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GEOLOGIC CONTROLS ON GROUND-WATER FLOW IN THE MIMBRES BASIN, SOUTHWESTERN NEW MEXICO

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Abstract — A three-dimensional calibrated regional ground-water flow model of the Mimbres Basin developed by McCoy and Finch (unpubl. report for Chino Mines Company, 2006) shows that ground-water flow is controlled by the geology and structure of the mountain bedrock and basin fill, and that the basin can be divided into four major hydrogeologic regions. These regions show distinct ground-water flow patterns based on recharge, discharge, and hydraulic properties controlled by geology and structure. Local and regional geologic controls on ground-water flow include permeability contrasts resulting from deposition, volcanism, and deformation associated with Basin and Range faulting, paleo-drainage, and topography. Bedrock plays an important role in each hydrogeologic region. About 24% of the ground water in storage in the ground-water flow model is within bedrock, and up to 30% of total modeled recharge to the Mimbres Basin occurs as areal recharge to bedrock hydrogeologic units. Recharge to bedrock hydrogeologic units becomes ground water in storage and ground-water flow to the basin fill. Hydraulic conductivity values for the bedrock of the Mimbres Basin are highly variable, ranging from 5 x 10^{-6} to 900 feet per day (ft/d) based on the degree of secondary permeability, while hydraulic conductivity values for the basin fill range from 0.01 to about 400 ft/d and decrease with depth and age.

INTRODUCTION

The Mimbres Basin is a hydrologically closed basin where the majority of domestic, municipal, agricultural, and industrial water supplies come from ground water. Historically, substantial volumes of ground water have been pumped from the basin fill and bedrock shown in Figure 1. Over 100,000 acre-feet per year (ac-ft/yr) of ground water are pumped from the Mimbres Basin (Wilson et al., 2003; Daniel B. Stephens & Associates, Inc., unpubl. report for Southwest New Mexico Regional Water Plan Steering Committee, 2005), and about 6% of this is pumped from bedrock.

Geologic, geophysical, and hydrogeologic studies of the Mimbres Basin over the past 90 years, including Darton (1916), White (1931), Trauger (1972), Hanson et al. (1994), Hawley et al. (2000), Kennedy et al. (2000), and McCoy and Finch (unpubl. report for Chino Mines Company, 2006), were compiled and integrated to explore local and regional geologic controls on ground-water flow in the Mimbres Basin. The U.S. Geological Survey (USGS) created a two-dimensional regional-scale ground-water flow model of the Mimbres basin-fill aquifer (alluvium and Gila Conglomerate), with bedrock simulated as no-flow blocks (Hanson et al., 1994). The USGS model only considered mountain-front recharge from upland runoff to the basin fill, leaving a significant portion of recharge unaccounted (Hanson et al., 1994). Ground-water inflow from surrounding bedrock, which is typically controlled by bedrock structures, was likely the unaccounted component of recharge. McCoy and Finch (unpubl. report for Chino Mines Company, 2006) drew upon the USGS model, hydrogeologic data in Trauger (1972), the hydrogeologic framework of the Mimbres Basin by Hawley et al. (2000) and Kennedy et al. (2000), in addition to local studies in the Tyrone and Santa Rita mining districts to create a three-dimensional calibrated regional ground-water flow model of the basin fill and bedrock of the Mimbres Basin.

The ground-water flow model also included the development of a detailed basin-fill thickness map (Fig. 1) based on New Mexico Bureau of Geology and Mineral Resources (NMBGMR) data and maps (Seager, 1995; Seager et al., 1982; Trauger, 1972), New Mexico Energy, Minerals and Natural Resources Department - Oil Conservation Division well files, USGS data and maps (Hedlund, 1978a, b, c, d, e, f; Hanson et al., 1994), New Mexico Water Resources Research Institute (NMWRRI) data, maps, and cross-sections (Hawley et al., 2000), data from Trauger and Coons (unpubl. report for Molzen-Corbin and Associates, Inc., 1984) and Blandford and Wilson (1987), unpublished data on basin-fill thickness in the Mimbres Basin (John Hawley, personal commun., 2005), and isostatic residual gravity data (Heywood, 2002).

The ground-water flow model showed that the Mimbres Basin can be divided into four major hydrogeologic regions: 1) Upper Mimbres, 2) San Vicente, 3) Deming, and 4) Florida (Fig. 1). Hydrogeologic regions are defined by topography, geology, and structure, in addition to ground-water recharge and discharge, and each region has a distinct hydrogeologic framework. Each region includes bedrock (may include Precambrian crystalline rocks, Paleozoic carbonates, Cretaceous sandstone and shale, and Tertiary volcaniclastic rocks) and basin fill (consisting of Tertiary to Quaternary Gila Conglomerate, and Quaternary alluvium).

In general, geology controls recharge, discharge, and hydraulic properties in the hydrogeologic regions of the Mimbres Basin. In turn, ground-water flow is controlled by higher heads in recharge areas, variable hydraulic properties, distribution of discharge locations, and ground-water pumping. The bedrock in the Upper Mimbres and San Vicente hydrogeologic regions receives substantial areal recharge, stores significant volumes of ground water, and transmits ground water to the basin fill. The basin fill represents the primary aquifer in the Deming and Florida hydrogeologic regions; however, shallow bedrock along faults controls ground-water flow. Regional ground-water flow is from north to south following recharge and discharge patterns (Fig. 1).

