transient simulations. This effort was again part of the RASA Program, and the model was used to evaluate water budgets and pumping-induced leakage to groundwater from surface water. The model simulated transient (1907–79) groundwater flow in the Albuquerque–Belen aquifer. This model also was superseded by models 7 through 11.

Model 4: McAda and Wasiolek (1988) Simulation of the Regional Geohydrology of the Tesuque Aquifer System near Santa Fe, New Mexico

McAda and Wasiolek (1988) developed a transient groundwater model of the Tesuque aquifer. The purpose of the model was to serve as a tool for water-resources management, specifically to simulate the effects of groundwater withdrawals on the Tesuque aquifer. The Rio Grande, Pojoaque River, Rio Tesuque, and Santa Fe River are individually simulated by the model. At the request of their cooperator, representations of geologic structure and surface-water/groundwater interactions were simplified (D. McAda, oral commun., 2010). Modified versions of this model are being used.

Model 5: McAda (1990) Simulation of the Effects of Ground-Water Withdrawal from a Well Field Adjacent to the Rio Grande, Santa Fe County, New Mexico

McAda (1990) modified the model by McAda and Wasiolek (1988) (model 4) to simulate proposed groundwater

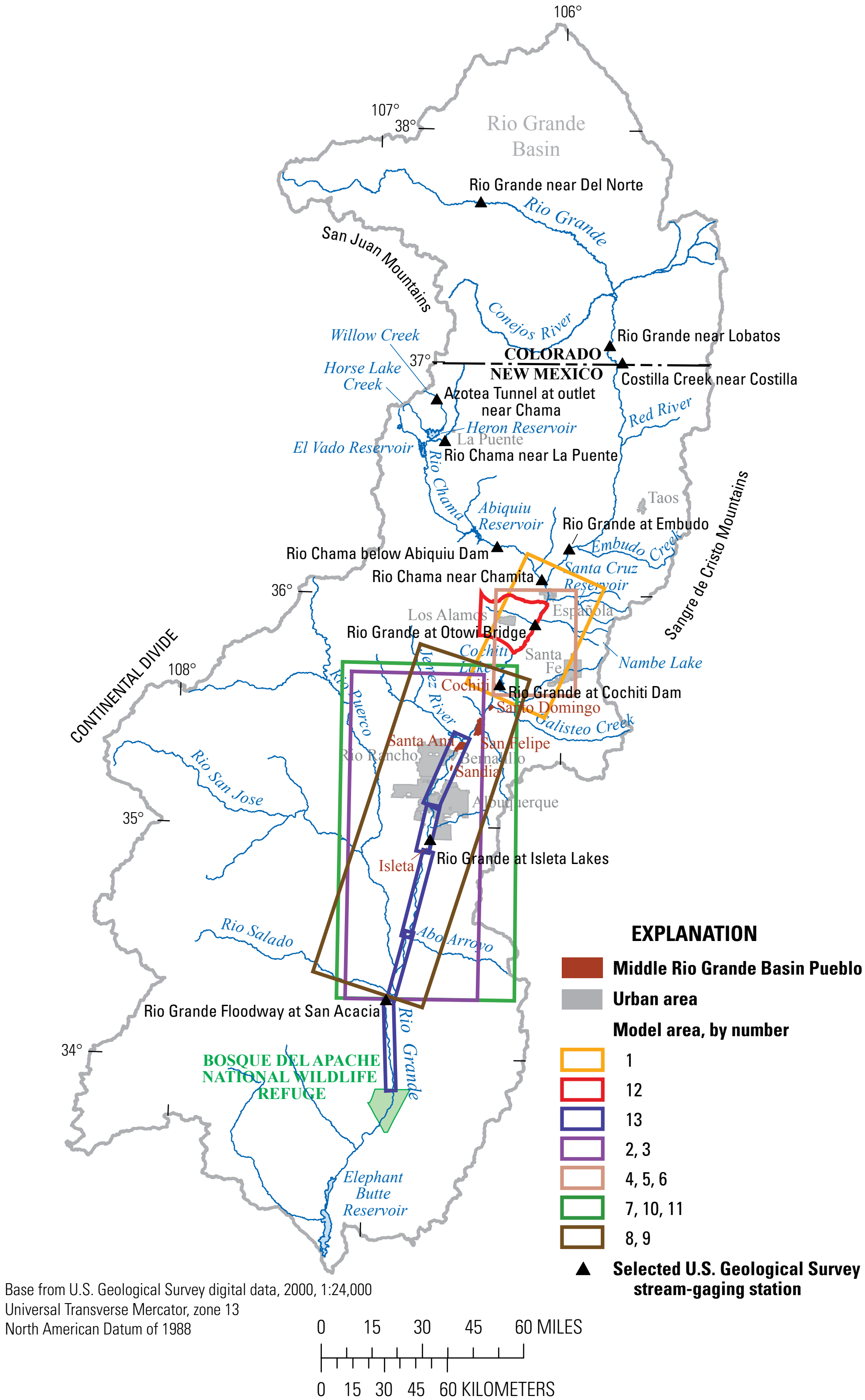


Figure 3. Generalized geographic extent of the surveyed groundwater models.

withdrawals at the Buckman well field to supply the City of Santa Fe. The transient simulations demonstrated that the proposed pumping wells would capture water from the Rio Grande, Pojoaque River, and Tesuque River.

Model 6: Frenzel (1995) Geohydrology and Simulation of Ground-Water Flow near Los Alamos, North-Central New Mexico

Frenzel (1995) modified the McAda and Wasiolek (1988) model (model 4). Changes were made to hydraulic conductivity and storage values and to specified head boundary conditions that affected simulated recharge to the aquifer (table 4). The purpose of the model was to incorporate new geologic understanding into the Tesuque aquifer model and to compare alternative groundwater withdrawal options. The Rio Grande, Pojoaque River, Rio Tesuque, and Santa Fe River are again simulated by the model. Modified versions of this model are being used by the New Mexico Office of the State Engineer (NMOSE) and engineering consultants (P. Barroll, oral commun., May 2010).

Model 7: Kernodle and others (1995) Simulation of Ground-Water Flow in the Albuquerque Basin, Central New Mexico, 1901–1994, with Projections to 2020

Kernodle and others (1995) developed a transient groundwater model of the Albuquerque Basin to represent a new understanding of the basin hydrogeologic framework. New features of the model, as compared to Kernodle and others (1987), included a geographic information system (GIS) database to organize and facilitate changes to the model and a more detailed representation of surface-water/groundwater interactions. The authors used the model to examine a number of groundwater-withdrawal scenarios and to quantify head declines, induced recharge (surface water drawn into an aquifer by groundwater pumping), and detailed hydrologic budgets. The Rio Grande, Santa Fe River, Galisteo Creek, Tijeras Arroyo, Jemez River, Rio Puerco, Abo Arroyo, Rio Salado, and Cochiti Lake are simulated by the model along with canals and drains. Kernodle (1998) subsequently modified some of the hydraulic conductivity zones and extended the period of historical simulation by 1 year, from 1994 to 1995. This model was computationally intensive to run and has been superseded by models 8 through 11.

Model 8: Tiedeman and others (1998) Application of Nonlinear-Regression Methods to a Ground-Water Flow Model of the Albuquerque Basin, New Mexico

Tiedeman and others (1998) applied nonlinear regression methods in modifying the model by Kernodle and others (1995). The revised transient model had a new grid based on information learned from the previous model, an improved representation of the hydrogeology, and revised aquifer parameters that resulted in a more robust model performance. The revised model was used to simulate a variety of scenarios in which sensitivity of the most important hydraulic characteristics was quantified by direct calculation. The Rio Grande, Santa Fe River, Galisteo Creek, Tijeras Arroyo, Jemez River, Rio Puerco, Abo Arroyo, Rio Salado, and Cochiti Lake are simulated by the model. This model was designed as a research model and is not in use.

Model 9: Barroll (2001) Documentation of the Administrative Groundwater Model for the Middle Rio Grande Basin

Barroll (2001) combined one of the conceptual models from Tiedeman and others (1998) and hydraulic characteristics from Kernodle and others (1995) and Kernodle (1998) to produce a transient groundwater model for use by the NMOSE in water-resource planning. This model uses the Tiedeman and others (1998) grid, but the model hydraulic parameters are based on the Kernodle and others (1995) and Kernodle (1998) models. Modifications were made to hydraulic conductivity and specific storage values, the vertical grid discretization, and boundary conditions representing the Jemez River. The model was used to simulate stream depletions and groundwater drawdowns to support water rights in the Albuquerque Basin. The Rio Grande, Santa Fe River, Galisteo Creek, Tijeras Arroyo, Jemez River, Rio Puerco, Abo Arroyo, Rio Salado, and Cochiti Lake are simulated by the model. This model is being used by the NMOSE for water-resource planning and permitting (P. Barroll, oral commun., 2010).

