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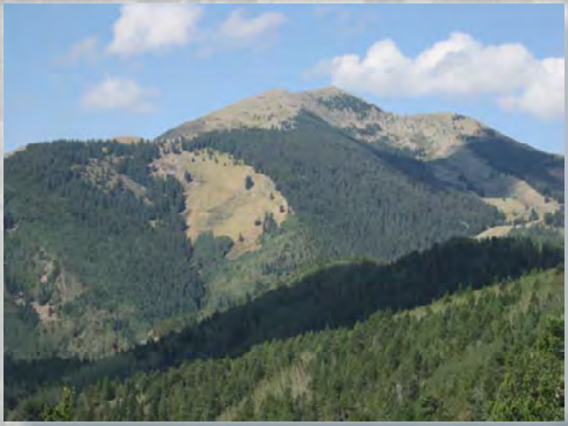
Hydrogeology, Water Resources, and Water Budget of the Upper Rio Hondo Basin, Lincoln County, New Mexico, 2010



Scientific Investigations Report 2014–5153

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

Front cover:

Top, View from Capitan Mountains looking northeast to Sierra Blanca, October 2011 (photograph by Michael J. Darr, U.S. Geological Survey).

Bottom, Eastern slopes of Sierra Blanca, summer 2009 (photograph by Michael J. Darr, U.S. Geological Survey) and winter 2006 (photograph by Gordon W. Rattray, U.S. Geological Survey).

Back cover, View of Capitan Mountains from plains near Fort Stanton, March 2011 (photograph by Michael J. Darr, U.S. Geological Survey).

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2014

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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)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/sec)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88), except in some cases to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Hydrogeology, Water Resources, and Water Budget of the Upper Rio Hondo Basin, Lincoln County, New Mexico, 2010

By Michael J. Darr, Gordon W. Rattray, Kurt J. McCoy, and Roger A. Durall

Abstract

The upper Rio Hondo Basin occupies a drainage area of 585 square miles in south-central New Mexico and comprises three general hydrogeologic terranes: the higher elevation "Mountain Block," the "Central Basin" piedmont area, and the lower elevation "Hondo Slope." As many as 12 hydrostratigraphic units serve as aquifers locally and form a continuous aquifer on the regional scale. Streams and aquifers in the basin are closely interconnected, with numerous gaining and losing stream reaches across the study area. In general, the aquifers are characterized by low storage capacity and respond to short-term and long-term variations in recharge with marked water-level fluctuations on short (days to months) and long (decadal) time scales. Droughts and local groundwater withdrawals have caused marked water-table declines in some areas, whereas periodically heavy monsoons and snowmelt events have rapidly recharged aquifers in some areas.

A regional-scale conceptual water budget was developed for the study area in order to gain a basic understanding of the magnitude of the various components of input, output, and change in storage. The primary input is watershed yield from the Mountain Block terrane, supplying about 38,200 to 42,300 acre-feet per year (acre-ft/yr) to the basin, as estimated by comparing the residual of precipitation and evapotranspiration with local streamgage data. Streamflow from the basin averaged about 21,200 acre-ft/yr, and groundwater output left the basin at an estimated 2,300 to 5,700 acre-ft/yr. The other major output (about 13,500 acre-ft/yr) was by public water supply, private water supply, livestock, commercial and industrial uses, and the Bonito Pipeline. The residual in the water budget, the difference between the totals of the input and output terms or the potential change in storage, ranged from -2,200 acre-ft/yr to +5,300 acre-ft/yr. There is a high degree of variability in precipitation and consequently in the water supply; small variations in annual precipitation can result in major changes in overall watershed yield. Changing water-use patterns, concentrated areas of groundwater withdrawal, and variations in precipitation have created localized areas where water-table declines and diminished surface flow are of concern.

Introduction

The upper Rio Hondo Basin, located in south-central New Mexico (fig. 1), is a semiarid, high-elevation basin. The area included in this report extends over the upper Rio Hondo Basin, spanning 585 square miles (mi^2) in the Rio Bonito and Rio Ruidoso watersheds. The upper Rio Hondo Basin contains several streams with perennial reaches, but other streams in the basin are ephemeral. There are several small manmade lakes and reservoirs in the basin that are used to store surface water for domestic supply. Groundwater is present in several aquifers of varying productivity and depth.

Recent, rapid increases in population and associated residential, recreational, and commercial development in parts of the basin have led to increased demand for water resources, while at the same time, agricultural users face possible surface-water shortages from drought and depletion. In addition, exceptional precipitation events such as floods or droughts could become more commonplace in the future as a result of the changing climate (New Mexico Office of the State Engineer, 2006), so it is important to understand the effects of these events on the magnitude and mechanics of the basin's water resources.

Diversion and (or) impoundment of stream water or pumping of groundwater from wells could result in reduced streamflow and (or) groundwater depletion. Areas of particular concern are in the Eagle Creek watershed and in the Rio Ruidoso and Rio Bonito watersheds downstream from diversions, dams, and well fields. Future diversions that could result from the transfer of water rights and the subsequent movement upstream from their original points of diversion are also of concern.

Natural and manmade stressors could affect the current and future quantity and quality of surface water and groundwater in the basin. Regional and local planners and officials have requested information on water resources availability, the functioning of the hydrologic system in the basin, and how the system is affected by drought and depletions in order to make informed decisions about current and future development and land use in the basin. Consequently, the U.S. Geological Survey (USGS), in cooperation with Lincoln County, New Mexico, is conducting

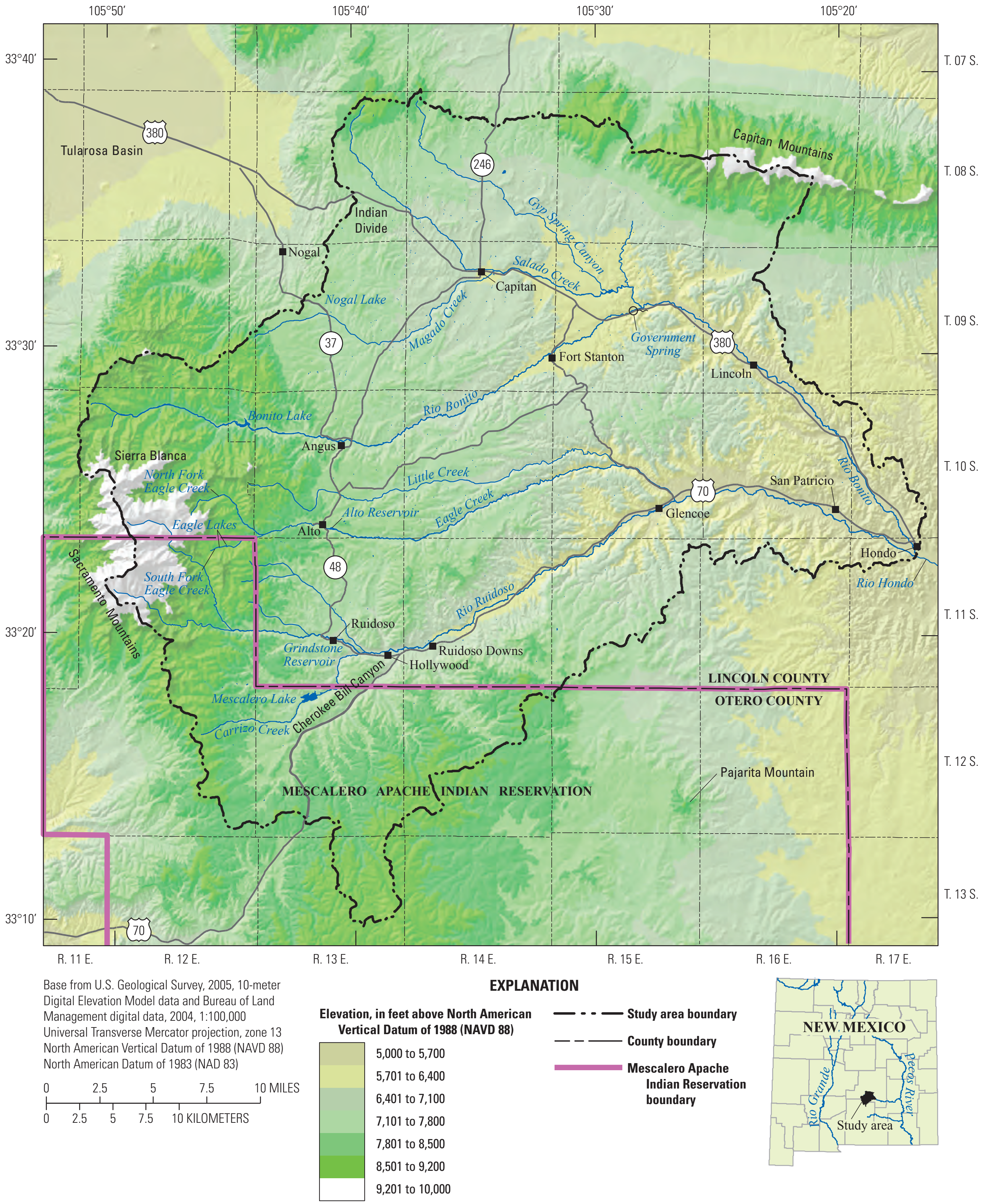


Figure 1. Upper Rio Hondo Basin study area, Lincoln County, New Mexico.

a multiyear study to (1) improve the understanding of the dynamics of the hydrologic system, (2) characterize the current quantity and quality of surface water and groundwater in the basin, and (3) investigate whether and how changes in climate, exceptional precipitation events, and increased water use and waste disposal have impacted water quantity and (or) quality.

Purpose and Scope

The purpose of this report is to provide an updated description of hydrologic conditions and water resources in the upper Rio Hondo Basin. This report provides a conceptual hydrogeologic model and water budget for the upper Rio Hondo Basin and includes an inventory of historical and current water-use patterns. This report also describes the hydrogeologic and structural features that may control the movement of groundwater in the upper Rio Hondo Basin; evaluates the hydrology of the basin and the hydrologic dynamics among precipitation, streams, and groundwater; characterizes the stream and groundwater resources in the basin; and evaluates whether and how changes in climate, precipitation events, and increased demand for water may have affected flow in streams and groundwater levels.

Data used in the report include the available geologic, hydrogeologic, hydrologic, climatic, and water-use data through the end of calendar year 2010. The description of the hydrogeologic and structural features was based on previous work (Mourant, 1963; Kelley, 1971; Rawling, 2004a, 2004b, 2004c, 2006, 2009, 2010a, 2010b; Skotnicki, 2009a, 2009b, 2010; Matherne and others, 2010) conducted on the upper Rio Hondo Basin. Evaluation of the hydrology of the basin was based on the existing hydrologic data and new data collected as part of this study. Details of each dataset are described throughout the report as each topic is reviewed and analyzed.

Understanding of the hydrologic dynamics of the basin was improved through analysis of changes in streamflow and groundwater levels in response to precipitation, which included the drought of 2003, the summer monsoon precipitation events of 2006 and 2008, and the abundant snowmelt runoff of spring 2010. Seepage investigations of parts of the Rio Ruidoso, Rio Bonito, and Eagle Creek were evaluated to understand recharge mechanics and stream-aquifer interaction. A water-level contour map was prepared for the upper Rio Hondo Basin, and water-level change maps were created to show the groundwater system response to stresses over long-term precipitation trends. A conceptual model was prepared, and water-budget estimates were developed for the long-term average conditions. Future water-use scenarios were developed to consider changes in climatic conditions and in water-use patterns.

Location and Setting

The upper Rio Hondo Basin is located in south-central New Mexico, primarily within Lincoln County but also within parts of Otero County and the Mescalero Apache Indian Reservation (referred to as the Mescalero Reservation in this report). The basin contains the Villages of Ruidoso and Capitan and the City of Ruidoso Downs and has a drainage area of 585 mi^2 in the Rio Ruidoso and Rio Bonito Basins (fig. 1). The study area focuses on the upper Rio Hondo Basin, located upstream from the confluence of the Rio Ruidoso and Rio Bonito, where they join to form the Rio Hondo.

Topography and Relief

The study area encompasses the eastern slopes of Sierra Blanca, which is a mountain range within the northern Sacramento Mountains. Drainage in the study area is generally eastward to the Pecos River. The elevation change across the study area is considerable, with the lowest point at the junction of the Rio Ruidoso and Rio Bonito (elevation 5,185 feet [ft]) near the town of Hondo and the highest point at the peak of Sierra Blanca (elevation 12,003 ft). The maximum relief is about 6,800 ft across a distance of 31 miles (mi).

The landscape includes rugged hills and mountains with narrow river valleys. Uplands exhibit deeply dissected mountain topography in the western part of the study area and steep V-shaped valleys falling eastward near the Villages of Ruidoso and Capitan. The southern and southwestern parts of the study area are bordered by the Mescalero Reservation, with rugged mountainous topography at elevations of 8,000 ft and above. The Capitan Mountains border the northern part of the study area and reach a peak elevation of 10,179 ft. From the Capitan Mountains, steep canyons drop south into the valleys of Salado Creek and the Rio Bonito watershed, forming an extensive network of gently sloping alluvial fans on the southern side of the mountains. Between the Capitan Mountains and Sierra Blanca, a pass at about 7,100 ft elevation separates the upper Rio Hondo from the Tularosa Basin to the west, where the town of Nogal is located. The Villages of Ruidoso, Alto, and Angus and the City of Ruidoso Downs lie at the foot of Sierra Blanca. In the eastern part of the study area, where elevations are lower, relief is less pronounced, and flat-topped mesas are drained by incised valleys, host to the communities of Glencoe, Lincoln, San Patricio, and Hondo.

Most of the study area is blanketed by thin veneers of soil with frequent bedrock exposures. Mountain meadows contain humus-rich, fertile soil, and the valleys are filled with deeper deposits of loamy alluvial soils. There are a few remnant terrace deposits in the central and eastern part of the study area, where the deposits form mesas lying well above the current river flood plains (Natural Resources Conservation Service, 2011).

Climate

Changes in elevation, relief, and aspect (the compass orientation of land surface maximum slope with respect to due south) create a varied climate in the upper Rio Hondo Basin. The eastern mesas and valleys with elevations of about 6,000 ft receive precipitation of about 15 inches (in.) or less (National Oceanic and Atmospheric Administration, 2011). On the slopes of Sierra Blanca near 10,000 ft, the average annual precipitation is 40 in., and snow lies to depths of up to several feet from December through April, totaling 14 ft or more in a normal year (Natural Resources Conservation Service, 2010). Net lake evaporation ranges from about 10 inches per year (in/yr) in the highest elevations to about 45 in/yr in the lowest elevations and averages more than 30 in/yr (Pecos Valley Water Users Association, 2001). Snowmelt in the higher elevations generally begins in March or April and is complete by April or May.

Land Use and Vegetation

The majority of land ownership in the upper Rio Hondo Basin is split among private landowners (33 percent), the U.S. Forest Service (30 percent), and the Mescalero Apache Tribe (29 percent), with the remaining land being owned by the Bureau of Land Management and the New Mexico State Land Office (Upper Hondo Watershed Coalition, 2004). Use of the land varies: more than 65 percent is devoted to livestock grazing, and as much as 25 percent is forested. A small percentage of the land area has been used for irrigated farming in the floors of the narrow river valleys and in some mountain meadows since the mid-1800s. The proportion of land used for both urban and recreational purposes has been estimated at 10 to 15 percent (Upper Hondo Watershed Coalition, 2004). The land area designated as “subdivision” or “municipal use” (urban and suburban areas) was estimated at about 9 percent on the basis of geographic information system (GIS) mapping data (Patsy Sanchez, Lincoln County GIS Department, written commun., 2010).

Most of the land cover in the study area is forest, interspersed with grasslands. Piñon-juniper forest dominates the eastern part of the basin, with ponderosa and mixed conifer predominant in the west. The highest elevation areas have high mountain grasslands interspersed with subalpine fir and spruce species. The Rio Ruidoso and Rio Bonito form the two dominant riparian ecosystems. Desert grasses, cacti, and shrubs occupy the far eastern part of the study area in the lowest elevations (Larry Cordova, U.S. Forest Service, written commun., 2014).

Population

Population in Lincoln County has grown markedly in the last four decades, almost tripling from 7,560 in 1970 to 20,497 in 2010 (U.S. Department of Commerce, Bureau of the Census, 1995, 2010). Most of the population growth was focused in the upper Rio Hondo Basin study area, which includes the Villages of Ruidoso and Capitan and the City of Ruidoso Downs (Wilson and Company, Inc., 2004). Permanent full-time residents, however, account for less than half of the population in the Ruidoso area (Wilson and Company, Inc., 2004), which may increase up to 40,000 during special event weekends; therefore, water-use estimates are greatly affected by the substantial number of part-time residents and tourists.

Regional Hydrogeology

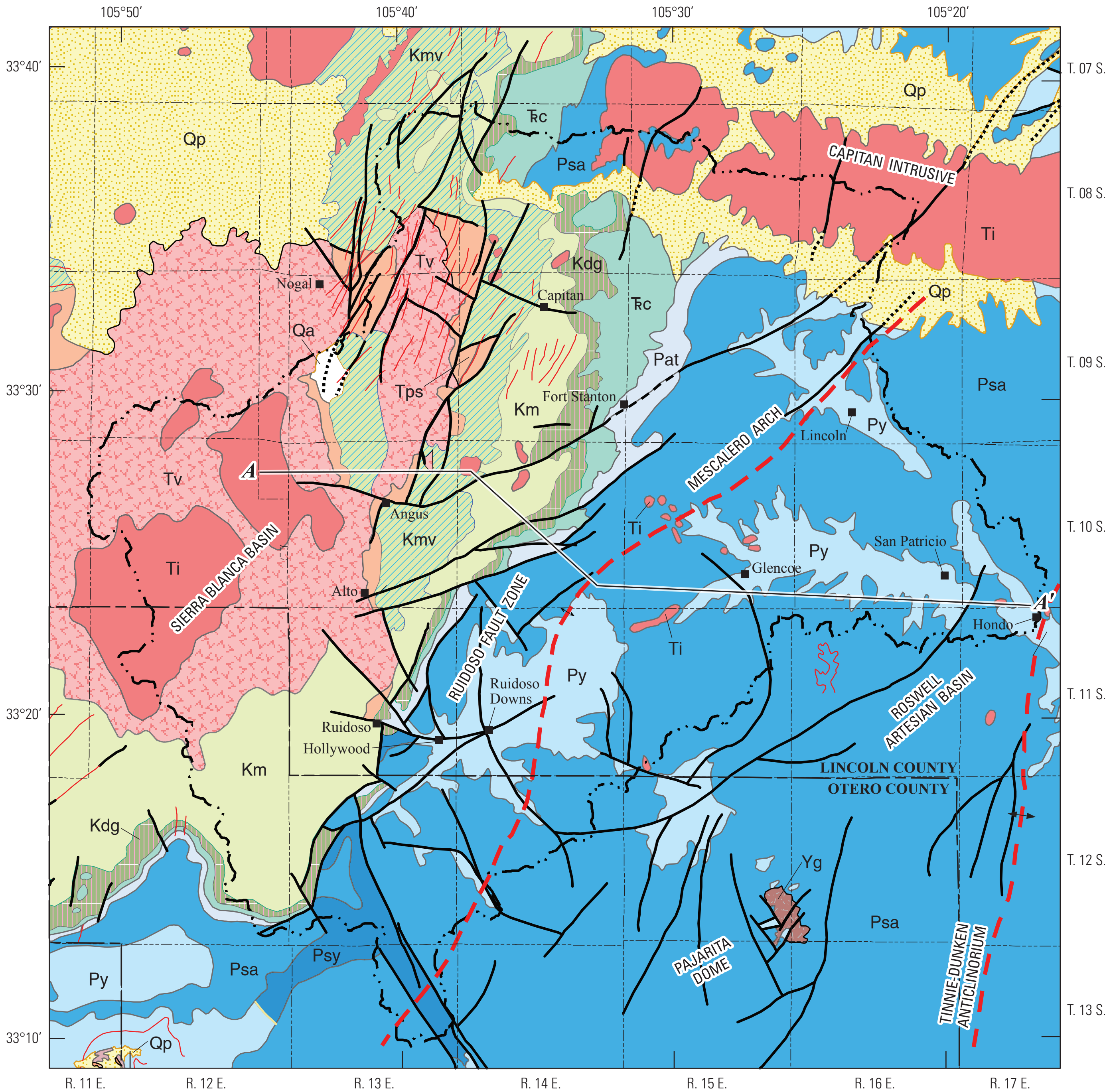
Streams in the upper Rio Hondo Basin generally flow eastward, carrying water from high-elevation areas in the Sacramento and the Capitan Mountains to lower elevations at the Rio Hondo. Most of the tributary streams are intermittent, but many streams are perennial in their upper reaches, such as Little, Magado, Salado, and Carrizo Creeks (Mourant, 1963). The 35-mi long Rio Bonito is largely perennial in its upper reaches but becomes intermittent downstream from the foot of Sierra Blanca and is augmented by springflow near Fort Stanton. The southernmost principal stream is the Rio Ruidoso, which is perennial for most of its 34-mi length. Eagle Creek is a tributary to the Rio Ruidoso and is also largely perennial in its uppermost tributary reaches but becomes intermittent farther downstream. The Rio Ruidoso and Rio Bonito join to create the Rio Hondo at the eastern study area boundary. The Rio Hondo is perennial at its source near the town of Hondo and for at least several miles downstream.

As many as 12 major sedimentary hydrostratigraphic units serve as aquifers, ranging from Permian to Mesozoic through Tertiary in age (fig. 2). Tertiary-age igneous intrusions in the Sacramento and the Capitan Mountains, as well as lava flows and interbedded sedimentary layers in Sierra Blanca, form aquifers as well. The water-bearing properties of the aquifer units in the study area vary widely. Alluvium on the valley floors consists of unconsolidated or loosely consolidated material that serves as a hydraulic connection between groundwater in bedrock and streamflow but can also serve as an aquifer for shallow wells.

The Ruidoso Fault Zone runs from northeast to southwest along the foot of Sierra Blanca (fig. 3) and has extensively fractured the consolidated rock units in the area. Many other faults occur in the study area, particularly along the basin margins. Much of the Permian-age strata contain limestone and gypsum beds, which have been extensively dissolved, improving their water-bearing characteristics.

Geologic age		Geologic map units		Hydrologic characteristics
Cenozoic	Quaternary	Qa	Alluvium	Local aquifers in river valleys and at foot of Capitan Mountains.
		Qp	Piedmont alluvial deposits	
	Tertiary	Ti	Intrusive rocks. Includes basaltic dikes and sills, large instrusive granitic stocks, and scattered laccoliths.	Typically not water bearing, except where heavily fractured.
		Tv	Sierra Blanca Volcanics	Modest to good aquifers in Mountain Block terrane.
		Tps	Cub Mountain Formation	
Mesozoic	Cretaceous	Kmv	Mesaverde Group (shales and sandstones)	Modest to poor aquifers in Central Basin terrane. Sandstone units in Mesaverde Group may form good aquifers in some areas.
		Km	Mancos Shale	
		Kdg	Dakota Group	Modest to good aquifer in Central Basin terrane, typically perched over deeper aquifer system.
	Triassic	TRc	Chinle Formation (shale and mudstone) and Santa Rosa Formation (sandstone), undivided	Sandstone forms modest localized aquifer at foot of Capitan Mountains, perched over regional system.
Paleozoic	Permian	Pat	Artesia Group, Grayburg Formation (fine sandstone, siltstone and gypsum)	Poor aquifer or aquiclude in north part of Central Basin terrane.
		Psa	San Andres Formation (limestone, dolomite, and sandstone)	Major regional aquifer system. San Andres forms a deep aquifer in north part of Central Basin terrane, and localized perched aquifers elsewhere. Yeso forms a moderate to good aquifer in the Hondo Slope terrane and localized perched aquifers elsewhere.
		Py	Yeso Formation (fine sandstone, limestone, dolomite and gypsum)	
		Psy	San Andres and Yeso Formations, undivided	
		Pa	Abo Formation (shale and sand)	Not tested.
Precambrian	Proterozoic	Yg	Precambrian rocks	Not water bearing (hydrologic bedrock) except where heavily fractured.

Figure 2. Diagram showing geologic units in the upper Rio Hondo Basin study area, Lincoln County, New Mexico.



Base from U.S. Geological Survey digital data, 2009, 1:500,000
Universal Transverse Mercator projection, zone 13
North American Datum of 1983 (NAD 83)

0 2.5 5 7.5 10 MILES
0 2.5 5 7.5 10 KILOMETERS

Geology modified from New Mexico Bureau of Geology and Mineral Resources, 2003, Geologic Map of New Mexico, 1:500,000

EXPLANATION

- **Study area boundary**
- **Tertiary dikes**
- **Fault**—Dashed where approximately located. Dotted where concealed
- **Geologic contact**
- *A* *A′* **Geologic section** (shown in figure 4)

Figure 3. Geologic map of the upper Rio Hondo Basin study area, Lincoln County, New Mexico. Explanation of geologic units is given in figure 2. Approximate location of major structural features indicated as discussed in text.

Previous Investigations

Geologic Studies

Regional mapping work by Mourant (1963) and by Kelley (1971) provides the foundation for interpreting the geology in the study area. Detailed geologic mapping of much of the study area was recently completed by Rawling (2004a,b,c, 2006, 2009, 2010a,b) and by Skotnicki (2009a,b, 2010).

Hydrologic Studies

A 1963 joint publication by the New Mexico Office of the State Engineer (NMOSE) and the USGS authored by Mourant (1963) was the first comprehensive analysis of the hydrogeology of the Rio Hondo Basin. Work by Donohoe (2004) provides a reference of available data in the upper Rio Hondo. Sandia National Laboratories (2010) completed a geohydrologic report of part of the study area near Alto that contains water-level and geochemical data. Matherne and others (2010) published a detailed analysis of the hydrogeology of North Fork Eagle Creek. Newton and others (2012) published a geohydrologic study on the southern Sacramento Mountains outside the study area that contains information on the hydrogeology of the upper Rio Hondo Basin.

A detailed source of study area data is the water planning report prepared by the Pecos Valley Water Users Association (2001). Water-use reports have been published by NMOSE every 5 years for the last several decades (Sorenson, 1977, 1982; Wilson, 1986, 1992; Wilson and Lucero, 1997; Wilson and others, 2003; Longworth and others, 2008), and several hydrologic surveys have been conducted by NMOSE over the last century (New Mexico Territorial Engineer, 1909; Lee, 1912, 1916; Follett, 1914; Neel, 1932; Martinez, 1974, 1975).

The records of NMOSE also contain numerous reports for water availability assessments, which often include aquifer test information, modeling work, and other detailed hydrogeologic analyses. Several numerical models have been prepared by consultants to support water-rights applications before NMOSE. Consultant reports for water rights proceedings also provide a publicly available source of hydrologic information. Most recently, Daniel B. Stephens and Associates, Inc. (2000), Peery and Finch (2001), Balleau Groundwater, Inc. (2004a, b), and Romero and Silver (2009) have studied aspects of the hydrogeologic system to address specific water-rights applications.

Hydrogeology, Water Resources, and Water Budget

Geologic Framework

This section of the report provides a description of the rocks that compose the groundwater system in the study area. The geologic structure and its effect on groundwater movement are also discussed. The geologic descriptions are synthesized from findings presented in Kelley and Thompson (1964); Kelley (1971); Allen and Kottlowksi (1981); Rawling (2009); and among others.

Geologic History

A thick sequence of Paleozoic sedimentary rocks of Permian age was deposited atop Precambrian bedrock over large areas of southeastern New Mexico, on a gently sloping shelf of the Permian seas (figs. 2 and 3). Ancient shoreline deposits are preserved on the slopes of Pajarita Mountain just southeast of the study area (fig. 1). Mesozoic (mostly Cretaceous) rocks were also deposited across broad areas of the interior seaway as flat or gently sloping layers. The entire package of sedimentary rocks is several thousand feet thick and for the most part is fairly flat-lying or has a gentle eastward tilt of no more than a few degrees (fig. 4).

Sierra Blanca and the Capitan Mountains are the most prominent geographic features in the study area and were formed by volcanic and igneous activity in Tertiary (Cenozoic) time. Sierra Blanca occupies a structural basin or depression, caused by the weight of the deposited volcanic rocks and the evacuation of the underlying magma chambers by eruption. An associated igneous intrusion occurs at the Capitan Mountains. These volcanic and igneous features form the western and northern geologic and topographic boundaries of the upper Rio Hondo study area (fig. 3). Structural collapse beneath Sierra Blanca caused downdropping of bedrock and overlying strata into the Sierra Blanca Basin. The Ruidoso Fault Zone runs along the foot of the mountain and displaces rocks downward to the west (figs. 3 and 4), with as much as 1,400 ft of throw along its length across some sections of the study area (Kelley and Thompson, 1964). The resulting adjustments created a hingeline in the eastern part of the study area (the Mescalero Arch), where the dip reverses and sedimentary rocks tilt either westward into the Sierra Blanca Basin or eastward into the Roswell Artesian Basin.

Subsequent erosion has carved the landscape. The pediment surface formed by outwash from Sierra Blanca has been dissected and largely removed, leaving a few flat-lying terraces east of the mountain front (fig. 4). The valleys of the Rio Bonito and Rio Ruidoso have been carved from depths of a few hundred feet to as much as 700 ft below the surrounding ridges and are floored with alluvium deposits, which are tens of feet thick.

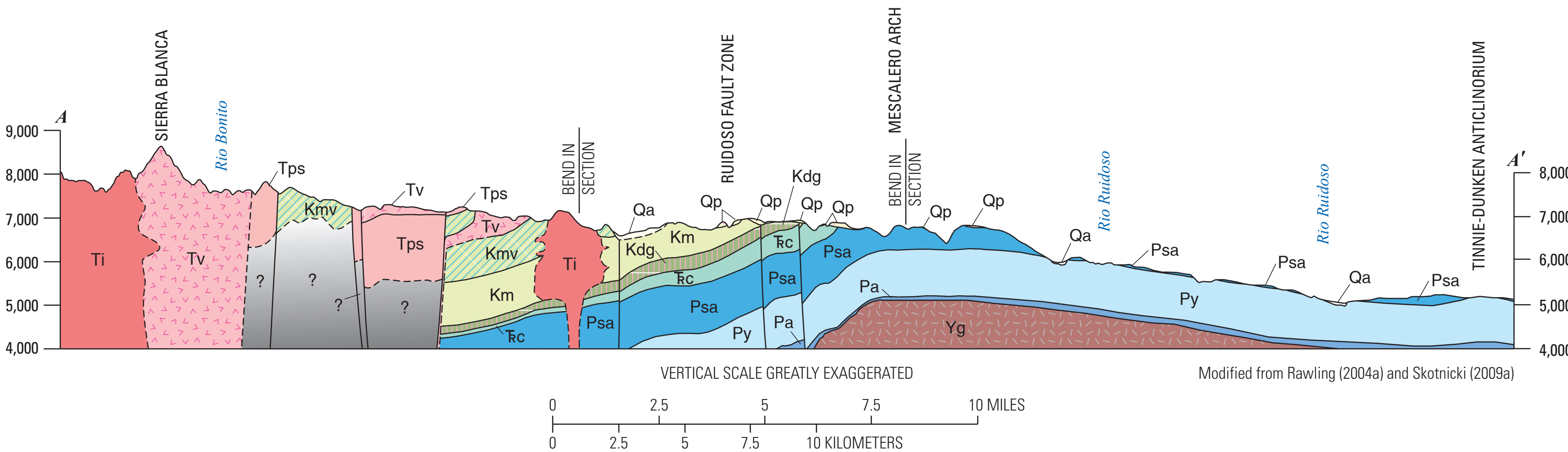


Figure 4. Schematic geologic cross section through the upper Rio Hondo Basin study area, Lincoln County, New Mexico. Explanation of geologic units is given in figure 2. Approximate location of major structural features is indicated in figure 3.

Geologic Units and their Hydrologic Properties

There are 15 distinct geologic units across the study area (fig. 2), each with unique water-bearing properties. The units can be grouped into five broad categories: Precambrian rocks, Permian sedimentary rocks, Triassic sedimentary rocks, Cretaceous rocks, Tertiary sedimentary rocks, and Quaternary alluvium. The stratigraphic column in figure 2 describes general properties of the units and summarizes their water-bearing characteristics. Each unit is described below from oldest to youngest.

Precambrian Rocks

Precambrian rocks are presumed to comprise the hydrologic basement (the lower hydrologic boundary) of the study area. Exposures of granites, gabbros, and syenites occur on Pajarita Mountain just southeast of the study area, where they are onlapped by the Yeso and San Andres Formations' near-shore deposits, which express the coastline of the ancient highlands of the axis of the Pedernal Uplift (Kelley, 1971). About 10 mi southwest of the study area, shoreline deposits in the Abo and Yeso Formations were found atop a Precambrian-age light gray quartzite intruded by granite (Bachman, 1964). At the crest of the Mescalero Arch just southeast of the town of Lincoln, oil test wells have penetrated Precambrian gabbro age-dated at 1.28 billion years (Bowsher, 1991). Facies of the San Andres and Yeso Formations are also found on the Tinnie-Dunken Anticlinorium, indicating that the anticline was active at this time (Bowsher, 1991).

Permian Sedimentary Rocks

Grayburg Formation

The Grayburg Formation is the lowermost member of the Permian-age Artesia Group, is as much as 500 ft thick in the northern part of the study area, and thins southward. It lies unconformably on the San Andres Formation and has filled karst depressions mapped on the Eagle Creek watershed and at another area near Fort Stanton (Rawling, 2006, 2009). The unit is predominantly fine-grained sandstone, with abundant siltstone, gypsum, shale, limestone, and dolomite (Mourant, 1963; Rawling, 2009).

The formation tends to be an aquitard on a regional scale, although it reportedly yields about 5 gallons per minute (gal/min) locally to wells, with poor quality water likely because of gypsum beds (Mourant, 1963). The thicker Grayburg Formation section to the north may create confined conditions near Capitan in underlying formations, reflecting low horizontal hydraulic conductivity (K_h) estimates (0.0001 foot per day [ft/d]) in regional modeling studies (Romero and Silver, 2009).

San Andres Formation

The San Andres Formation of Permian age is one of the most important regional aquifers in the study area and in the State of New Mexico. It consists of about 1,000 ft of gray limestone, dolomite, and thin to massively bedded carbonate mudstones, wackestones, and grainstones (Rawling, 2009).

On a regional scale, a number of mappable members are recognizable—the lower, thick-bedded Rio Bonito Member; a middle sandstone, the Hondo Sandstone Member or the Glorieta Sandstone; and the upper, thin-bedded Bonney Canyon Limestone. These divisions become more distinct in the eastern part of the study area; however, within most of the study area, the San Andres Formation tends to be more homogeneous, having little observable vertical change in bedding thickness or color (Rawling, 2009; Skotnicki, 2009a, b). In the eastern part of the study area, a thin irregular sandstone lens (20 ft thick or less) is typically present in the lower part of the formation (Kelley, 1971), where it forms a fairly consistent marker bed and a local aquifer unit (Mourant, 1963). On a regional scale, the San Andres Formation is capped by the thick gypsum-bearing Fourmile Draw Member (Kelley, 1971). Gypsum beds occur in the deep subsurface in the northern part of the study area near Capitan (Miller and others, 2008; Talbot, 2009) and may represent the uppermost San Andres Formation strata preserved by the northern structural dip, possibly interfingering with the overlying Grayburg Formation.

Outcrops of the San Andres Formation cover much of the eastern half of the study area. The unit has been thinned by dissolution and exhibits karst features, sinkholes, and collapse breccias, particularly where gypsum has been removed from the underlying Yeso Formation. Wells drilled in the formation encounter cavities, enlarged solution fractures, and joints. Caves are common in the San Andres Formation, such as Fort Stanton Cave, which is located northeast of Fort Stanton and has an ephemeral underground stream (Hallinger, 1964).

Wells in the San Andres Formation yield as much as 600 gal/min in the study area (Peery, 2006) and as much as 2,000 gal/min farther to the east, where it is the principal aquifer in the Roswell Artesian Basin (Mourant, 1963). Within the study area, the formation provides water to deep wells along the Ruidoso Fault Zone near Angus, Capitan, and Fort Stanton (Peery and Finch, 2001; Donohoe, 2004; Miller and others, 2008). The San Andres Formation is above the water table in most of the eastern part of the study area, although its basal sandstone may contain perched aquifers (Mourant, 1963). Water quality is moderate to poor, with total dissolved solids (TDS) values reported from 710 milligrams per liter (mg/L) (Peery, 2006) to 2,000 mg/L (Talbot, 2009).

Reported transmissivity (*T*) values can be extremely large (in the tens of thousands of square feet per day), but most are about 5,000 feet squared per day (ft^2/d) or less (Donohoe, 2004; Talbot, 2009). Two wells in the San Andres Formation near Fort Stanton and Capitan were pump tested with *T* values from 67 ft^2/d to 2,670 ft^2/d (Peery, 2006; Sandia National Laboratories, 2010); another San Andres well near the Village of Capitan had an aquifer test with a *T* value of 6,000 ft^2/d (Miller and others, 2008). Modeling study estimates vary widely, with K_h values from 0.02 ft/d to 10 ft/d and specific yield (*SY*) values of 0.01 (Romero and Silver, 2009) to K_h values from10 ft/d to 32 ft/d and *SY* values of 0.10 (Daniel B. Stephens and Associates, Inc., 2000; Finch and others, 2004).

Yeso Formation

The Permian-age Yeso Formation is the principal aquifer in much of the eastern, southern, and south-central parts of the study area, reaching at least 1,300 ft in thickness (Wasiolek, 1991). South of the study area, it is the principal aquifer in most of the northern Sacramento Mountains (Newton and others, 2012). The upper two-thirds of the formation are composed of yellow-to-red sandstone and siltstone interbedded with gray-to-tan silty limestone and dolomite; the lower one-third is mainly composed of gray-to-white gypsum and anhydrite and interbedded siltstone (Skotnicki, 2009a, b). South of the study area, the base of the Yeso Formation is exposed atop Precambrian bedrock on Pajarita Mountain, where it formed shoreline deposits that ring the highlands of the axis of the Pedernal Uplift and Mescalero Arch (Bowsher, 1991; Wasiolek, 1991). There is evidence of upwelling deep warm water possibly of poor quality in the eastern part of the study area from these sandstones (Reiter and Jordan, 1996).

The unit is poorly consolidated, forms slopes and valleys, and exhibits jumbled, chaotic bedding and ubiquitous slump features from the dissolution and collapse of gypsum beds. Fresh exposures of the Yeso Formation are rare but do occur on roadcuts along Highway 70 near Lincoln, where they form an unusual zone of tight folding that is either independent of or detached from overlying, flat slabs of San Andres Formation limestone. This folding has been attributed to slumps or landslides, as well as liquefaction or tectonic activity, which causes deformation of the Yeso Formation beds beneath the San Andres Formation caprock (Craddock, 1964; Foley, 1964; Yuras, 1991). Regardless of the cause, tightly folded sections in the Yeso Formation are believed to have poor water-yielding characteristics, with many dry wells reported along the Tinnie-Dunken Anticlinorium (Mourant, 1963). Locally poor water-yielding characteristics in the zone of folding near Lincoln may be caused by the Yeso Formation bedding planes steeply dipping to vertical, thereby restricting the penetration of a given well to a limited set of stratigraphic units and bedding planes. These steeply tilted bedding planes may also affect groundwater-flow patterns by causing groundwater to flow perpendicular to bedding planes, where low vertical hydraulic conductivity (K_v) values occur relative to high K_h values along bedding planes.

Limestone and dolomite beds with secondary permeability enlarged along joints or fractures appear to produce the majority of water in the Yeso Formation, although individual sandstone beds are also responsible for water production in the Sacramento Mountains (Wasiolek, 1991; Newton and others, 2012). Yields range generally from a few gallons per minute to more than 100 gal/min (Mourant, 1963); however, extremely productive limestone and dolomite beds (more than 1,000 gal/min) have been found in areas with cavernous porosity (Daniel B. Stephens and Associates, Inc., 1995), and active recharge in fractures has been documented in the southern Sacramento Mountains (Walsh, 2008). Values of *T* derived from pump tests of wells in the Yeso Formation were reported at 63 ft^2/d (Sandia National Laboratories, 2010); Wasiolek (1991) reported *T* values ranging from 3.5 ft^2/d to 5,900 ft^2/d in the Yeso Formation on the Mescalero Reservation. Representative K_h values were reported to range from 0.6 to 1.5 ft/d with the highest values in zones with good fracture or solution porosity, whereas zones of unfractured siltstone and gypsum beds exhibited K_h values of about 0.02 ft/d (Wasiolek, 1991). One modeling study estimated the K_h value of the Yeso Formation at 0.02 ft/d and the *SY* value at 0.01 (Romero and Silver, 2009), whereas others used K_h values from 0.8 to 1.0 ft/d and *SY* values of 0.10 (Daniel B. Stephens and Associates, Inc., 2000; Finch and others, 2004).

Abo Formation

A few hundred feet of Permian Abo Formation have been reported beneath the Yeso Formation and atop Precambrian bedrock in parts of the study area. This has been inferred from deep oil test wells on the Mescalero Arch (Skotnicki, 2010), which had a section from 360 to 470 ft thick of red shale and sand (Wasiolek, 1991; Skotnicki, 2010). The unit has not been tested for hydraulic properties, and it has not been included in modeling studies to date.

Triassic Sedimentary Rocks

Chinle Formation and Santa Rosa Formation

Triassic-age rocks crop out in a narrow band in the northern part of the study area near the Capitan Mountains but are progressively stripped off by erosion towards the south near Fort Stanton and are completely removed south of Ruidoso (fig. 3). The latest Triassic-age unit is the Chinle Formation, which comprises several hundred feet of reddish-brown mudstone with clay and sand lenses. At the base of the Triassic section is the Santa Rosa Formation, which consists of about 150 ft of dark red sandstone, siltstone, and conglomerate, with interbedded mudstone.