PHYSIOGRAPHIC SETTING

The Mimbres Basin lies within the Basin and Range and southern Transition Zone provinces, and is defined on the north and

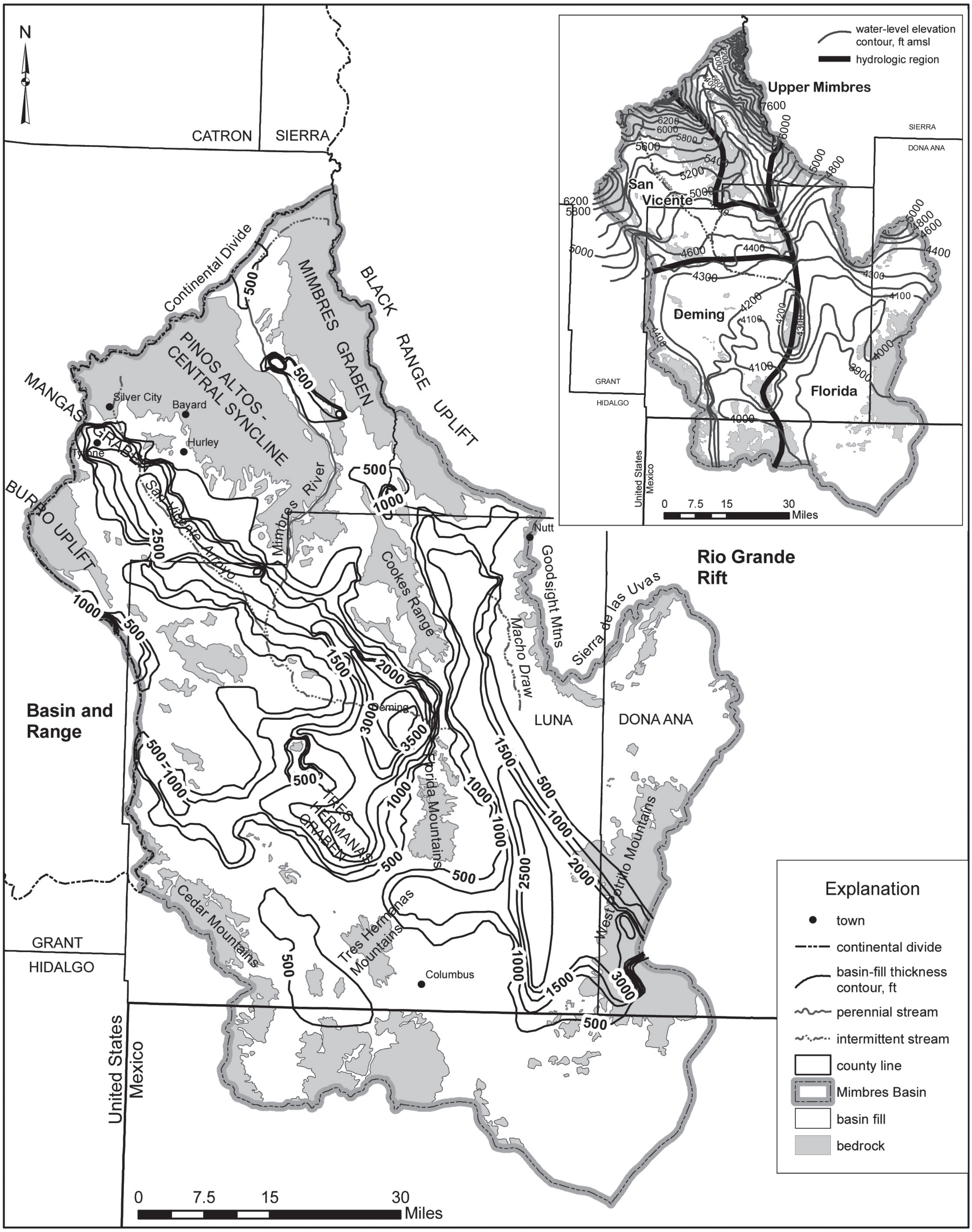

FIGURE 1. Map of Mimbres Basin showing geographic features and basin-fill thickness contours, and hydrogeologic zones and water-level elevation contours (see inset), Southwestern New Mexico.

west by the Continental Divide (Fig. 1). Predominantly northwest-trending grabens and half-grabens define sub-basins within the Mimbres Basin. Land-surface elevations in the Mimbres Basin range from about 3900 ft above mean sea level (amsl) in the Bolson de los Muertos in the south (Mexico), to about 10,000 ft amsl in the Black Range in the north. The Mimbres Basin climate is typical of the semi-arid to arid southwest, with average annual precipitation increasing with elevation and ranging from about 9 inches in the south to over 20 inches in the Upper Mimbres hydrogeologic region. The Mimbres River is a perennial stream along a 32 mile-long reach in the Upper Mimbres hydrogeologic region. The Mimbres River occasionally flows south into Mexico as a result of high-magnitude precipitation- and snowmelt events.

STRUCTURAL SETTING

The distribution of rocks in the Mimbres Basin has been influenced by Mesozoic tectonism, and Tertiary and Quaternary faulting, volcanism, and deposition. The Mimbres Basin is at the intersection of the Basin and Range, southern Rio Grande Rift, and southern Transition Zone tectonic provinces (Mack, 2004; Trauger, 1972), and is characterized by predominantly northwest-trending faults and folds associated with the Laramide orogeny, Tertiary magmatism, and Quaternary tectonism.