Model 10: McAda and Barroll (2002) Simulation of Ground-Water Flow in the Middle Rio Grande Basin Between Cochiti and San Acacia, New Mexico

McAda and Barroll (2002) built another transient model of the Albuquerque Basin. The new model included information learned from Barroll (2001), Tiedeman and others (1998), and Kernodle and others (1995) and featured a new grid and an extension of the simulation period to the year 2000. The purpose of the model was to (1) integrate the components of the groundwater-flow system, including the hydrologic interaction between the surface-water systems in the basin; (2) better understand the geohydrology of the basin; and (3) serve as a tool for water managers to plan and administer the use of water resources in the basin. The Rio Grande, Santa Fe River, Galisteo Creek, Tijeras Arroyo, Jemez River, Rio Puerco, Abo Arroyo, Rio Salado, Cochiti Lake, and Jemez Canyon Reservoir are simulated by the model in addition to canals and drains. Although interactions with surface water are modeled with limited detail and calibration, model output represents a reasonable reproduction of groundwater levels and stream losses (D. McAda, oral commun., May 2010). Modified versions of this model are being used by NMOSE for water-resource planning and to set boundary conditions for model 13 and for URGWOM.

Model 11: Sanford and others (2003) Use of Environmental Tracers To Estimate Parameters for a Predevelopment Ground-Water Flow Model of the Middle Rio Grande Basin, New Mexico

Sanford and others (2003) built a steady-state model of the Albuquerque Basin and used environmental tracer and hydrochemistry data to calibrate hydraulic conductivity and recharge values. The purpose of the model was to demonstrate the use of tracers as a calibration tool and to construct an improved model. The Rio Grande, Santa Fe River, Galisteo Creek, Tijeras Arroyo, Arroyo Tonque, Jemez River, Rio Puerco, Abo Arroyo, and Rio Salado are simulated by the model. This is a steady state model with recharge calibrated on the basis of the geochemistry. The model was intended as a research model and is not in use.

Model 12: Keating and others (2005) Development and Application of Numerical Models To Estimate Fluxes Through the Regional Aquifer Beneath the Pajarito Plateau

Keating and others (2005) developed a transient groundwater model to simulate a portion of the regional Española Basin aquifer. The model's purpose was to provide new insight into large-scale aquifer properties and groundwater fluxes beneath the Pajarito Plateau in the vicinity of the Los Alamos National Laboratory. The Santa Clara River, Rito de los Frijoles, and Rio Grande are simulated in the model. This is a detailed and adaptable model, a modified version of which is currently in use at the Los Alamos National Laboratory (B. Robinson, oral commun., May 2010).

Model 13: MacClune and others (2006) High-Resolution Groundwater Models for the Assessment of Riparian Restoration Options and River Conveyance Efficiency

MacClune and others (2006) developed a set of transient groundwater models for simulating the shallow riparian environment along the Rio Grande in New Mexico to support analysis of restoration options and river management strategies. The model set primarily was used to simulate exchanges between surface water and shallow groundwater within the flood plain of the Rio Grande. The Rio Grande and its associated drains and conveyance channels are the surface-water features simulated by the model. The model uses boundary conditions set by model 10 and land use data from 2002. The New Mexico Interstate Stream Commission uses the model to analyze river habitat.

Model Surveys

The accuracy of any model is, among other things, a function of the data that are input. Accurate and current input data will provide for more accurate and current model output values. The model surveys focus mainly on how the different models are handling input values and on what data they are relying.

Surface-Water Models

Many of the hydrologic elements surveyed in table 2 are shown as being included "implicitly" in a surface-water model. Implicit inclusion means that there is a place for that hydrologic element in the model, but instead of inputting data directly to represent that element, the element is either combined with other elements or is handled as a coefficient. Local flow calculations in URGWOM and URGSiM are examples of combining elements. Local flow is generally calculated as a portion of the difference between upstream main-stem flow and downstream main-stem flow for a particular reach, sometimes combined with irrigation diversions and return flows. In the case of the reach of the Rio Grande from Embudo to Otowi, even the largest tributary channels like the Santa Cruz River and the Pojoaque River, which flow much of the year, are included implicitly as a component of local flow. Although local flow is lumped for each reach, it does exhibit daily resolution in URGWOM because it is calculated for each day of the year, retroactively in that model. In URGSiM it is calibrated on a monthly basis. As shown in table 2, elements that are modeled implicitly as combined elements include tributary inflow, municipal and irrigation diversions, and return flows.

An example of using a coefficient would be to calculate a value as the difference between measured values and then to use the average of those differences over a time period in the model. Much of the flow loss for specific reaches above Cochiti Lake is addressed in both URGWOM and URGSiM through coefficients. Modeling elements implicitly through coefficients leads to an artificial smoothing in the temporal resolution of the model output. In other words, model outputs may agree with measured data on monthly, seasonal, or annual time scales, but the daily fluctuations of the hydrologic system will not be evident in the model output regardless of the model time step. As shown in table 2, elements that are modeled as coefficients include seepage gains and losses above Cochiti Lake.

For predictive and planning models such as URGSiM and the Forecast, Planning, and Water Operations modules of URGWOM, computed values rather than actual data must be used for certain hydrologic elements. Instead of using the stream-gaging station data at Otowi, for example, both URGWOM and URGSiM compute the flow at Otowi. Depending on the assumptions used, error may be introduced during these computations. URGWOM and URGSiM generally incorporate gage data inputs where they are available at the model margins and use gage data within the model extent for calibration. The Accounting module of URGWOM uses all gage data available to back-calculate the current conditions on the river.

Diversions and Return Flow

For the Embudo to Otowi and Rio Chama reaches, URGWOM and URGSiM rely on similar assumptions for irrigable land and crop distribution to calculate irrigation diversions and return flows. URGWOM uses a variety of methods including calculations based on assumed irrigable acreages and assumed return flow, coefficients based on historical streamflow data (for the Rio Chama reach), and the lumping of diversions and return flows into the channel loss coefficient. In URGSiM, diversions are calculated on the basis of historical flow data during calibration and diversion rules during scenario runs. Crop consumption is calculated on the basis of climate data and assumptions about agricultural acreage and crop type. Return flows are then calculated as available water in the conveyance system less crop consumption, with some portion of those flows going back to the river and the rest continuing in the conveyance system to the next reach. Those ratios are based on model results during the historical period.

For the Otowi to Isleta reach, diversions are handled differently by each of the four surface-water models. In URGWOM, average monthly hydrographs for Rio Grande water diverted at irrigation canals are input, but San Juan–Chama water downstream from Cochiti Lake is not tracked. URGWOM handles municipal diversions by inputting data from the City of Albuquerque. By contrast, URGSiM continues to track Albuquerque's allocation of San Juan–Chama water downstream to Albuquerque. URGSiM calculates irrigation diversions and lumps the values. URGSiM uses per capita water-use data to calculate municipal diversions. In the Otowi to Isleta reach, DSS uses gaged values for irrigation diversions but does not address municipal diversions because it is simulating flow only in the irrigation canals and not in the Rio Grande main-stem channel. The FLO-2D model uses outflow hydrographs to simulate both irrigation and municipal diversions and does not differentiate between Rio Grande water and San Juan–Chama water. In both URGWOM and URGSiM, irrigation return flows in the Otowi to Isleta reach are calculated on the basis of diversion schedules, crop evapotranspiration, seepage, and drain information. Irrigation return flows are measured in DSS and are based on historical records in FLO-2D.

Seepage

Values for seepage gains to and losses from surface water generally are taken from a groundwater component of the models when available and otherwise modeled implicitly as a component of local flow, a component of irrigation return flow, or with a coefficient. There are no publicly available groundwater basin models for the Rio Chama or the Rio Grande in New Mexico north of the City of Española.

URGWOM uses a variety of methods to address surface-water interaction with groundwater. Where possible, surface-water/groundwater interactions were calculated as the difference between observed and routed flow for a calibration period (Embudo to Otowi reach and portions of the Rio Chama). In some reaches, surface-water gains were lumped with return flow into a monthly coefficient. For the San Juan–Chama water, a monthly coefficient for surface-water losses is used as defined in the Rio Grande Compact (Public Act No. 96, 76), and for the Otowi to Isleta reach a coarsely gridded component of the groundwater model is used. Tables of computed loss coefficients for each reach are available in the URGWOM physical model documentation (USACE and others, 2005a).

URGSiM models groundwater dynamics between the City of Española and Elephant Butte Reservoir by using a spatially aggregated representation of three groundwater basin models: the McAda and Barroll (2002) regional groundwater model, the Española Basin model by Frenzel (1995), and the Socorro Basin model by Shafike (2005). Upstream from the City of Española and in the Rio Chama reach, where there are no applicable groundwater basin models, URGSiM estimates a constant groundwater contribution to the river on the basis of winter gage analysis 1975–99 (Roach, 2007).

DSS does not consider seepage gains to surface water but instead models return flow from the riverside drains. DSS uses a global value of 1.5 percent loss per mile for all irrigation canals. The FLO-2D model does not account for seepage gains to or losses from surface water.

