EXECUTIVE SUMMARY

INTRODUCTION

Purpose and Scope of Study

This study was undertaken to characterize binational aquifers in southwestern New Mexico and prepare data for an international data exchange with the Republic of Mexico. This project is a continuation of joint efforts by the governments of the United States and Mexico to identify transboundary aquifers, quantify the natural and induced chemical quality of each aquifer, determine the direction of groundwater flow, and develop Geographic Information System coverages.

Many of the surface and groundwater resources along the transboundary corridor are shared between both nations, yet little binational study of these resources has been undertaken. Solutions to water-related problems can be achieved only when a better understanding of transboundary water resources is attained. Because of the importance of water quality and quantity to the region, aggregation and analysis of the existing data/information base is vital. Much of the U.S./Mexico border region relies primarily on local transboundary groundwater resources for all uses. It is necessary to have an adequate understanding of these shared aquifers to address properly the variety of issues involved in good resource management and problem avoidance at the local, state, national and international levels.

Location and Physiographic Setting

This report covers an area of about 37,000 km^2 (14,300 mi^2) in southwestern New Mexico and adjacent parts of Arizona and Mexico. Most of the study area (31,600 km^2, 12,200 mi^2) is in New Mexico with a small portion extending into Arizona (1,000 km^2, 385 mi^2). The hydrogeologic units that form the transboundary aquifer system extend into Mexico (primarily Chihuahua) and cover the area between 31° 00' and 33° 45' north latitude, and 106° 55' and 109° 30' west longitude. Three basin systems– Mimbres, Hachita-Moscos, and Playas/San Basilio are located east of the Continental Divide, and three are to the west–Animas, Gila River and San Bernardino.

Most of the study area is located in the Mexican Highland section of the Basin and Range physiographic province. Elevations range from 2,600 m (8,532 ft) at Animas Peak to less than 1,200 m (3,940 ft) at the lower end of the Mimbres Basin system, and about 1,150 m (3,775 ft) in the Gila River and Rio (del) San Bernardino valleys. The more permeable (primarily alluvial) fill components of the deep structural basins that characterize the Mexican Highland section form the major aquifers described in this report. Topographically *closed* basins with piedmont and basin-floor alluvial surfaces grading to central playa (ephemeral-lake) depressions are designated *bolsons* (*bolsones*). Open basins with piedmont slopes grading to axial streams that discharge to lower-lying areas are referred to as *semibolsons*. All stream systems are ephemeral, except in the valleys of Animas Creek, and the upper Rio (del) San Bernardino, Mimbres and Gila River systems.

The northern and highest part of the study area is in the Datil-Mogollon section of the Transition Zone province (about 8,600 km^2, 3,320 mi^2). Elevations of highest peaks exceed 3,000 m (10,000 ft), and much of this region of high plateaus with deep canyons is above 1,800 m (5,900 ft). Perennial to intermittent reaches of the Gila and upper Mimbres River systems are located in this section. As the province name implies, large-scale geomorphic and structural features mark a broad zone of transition between the Colorado Plateau of west-central New Mexico and east-central Arizona and the Basin and Range province. The latter area has a much more extended crustal structure characterized by broad and deep fault-block depressions and is topographically lower.

Land Use and Landcover

The study area represents a wide variety of land use/landcover, with forest areas prevalent in the higher elevations and rangeland in the transition zone to drier, lower-elevation areas. Lowlands contain a mix of irrigated farmland, rangeland and alkali-flats. The major urban areas include Deming, Lordsburg, Silver City, and Hurley, with a number of smaller rural communities scattered throughout the area. The Silver City-Hurley area has been one of the largest metallic-mineral producing centers of the American Southwest for more than a century.

Climate

The study area is typical of the arid southwest, with mostly clear skies and limited rainfall and humidity. Average annual precipitation varies from less than 25.4 cm (10 in) per year in low lying basins to as much as 76.2 cm (30 in) per year at higher elevations in the mountain ranges. Annual rainfall at Deming (elevation 1,321 m; 4,332 ft) averaged 23.4 cm (9.22 in) over the 1948-1995 period. In the upper reach of the Mimbres River (elevation 1,904 m; 6,247 ft), the average was 43.3 cm (17.05 in) for the same period. Nearly half of the annual precipitation is from thunderstorms that occur from July through September.

In the lower elevation areas, the average high summer (June, July, and August) temperatures typically are above 32° C (90° F). Winter (December, January, and February) average low temperatures are usually about -4° C (25° F). In the higher elevation areas, average high summer temperatures are about 29° C (85° F) and winter low temperatures are about -7° C (20° F). Large diurnal changes in temperature of about 17° C (30° F) are common. Average class A pan evaporation is typically in the 251 to 261 cm/yr (99-103 in/yr) range in basin-floor areas.