Dominant structures in the northern part of the Mimbres Basin include the Black Range uplift, Mimbres graben, Pinos Altos-Central syncline, Cookes Peak horst, and Mangas graben (Fig. 1). Tertiary igneous rocks and Permian carbonates are bound by northwest-trending faults in the Black Range (Fig. 2). The Mimbres graben is a half graben bound by the northwest-trending, southwest-side up, normal Mimbres-Sarten fault, along which basin fill reaches a maximum thickness of 1500 ft (Trauger, 1972; Jicha, 1954).

The Pinos Altos-Central syncline is bound by the Mimbres-Sarten fault to the northeast and the northwest-trending, northeast-side up, normal Treasure Mountain fault (also referred to as the Silver City fault by Pratt (1967)) to the southwest. Paleozoic carbonates, Cretaceous sedimentary rocks, and Tertiary igneous rocks on the western edge of the Pinos Altos-Central syncline are locally fractured. The northeast-trending, southeast-side up, normal Blue Mountain fault is orthogonal to the Mimbres-Sarten Fault (Elston, 1957; Machette et al., 1998). The Cookes Range horst, bound by the Mimbres-Sarten fault, is structurally similar to the Pinos Altos-Central syncline.

The Mangas graben is a half graben bound to the northeast by the Treasure Mountain fault, with reported displacement of 1400 to 4300 ft (Mack, 2004), and to the southwest by the Burro uplift. Basin fill reaches a maximum thickness of over 2500 ft thick in the Mangas graben along the Treasure Mountain fault. Precambrian crystalline rocks are exposed in the Burro uplift southwest of the Mangas graben.

Dominant structures in the southern part of the Mimbres Basin include the West Potrillo, Florida, and Cedar Mountains uplifts, and various grabens containing thick accumulations of basin fill (Fig. 1). The West Potrillo uplift and primary Florida hydrogeologic region graben are structures characteristic of the Rio Grande Rift (Hawley, 1978; Keller and Cather, 1994). Basin fill reaches a maximum thickness of over 2500 ft in the Florida hydrogeologic region, along the West Potrillo uplift (Fig. 2). The Florida hydrogeologic zone includes structures characteristic of the Basin and Range, southern Rio Grande Rift, and southern Transition Zone tectonic provinces (Clemons, 1986; Seager, 1995; and Clemons, 1998), whereas the Deming hydrogeologic region includes structures characteristic of Basin and Range (Trauger, 1972).

HYDROGEOLOGIC CHARACTERISTICS OF BEDROCK AND BASIN FILL

From a hydrogeologic perspective, the most significant bedrock units of the Mimbres Basin include, from oldest to youngest, Paleozoic carbonates, Cretaceous sedimentary rocks, and Tertiary volcanic and volcaniclastic rocks (Fig. 2; Table 1). The basin-fill aquifer includes the Tertiary to Quaternary Gila Conglomerate and Quaternary alluvium.

Paleozoic Carbonate Rocks

Paleozoic carbonate rocks, including Cambrian sandstone, Ordovician and Silurian limestones and dolomites, Mississippian Lake Valley Limestone, Pennsylvanian Oswaldo Formation,

TABLE 1. Summary of bedrock and basin-fill hydrogeologic characteristics in the Mimbres Basin

Age	Key Formations	Thickness, ft	Rock Type	Hydraulic Conductivity, ft/d
Paleozoic	Lake Valley Ls Oswaldo Fm Abo Fm	300 to 400 300 to 400 up to 640	limestone dolomite shale, siltstone, limestone	0.01 to 900
Cretaceous	Colorado Fm Beartooth Quartzite	up to 1000 65 to 140	shale, limestone, sandstone quartzite	0.0005 to 1.4
Tertiary	Sugarlump Tuff Rubio Peak Fm Hurley Sill	up to 3600	volcanic, volcaniclastic, shallow intrusive	0.002 to 0.4
Tertiary to Quaternary	Gila Conglomerate alluvium	up to 3500 less than 100	poorly consolidated sediments	0.01 to 100 10 to 400