The Chinle Formation is a confining unit, or aquitard, near the Capitan Mountains, and sandstone beds in the Santa Rosa are a potential aquifer. Mourant (1963) reported that Triassic rocks form a local perched aquifer and yield from 5 to 10 gal/min to livestock and domestic wells near Capitan. The Chinle and Santa Rosa Formations have not been modeled as distinct units, but in one study they were grouped with the overlying Dakota Sandstone (Romero and Silver, 2009).

Cretaceous Rocks

Mesaverde Group

The Mesaverde Group is composed of as much as 1,500 ft of shales and sandstones of late Cretaceous age. Like the other Cretaceous units in the study area, it crops out only in the western half of the study area at the edge of the Sierra Blanca Basin. The shale layers tend to be black in color and commonly contain plant fossils, whereas the conglomerates may contain iron concretions. The sandstones tend to be yellow to orange in color and occur in thick, crossbedded layers and may be loosely consolidated. Bodine (1956) stated that the middle section of the Mesaverde Group is predominantly shale, whereas the upper and lower sections are predominantly sandstone.

Mourant (1963) reported that the Mesaverde Group yields from 5 to 20 gal/min of poor quality water to local domestic and livestock wells, citing coal and shale as likely causes of poor quality water. Donohoe (2004) reported T values from 47 to 344 ft^2/d and K_h values from 0.39 to 3.44 ft/d, whereas modeling studies (Romero and Silver, 2009) estimated K_h at 0.06 ft/d and SY at 0.01. Sandia National Laboratories (2010) reported aquifer test T values from 24 to 39 ft^2/d for two wells completed in the Mesaverde Group and a T value of 3,841 ft^2/d or higher for a third well.

Mancos Shale

The Mancos Shale of Cretaceous age is composed of 400 to 1,000 ft of predominantly black-to- dark gray fissile shale (Mourant, 1963; Rawling, 2009). Thin (one to several feet) beds of limestone, siltstone, and sandstone are common. In the northern part of the study area, gray limestone makes up more than half of the unit. Dikes and sills are common in the Mancos Shale, and it is heavily fractured along the Ruidoso Fault Zone.

The Mancos Shale yields groundwater to many area wells, producing from 6 to 75 gal/min (Mourant, 1963), with the best yield where fractured. Near Alto, the Mancos Shale exhibits T values ranging from about 10 to 250 ft^2/d (Donohoe, 2004); however, Sloan and Garber (1971) reported that the Mancos Shale does not yield water on Mescalero Reservation land in the southern part of the study area. Water from the Mancos Shale has some of the highest concentrations of TDS in the upper Rio Hondo Basin, with groundwater in some wells containing concentrations of more than 3,000 mg/L (Mourant, 1963; Sandia National Laboratories, 2010). Poor water quality in the Mancos Shale has also been noted in other areas of New Mexico (Titus, 1980). Regional modeling studies (Romero and Silver, 2009) estimated K_h at 0.04 ft/d and SY at 0.01 for the Mancos Shale.

Dakota Group

The Dakota Sandstone of Cretaceous age consists of as much as 300 ft of sandstone and is a regional aquifer in many areas of the State of New Mexico. The unit is gray to tan to purple and contains thin interbeds of shale and chert pebble conglomerate (Rawling, 2009). It has a gradational contact with the overlying Mancos Shale and a sharp unconformable erosional contact with the underlying units. Outcrops of the Dakota Sandstone form prominent cliffs and ledges marking the eastern edge of the Sierra Blanca Basin and trending northeast from Ruidoso to Fort Stanton.

The Dakota Sandstone yields more than 100 gal/min to wells near fault zones and as little as 5 gal/min where it is not fractured (Mourant, 1963; Newcomer and Shomaker, 1991). A number of wells near Alto are completed in the Dakota Sandstone and the overlying Mancos Shale and exhibit T values from 125 to 3,250 ft^2/d and K_h values from 0.20 to 5.28 ft/d. Modeling studies (Romero and Silver, 2009), however, have estimated K_h at 0.10 ft/d and SY at 0.01.

Tertiary Sedimentary Rocks

Intrusive Rocks

The Capitan intrusive is a stock or laccolith of Tertiary age, which has a uniform medium-to-fine texture (microgranite or syenite) across its length and is roughly 21 mi long by 4 mi wide (Kelley, 1971). Intrusive rocks also crop out over tens of square miles on the crest of Sierra Blanca and include two separate stocks of syenite composition (Thompson, 1973). The intrusive rocks are dense and effectively impermeable, except where fractured or jointed. Mourant (1963) pointed out that few wells obtain water from this material.

Diabase dikes and sills are common throughout the study area and tend to be mafic (andesite to basalt) in composition (Kelley, 1971). These small intrusive bodies typically have baked zones extending a few inches into the host rock and may exert strong control on local groundwater occurrence, either enhancing or restricting flow. Many sills have intruded between Permian units (such as the Yeso and San Andres Formations) along contact zones (Mourant, 1963). Sills as much as 300 ft thick have been mapped as laccoliths (Rawling, 2006, 2009), occurring as isolated intrusions of diorite composition north of Fort Stanton. Dikes are common throughout the area and increase in intensity westward towards the igneous bodies, especially in the northwest near Indian Divide (Kelley, 1971). Dikes in the swarm area have substantially replaced and altered the host rocks, mainly shaley intervals in the Mesaverde Group and Cub Mountain Formations. Groundwater from wells completed in these dikes, sills, and laccoliths had concentrations of TDS as much as 4,300 mg/L, the highest in the study area (Sandia National Laboratories, 2010).

One regional modeling study assumed a K_h value from 0.02 to 3.2 ft/d for the intrusive rocks of Capitan Peak (Daniel B. Stephens and Associates, Inc., 2000). Because measured values of K_v for intrusive rocks are not available, some modeling studies have assumed that K_h and K_v are equal (Romero and Silver, 2009), whereas others have assumed that K_h is greater by two to three orders of magnitude (Daniel B. Stephens and Associates, Inc., 2000).

Sierra Blanca Volcanics

Massively bedded lava flows, tuffs, and breccias make up the Sierra Blanca Volcanics of Tertiary age, which are exposed over most of the upper Sacramento Mountains and reach a maximum thickness of 3,340 ft (Thompson, 1973). Volcanic materials include 35 distinct, recognizable flow units, described as alternating layers of gray to dark green andesite, trachyte porphyry, and breccia, which are densely intruded by dikes and sills in many areas. Locally derived volcaniclastic materials are interbedded with the volcanic units (Matherne and others, 2010).

Estimates of the hydraulic properties of the volcanic rocks vary greatly and may be influenced by stratigraphy and fracturing. Recent modeling studies provide *SY* estimates for the Sierra Blanca volcanic unit of about 0.01 and K_h estimates of 0.03 ft/d or less (Peery and Finch, 2001; Romero and Silver, 2009). Donohoe (2004) reported aquifer-test-derived *T* values from 6 to 2,900 ft^2/d for aquifer tests in Tertiary units near Ruidoso, whereas Newcomer and Shomaker (1991) reported a *T* value of 427 ft^2/d for the area near Eagle Creek. Aquifer testing near the North Fork well field yielded *T* estimates from 1,440 to 8,300 ft^2/d (Finch and others, 2004) in the Sierra Blanca Volcanics. Aquifer testing in a 2,000-ft well near Ruidoso (Miller and others, 2007) found a *T* of 200 ft^2/d over a saturated interval of about 2,200 ft, or an average K_h of about 0.1 ft/d for the entire saturated thickness. Borehole temperature logging indicated a fairly flat geothermal gradient with a sharp rise at about 2,000 ft, suggesting that the active zone of aquifer recharge and circulation reaches this depth, providing an estimated effective saturated thickness of the Sierra Blanca volcanic unit at this location (Miller and others, 2007.

Drilling logs from wells in the Eagle Creek Basin completed in the Sierra Blanca Volcanics show yields in excess of 500 gal/min and extensive fracturing and oxidation at depths of approximately 300–500 ft (Matherne and others, 2010). Rapid response to storm events and nearby pumping noted in hydrographs (water-level time-series plots) from these wells imply that fracturing at depth in the Sierra Blanca Volcanics is locally well connected to surface-water resources and may be stratigraphically controlled.

Cub Mountain Formation

A thick sequence of continental clastic materials was deposited during the early stages of the formation of the Sierra Blanca Basin and has been termed the Cub Mountain Formation of Tertiary age (Rawling, 2009). The upper part of the formation consists of sandstone and siltstone, red to maroon in color, with occasional conglomerate lenses. The middle and lower parts of the formation consist of massive white to buff sandstone with red-to-maroon shale interbeds (Finch and others, 2004). The estimated thickness of the unit is 500–1,500 ft in the study area (Thompson, 1973; Rawling, 2009); the unit thickens to more than 2,200 ft to the west (Mourant, 1963). The formation tends to be poorly consolidated and has been pervasively intruded by dikes and sills throughout most of the study area. The Cub Mountain Formation yields from 5 to 50 gal/min to area wells (Mourant, 1963). Modeling studies estimate the K_h of the unit at 0.1 ft/d and the *SY* at 0.15 (Romero and Silver, 2009).

Quaternary Alluvium

Unconsolidated material of Quaternary age has accumulated in the main stream valleys as river alluvium, terrace deposits, and pediment gravels. Valley-fill deposits are reportedly as much as 40 ft thick in the western part of the study area (Rawling, 2009) and probably exceed 100 ft on the valley floor of the Rio Hondo (Skotnicki, 2009a, b).

At least three distinct terrace deposits are mappable on the Rio Ruidoso, the Rio Bonito, and Eagle Creek, inset above modern river valleys at heights as much as 50 ft above present stream grade. These deposits include perched meanders at similar heights above modern base level (Skotnicki, 2009a, b). Pediment gravels may be as much as 200 ft thick beneath mesas where remnants of these formerly extensive, flat-lying strata are preserved.

Alluvium is saturated on the valley floors in much of the study area, where it consists of unconsolidated to weakly consolidated silts, sands, gravels, clays, cobbles, and boulders. Yields range from as little as 10 gal/min to more than 100 or even 1,000 gal/min (Mourant, 1963), but the higher yields probably occur in wells open to various bedrock formations in addition to alluvium. Coarse boulder alluvium in North Fork Eagle Creek was estimated at 20 ft thick with a K_h from 500 to 1,000 ft/d (Matherne and others, 2010). On the basis of regional modeling studies, estimates of *SY* may range from 0.05 to 0.15, K_h may range from 5 to 20 ft/d, and K_v may be as little as one-fourth the horizontal (Peery and Finch, 2001; Romero and Silver, 2009).

Alluvial fans at the base of the Capitan Mountains have coalesced to form an apron ringing the mountain periphery, extending 1 to 4 mi outward. Some of the individual boulders contained in the alluvial fans are as much as 25 ft in diameter (Kelley, 1971). The thickness of the alluvial fan material exceeds 60 ft, where it forms a shallow aquifer on the southern flank of the Capitan Mountains.

Geologic Structure

The dominant tectonic features of the study area landscape are the sharply uplifted block of the Sacramento Mountains, the gentle structural low of the Roswell Artesian Basin, and the deep depression of the Sierra Blanca Basin. The Sacramento Mountains are formed by a large, east-tilted fault block, which was tectonically raised in the early Tertiary period, between the Rio Grande and Pecos River of New Mexico (fig. 1). This uplift is roughly coincident with the ancient axis of the Pedernal Uplift, which was a structurally high area during the late Paleozoic period (Kelly and Thompson, 1964). Exposures of Precambrian bedrock near the axis of the Pedernal Uplift occur south of the study area, where onlapping sedimentary deposits in the Permian-age Abo and Yeso Formations contain local coastline deposits (Bachman, 1964; Kelley, 1971).

A hingeline (the Mescalero Arch) formed in the eastern part of the study area, where rock layers reversed their gentle regional eastward dip and began to dip steeply westward into the Sierra Blanca Basin. The Mescalero Arch has been offset by numerous faults and contains a series of domes or noses that are progressively lower to the north, reflecting the plunge of an anticlinal structure. Shallow Precambrian bedrock has been confirmed in a number of borings across the arch. Erosion has thinned Permian rocks over the arch and removed Mesozoic rocks altogether. Mapping of Precambrian basement rock elevation (Kelley and Thompson, 1964) has shown that the crest of the Mescalero Arch extends across the center of the study area in a southwest to northeast direction, from the City of Ruidoso Downs to the community of Lincoln (fig. 3). The northern plunge of the Mescalero Arch has tilted the overlying sedimentary rocks and is reflected by thick sections of Permian Grayburg Formation and Triassic rocks in the north near Capitan, creating an important difference in the potential bedrock aquifers between the southern and northern parts of the study area.

The Ruidoso Fault Zone (fig. 3) is an extensive series of normal faults that trend north-northeast, forming the eastern margin of the Sierra Blanca Basin and creating a belt of highly fractured rocks in the west-central part of the study area. The throw in the fault zone is as much as 1,400 ft near Magado Creek in the northwestern part of the study area. The geologic structure of the study area is complex, with numerous normal faults oriented parallel or subparallel to the regional bedrock strike with fault traces trending approximately N. 20º E. (fig. 3). Cross-strike longitudinal and oblique faults also occur with traces between approximately N. 60º W. and N. 65º E. and include reaches paralleling the drainages of the Rio Bonito, the Rio Ruidoso, and Eagle Creek (Rawling, 2009). A fault on the southern margin of the Capitan Mountains extends westward and wraps around the northwestern basin margin, then turns south and joins the Ruidoso Fault Zone (Rawling, 2010b). Local faulting and fracturing are extensive and complex and are thought to affect groundwater availability in the study area (Newcomer and Shomaker, 1991).

Hydrology

This section of the report provides a summary and analysis of precipitation, surface water, and groundwater data in the study area. Estimates of mean annual precipitation, of the distribution of precipitation over the study area, and of the variability of precipitation over time are provided. Streamgage information is discussed with respect to data availability and the characteristics of each of the major watersheds in the study area. Basic data on surface-water bodies and springs in the study area are also provided. A regional water-table map developed for this study is presented. Historical water-level changes are analyzed by using hydrographs and areal mapping. Finally, evidence is presented for short-term water-level fluctuations resulting from periodic recharge and drought events.

Precipitation

Current and historical precipitation data-collection stations are shown in figure 5 and listed in table 1. As of 2010, there are three active precipitation stations in the upper Rio Hondo Basin operated by the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA) and located near Capitan, Hondo, and Ruidoso. The National Resource Conservation Service (NRCS) operates a snow course and a SNOwpack TELemetry (SNOTEL) site at an elevation of 10,280 ft, about 2 mi northeast of Sierra Blanca. Snow depth and snow water equivalent have been measured routinely on or about the first days of February, March, and April from 1986 through 2010 at the snow course; precipitation has routinely been measured hourly and compiled by month since October 2002. Mean annual precipitation data, elevation data, and other basic data are provided for selected stations in table 1.

A fourth active precipitation station, located outside the study area boundary, is operated by NOAA at Picacho, N. Mex., on the Rio Hondo about 7 mi downstream from the confluence of the Rio Bonito and the Rio Ruidoso. Data were also obtained from published sources for several historical precipitation stations located at Fort Stanton, Bonito Dam, and Nogal Lake (Powell, 1954). Data as early as 1856 are available from the Fort Stanton station.

Mean Annual Precipitation

The Parameter-elevation Regressions on Independent Slopes Model (PRISM) was used to obtain a dataset of the mean annual precipitation for each calendar year gridded on 4-kilometer centers and mean annual precipitation estimates at point locations corresponding to key precipitation stations of the NOAA or National Weather Service. These data were extracted from the National PRISM database (PRISM Climate Group, 2010a) for the climatological normal period of 1971–2000 as well as for the historical period of 1895–2010. The analytical PRISM model accounts for complex variations in climate that occur in mountainous regions (Daly and others, 2002) and includes a digital elevation model (DEM) to account for the orographic effect from seasonal storm tracks and the aspect. For the western United States, Daly and others (1994) optimized PRISM by using a jackknife cross-validation statistical method to address precipitation estimate uncertainty. At the 95-percent prediction interval, the potential precipitation estimate uncertainty for any given location may be as much as 16 percent (Daly and others, 1994).

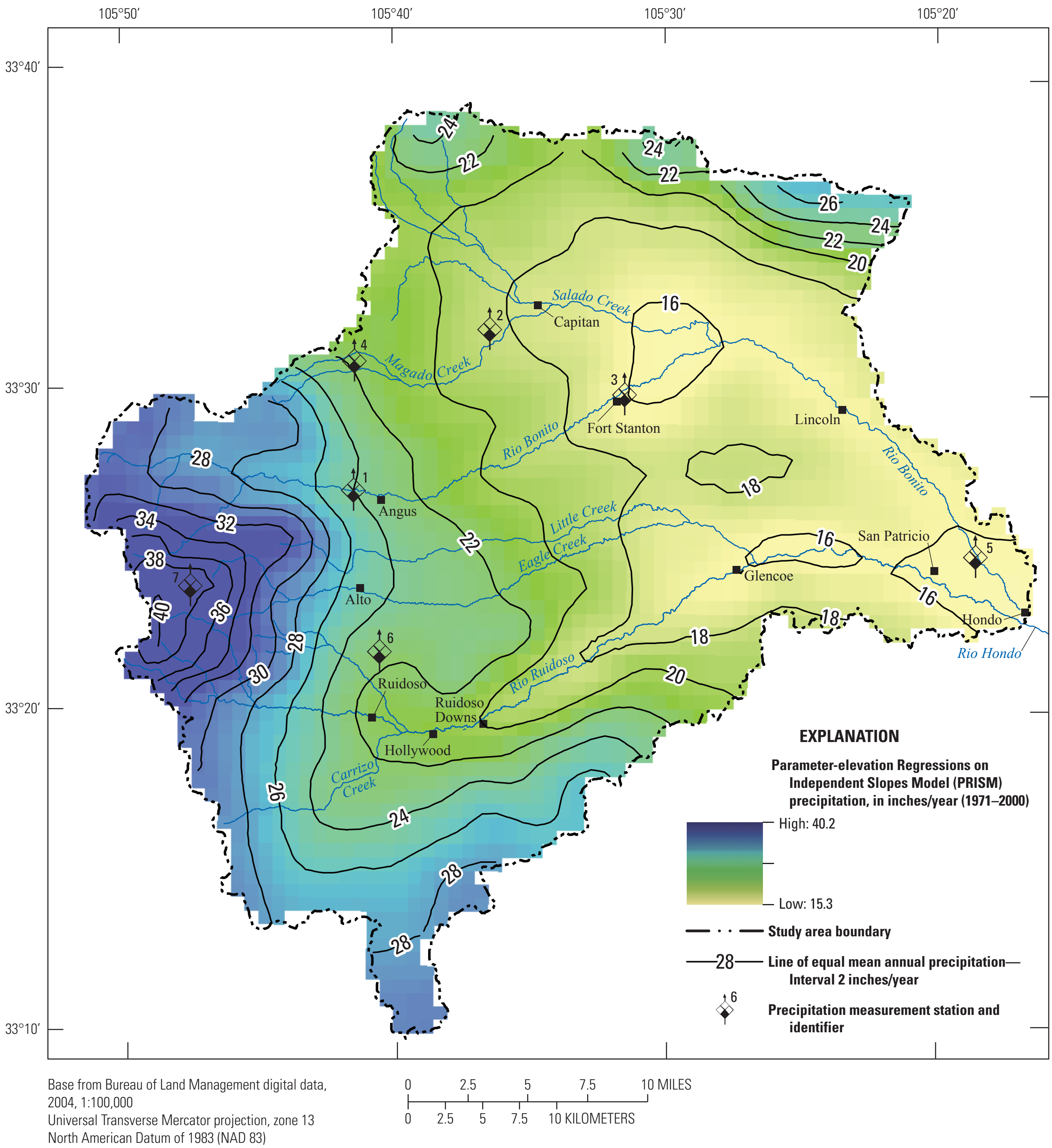


Figure 5. Current and historical precipitation data-collection stations and mean annual precipitation (1971–2000) in the upper Rio Hondo Basin study area, Lincoln County, New Mexico.

Table 1. Precipitation station information in the upper Rio Hondo Basin study area, Lincoln County, New Mexico.

[Latitude and longitude given in decimal degrees. NCDC refers to National Climatic Data Center, NRCS refers to National Resource Conservation Service. Data provided for calendar year through 2010]

Map number	Name	Elevation (feet)	Latitude	Longitude	Dates of record	Data source	Mean annual precipitation (inches)
1	Bonito Dam	7,055	33° 27′	105° 41′	1911–53	Powell (1954)	23.4
2	Capitan	6,480	33° 32′	105° 36′	1910–present	Powell (1954), NCDC (2010)	16.5
3	Fort Stanton	6,224	33° 30′	105° 31′	1856–1974	Powell (1954), NCDC (2010)	15.1
4	Nogal Lake	7,116	33° 31′	105° 41′	1947–70	Powell (1954)	26.6
5	Hondo	5,300	33° 25′	105° 18′	1947–present	NCDC (2010)	13.8
6	Ruidoso	6,930	33° 22′	105° 40′	1942–present	NCDC (2010)	22.2
7	Sierra Blanca	10,280	33° 24′	105° 47′	2002–present	NRCS (2010)	39.0

Figure 5 is a map of mean annual precipitation in the study area for the climatological normal period of 1971–2000, as interpolated from the gridded PRISM data. The mean annual precipitation ranges from about 15 to 40 in/yr, decreasing from west to east as elevation declines across the study area. Summing the grid blocks in figure 5 results in a mean annual precipitation of about 595,000 acre-feet per year (acre-ft/yr), or 19 in. across the entire upper Rio Hondo Basin.

Other factors besides elevation affect the amount of precipitation, as shown by comparing the data from the Ruidoso station (elevation 6,930 ft with 22.2 in. of precipitation annually) with the Capitan station (elevation 6,480 ft with 16.5 in. of precipitation annually). These variations may be caused by differences in the average elevation, by differences in aspect, and (or) by orographic effects relative to winter and summer storm tracks.

Variations between the Rio Ruidoso and Rio Bonito watersheds may also be important. The mean annual precipitation, calculated using PRISM data, totals about 283,000 acre-ft/yr for the 296-mi^2 Rio Bonito watershed and about 312,000 acre-ft/yr for the 289-mi^2 Rio Ruidoso watershed. Even though the two watersheds are almost the same size, the Rio Ruidoso receives greater mean annual precipitation.

Precipitation Patterns over Time

Most of the year's precipitation falls during the summer months as monsoon storms from July to September. At the Capitan station, this amounts to about 76 percent of the mean annual precipitation (fig. 6). Moisture from the Gulf of Mexico and the Gulf of California is drawn into the area during this time. Infrequent tropical depressions, tropical storms, and hurricanes can add a substantial amount of rain in late summer. Torrential rains often result from the passage of summer monsoon and tropical storms across the study area; for example, more than 13 in. of rain fell in the mountainous areas near Ruidoso from the remnants of Hurricane Dolly between July 26 and July 27, 2008, causing widespread flooding (Matherne and others, 2010).

During winter, broad frontal storms provide the upper Rio Hondo Basin with rain and snow. Winter season precipitation contributes a smaller proportion of the total annual precipitation (about 24 percent at the Capitan station; fig. 6). Snowmelt runoff in the spring months sustains streamflow in numerous drainages from the mountainous highlands; however, streamflow becomes ephemeral and dries up by late spring. Snow-water equivalent (SWE), or the water content of the existing snowpack, is the amount of water that would result from melting of the snowpack. At the Sierra Blanca station, SWE typically reaches its maximum in March through April (Natural Resources Conservation Service, 2010). The highest recorded SWE at this station for the period of record (2002–10) was 29.4 in. from March 24 to April 1, 2009. SWE data indicate that snowpack generally begins to melt in March or April and typically finishes by late April or early May.

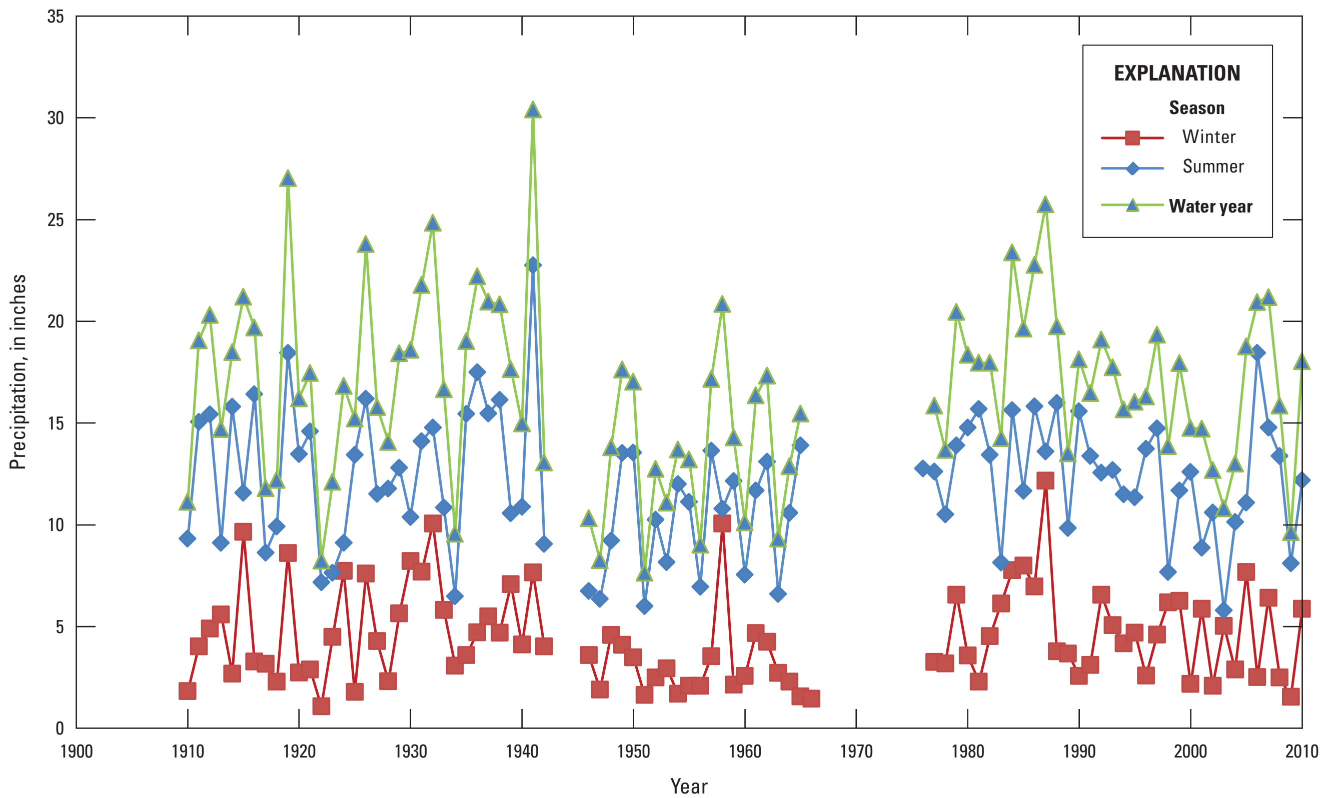


Figure 6. Seasonal and annual precipitation at the Capitan precipitation station, upper Rio Hondo Basin study area, Lincoln County, New Mexico.

Variations in mean annual precipitation are pronounced in the upper Rio Hondo Basin, as they are in much of the Southwestern United States. Figure 7 is a graph of mean annual precipitation over the period of record for key locations in the study area and includes the PRISM data since 1895 for each location to fill in the data gaps in the observed precipitation. The difference between consecutive years can exceed 10 in. in the lower-elevation areas and 20 in. in the higher-elevation areas. This difference between years amounts to variations of 50 percent or more in the amount of annual precipitation received and consequently results in large annual variations in streamflow and groundwater recharge. The data in figure 7 show that this high degree of variability extends throughout the period of record.

Moreover, figure 7 shows 2-year and 5-year moving averages of mean annual precipitation at the Sierra Blanca station. The drought of the late 1940s to mid-1950s is apparent, as is the drought of the early 2000s (fig. 7). Periods of higher rainfall culminated in 1941 and in the mid-1980s. PRISM data do not extend prior to 1895, but historical precipitation data from Fort Stanton suggest higher precipitation in the 1850s and lower precipitation lasting through the 1890s to 1901 (fig. 7). Tree-ring climate reconstructions also show substantial precipitation variations over the last 1,300 years in southern New Mexico (Grissino-Mayer and others, 1997).

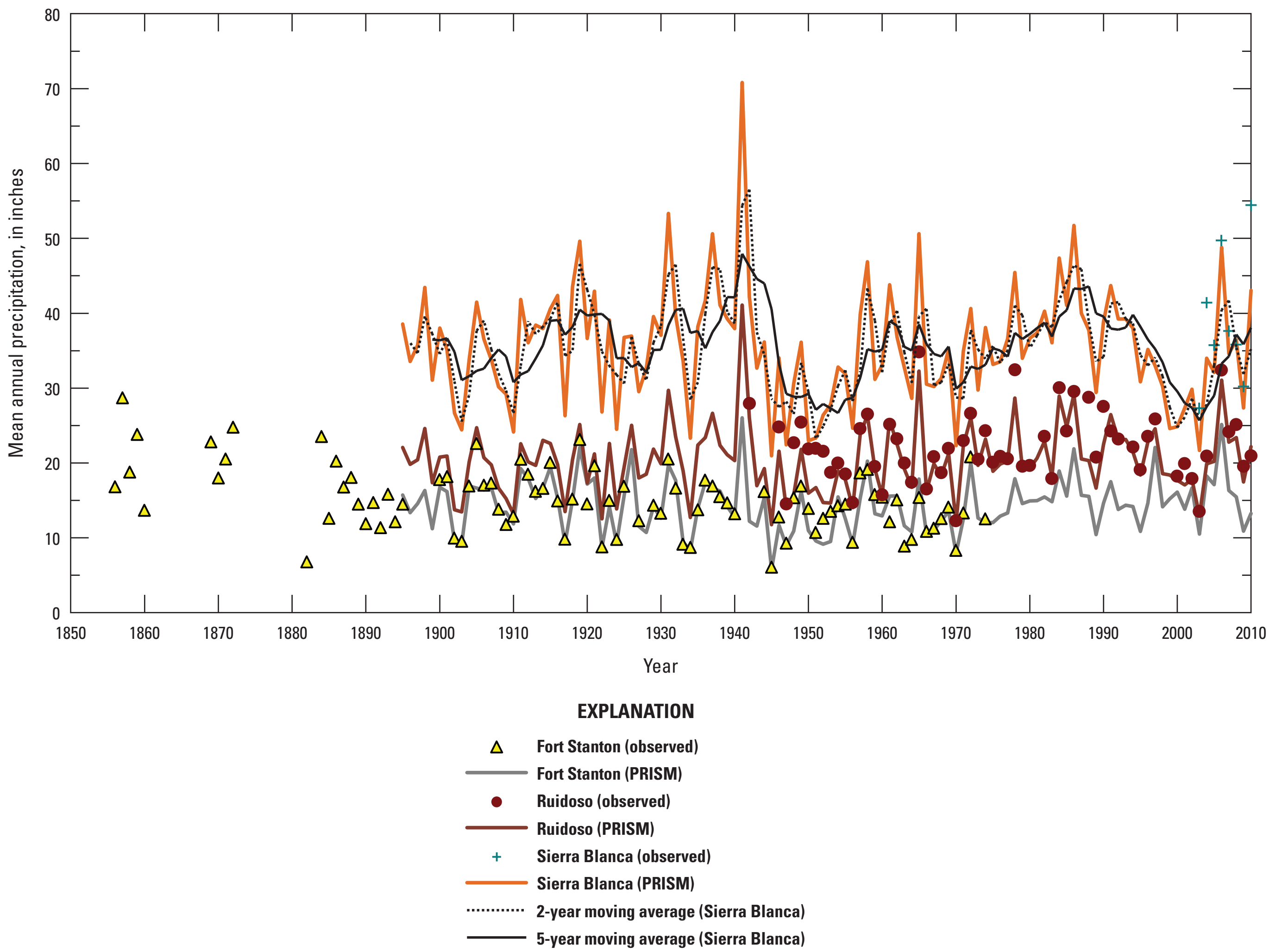


Figure 7. Historical mean annual precipitation for key stations in the upper Rio Hondo Basin study area, Lincoln County, New Mexico.

The Standardized Precipitation Index (SPI) method is a common way to measure drought and is a probability index that considers only precipitation at a given time scale (McKee and others, 1993). Using the SPI method, raw observations of precipitation are transformed or standardized to follow a normal distribution and a single numeric value, equivalent to the number of standard deviations that the observed data fall from the long-term mean. The SPI can be calculated on a variety of time scales, typically between 3 to 60 months, to illustrate short- and long-term variability and cycles in mean annual precipitation. For the upper Rio Hondo Basin, 24-month (2-year) and 60-month (5-year) time periods were used to calculate SPI values from the monthly precipitation data collected at the Capitan and Ruidoso precipitation stations from 1932 to 2010 (fig. 8). There are some gaps between the points which indicate time periods when no data were collected at one or the other site, but by combining the two graphs, a climate synthesis is formed. In general, the SPI results indicate an above-average SPI (wet conditions) in the early 1940s, a below-average SPI (dry conditions) in the mid-1950s to the early 1960s, and an above-average SPI (wet conditions) throughout the 1980s. The drought of the early to mid-2000s and the wet years experienced in 2006 and 2008 are evident in figure 8.

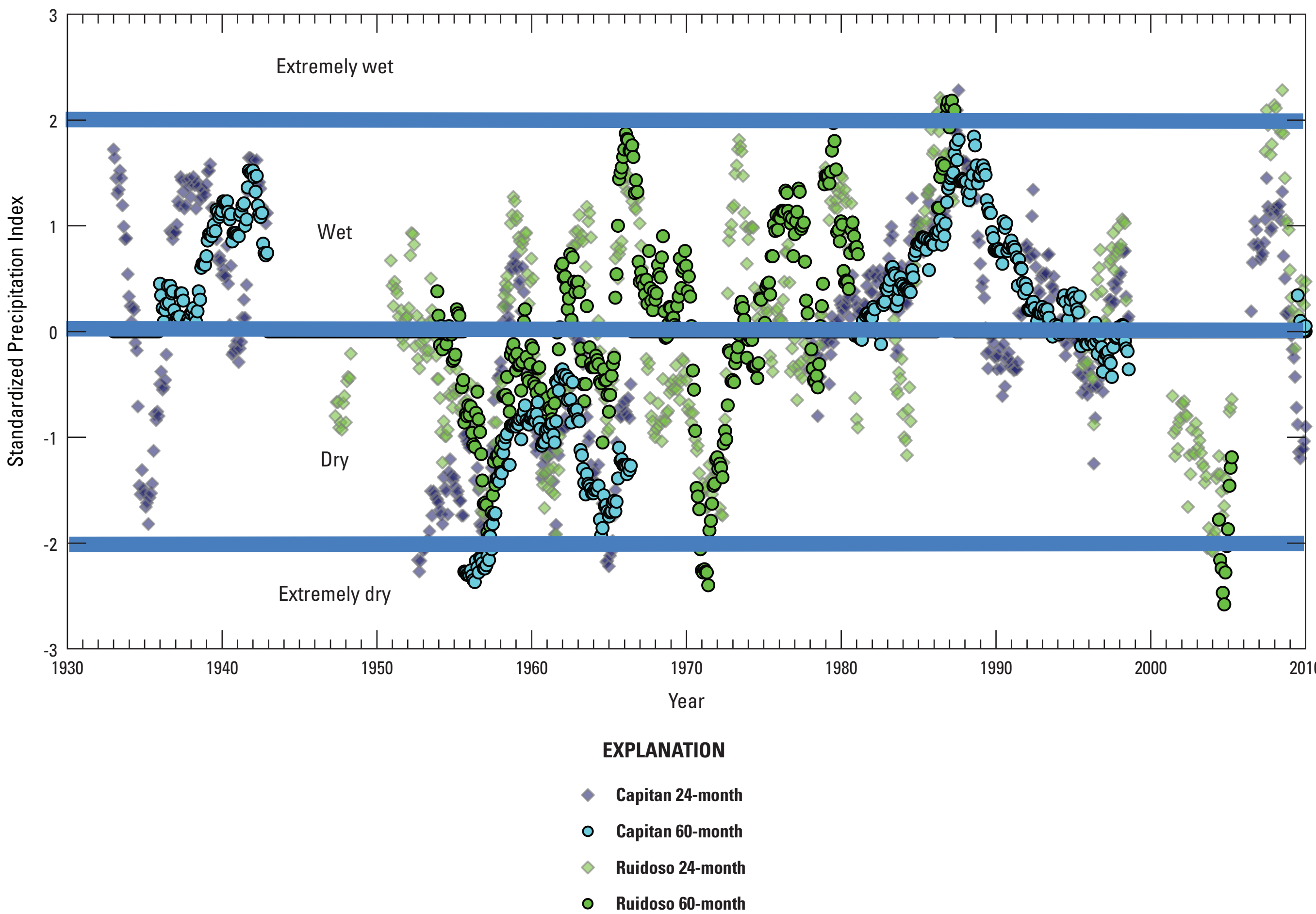


Figure 8. Standardized Precipitation Index of 24 and 60 months for the Capitan and Ruidoso precipitation stations, upper Rio Hondo Basin study area, Lincoln County, New Mexico.

The 2006 and 2008 monsoon seasons were anomalously wet. The 2006 monsoon season included almost 10 in. of rain measured at the Ruidoso station in the month of August. It is noteworthy that the monthly precipitation totals at the Capitan station in July 2006 and August 2008 were 7.15 and 7.62 in., respectively, and were only exceeded in its 102-year historical record by a 10.72-in. monthly precipitation total in September 1941 (National Climatic Data Center, 2010). The anomalous monsoon seasons are corroborated by data from the southern Sacramento Mountains, for which the two wettest months in the historical record both occurred in the 2006 and 2008 monsoon seasons (Talon Newton, New Mexico Bureau of Geology and Mineral Resources, oral commun., 2011). From July 26 to July 27, 2008, the remnants of Hurricane Dolly passed over the study area, generating a total rainfall of 13.1 in. at the Sierra Blanca precipitation station (Matherne and others, 2010) and causing widespread flooding.

Unusually wet conditions also occurred in the winter of 2009–10 and in the spring of 2010 snowmelt. In the upper Rio Hondo, measured precipitation at the Sierra Blanca SNOTEL station was 54 in. in 2010 (Natural Resources Conservation Service, 2010), well above the period of record average of 39 in. (fig. 7).

Surface Water

The watersheds and streams of the upper Rio Hondo study area are shown in figure 9. Also shown are the locations of USGS streamflow-gaging stations that provide modern and historical streamflow data—10 within the upper Rio Hondo Basin study area (4 on Eagle Creek, 4 on the Rio Ruidoso and adjoining ditches, and 2 on the Rio Bonito) and 2 downstream from the study area boundary on the Rio Hondo (fig. 9). A graph showing the mean annual streamflow (by water year) for key stations appears in figure 10, and basic information on these streamflow-gaging stations is summarized in table 2. Streamflow data for USGS streamflow-gaging stations are available in the USGS National Water Information System database (U.S. Geological Survey, 2010).

Figure 9. Subwatersheds and streamflow-gaging stations in the upper Rio Hondo Basin study area and on the Rio Hondo, Lincoln County, New Mexico.

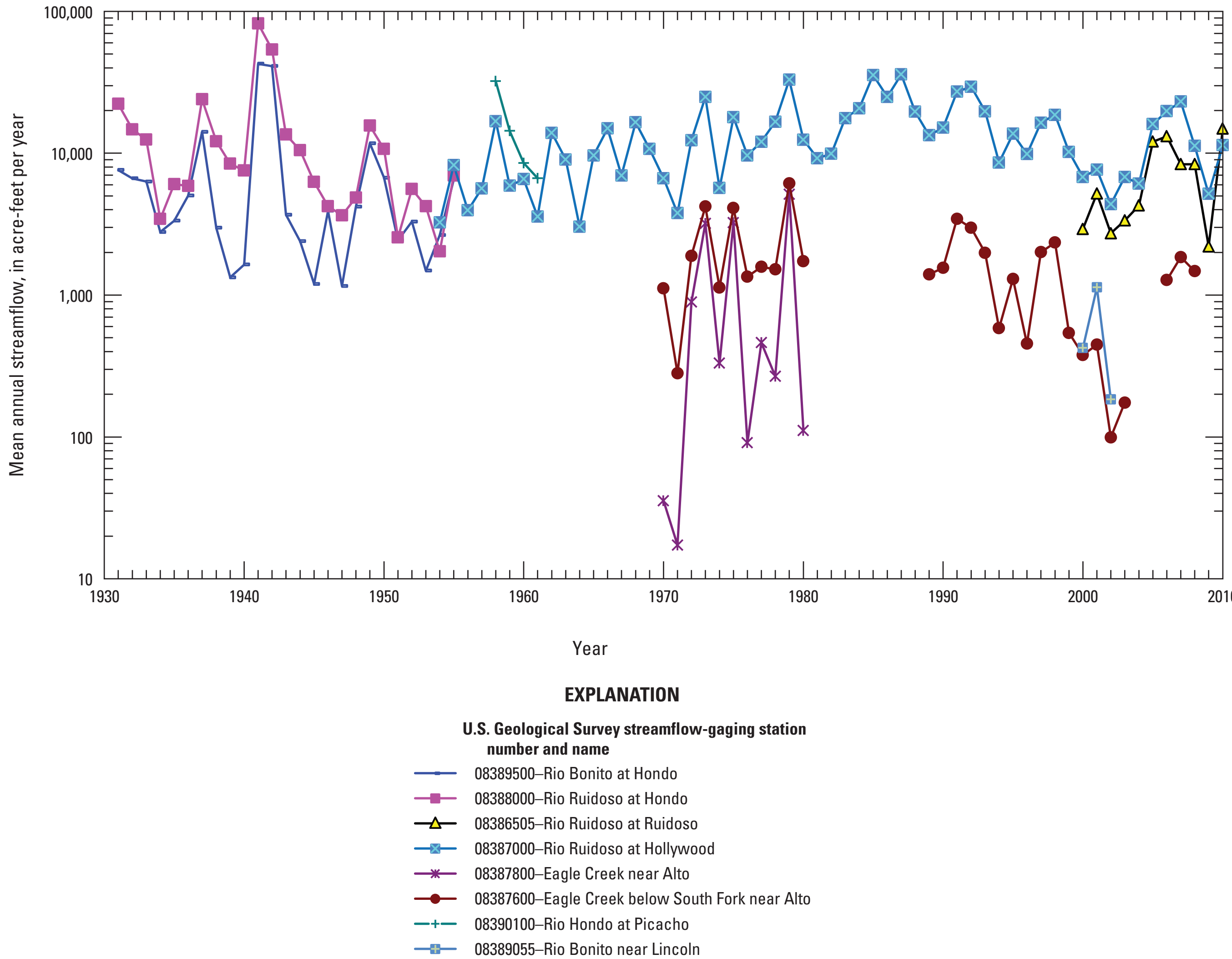


Figure 10. Mean annual streamflow at selected streamflow-gaging stations in the upper Rio Hondo study area, Lincoln County, New Mexico.