BASIC CONCEPTS OF AQUIFER HYDROGEOLOGY AND GROUNDWATER FLOW

Structural Boundary and Bedrock Components

In both the Mexican Highland and Datil-Mogollon sections, groundwater occurs primarily in the poorly consolidated sediments that have accumulated in structural basins between mountain ranges. The basins themselves are commonly referred to as “alluvial basins,” although their fills are not entirely of alluvial origin (i.e., stream deposits) since they also include a variety of lacustrine, eolian and colluvial sediments. Fractured volcanic rocks (basalts, adesites, and tuffs) that immediately underlie or are interlayered with the basin fill also form productive aquifers in some areas. The occurrence of groundwater in most consolidated rocks of the region is limited to water-filled fracture zones of very low yield. Such zones occur in a wide variety of *bedrock* units including sedimentary, volcanic, intrusive-igneous, and metamorphic types. Unlike some parts of the Basin and Range province (e.g., eastern Nevada and Trans-Pecos Texas), there are no extensive bodies of carbonate rock that provide conduits for interbasin groundwater flow. The two major roles played by hard rocks are (1) in the formation of surface and buried basin boundaries and (2) as ultimate source areas for most of the transported sediment that forms the basin fill. Boundary structures such as faults and flexures that separate bedrock uplifts from basin blocks are part of a group of tectonic and volcanic features that also play a major role in groundwater-flow dynamics.

Conceptual Hydrogeologic-Framework Model

Maps, schematic cross-sections, and supporting well-log interpretations (cited literature) are the key to the region’s complex hydrogeologic framework and constitute the major body of basic and interpretative information on aquifer characteristics used in preparation of this report. The conceptual model of the hydrogeologic framework of an interconnected surface-water, shallow valley-fill/basin-fill and deep-basin aquifer system was initially developed for use in groundwater flow models of the Mesilla and Albuquerque basins. However, original model design was flexible enough to allow it to be modified for use in other basins of the Rio Grande rift and adjacent parts of the southeastern Basin and Range province. This model is simply a qualitative description (graphical, numerical, and verbal) of how a given geohydrologic system is influenced by (1) bedrock-boundary conditions, (2) internal-basin structure, and (3) the textural character, mineralogical composition and geometry of various basin-fill stratigraphic units. It provides a mechanism for systematically organizing a large amount of relevant hydrogeologic information of widely varying quality (from very general drilling logs to detailed core-hole, geophysical and geochemical data). Model elements can be graphically displayed in a combined map and cross-section format so that basic information and inferences on geohydrologic attributes (e.g., hydraulic conductivity, transmissivity, anisotropy and general spatial distribution patterns) may be transferred to basin-scale, three-dimensional numerical models of groundwater-flow systems. The hydrogeologic framework of trans-international boundary aquifers, with special emphasis on features related to environmental concerns, is described here in terms of three basic conceptual building blocks: Hydrostratigraphic units (HSUs), lithofacies assemblages, and structural-boundary conditions.

Hydrostratigraphic units are mappable bodies of basin-fill and valley-fill deposits grouped on the basis of origin and position in both lithostratigraphic and chronostratigraphic sequences. The Upper, Middle, and Lower Gila and Santa Fe hydrostratigraphic units comprise the major basin-fill aquifer zones, and they correspond roughly to the (formal and informal) Upper, Middle and Lower lithostratigraphic subdivisions of the Gila and Santa Fe Groups used in local and regional geologic mapping. Santa Fe units are mapped only in the eastern part of the Mimbres Basin system that is transitional to the Rio Grande rift structural province. The other major hydrostratigraphic units comprise channel and floodplain deposits of the Gila and Mimbres rivers and Animas Creek in the United States, and the Casas Grandes and San Bernardino fluvial systems in Mexico. These inner river-valley fills of Late Quaternary age (most <30 ka) form the upper part of the region's major shallow-aquifer system. Surficial lake and playa deposits, fills of major arroyo valleys, and piedmont-slope alluvium are primarily in the unsaturated (*vadose*) zone. However, they may form important groundwater discharge and recharge sites. Historical saturated (*phreatic*) conditions exist, or have recently existed, in a few playa remnants of large pluvial lakes of Late Quaternary age. Notable examples are "alkali flats" in the lower Animas, Playas, Hachita (Laguna Los Moscos), Mimbres, Bolson de las Muertos, and Casa Grandes (Laguna Guzman) basins. The lower reaches of the Mimbres and Casas Grandes systems include extensive fluvial-fan and fan-delta deposits that are graded to playa-lake plain complexes that are remnants of pluvial Lake Palomas (max. Late Pleistocene surface area of 7,770 m^2; 3,000 mi^2).