Notes: ft/d - feet per day; Ls - Limestone; Fm - Formation

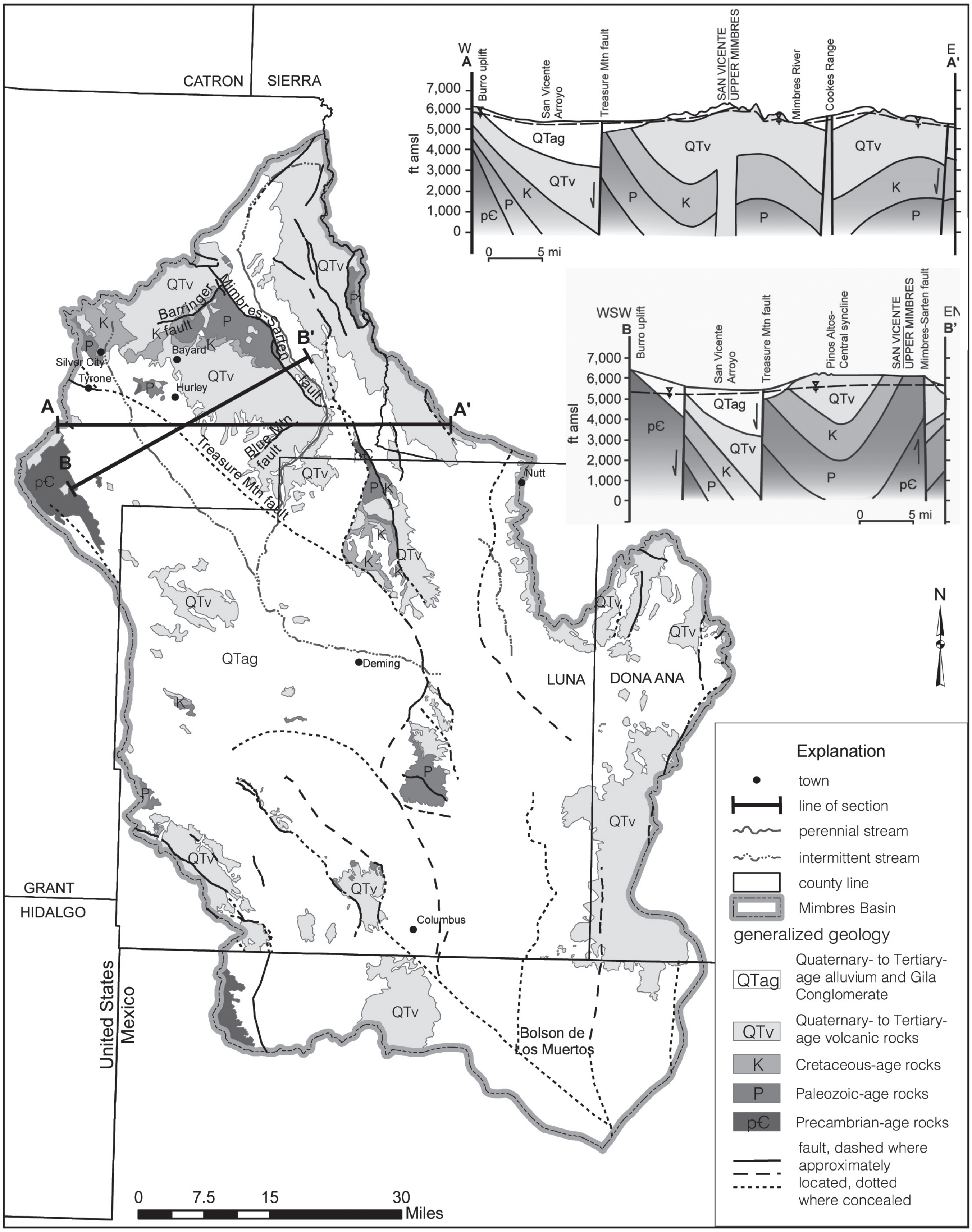

FIGURE 2. Map of Mimbres Basin showing generalized geology, faults, and cross-sections (see insets), Southwestern New Mexico.

and Permian Hueco and Abo Formations, overlie crystalline Precambrian rocks in the Mimbres Basin, and are exposed along the Black Range uplift, Pinos Altos-Central syncline, Cookes Peak horst, Florida Mountains, and Cedar Mountains uplift (Fig. 2).

The Lake Valley Limestone is about 300 to 400 ft thick, and the overlying Oswaldo Formation, also composed primarily of limestone, is about 300 to 400 ft thick (Trauger, 1972). Current water levels in wells completed in Lake Valley Limestone and Oswaldo Formation southwest of Hurley are about 200 ft lower than the regional water table, indicating poor local hydraulic connection between the Paleozoic rocks and overlying basin fill. Prior to ground-water development, ground water discharged from the Lake Valley Limestone and Oswaldo Formation at springs in this area instead of draining into the overlying basin fill. The Abo Formation is up to 640 ft thick, and is composed primarily of red shale and siltstone with thin beds of limestone (Trauger, 1972).

Paleozoic carbonate rocks are recharged in areas where stream channels flow over carbonates. The Lake Valley Limestone and Oswaldo Formation are recharged along Cameron Creek about 2 mi northwest of Hurley. The Abo Formation is recharged along Iron Creek at Emory Pass in the Black Range. Cambrian through Mississippian carbonates are recharged along drainages northeast of the Treasure Mountain fault.

In general, the Paleozoic carbonate rocks have variable permeability, depending on the degree of secondary permeability associated with fracturing and dissolution. Hydraulic conductivity values for Lake Valley Limestone and Oswaldo Formation with high secondary permeability, based on pumping test data for wells southwest of Hurley, range from 4 to 900 ft/d. Hydraulic conductivity values for less-fractured Lake Valley Limestone and Oswaldo Formation range from 0.01 to 9 ft/d (Finch and Peery, unpubl. report for Cobre Mining Company, 1999; Golder Associates, unpubl. report for Chino Mines Company, 2005), with the latter reporting a hydraulic conductivity value of 0.6 ft/d for the Abo Formation.