Changes in Reservoir Storage

Changes in storage for reservoirs included in the study area are modeled in similar ways by URGWOM and URGSiM but are not addressed by the DSS or FLO-2D models. Changes in reservoir storage are calculated as inflows less outflows in a given time step. Inflows include precipitation and river flows (Rio Grande water and San Juan–Chama water), and outflows include seepage, evaporation, and releases. Releases of Rio Grande water and San Juan–Chama water are controlled by a complex set of reservoir operation rules which guide all aspects of storage and release of water in the reservoirs. These reservoir operation rules, which are the most complex portions of both URGWOM and URGSiM, control release of Rio Grande water and San Juan–Chama water. El Vado Reservoir, Abiquiu Reservoir, and Cochiti Lake store Rio Grande water and San Juan–Chama water, but Heron Reservoir is authorized to store only San Juan–Chama water. Reduction in reservoir storage capacity due to sedimentation is also accounted for in Abiquiu Reservoir and Cochiti Lake by URGWOM.

The URGWOM Accounting module tracks four Rio Grande accounts for the El Vado Reservoir: Indian storage water (prior and paramount water), MRGCD drought water (based on a 2003 emergency drought water agreement), Rio Grande water, and supplemental water. According to the Accounting module documentation (USACE and others, 2005b), the amount of storage required for the six Middle Rio Grande Basin Pueblos is computed by the Bureau of Indian Affairs and the USBOR. Released prior and paramount water is simulated in the URGWOM Accounting module but is not tracked downstream from El Vado Reservoir.

Evapotranspiration

URGWOM and URGSiM calculate evaporation losses at reservoirs as the surface area of the reservoir times 70 percent of the panevaporation measured at the reservoir in a given time step. Both models then apportion losses between San Juan–Chama water and Rio Grande water according to accepted San Juan–Chama accounting rules. URGWOM handles evapotranspiration losses at locations other than reservoirs in the Rio Chama reach indirectly by assuming consumptive use of half of all agricultural diversions. In the Embudo to Otowi reach, URGWOM uses loss rates calculated for the reach between El Vado and Abiquiu Reservoirs on the Rio Chama. The URGSiM calculation for the Rio Chama reach and the Embudo to Otowi reach considers riparian, irrigated agricultural, and open river areas and the calculated potential loss rates from each. The FLO-2D model calculates monthly evaporation averages on the basis of free-surface evaporation for each hour of the day for the area north of Otowi but does not address evapotranspiration losses south of Otowi. Both URGWOM and URGSiM calculate daily evaporation for open water in Cochiti Lake and daily evapotranspiration values from riparian and agricultural areas in the reach between Otowi and Isleta. The DSS calculates evapotranspiration losses only for irrigated areas in this reach.

Elements Not Addressed by Surface-Water Models

None of the four surface-water models surveyed specifically address interaction between surface water and groundwater occurring at the wetlands downstream from Cochiti Lake. Both URGWOM and URGSiM do, however, model surface-water and groundwater interactions downstream from Cochiti Lake, an area that includes these wetlands. Other elements of interest that are not addressed by any of the surface-water models include the hydrological aspects of Santa Cruz Reservoir and Nambe Lake, those of Horse Lake Creek above Heron Reservoir, or any aspect of water quality throughout the system.

Groundwater Models

Model Characteristics

Because only six of the groundwater models surveyed are identified as being currently in use (table 3, models 4, 6, 9, 10, 12, and 13), this discussion will focus on those six models. URGSiM is not included explicitly here because its groundwater model is based on models 6 and 10. The purpose of models 4, 6, and 9 generally is to simulate the effect of groundwater withdrawals and drawdown. The purpose of models 10 and 12 is to improve understanding of the geohydrology of the areas modeled (Albuquerque Basin and the Los Alamos area, respectively). The purpose of model 13 contrasts with those of the other models in that model 13 is focused on simulating the shallow riparian groundwater environment. All six of these models are transient models, and all except model 13 have time periods beginning in the predevelopment period (predevelopment is considered to be prior to modern groundwater pumping). The ending time period for the six models is the early 21st century. Model 13 has higher temporal and spatial resolution with the shortest time step (2 weeks to 5 months) and the smallest cell sizes (0.02 mi horizontal and 20 ft vertical) of the six models. The more common time step for the groundwater models is months to years. Horizontal cell sizes for the other four models range from 0.1 mi to 1 mi, and the vertical cell sizes range from tens to thousands of feet. Unlike the other five models, however, model 13 is not calibrated. Models 4, 6, and 10 are manually calibrated, and models 9 and 12 are automatically calibrated.

Hydrologic Elements

Because of their lineage, models 9 and 10 have the most similarities in terms of how various hydrologic elements of interest are addressed by the six currently used models. Wastewater return flow is addressed in models 4 and 6 as wastewater return from the Santa Fe wastewater treatment plants and in models 9 and 10 as septic return, but it is not addressed in models 12 and 13. Agricultural withdrawals are not addressed by any of the six models, but domestic well withdrawals (table 3) are addressed in models 4, 9, and 10. Irrigation return flow is addressed by only model 10. Evapotranspiration is addressed and provided as an output in models 9, 10, and 13. With the exception of model 13, all of the models address groundwater withdrawals, usually based on NMOSE data. All five models provide groundwater levels as an output.

Model Calibration

All six currently used models employ water-level measurement data, but they differ in terms of model calibration and parameterization (table 3). Models 9 and 10 employ in situ seepage tests for model calibration or parameterization. Flow measurements at stream-gaging stations and differential streamflow seepage calculations are used in calibration or parameterization by all six models with the exception of model 13. Land use and (or) vegetative cover data are used in calibration or parameterization by models 9, 10, and 13.

Recharge

The surveyed groundwater models simulate recharge to the aquifer in different ways. Recharge to an aquifer can be dependent on elevation and surface geology. It can occur from mountain-front seepage, tributary seepage, septic return flow, or irrigation seepage. Table 5 indicates how rates, locations, and types of recharge were determined and simulated for each model.

In terms of the six currently used models, recharge is modeled by all but model 13, although output values on recharge are provided by all models but model 12 (table 3). Factors used to assign recharge rates vary among models 4, 6, 9, 10, and 12 (table 5). The list of factors used to assign recharge rates in models 4 and 6 is the most comprehensive; it includes elevation, surface geology, mountain-front seepage, tributary seepage, and irrigation recharge. Models 9 and 10 both depend on irrigation recharge, septic return flow, tributary seepage, and mountain-front seepage to assign recharge rates. Additionally, model 9 uses surface geology in assigning recharge rates. Model 12 bases recharge rates on only elevation and tributary seepage.

Surface-Water/Groundwater Interaction

Surface-water/groundwater interactions simulated by groundwater models can provide valuable information to the surface-water models. The exchange of water between the Rio Grande and underlying shallow aquifers is quite large under some conditions. For example, comparisons between McAda and Barroll (2002) model results and stream-gaging station data indicate that, during periods of average October flow, nearly the entire flow of the Rio Grande can be expected to cycle once through the riverside drainage network as it travels downstream from Cochiti Dam to San Acacia. The groundwater models that include surface-water/groundwater interactions can provide large-scale estimates of flow between the Rio Grande and shallow aquifers, which can be an important component of the Rio Grande water budget as a whole. Table 6 shows how each groundwater model simulates surface-water/groundwater interactions.

Hydrologic Data Needs for Tracking Flow on the Rio Grande

Several data gaps became apparent during the course of conducting the model surveys. Certain values in all models are estimated as coefficients or as calibration factors because the data do not exist or are insufficient. Deficient data or poorly constrained variables pertaining to surface-water models include data on seepage gains and losses in the Rio Grande, particularly upstream from Cochiti Lake and in the Rio Chama; irrigation return flows; seasonal and ephemeral tributary inflow; evapotranspiration rates; soil moisture values; high-flow, cross-section, and elevation surveys; and stream-gaging station data in sandy channels, which are of variable quality. Information on daily releases of San Juan–Chama water from Abiquiu Reservoir is available only when the URGWOM accounting model is run daily. A simulation of past prior and paramount releases made by using stream-gaging station data from the period of the release to quantify problems that occurred during the release (such as insufficient volume of water or a delay in delivery) has not been completed. Deficient data or poorly constrained variables affecting groundwater models include groundwater conditions including groundwater levels and hydraulic conductivities between Cochiti Lake and Albuquerque, recharge, basin geologic structure, and current riparian area coverage.

Data on evapotranspiration, particularly from agricultural and riparian areas, are sparse. Groundwater and surface-water models both are sensitive to evapotranspiration values, but models evaluated in this study generally use assumed evapotranspiration values that do not reflect spatial or temporal variability and that have unknown associated errors. Both URGWOM and URGSiM calculate reference evapotranspiration based on climate data that are both spatially and temporally varying and use crop areas and crop types that are both spatially and temporally (by year) varying as well.

Statewide, there are little data on the contribution of flow from ephemeral channels to the main-stem rivers. This lack can be particularly problematic for tracking flow on a real-time or daily basis. Some ephemeral channels in the study area have drainage areas covering hundreds of square miles and can have flow rates of tens of thousands of cubic feet per second for large storm events.