Lithofacies assemblages are the basic building blocks of the model. In this study, basin and valley fills are subdivided into thirteen major units. These mappable sedimentary bodies are defined primarily on the basis of grain-size distribution, mineralogy, sedimentary structures and degree of post-depositional alteration. They have distinctive geophysical, geochemical and hydrologic attributes, and are ranked in decreasing order of aquifer potential (1-10, a-c). Structural and bedrock features include basin-boundary mountain uplifts, bedrock units beneath the basin-fill, fault zones and flexures within and at the edges of the basin that influence aquifer composition and behavior, and igneous-intrusive and extrusive rocks that penetrate or are interbedded with basin deposits.

Basic Flow-Model Concepts

The conceptual model of surface-water and groundwater flow in the intermontane-basin aquifer systems of the study area is based on previous work in the Basin and Range province. The terms *closed* and *open* refer solely to the surface flow into, through and from intermontane basins, whereas the terms *undrained*, *partly drained*, and *drained* designate classes of groundwater flow involving intrabasin and or interbasin movement. *Phreatic playas* (with springs and seeps) are restricted to floors of *closed* basins that are *undrained* or *partly drained*, and *vadose playas* occur in both *closed* and *open, drained* basins. In the transboundary study region as well as in most other desert basins of western North America, the intermediate basin class referred to as *partly drained* is probably the major groundwater-flow regime. Few intermontane basins *(bolsons* and *semibolsons*) are truly *undrained* in terms of groundwater discharge, whether or not they are *closed* or *open* in terms of surface flow.

Under predevelopment conditions, groundwater discharge in the region occured mainly through subsurface leakage from one basin system into another, discharge into the gaining reaches of perennial or intermittent streams, discharge from springs, or by evapotranspiration from *phreatic playas* and cienegas (valley-floor-wetlands). Groundwater recharge occurs mainly by mountain-front mechanisms and along the losing reaches of larger streams. The upland networks of major stream valleys of the Datil-Mogollon section, and the Sierra Madre Occidental region of northwestern Mexico are the primary source areas for recharge of basin-fill aquifers in the Mexican Highland section. Secondary contributors to these groundwater reservoirs are the few high and massive mountain ranges that form isolated highlands within individual basin systems. Recharge estimates in this report are based on the assumption that (1) only 1 to 2% of average annual precipitation contributes to recharge, and (2) this precipitation contribution is distributed very unevenly over higher watersheds and in major stream valleys.

GROUNDWATER-FLOW SYSTEM IN BASIN-FILL AQUIFERS

Introduction

Each of the six basin systems described in this report is characterized by one or more distinct groundwater-flow regimes, and only three (Mimbres, Hachita-Moscos, and San Bernardino) have significant trans-international boundary aquifer components. The Gila River Basin system, which heads in the high plateaus of the Datil-Mogollon section, comprises a series of deep canyons and valleys that are cut well below most of the basin fill aquifers of the Mexican Highland section. While this basin has no direct relationship with transboundary aquifers, it acted as the regional sink for nearly all predevelopment groundwater flow in the Animas Basin system. Hydraulic properties of major aquifer systems are well documented in widely spaced areas of irrigation agricultural and near the few centers of urban population and mineral-processing activity. The hydrogeologic/geohydrologic setting of most of the region, however, has never been investigated at more than a reconnaissance level.

Preliminary numerical models of groundwater flow in the basin-fill aquifer system have only been developed for the Mimbres Basin (system) and the Lower Animas Subbasin. These models are two dimensional; and they are, therefore, poorly suited for relatively accurate characterization of the well-documented vertical changes in aquifer conditions such as head distribution and decreasing permeability with depth. The provisional three-dimensional hydrogeologic models of aquifer systems developed as part of the present study are an initial step toward creation of numerical models that more accurately portray the essential elements of the groundwater-flow system.

Hydraulic Properties

The most productive part of the basin-fill aquifer system is formed by (1) unconsolidated to partly indurated deposits of the Upper and Middle Gila Group, and (2) overlying basin and valley fills deposited by the Animas, Mimbres, Gila, San Bernardino, and Casas Grandes fluvial systems. The total saturated thickness of these hydrostratigraphic units rarely exceeds 150 m (500 ft).

The major sources of information on hydraulic properties of aquifer units are records of irrigation-well performance and irrigation-project activities in the Mimbres, Animas and Playas basin systems. Maximum discharge ranges for most irrigation wells are from 1,090 to 5,450 m^3/d (200 to 1,000 gpm). Calculated aquifer transmissivities are as high as 4,650 m^2/d (50,000 ft^2/d [374,000 gpd/ft]) at a few localities, but most values are in the 200 to 2,000 m^2/d (2,150-21,500 ft^2/d) range. Typical ranges in horizontal conductivity for the upper, more productive parts of the aquifer system are from 1 to 10 m/d (3-30 ft/d). Specific yield estimates vary from 0.1 to 0.2, assuming unconfined aquifer conditions. Since semiconfined to confined conditions prevail in many parts of the aquifer system, however, estimates of groundwater availability (as well as assessment of aquifer-deformation and land-subsidence potential) may require much smaller storage coefficient values. Limiting assumptions used in this study for preliminary estimates of available water stored in the basin-fill aquifer systems include: (1) aquifer is unconfined, (2) estimated average thickness is 100 m (330 ft), (3) specific yield is 0.1, and (4) quality is relatively good (< 1,000 mg/L TDS).