Cretaceous Sedimentary Rocks

Cretaceous sedimentary rocks, including the Colorado Formation and Beartooth Quartzite, overlie Paleozoic carbonate rocks in the Mimbres Basin, and are primarily exposed in the Pinos Altos-Central syncline, Cookes Peak horst, and Cedar Mountains uplift (Fig. 2). The Colorado Formation is up to 1000 ft thick, and is primarily composed of shale with interbedded limestone and sandstone (Trauger, 1972). The Beartooth Quartzite is 65 to 140 ft thick. In general, the Cretaceous sedimentary rocks have variable permeability that depends on the degree of fracturing, with hydraulic conductivity values ranging from 0.0005 to 1.4 ft/d (Finch and Peery, unpubl. report for Cobre Mining Company, 1999; Golder Associates, unpubl. report for Chino Mines Company, 2005).

Tertiary Volcanic Rocks

Tertiary volcanic rocks, including the Sugarlump Tuff, Rubio Peak Formation, and the Hurley sill, are interlayered with volcaniclastics in the Mimbres Basin (Fig. 2). Tertiary volcanic rocks are up to 3600 ft thick (Trauger, 1972). In general, the Tertiary volcanic rocks have variable permeability that depends on the degree of fracturing, and the presence of low-permeability ash beds and relatively high-permeability volcaniclastic beds. The depositional and compositional layering in the volcanic and volcaniclastic rocks typically strike to the northwest and dip about 5 degrees to the northeast. Hydraulic conductivity values for the Tertiary volcanic rocks in the Pinos Altos-Central syncline range from 0.002 to 6.0 ft/d (Daniel B. Stephens & Associates, Inc., unpubl. report for Phelps Dodge, 1999; McCoy and Finch, unpubl. report for Chino Mines Company, 2006).

Tertiary to Quaternary Basin Fill (Gila Conglomerate and Alluvium)

For the purposes of the current study, the Gila Conglomerate and alluvium are referred to as basin fill, with a maximum total thickness of over 3500 ft near Deming, the West Potrillo uplift, in the Mangas graben, and the Tres Hermanas graben. The Gila Conglomerate is poorly-consolidated and composed of rocks that have eroded from the surrounding highlands and filled in structural basins, paleo-drainages, and other lowlands. The Gila Conglomerate generally consists of poorly-sorted gravel, sand, silt, and clay, deposited in alluvial fan, stream channel, and lacustrine environments (Trauger, 1972). Localized uniform grain sizes within the Gila Conglomerate result in low-permeability mudstone or high-permeability sand and gravel. The Gila has been subdivided into upper and lower members by Trauger (1972) to reflect the degree of consolidation, and has been further subdivided into eight hydrostratigraphic units by Hawley et al. (2000). The alluvium consists of unconsolidated to poorly-consolidated deposits of silt, sand, gravel, cobbles, and boulders. The alluvium has been subdivided into dozens of hydrostratigraphic units by Hawley et al. (2000).

Hydraulic conductivity values for the basin fill can be relatively high, reflected by a gentle hydraulic gradient in the basin fringe and basin center. In general, permeability decreases with depth and age in the basin-fill hydrogeologic unit. Hydraulic conductivity values for the basin fill range from 0.01 to about 400 ft/d (McCoy and Finch, unpubl. report for Chino Mines Company, 2006; Hanson et al., 1994), varying according to grain size, sorting, and type of matrix. The highest hydraulic conductivity values (10 ft/d and greater) are associated with unconsolidated well-sorted sand and gravel lacking clay or carbonate matrix, in the Mangas and Tres Hermanas grabens.

RECHARGE

In the Mimbres Basin, recharge occurs as 1) areal recharge from direct infiltration of precipitation above elevations of 5000 ft amsl, and 2) mountain-front recharge from infiltration of redistributed runoff at the alluvial fans along the basin fringes and along San Vicente Arroyo. Mountain-front recharge is a concept developed by Maxey and Eakin (1949), Mifflin (1968), Feth (1964), and Feth et al. (1966). Areal recharge to bedrock units in the highlands of the southwestern United States has been commonly referred to as "mountain block" recharge (Hogan et al., 2004a; and Hogan et al., 2004b). Recent studies by the USGS (D'Agnese et al., 1997) have demonstrated the importance of relatively low-permeability units transmitting recharge to alluvial basins in ground-water flow modeling. The areal extent of most major basins is large enough that significant quantities of water can move through low-permeability units given long time scales (Alexander et al., 1987).

Total recharge to the Mimbres Basin was estimated to be about 29,000 ac-ft/yr (McCoy and Finch, unpubl. report for Chino Mines Company, 2006); about 30% of this was areal recharge to the bedrock and about 70% was mountain-front recharge. Simulated predevelopment ground-water recharge in the USGS model of the Mimbres Basin totaled 40,000 ac-ft/yr, with components of mountain-front recharge (about 70%), infiltration from the Mimbres River downstream from Faywood (about 25%), infiltration from Apache Tejo Spring (about 5%), and a minor amount of underflow from the Mangas graben and the Bolson de los Muertos. White (1931) estimated that an average recharge rate of 26,700 ac-ft/yr originates from infiltration of runoff and streamflow in the northern Mimbres Basin.

Areal Recharge

In the Mimbres Basin, areal recharge to the Paleozoic and Cretaceous rocks moves downward through fractures and solution channels, and areal recharge to the Tertiary volcanic rocks moves downward through fractures and volcaniclastics, until it reaches a low-permeability layer. Areal recharge is evidenced by higher ground-water elevations in the Pinos Altos and Black Range. As the recharge moves laterally, it discharges as ground-water underflow to the basin fill or as spring flow. Areal recharge to the bedrock hydrogeologic units may constitute up to 30% of total recharge to the basin, and likely accounts for base flow in the Mimbres River, and deep circulation of ground water (McCoy and Finch, unpubl. report for Chino Mines Company, 2006). Much of the areal recharge to the Mimbres Basin could be considered mountain-block recharge, as discussed in Hogan et al. (2004a).