Table 2. Streamflow-gaging station information for the upper Rio Hondo Basin study area, Lincoln County, New Mexico.

[USGS, U.S. Geological Survey. Latitude and longitude given in decimal degrees; mean annual flows given through end of water year 2010]

Name	USGS station number	Elevation (feet)	Latitude	Longitude	Dates of record	Mean annual streamflow (acre-feet per year)
Rio Ruidoso at Ruidoso, N. Mex.	08386505	7,160	33° 20.2′	105° 43.6′	1998–2010	7,052
Herrera Ditch S at Hollywood, N. Mex.	08386900	6,402	33° 19.6′	105° 36.8′	1960–83	263
Rio Ruidoso at Hollywood, N. Mex.	08387000	6,420	33° 19.6′	105° 37.5′	1953–2010	13,670
North Fork Eagle Creek near Alto, N. Mex.	08387550	7,900	33° 24.6′	105° 44.4′	2007–10	763
South Fork Eagle Creek near Alto, N. Mex.	08387575	7,630	33° 23.5′	105° 43.4′	2007–10	542
Eagle Creek below South Fork near Alto, N. Mex.	08387600	7,600	33° 23.6′	105° 43.4′	1969–2010	1,617
Eagle Creek near Alto, N. Mex.	08387800	6,838	33° 23.5′	105° 36.7′	1969–80	1,253
Rio Ruidoso at Hondo, N. Mex.	08388000	5,181	33° 23.0′	105° 16.5′	1930–55	13,754
Rio Bonito near Lincoln, N. Mex.	08389055	5,961	33° 31.4′	105° 27.9′	1999–2002	580
Rio Bonito at Hondo, N. Mex.	08389500	5,205	33° 23.3′	105° 16.5′	1930–55	7,485
Rio Hondo above Chavez Canyon near Hondo, N. Mex.	08390020	5,160	33° 22.3′	105° 15.5′	2008–10	19,725
Rio Hondo at Picacho, N. Mex.	08390100	4,945	33° 21.4′	105° 09.5′	1956–62	15,413

As of 2010, six of these key stations were in operation. The Rio Ruidoso at Ruidoso (08386505) and the Rio Ruidoso at Hollywood (08387000) provide data on the southwestern part of the study area. Three active stations on upper Eagle Creek (08387550, 08387575, and 08387600) provide data on the west-central area. Flow leaving the study area to the Rio Hondo is now measured by the Rio Hondo above Chavez Canyon (08390020), which replaced the Rio Hondo at Picacho (08390100) that was discontinued in 1962. Other discontinued streamflow-gaging stations include Herrera Ditch at Hollywood (08386900), Eagle Creek near Alto (08387800), Rio Ruidoso at Hondo (08388000), Rio Bonito near Lincoln (08389055), and Rio Bonito at Hondo (08389500).

Streamflow data have also been collected by NMOSE during hydrographic surveys and by others (New Mexico Territorial Engineer, 1909; Lee, 1912, 1916; Follett, 1914; Neel, 1932; Martinez, 1974, 1975). Typically the data collection efforts were performed as seepage investigations (measuring streamflow at specific points along the length of a stream reach at a specific time). A number of seepage investigations have been done along Eagle Creek (Finch and others, 2004; Matherne and others, 2010) and along the Rio Bonito (Atkins Engineering Associates, Inc., 2000). In 2007, 2008, and 2010, the USGS assisted NMOSE in conducting a series of detailed seepage investigations in sections of Eagle Creek, Rio Ruidoso, Rio Bonito, and Rio Hondo to identify gaining and losing stream reaches (Jack Veenhuis, New Mexico Office of the State Engineer, oral commun., 2010). The Bureau of Land Management (BLM) measures streamflow at Government Spring near its confluence with the Rio Bonito (Michael McGee, Bureau of Land Management, oral commun., 2010).

Stream Systems

The characteristics of the major stream systems are described below. Sixteen subwatersheds were defined within the upper Rio Hondo Basin as part of this study (fig. 9) and correspond to locations of existing and historical streamflow-gaging stations and to areas of focused studies or particular interest.

Rio Ruidoso

The watershed of the Rio Ruidoso encompasses the southern half of the study area (subwatersheds 9 through 16) and is perennial throughout most of its 34-mi length. A number of small tributary streams within the watershed contain short perennial reaches in their upper elevations, including Carrizo Creek (subwatershed 16) that drains part of the Mescalero Reservation. Little Creek, upper Eagle Creek, and middle Eagle Creek (subwatersheds 10, 11, and 13, respectively) are major tributaries and are discussed separately.

U.S. Geological Survey streamflow-gaging station 08386505 (Rio Ruidoso at Ruidoso, referred to herein as "the upper Ruidoso gage") measures streamflow in subwatershed 14, which drains about 18 mi^2 in the upper reaches of the Rio Ruidoso. There are no major diversions upstream from the streamflow-gaging station, and the watershed is relatively undeveloped, making it a good indicator of typical upland streamflow conditions. The mean annual streamflow at the upper Ruidoso gage was 7,052 acre-ft/yr (or 9.7 cubic feet per second [ft^3/s]) from 1998 to 2010 (fig. 10 and table 2). Annual streamflow at the upper Ruidoso gage varied from 2,200 to 13,200 acre-ft/yr (3.0 to 18.2 ft^3/s) from 1998 to 2010, which equates to an available water supply of as little as about one-third the average during dry years or as much as about twice the average during wet years (fig. 8). Therefore, just as precipitation is highly variable from year to year, the annual runoff and yield of the upland watersheds are also highly variable.

Downstream from the upper Ruidoso gage, the Rio Ruidoso passes by Ruidoso, and some of its flow is diverted for municipal water supply. There is also inflow from several tributaries through the Ruidoso suburban area along this reach. A seepage survey in 2008 showed that streamflow increased from 0.7 to 1.3 ft^3/s (a difference of 0.6 ft^3/s) in the area upstream from Carrizo Creek (New Mexico Office of the State Engineer, unpub. data, 2010), indicating that this section of the stream can be a gaining reach.

Continuing another 6 mi downstream from the upper Ruidoso gage, the stream receives inflow from Carrizo Creek and Cherokee Bill Canyon and reaches Ruidoso Downs and the location of USGS streamflow-gaging station 08387000 (Rio Ruidoso at Hollywood, referred to herein as "the Hollywood gage"). This streamflow-gaging station has operated continuously since 1953, with a mean annual streamflow of 13,670 acre-ft/yr (18.7 ft^3/s) from 1953 to 2010 (table 2), roughly double the flow in the upper Ruidoso gage. Wasiolek (1991) observed that east of Ruidoso, seepage investigations showed an increase in streamflow attributed to groundwater inflow from the Yeso Formation. Examination of streamflow over the period of record at the Hollywood gage (fig. 11) shows a general increase in streamflow from the 1950s drought period to the late 1980s wet period and a subsequent decrease over the next 20 years. This variation in flow parallels trends in precipitation, which have also been decreasing since the mid-1980s (fig. 11).

About 5 mi downstream from the Hollywood gage in subwatershed 12 (fig. 9), the Ruidoso Regional Wastewater Treatment Plant contributes flow to the Rio Ruidoso. From the wastewater treatment plant, the Rio Ruidoso continues downstream about 20 mi past the communities of Glencoe and San Patricio in subwatersheds 12 and 9, respectively. Diversions of streamflow to irrigate agricultural lands along the valley floor become more substantial downstream from the Hollywood gage, as shown by measured diversion at the Herrera Ditch (USGS streamflow-gaging station 08386900; fig. 9). A 2008 seepage investigation found a net decrease of 4.4 ft^3/s between Glencoe and San Patricio (New Mexico Office of the State Engineer, unpub. data, 2010).

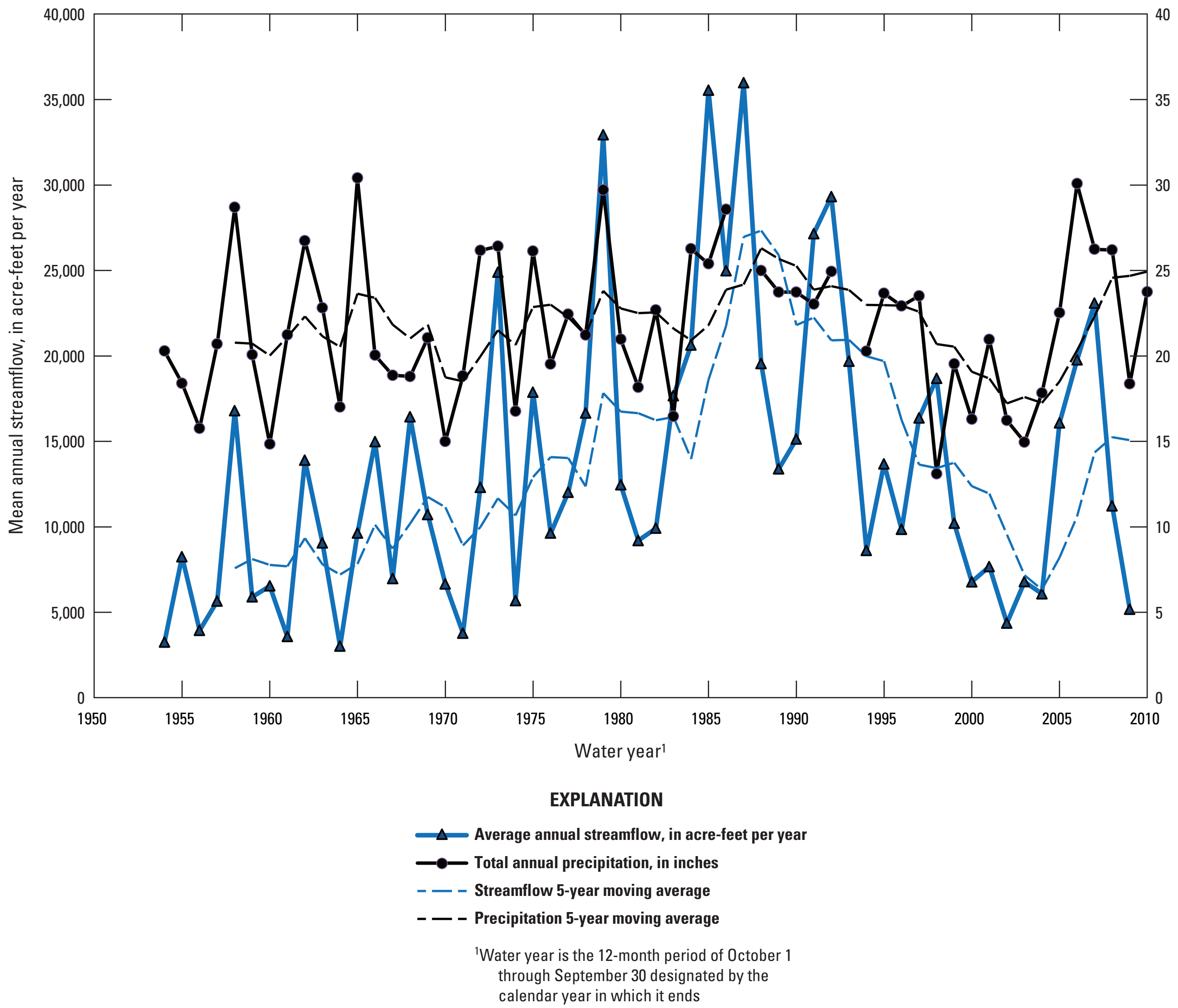


Figure 11. Mean annual streamflow at Rio Ruidoso at Hollywood (08387000) as compared to total annual precipitation at the Ruidoso precipitation station, upper Rio Hondo Basin study area, Lincoln County, New Mexico.

The Rio Ruidoso joins the Rio Bonito a few miles downstream from San Patricio to form the Rio Hondo. A USGS streamflow-gaging station was formerly maintained on the Rio Ruidoso near its confluence with the Rio Bonito (08388000, Rio Ruidoso at Hondo). Table 2 shows that during the period of record from 1930 to 1955, the mean annual streamflow at this site was 13,754 acre-ft/yr (19.0 ft^3/s). The lowest mean annual streamflow measured at this site was during the drought of the mid-1950s, when mean annual streamflow was about 2,000 acre-ft/yr (2.8 ft^3/s). Maximum flows at this streamflow-gaging station were measured in 1941, an abnormally high rainfall year (almost double the normal precipitation), when mean annual streamflow was about 82,200 acre-ft/yr (114 ft^3/s) at the streamflow-gaging station.

Eagle Creek

Eagle Creek is tributary to the Rio Ruidoso and has its headwaters in an upland watershed near Sierra Blanca (subwatershed 11 on fig. 9), where wells and surface diversions provide water for Ruidoso. The impoundment of Alto Reservoir occurs in its middle reaches (subwatershed 13), along with a network of wells, and provides water for the municipalities of Alto and Ruidoso. Eagle Creek is paralleled by Little Creek in the north (subwatershed 10) and joins Little Creek a few miles from Glencoe.

The highest reaches of Eagle Creek are largely perennial. At USGS streamflow-gaging station 08387600 (Eagle Creek below South Fork near Alto, herein referred to as the “Main Stem Eagle Creek gage”), the mean annual streamflow from

1970 to 1980 was 2,260 acre-ft/yr (3.1 ft^3/s) and from 1989 to 2008 was 1,290 acre-ft/yr (1.8 ft^3/s). Matherne and others (2010) completed a study in cooperation with the Village of Ruidoso on the hydrology of Eagle Creek Basin and the effects of North Fork well field pumping on streamflow. The report showed a close connection between surface water and groundwater. The report included seepage investigations which show ephemeral or intermittent conditions adjacent to pumping wells. The configuration of the alluvial fill and groundwater pumping was suggested as factors in the lack of surface flow in the creek. Finch and others (2004) and Balleau Groundwater, Inc. (2004b) also have documented intermittent flow conditions along North Fork Eagle Creek.

Alto Reservoir is located on Eagle Creek about 3 mi downstream from the Main Stem Eagle Creek gage. Four miles downstream from the lake, USGS streamflow-gaging station 08387800 (Eagle Creek near Alto, herein referred to as the “Alto gage”) measured a mean annual streamflow of 1,253 acre-ft/yr (1.7 ft^3/s) over the period of record (1969–80). The record at this gage shows zero streamflow (the creekbed was dry) for about 5 months of the year, usually in the winter months.

In the spring of 2010, record snowfall on Sierra Blanca created abundant snowmelt conditions, and seepage investigations were conducted by NMOSE to better understand streamflow losses below Alto Reservoir (Jack Veenhuis, New Mexico Office of the State Engineer, oral commun., 2010). An estimated 220 acre-ft were released to Eagle Creek from Alto Reservoir over the course of about 1 month, and the streamflow was measured at fixed locations downstream from the reservoir on several different occasions. Figure 12 shows the results of these seepage investigations, in

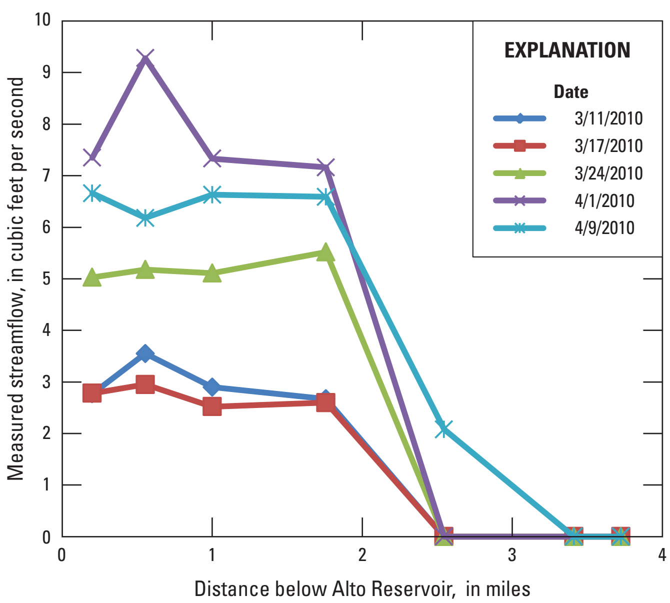


Figure 12. Seepage investigation results for Eagle Creek below Alto Reservoir, upper Rio Hondo Basin study area, Lincoln County, New Mexico.

which all available streamflow (about 2–9 ft^3/s) infiltrated into the streambed within 2–4 mi, where the streambed crosses the former location of the discontinued Alto gage (08387800).

The loss of streamflow along this 2–4 mi reach of Eagle Creek below Alto Reservoir is associated with a paleosinkhole mapped by Rawling (2009). The sinkhole was formed by karst processes (dissolution of limestone and gypsum) on the top of the San Andres Formation, likely when it was exposed to weathering by atmospheric conditions before Triassic strata were deposited. The sinkhole probably provides a very permeable conduit for water in the stream to flow into the subsurface. Sinkholes and related solution-collapse features are thought to be common in the region, and it is thought that more sinkholes occur along this same geologic contact (the Permo-Triassic unconformity), which extends along the margin of the Sierra Blanca Basin from southwest to northeast across the study area (Geoffrey Rawling, New Mexico Bureau of Geology and Mineral Resources, oral commun., 2010). Eagle Creek and Little Creek are intermittent or ephemeral in their lower 10–15 mi (the eastern part of subwatershed 10) below Alto Reservoir to their confluence with the Rio Ruidoso.

Rio Bonito

The Rio Bonito is one of the major streams in the study area; its drainage encompasses the northern half of the study area (fig. 9, subwatersheds 1 through 8). The headwaters of the Rio Bonito wrap around the northern slope of Sierra Blanca. Over its 35 mi length, the stream passes the town of Angus; extends past Fort Stanton, where it is joined by Salado Creek; and bends southeast past the town of Lincoln to its mouth near Hondo.

The high country drained by the Rio Bonito (subwatershed 8) covers about 40 mi^2. Flow from this upland area has been diverted since 1906 by a pipeline system and used as a source of freshwater outside the study area in the lowlands to the west; at times, flow from the Rio Bonito has been supplemented by diversions from Eagle Creek and the Rio Ruidoso. In 1931, a dam was constructed to form Bonito Lake, from which water has been diverted to the Bonito pipeline (Powell, 1954). Prior to construction of the dam, a seepage investigation was conducted in the streambed about 2 mi southwest (upstream) from the Bonito Lake damsite, releasing 2.9 ft^3/s from the pipeline diversion into the previously dry creekbed for the month of August 1908. After the first 6 days of the investigation, flow extended for the first half-mile of streambed below the dam before completely infiltrating into the stream alluvium; after 8 days flow extended to three-quarters of a mile below the dam (New Mexico Territorial Engineer, 1909).

Powell (1954) reported that from 1931 to 1940 the mean annual streamflow above the Bonito Lake damsite was 6,800 acre-ft/yr (9.4 ft^3/s). During the drought years of 1934, 1947, and 1953, flow at the damsite averaged 20 percent less than average for the period 1931–40, but the Rio Bonito was perennial to the town of Angus (Powell, 1954). A hydrographic survey made at the turn of the 20th century (New Mexico Territorial Engineer, 1909) stated that the maximum flow in the Rio Bonito occurred near the town of Angus at an estimated 3,000 acre-ft for a partial year (November 1908– August 1909), and it appears likely that the Rio Bonito below the damsite to Angus has historically been a perennial stream reach.

The Rio Bonito crosses a variety of geologic units along the 12 mi from Angus to Fort Stanton. Some reaches are dry, and others may gain or lose as much as 720 acre-ft/yr (1 ft^3/s) depending on the thickness of gravels in the streambed and the types of bedrock encountered (Lee, 1912). The 1909 hydrographic survey (New Mexico Territorial Engineer, 1909) reported a streamflow loss of about 1 ft^3/s between Angus and Fort Stanton, where the flow was estimated at 800 acre-ft/yr (about 1.1 ft^3/s). The 1931 hydrographic survey (Neel, 1932), however, reported a net gain of 0.4 ft^3/s from Angus to Fort Stanton.

The Rio Bonito is perennial from Government Spring for about 10 mi downstream to Lincoln, with flow augmented by additional groundwater discharge in this area (Daniel B. Stephens and Associates, Inc., 2000). The USGS maintained a streamflow-gaging station just downstream from Government Spring (08389055, Rio Bonito near Lincoln) from 1999 to 2002, with a mean annual streamflow of 580 acre-ft/yr (0.8 ft^3/s) for the 3-year period of record (table 2). A seepage investigation of the Rio Bonito in February 1998 found an increase in streamflow from 3.8 to 4.9 ft^3/s (a gain of 1.1 ft^3/s) in the vicinity of Government Spring (Atkins Engineering Associates, Inc., 2000). Flows were measured at 4.8 ft^3/s about 4 mi downstream from Government Spring, with nearby agricultural ditch diversion flow measurements from 0.6 to 1.4 ft^3/s (Atkins Engineering Associates, Inc., 2000). Measurements on the same reach by NMOSE in February 2008 found a streamflow increase from 0.25 to 1.80 ft^3/s (a gain of about 1.6 ft^3/s) (New Mexico Office of the State Engineer, unpub. data, 2010).

Mourant (1963) reported that flow in the Rio Bonito was intermittent in the final 10 mi to the mouth between the towns of Lincoln and Hondo. Seepage investigations by NMOSE along this stream reach in February 2008 found that flow increased from 1.8 ft^3/s below Government Spring to 4.0 ft^3/s at the Highway 380 crossing and then decreased to 3.2 ft^3/s at the mouth of the Rio Bonito at the Highway 70 crossing (New Mexico Office of the State Engineer, unpub. data, 2010). This suggests that the reach is first gaining and then losing. Measurements in this area are difficult because there are numerous ditches with diversions occurring year-round (Jack Veenhuis, New Mexico Office of the State Engineer, oral commun., 2010).

Near the mouth of the Rio Bonito, the USGS maintained a streamflow-gaging station from 1930 to 1955 (08389500, Rio Bonito at Hondo). The mean annual streamflow was 7,485 acre-ft/yr (10.4 ft^3/s) (table 2) for the period of record, with the lowest flow occurring during the winter months (December to March). Some zero-flow months occurred during most years.

Salado Creek

Salado Creek passes Capitan and drains the northwest quarter of the study area (fig. 9). Salado Creek is ephemeral and flows in response to precipitation events. Magado Creek and Cherry Creek lie to the southwest, drain higher-lying areas, and contain short perennial reaches in the upper parts of their watersheds.

A flood-control impoundment was constructed near the mouth of Salado Creek, where it joins the Rio Bonito. Mourant (1963) reported that the water table is about 50 ft below the streambed in this area, and water temporarily stored behind the dam sinks into the permeable limestone bedrock, described geologically as the San Andres Formation (Skotnicki, 2010).

Rio Hondo

The confluence of the Rio Bonito and Rio Ruidoso forms the Rio Hondo on the eastern edge of the study area, about 25 mi east of Ruidoso near Hondo. The Rio Hondo is outside the study area (fig. 1), but information on the Rio Hondo is provided in this report for background purposes. The Rio Hondo is perennial about 7 mi downstream from the confluence of the Rio Bonito and Rio Ruidoso, where the San Andres Formation intersects the stream and the river begins to lose water to the permeable limestone bed. This phenomenon along the Rio Hondo forms one of the principal intake areas for regional recharge to the Roswell Artesian Basin aquifer, along with infiltration along other streams draining the Sacramento Mountains and direct infiltration of precipitation (Fiedler and Nye, 1933). The loss of streamflow on the Rio Hondo has been estimated at about 19,400 acre-ft/yr in an average year (Mourant, 1963).

The USGS operated a streamflow-gaging station on the Rio Hondo from 1956 to 1962 (08390100, Rio Hondo at Picacho), during which time the mean annual flow was 15,413 acre-ft/yr (21.2 ft^3/s) (table 2). There was only 1 month of no-flow conditions during the period of record; during this time, the flows declined consistently from 32,100 acre-ft/yr (44.3 ft^3/s) in 1957 to 6,700 acre-ft/yr (9.3 ft^3/s) in 1960 (fig. 10). Precipitation during this 4-year period also declined about 50 percent from 1958 to 1960 at the Capitan and Ruidoso stations, providing an explanation for the anomalously low-flow conditions during this time. Direct-flow measurements on the Rio Hondo by the USGS were resumed in July 2008. Streamflow-gaging station 08390020 was installed on the Rio Hondo above Chavez Canyon near Hondo (fig. 9). The mean annual flow at this location is 19,725 acre-ft/yr (28.9 ft^3/s) for water years 2008–10 (table 2). Flow at the head of the Rio Hondo can be estimated by summing the flows at the mouths of the Rio Bonito and Rio Ruidoso (streamflow-gaging stations 08389500 and 08388000, respectively) (table 2). The mean annual streamflow for both stations combined was 21,239 acre-ft/yr (29.3 ft^3/s) for the 25-year period of record (1930–55).

Reservoirs/Lakes

There are several man-made lakes in the upper Rio Hondo Basin, as well as numerous small ponds and tanks (fig. 1). Alto Reservoir was constructed in 1964, about 3 mi north of Ruidoso in the community of Alto. The lake covers 17 acres and has a maximum storage capacity of 452 acre-ft. Ruidoso obtains water from wells and Eagle Creek and uses Alto Reservoir for storage and mixing. Direct surface-water diversions from Eagle Creek are also made to Alto Reservoir. In 1988, Ruidoso impounded Grindstone Canyon to create the 38-acre Grindstone Reservoir, located about 1 mi south of the townsite. The 1,520-acre-ft capacity of the lake is used primarily as a storage facility for municipal supplies and mixes waters from surface diversions of the Rio Ruidoso and from several wells. Surface diversions are limited during May, June, and July to maintain a flow of 6.0 ft^3/s at the Rio Ruidoso at Hollywood gage, except during declared drought emergencies (Wilson and Company, Inc., 2004).

Bonito Lake has a 44-acre surface area and a 2,500-acre-ft storage capacity and normally stores about half that amount (1,247 acre-ft). Leakage in the Bonito Pipeline was historically significant (the original pipeline was built of wood), but replacement of the pipeline with new materials has minimized system losses to ensure full use of the maximum permitted amount of 3,088 acre-ft/yr out of the upper Rio Hondo Basin to supply freshwater to municipalities in the adjacent Tularosa Basin through gravity flow (Roger Peery, Shomaker and Associates, oral commun., 2010). Nogal Lake (fig. 1) is a natural depression near the northwestern drainage divide of the upper Rio Hondo Basin that was adapted for use as a temporary storage reservoir for the Bonito Pipeline. Leakage from the lake was very high (nearly 1,000 acre-ft/yr; Powell, 1954), and use of the lake was eventually abandoned and the pipeline rerouted.

Mescalero Lake (fig. 1) is located about 6 mi southwest of Ruidoso on the Mescalero Reservation. It was constructed in 1974 and provides the reservation with water storage and recreation opportunities. The lake primarily is fed by a creek but is supplemented by a well (Sterling Cane, Jr., Mescalero Apache Water Department, oral commun., 2011). Two small lakes (Eagle Lakes, fig. 1) on South Fork Eagle Creek are used for recreation (Upper Hondo Watershed Coalition, 2004).

Seeping Springs Lakes (S84, fig. 13) is a set of seven small lakes (2 to 3 acres total area), located on the Rio Ruidoso, just east of Ruidoso Downs. Some of the lakes may be fed by springs that issue from the lakebeds at a discharge of more than 400 gal/min (White and Kues, 1992).

There are numerous small (1 acre or less) livestock ponds or dirt tanks in the study area. Many are located on arroyo floors across the study area, are fed by intermittent surface-water flows, and may hold water for some periods of time before being depleted by evaporation and infiltration.

Groundwater

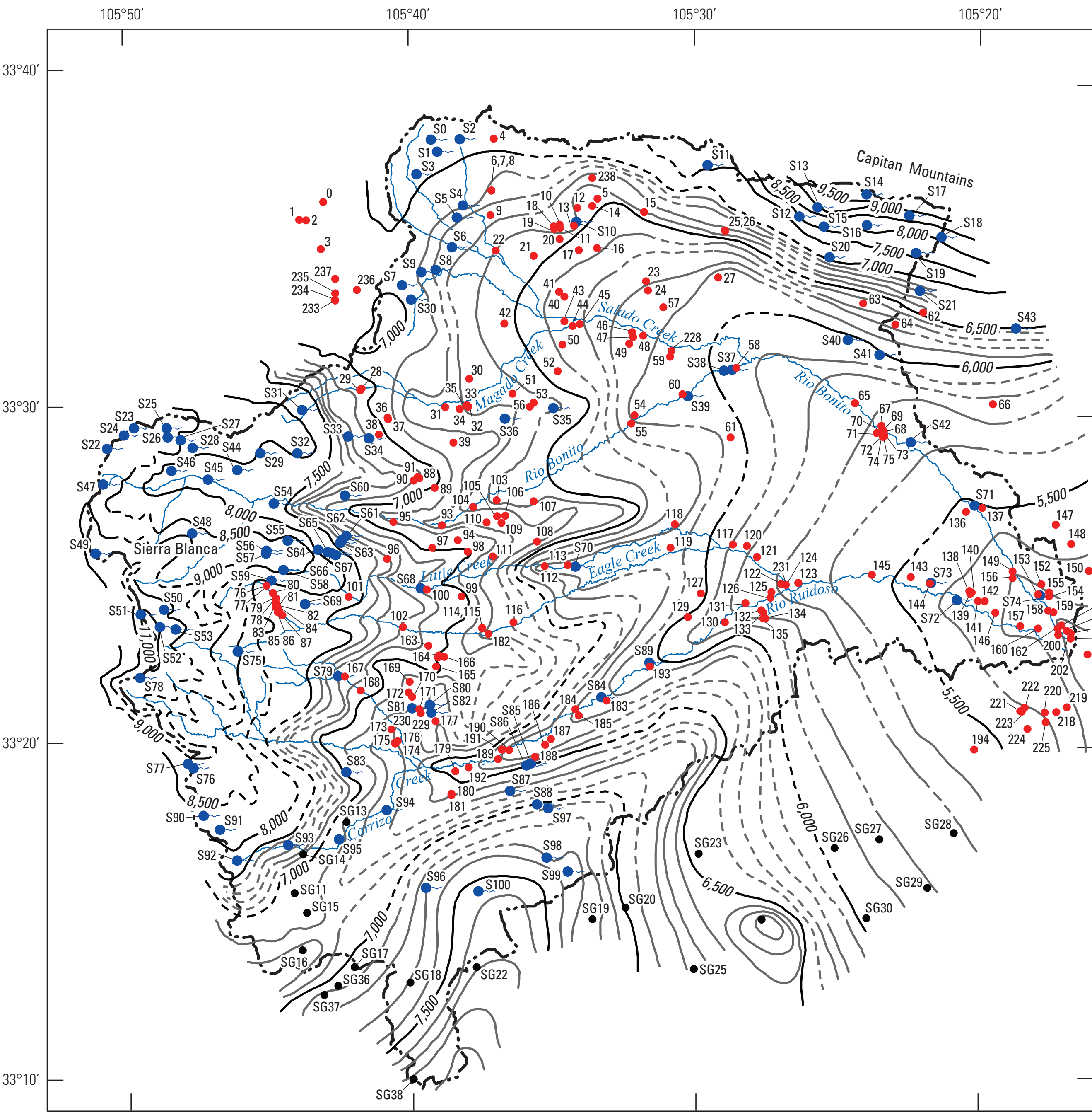
Springs

An inventory of springs was prepared as part of this study. Data points were collected from the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2010) and from previous studies (Mourant, 1963; Sloan and Garber, 1971; Davis and others, 1979; White and Kues, 1992). Additional seeps and springs were identified from USGS 1:24,000-scale topographic maps. The land-surface elevations of the seeps and springs were estimated from topographic maps and were interpreted as the expressions of the highest local water table. Spring locations are shown on the water-level map (fig. 13) and are listed in table 3. Spring elevations were used to help contour groundwater levels and to provide base-line data.

In Sierra Blanca, many small springs discharge groundwater from the igneous rocks, where the water table intersects land surface, or along contacts between units of different hydrologic properties (Mourant, 1963). Many springs emerge at the foot of the mountains, where topographic gradient flattens, and may flow only seasonally in response to snowmelt or runoff, but they are an important water source for wildlife and contribute to an understanding of the hydrologic system. Historic spring yields from the south side of the Capitan Mountains ranged from 3 to 450 gal/min (White and Kues, 1992).

There are several large springs in the middle part of the study area that issue from the San Andres and (or) Yeso Formation. Government Spring (S37, fig. 13) produces an estimated 250 gal/min (Mourant, 1963) near the Rio Bonito's sharp change in direction from northeast to southeast. Spring flow in this area could be caused by faulting, by the rise in bedrock elevation along the crest of the Mescalero Arch, or by both. On a regional scale, these springs occur near the point where the rock formations along the streambed of the Rio Bonito change from the San Andres to the Yeso Formation, perhaps reflecting the less transmissive nature of the Yeso Formation.

On the Rio Ruidoso, Hale Spring (S86, fig. 13) is the water supply for Ruidoso Downs and discharges an estimated 220 to 365 gal/min (Davis and others, 1979; Riesterer and others, 2006). Spring flow in this area could be occurring because of local folding in the Yeso Formation, as suggested by Riesterer and others (2006), or because of the juxtaposition of the Yeso and San Andres Formations by faulting, as mapped by Rawling (2004b). A few miles downstream on the Rio Ruidoso, Seeping Springs Lakes (S84, fig. 13) discharge an estimated 415 gal/min (White and Kues, 1992).



Base from U.S. Geological Survey digital raster graphics, 1:24,000
Universal Transverse Mercator projection, zone 13
North American Datum of 1983 (NAD 83)

0 2.5 5 7.5 10 MILES
0 2.5 5 7.5 10 KILOMETERS

EXPLANATION

Study area boundary

7,500 Water-level contour—Index contour shown in black. Intermediate contour shown in gray. Interval 100, 500, and 1,000 feet. Dashed where inferred

181 **Well and identification number**—From U.S. Geological Survey National Water Information System (2010) (table 4)

SG25 **Well and identification number**—From Sloan and Garber (1971)

S100 **Spring and identification number**—This report (table 3)

Figure 13. Generalized regional water-level map of the upper Rio Hondo Basin study area, Lincoln County, New Mexico.

Table 3. Inventory of seeps and springs in the upper Rio Hondo Basin study area, Lincoln County, New Mexico.

[ID, identification number; latitude and longitude referenced to North American Datum of 1983; elevation referenced to North American Vertical Datum of 1988; ft, feet; geologic units are Py (Yeso Formation), Psa (San Andres Limestone), Kmv (Mesaverde Group), Ti (Tertiary intrusive rock), and Qa (alluvium), ? denotes probable identification; gal/min, gallons per minute; °F, degrees Fahrenheit; °C, degrees Celsius; µS/cm, microsiemens per centimeter; °, degrees; ′, minutes]

ID (see fig. 13 for location)	Latitude	Longitude	Name	Elevation (ft)	Geologic units	Flow (gal/min)	Date	Temperature (°F)	Specific conductance at 25 °C (µS/cm)	Data source[1]	Comments[2]
S0	33° 38.0′	105° 38.8′	Unnamed	8,013	–	–	–	–	–	1	
S1	33° 37.7′	105° 38.6′	Felix	7,435	–	–	–	–	–	1	
S2	33° 38.1′	105° 37.8′	Unnamed	7,402	–	–	–	–	–	1	
S3	33° 37.0′	105° 39.3′	Silva	7,186	–	–	–	–	–	1	
S4	33° 36.1′	105° 37.6′	Unnamed	6,957	–	–	–	–	–	1	
S5	33° 35.7′	105° 37.8′	Guck	6,899	–	–	–	–	–	1	
S6	33° 34.9′	105° 38.0′	Unnamed	6,758	–	–	–	–	–	1	
S7	33° 33.7′	105° 39.8′	Bonnie	6,924	–	–	–	–	–	1	
S8	33° 34.2′	105° 38.6′	Zamora	6,777	–	–	–	–	–	1	
S9	33° 34.1′	105° 39.1′	Unnamed	6,875	–	–	–	–	–	1	
S10	33° 35.6′	105° 33.6′	Gyp Spring	6,545	–	–	–	–	–	1	
S11	33° 37.3′	105° 29.0′	Hammett	7,718	–	–	–	–	–	1	
S12	33° 36.1′	105° 25.1′	Upper padilla	9,336	Ti	3	05-08-56	51	158	1,2,3	
S13	33° 35.8′	105° 25.8′	Peppin	8,021	–	–	–	–	–	1	
S14	33° 36.5′	105° 23.4′	Summit	9,876	–	–	–	–	–	1	
S15	33° 35.5′	105° 24.9′	Padilla	8,085	–	–	–	–	–	1	
S16	33° 35.6′	105° 23.4′	Unnamed	8,077	–	–	–	–	–	1	
S17	33° 35.9′	105° 21.9′	Unnamed	8,993	–	–	–	–	–	1	
S18	33° 35.2′	105° 20.7′	Figure seven	8,124	–	–	–	–	–	1	
S19	33° 34.7′	105° 21.6′	Mitten bar	7,640	–	–	–	–	–	1	
S20	33° 34.6′	105° 24.7′	Lower padilla	7,194	Ti	450	11-03-55	49	140	1,2,3	Estimated flow 150 gal/min 05-08-56
S21	33° 33.6′	105° 21.5′	Baca	6,883	–	–	–	–	–	1	
S22	33° 28.8′	105° 50.1′	Argentina	8,938	–	–	–	–	–	1	
S23	33° 29.4′	105° 49.2′	Turkey	8,919	–	–	–	–	–	1	
S24	33° 29.2′	105° 49.5′	Unnamed	8,943	–	–	–	–	–	1	
S25	33° 29.5′	105° 48.0′	Red fox	8,688	–	–	–	–	–	1	
S26	33° 29.2′	105° 48.0′	Devil	8,618	–	–	–	–	–	1	
S27	33° 29.1′	105° 47.5′	Skull	8,134	–	–	–	–	–	1	
S28	33° 28.9′	105° 47.1′	Unnamed	8,025	Qa	10	08-09-77	55	590	1,3	
S29	33° 28.7′	105° 44.7′	Unnamed	7,846	Qa, Ti	54	08-09-77	–	1,290	1,5	
S30	33° 33.3′	105° 39.4′	Swan	6,933	–	–	–	–	–	1	
S31	33° 30.0′	105° 43.3′	Unnamed	7,638	–	–	–	–	–	1	
S32	33° 28.7′	105° 43.4′	Unnamed	8,035	–	–	–	–	–	1	
S33	33° 29.2′	105° 41.6′	Lamay	7,218	Qa	0.75	08-10-77	63	2,200	3	
S34	33° 29.2′	105° 40.9′	Unnamed	7,080	Qa	1	08-10-77	59	1,580	3	

Table 3. Inventory of seeps and springs in the upper Rio Hondo Basin study area, Lincoln County, New Mexico.—Continued

[ID, identification number; latitude and longitude referenced to North American Datum of 1983; elevation referenced to North American Vertical Datum of 1988; ft, feet; geologic units are Py (Yeso Formation), Psa (San Andres Limestone), Kmv (Mesaverde Group), Ti (Tertiary intrusive rock), and Qa (alluvium), ? denotes probable identification; gal/min, gallons per minute; °F, degrees Fahrenheit; °C, degrees Celsius; µS/cm, microsiemens per centimeter; °, degrees; ′, minutes]