Irrigation-well specific-capacity data provide the basis for many of the published interpretations of aquifer performance and hydraulic properties. Highest average specific capacities (232-304 $m^3/d/m$, 13-17 gpm/ft) are reported for wells completed mainly in the coarse-grained hydrostratigraphic units of the Upper Gila Group and overlying basin fill. Saturated thickness of these units is about 100m (330 ft). Wells completed in the 100 to 200m (330-660 ft) zone usually penetrate partly indurated basin-fill of the Middle Gila Hydrostratigraphic Unit (HSU), as well as the basal zone of Upper Gila deposits. Their specific capacities are typically in the 143-214 $m^3/d/m$ (8-12 gpm/ft) range. Wells completed at depths below 200 and 300m (660 and 1,000 ft), respectively, commonly penetrate partly indurated to well-consolidated deposits of the Middle and Lower Gila units, and average specific capacities range from 125 to 161 m^3/d (7-9 gpm/ft) to well below 90 $m^3/d/m$ (5 gpm/ft). Horizontal hydraulic conductivities in conglomeratic sandstones and mudstones of the Lower Gila HSU are estimated to be no more than 0.3 m/d (1 ft/d).

BASIN SYSTEM FLOW REGIMES

The Mimbres, Hachita-Moscos, and San Bernardino Basin systems are the only ones with important trans-international boundary aquifers and groundwater-flow components. All predevelopment (pre-1910) discharge was southward into Mexico. The estimated upper limit of transboundary groundwater movement through these basin-fill aquifer systems during the past century is about 17.3 x 10^6 m^3 (14,050 ac-ft). Groundwater-flow regimes in these systems as well as the two basin systems with very small transboundary aquifer components (Playas/San Basilio and Animas) are briefly summarized in the following sections.

Mimbres Basin System

The largest basin system described in this study is the *open* and *drained* Mimbres system, with six structural subbasins and three large intra-basin mountain ranges. The system has an area of about 11,300 km^2 (4,360 mi^2) in New Mexico and about 2,000 km^2 (770 mi^2) in Chihuahua. The Upper Mimbres Subbasin is located in the Datil-Mogollon Section adjacent to the Continental Divide and contains the only perennial reach of the Mimbres River. However, most of the Mimbres Basin system is in the Mexican Highland section and includes the largest trans-international boundary aquifer zone in the study area. Older channel and fluvial-fan deposits of the ancestral Mimbres River extend to the Mexican border in the Deming and Florida subbasins and occupy much of the basin-floor area between Deming and Columbus.

Maximum fill thicknesses in the deepest structural subbasins (San Vicente, Deming, Hermanas, and Florida) are in the 600 to 1,525 m (2,000-5,000 ft) range. As emphasized throughout this report, however, productive aquifer zones are usually only in the upper 200 to 300 m (660-1,000 ft) of the basin-fill sequence. Intervening structural highs form not only "insular" (Cooke's, Florida, Tres Hermanas) mountain ranges and hilly uplands, but also buried "bedrock sills." The latter features have a relatively thin cover of saturated basin fill and restrict southward groundwater flow between subbasins. A very "liberal" estimate of groundwater of relatively good quality stored in the unconfined part of the aquifer system is no more than 3.78 x 10^{10} m^3 (3.06 x 10^7 ac-ft). This estimate may be much too high, however, because at many localities most of the upper basin-fill aquifer is fine grained and semiconfined to confined conditions prevail. In addition, much of the water stored in thicker aquifer zones may be very old (thousands to tens of thousands of years and of poor quality), and it is not effectively recharged under Holocene climatic conditions. Published estimates suggest that 1 to 2% of average annual precipitation, primarily concentrated high mountain areas in the northern part of the basin system, contributes to groundwater recharge. Total annual recharge could be as high as about 7.4 x 10^7 m^3 (60,000 ac-ft), with the mountain-front component estimated at about 6.6 x 10^7 m^3 (55,300 ac-ft).

Groundwater in the Mimbres Basin system generally moves from the northern highlands to the interior basins flanking the Florida Mountains, and then southward toward the Hermanas-Columbus-West Portillo segment of the International Boundary. Estimated predevelopment (pre-1909) flow into Mexico was about 8 x 10^6 m^3 (6,500 ac-ft) annually. Much of this flow has been intercepted by irrigation wells in the Deming, Hermanas, and Columbus-Palomas areas during the past century. The *regional sink* for groundwater crossing the New Mexico-Chihuahua border is the complex of *vadose* and *phreatic playas* on the Bolson de los Muertos at the south end of the Columbus and Florida subbasins of the Mimbres system. This area includes the eastern part of the pluvial Lake Palomas basin (maximum highstand recorded by relict shoreline features at 1,225 m [4,018 ft]).