White (1931) suggested that areal recharge did not occur in the Mimbres Basin below the Mimbres River gaging station near Spalding, which is located where bedrock meets basin fill, and coincides with an elevation of 4750 ft amsl. A water budget analysis of surplus precipitation performed by Finch (2003) confirmed that recharge from direct infiltration of precipitation does not likely occur below 5000 ft amsl, except where runoff infiltrates along arroyos and the basin-fill fringe. Areal recharge is not only controlled by elevation, but also by the exposure of fractured bedrock and the steepness of slopes in the Pinos Altos and Black Range.

Mountain-Front Recharge

Mountain-front recharge was quantified and applied to the Mimbres Basin using a method modified from Stone et al. (2001) for recharge resulting from runoff redistributed from mountain to basin fringe sub-basins, and from basin fringe sub-basins to basin fill. The method considers soil type, and land cover type and density, to determine the magnitude of a precipitation event necessary to generate runoff. The runoff that leaves a mountain or basin fringe sub-basin is subtracted from the elevation-based potential recharge for that sub-basin (McCoy and Finch, unpubl. report for Chino Mines Company, 2006).

A percentage of the redistributed runoff, and remaining potential recharge (if any), infiltrates in the basin fringe or along arroyos in the basin fill, and becomes mountain-front recharge. White (1931) estimated that a minimum of 30% of streamflow infiltrates and becomes recharge to the Mimbres Basin. The percentage of redistributed runoff that becomes mountain-front recharge varies from zero to close to 100%, depending on local geologic controls (McCoy and Finch, unpubl. report for Chino Mines Company, 2006). In areas where bedrock has high secondary permeability, more precipitation may infiltrate, and contribute to areal recharge instead of mountain-front recharge. Areal recharge may be limited in mountainous areas with very steep slopes, and thus more runoff is redistributed and becomes mountain-front recharge. The distribution and magnitude of areal versus mountain-front recharge, which influences ground-water flow in the Mimbres Basin, are controlled by geology and topography.

DISCHARGE

In the Mimbres Basin, natural ground-water discharge primarily occurs through evaporation at the water table and evapotranspiration (ET) by riparian vegetation. Discharge areas were delineated from the Darton (1916) map of regions having less than 50 ft depth to water, and the USGS model ET areas (Hanson et al., 1994). Estimates of potential ET for the Mimbres Basin range from 22 to 32 in/yr (Climatography of the United States Map No. 60-29, U.S. Department of Commerce, as shown in Williams and McAllister, 1979). The USGS model used a maximum ET depth of 55 ft below ground level (bgl) (Hanson et al., 1994). Ground-water evaporation occurs at several playas covering about 890,000 acres in the southern part of the Mimbres Basin, and in riparian areas covering about 19,500 acres in the northern part of the basin. The calibrated ground-water flow model had a relatively low evaporation rate of 9 in/yr with an extinction depth of 50 ft bgl.

During the last 80 years, a significant component of ground-water discharge has occurred by pumping. Significant pumping associated with agriculture in the Deming hydrogeologic region began in the 1930s, with total withdrawals increasing from about 9500 ac-ft/yr in 1930 to about 70,000 ac-ft/yr in 1960 (Hanson et al., 1994). Significant pumping associated with mining operations in the San Vicente hydrogeologic region began in the 1960s. By 1962, the Kennecott Copper Co., U.S. Smelting, Refining, and Mining Co., and New Jersey Zinc Co. were using about 10,000 ac-ft/yr (Trauger, 1972). The current estimate of total ground water pumped from the Mimbres Basin is about 100,000 ac-ft/yr (Wilson et al., 2003; Daniel B. Stephens & Associates, Inc., unpubl. report for Southwest New Mexico Regional Water Plan Steering Committee,2005), which is nearly three times the natural recharge.

GEOLOGIC CONTROLS ON GROUND-WATER FLOW WITHIN HYDROGEOLOGIC REGIONS

Upper Mimbres Hydrogeologic Region

Ground-water flow in the Upper Mimbres hydrogeologic region is controlled by areal recharge, zones of high secondary permeability and preferential pathways in otherwise low-permeability bedrock, and the Mimbres River and associated hydrologic boundaries. Bedrock receives areal recharge in the highlands, and ground-water discharge is to the Mimbres River. The Mimbres River and underlying basin fill of the Mimbres graben convey surface water and ground water from the Upper Mimbres hydrogeologic region to the San Vicente hydrogeologic region. No deep ground-water flow regime is known to exist in the Upper Mimbres region. The storage capacity of the bedrock is generally low and likely decreases with depth and decreasing secondary porosity from fractures. Very little is known about the variations of ground-water quality in bedrock. The Mimbres River has an average total dissolved solids (TDS) concentration of 200 milligrams per liter (mg/L).