Gaged data also are lacking for numerous perennial streams, such as Rio Ojo Caliente and Rio Nambe, near tributary confluences with the main-stem rivers. The lack of data regarding perennial tributary inflow on Rio Ojo Caliente and El Rito prohibits accurate calculations of Rio Chama channel conveyance from Abiquiu to the confluence with the Rio Grande. Channel losses estimated by models could be different from actual losses. Differences between channel loss estimates and actual losses may be compensated for in some models by a tributary inflow factor.

Hydrologic data are generally more complete for the reach of the Rio Grande between Cochiti Lake and Isleta Pueblo than they are for upstream from Cochiti Lake. The combination of continual urban development and large-scale agricultural use of the river valley downstream from Cochiti Lake has resulted in more interested stakeholders and has necessitated accurate monitoring of the water.

In all cases, the model results are only as good as the input data. The most recent hydrologic data are needed to accurately track prior and paramount releases. Ideally, these data would be continuously updated; however, a comprehensive source of such real-time data does not exist. Even daily data are sometimes difficult to obtain in a timely fashion for model operators (D.M. Roark, oral commun., May 2010) because the data come from multiple sources. Analysis of the 4 publicly available surface-water models and 13 publicly available groundwater models shows that, although elements from many models can be helpful in tracking flow in the Rio Grande, numerous data gaps and modeling needs indicate that accurate, consistent, and timely tracking of flow on the Rio Grande could be improved.

Model Ability To Track Flow

Surface-Water Models

Because it takes time for prior and paramount water to be released and to travel downstream to the pueblos, a model that is run in real time, or at least daily, could provide sufficient warning that streamflows are becoming low enough to require a release of prior and paramount water. Real-time or daily simulations would allow the Designated Engineer and the pueblos to monitor upstream indicators that prior and paramount water will be needed and thereby would help to prevent an unnecessary and perhaps costly delay in delivery of needed water. None of the surface-water models evaluated were designed to track flows on a real-time basis. URGWOM and DSS, for example, are capable of running on a daily time step; however, generally only the URGWOM accounting module is run daily, with a 1-day lag. URGSiM is designed to run on only a monthly time step. In some cases, the models are not run in real time because of the lack of real-time data to be used as inputs for the models.

Although none of the four surface-water models surveyed were designed specifically to quantify flow in the Rio Grande on a real-time basis, each can be helpful in accounting for different aspects of flow on the Rio Grande. URGSiM is a comprehensive model used to simulate flow in the Rio Grande and is used primarily as a rapid screening tool. URGSiM, when compared to URGWOM, includes less detail and has coarser spatial and temporal resolutions. It is, however, simpler to use, and the runtimes for simulations are much shorter than those in URGWOM. The DSS does not simulate flow in the Rio Grande, but it does include highly detailed information on the canal system south of Cochiti Lake that directly affects flow in the Rio Grande. The DSS model could be used to account for water delivery efficiency or to assess losses in the MRGCD canal system. Part of the strength of the DSS is that it includes a large amount of measured data for various processes and elements in the Middle Rio Grande Valley, including soil moisture, canal seepage, and evaporation. The measured data and canal system simulation provided by the DSS could be incorporated into a comprehensive water-resource model.

The FLO-2D model also is not applicable for tracking separate flow accounts. The applicability of the FLO-2D model regarding accounting flow in the Rio Grande is in routing of total flow or providing accurate traveltimes for flow in the Rio Grande for different flow conditions. Use of the flow-routing information gleaned from the FLO-2D model would be valuable in a detailed water-resource model.

In the model documentation for both the URGWOM and FLO-2D there is minimal discussion of uncertainty and errors associated with the model analysis, including sources of errors such as data input errors, simulation output errors, and model simplifications.

The FLO-2D model may provide the most realistic river routing since that is the purpose of the model. URGSiM and the DSS do not address routing, and URGWOM uses a simplified routing method.

The purpose of URGWOM—to simulate water storage and delivery operations in the Rio Grande—corresponds more closely than any of the other models evaluated to the mission of the Designated Engineer and the pueblos to track the available supply of flow to predict a need for prior and paramount water releases. Specifically, the strengths of URGWOM in relation to modeling flow are the detail and attention paid to the accounting of Rio Grande flow and San Juan–Chama flow. URGWOM relies on groundwater head values derived from the McAda and Barroll (2002) model, which means that URGWOM will be affected by any uncertainties that affect the McAda and Barroll (2002) model. Although URGWOM is designed to account for daily flows in the Rio Grande, only the Accounting module is run on a daily basis, although not consistently, mainly because daily data are not available in a timely manner from the various sources that supply it. There is a task in the Enhancement and Development section of the URGWOM 5-year plan schedule (http://www.spa.usace.army.mil/urgwom/continuedevelopment.asp) for development of a real-time water operations model to be effective in 2015.

Groundwater Models

Basic differences between the processes governing groundwater and surface-water flow lead to basic differences in the way groundwater and surface-water models are developed. Groundwater generally moves much more slowly than does surface water, and therefore, groundwater-model time steps are generally much larger than those used by surface-water models. In addition, groundwater models generally have monthly or longer stress periods or time steps because stress data (recharge and pumpage) are generally only available for monthly or longer time periods. The groundwater models surveyed for this report cannot be expected to provide simulations of flow at time scales less than the simulated time step (1 month to 1 year in most cases).

Aquifers generally encompass areas much wider than do stream channels. Grid spacing in groundwater models is, therefore, often too large to accurately simulate local-scale processes active in surface-water channels. Although many groundwater models that include surface-water/groundwater interactions have smaller grid spacing near streams, the groundwater models surveyed in this report cannot provide accurate simulations of individual river drains or any feature that is smaller than the model cell size, for example, 0.6 mi in the case of the McAda and Barroll (2002) model.

Of those of the currently used groundwater models, the purpose of model 13 (MacClune and others, 2006), to simulate the shallow riparian groundwater environment, is the most appropriate for examining local-scale surface-water/groundwater interactions. The basin-scale models, however, are also important in understanding the large-scale water balances between the aquifers and the surface water. As evident in table 6, all of the groundwater models surveyed address surface-water/groundwater interactions at some level. Any surface-water model would benefit from incorporating data from the most accurate and current groundwater model available. In the case of the Upper and Middle Rio Grande Valley, models 6 (Frenzel, 1995), 10 (McAda and Barroll, 2002), and 12 (Keating and others, 2005) are the most accurate and current groundwater models available.

Summary

The six Middle Rio Grande Basin Pueblos have prior and paramount rights to deliveries of water from the Rio Grande for their use. When the pueblos or the Bureau of Indian Affairs Designated Engineer identifies a need for additional flow on the Rio Grande, the Designated Engineer is tasked to decide when and how much prior and paramount water to release from storage at El Vado Reservoir to meet the needs of the pueblos. Over the last three decades, numerous models have been developed by Federal, State, and local agencies in New Mexico to simulate, understand, and (or) manage flows in the Middle Rio Grande upstream from Elephant Butte Reservoir. Analysis of 4 publicly available surface-water models and 13 publicly available groundwater models shows that, although elements from many models can be helpful in tracking flow in the Rio Grande, numerous data gaps and modeling needs indicate that accurate, consistent, and timely tracking of flow on the Rio Grande could be improved.

Deficient or poorly constrained hydrologic variables are sources of uncertainty that can be reduced with the acquisition of more refined data. Data gaps need to be filled to allow hydrologic models to be run on a real-time basis and thus ensure predictable water deliveries to meet needs for irrigation, domestic, stock, and other water uses. Deficient data or poorly constrained variables pertaining to surface-water models include data on seepage gains and losses in the Rio Grande, particularly upstream from Cochiti Lake and in the Rio Chama; irrigation return flows; seasonal and ephemeral tributary inflow; evapotranspiration rates; soil-moisture values; high-flow, cross-section, and elevation surveys on the Rio Grande; and stream-gaging station data in sandy channels, which are of variable quality. Information on daily releases of San Juan–Chama water from Abiquiu Reservoir is available in only a provisional form from the Accounting module of the Upper Rio Grande Water Operations Model (URGWOM) model with a 1-day lag. Deficient data or poorly confined hydrologic variables affecting groundwater models include groundwater conditions including groundwater levels and hydraulic conductivities between Cochiti Lake and Albuquerque, recharge, basin geologic structure, and current riparian area coverage. Data on evapotranspiration, particularly from agricultural and riparian areas, are sparse.

In all cases, the model results are only as good as the input data. The most recent hydrologic data are needed to accurately track prior and paramount releases. Ideally, these data would be continuously updated; however, a comprehensive source of such real-time data does not exist. Daily data are even sometimes difficult to obtain in a timely fashion for model operators because the data come from multiple sources.