Hachita-Moscos Basin System

The *closed* and *partly drained* Hachita-Moscos Basin system includes an important trans-international boundary aquifer component and covers an area of about 2,700 km^2 (1,040 mi^2), with about 1,100 km^2 (425 mi^2) in Mexico. The system comprises three subbasins: Upper Hachita, Wamel-Moscos and Lower Hachita, which converge in a large closed depression that is occupied by the ephemeral lake plain of Laguna los Moscos. Bordering mountain ranges effectively separate this basin system from the Mimbres and Playas basin systems except in the Hatchet Gap area. Ephemeral axial streams (Hachita and Wamels Draws) carry surface runoff from highland areas to Laguna los Moscos in Chihuahua.

Maximum fill thicknesses in the half-graben subbasins range from about 600 to 900 m (2,000 to 3,000 ft), but the primary aquifer system comprises basin-floor and piedmont-slope deposits of the Upper and Middle Gila Group that are unconsolidated to partly indurated and as much as 200 m (660 ft) thick. A very liberal estimate of available groundwater of relatively good quality in storage is no more than 6 x 10^9 m^3 (4.86 x 10^6 ac-ft). Estimated annual recharge to the Hachita-Moscos aquifer system is about 6 x 10^6 m^3 (4,800 ac-ft). This estimate includes a small annual underflow component (less than 10,000 m^3 [8 ac-ft] that "spills" from the Upper Playas Subbasin into the Upper Hachita Subbasin through Hatchet Gap.

Groundwater flow generally mimics surface topography and moves eastward along basin axial trends toward Laguna los Moscos. This ephemeral-lake plain appears to have both *phreatic* and *vadose* flow components, with a partial underflow drainage connection with the Lower Valley of Rio Casas Grandes, which is located only 10 km (6 mi) to the east across a very low topographic divide. During Late Pleistocene glacial-pluvial stages, the Laguna los Moscos depression was flooded by pluvial Lake Hachita (surface area of about 150 km^2 [58 mi^2] based on shoreline features at about 1,262 m [4,140 ft] elev.). A preliminary estimate of potential transboundary groundwater from the combined Upper Hachita and Wamel-Moscos International Boundary sectors is no more than 2.5 x 10^6 m^3 (2,000 ac-ft) annually.

Playas and San Basilio Basin Systems

The north-south trending group of (half-graben) structural basins that form the Playas and San Basilio Basin systems have two distinct groundwater-flow regimes and are treated as separate geohydrologic units in this report. The *closed* and *undrained* to *partly drained* San Basilio Basin, with an area of about 1,000 km^2 (385 mi^2), is almost entirely in northwestern Chihuahua. Ephemeral surface flow and all groundwater movement is southward away from the watershed divide that forms the southern and southwestern perimeter of the Playas and Hachita-Moscos basin systems, respectively. This drainage divide parallels the International Boundary sector that includes the Antelope Wells and El Berrendo ports of entry. Part of the basin's western border follows the Continental Divide along the crest of Sierra San Luis. The terminal *sink* for both surface and subsurface flow is a large ephemeral-lake plain and alkali flat here designated La Soda "Playa." Some underflow drainage from this complex *phreatic* and *vadose playa* system probably "leaks" into the northwestern drainage basin of the Rio Casas Grandes.

The *partly closed, partly drained* Playas Basin system also has no significant trans-international boundary aquifer component. The Basin system has an area of about 2,400 km^2 (925 mi^2), which is almost entirely in New Mexico, and it comprises two subbasins. The Upper (southern) Playas Subbasin is an *open* and *drained* geohydrologic system that primarily discharges to the *closed* and *partly drained* Lower (northern) Playas Subbasin. However, a small amount of surface flow and groundwater underflow (<10,000 m^3 [8 ac-ft]/yr) spills through Hatchet Gap (between the Big and Little Hatchet ranges) into the Upper Hachita Subbasin. The Lower Playas Subbasin includes a large ephemeral-lake plain (*phreatic-vadose playa*) complex now periodically flooded by Playas Lake. During Late Quarternary pluvial stages, this depression was flooded by Lake Playas, which had a maximum surface area of about 65 km^2 (25 mi^2) based on high shoreline features at about 1,311 m (4,300 ft) elevation.

Maximum basin-fill thickness is estimated to be about 600 m (2,000 ft), but the primary aquifer system comprises basin-floor and piedmont-slope deposits of the Upper and Middle Gila Group. The hydrostratigraphic units are unconsolidated to partly indurated and no more than 300 m (1,000 ft) thick. A very liberal estimate of available groundwater of relatively good quality stored in the unconfined part of the saturated zone is no more 6 x 10^9 m^3 (4.86 x 10^6 ac-ft). Estimated annual recharge to the Playas Basin aquifer system is about 7 x 10^6 m^3 (5,670 ac-ft). The major recharge sources in both the Playas and San Basilio systems is from the high Sierra San Luis and Animas mountain ranges that border the basin on the west.