Areal recharge to the Upper Mimbres hydrogeologic region accounts for 11% of total recharge to the Mimbres Basin (Table 2). In the Black Range near Emory Pass, fractured Abo Formation is recharged where it is exposed in the streambed of Iron Creek near a north-trending fault. Areal recharge rates in the ground-water flow model were about 0.7 in/yr compared to 0.04 in/yr in the surrounding area (McCoy and Finch, unpubl. report for Chino Mines Company, 2006). Steep slopes of about 0.5 ft/ft or greater limit areal recharge in higher elevation areas (above elevations of 7200 ft amsl in the Black Range and 8200 ft amsl in the Pinos Altos Range). Areal recharge rates were about 0.04 in/yr compared to 0.1 and 0.3 in/yr in adjacent areas with gentler slopes (McCoy and Finch, unpubl. report for Chino Mines Company, 2006).

Recharge from the Upper Mimbres hydrogeologic region to the San Vicente hydrogeologic region creates a hydraulic boundary that offsets pumping effects associated with the San Vicente and Deming hydrogeologic regions, and defines the boundary between the two regions.

San Vicente Hydrogeologic Region

Ground-water flow in the San Vicente hydrogeologic region is controlled primarily by mountain-front recharge, zones of high secondary permeability and preferential pathways in bedrock, and thickness and permeability contrasts in basin fill. Bedrock is exposed in the highlands along the western, northern, and eastern boundaries of the hydrogeologic region, and basin-fill thickness reaches 2500 ft in the Mangas graben. In the San Vicente hydrogeologic region, fracture zones along northwest-trending faults like the Treasure Mountain fault generally convey ground water, while northeast-trending faults like the Blue Mountain fault typically act as barriers to ground-water flow. The Pinos Altos-Central syncline controls regional stratigraphy and zones of high secondary permeability and preferential pathways associated with intense fracturing of bedrock in the limbs of the syncline near bounding faults, evidenced by ground water discharge at Apache-Tejo Springs, Warm Springs, and Faywood Hot Springs.

Recharge to the San Vicente hydrogeologic region accounts for 63% of total recharge to the Mimbres Basin (Table 2). Recharge to the San Vicente hydrogeologic region includes mountain-front recharge (about 15,650 ac-ft/yr) and areal recharge (about 2690 ac-ft/yr). Areal recharge rates are highest where bedrock with high secondary permeability is exposed along drainages. The Lake Valley Limestone and Oswaldo Formation are recharged along Cameron Creek, along the southwestern limb of the Pinos Altos-Central syncline about 2 mi northwest of Hurley. Areal recharge rates in the ground-water flow model were about 4.4 in/yr compared to about 0.09 in/yr in the surrounding area (McCoy and Finch, unpubl. report for Chino Mines Company, 2006). In the Burro uplift, fractured Precambrian granite and Tertiary volcanic rocks are recharged along Walnut Creek. Areal recharge rates were 3.5 in/yr compared to about 0.09 in/yr in the surrounding area (McCoy and Finch, unpubl. report for Chino Mines Company, 2006). Mountain-front recharge occurs along major arroyos

TABLE 2. Summary of hydrogeologic regions of the Mimbres Basin,based on steady-state calibrated ground-water-flow model (McCoy and Finch, unpubl. report for Chino Mines Company, 2006)

	Upper Mimbres	San Vicente	Deming	Florida	Mimbres Basin
Areal recharge, ac-ft/yr	3058	2691	223	510	6480
Mountain-front recharge, ac-ft/yr	0	15,653	5840	1078	22,570
Total recharge, ac-ft/yr	3058	18,344	6063	1588	29,050
Percent of total mountain-front recharge	0	69	26	5	100
Percent of total areal recharge	47	42	3	8	100
Percent of total recharge	11	63	21	5	100
*Ground water in storage in bedrock, ac-ft/yr	7.9 mil	12.2 mil	14.5 mil	24.3 mil	58.9 mil
*Ground water in storage in basin fill, ac-ft/yr	1.5 mil	40.3 mil	62.2 mil	83.6 mil	187.6 mil
*Total ground water in storage, ac-ft/yr	9.4 mil	52.5 mil	76.7 mil	107.9 mil	246.5 mil
Evapotranspiration, ac-ft/yr	0	3236	7552	16,182	26,970

Notes: *estimated from ground-water-flow model and does not represent ground water available for development; mil - million
ac-ft/yr - acre-feet per year

that drain the highlands. Mountain-front recharge rates along these arroyos are one to two orders of magnitude greater than in the surrounding areas. Over 50% of the estimated runoff from the Burro uplift and San Vicente Arroyo becomes recharge to basin fill in the Mangas graben.

The basin fill has relatively high hydraulic conductivity along the Pinos Altos mountain front and the Treasure Mountain fault, and grain size and sorting decreases, and cementation increases with depth and distance from the mountain front. In places, basin fill has lower hydraulic conductivity than bedrock, and acts as a hydraulic barrier to ground-water flow.

Ground-water quality in bedrock can vary significantly, with TDS concentrations ranging from 250 to over 1000 mg/L, according to rock type, flow path, and residence time. Ground water in the basin fill has low TDS (250 to 500 mg/L) due to mountain-front recharge.

In the San Vicente hydrogeologic region, ground-water discharge is due to evapotranspiration in riparian areas that cover about 19,500 acres near the confluence of San Vicente Arroyo and the Mimbres River, and ground-water outflow to the Deming hydrogeologic region.