Each surface-water model produces results that could be helpful in quantifying the flow of the Rio Grande, specifically by helping to track water as it moves down the channel of the Rio Grande and by improving the understanding of river hydraulics for the specified reaches. The ability of each surface-water model to track flow on the Rio Grande varies according to the purpose for which each model was designed. The purpose of URGWOM—to simulate water storage and delivery operations in the Rio Grande—is more applicable to tracking flow on the Rio Grande than are any of the other surface-water models surveyed. Specifically, the strengths of URGWOM in relation to modeling flow are the details and attention given to the accounting of Rio Grande flow and San Juan–Chama flow at a daily time step.

The most significant difficulty in using any of the surveyed surface-water models for the purpose of predicting the need for requested water releases is that none of the surface-water models surveyed consider water accounting on a real-time basis. The Accounting module of URGWOM is capable of tracking flows on a daily basis but does so only with a 1-day lag. In most cases, it is the lack of a dependable database or source of real-time data that prohibits the models' abilities to run in real time.

Groundwater models that provide detailed simulations of shallow groundwater flow in the vicinity of the Rio Grande can provide large-scale estimates of flow between the Rio Grande and shallow aquifers, which can be an important component of the Rio Grande water budget as a whole. The groundwater models surveyed for this report cannot, however, be expected to provide simulations of flow at time scales of less than the simulated time step (1 month to 1 year in most cases). Although many groundwater models that include surface-water/groundwater interactions have smaller grid spacing near streams, the groundwater models surveyed in this report cannot provide accurate simulations of individual river channels, drains, or any feature smaller than the model cell size, for example, 0.6 miles in the case of model 10. Of those of the currently used groundwater models, the purpose of model 13—to simulate the shallow riparian groundwater environment—is the most appropriate for examining local-scale surface-water/groundwater interactions. The basin-scale models, however, are also important in understanding the large-scale water balances between the aquifers and the surface water. In the case of the Upper and Middle Rio Grande Valley, models 6, 10, and 12 are the most accurate and current groundwater models available.

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Table 1. General characteristics of the surveyed surface-water models.

[SNL, Sandia National Laboratory; USACE, U.S. Army Corps of Engineers; USGS, U.S. Geological Survey; MRGCD, Middle Rio Grande Conservancy District; N/A, not applicable]

Model number	1	2	3	4
Model	**Upper Rio Grande Water Operations Model (URGWOM)[1]**	**Upper Rio Grande Simulation Model (URGSiM)[2]**	**Middle Rio Grande Conservancy District Decision Support System (MRGCD DSS)[3]**	**Tetra Tech, Middle Rio Grande FLO-2D Flood Routing Model[4]**
Responsible agency	URGWOM Executive Committee	SNL	Interstate Stream Commission	USACE
Individual interviewed	Mike Roark, USGS; Mark Sidlow, USACE	Vince Tidwell and Jesse Roach, SNL	Nabil Shafike, MRGCD	Marc Sidlow, Darrell Eidson, Ryan Gronewold, USACE
Model type	Management (forecast, planning, accounting, operations)	Water balance (planning)	Management (operations)	Process
Software or platform	Riverware	Powersim	Specific to project	Flow-2D
Time step used	Daily	Monthly	Daily	Seconds
Time steps capable of	Daily	Monthly	Daily	Daily or less
Upstream model extent	Lobatos, Colo.	Lobatos, Colo.	Cochiti Dam, N. Mex.	Cochiti Dam, N. Mex.
Downstream model extent	El Paso, Tex.	Caballo Reservoir, N. Mex.[5]	Bosque del Apache National Wildlife Refuge, N. Mex.	Elephant Butte Reservoir, N. Mex.
Reaches	23	17	N/A	Gridded, 250-foot spacing
How often is the model run?	Several times/year	Intermittently	Weekly	Intermittently
Model simulation period	Variable from 1975–present	1960–2004	2003–present	Present
Model updated	Monthly for operations model; daily for accounting module.	Continually, published every 2 years.	Yearly	When needed
River routing	Variable time lag	None	None	Purpose of model
Groundwater data used	From McAda and Barroll (2002) model output	Per capita consumption	None	None
Geospatial coverages incorporated	Agricultural and crop information	Agricultural and riparian area information	Rainfall and soils	Topography, geology, vegetation

[1]U.S. Army Corps of Engineers and others, 2005a and 2005b.

[2]Roach, 2007.

[3]Oad and others, 2009.

[4]Tetra Tech, Inc., 2004, and Riada Engineering, Inc., 2008.

[5]Caballo Reservoir is approximately 25 river miles downstream of Elephant Butte Reservoir.

Table 2. Summary of treatments of hydrologic elements by the surveyed surface-water models.

[N/A, not applicable; EPA, Environmental Protection Agency; %, percent; cfs, cubic feet per second; SJC, San Juan–Chama; DD, diversion dam; AMAFCA, Albuquerque Metropolitan Arroyo Flood Control Authority]

Model number	1	2	3	4
Hydrologic elements	**Upper Rio Grande Water Operations Model (URGWOM)[1]**	**Upper Rio Grande Simulation Model (URGSIM)[2]**	**Middle Rio Grande Conservancy District Decision Support System (MRGCD DSS)[3]**	**Tetra Tech, Middle Rio Grande FLO-2D Flood Routing Model[4]**
Rio Grande, Embudo to Otowi Bridge reach				
Inflow				
Rio Grande at Embudo	Computed from upstream inflows.	Computed from upstream inflows.	N/A	N/A
Santa Cruz River	Included implicitly[5] as component of local flow.	Included implicitly as component of local flow.	N/A	N/A
Pojoaque River	Included implicitly as component of local flow	Included implicitly as component of local flow.	N/A	N/A
Ephemeral channel storm-water flow	Included implicitly as component of local flow.	Included implicitly as component of local flow, calibrated to historical rainfall data.	N/A	N/A
City of Española effluent return	Input EPA time series data.	Calculated on the basis of population and water use characteristics.	N/A	N/A
Irrigation return flows	Model assumes approximately 5,000 acres of irrigable land and assumes 50% return flow.	Model assumes approximately 5,000 acres of irrigable land, assumes crop distribution is same as Rio Chama reach, and assumes double potential crop consumption diverted and half of that returns.	N/A	N/A
Seepage gains	Simulated by using the Riverware "Seasonal Gain Loss Flow Table" and part of the local inflow hydrograph.	Above Española, it is a component (71 cfs) of the local inflow; downstream of Espanola it is taken from the Espanola basin groundwater model in URGSiM.	N/A	N/A
Outflow				
Rio Grande at Otowi Bridge	Computed from upstream inflows in Water Operations Module and input directly into the Accounting module to compute local inflows.	Computed from upstream inflows.	N/A	Model simulates a variety of flows at Otowi.
Rio Grande water irrigation diversions; Los Chicos, La Canova, El Medio, Garcia, Lyden, Rinconada Isla, Alcalde, El Guique, San Juan	Included implicitly within input time series "return flow amount" derived during calibration.	Model assumes approximately 5,000 acres of irrigable land, assumes crop distribution is same as Rio Chama reach, and assumes double potential crop consumption diverted.	N/A	

Table 2. Summary of treatments of hydrologic elements by the surveyed surface-water models.—Continued

[N/A, not applicable; EPA, Environmental Protection Agency; %, percent; cfs, cubic feet per second; SJC, San Juan–Chama; DD, diversion dam; AMAFCA, Albuquerque Metropolitan Arroyo Flood Control Authority]

Model number	1	2	3	4
Hydrologic elements	**Upper Rio Grande Water Operations Model (URGWOM)[1]**	**Upper Rio Grande Simulation Model (URGSIM)[2]**	**Middle Rio Grande Conservancy District Decision Support System (MRGCD DSS)[3]**	**Tetra Tech, Middle Rio Grande FLO-2D Flood Routing Model[4]**
Municipal diversions, Española diversion and groundwater development, tribal drinking water systems	Included implicitly as part of the "return flow" calibration values.	Based on per capita use and overall county use. Pumping data comes from groundwater models. Groundwater diversion only.	N/A	Not addressed.
Evaporation losses at Santa Cruz Reservoir and Nambe Lake	Calculated for Nambe Lake only, in accounting model.	Not addressed.	N/A	Channel only; not for reservoirs.
Evapotranspiration losses	Used loss rates calculated for reach between El Vado and Abiquiu.	Calculated directly for riparian, irrigated agricultural, and open river areas.	N/A	Calculates monthly average, free surface evaporation for each hour of the day.
Seepage losses	Calculated as a function of the difference between observed flow and routed flow for the period 1975–86.	Calculated by the Española basin groundwater model included in URGSiM.	N/A	Not addressed
Changes in storage				
Santa Cruz Reservoir	Not addressed.	Not addressed.	N/A	Not addressed.
Nambe Lake	Will be included in future updates.	Not addressed.	N/A	Not addressed.
Rio Chama reach				
Inflow				
Horse Lake Creek above Heron Reservoir	Not addressed.	Part of native contributions to Heron Reservoir.	N/A	N/A
Willow Creek above Heron Reservoir	Calculated as the difference between the Heron Reservoir outlet and the gage above Heron Reservoir.	Calclulated as tunnel flows less losses, plus native contributions to Heron.	N/A	N/A
Rio Chama near La Puente	Included implicitly as component of local flow.	Input gage data.	N/A	N/A
Rio Ojo Caliente	Included implicitly as component of local flow.	Input gage data.	N/A	N/A
Ephemeral channel storm-water flow	Included implicitly as component of local flow.	Included implicitly as component of local flow.	N/A	N/A