A provisional estimate of annual northward flow from the Upper to Lower Playas subbasins in the Middle to Upper Gila basin-fill aquifer system is about 5.48 x 10^6 m^3 (4,730 ac-ft). Most of this flow was discharged by evaporation and transpiration in the southern Playas Lake depression in predevelopment time (pre-1945). However, a very small amount of flow also appears to have "leaked" from the Lower Playas area into aquifers of the northern Animas Basin system via conduits beneath the Continental Divide northwest of Playas Lake.

Animas Basin System

The Animas Basin system is an interconnected group of four structural and geohydrologic subbasins that has a watershed area of about 6,340 km^2 (2,448 mi^2). The Continental Divide (including the crests of the San Luis and Animas ranges) forms the entire eastern boundary of the system; and on the west, it is separated from the San Bernardino and San Simon Basin system (mainly in Arizona) by the Peloncillo-Guadalupe range. About 90 km^2 (35 mi^2) of the *closed* and *partly drained* Cloverdale (San Luis) Subbasin, at the south end of the system, extends into Mexico and straddles the New Mexico-Chihuahua-Soñora Border. This subbasin, with a total area of 480 km^2 (185 mi^2), is the only part of the basin system that has any trans-international boundary aquifer component. It includes *phreatic-vadose playa* complex in a *closed* depression that was flooded by pluvial Lake Cloverdale during Late Pleistocene glacial stages (and probably also during wetter intervals of the Late Holocene). Maximum lake area was about 104 km^2 (40 mi^2) based on high shoreline features at about 1,576 m (5,170 ft).

The only perennial to intermittent streams in the Animas Basin system are in the valleys of Animas Creek and its major headwater tributaries. These channel reaches are located in the southern part of the *open* and *drained* Upper Animas Subbasin, which is separated from the Cloverdale Subbasin by a low topographic divide. The Upper Animas Subbasin opens northward into the *closed* and *drained* Lower Animas Subbasin, which includes the major area of irrigation agriculture west of the central Mimbres Basin system (Animas-Cotton City area). Dominant surficial units are widespread fluvial-deltaic deposits of ancestral Animas Creek and an extensive Middle Pleistocene basalt flow west of Animas. The northern part of the Lower Animas Subbasin includes dune fields and a large ephemeral-lake plain with alkali flats that comprise a *vadose playa* complex. During Late Pleistocene glacial-pluvial intervals, the entire basin floor below an elevation of 1,279 m (4,195 ft) was episodically flooded by pluvial Lake Animas (maximum surface area of about 390 km^2 (150 mi^2).

The *open* and *drained* Lordsburg Subbasin, which heads in the Burro Mountain-Continental Divide area contiguous to the Mimbres Basin system, joins the Lower

Animas Subbasin at the eastern edge of the Lake Animas–Alkali flat depression. The major drainageway in this subbasin is Lordsburg Draw. A basin-fill aquifer with an area of about 315 km^2 (122 mi^2) at the east edge of the Lordsburg Subbasin (China Draw section) contributes underflow discharge to the Mimbres Basin system across the Continental Divide.

Maximum basin-fill thickness is estimated to be about 600 m (2,000 ft). The primary aquifer, however, comprises coarse-grained basin-floor facies assemblages deposited by the ancestral Animas Creek and Lordsburg Draw fluvial systems. Hydrostratigraphic units include the Upper and Middle (?) Gila Group and post-Gila stream and fan-delta deposits of Middle and Late Pleistocene age. Maximum thickness of productive aquifer zones may locally be as much as 300 m (1,000 ft), but most groundwater production in the Animas-Cotton City-Lordsburg area is from the upper 150 m (500 ft) of saturated basin fill. A very liberal estimate of available groundwater of relatively good quality stored in the unconfined part of the saturated zone is no more than 1.2 x 10^{10} m^3 (9.5 x 10^6 ac-ft). Estimated annual recharge to the Animas Basin aquifer system in the Lower Animas Subbasin is about 1.58 x 10^7 m^3 (12,800 ac-ft). The major recharge sources are from the high ranges that flank the Upper Animas Subbasin.

A very small component of groundwater flow from a thin "perched" aquifer zone in the Cloverdale playa area may leak southwestward into the Soñora part of the San Bernardino Basin via Guadalupe Canyon and Cajon Bonito. Most groundwater in the Cloverdale Subbasin, however, discharges as underflow to "perched" and "deep" aquifers of the Upper Animas Subbasin (following the valley of Animas Creek). It then moves northward toward the northern end of the Lower Animas Subbasin. Under predevelopment conditions a large volume of groundwater moved beyond the alkali flat (*vadose playa*) area and discharged as underflow to the Gila River Basin aquifer system. Published estimates of predevelopment basin outflow are as much as 16 x 10^6 m^3 yr (12,700 ac-ft/yr). Agricultural and urban pumping centers now capture most of this flow.