ID (see fig. 13 for location)	Latitude	Longitude	Name	Elevation (ft)	Geologic units	Flow (gal/min)	Date	Temperature (°F)	Specific conductance at 25 °C (µS/cm)	Data source[1]	Comments[2]
S35	33° 30.1′	105° 34.4′	Unnamed	6,633	–	–	–	–	–	1	
S36	33° 29.8′	105° 36.1′	Unnamed	6,703	–	–	–	–	–	1	
S37	33° 31.3′	105° 28.1′	Government	5,972	Psa	250	09-04-57	56	580	1,2,3	Noted as “intermittent”
S38	33° 31.3′	105° 28.4′	Govt sps ft s	5,981	–	–	–	–	–	1	
S39	33° 30.5′	105° 29.7′	Ft. Stanton cave	6,108	–	300	04-22-07	–		1	
S40	33° 32.2′	105° 24.0′	Lincoln tank	6,731	–	–	–	–	–	1	
S41	33° 31.7′	105° 22.9′	Lincoln Canyon	6,060	Py?	10	01-13-56	–	–	1,2,3	Folded and fractured zone
S42	33° 29.2′	105° 21.8′	Hulbert	5,754	Py	15–20	08-11-77	64	870	1,3,5	
S43	33° 32.5′	105° 18.1′	Raton	6,498	–	–	–	–	–	1	
S44	33° 28.2′	105° 45.5′	Littleton	7,958	–	–	–	–	–	1	
S45	33° 27.9′	105° 46.6′	Unnamed	7,657	Ti	1	08-09-77	54	1,000	3,5	Mine pit discharge
S46	33° 28.2′	105° 47.9′	Unnamed	7,843	–	–	–	–	–	1	
S47	33° 27.8′	105° 50.3′	Little Bonito	8,829	–	–	–	–	–	1	
S48	33° 26.3′	105° 47.1′	Unnamed	8,608	–	–	–	–	–	1	
S49	33° 25.7′	105° 50.5′	Bonito	9,385	–	–	–	–	–	1	
S50	33° 24.1′	105° 48.1′	Unnamed	10,166	–	–	–	–	–	1	
S51	33° 23.9′	105° 48.9′	Ice	11,016	–	–	–	–	–	1	
S52	33° 23.6′	105° 48.2′	Vanishing	10,923	–	–	–	–	–	1	
S53	33° 23.5′	105° 47.7′	Unnamed	10,174	–	–	–	–	–	1	
S54	33° 27.2′	105° 44.2′	Unnamed	7,500	Qa, Ti	32	08-09-77	53.5	280	3	On side of Bonito Lake
S55	33° 26.2′	105° 43.8′	Fox	8,799	–	–	–	–	–	1	
S56	33° 25.9′	105° 44.5′	Unnamed	8,543	–	–	–	–	–	1	
S57	33° 25.8′	105° 44.5′	Unnamed	8,665	–	–	–	–	–	1	
S58	33° 25.3′	105° 43.9′	Little Creek	8,720	Ti	0.4	08-09-77	57	370	1,3	
S59	33° 25.0′	105° 44.3′	Unnamed	8,278	Ti	54	08-09-77	59	180	1,3	
S60	33° 27.5′	105° 41.7′	Unnamed	7,179	Ti	4	08-10-77	57	955	3	
S61	33° 26.3′	105° 41.7′	Unnamed	7,273	–	–	–	–	–	1	
S62	33° 26.1′	105° 41.9′	Unnamed	7,370	–	–	–	–	–	1	
S63	33° 26.2′	105° 41.8′	Unnamed	7,326	–	–	–	–	–	1	
S64	33° 25.9′	105° 42.7′	Unnamed	7,933	–	–	–	–	–	1	
S65	33° 25.8′	105° 42.3′	Unnamed	7,728	–	–	–	–	–	1	
S66	33° 25.8′	105° 42.2′	Unnamed	7,638	–	–	–	–	–	1	
S67	33° 25.7′	105° 42.1′	Unnamed	7,560	–	–	–	–	–	1	
S68	33° 24.8′	105° 39.1′	Unnamed	7,101	Kmv	2	12-08-55	53	–	2,3	Seepage at stream bank
S69	33° 24.3′	105° 43.1′	Unnamed	7,905	–	–	–	–	–	1	

Table 3. Inventory of seeps and springs in the upper Rio Hondo Basin study area, Lincoln County, New Mexico.—Continued

[ID, identification number; latitude and longitude referenced to North American Datum of 1983; elevation referenced to North American Vertical Datum of 1988; ft, feet; geologic units are Py (Yeso Formation), Psa (San Andres Limestone), Kmv (Mesaverde Group), Ti (Tertiary intrusive rock), and Qa (alluvium), ? denotes probable identification; gal/min, gallons per minute; °F, degrees Fahrenheit; °C, degrees Celsius; µS/cm, microsiemens per centimeter; °, degrees; ′, minutes]

ID (see fig. 13 for location)	Latitude	Longitude	Name	Elevation (ft)	Geologic units	Flow (gal/min)	Date	Temperature (°F)	Specific conductance at 25 °C (µS/cm)	Data source[1]	Comments[2]
S70	33° 25.4′	105° 33.6′	Little	6,603	–	–	–	–	–	1	
S71	33° 27.3′	105° 19.5′	Emil Fritz	5,535	Py	5	09-29-55	63	1,200	1,2,3	
S72	33° 24.5′	105° 20.2′	Peter Hurd	5,360	Qa,Py	100	08-23-55	59	1,820	1,2,3	Estimated flow 200 gal/min 05-16-77
S73	33° 25.0′	105° 21.1′	Crouse	5,700	Qa	–	–	–	–	1,2,3	Reported “dry” in 1955
S74	33° 24.6′	105° 17.2′	Colonel Fritz	5,329	Psa	390	10-19-55	63	861	1,2,3	Estimated flow 332 gal/min 06-06-77
S75	33° 22.9′	105° 45.5′	Unnamed	8,323	–	–	–	–	–	1	
S76	33° 19.4′	105° 47.0′	Unnamed	8,696	–	–	–	–	–	1	
S77	33° 19.5′	105° 47.2′	Cienegita	8,871	–	–	–	–	–	1	
S78	33° 22.1′	105° 48.9′	Unnamed	10,736	–	–	–	–	–	1	
S79	33° 22.2′	105° 41.9′	Unnamed	7,166	Qa,Ti	2	08-02-77	64	780	1,3	
S80	33° 21.3′	105° 38.7′	Unnamed	6,771	–	–	–	–	–	1	
S81	33° 21.2′	105° 39.3′	Bog	6,818	Qa		08-12-77	54	2,250	1,3	
S82	33° 21.1′	105° 38.7′	Unnamed	6,754	–	–	–	–	–	1	
S83	33° 19.3′	105° 41.6′	Unnamed	6,968	–	–	–	–	–	1	
S84	33° 21.6′	105° 32.7′	Seeping Springs Lakes	6,125	Qa,Py	415	08-12-77	59	1,650	3	Seven springs reported.
S85	33° 19.6′	105° 35.1′	Unnamed	6,566	–	–	–	–	–	1	
S86	33° 19.6′	105° 35.3′	Hale	6,598	Py	246	04-27-55	54	1,570	1,2,3,6	Also “Agua Fria Spring;” estimated flow 365 gal/min in 1999
S87	33° 18.8′	105° 35.9′	Baston	6,757	Py	2	08-02-77	56	1,070	1,3	
S88	33° 18.4′	105° 34.9′	Unnamed	7,038	–	–	–	–	–	1	
S89	33° 22.6′	105° 31.0′	Fox cave	6,043	–	–	–	–	–	1	
S90	33° 18.0′	105° 46.6′	Miserable	8,428	–	–	–	–	–	1	
S91	33° 17.6′	105° 46.1′	Unnamed	8,390	–	–	–	–	–	1	
S92	33° 16.7′	105° 45.4′	Jose 2nd	7,881	–	–	–	–	–	1,4	Also “Mud”
S93	33° 17.2′	105° 43.7′	Unnamed	7,306	Ti	0.5–1	–	–	–	4	
S94	33° 18.2′	105° 40.2′	Carrizo	6,756	Psa	0.3	12-22-47	53	1,330	1,2,4	
S95	33° 17.3′	105° 41.9′	Unnamed	6,970	–	–	–	–	–	1	
S96	33° 15.9′	105° 38.8′	Snow	7,390	Psa	0–1	–	–	–	1,4	
S97	33° 18.3′	105° 34.5′	Pine	7,163	–	–	–	–	–	1	
S98	33° 16.8′	105° 34.6′	Turkey no 2	7,243	Psa	3	04-29-66	–	880	1,4	Also “Turkey”
S99	33° 16.4′	105° 33.8′	Turkey	7,360	–	–	–	–	–	1	
S100	33° 15.8′	105° 36.9′	Bear	7,592	Psa	0–1	–	–	–	1,4	

[1]Data sources as indicated: 1 (USGS 1:24,000 topographic maps); 2 (Mourant, 1963); 3 (White and Kues, 1992); 4 (Sloan and Garber, 1971); 5 (Davis and others, 1979); 6 (Riesterer and others, 2006).

[2]Comments include other names, additional information, or other observations such as estimated flow on other dates.

On the east end of the study area, a large zone of spring flow occurs near the mouths of the Rio Bonito and Rio Ruidoso, where Colonel Fritz (S74, fig. 13) and Peter Hurd (S72, fig. 13) Springs produce about 500 gal/min of combined flow. Both springs are located within 3 mi of the Rio Hondo, where the Tinnie-Dunken Anticlinorium crosses the Rio Hondo. Both springs are interpreted as expressions of the decreased transmissivity of the groundwater system because of folding of the Yeso Formation, thereby creating a damming effect and resulting in the emergence of spring flow in the river valleys.

Groundwater Levels

The USGS NWIS database contains water-level measurements from 218 wells in the upper Rio Hondo Basin (table 4; numbers are not sequential, and there are gaps after wells 195 and 202). Water-level data begin in 1947, and periods of water-level record for these wells range from less than 1 year to 57 years. These historical data were examined and used to evaluate long-term water-level changes in the basin.

As part of this study, bimonthly water-level measurements were made at 47 wells from 2008 to 2010, following procedures described in Cunningham and Schalk (2011). This monitoring well network was used to construct water-level maps and to measure the water-level response to seasonal changes in precipitation. These data are available in the USGS NWIS (http://waterdata.usgs.gov/nwis) database (U.S. Geological Survey, 2010).

The USGS also deployed vented continuous (hourly) data recorders in four wells that recorded water levels (wells 95, 164, 168, 176; fig. 13, table 4); the data were collected and processed following procedures in Freeman and others (2004). Data from six additional continuous recorders, deployed between 2006 and 2009, were obtained from the Sandia National Laboratory (Sandia National Laboratories, 2010) and compared with the records from the USGS recorders. Continuous data recorders were also deployed in several wells in the southern Sacramento Mountains as part of a multiyear study by the NMBGMR (Newton and others, 2012) and provided data for comparison to the upper Rio Hondo Basin. The continuous water-level data provided more detailed and complete records of water-level changes over the scale of hours, days, and weeks and were used to examine water-level response to recharge or other events.

A generalized, regional-scale water-level map of the study area was constructed (fig. 13) by using data contained in the USGS NWIS database (table 4) and from the spring inventory (table 3). Contour intervals of 100 ft were used over most of the area, which is consistent with potential estimation error in topographic elevation (as much as 20 ft) and with historical water-level variations, which only rarely showed fluctuations of more than 25–50 ft (see “Long-Term Water-Level Changes” section). The most recent water level in the period of record from each well was used in constructing the map. User-reported depth-to-water data from New Mexico Office of the State Engineer (2010) were also used as indicators of additional points for the water-level map, but these were not always used in the contouring process because the locations and depths were not verified in the field by the USGS.

Contouring identified two areas where shallow and deep wells were completed over separate vertical extents, and a large vertical head difference was found in the depth-to–water data. The steep downward vertical gradient in these areas could be because of recharge conditions, deep pumping, or both. This situation was observed in the north part of the study area near the Capitan Mountains, where a shallow aquifer (depth to water about 50 ft) in alluvium or Triassic rocks overlies a deep aquifer (depth to water about 600 ft) in Permian rocks. These aquifers are separated by the Grayburg Formation, which presumably acts as an aquitard between the two. A similar situation was observed near Alto and Angus, where wells are completed in shallow and deep aquifers, reflecting a large vertical head difference between the Cretaceous and Permian aquifers, or between wells completed in the alluvium and in the underlying bedrock. For the most part, however, head differences between closely spaced wells generally fell within the 100-ft contour interval.

Figure 13 shows that on a regional scale, the aquifer systems are interconnected and continuous, allowing for a smooth contouring of observed water levels. Where sufficient data are available, more detailed local-scale water-level maps for specific areas could identify areas where geology or structural features may affect local groundwater-movement patterns. Groundwater-flow direction is generally eastward and towards the river valleys. The contours flatten markedly at the foot of the Capitan Mountains and Sierra Blanca, indicating a lower gradient and higher transmissivity in the sedimentary strata as opposed to the volcanic rocks. In the westernmost part of the study area, the gradient is on the order of 0.1 (more than 500 feet per mile [ft/mi]), whereas in the eastern part, the gradient is on the order of 0.006 (30 ft/mi).

The gradient is also markedly lower in the northwestern part of the study area near Capitan, indicating either a higher transmissivity in this area or less recharge from Salado Creek. Contours do not deflect around the stream, thereby indicating little stream-aquifer interaction, most likely because of the intermittent nature of the stream and the presence of the thick, low-permeability Grayburg Formation.

Deep upstream retrenchments in the contour patterns indicate groundwater discharge to the upper part of the Rio Ruidoso, which accounts for the gaining stream reach in this section. Contours are much steeper on the southern side of the Rio Ruidoso, indicating lower transmissivity or steeper topographic relief in recharge areas on this side and suggesting that the deep topographic indentation of the Rio Ruidoso intercepts groundwater moving northward and discharges it to the stream. The same water-level patterns occur for the last few miles near the mouth of the Rio Ruidoso.

Table 4. Groundwater wells and water levels in the upper Rio Hondo Basin study area.

[ID, identification number; latitude and longitude referenced to the North American Datum of 1983; °, degree; ′, minute; water surface elevation, WSEL; WSEL referenced to the North American Vertical Datum of 1988; 1950s water levels were collected from 1947–66 and 1980s water levels were collected from 1984–94; –, no data]

Well ID	Latitude	Longitude	U.S. Geological Survey site ID	Most recent WSEL date	Most recent WSEL	1950s–80s water-level change (feet)	1980s–2003 water-level change (feet)	2003–10 water-level change (feet)
0	33° 36.2′	105° 42.8′	333610105424301	04-17-57	6,232.57	–	–	–
1	33° 35.6′	105° 43.6′	333538105433301	01-31-01	6,150.26	–	–	–
2	33° 35.6′	105° 43.3′	333537105431901	01-31-01	6,100.06	–	–	–
3	33° 34.8′	105° 42.8′	333446105424701	01-31-01	6,245.87	–	–	–
4	33° 38.1′	105° 36.7′	333804105364201	07-24-03	7,175.30	–	–	–
5	33° 36.3′	105° 33.1′	333619105330201	01-13-94	6,504.41	–	–	–
6	33° 36.5′	105° 36.8′	333632105364701	03-01-56	6,872.60	–	–	–
7	33° 36.5′	105° 36.8′	333632105364702	03-01-56	6,868.96	–	–	–
8	33° 36.5′	105° 36.8′	333632105364703	06-23-88	6,804.35	–	–	–
9	33° 35.8′	105° 36.8′	333549105364801	07-24-03	6,779.39	5.9	-1.0	–
10	33° 35.5′	105° 34.4′	333532105342201	07-22-03	6,629.65	–	–	–
11	33° 35.4′	105° 34.4′	333526105342101	07-22-03	6,638.12	–	-2.4	–
12	33° 36.0′	105° 33.8′	333602105334401	07-24-03	6,539.93	–	-48.2	–
13	33° 35.5′	105° 33.9′	333531105335101	07-24-03	6,543.43	–	–	–
14	33° 36.1′	105° 33.3′	333606105331301	07-24-03	6,540.53	–	-1.9	–
15	33° 35.9′	105° 31.4′	333555105312301	06-28-88	6,603.12	0.2	–	–
16	33° 34.8′	105° 33.1′	333451105330201	08-13-09	6,440.28	6.5	-5.5	1.9
17	33° 34.8′	105° 33.7′	333447105334101	03-31-94	6,459.65	33.1	–	–
18	33° 35.5′	105° 34.6′	333530105343401	07-22-03	6,652.46	–	-22.2	–
19	33° 35.4′	105° 34.6′	333525105343301	07-22-03	6,640.33	–	–	–
20	33° 35.1′	105° 34.4′	333507105342201	07-24-03	6,571.38	–	–	–
21	33° 34.6′	105° 35.3′	333437105351601	07-23-03	6,529.68	–	-97.9	–
22	33° 34.8′	105° 36.6′	333446105363701	07-24-03	6,599.57	–	-6.0	–
23	33° 33.9′	105° 31.3′	333353105311801	03-04-03	6,210.24	–	-1.0	–
24	33° 33.6′	105° 31.3′	333340105310901	07-26-10	6,184.38	–	–	–
25	33° 35.4′	105° 28.5′	333523105283101	07-28-10	6,617.89	23.2	-4.9	-12.5
26	33° 35.4′	105° 28.6′	333524105283201	03-06-56	6,621.22	–	–	–
27	33° 34.0′	105° 28.8′	333400105284601	06-28-88	6,020.54	0.9	–	–
28	33° 30.7′	105° 41.4′	333040105411901	07-27-10	7,078.32	36.1	-18.3	9.0
29	33° 30.6′	105° 41.4′	333036105412201	03-07-03	7,084.64	–	–	–
30	33° 31.0′	105° 37.6′	333058105373101	07-26-10	6,668.77	–	–	2.3
31	33° 30.1′	105° 38.4′	333008105382201	08-01-68	6,745.02	18.2	–	–
32	33° 30.1′	105° 37.6′	333009105373301	05-25-10	6,676.74	–	–	–
33	33° 30.2′	105° 37.6′	333011105373601	06-01-56	6,692.18	–	–	–
34	33° 30.1′	105° 37.9′	333004105375101	03-31-94	6,727.34	1.5	–	–
35	33° 30.1′	105° 37.9′	333004105375102	03-07-03	6,725.52	–	-2.9	–
36	33° 29.8′	105° 40.4′	332948105402301	03-07-03	6,977.13	2.7	-6.9	–
37	33° 29.8′	105° 40.4′	332946105402201	01-28-04	6,965.89	5.2	-7.7	–
38	33° 29.3′	105° 40.7′	332918105404201	01-11-79	7,051.09	–	–	–
39	33° 29.1′	105° 38.1′	332905105380401	01-06-84	6,854.39	5.9	–	–
40	33° 33.4′	105° 34.2′	333325105341101	08-13-09	6,376.39	4.7	-1.0	1.0
41	33° 33.6′	105° 34.4′	333333105342201	03-06-03	6,378.34	–	–	–
42	33° 32.6′	105° 36.3′	333229105361401	07-26-10	6,517.38	–	-9.5	[1]5.0
43	33° 32.7′	105° 34.2′	333241105341101	08-01-68	6,299.17	33.2	-1.2	–

Table 4. Groundwater wells and water levels in the upper Rio Hondo Basin study area.—Continued

[ID, identification number; latitude and longitude referenced to the North American Datum of 1983; °, degree; ′, minute; water surface elevation, WSEL; WSEL referenced to the North American Vertical Datum of 1988; 1950s water levels were collected from 1947–66 and 1980s water levels were collected from 1984–94; –, no data]

Well ID	Latitude	Longitude	U.S. Geological Survey site ID	Most recent WSEL date	Most recent WSEL	1950s–80s water-level change (feet)	1980s–2003 water-level change (feet)	2003–10 water-level change (feet)
44	33° 32.5′	105° 33.9′	333233105335301	03-30-94	6,303.38	–	–	–
45	33° 32.6′	105° 33.7′	333236105333801	07-28-93	6,304.40	–	–	–
46	33° 32.4′	105° 31.8′	333222105314701	07-22-03	6,173.97	–	-40.9	–
47	33° 32.2′	105° 31.8′	333214105314501	07-21-03	6,165.94	34.3	-11.9	–
48	33° 32.3′	105° 31.4′	333216105312401	07-22-03	6,159.91	–	–	–
49	33° 32.0′	105° 31.9′	333156105315001	07-26-10	6,165.32	–	-19.5	9.3
50	33° 32.0′	105° 34.3′	333154105341001	07-26-10	6,378.06	–	1.8	-4.2
51	33° 30.5′	105° 36.0′	333032105355901	07-23-03	6,648.92	–	4.5	–
52	33° 31.2′	105° 34.4′	333107105341901	05-24-10	6,435.32	–	-1.3	[1]1.0
53	33° 30.3′	105° 35.3′	333016105351501	07-23-03	6,589.09	3.5	-1.4	–
54	33° 29.9′	105° 31.7′	332953105313401	07-28-10	6,026.84	–	-17.3	9.1
55	33° 29.7′	105° 31.8′	332937105314501	07-28-10	6,193.27	–	–	3.7
56	33° 30.1′	105° 35.4′	333009105352301	07-27-88	6,601.81	–	–	–
57	33° 33.1′	105° 30.7′	333307105304101	07-24-03	6,148.43	10.1	-11.8	–
58	33° 31.3′	105° 28.1′	333139105302601	07-26-10	5,982.33	2.5	-0.7	2.8
59	33° 31.7′	105° 30.5′	333139105302601	03-13-86	6,035.64	–	–	–
60	33° 30.5′	105° 30.0′	333030105294801	07-26-10	6,037.56	–	–	–
61	33° 29.3′	105° 28.3′	332914105281201	07-28-10	6,067.59	–	–	–
62	33° 33.0′	105° 21.6′	333259105213101	07-26-10	6,542.07	–	–	–
63	33° 33.3′	105° 23.7′	333315105233801	03-04-03	6,338.32	–	-7.0	–
64	33° 32.6′	105° 22.5′	333238105223001	07-26-10	6,212.78	–	–	–
65	33° 30.3′	105° 24.0′	333018105235501	05-01-56	5,738.62	–	–	–
66	33° 30.3′	105° 19.1′	333017105190301	01-01-45	5,770.40	–	–	–
67	33° 29.6′	105° 23.0′	332938105225901	01-12-94	5,679.94	0.9	–	–
68	33° 29.5′	105° 23.0′	332929105225701	02-02-04	5,679.52	2.6	-2.8	–
69	33° 29.5′	105° 23.0′	332932105225901	07-26-10	5,679.82	–	–	–
70	33° 29.5′	105° 23.0′	332928105225901	12-15-55	5,677.47	–	–	–
71	33° 29.4′	105° 23.0′	332927105225801	12-15-55	5,677.56	–	–	–
72	33° 29.4′	105° 23.2′	332925105230901	02-15-89	5,680.46	1.3	–	–
73	33° 29.5′	105° 22.9′	332928105225301	07-24-56	5,662.42	–	–	–
74	33° 29.3′	105° 22.9′	332919105225501	02-01-54	5,673.29	–	–	–
75	33° 29.3′	105° 22.9′	332920105225201	02-02-04	5,666.84	–	-7.8	–
76	33° 24.8′	105° 44.7′	332449105443901	03-17-09	7,972.43	–	–	–
77	33° 24.6′	105° 44.4′	332436105442601	03-17-09	7,912.30	–	–	–
78	33° 24.3′	105° 44.3′	332419105441901	05-26-07	7,818.26	–	–	–
79	33° 24.3′	105° 44.3′	332419105441902	05-26-07	7,814.76	–	–	–
80	33° 24.4′	105° 44.3′	332427105441901	03-17-09	7,842.14	–	–	–
81	33° 24.2′	105° 44.3′	332413105441601	09-03-08	7,826.92	–	–	–
82	33° 24.2′	105° 44.3′	332411105441701	07-28-93	7,735.37	–	-310.0	–
83	33° 24.2′	105° 44.3′	332410105441501	11-16-07	7,783.41	–	–	–
84	33° 24.1′	105° 44.2′	332405105441201	09-06-08	7,773.52	–	–	–
85	33° 24.0′	105° 44.2′	332402105441401	03-17-08	7,726.06	–	–	–
86	33° 24.0′	105° 44.2′	332402105441201	03-08-03	7,360.12	–	–	–
87	33° 24.0′	105° 44.1′	332357105440401	06-9-09	7,738.04	–	–	–

Table 4. Groundwater wells and water levels in the upper Rio Hondo Basin study area.—Continued

[ID, identification number; latitude and longitude referenced to the North American Datum of 1983; °, degree; ′, minute; water surface elevation, WSEL; WSEL referenced to the North American Vertical Datum of 1988; 1950s water levels were collected from 1947–66 and 1980s water levels were collected from 1984–94; –, no data]

Well ID	Latitude	Longitude	U.S. Geological Survey site ID	Most recent WSEL date	Most recent WSEL	1950s–80s water-level change (feet)	1980s–2003 water-level change (feet)	2003–10 water-level change (feet)
88	33° 28.0′	105° 39.3′	332801105391601	03-29-94	7,047.83	–	–	–
89	33° 27.7′	105° 38.7′	332744105384301	01-14-99	6,983.30	13.0	–	–
90	33° 27.9′	105° 39.5′	332757105392801	03-29-94	7,161.35	37.8	–	–
91	33° 28.1′	105° 39.3′	332804105391901	07-23-03	7,058.10	–	–	–
93	33° 26.6′	105° 38.5′	332638105382901	07-27-10	6,756.80	–	–	–
94	33° 26.2′	105° 37.9′	332611105375501	07-27-10	6,947.19	–	–	–
95	33° 26.7′	105° 40.2′	332641105394501	7-27-10	6,892.37	0.7	–	–
96	33° 25.6′	105° 40.4′	332538105402301	07-27-10	7,356.87	–	-28.7	19.3
97	33° 26.0′	105° 38.8′	332558105384901	07-27-10	6,999.89	–	–	–
98	33° 25.9′	105° 37.6′	332552105373401	07-28-10	7,004.86	–	–	–
99	33° 24.5′	105° 37.8′	332432105374501	04-05-94	7,063.56	–	–	–
100	33° 24.7′	105° 39.0′	332444105385801	07-21-93	7,093.85	–	–	–
101	33° 24.5′	105° 41.7′	332430105414301	10-01-60	7,624.80	–	–	–
102	33° 23.6′	105° 39.8′	332337105394801	01-14-99	7,187.25	–	-105.3	–
103	33° 27.4′	105° 36.6′	332723105363401	07-27-10	6,574.16	–	–	–
104	33° 27.2′	105° 37.4′	332710105372301	07-27-10	6,673.87	–	–	–
105	33° 26.9′	105° 36.6′	332655105363101	01-11-94	6,718.88	3.8	–	–
106	33° 26.9′	105° 36.3′	332655105361501	07-27-10	6,786.25	–	–	–
107	33° 27.4′	105° 35.3′	332722105351301	07-07-88	6,576.95	–	–	–
108	33° 26.2′	105° 35.1′	332610105350601	07-23-03	6,705.49	1.6	7.8	–
109	33° 26.7′	105° 36.4′	332643105362301	07-27-10	6,717.50	–	–	–
110	33° 26.7′	105° 36.9′	332644105365501	07-27-10	6,782.62	–	–	–
111	33° 25.7′	105° 36.7′	332543105363901	02-02-04	6,882.62	32.4	-18.8	–
112	33° 25.4′	105° 34.8′	332527105345101	07-27-10	6,164.65	–	–	–
113	33° 25.5′	105° 34.0′	332529105340201	07-27-10	6,172.75	–	–	–
114	33° 23.6′	105° 37.0′	332336105370301	01-07-09	6,740.47	–	–	–
115	33° 23.6′	105° 37.0′	332343105362701	07-27-10	6,806.96	–	–	2.4
116	33° 23.8′	105° 35.9′	332347105355601	12-02-08	6,706.20	–	–	–
117	33° 26.1′	105° 28.2′	332607105281101	02-22-07	5,859.54	1.7	-0.3	–
118	33° 26.7′	105° 30.3′	332642105301501	07-22-03	6,288.63	–	-0.2	–
119	33° 26.0′	105° 30.4′	332600105302401	07-22-03	6,138.68	–	-8.5	–
120	33° 26.1′	105° 27.7′	332604105274201	02-02-04	5,830.60	1.0	-2.2	–
121	33° 25.8′	105° 27.4′	332545105272101	01-15-99	5,769.73	1.7	–	–
122	33° 25.0′	105° 25.9′	332459105255301	07-14-55	5,665.43	–	–	–
123	33° 25.0′	105° 25.9′	332459105255302	04-05-94	5,670.37	3.0	–	–
124	33° 24.9′	105° 26.4′	332456105261901	02-04-04	5,694.62	–	–	–
125	33° 24.7′	105° 26.9′	332443105265001	01-11-79	5,722.22	–	–	–
126	33° 24.5′	105° 26.9′	332446105264901	09-03-08	5,739.26	1.5	0.0	12.1
127	33° 24.7′	105° 29.4′	332440105291901	02-04-04	6,018.65	–	-3.2	–
128	33° 24.0′	105° 29.8′	332358105294601	01-12-84	5,903.02	–	–	–
129	33° 24.0′	105° 29.8′	332358105294602	07-17-56	6,001.57	–	–	–
130	33° 23.8′	105° 28.5′	332402105282201	07-26-10	5,823.17	4.2	-3.9	3.4
131	33° 24.4′	105° 27.8′	332423105274599	01-06-84	5,759.38	-4.2	–	–
132	33° 24.2′	105° 27.2′	332410105271101	07-22-03	5,762.92	–	–	–

Table 4. Groundwater wells and water levels in the upper Rio Hondo Basin study area.—Continued

[ID, identification number; latitude and longitude referenced to the North American Datum of 1983; °, degree; ′, minute; water surface elevation, WSEL; WSEL referenced to the North American Vertical Datum of 1988; 1950s water levels were collected from 1947–66 and 1980s water levels were collected from 1984–94; –, no data]

Well ID	Latitude	Longitude	U.S. Geological Survey site ID	Most recent WSEL date	Most recent WSEL	1950s–80s water-level change (feet)	1980s–2003 water-level change (feet)	2003–10 water-level change (feet)
133	33° 23.9′	105° 27.2′	332355105270701	07-26-10	5,767.70	–	–	[1]4.0
134	33° 24.1′	105° 27.2′	332406105270701	07-22-03	5,763.96	–	–	–
135	33° 23.9′	105° 27.1′	332356105270301	07-22-03	5,752.81	–	–	–
136	33° 27.1′	105° 20.0′	332706105195901	02-15-89	5,479.14	-1.1	–	–
137	33° 27.2′	105° 19.5′	332713105192501	02-22-07	5,475.18	3.3	-2.4	–
138	33° 24.8′	105° 19.9′	332446105195201	01-10-89	5,358.20	–	–	–
139	33° 24.7′	105° 19.8′	332441105194901	01-12-79	5,357.16	–	–	–
140	33° 24.7′	105° 19.8′	332443105194601	02-04-04	5,356.80	–	–	–
141	33° 24.5′	105° 19.6′	332428105193301	01-16-79	5,343.30	–	–	–
142	33° 24.5′	105° 19.4′	332428105191901	01-04-94	5,334.91	-12.5	–	–
143	33° 25.2′	105° 21.9′	332510105215501	01-11-84	5,469.78	6.3	–	–
144	33° 25.0′	105° 21.3′	332459105211501	01-16-79	5,438.28	5.4	–	–
145	33° 25.2′	105° 23.3′	332514105231801	01-15-99	5,537.28	3.8	–	–
146	33° 24.1′	105° 19.0′	332408105185701	04-06-94	5,311.83	4.4	–	–
147	33° 26.7′	105° 16.8′	332644105164901	01-01-54	5,426.31	–	–	–
148	33° 26.2′	105° 16.3′	332610105161701	07-21-03	5,453.61	–	–	–
149	33° 25.3′	105° 18.4′	332521105180701	02-22-07	5,328.28	7.6	-7.6	–
150	33° 25.4′	105° 15.7′	332522105152801	08-09-88	5,350.10	–	–	–
152	33° 25.0′	105° 17.4′	332458105170701	02-15-89	5,316.31	18.8	–	–
153	33° 24.7′	105° 17.5′	332440105172601	01-01-55	5,479.22	–	–	–
154	33° 24.6′	105° 17.1′	332437105170301	07-26-10	5,284.19	–	–	4.0
155	33° 24.7′	105° 17.1′	332444105165201	06-30-09	5,319.59	-0.9	1.0	-1.2
156	33° 25.2′	105° 18.4′	332509105182001	01-01-54	5,293.22	–	–	–
157	33° 23.7′	105° 18.1′	332344105180401	01-04-62	5,244.70	–	–	–
158	33° 24.2′	105° 17.1′	332411105170501	05-26-93	5,213.00	–	–	–
159	33° 24.2′	105° 16.9′	332409105165401	08-10-91	5,209.00	–	–	–
160	33° 23.7′	105° 17.5′	332340105171401	02-23-07	5,246.14	0.0	-1.7	–
161	33° 23.8′	105° 16.6′	332346105163601	07-22-03	5,178.75	–	–	–
162	33° 23.7′	105° 16.8′	332340105163101	07-22-03	5,204.72	–	-3.2	–
163	33° 23.1′	105° 38.9′	332304105385401	05-06-82	7,080.00	–	–	–
164	33° 22.8′	105° 38.6′	332247105383401	07-27-10	7,021.30	–	–	–
165	33° 22.7′	105° 38.6′	332244105383401	05-05-82	7,016.92	–	–	–
166	33° 22.8′	105° 38.4′	332245105382001	05-05-82	6,982.00	–	–	–
167	33° 22.2′	105° 41.9′	332209105415001	01-06-84	7,149.88	0.9	–	–
168	33° 21.7′	105° 41.3′	332144105411901	07-27-10	7,042.42	-1.4	-4.3	[1]1.0
169	33° 22.0′	105° 39.6′	332209105415001	07-27-10	6,886.23	–	–	–
170	33° 22.5′	105° 38.7′	332228105383801	07-27-10	6,983.77	–	–	–
171	33° 21.2′	105° 39.2′	332112105391201	05-06-82	6,817.17	–	–	–
172	33° 21.7′	105° 39.6′	332141105393501	11-18-09	6,896.21	–	–	–
173	33° 20.6′	105° 40.2′	332036105401101	01-27-03	6,761.86	29.1	-53.5	–
174	33° 20.2′	105° 40.0′	332015105395801	02-02-89	6,724.83	23.0	–	–
175	33° 20.2′	105° 40.1′	332036105401101	08-05-02	6,696.90	6.5	-12.0	–
176	33° 20.2′	105° 40.1′	332005105400201	07-28-10	6,718.81	77.0	-3.2	5.0
177	33° 20.8′	105° 38.7′	332051105383801	07-28-10	6,666.00	–	–	2.0

Table 4. Groundwater wells and water levels in the upper Rio Hondo Basin study area.—Continued

[ID, identification number; latitude and longitude referenced to the North American Datum of 1983; °, degree; ′, minute; water surface elevation, WSEL; WSEL referenced to the North American Vertical Datum of 1988; 1950s water levels were collected from 1947–66 and 1980s water levels were collected from 1984–94; –, no data]

Well ID	Latitude	Longitude	U.S. Geological Survey site ID	Most recent WSEL date	Most recent WSEL	1950s–80s water-level change (feet)	1980s–2003 water-level change (feet)	2003–10 water-level change (feet)
178	33° 19.4′	105° 38.0′	331922105375601	04-17-56	6,456.57	–	–	–
179	33° 19.5′	105° 37.5′	331929105372701	01-05-79	6,434.88	–	–	–
180	33° 18.7′	105° 38.1′	331842105380301	01-11-94	6,610.65	17.1	–	–
181	33° 18.7′	105° 38.1′	331840105380301	04-19-56	6,599.26	–	–	–
182	33° 23.4′	105° 36.8′	332326105364701	01-04-79	6,863.95	–	–	–
183	33° 21.5′	105° 32.7′	332129105323701	01-10-79	6,118.91	–	–	–
184	33° 21.2′	105° 33.8′	332113105334301	07-22-03	6,177.11	-1.0	-0.9	–
185	33° 21.0′	105° 33.6′	332102105333601	08-01-68	6,179.93	1.8	-2.5	–
186	33° 20.2′	105° 34.8′	332010105344601	01-10-79	6,266.12	–	–	–
187	33° 20.3′	105° 34.6′	332020105343401	01-15-99	6,259.25	0.1	–	–
188	33° 19.8′	105° 35.2′	331948105350101	07-28-10	6,268.01	–	–	–
189	33° 20.0′	105° 36.3′	332001105361701	07-22-03	6,212.81	–	–	–
190	33° 20.0′	105° 36.1′	322000105360201	05-18-94	6,301.00	–	–	–
191	33° 20.0′	105° 36.3′	321959105360201	03-22-10	6,302.62	–	-15.5	[1]16.0
192	33° 19.7′	105° 36.5′	331944105362501	03-06-03	6,294.81	–	–	–
193	33° 22.5′	105° 31.1′	332230105310601	07-26-10	6,014.14	–	–	–
194	33° 20.1′	105° 19.7′	332005105194001	10-04-93	5,532.48	–	–	–
195	33° 22.9′	105° 15.7′	332254105154101	07-23-93	5,174.56	–	–	–
199	33° 23.6′	105° 16.5′	332336105160801	01-13-56	5,189.12	–	–	–
200	33° 23.4′	105° 16.3′	332322105161701	07-22-03	5,180.60	–	–	–
201	33° 23.5′	105° 16.3′	332331105160101	01-13-56	5,181.72	–	–	–
202	33° 23.5′	105° 16.8′	332329105164301	07-28-10	5,221.17	–	-0.4	-0.5
218	33° 21.2′	105° 16.8′	332112105164701	12-13-55	5,342.19	–	–	–
219	33° 21.3′	105° 16.5′	332120105162501	01-05-94	5,340.98	–	–	–
220	33° 21.2′	105° 17.2′	332111105171101	01-05-94	5,369.64	–	–	–
221	33° 21.2′	105° 18.1′	332113105180301	01-05-94	5,411.26	–	–	–
222	33° 21.3′	105° 17.9′	332119105173702	01-11-79	5,407.26	–	–	–
223	33° 21.2′	105° 18.0′	332112105180001	10-04-93	5,418.87	–	–	–
224	33° 20.7′	105° 17.8′	332042105174801	01-05-94	5,418.85	–	–	–
225	33° 20.9′	105° 17.2′	332054105170901	01-17-79	5,405.13	–	–	–
227	33° 30.6′	105° 30.0′	333033105300201	01-08-09	6,032.62	–	–	–
228	33° 31.8′	105° 30.4′	333149105302601	07-26-10	6,030.40	–	–	–
229	33° 21.1′	105° 39.2′	332105105390901	09-15-90	6,787.50	–	–	–
230	33° 21.6′	105° 39.5′	332134105392801	04-25-90	6,843.00	–	–	–
231	33° 24.9′	105° 26.5′	332457105263001	07-24-56	5,674.45	–	–	–
232	33° 33.3′	105° 42.3′	333315105421601	01-10-81	6,457.58	–	–	–
233	33° 33.3′	105° 42.3′	333316105421701	02-17-76	6,433.80	–	–	–
234	33° 33.3′	105° 42.3′	333316105421702	03-18-57	6,433.46	–	–	–
235	33° 33.5′	105° 42.3′	333328105421601	01-10-81	6,421.84	–	–	–
236	33° 33.6′	105° 41.5′	333334105413001	02-23-76	6,487.58	–	–	–
237	33° 33.9′	105° 42.3′	333354105421601	01-10-81	6,381.94	–	–	–
238	33° 36.9′	105° 33.3′	333655105331301	05-08-56	6,666.80	–	–	–

[1]Water-level change is rounded to the nearest foot because of uncertainties associated with the historical measuring point.

Contours along the Rio Bonito indicate that groundwater discharges to the stream for several miles east of Bonito Lake to near Angus, suggesting that streamflow should increase from groundwater discharge in this reach. Contours are not strongly deflected by the stream channel between Angus and Fort Stanton, suggesting there is little net gain or loss between the stream and groundwater system in this area. Near Government Spring, an anomalously low-gradient area occurs along the Rio Bonito, possibly indicating higher transmissivity in this area. Contours are poorly constrained for several miles east of Government Spring along the Rio Bonito and do not clearly define the stream-aquifer connection in this area. The last several miles of the Rio Bonito show that groundwater contours deflect upstream into the valley and suggest that streamflow is sustained by groundwater inflow in this reach.

Long-Term Water-Level Changes

Changes in water levels over the last 60 years were evaluated by comparing water-level maps, by reviewing historical well hydrographs, and by mapping the changes in water levels between selected time periods. These changes in water levels were evaluated in order to analyze the effects of decadal-scale climate cycles (wet and dry periods) on water levels within the study area. It should be noted that the analysis period began during a drought period in the 1950s and ended in 2010 after three anomalously wet periods in the preceding 5 years (2006, 2008, and 2010).

The regional water-table map in figure 13 was compared with earlier water-table maps of the study area prepared by Mourant (1963) and by Donohoe (2004). The general water-level contour patterns and water-table elevations among the maps are similar, indicating that any changes in the groundwater-flow system are not discernible with the available data density and at the scale illustrated by 100-ft contour intervals.

Long-term water-level changes were also reported by Donohoe (2004), who compared 64 water-level measurements from wells measured in the 1950s to those measured in 2003. Several hydrographs contained in the Donohoe (2004) report show that water levels rose from the 1950s to the 1980s and 1990s but declined by 2003. Water levels were found to have had a median increase of about 4 ft in the north and 2 ft in the south. Both the 1950s and 2003 were drought periods in the study area.

Well hydrographs were analyzed for 75 wells for which sufficient period of record existed in the USGS NWIS database (table 4). Selected hydrographs, presented in figure 14, indicate that changes in water levels have occurred over decadal-scale cycles. In general, wells show lower water levels in the 1950s, broad water-level rises in the late 1980s and early 1990s, lower water levels in 2003, and water-level rises from 2006 to 2010. These decadal-scale water-level changes are broadly coincident with periods of drought in the 1950s, wet periods in the late 1980s and early 1990s, periods of drought in the early to mid-2000s, and wet periods from 2006 to 2010 (fig. 7). Water-level data for wells in the NWIS database with sufficient data in the selected time periods were reviewed to identify the lowest water levels in the mid-1950s, the highest water levels in the late 1980s to early 1990s, the lowest water levels in 2003, and the highest water levels in 2010. Water-level changes among these time periods were then calculated (table 4) and displayed on the maps in figures 15*A*, 15*B*, and 15*C*.

Water-level changes from the 1950s to the 1980s are presented in figure 15*A*. Water levels designated as the 1950s were collected from 1947 to 1966, and the 1980 water levels were collected from 1984 to 1994. The average water-level change in these 55 wells for the 1950s to 1980s time period was a rise of 9.4 ft. The largest rises in water levels were 77 ft near Ruidoso and almost 40 ft in the areas around Angus and Capitan; water-level rises in the eastern part of the study area were from 2 ft to almost 20 ft. Figure 15*B* shows the water-level change from the 1980s to 2003, with an average water-level decline of 17.0 ft in 55 wells. Again, the greatest changes were in the central part of the study area. Declines of more than 100 ft were observed along Eagle Creek and of nearly 100 ft were observed near Capitan, but most water levels declined from 1 to 25 ft in the central part of the study area. In the eastern part of the area, the water-level declines ranged from less than a foot to nearly 8 ft (fig. 15*B*). Between 2003 and 2010, water levels rose an average of 4.0 ft at 24 sites in the study area (fig. 15*C*). The largest responses were about 16 to nearly 20 ft and were centered in the central and southern parts of the study area. Responses in the eastern part of the study area ranged from slight declines to water-level rises of as much as 4 ft.