Table 2. Summary of treatments of hydrologic elements by the surveyed surface-water models.—Continued

[N/A, not applicable; EPA, Environmental Protection Agency; %, percent; cfs, cubic feet per second; SJC, San Juan–Chama; DD, diversion dam; AMAFCA, Albuquerque Metropolitan Arroyo Flood Control Authority]

Model number	1	2	3	4
Hydrologic elements	**Upper Rio Grande Water Operations Model (URGWOM)[1]**	**Upper Rio Grande Simulation Model (URGSIM)[2]**	**Middle Rio Grande Conservancy District Decision Support System (MRGCD DSS)[3]**	**Tetra Tech, Middle Rio Grande FLO-2D Flood Routing Model[4]**
Intermountain transfer from Azotea Tunnel	Gaged at the tributary tunnels to Azotea Tunnel and calculated for Azotea Tunnel.	Input gage data (from Azotea Tunnel). (Recent versions of URGSiM calculate Azotea flows based on flows in San Juan tributaries that are diverted and diversion rules).	N/A	N/A
Irrigation return flows	Included implicitly as part of the channel loss coefficient. Calculated by using 1971–85 historical streamflow data and assuming 50% return flow.	Model uses Chama adjudication agricultural areas and crop mix and calculates crop demand. Returns diversions in excess of crop demand.	N/A	N/A
Seepage gains	Included implicitly, lumped in with the irrigation return flow coefficient.	Uses a constant groundwater inflow based on winter gage analysis.	N/A	N/A
Outflow				
Rio Chama at Chamita gage	Calculated.	Calculated.	N/A	N/A
Chama water irrigation diversions	Included implicitly, lumped with the irrigation return flow coefficient.	Model uses Chama adjudication agricultural areas and crop mix and calculates crop demand. Diversions are historical values during calibration and double crop demand in scenario period.	N/A	N/A
Evaporation losses from Rio Chama reservoirs	Total is 70% of panevaporation multiplied by surface area at gaged reservoir elevation. SJC portion is based on accounting calculations.	Total is 70% of panevaporation multiplied by surface area at gaged reservoir elevation. SJC portion is based on accounting calculations.	N/A	N/A
Evapotranspiration losses	Combined with seepage loss calculations.	Calculated.	N/A	N/A
Seepage losses	For SJC water, uses monthly loss coefficient defined in the Rio Grande Compact, otherwise calculated the same as for Embudo reach for Rio Grande Water.	None; all reaches modeled as constant gaining based on winter gage analysis.	N/A	N/A
Distinction between stored and nonstored water in Rio Chama	Calculates total Rio Grande and SJC project water storage.	Calculates total Rio Grande and SJC project water storage.	N/A	N/A

Table 2. Summary of treatments of hydrologic elements by the surveyed surface-water models.—Continued

[N/A, not applicable; EPA, Environmental Protection Agency; %, percent; cfs, cubic feet per second; SJC, San Juan–Chama; DD, diversion dam; AMAFCA, Albuquerque Metropolitan Arroyo Flood Control Authority]

Model number	1	2	3	4
Hydrologic elements	**Upper Rio Grande Water Operations Model (URGWOM)[1]**	**Upper Rio Grande Simulation Model (URGSIM)[2]**	**Middle Rio Grande Conservancy District Decision Support System (MRGCD DSS)[3]**	**Tetra Tech, Middle Rio Grande FLO-2D Flood Routing Model[4]**
Changes in storage				
Rio Grande water				
El Vado Reservoir	Calculated as the difference between Rio Grande inflow and outflow minus the SJC water.	Calculated similar to URGWOM by using reservoir release rules in combination with a mass balance to track inflows and outflows while accounting for seepage, ice cover, and other variables.	N/A	N/A
Abiquiu Reservoir	Calculated similar to El Vado except sediment displacement calculations are added.	Calculated as with El Vado Reservoir.	N/A	N/A
SJC water				
El Vado Reservoir (mainly stores native runoff but can store SJC water)	Calculated in accounting, water operations, and planning models.	Calculated similar to URGWOM by using reservoir release rules in combination with a mass balance to track inflows and outflows while accounting for seepage, ice cover, and other variables.	N/A	N/A
Abiquiu Reservoir (mainly flood control and some SJC storage)	Calculated in accounting, water operations, and planning models.	Calculated as with El Vado Reservoir.	N/A	N/A
Heron Reservoir (SJC water storage)	Calculated in accounting, water operations, and planning models.	Calculated as with El Vado Reservoir.	N/A	N/A
Rio Grande, Otowi Bridge to Isleta Pueblo reach				
Inflow				
Rio Grande at Otowi Bridge	Calculated.	Calculated.	Not addressed.	Input hydrographs.
Jemez River	Input gage data near Jemez Pueblo with modeled gains and losses between there and Rio Grande.	Input gage data near Jemez Pueblo with modeled gains and losses between there and Rio Grande.	Not addressed.	Input hydrographs.
Rito de los Frijoles	Not addressed.	Not addressed.	Not addressed.	Input hydrographs.
Santa Fe River	Present, but input data not populated.	Input data.	Not addressed.	Input hydrographs.
Galisteo flood control	Input data.	Input data.	Not addressed.	Input hydrographs.

Table 2. Summary of treatments of hydrologic elements by the surveyed surface-water models.—Continued

[N/A, not applicable; EPA, Environmental Protection Agency; %, percent; cfs, cubic feet per second; SJC, San Juan–Chama; DD, diversion dam; AMAFCA, Albuquerque Metropolitan Arroyo Flood Control Authority]

Model number	1	2	3	4
Hydrologic elements	Upper Rio Grande Water Operations Model (URGWOM)[1]	Upper Rio Grande Simulation Model (URGSIM)[2]	Middle Rio Grande Conservancy District Decision Support System (MRGCD DSS)[3]	Tetra Tech, Middle Rio Grande FLO-2D Flood Routing Model[4]
Ephemeral channel storm-water flow	Included implicitly as component of local flow and explicitly from gages on north and south AMAFCA channels and Tijeras arroyo gages.	Included implicitly as component of local flow and explicitly from gages on north and south AMAFCA channels and Tijeras arroyo gages.	Not addressed.	Not addressed.
Intermountain transfer inflow at Otowi	Calculated explicitly.	Calculated explicitly.	Not addressed.	Not addressed.
Irrigation return flows	Calculated by using diversion schedules, crop information, and seepage and drain information.	Calculated by using diversion schedules, crop information, and seepage and drain information.	Measured in main canals.	Major return flows are lumped and input as hydrographs, created in collaboration with MRGCD and based on historical records.
Municipal effluent return (Albuquerque, Rio Rancho, Bernalillo, Cochiti)	Input wastewater treatment plant return flows.	Calculated as roughly 50% of total municipal use.	Not addressed.	Not addressed.
Wetlands	Not addressed.	Not addressed.	Not addressed.	Not addressed.
Seepage gains	Calculated in URGWOM with a coarsely gridded groundwater model.	Calcluated in URGSiM based on coarsely gridded regional groundwater model based on Frenzel 1995 and McAda Barroll 2002.	No seepage gains for this reach, but drain return flow is included.	Not currently addressed, but the model is capable of addressing it.
Outflow				
Rio Grande at Isleta Lakes	Calculated.	Input data.	Not addressed.	Not addressed.
Rio Grande water irrigation diversions (Sili Main Canal, Cochiti Main Canal, and Angostura DD)	Input to the program as average monthly hydrographs.	Calculated and lumped per model reach.	Input measured data but not identified as Rio Grande or SJC water.	Modeled as outflow hydrographs subtracted from the Rio Grande flow, not identified as Rio Grande or SJC water.