Deming Hydrogeologic Region

Ground-water flow in the Deming hydrogeologic region is controlled by thick sequences of relatively high-permeability basin fill, ground-water inflow from the San Vicente hydrogeologic region, and limited mountain-front recharge. Relatively low-permeability bedrock is exposed in the highlands of the Florida Mountains, Cedar Mountains, and Tres Hermanas Mountains, and maximum basin-fill thickness is over 3500 ft east of Deming, and 2500 ft west of the Florida Mountains. Substantial ground-water pumping for irrigation occurs within the basin fill of the Deming hydrogeologic region.

Recharge to the Deming hydrogeologic region accounts for 21% of total recharge to the Mimbres Basin (Table 2), limited by low elevations and the small size of the watersheds. Recharge to the Deming hydrogeologic region includes areal recharge (220 ac-ft/yr) and mountain-front recharge (5840 ac-ft/yr). The most significant components of ground-water inflow come from the San Vicente hydrogeologic region and infiltration of storm-water flow in the Mimbres River.

In the Deming hydrogeologic region, ground-water discharge is due to evaporation in playa areas that cover about 120,000 acres, and ground-water outflow to the Florida hydrogeologic region.

Kennedy et al. (2000) noted that ground-water flow is constricted by “intervening structural highs from not only “insular” mountain ranges and hilly uplands but also buried bedrock highs and sills” in the Deming hydrogeologic region. Between the Florida Mountains and Tres Hermanas Mountains, a ground-water flow constriction results from relatively shallow bedrock present at a depth of less than 500 ft beneath the basin fill (Hawley et al., 2000; John Hawley, personal commun., 2005; Blandford and Wilson, 1987). Between Cookes Peak and the Florida Mountains, a ground-water flow constriction results from relatively shallow bedrock present at a depth of less than 500 ft beneath basin fill (Hawley et al., 2000; John Hawley, personal commun., 2005). Thus, these constrictions limit ground-water outflow to the Florida hydrogeologic region.

The quality of ground water in the Deming hydrogeologic region is better to the north (due to recharge from the Mimbres River) with increasing TDS concentrations to the south towards discharge areas. TDS concentrations in ground water can range from less than 250 to greater than 1000 mg/L.

Florida Hydrogeologic Region

The primary component of ground-water inflow to the Florida hydrogeologic region is from the basin fill of the Deming hydrogeologic region, and is limited by the presence of relatively shallow bedrock along structures between the Tres Hermanas and the Floridas, and between Cookes Peak and the Floridas, as discussed above. Bedrock is exposed in the highlands at Cookes Peak, the Florida Mountains, and in the Goodsight Mountains/Sierra de Las Uvas in the northeast part of the hydrogeologic region. Very little is known about ground-water conditions in the volcanic bedrock in the northern part of the hydrogeologic region. In places, perched ground water may be found in fractured volcanic rocks. Along a north-trending fault between the Florida uplift and the West Potrillo uplift, the basin fill is over 2500 ft thick (Hawley et al., 2000; John Hawley, personal commun., 2005). In addition, the basin fill is over 2500 ft thick along the West Potrillo uplift. Ground-water quality is similar to the Deming hydrogeologic region.

Recharge to the Florida hydrogeologic region accounts for only 5% of total recharge to the Mimbres Basin (Table 2), limited by low elevations and the small size of the watersheds. Almost no runoff from Macho Draw and the West Potrillo uplift becomes mountain-front recharge. Although the Mimbres River has occasionally flowed into the Florida hydrogeologic region as a result of high-magnitude precipitation- and snow-melt events, almost no flow becomes recharge.

In the Florida hydrogeologic region, ground-water discharge is to evaporation in playa areas that cover about 770,000 acres and possibly ground-water outflow to the Bolson de los Muertos in Mexico.

CONCLUSIONS

The hydrogeologic framework developed by Hawley et al. (2000) and McCoy and Finch (unpubl. report for Chino Mines Company, 2006) resulted in a regional ground-water flow model (McCoy and Finch, unpubl. report for Chino Mines Company, 2006) and defines four hydrogeologic regions of the Mimbres Basin, in which ground-water flow is controlled by geology and structure.

In the Upper Mimbres hydrogeologic region, ground-water flow is controlled by areal recharge, zones of high secondary permeability in bedrock, and the Mimbres River. In the San Vicente hydrogeologic region, ground-water flow is controlled by mountain-front recharge, zones of high secondary permeability in bedrock, thickness and permeability contrasts in basin fill, and evapotranspiration from riparian areas. In the Deming hydrogeologic region, ground-water flow is controlled by thick sequences of relatively high-permeability basin fill, ground-water inflow from the San Vicente hydrogeologic region, limited mountain-front recharge, and evapotranspiration in playa areas. In the Florida hydrogeologic region, ground-water flow is controlled by constrictions in the basin fill that limit ground-water inflow from the Deming region, thick sequences of relatively high-permeability basin fill, and evapotranspiration in playa areas.

Ground-water pumping effects in each hydrogeologic region are isolated by geologic or hydraulic barriers, and pumping from one region does not significantly affect the other. For example, pumping from the San Vicente and Deming hydrogeologic regions does not affect streamflow in the Upper Mimbres hydrogeologic region (McCoy and Finch, unpubl. report for Chino Mines Company, 2006).

The importance of bedrock units in conveying recharge to the basin fill and in controlling ground-water flow exemplifies the need to consider entire basins when assessing regional- and local-scale ground-water resources in the Southwestern United States.

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