Based on the analysis of groundwater data, it is apparent that long-term, decadal scale, groundwater-level changes occur across the upper Rio Hondo Basin. Groundwater-level declines and recoveries on the order of tens of feet are typical in the central part of the study area, whereas 2- to 5-ft variations are typical in the eastern part of the study area. Larger magnitude groundwater-level changes also can occur in localized areas, such as along Eagle Creek. These water-level variations are generally coincident with periods of higher and lower precipitation in the study area and may also be affected by localized groundwater withdrawals.

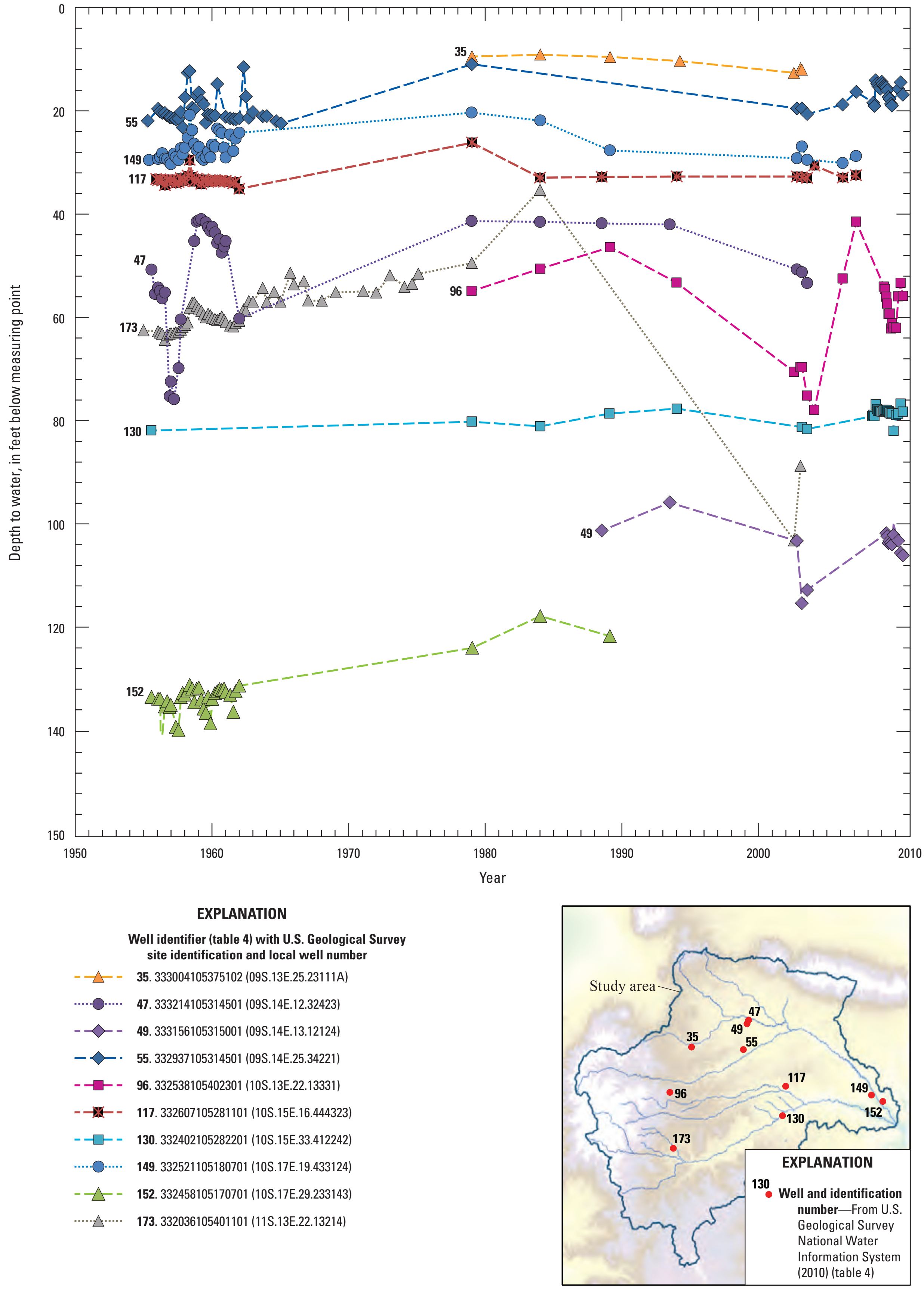


Figure 14. Long-term hydrographs for selected wells in the upper Rio Hondo Basin study area, Lincoln County, New Mexico.

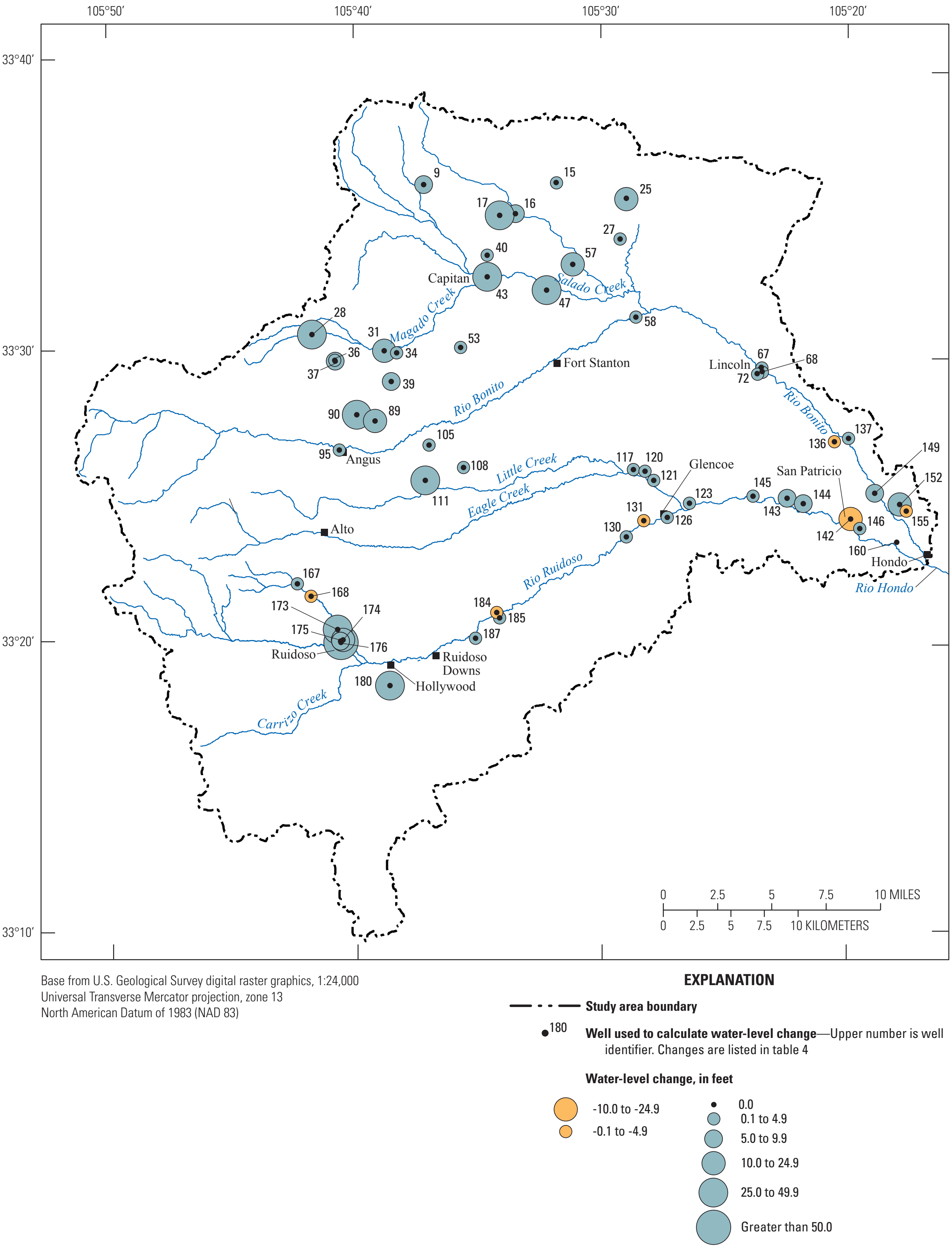


Figure 15*A*. Generalized long-term water-table elevation. *A*, changes from the 1950s lows to the 1980s highs; *B*, changes from the 1980s highs to 2003 lows; and *C*, changes from 2003 lows to 2010 highs for the upper Rio Hondo Basin study area, Lincoln County, New Mexico.

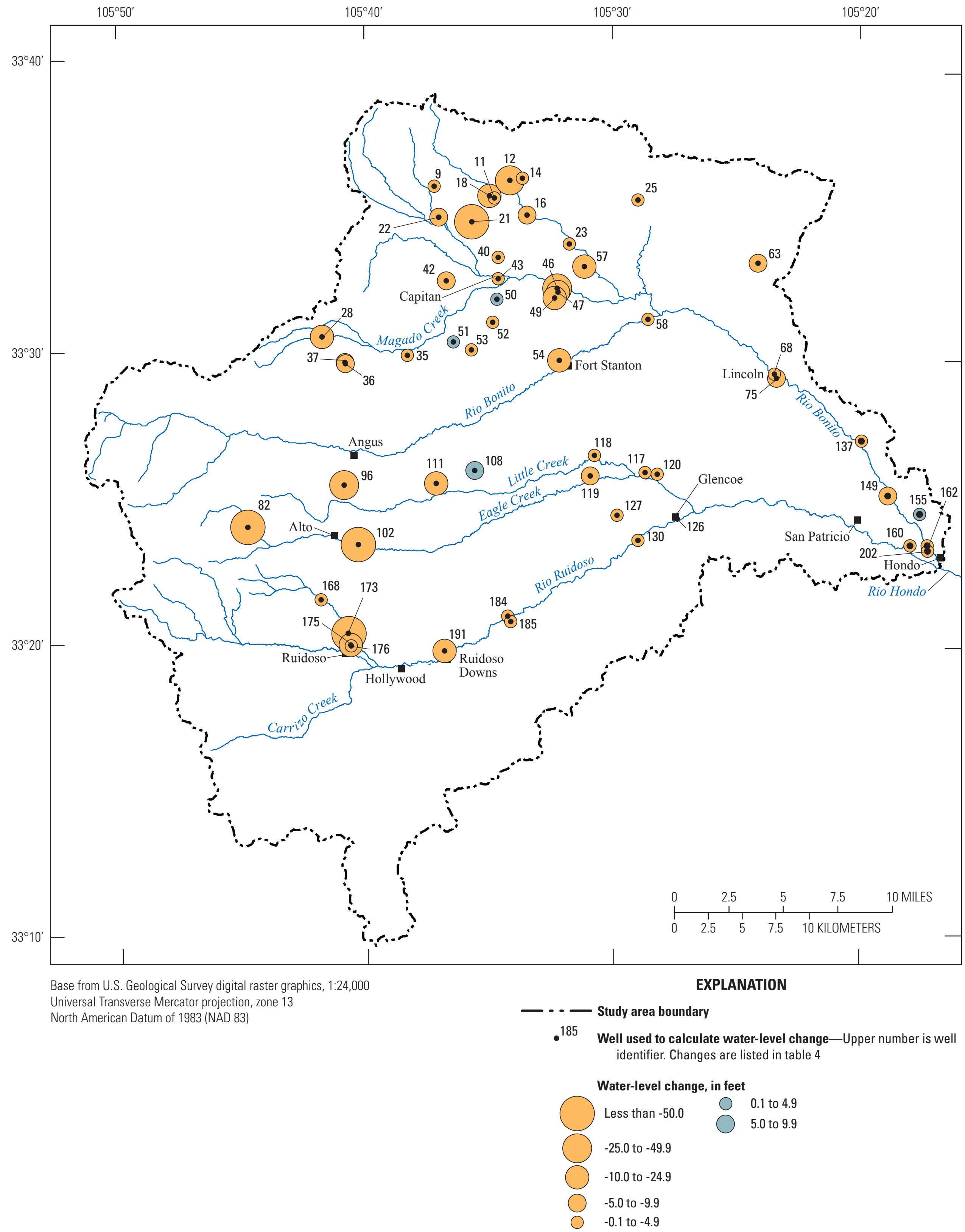


Figure 15*B*. Generalized long-term water-table elevation. *A*, changes from the 1950s lows to the 1980s highs; *B*, changes from the 1980s highs to 2003 lows; and *C*, changes from 2003 lows to 2010 highs for the upper Rio Hondo Basin study area, Lincoln County, New Mexico.—Continued

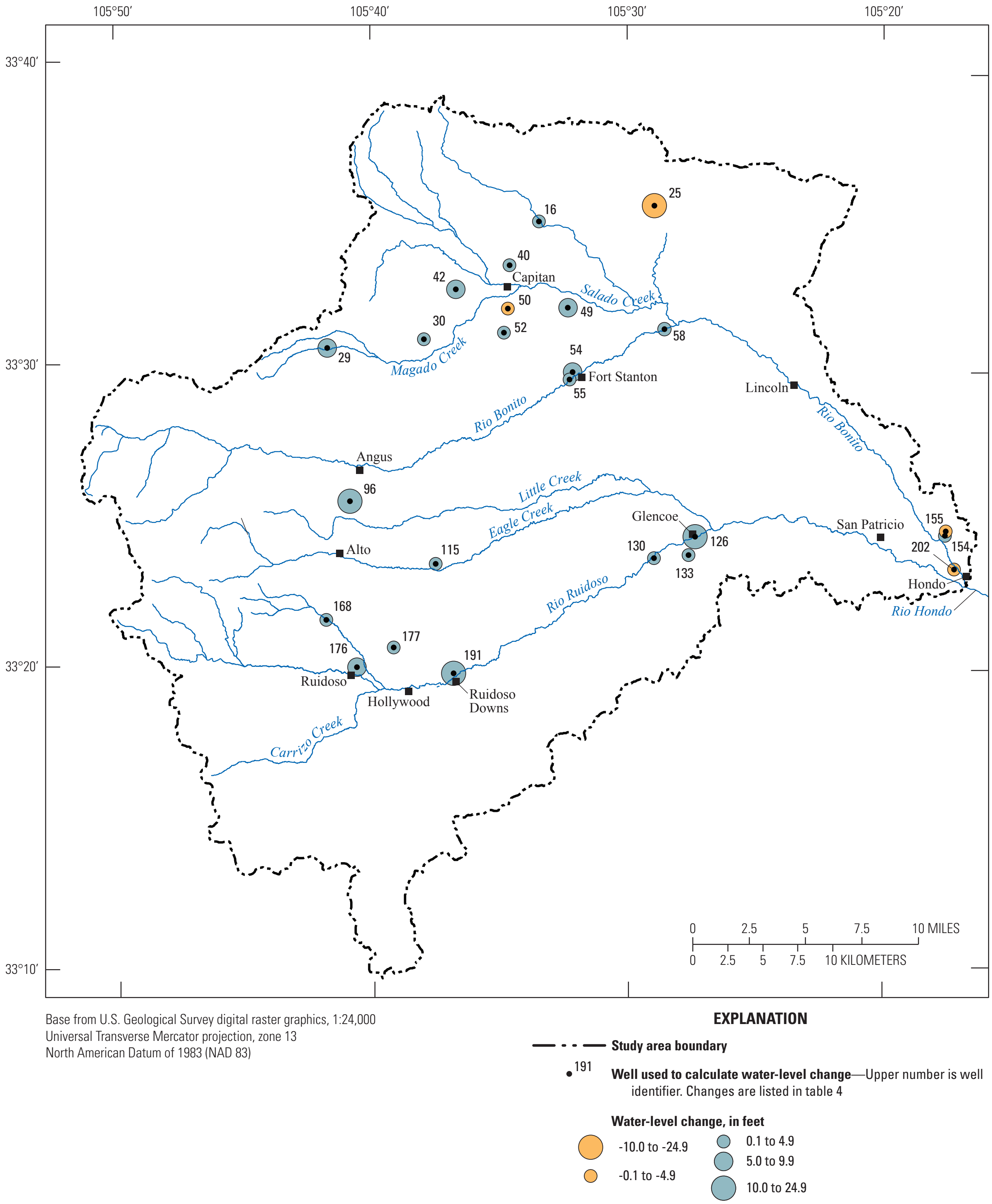


Figure 15*C*. Generalized long-term water-table elevation. *A*, changes from the 1950s lows to the 1980s highs; *B*, changes from the 1980s highs to 2003 lows; and *C*, changes from 2003 lows to 2010 highs for the upper Rio Hondo Basin study area, Lincoln County, New Mexico.—Continued

Short-Term Water-Level Changes

Short-term water-level changes (defined as those occurring on a daily, monthly, or annual scale) were identified by examining data collected from four wells fitted with continuous data recorders in 2008. Data show short-term water-table rises in 2008 and 2010 in response to a large monsoon and snowmelt season, respectively (fig. 16); aquifer response time to the recharge events varied from hours to several months.

Donohoe (2004) measured water levels in 64 wells in the upper Rio Hondo Basin in March and July of 2003 and found that water levels in 51 wells declined during this time by a few feet to as much as 10 ft. These declines were probably influenced by seasonal pumping, which is greatest in late spring to early July before the monsoon season begins. These declines may have also been influenced by the drought that culminated in 2003. At the foot of the Capitan Mountains following spring runoff, increases in water levels near the mountain front exceeded 10 ft in wells completed in the Grayburg Formation and in Triassic aquifers (wells 13, 30, and 31; Donohoe, 2004), indicating a local recharge source to these shallow perched aquifer systems.

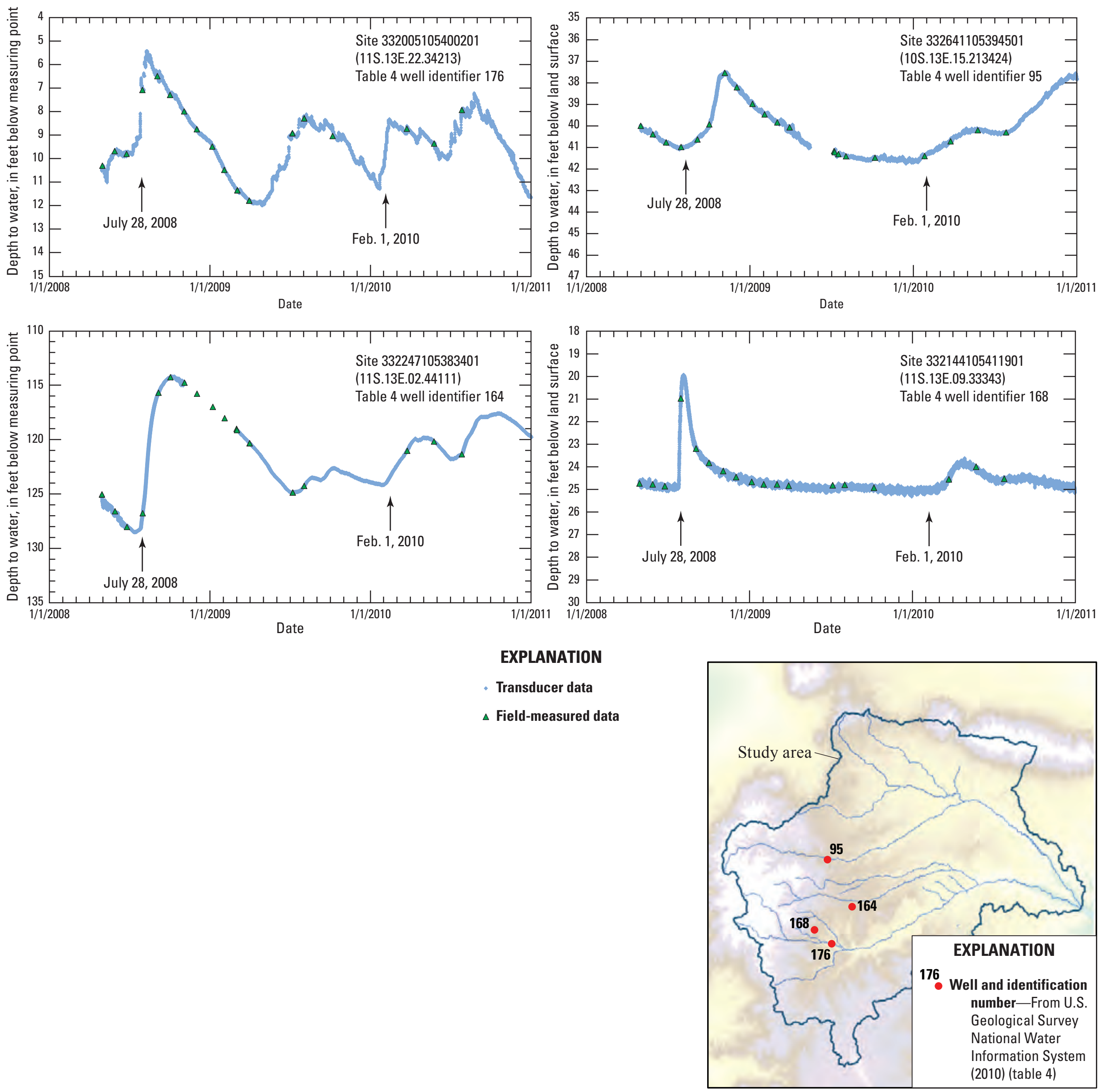


Figure 16. Hydrographs (water-level time series) of wells with continuous water-level recorders in the upper Rio Hondo Basin study area, Lincoln County, New Mexico.

Analogous responses to individual recharge events have also been documented in the similar nearby climatic and hydrogeologic setting of the southern Sacramento Mountains (Walsh, 2008; Newton and others, 2012). Continuous data recorders deployed in this area from 2006 through 2008 showed water-level rises of a few feet to as much as 45 ft in response to recharge events (Newton and others, 2012). It is notable that the wettest months in the local historical record, which spans more than 100 years, occurred during the monsoon seasons of 2006 and 2008, and pumping wells were reportedly not present in the area where these water-level recorders were deployed (Talon Newton, New Mexico Bureau of Geology and Mineral Resources, oral commun., 2011).

Corroborating evidence of the existence of punctuated instantaneous recharge events is the periodic occurrence of streamflow in the Snowy River Passage, a recently discovered section of Fort Stanton cave located northeast of Fort Stanton. The cave had been dry since its discovery, but streamflow lasting for several weeks or months was noted on the cavern floor in the summer of 2006, the summer of 2008, and the spring of 2010 (Talon Newton, New Mexico Bureau of Geology and Mineral Resources, oral commun., 2010).

Additional evidence of short-term groundwater-level changes was obtained from the operators of the Alto Lakes water system, where groundwater levels have been monitored regularly since the early 2000s. Nonpumping groundwater levels in this area were depressed by hundreds of feet during the drought of 2003, and decline rates as much as 20 feet per year (ft/yr) were reported (Livingston Associates P.C., 2004). Water-level rises from 70 to 290 ft, however, occurred in the summers of 2006 and 2008 (David Edington, Alto Lakes Water and Sanitation District, oral commun., 2011). These groundwater-level changes were heavily influenced by local pumping, but their rapid recovery supports the interpretation of quick recharge response.

Short-term water-level variations have also been documented in the North Fork Eagle Creek watershed. Several wells were installed in the North Fork Eagle Creek well field and were instrumented with continuous data recorders in 2007 and 2008. Shallow wells showed immediate water-level responses of 10 ft or more to streamflow from storm-runoff events (Matherne and others, 2010). The study also used temperature sensors to document recharge pulses from individual streamflow events in shallow monitoring wells.

Water Use from 1950 to 2010

This section of the report describes the data bearing on water use in the study area and provides summaries and estimates of water use over the last six decades. The types of uses, the sources (groundwater and surface water), the distributions in the study area, and the relative proportions of diversions, returns, and depletions are described. Changes in water-use patterns over the last six decades are also discussed.

The water-use estimates presented in this report were collected from a variety of sources. The NMOSE has prepared estimates of water diversions and depletions every 5 years for the last 3 decades (Sorenson, 1977, 1982; Wilson, 1986, 1992; Wilson and Lucero, 1997; Wilson and others, 2003; Longworth and others, 2008). Records from NMOSE Water Administration Technical Engineering Resource System database (New Mexico Office of the State Engineer, 2010) were examined for water use by individual wells and systems. Records of surface diversions and irrigated areas were adapted from NMOSE reports and from several hydrographic surveys conducted in the study area over the last century (New Mexico Territorial Engineer, 1909; Lee, 1912, 1916; Follett, 1914; Neel, 1932; Martinez, 1974, 1975).

Population estimates are included in NMOSE reports and were also taken from U.S. Census records (U.S. Department of Commerce, Bureau of the Census, 1995, 2000, 2010). Projections of population were taken from the Bureau of Business and Economic Research (University of New Mexico, 2008) and from a 40-year water plan prepared for the Village of Ruidoso (Wilson and Company, Inc., 2004). Additional data on water-supply systems were collected by reviewing consultant reports (Powell, 1954; Peery and Finch, 2001; Finch and others, 2004; Livingston Associates P.C., 2004; Daniel B. Stephens and Associates, Inc., 2007; Miller and others, 2007, 2008).

Land- and Water-Use Patterns

In the early 1800s, water resources in the study area began to be used for agricultural purposes such as farm use along the valleys of the Rio Bonito and Rio Ruidoso and livestock use over much of the area. The history of the upper Rio Hondo Basin includes a strong military presence in the late 1800s at Fort Stanton. Large-scale diversions for industrial purposes started in 1906 with the construction of the Bonito Pipeline to provide water for locomotive steam boilers. In the 1950s, the resident population increased because of tourism, recreation, horseracing, golf, and residential development. These changing patterns and quantities of water use have modified the hydrologic system and continue to do so.

The areal distribution of surface-water diversions, private domestic wells, agricultural or livestock wells, and municipal-supply or public-supply wells are portrayed in the map on figure 17. Irrigated agricultural lands are located along the main river valleys and in the eastern part of the study area and are primarily supplied by surface water through ditch systems known as acequias, which were established more than a century ago. Numerous private wells that supply homes and livestock with groundwater, as well as supplement agricultural needs, are also found along the river valleys. Subdivisions and incorporated areas are concentrated along the foothills of Sierra Blanca and the western Capitan Mountains and are supplied by public water-supply systems and private wells (fig. 17). Groundwater is used for public water supply, for commercial and recreational uses, for irrigation and livestock needs, and for domestic use, constituting the sole source for residential developments and subdivisions that are not connected to a centralized water supply. Three major surface-water diversions occur in the headwaters of the Rio Bonito, Rio Ruidoso, and Eagle Creek (fig. 17).

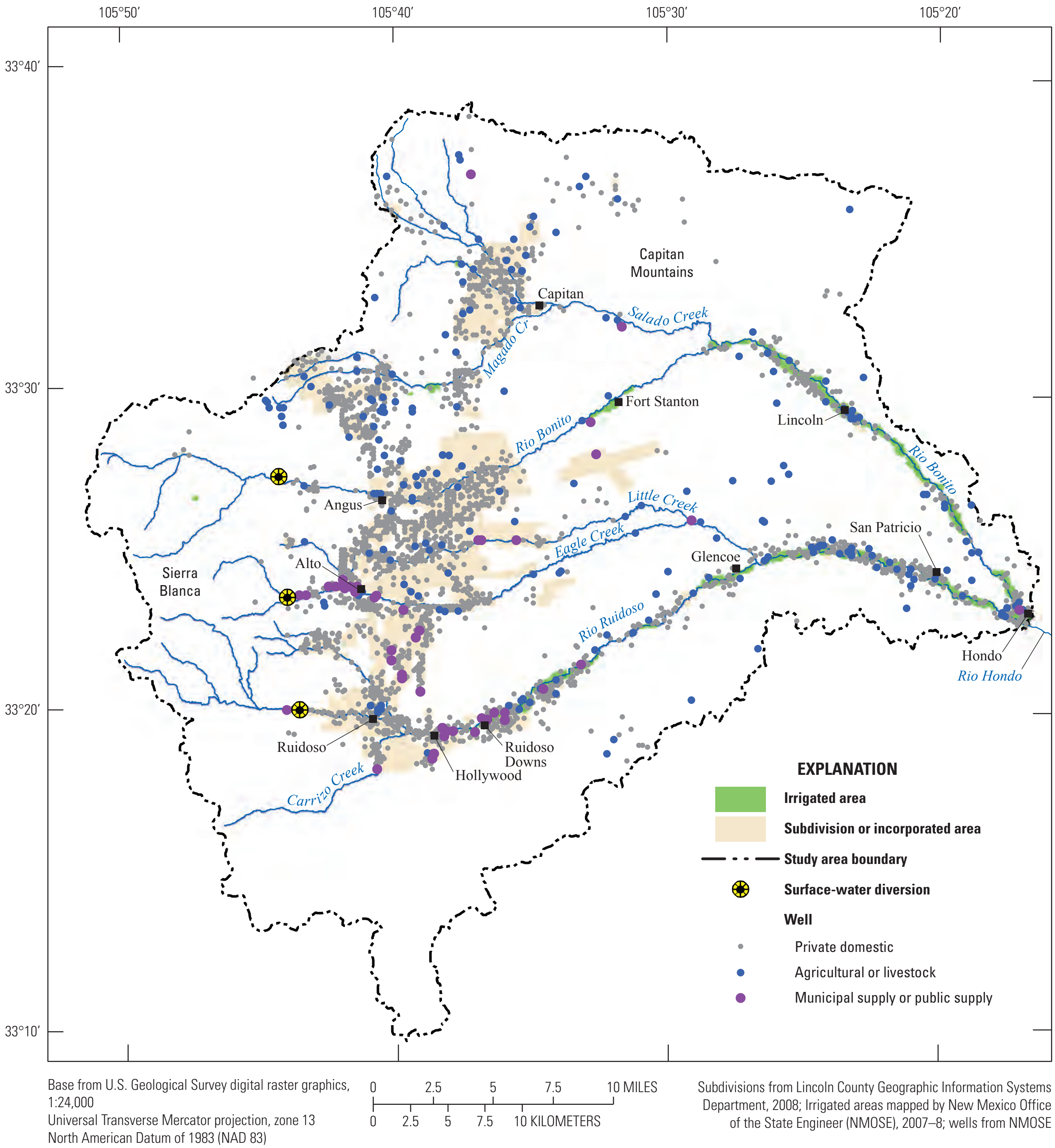


Figure 17. Areal distribution of surface-water diversions, private domestic wells, agricultural or livestock wells, and municipal-supply or public-supply wells in the upper Rio Hondo Basin study area, Lincoln County, New Mexico.

Diversion and Depletion Estimates

The 2005 water-use estimates are listed by category in table 5 and shown graphically in figure 18. Total diversions, defined as the total amount taken or withdrawn from a groundwater or surface-water source, were estimated at 24,413 acre-ft/yr (fig. 18*A–C*, table 5): about one-half for agricultural uses; one-quarter for public water supply, private-supply wells, livestock, and commercial and industrial uses; and the remainder for the Bonito Pipeline. Groundwater accounted for about one-third of the total (7,720 acre-ft/yr) and surface water about two-thirds (16,693 acre-ft/yr). Much of the water that is diverted is returned to the aquifer system by deep percolation or to the stream system by direct discharge. Depletion, defined as the net consumptive water use, was estimated at 13,527 acre-ft/yr or slightly more than one-half the amount of water diverted (fig. 18*D–F*): about one-half from agricultural uses; one-quarter from the Bonito Pipeline; and the remainder from other uses. About two-thirds of the water depleted (8,874 acre-ft/yr) were from surface water and the remainder (4,653 acre-ft/yr) was from groundwater. Each of the main categories of water use is discussed in the following sections in terms of the 2005 estimated water diversion and depletion.

Public Supply

The largest public water-supply system in the upper Rio Hondo Basin supplies the Village of Ruidoso, with total diversions in 2005 of 2,886 acre-ft/yr, as estimated by using per-capita water use and reported population (Longworth and others, 2008). The results agree with projected 2005 water-use estimates of 2,557 acre-ft/yr on the basis of metered production adjusted for losses from leakage, meter errors, and other factors (Wilson and Company, Inc., 2004). Surface water can account for as much as 70 percent of the Village of Ruidoso's water supply in years of adequate runoff (Daniel B. Stephens and Associates, Inc., 2007); although, in dry years, supply is provided entirely from groundwater. The Village of Ruidoso obtains surface water from two main sources: the Rio Ruidoso and Eagle Creek (fig. 17). The water is stored in Alto and Grindstone Reservoirs (fig. 1) and is mixed with groundwater from a network of as many as 10 wells. Direct surface-water diversions of as much as 306 acre-ft/yr from the Rio Ruidoso are permitted, although as much as about 800 acre-ft/yr of additional diversions are possible by using effluent credit at the wastewater-treatment plant downstream on the Rio Ruidoso. Four wells located in the North Fork Eagle Creek watershed together are capable of producing as much as about 1,200 acre-ft/yr (Finch and others, 2004). A number of supplemental wells are also piped either to the Alto Reservoir or directly to the adjacent water-treatment system. Direct surface-water diversions of Eagle Creek streamflow are also made to Alto Reservoir and may reach a maximum of 2,172 acre-ft/yr (Wilson and Company, Inc., 2004).

Another important municipal diversion is the Bonito Pipeline, which began diverting water from the upper Rio Bonito watershed in 1906 for commercial use as a freshwater supply (fig. 17). Early diversion estimates exceeded 5,000 acre-ft/yr, but system losses from the wooden pipeline and leakage from Nogal Lake probably returned a large percentage to the local system (Powell, 1954). Water-rights procedures in the 1950s limited the diversions to 3,088 acre-ft/yr, and since then, pipeline repairs and rerouting to bypass Nogal Lake have limited leakage and transmission losses. Water diverted through the Bonito Pipeline is considered a depletion because there is no return flow to the upper Rio Hondo Basin.

Public water suppliers include the City of Ruidoso Downs (407 acre-ft/yr), which diverts water primarily from Hale Spring (table 3, site S86, fig. 13), and the Village of Capitan (217 acre-ft/yr) and Fort Stanton (89 acre-ft/yr), which obtain water from pipelines and several groundwater wells (Longworth and others, 2008). Alto Lakes Water Corporation (201 acre-ft/yr) supplies water from wells in the Eagle Creek and Little Creek watersheds north of Ruidoso (New Mexico Office of the State Engineer, 2010). There are also numerous smaller public water-supply systems in the study area that are most concentrated between the Rio Ruidoso and the Rio Bonito watersheds along the foothills of Sierra Blanca (fig. 17). Typically, these smaller systems are cooperatives or subdivisions supplied by groundwater, with annual water use ranging from a few acre-feet per year to 55 acre-ft/yr. Records from NMED indicate there are more than two dozen smaller public water suppliers (each serving more than 15 connections or more than 24 persons), such as restaurants, campgrounds, lodges, and cabins. Of the total water diverted for public supply, wastewater-treatment plants typically return about 50 percent to the surface-water system; for example, the wastewater-treatment plant for the Village of Capitan returns about 55 percent of the total water diverted for public supply. Wastewater-treatment plants for the Village of Ruidoso and the City of Ruidoso Downs have very high return flows (82 percent), which may be the result of groundwater inflow to sewer lines (Pecos Valley Water Users Association, 2001). The wastewater-treatment plant for the Village of Ruidoso is an important source of return flow to the surface-water system. Losses in the water-supply system occur from leaks in piping systems, and estimates of water losses for the Village of Ruidoso are about 30 percent (Wilson and Associates, Inc., 2004; Daniel B. Stephens and Associates, Inc., 2007). In this report, 50 percent of the water diverted for all public water-supply use was considered as depletion and 50 percent as combined return flow from distribution losses and wastewater-treatment plant returns in order to provide a consistent comparison between the various public water-supply systems in the study area.

Table 5. Estimated 2005 water diversions and depletions from the upper Rio Hondo Basin study area, Lincoln County, New Mexico.

[All values in acre-ft/yr, acre-feet per year]

2005 diversions (acre-ft/yr)									
Source	Public water supply (domestic) systems[1]	Agriculture[2]	Private supply wells[3]	Bonito Pipeline[4]	Livestock[5]	Commercial and industrial[5]	Subtotal of domestic, commercial and industrial, and pipeline	Subtotal of agriculture and livestock	Total diversions
Groundwater	1,614	3,353	920	0	228	1,605	4,139	3,581	7,720
Surface water	2,383	11,028	0	3,088	194	0	5,471	11,222	16,693
Total	3,997	14,381	920	3,088	422	1,605	9,610	14,803	24,413

2005 depletions (acre-ft/yr)									
Source	Public water supply (domestic) systems[6]	Agriculture[7]	Private supply wells[8]	Bonito Pipeline[4]	Livestock[8]	Commercial and industrial[9]	Subtotal of domestic, commercial and industrial, and pipeline	Subtotal of agriculture and livestock	Total depletions
Groundwater	807	1,911	690	0	228	803	2,514	2,139	4,653
Surface water	1,192	4,400	0	3,088	194	214	4,280	4,594	8,874
Total	1,999	6,311	690	3,088	422	1,017	6,794	6,733	13,527

[1]Data reported from Longworth and others (2008).

[2]Based on water-use estimates in entire Rio Hondo Basin (Longworth and others, 2008), reduced to 71 percent to account for irrigated acreage.

within study area (2,720 acres on Rio Bonito and Rio Ruidoso) and excluding additional irrigated acreage on Rio Hondo (1,133 acres).

[3]Calculated based on number of wells in New Mexico Office of the State Engineer (2010) using 0.35 acre-ft/yr for private wells and 3.0 acre-ft/yr for shared wells.

[4]Based on allocated water right.

[5]As reported by Longworth and others (2008) for all of Lincoln County.

[6]Assumes 50 percent return flow for public water-supply systems.

[7]Excludes conveyance loss and assumes 57 percent crop consumptive use (Wilson, 1992; Wilson and Lucero, 1997).

[8]Assumes 25 percent return flow for self-supplied domestic wells and no return flow for stock wells.

[9]Assumes 50 percent return flow for most uses, and 214 acre-ft/yr lake evaporation loss (Wilson, 1986).

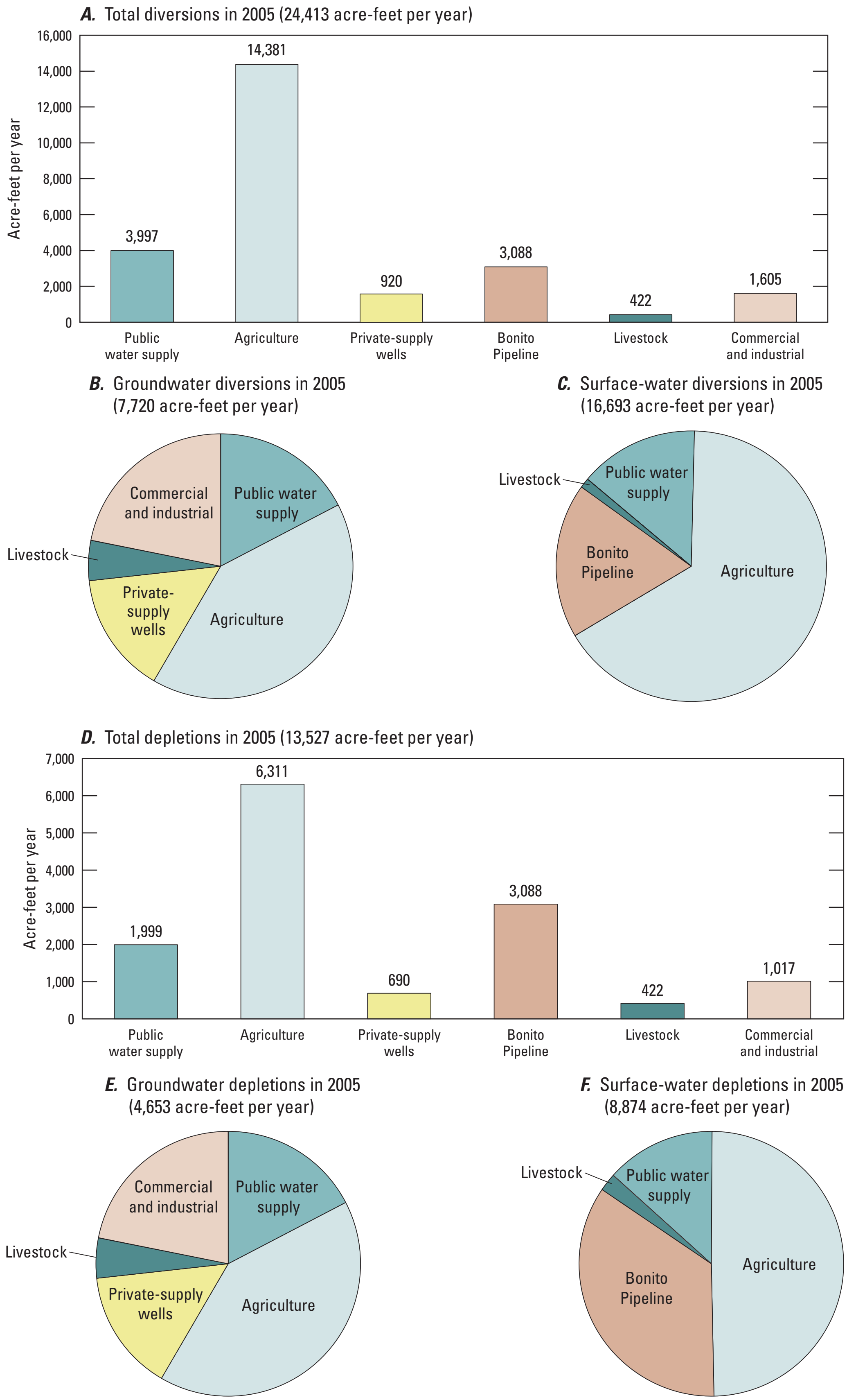


Figure 18. Charts showing diversions and depletions from the upper Rio Hondo Basin study area, Lincoln County, New Mexico, in 2005. *A*, total diversions; *B*, groundwater diversions; *C*, surface-water diversions; *D*, total depletions; *E*, groundwater depletions; and *F*, surface-water depletions.