Table 2. Summary of treatments of hydrologic elements by the surveyed surface-water models.—Continued

[N/A, not applicable; EPA, Environmental Protection Agency; %, percent; cfs, cubic feet per second; SJC, San Juan–Chama; DD, diversion dam; AMAFCA, Albuquerque Metropolitan Arroyo Flood Control Authority]

Model number	1	2	3	4
Hydrologic elements	**Upper Rio Grande Water Operations Model (URGWOM)[1]**	**Upper Rio Grande Simulation Model (URGSIM)[2]**	**Middle Rio Grande Conservancy District Decision Support System (MRGCD DSS)[3]**	**Tetra Tech, Middle Rio Grande FLO-2D Flood Routing Model[4]**
Irrigation diversions of SJC water (Sili Main Canal, Cochiti Main Canal, and Angostura DD)	SJC water is tracked separately from Rio Grande water as far downstream as the Elephant Butte Reservoir. Irrigation diversions of SJC water may be tracked, depending on model settings selected by the user.	Only the City of Albuquerque's allocation of SJC water is tracked downstream of Cochiti.	Input measured data but not identified as Rio Grande or SJC water.	Modeled as outflow hydrographs subtracted from the Rio Grande flow, not identified as Rio Grande or SJC water.
Municipal diversions of Rio Grande water (including Buckman well field)	Input data from City of Albuquerque.	Calculated by using population and per capita water use data. Buckman well field is incorporated into the Española groundwater model.	Not addressed.	Not addressed.
Municipal diversions of SJC water (Albuquerque SJC DD)	SJC water is tracked separately from Rio Grande water as far downstream as Elephant Butte Reservoir. Municipal diversions of SJC water are input for the Albuquerque diversion.	Model tracks four types of SJC water downstream to Cochiti. Only Albuquerque's SJC allocation is tracked from Cochiti to Albuquerque. According to model, all Albuquerque SJC water is diverted at Albuquerque.	Not addressed.	Municipal diversions are accounted for but not identified as SJC or Rio Grande water.
Evaporation losses from Cochiti Reservoir	Calculated in accounting, water operations, and planning models.	Calculated.	Not addressed.	Not addressed.
Evapotranspiration losses	Calculated incorporating panevaporation, crop area, riparian area, and evapotranspiration rates from each reach in middle valley.	Calculated for crops, riparian vegetaion, and open water.	Calculated for irrigated areas.	Not addressed.
Seepage losses	Comprehensive calculation based on hydraulic gradients between the river and the drains and compared with actual seepage measurements. Values range from 85–95 cfs lost to seepage per day during winter months.	Calcluated in URGSiM based on coarsely gridded regional groundwater model based on Frenzel 1995 and McAda Barroll 2002.	Use global value of 1.5% loss per mile for all irrigation canals.	Not currently addressed, but the model is capable of addressing it.
Wetlands	Not addressed.	Not addressed.	Not addressed.	Not addressed.

Table 2. Summary of treatments of hydrologic elements by the surveyed surface-water models.—Continued

[N/A, not applicable; EPA, Environmental Protection Agency; %, percent; cfs, cubic feet per second; SJC, San Juan–Chama; DD, diversion dam; AMAFCA, Albuquerque Metropolitan Arroyo Flood Control Authority]

Model number	1	2	3	4
Hydrologic elements	**Upper Rio Grande Water Operations Model (URGWOM)[1]**	**Upper Rio Grande Simulation Model (URGSIM)[2]**	**Middle Rio Grande Conservancy District Decision Support System (MRGCD DSS)[3]**	**Tetra Tech, Middle Rio Grande FLO-2D Flood Routing Model[4]**
Changes in storage				
Rio Grande waters				
Cochiti Reservoir	Calculated in accounting, water operations, and planning models including considerations for sediment deposition.	Calculated with reservoir release rules.	Not addressed.	Not addressed.
SJC water				
Cochiti Reservoir	Calculated with reservoir release rules.	Calculated with reservoir release rules.	Not addressed.	Not addressed.
Water-quality component	Not addressed.	Not addressed currently, but the model is capable of including it.	Not addressed.	Sediment transport.

[1]U.S. Army Corps of Engineers and others, 2005a and 2005b.

[2]Roach, 2007.

[3]Oad and others, 2009.

[4]Tetra Tech, Inc., 2004.

[5]The term “implicitly” is used when a flow element is not included explicitly in the model but is addressed in combination with other hydrologic elements or as a coefficient.

Table 3. Characteristics and hydrologic elements of the surveyed groundwater models.

[Shaded columns indicate models currently in use. USGS, U.S. Geological Survey; NMOSE, New Mexico Office of the State Engineer; LANL, Los Alamos National Laboratory; SSPA, S.S. Papadopulos & Associates Inc.; ISC, New Mexico Interstate Stream Commission; NA, not applicable; predevel, predevelopment; mi, miles; ft, feet; ET, evapotranspiration]

Model number	1	2	3	4	5	6
Model authors	Hearne, 1985a	Kernodle and Scott, 1986	Kernodle and others, 1987	McAda and Wasiolek, 1988	McAda, 1990	Frenzel, 1995
Characteristics						
Agency	USGS	USGS	USGS	USGS	USGS	USGS
When/how often is the model run?	Discontinued	Discontinued	Discontinued	Occasionally	Unknown	Occasionally
When/how often is the model input updated?	Discontinued	Discontinued	Discontinued	Unknown		
Is it recalibrated when updated?	NA	NA	NA			
Who runs (ran) the model?	BIA	NA	NA	NMOSE, consulting firms		NMOSE, consulting firms
Precursor model(s)	--	--	2	--	4	4
Model platform/software used	precursor to MODFLOW	MODFLOW	MODFLOW	MODFLOW	MODFLOW	MODFLOW
Is the model steady state or transient?	Transient	Steady state	Transient	Transient	Transient	Transient
If transient: What is the model's time period?	1947–80	Predevelopment	1907–79	1947–2020	1972–2045	1947–2012
What is the model time step?	1 year	NA	2–25 years	1 year	Monthly	1–20 years
How many spatial dimensions (1 or 2 or 3)?	3	3	3	3	3	3
Horizontal cell size	1–4.5 mi	0.5–6 mi	0.5–6 mi	1 mi	0.33–1 mi	1 mi
Vertical cell size	650–1,950 ft	220–2,250 ft	220–2,250 ft	800–1,800 ft	300–650 ft	200–1,400 ft
Surficial aquifer layer unconfined	Yes	Yes	Yes	Yes	Yes	Yes
Does the model have a component specifically designed for simulation of riparian areas?	Yes	No	No	No	No	No
How are riparian areas simulated?	Specified flux to river cells represents vegetative ET	--	--	--	--	--
Model calibration	Manually	Manually	Manually	Manually	Manually	Manually
Water quality component	No	No	No	No	No	No
Does the model include the following inputs?						
Surficial recharge from natural infiltration	Yes	Yes	Yes	Yes	Yes	Yes
Is surficial recharge spatially variable? See table (5)	Yes	Yes	Yes	Yes	Yes	Yes
Wastewater return flows	No	No	No	Yes	Yes	Yes
How is wastewater return flow input to the model?	NA	NA	NA	Wastewater to tributaries recharges aquifer	Wastewater to tributaries recharges aquifer	Wastewater to tributaries recharges aquifer

7	8	9	10	11	12	13
Kernodle and others, 1995	**Tiedeman and others, 1998**	**Barroll, 2001**	**McAda and Barroll, 2002**	**Sanford and others, 2003**	**Keating and others, 2005**	**MacClune and others, 2006**
Characteristics						
USGS	USGS	NMOSE	USGS	USGS	LANL	SSPA
Not used	Not used	Regularly	Occasionally	Not used	Often	Weekly or monthly
Not used	Not used	Regularly	Unknown	Not used	Monthly	When run
NA	NA	No	Unknown	Not used	Yes	Yes, annually
NA	NA	NMOSE	USGS, ISC, consulting firms, and students	USGS	LANL	ISC
--	7	7, 8	7, 8, 9	7, 8, 9, 10	--	--
MODFLOW	MODFLOW	MODFLOW	MODFLOW	MODFLOW, MODPATH	FEHM	MODFLOW, FLO-2D
Transient	Transient	Transient	Transient	Steady state	Transient	Transient
1901–94	1900–95	predevel to 2040	predevel to 2000	NA	1945–2004	2003–4
3 months to 5 years	2–5 years	2.5 months to 5 years	2.5 months to 5 years	NA	1 year	2 weeks to 5 months
3	3	3	3	3	3	3
0.1–0.6 mi	0.5–3.1 mi	0.5–3.1 mi	0.6 mi	0.6 mi	0.1–0.2 mi	0.02–0.05 mi
200–500 ft	40–1,800 ft	40–800 ft	30–7,800 ft	20–6,000 ft	135–21,000 ft	20–100 ft
Yes	Yes	Yes	Yes	Yes	No	Yes
Yes	Yes	Yes	Yes	Yes	No	Yes
ET rates depend on riparian area in cells	ET rates depend on riparian area in cells	ET rates depend on riparian area in cells	ET rates depend on riparian area in cells	ET rates depend on riparian area in cells	--	Riparian ET rates depend on vegetation cover
Manually	Automated	Automated	Manually	Automated	Automated	Not calibrated
No	No	No	No	No	No	No
Does the model include the following inputs?						
Yes	Yes	Yes	Yes	Yes	Yes	No
Yes	Yes	Yes	Yes	Yes	Yes	NA
Yes	Yes	Yes	Yes	No	No	No
Septic return flow recharges aquifer	Septic return flow recharges aquifer	Septic return flow recharges aquifer	Septic return flow recharges aquifer	NA	NA	NA

Table 3. Characteristics and hydrologic elements of the surveyed groundwater models.—Continued