San Bernardino Basin

The *open* and *drained* San Bernardino Basin includes an important trans-international boundary aquifer component, and covers an area of about 1,090 km^2 (420 mi^2) in the United States. Only about 90 km^2 (35 mi^2) of the basin's eastern mountain watershed, which extends to the Cloverdale Subbasin rim, is in New Mexico. Ephemeral to intermittent streams in the northern part of the basin converge near the Arizona-Soñora border to form the headwaters of the perennial to intermittent Rio (del) San Bernardino. The confluence area includes the lower reaches of Black Draw, Cottonwood Draw, and Silver Creek, as well as an area of cienegas and flowing wells at the San Bernardino National Wildlife Refuge (and historic ranch site). Rio Guadalupe and Rio (de) Cajon Bonito, which head along the southwestern rim of the Cloverdale Subbasin, join the Rio (del) San Bernardino south of the International Boundary.

Interbedded basalt flows and vent units of the Late Miocene to Middle Pleistocene Geronimo volcanic field are a major component of the upper (Gila Group) basin-fill sequence. However, only the western half of the basin floor area is underlain by thick basin fill deposits (as much as 500 m, 1,650 ft). Basalt flows interbedded with the Upper Gila Group form local confining beds as well as aquifers. A very liberal estimate of available groundwater of relatively good quality stored in Upper to Middle Gila hydrostratigraphic units is no more than 5 x 10^9 m^3 (4 x 10^6 ac-ft). The estimated annual recharge to the San Bernardino Basin aquifer system is about 8 x 10^6 m^3 (6,480 ac-ft).

Basinwide groundwater movement in the San Bernardino Basin coincides with the general southward flow direction of the surface water system. The northern basin boundary is the watershed divide at the southern edge of the *open* and *drained* San Simon Subbasin. The latter (northward) surface-and subsurface-flow system is tributary to the Safford Valley reach of the Gila River Basin, while the San Bernardino flow system ultimately contributes to the Rio Yaqui (Bavispe, Batepito) fluvial system in Soñora. The Rio Yaqui empties into the Gulf of California west of Ciudad Obregón. A very preliminary estimate of annual trans-boundary groundwater flow for the Arizona part the basin into Mexico is 6.8 x 10^6 m^3 (5,545 ac-ft).

GROUNDWATER QUALITY

The complex and highly variable lithologies and rock types in the study region create a variety of hydrochemical facies that contribute to the irregular distribution of salinity in the aquifers. Groundwater varies from very dilute to moderately saline and hydrochemical facies vary from calcium-magnesium-bicarbonate to sodium-chloride-sulfate type waters. Irrigation water quality is generally acceptable, with many groundwaters characterized by medium salinity hazard and low alkali hazard. Some groundwaters have marginal water quality for domestic, livestock, and irrigation purposes. Nitrate in groundwater seldom exceeds the USEPA drinking water standard of 10 mg/L NO$_3$-N.

The evolutionary hydrochemical trends that are evident in most of the basins in the study area include the development of dilute, calcium-magnesium-bicarbonate groundwaters in the mountains that evolve to dilute, sodium-bicarbonate groundwaters in alluvial fans. Groundwater continues to evolve to slightly saline, sodium-bicarbonate-sulfate type waters in many basins–the sulfate concentrations in groundwater becoming greater than the bicarbonate concentrations as groundwater moves further downgradient.

Mimbres Basin System

Groundwater in the northern half of the Mimbres Basin system is usually less than 500 mg/L TDS (total dissolved solids). Near and extending across the U.S./Mexico border, groundwater is usually greater than 500 mg/L TDS, reaching concentrations greater than 1,000 mg/L in the southernmost part of the Mimbres Basin system. Groundwater has low alkali hazard and medium salinity hazard for irrigation purposes in most groundwaters in the northern part of the basin. Salinity risks increase to high hazard, and alkali hazard is low to very high in the southern Mimbres Basin system. Nearly all of the water quality analyses are well below 5 mg/L NO$_3$-N.

Hachita-Moscos Basin System

Water quality data are limited in the Hachita-Moscos Basin. The available data indicate that most groundwater samples in the northern Moscos Basin and Hachita Basin are less than 500 mg/L TDS. In the southern Moscos Basin, groundwater often exceeds 500 mg/L TDS and several samples are greater than 1,000 mg/L TDS. Groundwater has low alkali hazard and medium salinity hazard for irrigation purposes in most groundwaters in the Hachita Basin and northern Moscos Basin. About half the samples in the southern Moscos Basin have medium to very high alkali hazard and high salinity hazard. The other samples have low alkali hazard and medium salinity hazard. Nearly all of the water quality analyses are well below 5 mg/L NO$_3$-N.