Commercial and Industrial

The Links at Sierra Blanca golf course uses groundwater from two production wells supplied by the Village of Ruidoso, totaling an estimated 200 acre-ft/yr (Daniel B. Stephens and Associates, Inc., 2007). Cree Meadows Country Club and Innsbrook Village Country Club and Resort golf courses use groundwater from private wells and irrigation systems. Alto Lakes Water Corporation provides water for residents, golf courses, and country clubs; detailed water-use information is available for Alto Lakes Golf and Country Club (Peery and Finch, 2001), which has 143 irrigated acres and requires 270 acre-ft/yr of water. Other golf courses in the Ruidoso area include the Rainmakers Golf Community and the Outlaw Club at Lincoln Hill near Alto and the Inn of the Mountain Gods Resort and Casino near Mescalero Lake on the Mescalero Reservation.

Records of water diversions on the Mescalero Reservation are not publicly available. The Inn of the Mountain Gods Resort and Casino is supplied by wells and is the only large water user in the northern part of the Mescalero Reservation. No records were available for water-use estimates, but it is likely in the hundreds of acre-feet per year based on the size of the facility.

Ski Apache uses water to manufacture snow. Two ponds are used for storage in order to make snow when temperatures are sufficiently cold (Sterling Cane, Jr., Mescalero Apache Water Department, oral commun., 2010). Diversion from the ponds temporarily affects streamflow but returns to the system as snowmelt. Sublimation of the artificial snowpack also occurs, but a significant depletion is not anticipated from snowmaking at Ski Apache. A study on the Santa Fe Ski Area (Smart and Fleming, 1985) found a depletion of about 10 percent of the amount diverted, mostly because of evaporation during the snowmaking process. For the Santa Fe Ski Area, a total of 14 acre-ft/yr was diverted, and the depletion was calculated at 1.4 acre-ft/yr (Smart and Fleming, 1985). Another study at a northern New Mexico ski area estimated that 55 acre-ft/yr were diverted, of which 16 percent was lost, for a total depletion of 8.8 acre-ft/yr (Hirsch, 1988).

The total estimated commercial and industrial water diversion in 2005 was 1,605 acre-ft/yr from groundwater sources (fig. 18*A*, table 5). For this study, half of this amount (803 acre-ft/yr) was assumed to return to the aquifer system as deep percolation from irrigation of golf courses. Evaporation from lakes and reservoirs was estimated to average 214 acre-ft/yr (Wilson, 1986) and is considered a net depletion. Leakage from lakes was not considered in the water-use estimates because this water is returned directly to the subsurface.

Off-System Residential and Domestic Wells

Private domestic and shared wells are the source of water supply to private homes and to developments and subdivisions that are not connected to public water-supply systems. The 2005 NMOSE water-use summary report (Longworth and others, 2008) estimates rural self-supplied water in Lincoln County at 182 acre-ft/yr on the basis of a rural population of 2,026 and a per-capita water use of 80 gallons per day (or 0.09 acre-ft/yr). Review of the State well registry (New Mexico Office of the State Engineer, 2010), however, shows that the number of private domestic wells within the upper Rio Hondo Basin study area has increased by as much as 112 new wells each year to a 2010 total of 2,631 (fig. 19). This total excludes about 600 wells in the NMOSE database without proof of completion, such as drilling dates or drilling records.

The Pecos Valley Water Users Association (2001) used a higher water-use estimate for private single-household domestic wells than NMOSE: 0.25 acre-ft/yr to 0.35 acre-ft/yr. Private shared (or multiple-use) wells are allowed by permit to withdraw a total of 3.0 acre-ft/yr (New Mexico Office of the State Engineer, 2010). By using these higher water-use estimates, diversions in 2005 for all private domestic wells in the upper Rio Hondo Basin study area are estimated at 920 acre-ft/yr (fig. 18*A*, table 5). The percentage of private water use from wells has held constant relative to municipal water use, averaging 14 to 23 percent of municipal supply since 1980 (table 6).

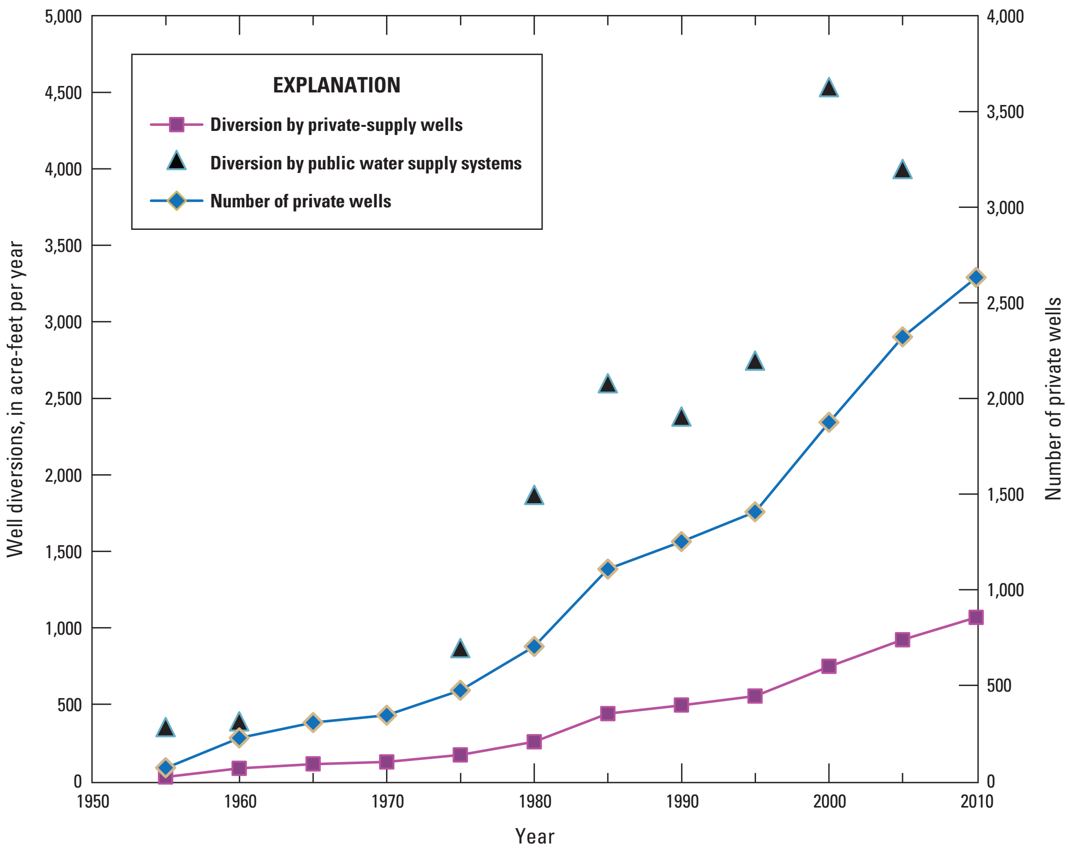


Figure 19. The diversion amounts for private and public water supply and the number of private wells registered in the upper Rio Hondo Basin study area, Lincoln County, New Mexico, 1955 to 2010.

Private domestic wells return wastewater to the system by septic tank infiltration. The quantity of return flow from septic tanks is not known, but it is reasonable to presume that a 50-percent return flow occurs in areas where depth to water is shallow (less than 30 ft), such as river valleys, or in areas where homes are close to streambeds (within 100 ft), such as along canyon sides (Pecos Valley Water Users Association, 2001). Assuming that half of the private domestic wells in the upper Rio Hondo Basin meet these criteria, the return flow would be 25 percent of diversions, or 230 acre-ft/yr, leaving a depletion estimate of 690 acre-ft/yr (fig. 18*D*, table 5). Considering the assumptions applied, this estimate is a reasonable maximum for water use by private domestic wells in the study area.

Livestock

As of 2010, there are 93 livestock wells registered with NMOSE in the upper Rio Hondo Basin with sufficiently detailed records to confirm the wells had been drilled and are likely in operation. There are an additional 91 livestock wells also listed in the NMOSE database for livestock use; however, the available records do not indicate depth, date, condition, yield, or any other information to confirm the wells had been drilled or are in operation. Many of these wells, however, may have been installed decades ago (prior to NMOSE registration requirements) and may still be in operation. Most of the livestock wells supply drinkers or small galvanized tanks (Juan Hernandez, New Mexico Office of the State Engineer, Roswell, oral commun., 2010). On the basis of this information, a maximum of 184 livestock wells are estimated to be in use in the study area.

Where these wells feed livestock ponds or tanks, it is likely that most of the water is used by the livestock or lost to evaporation or infiltration. Well permits for livestock use allow up to 3 acre-ft/yr for a single well, which may be piped several miles to feed multiple ponds or tanks, depending on the need. This amounts to a maximum total diversion of 552 acre-ft/yr for livestock wells in the study area. Over the last 25 years, NMOSE has estimated average livestock diversions of about 422 acre-ft/yr from groundwater and surface for Lincoln County (Longworth and others, 2008). Presuming that the study area contains most of the livestock in Lincoln County, this value is considered a maximum estimate of actual livestock diversion in the study area (fig. 18*A*, table 5).

Table 6. Estimated historical water diversion from the upper Rio Hondo Basin, Lincoln County, New Mexico.

[All values in acre-ft/yr, acre-feet per year; –, no data]

Year	Public water supply (domestic) systems[1]	Self-supplied (private) domestic wells[2]	Percentage of self-supplied wells to public water supply systems	Commercial and industrial[1,6]	Bonito Pipeline[3]	Stock[3,6]	Agriculture[5]	Subtotal of domestic, commercial, and industrial	Subtotal of agriculture and livestock	Total[6]
1950	349	23	7	–	3,088	–	17,580	–	–	21,930
1960	387	81	21	–	3,088	–	19,690	–	–	24,136
1970	–	122	–	–	3,088	–	20,393	–	–	25,119
1975	865	168	19	211	3,088	679	22,362	1,244	23,041	27,373
1980	1,866	253	14	725	3,088	753	18,389	2,844	19,142	25,074
1985	2,596	437	17	729	3,088	556	17,703	3,762	18,259	25,109
1990	2,379	493	21	822	3,088	563	17,721	3,694	18,284	25,066
1995	2,744	553	20	968	3,088	543	19,742	4,265	20,285	27,638
2000	4,531	746	16	1,040	3,088	605	14,363	6,317	14,968	24,373
2005	3,997	920	23	1,605	3,088	422	14,381	6,522	14,803	24,413
Average										25,023

[1]Data reported from New Mexico Office of the State Engineer for 1975–2005 (Sorenson, 1972, 1975; Wilson, 1986, 1992; Wilson and Lucero, 1997; Wilson and others, 2003; and Longworth and others, 2008). Estimates for 1950 and 1960 based on Dinwiddie (1963).

[2]Calculated based on number of wells reported by New Mexico Office of the State Engineer (2010) using 0.35 acre-ft/yr for private wells and 3.0 acre-ft/yr for shared wells.

[3]Based on allocated water right.

[4]Data reported from New Mexico Office of the State Engineer for 1975–2005 (Sorenson, 1972, 1975; Wilson, 1986, 1992; Wilson and Lucero, 1997; Wilson and others, 2003; and Longworth and others, 2008), for all stock wells in Lincoln County, provided as a maximum possible esimate.

[5]Estimate for 2005 based on New Mexico Office of the State Engineer water use estimates (Longworth and others, 2008) in entire Rio Hondo Basin, reduced by 71 percent to account for irrigated areas within only the Upper Rio Hondo study area; estimates for 1950 to 2000 based on total irrigated acreage in Lincoln County (Sorenson, 1972, 1975; Wilson, 1986, 1992; Wilson and Lucero, 1997; Wilson and others, 2003) reduced by 67 percent to account for irrigated areas within only the upper Rio Hondo study area, and applying the 2005 study area ratio of 5.3 of irrigated acreage to total agricultural diversion.

[6]For 1950, assume 1975 estimates for stock, commercial, and industrial diversions; for 1970 public water supply estimate, assume average of 1960 and 1975 estimates.

There are also a number of livestock ponds or dirt tanks that are fed solely by interception of ephemeral surface water. Permits allow storage of as much as 10 acre-ft of water in livestock ponds, and livestock ponds are often placed in ephemeral arroyos or in areas with high seepage and evaporation losses (Pecos Valley Water Users Association, 2001). In some reports, NMOSE had estimated livestock pond evaporation losses at 1,475 acre-ft/yr for Lincoln County (Sorenson, 1982; Wilson, 1986). Within the study area, however, temporary interception of runoff and retention in dry arroyo floors by livestock ponds or dirt tanks was not considered a depletion because retention of the surface flow allows slow infiltration of runoff that could have otherwise been lost to evaporation or outflow.

Agriculture

Irrigation for agriculture uses surface water and groundwater. When sufficient surface water is available, the acequias (irrigation ditches) can divert streamflow to meet crop needs; when sufficient surface water is not available, supplemental wells can be used. Over the last 20 years in the Rio Hondo Basin, 68 percent of the farms have been irrigated with surface water and 32 percent with groundwater (Wilson, 1986; Wilson and Lucero, 1997; Wilson and others, 2003; Longworth and others, 2008). Detailed estimates of agricultural depletions have been prepared by NMOSE for flood, sprinkler, and drip irrigation. The average depletion, or water loss because of crop consumptive use, was 57 percent of the total water applied to 1995 and 2000 agricultural acreage in the Rio Hondo Basin (Wilson and Lucero, 1997; Wilson and others, 2003).

As of 2005, there was a total of 2,720 acres of irrigated agricultural land in the study area, with 1,021 acres in the Rio Bonito watershed and 1,699 in the Rio Ruidoso watershed (Julie Valdez, New Mexico Office of the State Engineer, oral commun., 2010). An additional 1,100 or more acres were irrigated on the Rio Hondo watershed outside of the study area. Irrigated agricultural lands within the study area therefore comprised 71 percent of the total irrigated agricultural lands in the Rio Hondo Basin in 2005. More recent (2008) data show a drop in irrigated agricultural land in the upper Rio Hondo Basin to 2,471 acres (Ralph Campbell, New Mexico Office of the State Engineer, oral commun., 2010).

There are about 77 mi of ditch-conveyance systems on the Rio Ruidoso and Rio Bonito (Pecos Valley Water Users Association, 2001); considerable conveyance losses (leakage between the diversion point and the farm headgate) would be expected to occur from unlined ditches. The NMOSE estimates of conveyance losses in the entire Rio Hondo Basin ranged from 6,568 acre-ft/yr to 4,660 acre-ft/yr in 1995 and 2005, respectively (Wilson and Lucero, 1997; Longworth and others, 2008). These losses are not considered a depletion to the flow system because the leaked water returns directly to the local aquifer, reaching 80 percent or more of the amount flowing in the ditches in some New Mexico acequias (Fernald and others, 2010). Considering an average width of 2 ft and an evaporation rate of 4 ft/yr, open-water evaporation is about 75 acre-ft/yr over the 77 mi of ditches in the study area.

Table 5 summarizes the diversion and depletion estimates for 2005 in the study area. Agricultural diversions in the upper Rio Hondo Basin were estimated at 14,381 acre-ft/yr in 2005. Conveyance losses in the upper Rio Hondo Basin returned 3,309 acre-ft/yr to the system, and deep percolation returned 4,761 acre-ft/yr to the groundwater system. The net depletion from agriculture was 6,311 acre-ft/yr.

Historical Changes in Land and Water Use

Patterns in land and water use in the upper Rio Hondo Basin have changed since the 1950s, with a shift from primarily agricultural use to include expanding municipal, commercial, and recreational use. The proportion of land used for urban and recreational purposes has been estimated from 10 to 15 percent and is increasing rapidly (Upper Hondo Watershed Coalition, 2004). GIS data of the areal coverage of incorporated and subdivided areas, which do not include homes, cabins, and ranches in unincorporated areas, were analyzed and show a total of 34,168 acres, or 9.1 percent of the watershed area (Patsy Sanchez, Lincoln County, oral commun., 2010).

Historical trends in Lincoln County population and land-use patterns are shown in figure 20 and table 7. The population in Lincoln County roughly doubled from 10,997 to 21,016 for the period from 1980 to 2010 (U.S. Department of Commerce, Bureau of the Census, 1995, 2000, 2010). Population breakdowns of the Rio Hondo Basin, which include the town of Hondo outside the upper Rio Hondo Basin, have been prepared by NMOSE. The Rio Hondo Basin had a population of less than 3,000 residents in 1960 but more than 19,000 residents in 2005; in part, this reflects the population of Ruidoso, which has almost doubled from 1990 to 2005 (fig. 20, table 7). Nonresident population (summer residents and tourists) may also have a substantial effect on water use. Irrigated agricultural acreage, by contrast, has shrunk over the same time period, falling from a peak of more than 6,000 acres in the 1970s to about 4,000 acres countywide in 2005 (fig. 20). Almost all of the irrigated agricultural land in Lincoln County is within the Rio Hondo Basin, so these water-use trends reflect the increase in urban, commercial, and recreational activities in the incorporated areas and the gradual decrease of agricultural activities in the study area.

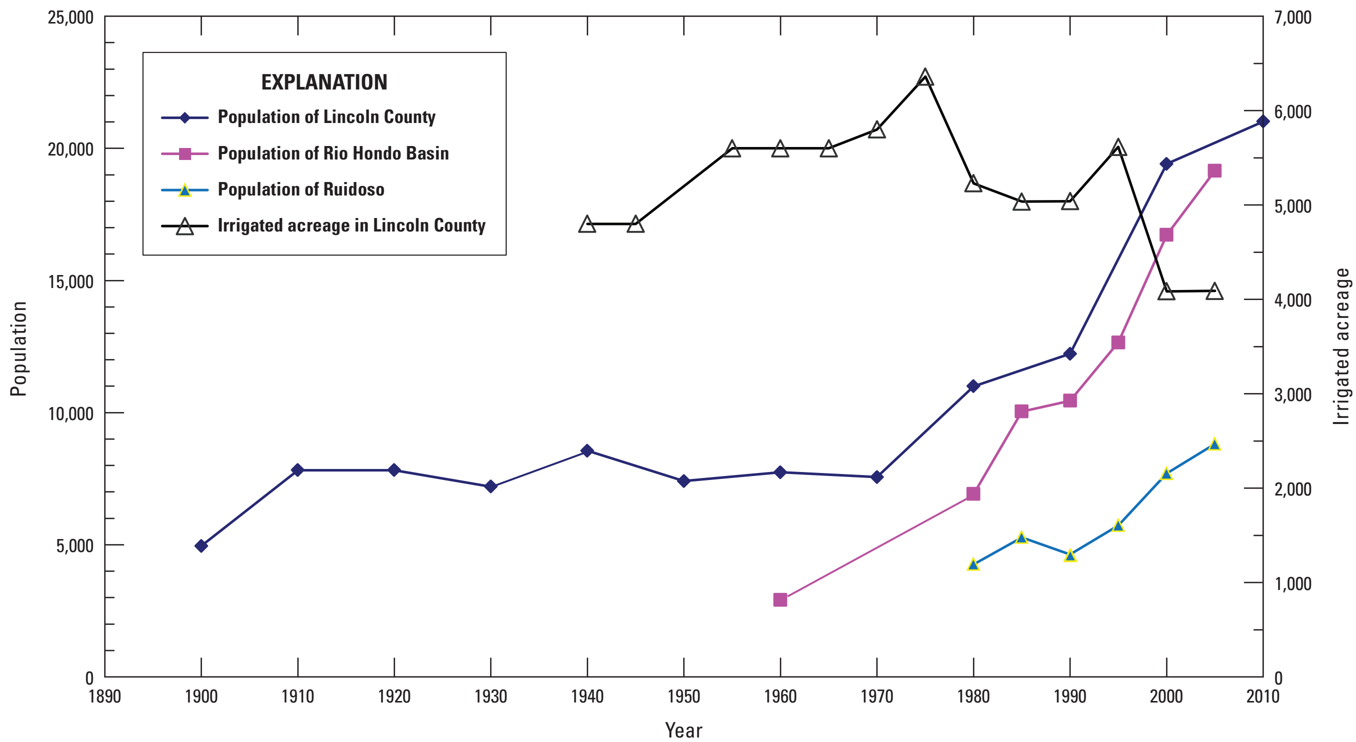


Figure 20. Historical population in Ruidoso, the Rio Hondo Basin, and in Lincoln County, compared to irrigated acreage in Lincoln County.

Table 7. Population and land-use patterns in Lincoln County, New Mexico, and in the upper Rio Hondo Basin, New Mexico.

[–, no data]

Year	Population of Lincoln County[1]	Population of Rio Hondo Basin[2,3]	Population of Ruidoso[3]	Percentage of Lincoln County population in Rio Hondo Basin[2]	Total irrigated acreage in Lincoln County[3]
1900	4,953	–	–	–	–
1910	7,822	–	–	–	–
1920	7,823	–	–	–	–
1930	7,198	–	–	–	–
1940	8,557	–	–	–	4,800
1945	–	–	–	–	4,800
1950	7,409	–	–	–	5,000
1955	–	–	–	–	5,600
1960	7,744	2,916	–	38	5,600
1965	–	–	–	–	5,600
1970	7,560	–	–	–	5,800
1975	–	–	–	–	6,360
1980	10,997	6,922	4,260	63	5,230
1985	–	10,043	5,280	–	5,035
1990	12,223	10,449	4,600	85	5,040
1995	–	12,653	5,728	–	5,615
2000	19,411	16,724	7,698	86	4,085
2005	–	19,156	8,812	–	4,090
2010	21,016	–	–	–	–

[1]Census data from U.S. Department of Commerce, Bureau of the Census (1995, 2000, 2010).

[2]Includes the towns of Picacho and Hondo, outside the upper Rio Hondo study area.

[3]Data from Sorenson (1977, 1982), Wilson (1986, 1992), Wilson and Lucero (1997), Wilson and others (2003), and Longworth and others (2008).

Historical water diversions are shown in figure 21 and table 6. Total diversions have increased from 21,930 acre-ft/yr in 1950 to 24,413 acre-ft/yr in 2005, averaging about 25,000 acre-ft/yr over that time period. Variations in the diversion rates are apparent with highs of more than 27,000 acre-ft/yr in 1975 and 1995. The total water diversion in figure 21 shows an annual increase of about 0.2 percent, or about 400 acre-ft/yr per decade. It is apparent from figure 21 that since about 1975 there has been an increase in the amount of water diverted for domestic purposes (public water supply and private wells), and commercial and industrial uses, and a decrease in the amount diverted for agricultural purposes.

Conceptual Hydrogeologic Model

Three hydrogeologic terranes in the upper Rio Hondo Basin are defined on the basis of aquifer characteristics, geologic structure, and hydrologic behavior: the Mountain Block, the Central Basin, and the Hondo Slope terranes (fig. 22). The terrane concept allows simplification of geologic and hydrologic properties on a regional scale with the purpose of integrating and conceptualizing the hydrogeologic framework of the study area. Each of these terranes exhibits unique hydrologic behavior with respect to the types of aquifer materials, groundwater recharge and movement, stream-aquifer interaction, and water availability and use. It should be noted that the boundaries of the hydrogeologic terranes are generalized and were selected to illustrate the functioning of the hydrologic system and do not necessarily follow the boundaries of individual subwatersheds (fig. 9).

Mountain Block Terrane

The Mountain Block terrane is coincident with Sierra Blanca and the Capitan Mountains and includes the areas higher than 8,000 ft in the study area (fig. 22). The area is characterized by high hydraulic gradients and high recharge rates. Precipitation exceeds evapotranspiration in the upland areas of the Mountain Block terrane. Streams exit the area onto the piedmont below. Groundwater flows eastward and is hydraulically well connected to surface flows. Runoff and aquifer recharge from the Mountain Block terrane serve as the source of almost all the groundwater and surface water in the upper Rio Hondo Basin.

Geologic units that form aquifers in the Mountain Block terrane include the Sierra Blanca Volcanics, the Cub Mountain Formation, and the intrusive rocks of the Capitan Mountains. The transmissivity of the Sierra Blanca Volcanics and Cub Mountain Formation is moderate to good, although the intrusive rocks are only water-bearing where heavily fractured. Brecciated or volcaniclastic zones between multiple flow units may create stratigraphically controlled water producing zones. Groundwater storage capacity in Mountain Block terrane units is likely to be relatively low to moderate, though the units may reach 2,000 ft in thickness. A regional study in the high Sacramento Mountains south of the study area (Newton and others, 2012) used geochemical and isotopic data to illustrate that spring water and groundwater in the high mountains is young (recently recharged) water.

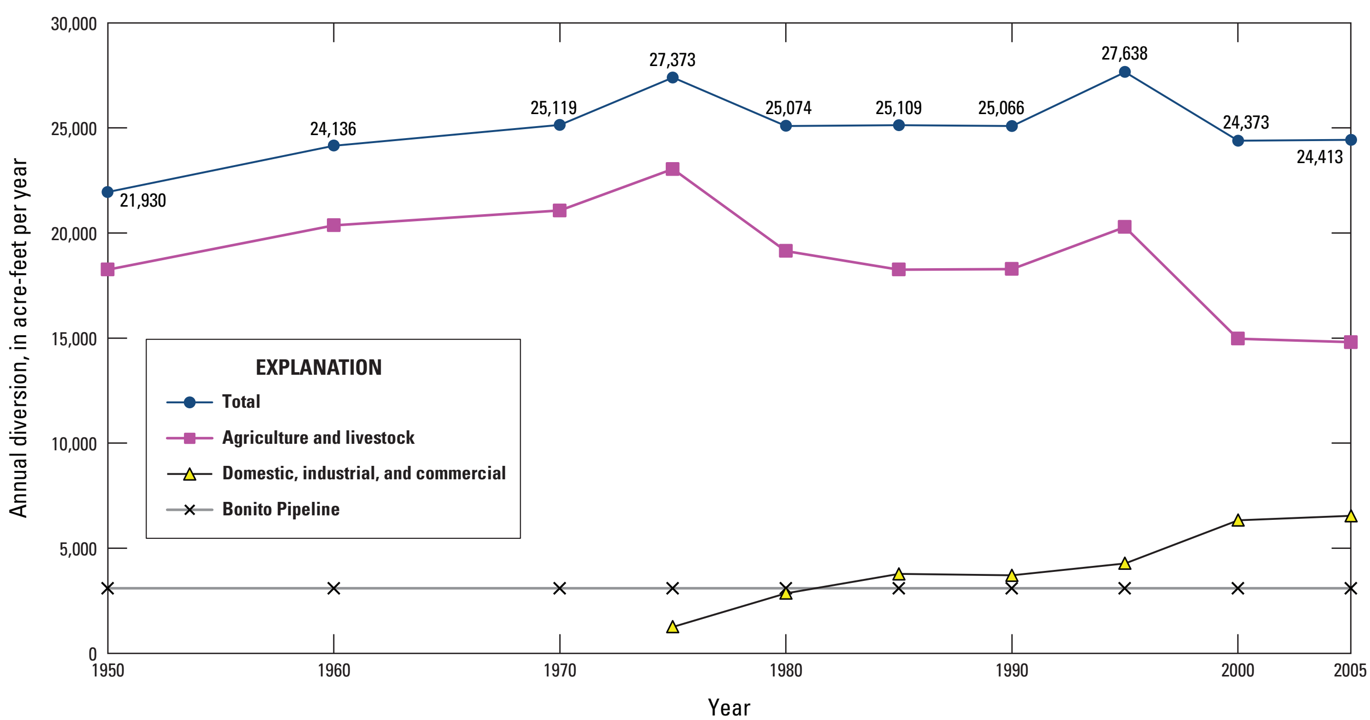
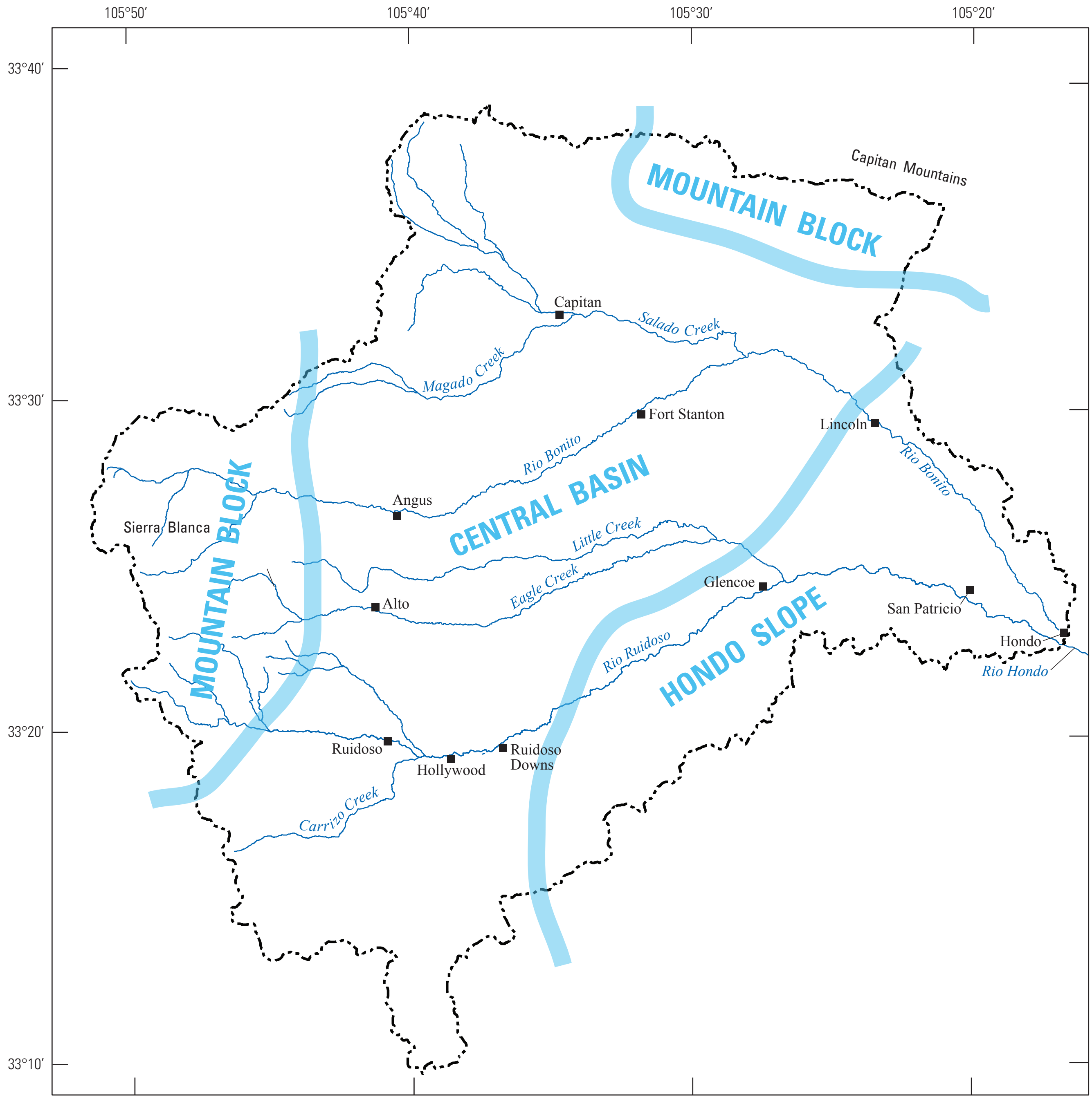


Figure 21. Estimated historical water diversions in the upper Rio Hondo Basin study area, Lincoln County, New Mexico.



Base from U.S. Geological Survey 10-meter Digital Elevation Model data, 2005, and digital raster graphics, 2003, 1:24,000
Universal Transverse Mercator projection, zone 13
North American Datum of 1983 (NAD 83)

0 2.5 5 7.5 10 MILES
0 2.5 5 7.5 10 KILOMETERS

Figure 22. Hydrogeologic terranes in the upper Rio Hondo Basin study area, Lincoln County, New Mexico.

Groundwater flow out of the Mountain Block terrane may occur through the Sierra Blanca Volcanics, the Cub Mountain Formation, or other permeable units and along faults and fractures. In some areas, such as upper Eagle Creek, very little underflow is thought to occur (Finch and others, 2004); this is a reasonable assumption for upper Eagle Creek because there are no major faults running along the creek that could form conduits for groundwater flow away from the creek. By contrast, a fault extends along the Rio Bonito for several miles, spanning the transition from the Mountain Block terrane to the Central Basin terrane, and potentially forming a conduit for groundwater underflow from the Sierra Blanca Volcanics of the Mountain Block terrane into Cretaceous units of the Central Basin terrane. The Rio Ruidoso crosses the unfaulted Sierra Blanca Volcanics in its upland watershed and then traces a fault zone in Cretaceous rocks for several miles before reaching the Ruidoso Fault Zone, thereby creating a potentially complex set of hydrologic conditions relative to recharge and underflow.

The Capitan Mountains have a much smaller drainage area than Sierra Blanca, are lower in elevation, and have a southerly aspect, so they receive proportionately smaller amounts of total precipitation. Aquifer materials are limited to granitic intrusive rocks. Uplift of the Yeso Formation exposed bedding planes capable of providing avenues for infiltration of precipitation and runoff, which may recharge the Yeso Formation in some areas at the foot of the Capitan Mountains. Runoff leaves the area by short, steep, ephemeral streams and empties onto the extensive alluvial fan system at the foot of the mountain, where it collects to form a local perched aquifer. Springs on the slope and base of the Capitan Mountains also represent areas where aquifer recharge has been concentrated.

Central Basin Terrane

The Central Basin hydrogeologic terrane occupies the piedmont at the foot of Sierra Blanca and the Capitan Mountains, extending eastward to the Mescalero Arch (fig. 3, fig. 22). The Central Basin terrane receives inflow from the Mountain Block terrane. Water from the Central Basin terrane is diverted to serve the majority of the study area population. Some recharge may occur on the mountain foothills as diffuse areal recharge from direct infiltration of precipitation. Streams exiting onto the mountain foothills, however, serve as the major sources of groundwater recharge, particularly where the foothills are faulted or fractured. Individual west-to-east trending faults have been mapped along the piedmont valley floors of the Rio Ruidoso, Rio Bonito, and Eagle Creek (Rawling, 2009) and could enhance aquifer recharge in the valley floors. Collapse features interpreted as karst zones or paleosinkholes (Rawling, 2009) may also serve as enhanced recharge zones in the Central Basin terrane.

Structurally, the Central Basin terrane is composed of the eastern margin of the Sierra Blanca Basin and is essentially a west-dipping ramp of fractured sedimentary rock layers extending from the edge of Sierra Blanca to the Mescalero Arch. The attitude of the sedimentary rock units is counter to the regional eastward groundwater-flow direction, forming unique and complex local flow conditions. The northeast plunge of the Mescalero Arch gives the Central Basin terrane a wedge-shaped configuration, which opens northward across the study area. Because of the northeast plunge of the arch, the Rio Ruidoso, the southernmost of the major drainages, intercepts recharge from high-lying areas south of the study area. The recharge source of the Rio Bonito and Eagle Creek Basins is the east-facing Sierra Blanca, and the most northern drainage, Salado Creek, receives minor recharge from the Capitan Mountains.

A variety of rock units, exhibiting highly variable transmissivities and storage coefficients, serve as aquifers in the Central Basin terrane. Cretaceous rocks (the Dakota Group, the Mancos Shale, and the Mesaverde Group) form modest to poor aquifers in much of the area, whereas Triassic rocks of the Chinle Formation form a shallow perched aquifer near Capitan. The Permian Grayburg Formation forms a poor aquifer, or aquiclude, that is thickest in the north. The deepest aquifer in the Central Basin terrane is the Yeso Formation, which has been downfaulted below the water table in some areas. Water in Central Basin terrane rocks flows primarily through faults, joints, cleavage, and dissolution-enhanced bedding planes. These features may provide sites for substantial secondary porosity and permeability, particularly in areas like the Ruidoso Fault Zone (fig. 3) where densely spaced faults and fractures may exist.

The regional groundwater-flow direction is eastward in the Central Basin terrane, and the regional horizontal gradient is moderate. On the local scale, however, groundwater movement may be affected by the cross-gradient (westward) dip of the rock layers or may be impeded by vertical heterogeneities, such as low-permeability shales or unfractured strata juxtaposed with faults. Pervasive intrusions by dikes and sills have also extensively altered the water-bearing characteristics of the rocks in some areas, such as the dike swarm near Capitan or the laccolith near Angus. In a given area, more than one water-bearing unit may be present, leading to locally perched groundwater conditions. Heavy groundwater extraction by pumping and (or) active recharge zones may also result in locally steep downward vertical gradients. Complex local flow conditions can therefore be expected in the Central Basin terrane, superimposed on the generalized regional hydrogeologic setting. Discharge from the Central Basin terrane is mostly from groundwater pumping and surface-water diversion. The change in dip direction of Permian units along the Mescalero Arch may direct recharge along bedding to discharge points along faults, possibly explaining the occurrence of spring discharge zones at Government Spring and Hale Spring in Ruidoso Downs. Outflow from the Central Basin terrane in deep aquifers may be hindered by the structural high of the Mescalero Arch (Wasiolek, 1991).

Hondo Slope Terrane

The Hondo Slope terrane covers the eastern and southeastern parts of the study area, gently ramping downward from the Mescalero Arch into the margin of the Roswell Artesian Basin (fig. 3, fig. 22). Precipitation is exceeded by evapotranspiration in this zone, so little areal recharge likely occurs. Inflow to this zone is from Rio Ruidoso and Rio Bonito streamflow and from aquifer underflow across the Mescalero Arch.

Sandstones and limestones in the Yeso Formation comprise the main aquifer materials in the Hondo Slope terrane. The Yeso Formation dips gently eastward, forming a broad ramp of largely unfaulted materials punctuated by intensely folded zones such as the Tinnie-Dunken Anticlinorium (fig. 3). Bedrock aquifers in the Yeso Formation exhibit highly variable transmissivities and storage coefficients (Wasiolek, 1991). Alluvium lines the river valleys and is a small but important local aquifer, providing the media for interactions between sedimentary bedrock and streamflow. The alluvium has appreciable primary porosity and permeability that provide for adequate well yields for many uses. The alluvium is shallow and therefore accessible, and its water quality tends to be preferable to other local aquifers.

Groundwater in the Yeso Formation moves to the east at a fairly low gradient under water-table conditions and through dissolution-enhanced limestone beds and thin beds of sandstone (Wasiolek, 1991) and is locally impeded by folding (Mourant, 1963). There are gaining and losing stream reaches on the eastern side of the Mescalero Arch, indicating that close stream-aquifer relations occur in lower reaches of the Rio Bonito and Rio Ruidoso. Downstream from the Mescalero Arch, the Rio Hondo, Rio Bonito, and Rio Ruidoso are incised into the Yeso Formation and have similar chemical composition to that of waters collected from the Yeso Formation (Hall, 1964).

Outflow from the Hondo Slope terrane occurs as surface runoff and as deep aquifer underflow. Deep underflow may occur through the Yeso Formation, but there is evidence to suggest that the quantity of underflow is limited by decreased aquifer transmissivity. Wasiolek (1991) noted closely spaced water-table contours on the western (upgradient) side of the Mescalero Arch, indicating a relatively steep hydraulic gradient and more widely spaced contours and a less steep hydraulic gradient on the eastern side of the arch. Wasiolek (1991) attributed this aberration in the hydraulic gradient to faults, localized thinning of the aquifer (over the Mescalero Arch), and the presence in this area of the Precambrian core of the ancient Pedernal Uplift. The thinner aquifer over the Mescalero Arch would have a smaller transmissivity than would the aquifer farther west or east of the arch. Wasiolek (1991) attributes the lower hydraulic gradient east of Mescalero Arch to a greater saturated thickness (and thus greater transmissivity) of the Yeso Formation. Poor water-yielding characteristics in folded Yeso Formation beds near the town of Hondo were reported by Mourant (1963), who cited numerous dry wells in this area. The decrease in transmissivity in these zones, where Yeso Formation bedding planes are steeply dipping to vertical, may be because of the low hydraulic conductivity normal to groundwater-flow direction or to infilling of slump structures and fractures by fine-grained materials in the Yeso Formation. The damming effect because of the Tinnie-Dunken Anticlinorium forces groundwater to the surface, where it emerges as streamflow and sustains several miles of perennial streamflow in the Rio Hondo. Outflow from the Hondo Slope terrane would therefore be expected to include minimal deep aquifer underflow with most of the outflow from the study area leaving as surface flow (Motts and Cushman, 1964).

Analogous conditions were observed south of the study area in the Sacramento Mountains, where Newton and others (2012) found closely spaced water-level contours across the southward extension of the Tinnie-Dunken Anticlinorium, indicating decreased transmissivity and restricted water-transmitting characteristics. Hydrogeothermal studies across the Tinnie-Dunken Anticlinorium indicated greater heat flow, suggesting upward flow of warm groundwater from depth (Reiter and Jordan, 1996), consistent with a restriction of horizontal groundwater flow.

East of the study area, the permeable San Andres Formation crops out on land surface, and streamflow in the Rio Hondo infiltrates and becomes aquifer recharge to the Roswell Artesian Basin aquifer. Hoy and Gross (1982) used isotopic age dating to show that groundwater is relatively young on the western flanks of the Roswell Artesian Basin, supporting the predominance of recharge from Rio Hondo streamflow as opposed to deep aquifer underflow. Recharge to the western Roswell Artesian Basin is dominated by a surface component consisting of winter and summer storm runoff (Gross and others, 1982) that occurs as direct infiltration of precipitation on outcrops of the San Andres or Yeso Formations and stream infiltration from the Rio Hondo (Mourant, 1963).

Conceptual Water Budget

The conceptual water budget for the upper Rio Hondo Basin was developed to describe the basinwide input and output terms and to provide estimates of each term. Local and site-specific values of recharge, pumping, and streamflow were estimated and are described in more detail in the following paragraphs and in tables 8–11.

The water budget provides useful estimates for the magnitude and range of the sources of input and output and offers a way to integrate the key hydrologic components of the study area. Ideally, a water budget should balance—that is, the residual should be as close to zero as possible. Each component of the water budget, however, has associated levels of uncertainty and variability, so the ranges in each of the estimates may create imbalances in the water budget and highlight areas where future studies may be useful.