[Shaded columns indicate models currently in use. USGS, U.S. Geological Survey; NMOSE, New Mexico Office of the State Engineer; LANL, Los Alamos National Laboratory; SSPA, S.S. Papadopulos & Associates Inc.; ISC, New Mexico Interstate Stream Commission; NA, not applicable; predevel, predevelopment; mi, miles; ft, feet; ET, evapotranspiration]

Model number	1	2	3	4	5	6
Model authors	Hearne, 1985a	Kernodle and Scott, 1986	Kernodle and others, 1987	McAda and Wasiolek, 1988	McAda, 1990	Frenzel, 1995
Wastewater inputs	NA	NA	NA	Santa Fe wastewater treatment plants (Siler Rd & SF Airport)	Santa Fe wastewater treatment plants (Siler Rd & SF Airport)	Santa Fe wastewater treatment plants (Siler Rd & SF Airport)
Agricultural withdrawals	Yes	No	No	No	No	No
Domestic well withdrawals	No	No	No	Yes	No	No
Groundwater injection	No	No	No	No	No	No
Are the following processes explicitly modeled?						
Irrigation return flows	No	No	No	No	No	No
How is irrigation return flow modeled?	NA	NA	NA	NA	NA	NA
Evapotranspiration	Yes	No	No	No	No	No
Is ET time varying?	No	NA	NA	NA	NA	NA
Springflow	No	No	No	No	No	No
Groundwater withdrawals	Yes	No	Yes	Yes	Yes	Yes
Data source for groundwater withdrawals	Data from Public Service Co. Of NM	NA	NMOSE	Data from NMOSE and Sangre de Cristo Water Company	Data from NMOSE and Sangre de Cristo Water Company	Data from NMOSE and Sangre de Cristo Water Company
Does the model include the following outputs explicitly?						
Groundwater Levels	Yes	Yes	Yes	Yes	Yes	Yes
Base flow/Streamflow	Yes	No	No	Yes	Yes	Yes
Evapotranspiration	No	No	No	No	No	No
Recharge/seepage from surface water to aquifer	Yes	Yes	Yes	Yes	Yes	Yes
Discharge from aquifer to surface water	Yes	Yes	Yes	Yes	Yes	Yes
Springflow	No	No	No	No	No	No
Were the following data used to calibrate or parameterize the model?						
Water level measurements in wells	Yes	Yes	Yes	Yes	Yes	Yes
In-situ seepage tests	Yes	No	No	No	No	No
Stream gage flow measurements	Yes	No	No	Yes	Yes	Yes
Differential streamflow seepage calculations	Yes	No	No	Yes	Yes	Yes
Land use/vegetative cover data	Yes	No	No	No	No	No

7	8	9	10	11	12	13
Kernodle and others, 1995	**Tiedeman and others, 1998**	**Barroll, 2001**	**McAda and Barroll, 2002**	**Sanford and others, 2003**	**Keating and others, 2005**	**MacClune and others, 2006**
Domestic septic discharges	Domestic septic discharges	Domestic septic discharges	Domestic septic discharges	NA	NA	NA
No	No	No	No	No	No	No
Yes	Yes	Yes	Yes	No	No	No
No	No	No	No	No	No	No
Are the following processes explicitly modeled?						
Yes	No	No	Yes	No	No	No
Recharge rates increased in irrigated areas	NA	NA	Recharge rates increased in irrigated areas	NA	NA	NA
Yes	Yes	Yes	Yes	No	No	Yes
Yes	Yes	Yes	Yes	NA	NA	Yes
No	No	No	No	No	No	No
Yes	Yes	Yes	Yes	No	Yes	No
NMOSE	NMOSE	NMOSE	NMOSE and City of Albuquerque	NA	Not specified in documentation	NA
Does the model include the following outputs explicitly?						
Yes	Yes	Yes	Yes	Yes	Yes	Yes
No	No	No	No	No	No	No
Yes	Yes	Yes	Yes	No	No	Yes
Yes	Yes	Yes	Yes	Yes	No	Yes
Yes	Yes	Yes	Yes	Yes	No	Yes
No	No	No	No	No	No	No
Were the following data used to calibrate or parameterize the model?						
Yes	Yes	Yes	Yes	Yes	Yes	Yes
Yes	Yes	Yes	Yes	Yes	No	No
No	Yes	Yes	Yes	Yes	Yes	No
No	Yes	Yes	Yes	Yes	Yes	No
Yes	Yes	Yes	Yes	Yes	No	Yes

Table 4. Well fields included in each groundwater model.

[Shaded columns indicate models currently in use]

Model number	**1**	**2**	**3**	**4**	**5**	**6**
Model	**Hearne, 1985a**	**Kernodle and Scott, 1986**	**Kernodle and others, 1987**	**McAda and Wasiolek, 1988**	**McAda, 1990**	**Frenzel, 1995**
Well field name						
Guaje	Yes	No	No	Yes	No	Yes
Los Alamos	Yes	No	No	Yes	No	Yes
Panjarito	Yes	No	No	Yes	No	Yes
Buckman	Yes	No	No	Yes	Yes	Yes
Albuquerque	No	No	Yes	No	No	No
Otowi	No	No	No	No	No	No
Santa Fe	No	No	No	Yes	No	Yes

Model number	7	8	9	10	11	12	13
Model	Kernodle and others, 1995	Tiedeman and others, 1998	Barroll, 2001	McAda and Barroll, 2002	Sanford and others, 2003	Keating and others, 2005	MacClune and others, 2006
Well field name							
Guaje	No	No	No	No	No	Yes	No
Los Alamos	No	No	No	No	No	Yes	No
Panjarito	No	No	No	No	No	Yes	No
Buckman	No	No	No	No	No	Yes	No
Albuquerque	Yes	Yes	Yes	Yes	No	No	No
Otowi	No	No	No	No	No	Yes	No
Santa Fe	No	No	No	No	No	No	No

Table 5. Factors used by each surveyed groundwater model to simulate recharge.

[Shaded columns indicate models currently in use]

	Hearne, 1985a	Kernodle and Scott, 1986	Kernodle and others, 1987	McAda and Wasiolek, 1988	McAda, 1990	Frenzel, 1995
	1	2	3	4	5	6
Is recharge spatially variable?						
	Yes	Yes	Yes	Yes	Yes	Yes
Factors used to assign recharge rates						
Elevation dependent	No	No	No	Yes	Yes	Yes
Surface geology dependent	No	No	No	Yes	Yes	Yes
Mountain-front seepage	Yes	Yes	Yes	Yes	Yes	Yes
Tributary seepage	Yes	Yes	Yes	Yes	Yes	Yes
Septic return flow	No	No	No	No	No	No
Irrigation recharge	No	No	No	Yes	Yes	Yes

	Kernodle and others, 1995	Tiedeman and others, 1998	Barroll, 2001	McAda and Barroll, 2002	Sanford and others, 2003	Keating and others, 2005	MacClune and others, 2006
	7	8	9	10	11	12	13
Is recharge spatially variable?							
	Yes	Yes	Yes	Yes	Yes	Yes	No
Factors used to assign recharge rates							
Elevation dependent	No	No	No	No	No	Yes	No
Surface geology dependent	No	Yes	Yes	No	No	No	No
Mountain-front seepage	Yes	Yes	Yes	Yes	Yes	No	No
Tributary seepage	Yes	Yes	Yes	Yes	Yes	Yes	No
Septic return flow	Yes	Yes	Yes	Yes	No	No	No
Irrigation recharge	Yes	Yes	Yes	Yes	No	No	No

Table 6. Methods used for modeling surface-water/groundwater interactions in the groundwater models surveyed.

[Shaded columns indicate models currently in use]

Model	1	2	3	4	5	6
	Hearne, 1985a	Kernodle and Scott, 1986	Kernodle and others, 1987	McAda and Wasiolek, 1988	McAda, 1990	Frenzel, 1995
Methods used to model surface-water recharge to groundwater						
Specified heads	Yes	Yes	Yes	No	No	No
Specified flux boundaries	Yes	Yes	Yes	Yes	Yes	Yes
Head dependent flux boundaries	Yes	No	No	Yes	Yes	Yes
Methods used to model groundwater discharge to surface water						
Specified heads	Yes	Yes	Yes	No	No	No
Specified flux boundaries	No	No	No	No	No	No
Head dependent flux boundaries	Yes	No	No	Yes	Yes	Yes

Model	7	8	9	10	11	12	13
	Kernodle and others, 1995	Tiedeman and others, 1998	Barroll, 2001	McAda and Barroll, 2002	Sanford and others, 2003	Keating and others, 2005	MacClune and others, 2006
Methods used to model surface-water recharge to groundwater							
Specified heads	No	No	No	No	No	Yes	No
Specified flux boundaries	Yes	Yes	Yes	Yes	Yes	Yes	No
Head dependent flux boundaries	Yes	Yes	Yes	Yes	Yes	No	Yes
Methods used to model groundwater discharge to surface water							
Specified heads	No	No	No	No	No	Yes	No
Specified flux boundaries	No	No	No	No	No	No	No
Head dependent flux boundaries	Yes	Yes	Yes	Yes	Yes	No	Yes

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