Playas and San Basilio Basin Systems

Groundwaters in the Upper Playas Subbasin are less than 500 mg/L TDS. The southern half of the Lower Playas Subbasin is also characterized by groundwater with salinities less than 500 mg/L TDS. Groundwater salinities in the northern half of the Lower Playas Subbasin often vary from 500 to 1,000 mg/L TDS. Groundwater has low alkali hazard and low-to-medium salinity hazard for irrigation in the Upper Playas Subbasin. Nearly all of the groundwater samples in the Lower Playas Subbasin have low-to-medium alkali hazard and medium salinity hazard. Most groundwater samples have less than 1 mg/L NO$_3$-N.

Animas Basin System

Groundwater in the southern part of the Animas Basin is usually less than 250 mg/L TDS. Groundwater is usually greater than 250 mg/L TDS in the northern part of the Animas Basin, reaching concentrations greater than 1,000 mg/L in several areas. Groundwater has low alkali hazard and low to medium salinity hazard in the southern part of the Animas Basin. Groundwater in the northern part of the basin has highly variable salinity and alkali hazard; most samples exhibiting medium-to-high salinity hazard and low-to-high alkali hazard. Most of the water quality analyses for this basin are below 5 mg/L NO$_3$-N.

San Bernardino Basin

Groundwaters in the San Bernardino Basin are less than 1000 mg/L TDS. Several clusters of samples at the international border, near the axis of the basin, are less than 250 mg/L TDS. The data in Mexico are too limited to evaluate relationships of salinity to spatial locations in the basin. Groundwater has low alkali hazard and low-to-medium salinity hazard in the Mexican portion of the San Bernardino Basin. Most groundwater samples in the U.S. part of the San Bernardino Basin have low alkali hazard and medium salinity hazard. Nitrate data are very limited in the San Bernardino Basin. The very limited data are all less than 2.0 mg/L NO$_3$-N, both in the United States and Mexico.

RECOMMENDATIONS

- Only three aquifers (Mimbres, Hachita-Moscos, and San Bernardino) have significant trans-international boundary aquifer components. All predevelopment (pre-1910) discharge was southward into Mexico. The estimated upper limit of this pre-development transboundary groundwater movement through these basin-fill aquifer systems is about 17.3 x 10^6 m^3 (14,050 ac-ft) annually. A significant portion of this flow from the Mimbres Basin system into Mexico (about 8 x 10^6 m^3 [6,500 ac-ft]) annually has been intercepted by irrigation wells in the Deming, Hermanas, and Columbus-Palomas areas during the past century. Current transboundary groundwater flow is estimated to be about 9.2×10^6 m^3 (7,550 ac-ft) annually. Data collection efforts in the U.S. component of these shared groundwater aquifers should be expanded. Arrangements for sharing of these data with the Republic of Mexico are encouraged. Joint bi-national efforts to model these groundwater systems should be pursued.

- The estimates of groundwater of relatively good quality stored in the unconfined parts of the Mimbres, Hachita-Moscos, Playas, Animas, and San Bernardino aquifer systems is about 6.7×10^{10} m^3 (54×10^6 ac-ft). This estimate may be much too high, because at many localities much of the upper basin-fill aquifer is fine grained and semiconfined to confined conditions prevail. In addition, much of the water stored in the thicker aquifer zones may be very old (thousands to tens of thousands of years) and of poor quality. The recharge to these aquifers is estimated to be about 1.1×10^8 m^3 (90,000 ac-ft) annually. This indicates that only 0.2 % of this resource is being replenished annually. Efforts to monitor the impacts of withdrawals are recommended.
- The estimates of recharge to the groundwater aquifers addressed in this study were based on published estimates that suggest that only 1 to 2% of average annual precipitation, primarily concentrated in high mountain areas of the basin system, contributes to groundwater recharge. Investigations should be undertaken to improve and develop techniques that can more accurately quantify recharge.
- Preliminary numerical models of groundwater flow in the basin-fill aquifer system have only been developed for the Mimbres Basin (system) and the Lower Animas Subbasin. These models are two dimensional, and they are, therefore, poorly suited for relatively accurate characterization of the well-documented vertical changes in aquifer conditions such as head distribution and decreasing permeability with depth. The provisional three-dimensional hydrogeologic models of the aquifer systems developed as part of this study are an initial step toward creation of numerical models that can more accurately portray the essential elements of the groundwater-flow system. Efforts to develop numerical models as well as the enhancement of data required are encouraged.
- Generally the groundwater quality of the aquifers is relative good. However, the complex and highly variable lithologies and rock types create a variety of hydrochemical facies that contribute to irregular distribution of salinity. Hydrochemical analysis of groundwater samples are severely limited in most of the aquifers and there is insufficient time-series data to evaluate trends. Data collection efforts should be expanded to provide increased geographic distribution of sample sites and long-term monitoring programs should be expanded and maintained.