Precipitation is the primary hydrologic input to the basin. Sources of output on the regional scale include streams and deep aquifer underflow exiting the eastern study area boundary and depletions for domestic, agricultural, recreational, and commercial uses. Any long-term average difference between the input and output will result in a long-term change in storage of the hydrologic system and an accompanying change in output.

Input

Precipitation is the primary hydrologic input to the basin, and after losses to evapotranspiration, there is a small remainder as watershed yield. Watershed yield is a term used in this analysis to describe the net quantity of streamflow or groundwater flow produced on a local scale by an individual watershed. Streamflow can further be separated into direct runoff, which is the direct and short-term product of precipitation events, and base flow, which is derived from groundwater discharge. In practice, it is often impossible to distinguish base flow, bank storage, and shallow aquifer flow without detailed investigations; therefore, in this study, base flow, bank storage, and shallow aquifer flow are combined to provide a reasonable and useful first approximation of watershed yield.

A number of approaches were explored to arrive at watershed-yield estimates. The residual of precipitation less evapotranspiration (referred to here as the “RPLE”) was used to arrive at a basinwide estimate of the potential watershed yield. The RPLE was calculated by using the PRISM precipitation estimates and evapotranspiration estimates as calculated by using the methods of MacDonald and Stednick (2003). The RPLE estimates are subject to uncertainties in estimating precipitation and evaporation and the accuracy of watershed definition. In upland watersheds, streamflow as measured at USGS streamflow-gaging stations was used as a direct measurement of watershed yield; base-flow separation of the streamflow record indicates the component of watershed yield provided by groundwater recharge. For watersheds without streamflow-gaging stations, the streamflow was estimated by comparison with nearby gaged watersheds constrained by comparison to regional water-yield regression estimates. Finally, the chloride mass-balance approach was used in upland watersheds in order to evaluate the groundwater-recharge components to piedmont areas. The chloride mass-balance approach was not applicable to lower-elevation watersheds where naturally occurring chloride-bearing strata and possible domestic wastewater could influence chloride concentrations.

Watershed Yield from Residual of Precipitation Less Evapotranspiration

Total precipitation in the upper Rio Hondo Basin, determined from PRISM data, was 594,918 acre-ft/yr for the period 1971–2000 (table 8). The mean annual precipitation

Table 8. Watershed-yield estimates from residual of precipitation less evaporation (RPLE) for the upper Rio Hondo Basin study area, Lincoln County, New Mexico.

[Source for precipitation data is PRISM (1971–2000); acre-ft/yr, acre-feet per year; –, method does not apply because mean annual precipitation is 18.1 inches or less]

Subwatershed number	Subwatershed name	Area (square miles)	Mean annual precipitation (inches)	Total precipitation (acre-ft/yr)	Mean annual evapo-transpiration (inches)[1]	Total evapo-transpiration (acre-ft/yr)[1]	Residual of precipitation less evapo-transpiration (acre-ft/yr)
1	Gyp Spring Canyon	33.4	16.8	29,934	16.8	29,934	–
2	Upper Salado Creek	31.0	17.3	28,550	17.3	28,550	–
3	Peppin and Padilla Canyons	32.4	15.9	27,505	15.9	27,505	–
4	East Salazar	23.1	17.9	22,013	17.9	22,013	–
5	Magado Creek	34.9	18.6	34,577	18.2	33,945	632
6	Lower Rio Bonito	50.4	14.4	38,614	14.4	38,614	–
7	Middle Rio Bonito	50.2	16.7	44,719	16.7	44,719	–
8	Upper Rio Bonito	40.4	26.5	57,159	20.5	44,093	13,067
9	Lower Rio Ruidoso	32.4	14.3	24,796	14.3	24,796	–
10	Lower Eagle Creek	42.1	18.1	40,673	18.1	40,673	–
11	Upper Eagle Creek	8.1	29.2	12,630	21.3	9,183	3,447
12	Middle Rio Ruidoso	58.0	17.9	55,524	17.9	55,524	–
13	Middle Eagle Creek	8.0	22.1	9,373	19.2	8,160	1,213
14	Upper Rio Ruidoso	18.3	29.7	28,923	21.4	20,804	8,119
15	Waterhole Canyon	20.6	17.7	19,508	17.7	19,508	–
16	Carrizo Creek	101.9	22.2	120,421	19.2	104,588	15,832
Total		585.3		594,918		552,608	42,310

[1]Evapotranspiration calculated by using the MacDonald and Stednick (2003) method.

over the entire upper Rio Hondo Basin was 19.7 in., and the mean annual evapotranspiration estimate was 17.9 in. Precipitation in the upland subwatersheds exceeded evapotranspiration, which resulted in a net input.

The MacDonald and Stednick (2003) method was developed for mixed-conifer forests in southwestern Colorado and is applicable to the upland subwatersheds of the upper Rio Hondo Basin. In MacDonald and Stednick (2003), all of the annual precipitation, or as much as 18.1 in., was considered to be utilized by vegetation or lost to evapotranspiration. Of the annual precipitation above 18.1 in., about 28 percent, was considered to be utilized by vegetation or lost to evapotranspiration, with the remaining 72 percent available as potential watershed yield. The RPLE estimates the amount of water potentially available for recharge or streamflow in a given subwatershed by the following equations:

$$ET = P - (18.11 + 0.28(P - 18.11)), \qquad (1)$$

$$RPLE = (P - ET) * A * 53.33 \qquad (2)$$

where

ET	is mean annual evapotranspiration, in inches,
P	is mean annual precipitation, in inches,
$RPLE$	is residual of precipitation less evapotranspiration, in acre-feet per year,
A	is area, in square miles, and
53.33	is a factor used to convert the mixed units to acre-feet per year.

Applying the MacDonald and Stednick (2003) method to each of the 16 subwatersheds identified in the study area (fig. 9) resulted in an estimated total evapotranspiration in the upper Rio Hondo Basin of 552,608 acre-ft/yr, which is about 93 percent of the mean total precipitation in the basin (594,918 acre-ft/yr) (table 8). Subwatersheds with a mean annual precipitation of 18.1 in. or less were considered to be in a water deficit, with all available precipitation utilized by vegetation or lost to evapotranspiration.

Mean annual precipitation was18.1 in. or less in 10 of the subwatersheds identified in the study area (table 8). These subwatersheds are located in the central and eastern parts of the study area and occupy 374 mi^2, or 64 percent of the upper Rio Hondo Basin. In these subwatersheds, evapotranspiration is considered to be 100 percent of the local precipitation and the RPLE is assumed to be zero. The remaining six subwatersheds are in upland areas of the study area with mean annual precipitation equal to or exceeding 18.1 in. These subwatersheds occupy about 212 mi^2 and occur in the higher-elevation areas in the central and western parts of the study area, where conditions are similar to those found in MacDonald and Stednick (2003). The six subwatersheds have a combined total precipitation of 263,083 acre-ft/yr and a combined total evapotranspiration of 220,773 acre-ft/yr, leaving a net positive RPLE of 42,310 acre-ft/yr (table 8).

The RPLE of 42,310 acre-ft/yr is an approximation of the total yield of the upland subwatersheds of the upper Rio Hondo Basin and represents the regional net input. This value is about 7.1 percent of the total precipitation in the upper Rio Hondo Basin. Of the RPLE of 42,310 acre-ft/yr, the Rio Bonito watershed (subwatersheds 1–8) has a RPLE of 13,699 acre-ft/yr, whereas the Rio Ruidoso watershed (subwatersheds 9–16) has a RPLE of 28,611 acre-ft/yr. The greater value for the Rio Ruidoso watershed is largely because of the higher total precipitation in the Rio Ruidoso watershed (about 312,000 acre-ft/yr) as compared to the Rio Bonito watershed (about 283,000 acre-ft/yr) and despite having a smaller drainage area (289 and 296 mi^2, respectively).

Watersheds on the southern flank of the Capitan Mountains (subwatersheds 1, 3, and 4 in fig. 9) receive an average of only 15.9 to 17.9 in. of mean annual precipitation (table 8). At the scale of the subwatersheds defined in figure 9, the RPLE is zero, and there is no net recharge; however, springs on the southern flank of the mountain may yield considerable quantities of water, and recharge from these subwatersheds sustains perched local aquifers near the Village of Capitan. A more detailed study of the higher-elevation parts of the subwatersheds on the Capitan Mountains would be necessary to define areas where recharge may be occurring. In addition, there may be parts of some watersheds located in the Central Basin terrane that have a net positive RPLE, but a more detailed spatial division of each watershed would be required to identify those parts of the watersheds.

Watershed Yield from Streamflow-Gaging Station Analysis

Streamflow-gaging stations provide measurements of surface flow and directly reflect watershed yield if no upstream diversions or no deep aquifer underflow exists. While these conditions are rarely met, streamflow-gaging station measurements are a valuable tool in order to understand watershed yield. In the upper Rio Hondo Basin, the upper Rio Ruidoso (subwatershed 14 on fig. 9) covers 18.3 mi^2 of undeveloped lands with no major upstream surface-water diversions and with its flow measured by the Rio Ruidoso at Ruidoso gage (08386505). The upper Rio Ruidoso is therefore considered a good indicator of upland watershed characteristics in the study area.

One characteristic of small upland watersheds is that the runoff ratio, or percentage of precipitation that exits the watershed as runoff, increases with increased precipitation. As shown in figure 23, the runoff ratio has varied from about 10 to 40 percent of precipitation for water years 2003–10 in the upper Rio Ruidoso subwatershed.

Base flow and total runoff for upland watersheds were determined with a hydrograph separation tool (Lim and Engel, 2004; Lim and others, 2005), which uses a digital filter to discriminate a high-frequency signal corresponding to streamflow runoff events and a low frequency signal for base flow (Eckhardt, 2005). Lim and Engel (2004) and Lim and others (2005) suggest using a base-flow index (BFI) of

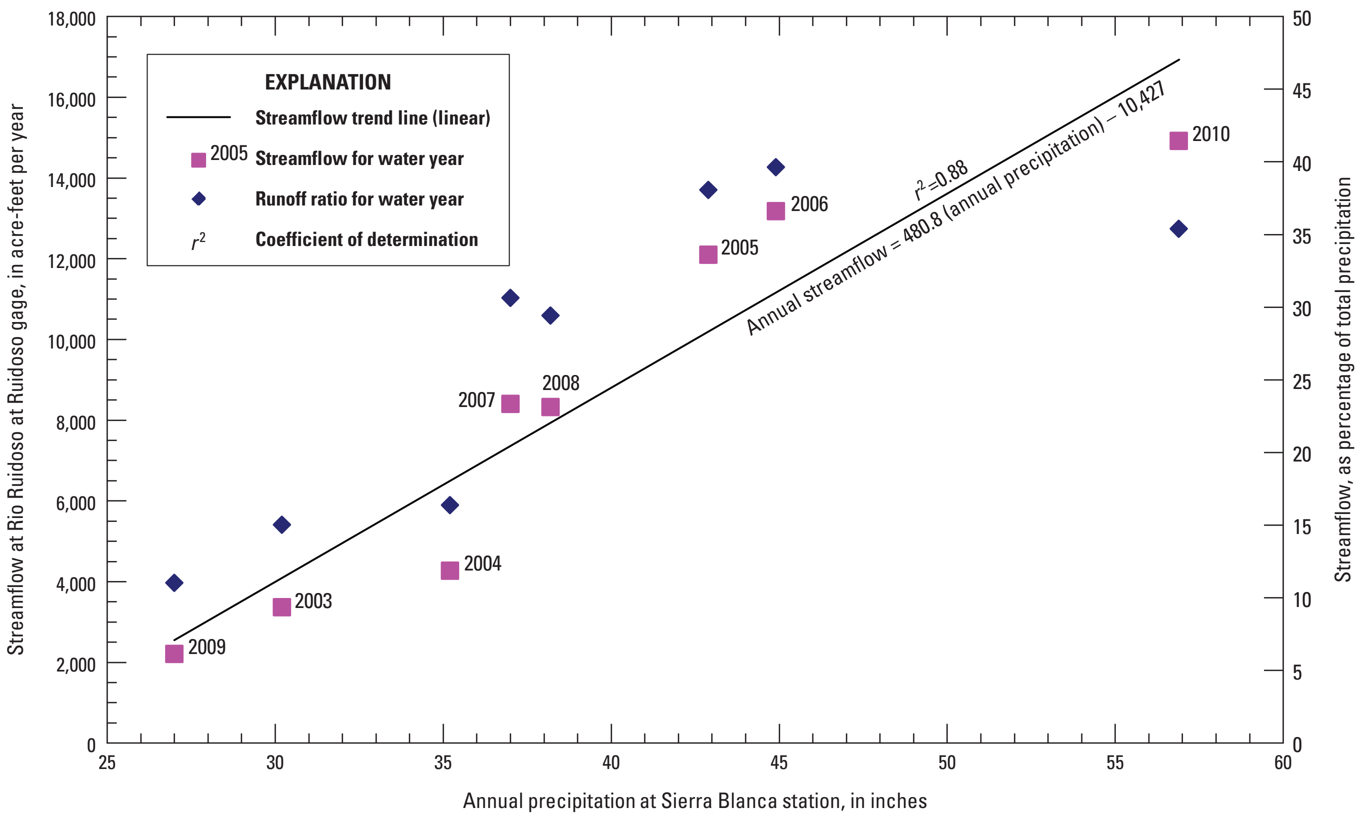


Figure 23. Streamflow at the Rio Ruidoso at Ruidoso gage (08386505) plotted against annual precipitation at the Sierra Blanca precipitation station for water years 2003–10 in the upper Rio Hondo Basin study area, Lincoln County, New Mexico.

0.25 for perennial streams with bedrock aquifers and a BFI of 0.50 for ephemeral streams with porous aquifers. Most of the streams in the study area flow through alluvium underlain by bedrock; therefore, an intermediate BFI of 0.40 was used in this analysis (Matherne and others, 2010). Table 9 includes estimates of base flow for upland watersheds.

Streamflow-gaging stations from the upper Rio Ruidoso and other subwatersheds were used to extrapolate the watershed yields for all the upland watersheds. Watershed yield may be normalized by dividing the amount of streamflow by the contributing area and expressed as yield per unit area. For the upper Rio Ruidoso subwatershed, this area-normalized base flow amounted to 0.5–4.5 inch per square mile (in/mi^2), and total runoff was 2.0–15 in/mi^2. The upper Rio Ruidoso had a mean annual streamflow of 7,052 acre-ft/yr and an estimated mean annual base flow of 2,304 acre-ft/yr over the period of record (table 9). The total precipitation in the subwatershed was 28,923 acre-ft/yr, resulting in an average runoff ratio of 24 percent, and the percentage of precipitation as base flow was 8 percent.

The area, mean annual precipitation, mean annual streamflow, and estimated mean annual base flow for six upland subwatersheds are given in tables 8 and 9. The upper Eagle Creek, middle Eagle Creek, upper Rio Ruidoso, and Carrizo Creek subwatersheds (11, 13, 14, and 16, respectively) are gaged, whereas the Magado Creek and upper Rio Bonito subwatersheds (5 and 8) were not gaged as of 2010 (table 9). Analyses from subwatersheds on the southern flank of the Capitan Mountains were not included in this analysis because there are no perennial streams in these subwatersheds.

Matherne and others (2010) studied the 8.1-mi^2 upper Eagle Creek subwatershed (11) in detail. For the prepumping period of record (1970–80), the measured streamflow was 2,278 acre-ft/yr, which was 18 percent of the average annual subwatershed precipitation, and the base flow was 819 acre-ft/yr, or 6 percent of the subwatershed precipitation (table 9).

U.S. Geological Survey streamflow-gaging station data are not available for the upper Rio Bonito subwatershed (8); however, there are historical streamflow measurements from 1931–40 that cover part of the upper Rio Bonito subwatershed (29.3 mi^2 of the 40.4 mi^2) above the Rio Bonito dam. The mean annual streamflow was 6,794 acre-ft/yr for this time period (Powell, 1954). By extrapolating the ratio of mean annual streamflow per unit area for the upper subwatershed to the entire subwatershed, a value of 9,368 acre-ft/yr, or 16 percent of the total annual precipitation of 57,159 acre-ft/yr, may be calculated. This runoff ratio is

Table 9. Watershed-yield and base-flow calculations for the upland watersheds in the upper Rio Hondo Basin study area, Lincoln County, New Mexico, from extrapolation of available streamflow-gaging station measurements.

[acre-ft/yr, acre-feet per year; –, not measured or not exrapolated]

Subwatershed number	Subwatershed name	Total precipitation (acre-ft/yr)	Streamflow as percentage of subwatershed precipitation	Mean annual streamflow (acre-ft/yr)	Mean annual base flow, estimated (acre-ft/yr)[1,2]	Base flow as percentage of subwatershed precipitation	Mean annual base flow, extrapolated (acre-ft/yr)[3]	Total estimated base flow (acre-ft/yr)
5	Magado Creek	34,577	–	[1]3,804	–	–	1,383	1,383
8	Upper Rio Bonito	57,159	–	[1]10,289	–	–	3,430	3,430
11	Upper Eagle Creek	12,630	18	[1]2,278	819	6	–	819
13	Middle Eagle Creek	9,373	13	1,253	345	4	–	345
14	Upper Rio Ruidoso	28,923	24	7,052	2,304	8	–	2,304
16	Carrizo Creek	120,421	11	13,511	5,158	4	–	5,158
Total		263,083		38,187				13,439

[1]For Magado Creek subwatershed, 11 percent of precipitation was used to extrapolate streamflow; for upper Rio Bonito subwatershed, 18 percent of precipitation was used to extrapolate streamflow. For Upper Eagle Creek subwatershed, mean annual 1970–80 streamflow and calculated base flow were used (Matherne and others, 2010).

[2]Base flow was derived using digital hydrograph separation method (Lim and Engel, 2004).

[3]For Magado Creek subwatershed, 4 percent of precipitation was used to extrapolate base flow; for upper Rio Bonito subwatershed, 6 percent of precipitation was used to extrapolate base flow.

slightly less than the ratio of 18 percent derived for upper Eagle Creek. If the streamflow and base-flow characteristics for the upper Rio Bonito are assumed to be the same as for upper Eagle Creek, then the extrapolated mean annual streamflow and base flow would be 10,289 acre-ft/yr and 3,430 acre-ft/yr, respectively (table 9).

Streamflow-gaging stations data for the middle Eagle Creek and Carrizo Creek subwatersheds (13 and 16) were used to estimate a runoff ratio of 13 percent and 11 percent, respectively, and a base flow of 4 percent of precipitation for both subwatersheds (table 9). These runoff ratios are lower than those estimated for the upper Rio Ruidoso and upper Eagle Creek, probably because there are diversions upstream from the streamflow-gaging stations. Magado Creek is somewhat lower in elevation than other upland subwatersheds and is perennial only in its upper reaches. If the runoff ratio of Magado Creek is assumed to be similar to those of middle Eagle Creek and Carrizo Creek, then the extrapolated mean annual streamflow and base flow would be 3,804 acre-ft/yr and 1,383 acre-ft/yr, respectively (table 9). Summing the estimated contributions from the six upland subwatersheds gives a total watershed yield for streamflow of about 38,187 acre-ft/yr (table 9) and represents about 15 percent of the total precipitation of about 263,083 acre-ft/yr in the upland subwatersheds.

Chloride Mass-Balance Method

The chloride mass-balance method has been utilized by investigators (Anderholm, 1994, 2000) in semiarid environments to determine the rates of recharge to the groundwater system as chloride generally behaves conservatively in the hydrologic system. In most cases, chloride in groundwater is sourced from bulk precipitation recharge (the aggregate of chloride in precipitation and from atmospheric deposition between precipitation events); however, chloride can also be introduced into the groundwater system from dissolution of chloride-bearing geologic materials, dusts from surficial deposits, or from anthropogenic sources such as septic systems and road deicing salts (Mullaney and others, 2009). Uncertainties in estimated recharge using the chloride mass-balance method can occur when groundwater is partially evaporated prerecharge or postdischarge, or when chloride is added to the groundwater from geologic or anthropogenic sources, resulting in underestimation of the amount of recharge. Conversely, the retention of chloride in the solid phase (undissolved in groundwater or retained in vadose zone) would lead to an overestimation of recharge.

This method is applicable for use in the upland subwatersheds of the upper Rio Hondo Basin because chloride sources are typically not present in volcanic rocks (Feth, 1981), and chloride concentrations were found to be relatively low in shallow groundwater in volcaniclastic rocks of the Mountain Block terrane (Matherne and others, 2010). In the Central Basin and Hondo Slope terranes, sources of chloride are present in shale and gypsum beds, in salt used to clear roadways, and in domestic wastewater.

In order to use the most simplified application of the chloride mass-balance method, only chloride concentrations from upland springs were considered in this study. This limits the sources and sinks of chloride to precipitation and the local aquifer, respectively, and excludes complications and assumptions related to surface outflow of chloride. The reduced form of the chloride mass-balance equation used to estimate recharge is:

$$R = \frac{C_p \times P}{C_r} \qquad (3)$$

where

R is recharge, in acre-feet;

C_p is chloride concentration in bulk precipitation, in milligrams per liter;

P is precipitation over the upland subwatersheds, in acre-feet; and

C_r is chloride concentration in recharge, in milligrams per liter.

Chloride mass-balance groundwater-recharge estimates, made by using data from upland springs in the study area (Mourant, 1963), range from 2.9 percent to 5.0 percent of precipitation (table 10). Applying these percentages to all the upland subwatersheds results in estimated recharge values of approximately 7,738 to 13,154 acre-ft/yr, with an average of 10,212 acre-ft/yr, or about 4 percent of precipitation (table 10). These values are consistent with the estimates of Matherne and others (2010), who reported a range from 3.9 percent to 4.1 percent of precipitation for groundwater recharge in the North Fork Eagle Creek Basin.

Regional Net Input to Water Budget

Net inputs to the upper Rio Hondo Basin are summarized in table 11; values are rounded to hundreds of acre-feet per year to reflect uncertainties associated with the determination of the various inputs. The watershed yield had some components of local groundwater recharge, which ranged from 10,200 acre-ft/yr to 13,400 acre-ft/yr (table 11). The base-flow estimate of 13,400 acre-ft/yr represents that part of streamflow sustained by groundwater discharged to the stream (table 9); however, there may also be recharge to deep aquifers that does not emerge as base flow in subwatersheds of the upper Rio Hondo Basin and is not measured at streamflow-gaging stations.

The range of estimated watershed yield was about 38,200 to 42,300 acre-ft/yr (table 11). As a comparison, the water budgets of two regional flow models were examined (Romero and Silver, 2009; Daniel B. Stephens and Associates, Inc., 2000). The first model had total local inputs and outputs of about 31,000 acre-ft/yr and included the entire upper Rio Hondo Basin. The second model included only the Rio Bonito watershed and had inputs and outputs of about 20,000 acre-ft/yr.

Output

Diversions and Depletions

Pumping, agricultural uses, and transbasin exports are all outputs and therefore represent diversions from or depletions to the regional hydrologic system. As detailed in the "Water Use from 1950 to 2010" section of this report, total water diversions since 1950 have averaged about 25,000 acre-ft/yr and have increased by about 0.2 percent annually (fig. 21).

The most recent diversion and depletion estimates are from 2005 (fig. 18 *A–F*, table 5). Diversions totaled 24,413 acre-ft/yr, of which 14,381 acre-ft/yr, or 59 percent, were for agricultural uses. Surface-water diversions totaled 16,693 acre-ft/yr, or 68 percent of diversions, and were used mainly for agriculture, public water supply, and transbasin export through the Bonito Pipeline. Groundwater diversions totaled 7,720 acre-ft/yr and were used for agricultural uses, public and private water supply, and commercial and industrial purposes. Depletions in 2005 totaled 13,527 acre-ft/yr, or 55 percent of diversions. Depletions from agricultural uses

Table 10. Recharge estimates calculated by using the chloride mass-balance method for the upland watersheds in the upper Rio Hondo Basin study area, Lincoln County, New Mexico.

[acre-ft/yr, acre-feet per year]

Area	Chloride concentration in water, from Mourant (1963) (milligrams per liter)	Bulk chloride concentration in precipitation, from Anderholm (2000) (milligrams per liter)	Recharge as percentage of precipitation	Total precipitation in all higher-elevation watersheds (acre-ft/yr)	Estimated recharge in all upper watersheds (acre-ft/yr)
Upper Padilla Spring	6.0	0.30	5.0	263,083	13,154
Lower Padilla Spring	6.5	0.30	4.6	263,083	12,142
Little Creek Spring	10.1	0.30	3.0	263,083	7,814
Spring at Bonito Lake	10.2	0.30	2.9	263,083	7,738
Average			3.9		10,212

Table 11. Regional water-budget components for the upper Rio Hondo Basin study area, Lincoln County, New Mexico.

[All values rounded to hundreds of acre-feet per year (acre-ft/yr); –, no data]

Inputs (acre-ft/yr)	Total annual precipitation	Total annual evapotrans-piration	Watershed yield from precipitation less evapotrans-piration (table 8)	Watershed yield from streamgage extrapolation (table 9)	Recharge from base-flow analysis (table 9)	Mountain-front recharge from chloride mass balance (table 10)
Watershed yield	594,900	552,600	42,300	38,200	13,400	10,200
Total inputs (range): 38,200–42,300						
Recharge (range): 10,200–13,400						
Outputs (acre-ft/yr)	**Diversions for all water uses**	**Returns from all water uses**	**Net depletion from all water uses**	**Basin output from streamgage records**	**Groundwater underflow (low estimate)**	**Groundwater underflow (high estimate)**
Diversions and depletions	24,400	10,900	13,500	–	–	–
Surface-water output	–	–	–	21,200	–	–
Deep groundwater output	–	–	–	–	2,300	5,700
Total outputs (range): 37,000–40,400						
Residual (acre-ft/yr)	**Low**	**High**				
Range in sum of input and output terms	-2,200	+5,300				

were 6,311 acre-ft/yr, or 44 percent of the amount diverted for that purpose, whereas depletions from other uses (except the Bonito Pipeline, where the diversion equals the depletion) totaled 4,128 acre-ft/yr, or 59 percent of the amount diverted for these purposes. Agricultural uses therefore diverted more water than other uses but depleted a smaller percentage of the diverted water on the basis of 2005 estimates.

Since about 1975, there has been a decrease in diversions for agricultural uses and an increase in diversions for other uses (fig. 21). Agricultural and livestock uses comprised 83 percent of diversions in 1950 as compared to 61 percent in 2005. Presuming that delivery systems and other factors affecting return flows and depletions have not changed from 2005 conditions, the overall depletion for 2010 would be about 49 percent of diversions in 1950, which is lower than the value of 55 percent calculated for 2005.

Surface-Water Output

Surface-water outputs originating in the study area are one of the principal output components from the hydrologic system. The Rio Hondo is perennial at the eastern boundary of the study area where it is a gaining reach sourced in part by groundwater discharge. The Tinnie-Dunken Anticlinorium creates a low-permeability constriction or groundwater dam near the outlet of the upper Rio Hondo Basin, contributing to groundwater mounding. Because of this mounding, the majority of the basin yield probably exits the basin as perennial streamflow instead of underflow as suggested by Motts and Cushman (1964).

Surface-water output from the study area was measured from 1956 to 1962 at USGS streamflow-gaging station 08390100 (Rio Hondo at Picacho). The mean annual streamflow was 15,413 acre-ft/yr (table 2). Flow measurements on the Rio Hondo at USGS streamflow-gaging station 08390020 (Rio Hondo above Chavez Canyon near Hondo) averaged 19,725 acre-ft/yr over the period of record from 2008 to 2010 (table 2). Longer time periods for surface-output estimates can be calculated by summing the flows at the mouths of the Rio Bonito and Rio Ruidoso (USGS streamflow-gaging stations 08389500 and 08388000, respectively), immediately upstream from the confluence that forms the Rio Hondo. The average total streamflow was 21,239 acre-ft/yr for the 25-year period of record from 1930 to 1955. This agrees reasonably well with mean annual streamflow from the USGS streamflow-gaging station 08390020 (19,725 acre-ft/yr) and with the estimate from Mourant (1963) of 19,400 acre-ft/yr total streamflow from the Rio Hondo. Therefore, the average long-term output from the Rio Hondo is estimated at 21,200 acre-ft/yr (table 11).

Groundwater Output

Groundwater leaving the Hondo Slope terrane constitutes the subsurface discharge of the entire upper Rio Hondo Basin study area and is a source of deep recharge that flows downgradient (eastward) in the Yeso Formation and, in turn, recharges the Roswell Artesian Basin. This may be characterized as "slow recharge," and tritium concentrations indicate that the water is relatively old (Gross and others, 1976, 1979, 1982; Gross and Hoy, 1980). Regional modeling studies have shown that much of the deep recharge entering the Roswell Artesian Basin is either from the north or from diffuse deep aquifer underflow as opposed to well defined aquifer input from the western basin boundary (Daniel B. Stephens and Associates, Inc., 2000). The amount of deep aquifer underflow from the eastern limit of the upper Rio Hondo Basin can be calculated by using Darcy's Law:

$$Q = b * K * i * w \tag{4}$$

where

- Q is groundwater flow, in cubic feet per day;
- b is saturated thickness of the aquifer, in feet;
- K is hydraulic conductivity, in feet per day;
- i is hydraulic gradient, dimensionless; and
- w is aquifer width perpendicular to flow path, in feet.

Underflow may range from about 2,300 to 5,700 acre-ft/yr, which is based on a saturated aquifer thickness of 1,200 ft, a hydraulic conductivity of 0.6 to 1.5 ft/d (Wasiolek, 1991), a hydraulic gradient of 0.006 or 30 ft/mi, and a 12-mi aquifer width. Lower hydraulic conductivity values and decreased thicknesses are likely, however, because of the presence of the Tinnie-Dunken Anticlinorium and the damming effect of the Mescalero Arch, respectively. One regional modeling study calculated underflow from the upper Rio Hondo Basin at 2,750 acre-ft/yr (Romero and Silver, 2009), which is within the range of estimates provided in this report.

The hydraulic gradient decreases from west to east in the upper Rio Hondo Basin by more than an order of magnitude. In the west, the hydraulic gradient is on the order of 0.1 (more than 500 ft/mi), whereas in the east, the hydraulic gradient is on the order of 0.005 (30 ft/mi). The width of the aquifer perpendicular to flow also decreases by half from about 24 to 12 mi from west to east. The reduction in hydraulic gradient and aquifer width from west to east indicates a decrease in Q, most likely because groundwater flow is captured by withdrawals or is discharged to streams. In addition, the changes in hydraulic gradient and width may indicate an increase in transmissivity, which is indicated by highly productive sections of the Yeso Formation in the eastern part of the study area.

Table 11 summarizes the sources of output in the upper Rio Hondo Basin. Depletions of about 13,500 acre-ft/yr and surface-water output of about 21,200 acre-ft/yr were the major sources of output, whereas deep groundwater output ranged from 2,300 to 5,700 acre-ft/yr. The sum of all the outputs ranged from 37,000 to 40,400 acre-ft/yr.

Change in Storage

The water budget uses the principle of conservation of mass, whereby input less output must equal change in storage. If input and output balance, the change in storage is zero. By contrast, a net water surplus (more input than output) or deficit (more output than input) results in a change in storage and is expressed by a change in average groundwater levels, which affects streamflow where streamflow is sustained by groundwater discharge. Table 11 summarizes the residual in the water budget, which is the difference between the totals of the input and output terms, or potential change in storage. By using the range in estimates of each term, the residual ranges from -2,200 acre-ft/yr to +5,300 acre-ft/yr.

Aquifers in the upper Rio Hondo Basin are characterized by low storage capacity and respond to short-term and long-term variations in recharge with marked water-level fluctuations on short (days to months) and long (decadal) time scales. Water levels responded quickly to the heavy monsoon rains of the summer 2008 and to the heavy snowmelt of the spring of 2010. Aquifer response time to the recharge events varied from hours to several months as shown in the plots of available data for continuous water-level data recorders (fig. 16), but these high peaks were short-lived and began to decline again after the precipitation event. These punctuated recharge and recovery events were superimposed on decadal scale fluctuations of groundwater levels from the mid-1950s to 2010 across the upper Rio Hondo Basin (fig. 15*A*–*C*). The average water-level change was +9.4 ft for the 1950s to 1980s time period (fig. 15*A*), -17.0 ft for the 1980s to 2003 time period (fig. 15*B*), and +4.0 ft for the 2003 to 2010 time period (fig. 15*C*). Because of the uneven distribution and low density of wells for each time period, extrapolation of change in storage across the entire upper Rio Hondo Basin between time periods is prone to large errors.

The quantity of groundwater in storage yielded to wells (specific yield, equal to porosity minus specific retention) beneath the study area can be estimated by taking into account the storage characteristics of the aquifers, the aquifer thicknesses, and the areal extent of the aquifers. The formula to calculate the volume of water in aquifer storage is:

$$V = a * b * SY \tag{5}$$

where

- V is volume in storage, in acre-feet;
- a is area, in acres;
- b is saturated thickness of aquifer, in feet; and
- SY is specific yield, dimensionless.

The presumed values for specific yields were 0.01 for fractured rock of the Mountain Block and Central Basin terranes, with a reasonable range from 0.005 to 0.03, and 0.10 for the alluvial and San Andres Formation aquifers of the Hondo Slope terrane, with a reasonable range from 0.05 to 0.20. The range in specific yield is based on rock and aquifer properties discussed in the "Geologic Framework" section of this report and is presumed to average 0.01 (or 1 percent) for all three hydrogeologic terranes.

A saturated aquifer thickness of 1,000 ft appears to be a reasonable approximation for the aquifers in the upper Rio

Hondo Basin. In the Mountain Block terrane, 1,000 to 2,000 ft of aquifer thickness has been verified at certain locations, but it is probable that these aquifer thicknesses are not fully saturated across the terrane. Water-bearing strata dip into the Central Basin terrane, and the total aquifer thickness increases towards the west. The shallow aquifer in the Central Basin terrane, which consists of Cretaceous rocks, and the deep aquifer, which consists of the Yeso and San Andres Formations, can exceed 2,000 ft in thickness, but water quality may constrain the usable saturated thickness of these aquifers. Deep-well tests in the area have not yielded appreciable amounts of good quality water to date (2010). Data from NMOSE records (wells H–3923 and H–4043; New Mexico Office of the State Engineer, 2010) have indicated wells with total depths from 3,100 to 3,500 ft and depths to water from 144 to 202 ft; however, production was low (100 gal/min), and water was saline. A deep test well near the Sierra Blanca Regional Airport (H–3726; New Mexico Office of the State Engineer, 2010) reached a total depth of 1,413 ft and had good yield (600 gal/min) and acceptable water quality (710 mg/L of TDS) but had a deep static water level (788 ft) resulting in a water column of 625 ft. Deep wells near the Village of Capitan have similar results with water columns ranging from less than 500 ft to 1,000 ft with total depths as much as 1,600 ft, with good yields but poor water quality (2,000 mg/L of TDS). A reasonable estimate for aquifer thickness in the Central Basin terrane therefore is presumed to be no more than 1,000 ft. In the Hondo Slope terrane, the sole aquifer is the Yeso Formation, which has a minimum thickness of 1,300 ft across the Mescalero Arch. Water levels are shallow in the Hondo Slope terrane, with an average total depth less than 250 ft (New Mexico Office of the State Engineer, 2010). Presuming an average saturated thickness of 1,000 ft across the 585-mi^2 basin and a specific yield of 0.01, the total amount of water in storage would be about 3.7 million acre-ft.

Future Water-Resource Scenarios

Changes in vegetation, land- and water-use patterns, and climate are of concern to the residents of the upper Rio Hondo Basin. Increasing water use because of growth, relocation of resources to upstream users, and changes in long-term recharge or streamflow quantities are all important concerns to the future management of water resources in the study area. This section of the report describes how the groundwater and surface-water resources of the upper Rio Hondo Basin may be affected by changes in watershed vegetation, changes in land- and water-use patterns, and climate change.

Changes in Watershed Vegetation

Forest density in the study area has changed over the historical record, primarily because of fire suppression, from a density of 20 to 70 trees per acre to a density of 200 to 250 trees per acre (Garrett and Garrett, 2001). Naturally occurring wildfires historically killed seedlings at 3- to 15-year cycles, clearing the forest floor and creating large open areas. Fire suppression, grazing, and other factors have led to dense forests and minimal grass cover. Open areas more than 100 acres in size are now rare in Lincoln National Forest, whereas such areas historically occupied much of the forest (Garrett and Garrett, 2001). Controlled burns were introduced in the 1970s and 1980s, and these low-intensity ground fires have become an important component of watershed-restoration strategies (Upper Hondo Watershed Coalition, 2004).

In many cases, forest management can result in improved watershed yields. Grasslands and meadows growing in open areas can slow the rate of runoff, possibly allowing more infiltration and less soil erosion. In addition, tree thinning may prevent the canopy from intercepting precipitation and allowing it to evaporate. Ongoing watershed thinning studies in the southern Sacramento Mountains (Newton and others, 2012) may yield results applicable to the upper Rio Hondo Basin.

Postwildfire flooding can increase erosion rates and debris-flow potential, thereby altering the geomorphology and hydrology of burned areas. For example, the Peppin Fire burned about 65,000 acres on the slopes of the Capitan Mountains in 2004, reportedly causing some springs to begin flowing again (April Banks, Bureau of Land Management, oral commun., 2010). The 2011 White Fire and the 2012 Little Bear Fire in the upper Rio Hondo Basin were not part of this study.

Changes in Land- and Water-Use Patterns

Urbanization is a factor affecting runoff characteristics for area watersheds. Roadways, home sites, and other land use for urban, suburban, and recreational purposes have been estimated at 10 to 15 percent and growing rapidly (Upper Hondo Watershed Coalition, 2004). Data from Lincoln County (Patsy Sanchez, written commun., 2010) included areal coverage of incorporated and subdivided areas, not including homes, cabins, and ranches located in unincorporated areas, which totaled 34,168 acres, or 9.1 percent of the watershed area. These changes in land use may also affect runoff and streamflow characteristics because urbanized watersheds characteristically exhibit rapid runoff from storm events (U.S. Environmental Protection Agency, 2011).

As described in the “Water Use from 1950 to 2010” section of this report, patterns in water use have changed since 1950. The amount of diversions has generally increased by about 0.2 percent per year during this time, but the type and location of diversions have shifted from primarily agricultural use in the Hondo Slope terrane to primarily municipal, commercial, and recreational use in the Central Basin terrane. Much of this trend can be attributed to the sale and transfer of water rights from agricultural lands to the villages and developments. If historical water-use patterns continue, total depletions will not increase or decrease substantially, but there will be shifts from agricultural to domestic use and from the eastern to central parts of the study area. Transferring water rights from one purpose or place of use to another may involve reallocations from one hydrogeologic terrane to another. In such cases, the effects may be difficult to predict because of the complexities and heterogeneities of the hydrogeologic system. In addition, changes in location or the amount of recharge may cause local changes in streamflow or water-table elevations.

Changes in Climate

Potential effects of climate change in New Mexico include an increase in mean annual temperature and a decrease in precipitation (Seager and others, 2007), along with an increase in the percentage of precipitation falling as rain instead of snow (Knowles and others, 2006). Some researchers have predicted an increase in variability of weather patterns with more frequent extreme precipitation events such as floods and droughts (Karl and Knight, 1998; New Mexico Office of the State Engineer, 2006). The record monsoon seasons of 2006 and 2008 could be examples of extreme precipitation events. Notable droughts occurred in the 1930s, 1950s, and the early to mid-2000s in the Southwestern United States. Tree-ring studies have indicated that severe drought periods also occurred in the 12th and 17th centuries (Grissino-Mayer, 1996; Seager and others, 2007; Brekke and others, 2009).

It is apparent that droughts are common to the New Mexico climate and should be a part of the water-resource planning process. The average annual precipitation in the entire upper Rio Hondo Basin was about 594,900 acre-ft/yr for the period 1971–2000 (table 11). Natural variability in the amount of precipitation is extreme and may vary 40 to 50 percent or more from year to year. The typical quantity of input from precipitation can therefore be expected to range from about 300,000 to 900,000 acre-ft/yr on a basinwide scale. The historical record of streamflow shows wide ranges of fluctuations (tens of thousands of acre-feet per year) corresponding to wet and dry cycles, with many streams drying entirely or becoming raging torrents. Variability is inherent in precipitation and streamflow and therefore in available water resources. Water-resource planners need to be prepared for short-term and long-term departures from conditions that were previously considered to be average.

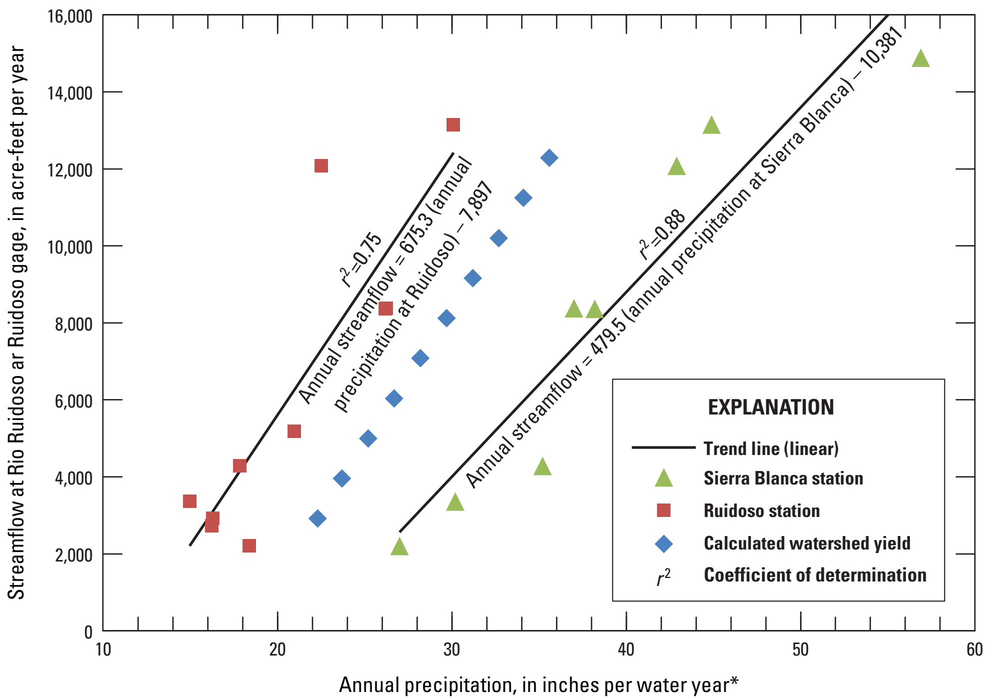
The timing of snowmelt runoff in the Western United States has become earlier in recent decades, advancing by 2 to 3 weeks in southwestern New Mexico (U.S. Geological Survey, 2005). Analysis of streamflow in the Rio Ruidoso has suggested that snowmelt arrives earlier by up to one month and exhibits a more rapid onset, with increased flow rates prior to its peak (Hall and others, 2006), which would also result in lower, late summer streamflow (Brekke and others, 2009). Base flow could potentially decrease by 10 to 30 percent in the Southwestern United States (Brekke and others, 2009).

Regardless of the causes, earlier snowmelt runoff is relevant to water-supply planning in the upper Rio Hondo Basin. Examination of USGS streamflow data collected in the past decade in the watershed of the upper Rio Ruidoso is useful to understand the response of upland watersheds to floods and droughts, particularly given the drought in the early to mid-2000s, the record monsoons in 2006 and 2008, and the heavy snowmelt in 2010. Figure 23 shows the runoff ratio, or the percentage of annual precipitation that appears as runoff, for each year from 2003 to 2010. The runoff ratio varies from as low as 5 to 10 percent in drought years to as high as 35 to 40 percent in wet years. These ratios indicate that periodic high precipitation events provide opportunities for increased recharge because increasing watershed yield percentages from larger precipitation events provide additional available streamflow for recharge or storage.

Observed streamflow of the upper Rio Ruidoso watershed was compared with the estimated watershed yield from table 8. The results from this calculation and others based on varying potential precipitation totals are shown in figure 24 and correspond with observed precipitation at both the Ruidoso and Sierra Blanca precipitation stations. The precipitation-streamflow relation expressed by figure 23 shows a similar trend, such that a 20-percent change in precipitation would result in a 50- percent change in streamflow, either positive or negative. For example, if the average watershed precipitation (29 in.) were reduced by 20 percent (to 23 in.), then streamflow would be reduced by a factor of 50 percent (from 8,600 to 4,200 acre-ft/yr). Conversely, a 20-percent increase in precipitation (to 35 in.) would result in a streamflow value of more than 12,000 acre-ft/yr (or an increase of about 50 percent), which indicates that the natural variability in precipitation will create cycles of greater and lesser streamflow and watershed yield.

On the regional scale of the upper Rio Hondo Basin, estimates of the RPLE were applied to all the subwatersheds for wet and dry cycles in order to gain a sense of the degree of expected interannual variability in watershed yield. Departures from normal conditions (42,300 acre-ft/yr) were calculated at 5 percent increments by using the RPLE method and by holding the values of evapotranspiration constant as a simplifying assumption. The results (fig. 25) indicate that a 10-percent decrease or increase in average annual precipitation would result in substantial changes in total basin watershed yield, from a reduction of about 40 percent to more than doubling the yield. Figure 25 highlights the sensitivity of watershed yield to drought conditions, given that annual precipitation variations of 25 to 50 percent are common in the historical record of the upper Rio Hondo Basin (fig. 7). Under drought conditions, the basin-contributing area is less, whereas under wet conditions, there is greater runoff as a percentage of precipitation and an increase in contributing area within the basin, resulting in a nonlinear response in figure 25.

Decreased rainfall or snowfall have the immediate consequence of reducing streamflow, and several years of reduced precipitation can result in a severe lack of available surface water for diversions. One consequence of reduced precipitation is increased reliance on groundwater with



*Water year is the 12-month period of October 1 through September 30 designated by the calendar year in which it ends.

Figure 24. Observed watershed yields as compared to calculated watershed yields in the upper Rio Ruidoso subwatershed.

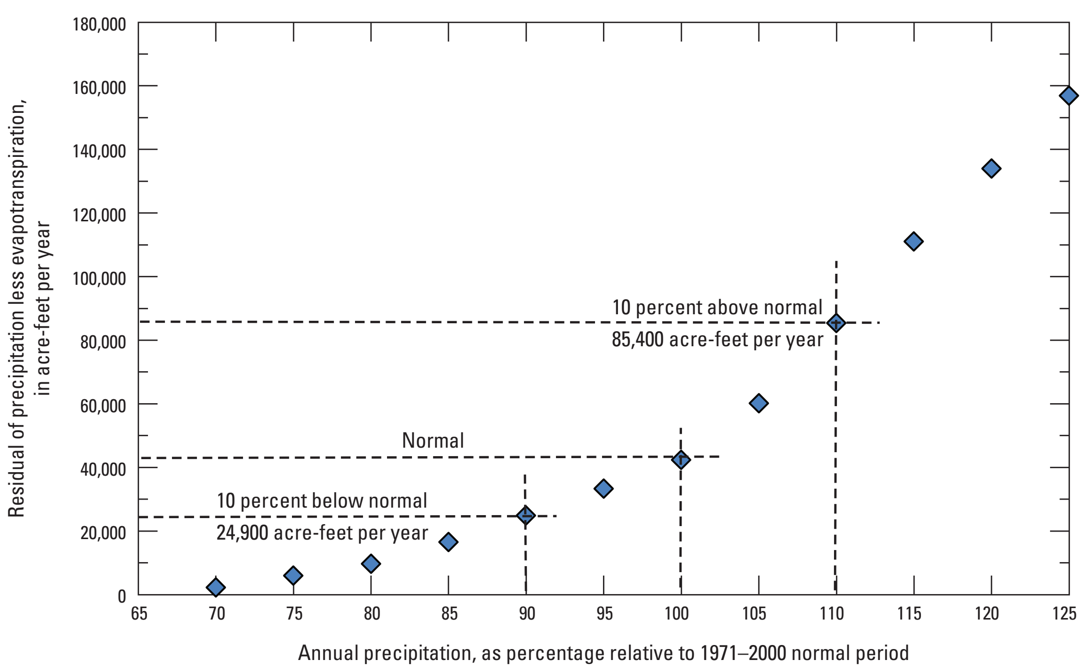


Figure 25. Potential watershed yield of all combined subwatersheds in the upper Rio Hondo Basin study area, Lincoln County, New Mexico, as a function of changes in mean annual precipitation.

attendant water-table declines and additional depletions of streamflow. Only a small part of the total water in storage can be reasonably accessed because of limitations in well locations, well depths, and water quality.

Possible Future Work

This report has identified a number of areas where additional data collection and interpretation may help to narrow uncertainties in the magnitude and variability of the components in the water budget of the upper Rio Hondo Basin. A comprehensive hydrologic model would offer a platform to integrate these water-budget components with the complex hydrogeologic framework to better understand the hydrologic system, its functions, and its response to stresses such as water diversions, droughts, and water-use transfers, among others.

Numerical modeling would allow more detailed division of watershed boundaries to match hydrogeologic terranes and to better understand stream-aquifer relations in different areas. Water budgets for individual terranes could be prepared and used to explain the relations among the areas, such as how surface-water withdrawals from one terrane might affect groundwater levels in another. In addition, hydrologic models can take into account the interplay of stream diversions, return flows, and conveyance losses from acequias and irrigated lands. Better understanding of the close relations between surface water and groundwater in the upper Rio Hondo Basin may help water-resource managers develop conjunctive-use strategies.

One basic area of future research is to identify the recharge sources and pathways from the Capitan Mountains. The RPLE method used a coarse definition of subwatersheds, resulting in zero net recharge from the Capitan Mountains. A finer definition of subwatersheds would likely show, however, that recharge occurs on some high-lying areas of the mountains because springs exist along the southern margin of the mountains. The same process of detailed spatial analysis may also reveal portions of other subwatersheds where recharge is likely to occur, which could help local planners prioritize watershed-management strategies.

Additional data are also needed in the northern part of the Central Basin terrane near Capitan, where instantaneous response to recharge events was dampened or not observed. The mechanics by which recharge reaches the northern part of the Central Basin terrane near Capitan bear further investigation because deep confining layers prevent direct infiltration of runoff water except to perched Triassic or alluvial aquifers.

Continued monitoring of selected wells would allow long-term evaluation of water-level trends in key areas and would assist water-resource planners in dealing with natural climate variability as well as any future changes in water-resource dynamics. Some wells have more than six decades of water-level records and could serve as calibration points for any future modeling efforts. The effects of future drought, wildfire, and floods on the hydrologic system could also be examined by way of continued monitoring at key water-level measurement points.

Water-quality studies can also help to reveal the complex interplay of components in the hydrologic system. Isotope data have shown that snowmelt is the primary source of recharge water in the southern Sacramento Mountains (Newton and others, 2012). If snowmelt is also the primary source of recharge water in the upper Rio Hondo Basin, then the recharge pulses from the 2006 and 2008 monsoons represent anomalous recharge events. Isotope analysis of springs, streams, and well water would help determine the mechanics of hydrologic provenance and the seasonality of recharge contributions. Age dating of groundwater could be used to better understand when recharge entered the aquifer system, which has implications in establishing sustainable levels of water use. Finally, the occurrence of water-quality constituents indicative of burned areas may be useful in delineating areas where recharge has been affected by wildfires.

Summary

The U.S. Geological Survey, in cooperation with Lincoln County, New Mexico, conducted this study to provide an updated description of hydrologic conditions and water resources in the upper Rio Hondo Basin. This report provides a conceptual hydrogeologic model and water budget for the upper Rio Hondo Basin and includes an inventory of historical and current water-use patterns.

The upper Rio Hondo Basin has a drainage area of 585 square miles with elevations of 5,185 feet (ft) near the confluence of the Rio Ruidoso and Rio Bonito, where the rivers join to form the Rio Hondo, to 12,003 ft at the peak of Sierra Blanca. Changes in elevation, relief, and aspect (the compass orientation of land surface maximum slope with respect to due south) create varied climates in the upper Rio Hondo Basin; annual precipitation ranges from 15 inches per year (in/yr) in the lower-elevation watersheds to 40 in/yr in the upland watersheds. Most precipitation occurs during the summer months as monsoon events, whereas the spring runoff provided by winter snows typically finishes by late April or early May. Long-term trends in precipitation include marked droughts in the 1930s, 1950s, and early 2000s, and a wet period centered in the mid-1980s.

As many as 12 major hydrostratigraphic units serve as aquifers, ranging from Permian to Mesozoic through Tertiary in age; alluvium on the valley floors can also serve as an aquifer for shallow wells. The Ruidoso Fault Zone runs northeast to southwest along the foot of Sierra Blanca and has extensively fractured the consolidated rock units in the study area. The Mescalero Arch forms a hingeline in the eastern part of the study area where the dip reverses, and sedimentary rocks tilt either westward into the Sierra Blanca Basin or eastward into the Roswell Artesian Basin.

On a regional scale, the aquifer systems are interconnected and continuous. Perched aquifers near the Capitan Mountains and near Alto and Angus indicate the presence of local aquitards. Streamflow and aquifers are closely interconnected, with numerous gaining and losing reaches across the study area. Major watersheds are largely perennial in the south (Rio Ruidoso), intermittent in the center (Rio Bonito), and ephemeral in the north (Salado Creek), owing in part to the northeast plunge of the Mescalero Arch. The Tinnie-Dunken Anticlinorium creates groundwater mounding, which increases saturated aquifer thickness and causes groundwater discharge across the eastern end of the study area. The mounding creates a gaining stream reach that constitutes most of the output from the upper Rio Hondo Basin as surface discharge to the Roswell Artesian Basin.

Population in Lincoln County has almost tripled in the last four decades and reached 20,497 residents in 2010. Since 1950, total diversions have averaged about 24,400 acre-feet per year (acre-ft/yr), and total depletions have averaged about 13,500 acre-ft/yr, or a little more than half of total diversions. Groundwater accounted for about one-third of the total and surface water about two-thirds. Changes in land-use patterns since about 1970 have led to greater diversions from upland watersheds for municipal, commercial, and recreational use, relative to decreasing diversions in lower-lying areas for agricultural use.

Three hydrogeologic terranes in the upper Rio Hondo Basin are defined on the basis of aquifer characteristics, geologic structure, and hydrologic behavior—the Mountain Block, the Central Basin, and the Hondo Slope terranes. The Mountain Block terrane is coincident with Sierra Blanca and the Capitan Mountains, with Tertiary-age volcanic and intrusive aquifers. Precipitation exceeds evapotranspiration in the Mountain Block terrane, and the upland watersheds in this terrane are the source of runoff for the upper Rio Hondo Basin. The Central Basin terrane is characterized by a west-dipping ramp of fractured sedimentary rock layers. Water from the Central Basin terrane is diverted to serve the majority of the population in the study area. The Hondo Slope terrane, where the Yeso Formation is the main aquifer, gently ramps downward from the Mescalero Arch into the margin of the Roswell Artesian Basin.

A regional-scale conceptual water budget was developed for the study area in order to gain a basic understanding of the magnitude of the various components of input, output, and change in storage. The upper Rio Hondo Basin received an average of about 594,900 acre-ft/yr of precipitation. Natural variability in the amount of precipitation was extreme and varied by 40 to 50 percent or more from year to year. Almost all of the precipitation entering the study area was lost to evaporation or used by plants as transpiration, and the remaining watershed yield was estimated to range from 38,200 to 42,300 acre-ft/yr. Up to an estimated 13,400 acre-ft/yr of recharge occurred as base flow or mountain-front recharge from local aquifers in the upland watersheds, with the remaining watershed yield as runoff to the lower watersheds. Streamflow from the basin averaged about 21,200 acre-ft/yr, and groundwater output left the basin at an estimated 2,300 to 5,700 acre-ft/yr. The other major output (about 13,500 acre-ft/yr) was by public water supply, private-supply wells, livestock, commercial and industrial uses, and the Bonito Pipeline. The residual in the water budget, the difference between the totals of the input and output terms or the potential change in storage, ranged from -2,200 acre-ft/yr to +5,300 acre-ft/yr.

In general, the aquifers of the upper Rio Hondo Basin are characterized by low storage capacity and respond to short-term and long-term variations in recharge with marked water-level fluctuations on short (days to months) and long (decadal) time scales. Droughts and local groundwater withdrawals have caused marked water-table declines in some areas, whereas periodically heavy monsoons and snowmelt events have rapidly recharged aquifers in some areas. Changing water-use patterns, concentrated areas of groundwater withdrawal, and variations in precipitation have created localized areas where water-table declines and diminished surface flow are of concern.

References

Allen, J.E., and Kottlowksi, F.E., 1981, Scenic trips to the geologic past series no. 3: Roswell-Ruidoso-Valley of Fires: Socorro, New Mexico Bureau of Mines and Mineral Resources, 96 p.

Anderholm, S.K., 1994, Ground-water recharge near Santa Fe, north-central New Mexico: U.S. Geological Survey Water-Resources Investigations Report 94–4078, 68 p.

Anderholm, S.K., 2000, Mountain-front recharge along the eastern side of the Middle Rio Grande Basin, central New Mexico: U.S. Geological Survey Water-Resources Investigations Report 00–4010, 36 p.

Atkins Engineering Associates, Inc., 2000, Rio Bonito streamflow conditions and surface water irrigation requirements below Government Springs, Lincoln County, New Mexico: Albuquerque, N. Mex., on file at the New Mexico Water Science Center, 22 p.

Bachman, G.O., 1964, Southwestern edge of the late Paleozoic landmass, *in* Ash, S.R., and Davis, L.R., eds., Ruidoso Country: New Mexico Geological Society, 15th Field Conference Guidebook, p. 70–72.

Balleau Groundwater, Inc., 2004a, Analysis of North Fork well field and effects on Eagle Creek: Technical Memorandum, prepared for the Ford Secure Trust, November 3, 2004, on file at the New Mexico Water Science Center, Albuquerque, N. Mex., 12 p.

Balleau Groundwater, Inc., 2004b, Mountain-front hydrology of Eagle Creek and Rio Ruidoso tributaries of Rio Hondo: Technical Memorandum, prepared for the Ford Secure Trust, November 3, 2004, on file at the New Mexico Water Science Center, Albuquerque, N. Mex., 13 p.

Bodine, M.W., Jr., 1956, Geology of Capitan coal field, Lincoln County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 35, 25 p.

Bowsher, A.L., 1991, Some effects of Precambrian basement on the development of the Sacramento Mountains, *in* Barker, J.M., Kues, B.S., Austin, G.S., and Lucas, S.G., eds., Geology of the Sierra Blanca, Sacramento, and Capitan Ranges, New Mexico: New Mexico Geological Society, 42nd Field Conference Guidebook, p. 81–90.

Brekke, L.D., Kiang, J.E., Olsen, J.R., Pulwarty, R.S., Raff, D.A., Turnipseed, D.P., Webb, R.S., and White, K.D., 2009, Climate change and water resource management—A Federal perspective: U.S. Geological Survey Circular 1331, 65 p.

Craddock, Campbell, 1964, The Lincoln fold system, *in* Ash, S.R., and Davis, L.R., eds., Ruidoso Country: New Mexico Geological Society, 15th Field Conference Guidebook, p. 122–133.

Cunningham, W.L., and Schalk, C.W., comps., 2011, Groundwater technical procedures of the U.S. Geological Survey: U.S. Geological Survey Techniques and Methods 1–A1, 151 p. (available only online at http://pubs.usgs.gov/tm/1a1/).

Daly, Christopher, Gibson, W.P., Taylor, G.H., Johnson, G.L., and Pasteris, P., 2002, A knowledge-based approach to the statistical mapping of climate: Climate Research, v. 22, p. 99–113.

Daly, Christopher, Neilson, R.P., and Phillips, D.L., 1994, A statistical-topographic model for mapping climatological precipitation over mountainous terrain: Journal of Applied Meteorology, v. 33, p. 140–158.

Daniel B. Stephens and Associates, Inc., 1995, Comprehensive review and model of the Roswell Basin: Consultant's report prepared for New Mexico State Engineer Office, on file at the New Mexico State Engineer's Office, Santa Fe, N. Mex., 259 p.

Daniel B. Stephens and Associates, Inc., 2000, Groundwater impact analysis for proposed transfer applications, water rights 02696, 02894, 01400, 01401, H209, 01406C, 01384, H–47, H–2068, and H–2070 through H–2076: Consultant's report prepared for R.D. Hubbard Enterprises, on file at the New Mexico State Engineer's Office, Santa Fe, N. Mex., 31 p.

Daniel B. Stephens and Associates, Inc., 2007, Ruidoso water audit summary report: Consultant's report prepared for Village of Ruidoso, on file at the New Mexico State Engineer's Office, Santa Fe, N. Mex., 35 p.

Davis, Paul, Wilcox, Ralph, and Gross, G.W., 1979, Spring characteristics of the western Roswell Artesian Basin: New Mexico Water Resources Research Institute Report 116, 93 p.

Donohoe, L.C., 2004, Selected hydrologic data for the upper Rio Hondo Basin, Lincoln County, New Mexico, 1945–2003: U.S. Geological Survey Scientific Investigations Report 2004–5275, 28 p.

Eckhardt, Klaus, 2005, How to construct recursive digital filters for baseflow separation: Hydrological Processes, v. 19, no. 2, p. 507–515.

Fernald, A.G., Cevik, S.Y., Ochoa, C.G., Tidwell, V.C., King, J.P., and Guldan, S.J., 2010, River hydrograph retransmission functions of irrigated valley surface water—Groundwater interactions: Journal of Irrigation and Drainage Engineering, v. 136, no. 12, p. 823–835.

Feth, J.H., 1981, Chloride in natural continental water—A review: U.S. Geological Survey Water-Supply Paper 2176, 30 p., available at http://pubs.usgs.gov/wsp/2176/report.pdf.

Fiedler, A.G., and Nye, S.S., 1933, Geology and ground-water resources of the Roswell Basin, New Mexico: U.S. Geological Survey Water-Supply Paper 639, 372 p.

Finch, S.T., Peery, R.L., and McCoy, A.M., 2004, Water-resource evaluation of Eagle Creek watershed, Village of Ruidoso, New Mexico: Albuquerque, N. Mex., John Shomaker and Associates, Inc., 36 p.

Foley, E.J., 1964, The Lincoln folds, Lincoln, New Mexico, *in* Ash, S.R., and Davis, L.R., eds., Ruidoso Country: New Mexico Geological Society, 15th Field Conference Guidebook, p. 134–139.

Follett, W.W., 1914, Final report on a hydrographic survey of the Bonito and Hondo Rivers and of Eagle Creek in Lincoln County, New Mexico: Prepared for the El Paso and Rock Island Railway Company in 1913 and 1914, on file at the New Mexico State Engineer's Office, Santa Fe, N. Mex., 251 p.

Freeman, L.A., Carpenter, M.C., Rosenberry, D.O., Rousseau, J.P., Unger, R., and McLean, J.S., 2004, Use of submersible pressure transducers in water-resources investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 8, chap. A, 65 p.

Garrett, L.D., and Garrett, P.J., 2001, Evaluating forest restoration opportunities on the Lincoln National Forest: Consultant's report prepared by M3 Research, on file at the New Mexico Water Science Center, Albuquerque, N. Mex., 192 p.

Grissino-Mayer, H.D., 1996, A 2,129-year reconstruction of precipitation in northwestern New Mexico, USA, *in* Dean, J.S., Meko, D.M., and Swetnam, T.W., ed., Tree rings, environment, and humanity: Proceedings of the International Conference, Tucson, Ariz., May 17–21, 1994: University of Arizona, Radiocarbon, p. 191–204.

Grissino-Mayer, H.D., Baisan, C.H., Swetnam, T.W., 1997, A 1,373 year reconstruction of annual precipitation for the southern Rio Grande Basin: Consulting report prepared for the Directorate of Environment, Natural Resources Division, Fort Bliss, Texas, on file at the New Mexico Water Science Center, Albuquerque, New Mexico, 63 p.

Gross, G.W., Davis, Paul, and Rehfeldt, K.R., 1979, Paul Spring—An investigation of recharge in the Roswell (NM) Artesian Basin: New Mexico Water Resources Research Institute Report 113, 135 p.

Gross, G.W., and Hoy, R.N., 1980, A geochemical and hydrological investigation of groundwater recharge in the Roswell Basin of New Mexico—Summary of results and updated listing of tritium determinations: New Mexico Water Resources Research Institute Report 122, 141 p.

Gross, G.W., Hoy, R.N., and Duffy, C.J., 1976, Application of environmental tritium in the measurement of recharge and aquifer parameters in a semi-arid limestone terrain: New Mexico Water Resources Research Institute Report 080, 212 p.

Gross, G.W., Hoy, R.N., Duffy, C.J., and Rehfeldt, K.R., 1982, Isotope studies of recharge in the Roswell Basin, *in* Perry, E.C., Jr., and Montgomery, C.W., eds., Isotope studies of hydrologic processes: DeKalb, Ill., Northern Illinois University Press, p. 25–33.

Hall, A.W., Whitfield, P.H., and Cannon, A.J., 2006, Recent variations in temperature, precipitation, and streamflow in the Rio Grande and Pecos River Basins of New Mexico and Colorado: Reviews in Fisheries Science, v. 14, p. 51–78.

Hall, F.R., 1964, Chemistry of water of a section of the eastern flank of the Sacramento Mountains, Lincoln and Otero Counties, New Mexico, *in* Ash, S.R., and Davis, L.R., eds., Ruidoso Country: New Mexico Geological Society, 15th Field Conference Guidebook, p. 161–170.

Hallinger, D.E., 1964, Caves of the Fort Stanton area, New Mexico: New Mexico Geological Society, 15th Field Conference Guidebook, p. 181–184.

Hirsch, R.J., 1988, The hydrologic impacts from the diversion of winter flows of Cordova Creek for snowmaking purposes: New Mexico State Engineer Office Technical Division Hydrology Report 88–6, 23 p.

Hoy, R.N., and Gross, G.W., 1982, A baseline study of oxygen-18 and deuterium in the Roswell, New Mexico, groundwater basin: New Mexico Water Resources Research Institute Report 144, 95 p.

Karl, T.R., and Knight, R.W., 1998, Secular trends of precipitation amount, frequency, and intensity in the United States: Bulletin of the American Meteorological Society, v. 79, no. 2, p. 231–241.

Kelley, V.C., 1971, Geology of the Pecos country, southeastern New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 24, 75 p.

Kelley, V.C., and Thompson, T.B., 1964, Tectonics and general geology of the Ruidoso–Carrizozo region, central New Mexico, *in* Ash, S.R., and Davis, L.R., eds., Ruidoso Country: New Mexico Geological Society, 15th Field Conference Guidebook, p. 110–121.

Knowles, Noah, Dettinger, M.D., and Cayan, D.R., 2006, Trends in snowfall versus rainfall in the western United States: Journal of Climate, v. 19, p. 4545–4559.

Lee, C.H., 1912, Report of hydrographic conditions on Rio Bonito, New Mexico, in connection with the water-supply of the Fort Stanton Sanatorium: On file at the New Mexico State Engineer's Office, Santa Fe, N. Mex. [variously paged].

Lee, C.H., 1916, Report of hydrographic and irrigation studies on the Rio Bonito, Lincoln County, New Mexico, in connection with the water supply of Fort Stanton Sanatorium: Report to the Surgeon General, Washington, D.C., U.S. Public Health Service, on file at the New Mexico State Engineer's Office, Santa Fe, N. Mex., 151 p.

Lim, K.J., and Engel, B.A., 2004, WHAT—Web-based Hydrograph Analysis Tool: accessed August 16, 2009, at http://pasture.ecn.purdue.edu/~what.

Lim, K.J., Engel, B.A., Tang, Zhenxu, Choi, Joongdae, Kim, Ki-Sung, Muthukrishnan, Suresh, and Tripathy, Dibyajyoti, 2005, Automated web GIS based hydrograph analysis tool, WHAT: Journal of the American Water Resources Association, v. 41, no. 6, p. 1407–1416.

Livingston Associates P.C., 2004, Water and wastewater system master plan: Consultant's report prepared for Alto Lakes Water Corporation, on file at the New Mexico Water Science Center, Albuquerque, N. Mex., 69 p.

Longworth, J.W., Valdez, J.M., Magnuson, M.L., Sims Albury, Elisa, and Keller, Jerry, 2008, New Mexico water use by categories, 2005: New Mexico State Engineer Office Technical Report 52, 111 p.

MacDonald, L.H., and Stednick, J.D., 2003, Forests and water—A state-of-the-art review for Colorado: Colorado Water Resources Research Institute CWRRI Completion Report No. 196, 65 p.

Martinez, E.L., 1974, Rio Hondo-Bonito-Ruidoso hydrographic survey—Rio Bonito subsection: Memorandum to S.E. Reynolds, State Engineer, on file at the New Mexico State Engineer's Office, Santa Fe, N. Mex., v. 1, 209 p.

Martinez, E.L., 1975, Rio Hondo-Bonito-Ruidoso hydrographic survey—Rio Ruidoso subsection: Memorandum to S.E. Reynolds, State Engineer, on file at the New Mexico State Engineer's Office, Santa Fe, N. Mex., v. 2, 427 p.

Matherne, A.M., Myers, N.C., and McCoy, K.J., 2010, Hydrology of Eagle Creek Basin and effects of groundwater pumping on streamflow, 1969–2000: U.S. Geological Survey Scientific Investigations Report 2010–5205, 73 p. (Revised November 2010.)

McKee, T.B., Doesken, N.J., and Kleist, John, 1993, The relationship of drought frequency and duration to time scales: Anaheim, Calif., Eighth Conference on Applied Climatology, January 17–22, 1993, 6 p.

Miller, Sherry, Melis, Erwin, Peery, Roger, and Sublett, Leslie, 2007, Well report for Village of Ruidoso, emergency replacement of well H–1497 (Green Well), Ruidoso, New Mexico: Consultant's report, prepared by John Shomaker and Associates, Inc., for U.S. Department of the Interior, Bureau of Reclamation, on file at the New Mexico Water Science Center, Albuquerque, N. Mex., 10 p.

Miller, Sherry, Peery, Roger, Street, James, and Sublett, Leslie, 2008, Well report for Village of Capitan, emergency replacement of well H–685–S–3, Village of Capitan, New Mexico: Consultant's report, prepared by John Shomaker and Associates, Inc., for U.S. Department of the Interior, Bureau of Reclamation, on file at the New Mexico Water Science Center, Albuquerque, New Mex., 76 p.

Motts, W.S., and Cushman, R.L., 1964, An appraisal of the possibilities of artificial recharge to ground-water supplies in part of the Roswell Basin, New Mexico: U.S. Geological Survey Water-Supply Paper 1785, 86 p.

Mourant, W.A., 1963, Water resources and geology of the Rio Hondo drainage basin, Chaves, Lincoln, and Otero Counties, New Mexico: New Mexico State Engineer Technical Report 28, 85 p., 7 pls.

Mullaney, J.R., Lorenz, D.L., Arntson, A.D., 2009, Chloride in groundwater and surface water in areas underlain by the glacial aquifer system, northern United States: U.S. Geological Survey Scientific Investigations Report 2009–5086, 41 p.

National Climatic Data Center, 2010, Find a station: National Oceanic and Atmospheric Administration: accessed September 27, 2010, at http://www.ncdc.noaa.gov/oa/climate/stationlocator.html.

National Oceanic and Atmospheric Administration, 2011, Atlas 14 point precipitation frequency estimates: NM: accessed January 2011, at http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=nm.

Natural Resources Conservation Service, 2010, SNOTEL precipitation data: accessed September 27, 2010, at http://www.wcc.nrcs.usda.gov/snow/snotel-precip-data.html.

Natural Resources Conservation Service, 2011, Web soil survey: accessed January 2011, at http://websoilsurvey.sc.egov.usda.gov/.

Neel, G.W., 1932, Report on the Bonito River hydrographic survey within Lincoln and Chaves Counties, New Mexico, 1931–1932: Prepared by the New Mexico Office of the State Engineer, on file at the New Mexico State Engineer's Office, Santa Fe, N. Mex., 265 p.

Newcomer, R.W., Jr., and Shomaker, J.W., 1991, Water resources of the Ruidoso-Carrizozo-Tularosa areas, Lincoln and Otero Counties, New Mexico, *in* Barker, J.M., Kues, B.S., Austin, G.S., and Lucas, S.G., eds., Geology of the Sierra Blanca, Sacramento, and Capitan Ranges, New Mexico: New Mexico Geological Society, 42nd Field Conference Guidebook, p. 339–341.

New Mexico Bureau of Geology and Mineral Resources, 2003, Geologic map of New Mexico, scale 1:500,000: accessed November 2010, at https://geoinfo.nmt.edu/publications/maps/geologic/state/home.cfml.

New Mexico Office of the State Engineer, 2006, The impact of climate change on New Mexico's water supply and ability to manage water resources: accessed December 2011, at http://www.nmdrought.state.nm.us/ClimateInfo.html.

New Mexico Office of the State Engineer, 2010, New Mexico Water Rights Reporting System: accessed October 2010, at http://nmwrrs.ose.state.nm.us/nmwrrs/index.html.

New Mexico Territorial Engineer, 1909, Report on the Hondo hydrographic survey: Report made by the Territorial Engineer to the Court of the Sixth Judicial District, Territory of New Mexico, on file at the New Mexico State Engineer's Office, Santa Fe, N. Mex., 34 p.

Newton, Talon, Timmons, Stacy, Rawling, Geoff, Partey, Frederick, Kludt, Trevor, Land, Lewis, Timmons, Mike, and Walsh, Patrick, 2012, Sacramento Mountains hydrogeology study: New Mexico Bureau of Geology and Mineral Resources Open-File Report 518, 64 p.

Pecos Valley Water Users Association, 2001, Lower Pecos Valley regional water plan: Prepared for New Mexico Interstate Stream Commission, on file at the New Mexico State Engineer's Office, Santa Fe, N. Mex., 319 p.

Peery, R.L., 2006, Well report for Village of Ruidoso airport exploratory well H–3726, Ruidoso, New Mexico: Consulting report prepared for Village of Ruidoso, on file at the New Mexico Water Science Center, Albuquerque, N. Mex., 6 p.

Peery, R.L., and Finch, S.T., 2001, Hydrogeologic assessment of well H–272–S–9, Village of Ruidoso, New Mexico: Consulting report prepared for Stein and Brockmann, P.A., Attorneys at Law, Santa Fe, N. Mex., on file at the New Mexico Water Science Center, Albuquerque, N. Mex., 13 p.

Powell, C.W., 1954, Report on the supply and uses of the water of upper Bonito River and Eagle Creek, Lincoln County, New Mexico: On file at the New Mexico State Engineer's Office, Santa Fe, N. Mex., 93 p.

PRISM Climate Group, 2010a, 103-year high-resolution precipitation climate data set for the coterminous United States: accessed November 2010, at http://prism.oregonstate.edu/docs/meta/ppt_103yr.htm.

PRISM Climate Group, 2010b, Maximum temperature—Annual climatology (1971–2000): accessed October 2010, at http://prism.oregonstate.edu/products/viewer.phtml?file=/pub/prism/us_30s/graphics/tmax/Normals/us_tmax_1971_2000.14.png&year=1971_2000&vartype=tmax&month=14&status=final.

Rawling, G.C., 2004a, Preliminary geologic map of the Ruidoso 7.5-minute quadrangle, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open File Geologic Map OF–GM–93, scale 1:24,000.

Rawling, G.C., 2004b, Preliminary geologic map of the Ruidoso Downs 7.5-minute quadrangle, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open File Geologic Map OF–GM–94, scale 1:24,000.

Rawling, G.C., 2004c, Preliminary geologic map of the Angus 7.5-minute quadrangle, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open File Geologic Map OF–GM–95, scale 1:24,000.

Rawling, G.C., 2006, Preliminary geologic map of the Fort Stanton 7.5-minute quadrangle, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open File Geologic Map OF–GM–119, scale 1:24,000.

Rawling, G.C., 2009, Geology of the Ruidoso Area, Lincoln and Otero Counties, New Mexico, New Mexico Bureau of Geology and Mineral Resources, Open-File Report OFR–507, scale 1:24,000.

Rawling, G.C., 2010a, Preliminary geologic map of the Nogal quadrangle, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open File Geologic Map OF–GM–195, scale 1:24,000.

Rawling, G.C., 2010b, Preliminary geologic map of the Capitan quadrangle, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open File Geologic Map OF–GM–196, scale 1:24,000.

Reiter, Marshall, and Jordan, D.L., 1996, Hydrogeothermal studies across the Pecos River Valley, southeastern New Mexico: GSA Bulletin, v. 208, no. 6, p. 747–756.

Riesterer, Jim, Drakos, Paul, Lazarus, Jay, and Chudnoff, Mustafa, 2006, Hydrogeology of Hale Spring and evaluation of declining spring discharge, Ruidoso Downs, New Mexico, *in* Land, Lewis, Leuth, V.W., Raatz, William, Boston, Penny, and Love, D.W., eds., Caves and karst of southeastern New Mexico: New Mexico Geological Society, 57th Field Conference Guidebook, p. 121–130.

Romero, D.M., and Silver, S.E., 2009, Hydrogeologic model of Rio Hondo Basin area: Consultant's memorandum, Balleau Groundwater, Inc., to New Mexico Office of the State Engineer, File No. H–695 et al. into H–2049 et al., on file at the New Mexico State Engineer's Office, Santa Fe, N. Mex., 8 p.

Sandia National Laboratories, 2010, Hydrogeologic investigation report, Upper Hondo Basin in the vicinity of Alto, Lincoln County, New Mexico: Report prepared for participating small businesses, on file at the New Mexico Water Science Center, Albuquerque, N. Mex., 36 p.

Seager, Richard, Ting, Mingfang, Held, Isaac, Kushnir, Yochanan, Lu, Jian, Vecchi, Gabriel, Huang, Huei-Ping, Harnik, Nili, Leetmaa, Ants, Lau, Ngar-Cheung, Li, Chihua, Velez, Jennifer, and Naik, Naomi, 2007, Model projections of an imminent transition to a more arid climate in southwestern North America: Science, v. 316, p. 1181–1184.

Skotnicki, S.J., 2009a, Preliminary geologic map of the Lincoln quadrangle, Lincoln County, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open-File Digital Geologic Map OF–GM 188, scale 1:24,000.

Skotnicki, S.J., 2009b, Preliminary geologic map of the San Patricio quadrangle, Lincoln County, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open-File Digital Geologic Map OF–GM 189, scale 1:24,000.

Skotnicki, S.J., 2010, Preliminary geologic map of the Capitan Pass quadrangle, Lincoln County, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open-File Digital Geologic Map OF–GM 208, scale 1:24,000.

Sloan, C.E., and Garber, M.S., 1971, Ground-water hydrology of the Mescalero Apache Indian Reservation, south-central New Mexico: U.S. Geological Survey Hydrologic Investigations Atlas HA–349, 1 sheet.

Smart, A.W., and Fleming, W.F., 1985, Consumptive water use in artificial snowmaking, Santa Fe Ski Area, New Mexico: New Mexico State Engineer Office Technical Report 45, 14 p.

Sorenson, E.F., 1977, Water use by categories in New Mexico counties and river basins, and irrigated and dry cropland acreage in 1975: New Mexico State Engineer Office Technical Report 41, 34 p.

Sorenson, E.F., 1982, Water use by categories in New Mexico counties and river basins, and irrigated acreage in 1980: New Mexico State Engineer Office Technical Report 44, 51 p.

Talbot, W.R., 2009, Village of Capitan emergency replacement well independent technical review, Village of Capitan, New Mexico: Bureau of Reclamation, on file at the New Mexico Water Science Center, Albuquerque, N. Mex., 46 p.

Thompson, T.B., 1973, Mineral deposits of Nogal and Bonito Mining Districts, New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 123, 29 p.

Titus, F.B., 1980, Ground water in the Sandia and northern Manzano Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Hydrologic Report 5, 66 p.

University of New Mexico, 2008, A report on historical and future population dynamics in New Mexico water planning regions: Report prepared by the Bureau of Business and Economic Research, on file at the New Mexico Water Science Center, Albuquerque, N. Mex., 90 p.

Upper Hondo Watershed Coalition, 2004, Watershed restoration action strategy, upper Rio Hondo: Prepared for New Mexico Environment Department, Surface Water Quality Bureau, on file at the New Mexico Water Science Center, Albuquerque, N. Mex., 61 p.

U.S. Department of Commerce, Bureau of the Census, 1995, New Mexico population of counties by decennial census—1900 to 1990, New Mexico: Washington, D.C., accessed August 2011, at http://www.census.gov/population/www/censusdata/cencounts/files/nm190090.txt.

U.S. Department of Commerce, Bureau of the Census, 2000, Census 2000 data for the State of New Mexico: accessed November 15, 2010, at http://census.gov/census2000/states/nm.html.

U.S. Department of Commerce, Bureau of the Census, 2010, 2010 census: accessed May 2011, at http://www.census.gov/2010census/data/embedstate.html?state=NM” frameborder=”0” scrolling=”no” marginheight=”0” marginwidth=”0” width=”800” height=”510”>IFRAMES not supported</iframe>.

U.S. Environmental Protection Agency, 2011, Managing urban runoff: accessed January 2011, at http://water.epa.gov/polwaste/nps/outreach/point7.cfm.

U.S. Geological Survey, 2005, Changes in streamflow timing in the Western United States in recent decades: National Streamflow Information Program Fact Sheet 205–3018, 4 p.

U.S. Geological Survey, 2010, National Water Information System: accessed December 15, 2010, at http://waterdata.usgs.gov/nwis.

Walsh, Patrick, 2008, A new method for analyzing the effects of joints and stratigraphy on spring locations—A case study from the Sacramento Mountains, south central New Mexico, USA: Hydrogeology Journal, v. 16, p. 1459–1467.

Wasiolek, Maryann, 1991, The hydrogeology of the Permian Yeso Formation within the upper Rio Hondo Basin and the eastern Mescalero Apache Indian Reservation, Lincoln and Otero Counties, New Mexico, *in* Barker, J.M., Kues, B.S., Austin, G.S., and Lucas, S.G., eds., Geology of the Sierra Blanca, Sacramento, and Capitan Ranges, New Mexico: New Mexico Geological Society, 42nd Field Conference Guidebook, p. 343–351.

White, W.E., and Kues, G.E., 1992, Inventory of springs in the State of New Mexico: U.S. Geological Survey Open-File Report 92–118, 253 p.

Wilson, B.C., 1986, Water use in New Mexico in 1985: New Mexico State Engineer Office Technical Report 46, 84 p.

Wilson, B.C., 1992, Water use by categories in New Mexico counties and river basins, and irrigated acreage in 1990: New Mexico State Engineer Office Technical Report 47, 141 p.

Wilson, B.C., and Lucero, A.A., 1997, Water use by categories in New Mexico counties and river basins, and irrigated acreage in 1995: New Mexico State Engineer Office Technical Report 49, 149 p.

Wilson, B.C., Lucero, A.A., Romero, J.T., and Romero, P.J., 2003, Water use by categories in New Mexico counties and river basins, and irrigated acreage in 2000: New Mexico State Engineer Office Technical Report 51, 164 p.

Wilson and Company, Inc., 2004, Village of Ruidoso, NM 40-year water plan: Consultant’s report prepared for the Village of Ruidoso, on file at the New Mexico Water Science Center, Albuquerque, N. Mex., 49 p.

Yuras, Walter, 1991, Origin of folds in the Permian Yeso Formation, Lincoln County, New Mexico, *in* Barker, J.M., Kues, B.S., Austin, G.S., and Lucas, S.G., eds., Geology of the Sierra Blanca, Sacramento, and Capitan Ranges, New Mexico: New Mexico Geological Society, 42nd Field Conference Guidebook, p. 165–170.

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